Cost-effectiveness of countermeasures

1. Background

It needs to be emphasized that cost-effectiveness – as defined in this document – does not include the cost of managing wastes produced by countermeasures or the incremental doses to those implementing the countermeasures.

As stated by ICRP 63, any countermeasure used for intervention in a radiological emergency should do more good than harm and the form, scale and duration should be optimised so as to maximise the net benefit. It also states that "The first step in deciding on the intervention likely to be needed in the event of an accident is to define the type of all the likely protective actions and to consider the costs and disadvantages as well as the expected reductions in individual and collective doses as functions of the scale and duration of each. For individual doses, both the average dose and the distribution of doses within the population will have to be taken into consideration. A substantial amount of preliminary work on economic and environmental models and on accident forecasting is needed for these assessments".

If the projected dose for a population group or an individual person is expected to be above accepted limits, countermeasures should be implemented to reduce the dose. Care should be taken that the magnitude of the averted dose is sufficient to justify the implementation of any protective action, irrespective of implementation strategy.

Some radiological protection factors are more quantifiable than others, e.g. averted individual and collective doses to members of the public, and monetary costs of countermeasure implementation. Less quantifiable factors include reassurance to the public and workers, anxiety caused by implementation, or lack of implementation, and the individual and societal disruption due to implementation of countermeasures.

The aim of STRATEGY is to include a wide range of different factors in a decision making approach. This document focuses on the cost-effectiveness of countermeasures, i.e. the direct monetary cost of reducing a unit collective dose (€/personSv) when implementing a countermeasure. It is only possible to calculate cost-effectiveness if the countermeasure achieves an averted collective dose. For countermeasures where this is not the case, neither averted dose nor cost equations are given (e.g. dilution and medical check-up). Collective doses are useful for cost-effectiveness calculations, as well as for justification and optimisation of countermeasures. This document gives a generic description of how to calculate cost-effectiveness, based on the STRATEGY database of selected countermeasures. Actual averted doses and costs can only be calculated according to a specific scenario, an example of which is given in chapter 5.

2. Averted doses

When countermeasures are implemented after nuclear accidents, the reduction in radiation dose achieved is referred to as the averted dose. The averted dose can be calculated either for exposed individuals (individual averted dose) or for an exposed population (collective averted dose). For calculating the cost-effectiveness of countermeasures, only collective averted doses are used. A short presentation of the relevant equations for calculating this value is given below. The full averted dose methodology is described in Averted dose methodology.

A table is included at the end of chapter 4 where all STRATEGY countermeasures are attributed to an appropriate averted dose equation.

2.1 Agricultural land

We assume that all the agricultural produce from an agricultural area would be eaten sometime, somewhere by someone without specifying the actual recipient. The resulting averted collective (AD^{coll}; personSv) doses when implementing countermeasures will then be:

For crops:

$$AD^{coll}(t) = \int_{t_c}^{t} A_s(t) \cdot P_{area} \cdot Y_p \cdot T_{ag} \cdot f_e \cdot DCF_{ing} \cdot E_{CM}\, dt \qquad \textbf{(Eq. 1)}$$

For animal produce:

$$AD^{coll}(t) = \int_{t_c}^{t} A_s(t) \cdot T_{ag} \cdot FR \cdot TF \cdot Y_a \cdot No^a \cdot DCF_{ing} \cdot E_{CM}\, dt \qquad \textbf{(Eq. 2)}$$

where

$A_s(t)$ = *Soil activity (Bq/m²) at time t* given by:

$$A_s(t) = DEP \cdot e^{\frac{-ln2 \cdot t}{T_{eff,ecol}}} \qquad \textbf{(Eq. 3)}$$

and

DEP = *Initial deposition (Bq/m²)*

P_{area} = *Production area (m²)*

Y_p = *Production yield for crops (kg/m² per unit time)*

T_{ag} = *Aggregated transfer factor (from soil to plant) (m²/kg)*

f_e = *Edible fraction of crop (dimensionless) according to processing*

FR = *Feeding rate of animal (kg/unit time)*
TF = *Transfer factor (from feed to animal produce) (unit time/kg)*
Y_a = *Animal yield (kg per unit time)*
No^a = *Number of animals*
DCF_{ing} = *Nuclide dependent Dose Conversion Factor for ingestion (Sv/Bq) (ICRP, 1996)*
E_{CM} = *Countermeasure effectiveness (dimensionless), fraction as specified in data sheets*
$T_{eff,ecol}$ = *Effective ecological half time for the given nuclide in the given ecosystem (unit time)*
t = *Time since deposition (unit time)*

If several feed types are used per animal, we need to sum up over all relevant feed types 1-m:

$$\sum_{1}^{m} T_{ag}^{m} \cdot FR^{m} \cdot TF^{m} \qquad \textbf{(Eq. 4)}$$

If we know the activity concentration in a produce, either by measurements or by using models, such as the STRATEGY model, the equations can be simplified to:

For crops:

$$AD^{coll}(t) = \int_{t_c}^{t} A_i(t) \cdot P_{area} \cdot Y_p \cdot DCF_{ing} \cdot E_{CM}\, dt \qquad \textbf{(Eq. 5)}$$

For animal produce:

$$AD^{coll}(t) = \int_{t_c}^{t} A_j(t) \cdot Y_a \cdot No^a \cdot DCF_{ing} \cdot E_{CM}\, dt \qquad \textbf{(Eq. 6)}$$

where
$A_i(t)$ = *Activity concentration in vegetable produce i (Bq/kg) at time t*
$A_j(t)$ = *Activity concentration in animal produce j (Bq/kg) at time t*
P_{area} = *Production area (m^2)*
Y_p = *Production yield for crops (kg/m^2 per unit time)*
Y_a = *Animal yield (kg per unit time)*
No^a = *Number of animals*
DCF_{ing} = *Nuclide dependent Dose Conversion Factor for ingestion (Sv/Bq) (ICRP, 1996)*
E_{CM} = *Countermeasure effectiveness (dimensionless), fraction as specified in data sheets*

Averted collective doses for different food products can be summed if a countermeasure has an impact on several products at a time.

2.2 Semi-natural products and drinking water

Activity concentrations in foodstuffs such as game, mushrooms, berries and freshwater fish (later referred to as *free foods*) are usually specified either by measuring samples or by using an aggregated transfer factor (T_{ag}) relative to deposition in a given area. If Eq. 7 is used to calculate the activity concentration:

$$A(t) = DEP \cdot T_{ag} \cdot e^{\frac{-\ln 2 \cdot t}{T_{eff,ecol}}} \tag{Eq. 7}$$

where

DEP = *Initial deposition (Bq/m²)*

T_{ag} = *Aggregated transfer factor (from deposition to foodstuff) (m²/kg)*

$T_{eff,ecol}$ = *Effective ecological half time for the given nuclide in a given ecosystem (unit time)*

t = *Time since deposition (unit time)*

then the averted dose can be calculated on a production basis from Eq. 8 or on a consumption basis from Eq. 9. The former is suitable for instance for game where the total amount of game meat hunted annually is usually known from hunting statistics. The latter is suitable for all foodstuffs where the consumption rate per person (CR) and the number of consumers (No^p) is known.

$$AD^{coll}(t) = \int_{t_c}^{t} A(t) \cdot W_{gathered} \cdot DCF_{ing} \cdot E_{CM}\, dt \tag{Eq. 8}$$

$$AD^{coll}(t) = \int_{t_c}^{t} A(t) \cdot CR \cdot No^{P} \cdot DCF_{ing} \cdot E_{CM}\, dt \tag{Eq. 9}$$

where

$W_{gathered}$ = *Weight of gathered food (kg per unit time)*

CR = *Consumption rate per person (kg per unit time)*

No^p = *Number of persons*

DCF_{ing} = *Nuclide dependent Dose Conversion Factor for ingestion (Sv/Bq) (ICRP, 1996)*

E_{CM} = *Countermeasure effectiveness (dimensionless), fraction as specified in data sheets*

Eq. 9 can also be used for drinking water. However, the activity concentration in water may be difficult to estimate, requiring advanced models. Focusing on medium to long term time perspectives, the VAMP or MOIRA models (IAEA, 2000; Håkanson, 2003) could be used to predict activity concentrations (of Cs and Sr) in water and freshwater fish. Effects of aquatic countermeasures may also be simulated using the latter model.

2.3 Recreational areas

The external dose to people spending time in recreational areas such as parks and forests can be reduced by implementing countermeasures. The resulting collective averted dose can be calculated by Eq. 10. The dose rate can be measured directly at the location or estimated by computerized models. The occupancy factor specifies the fraction of time spent in the effected area.

$$AD^{coll}(t) = \int_{t_c}^{t} D_{rate}(t) \cdot OF(t) \cdot No^{p} \cdot E_{CM}\, dt \qquad \textbf{(Eq. 10)}$$

where

$D_{rate}(t)$ = *Dose rate at time t (Sv/unit time)*
$OF(t)$ = *Occupancy factor (dimensionless)*
No^{p} = *Number of persons spending time in the affected area*
E_{CM} = *Countermeasure effectiveness (dimensionless), fraction as specified in data sheets*

2.4 Urban and industrial areas

For the urban and industrial environment in STRATEGY, external doses are modelled by Monte Carlo simulation as air kerma rates (Gy/unit time).

The averted collective doses for urban and industrial areas may be given as:

$$AD^{coll}(t) = \int_{t_c}^{t} K_{rate}(t) \cdot OF(t) \cdot No^{p} \cdot DCF_{kerma} \cdot E_{CM}\, dt \qquad \textbf{(Eq. 11)}$$

where

$K_{rate}(t)$ = *Kerma rate at time t (Gy/unit time)*
$OF(t)$ = *Occupancy factor (dimensionless)*
No^{p} = *Number of persons spending time in the affected area*
DCF_{kerma} = *Dose conversion factor from kerma to dose (Sv/Gy)*[1]
E_{CM} =*Countermeasure effectiveness (dimensionless), fraction as specified in data sheets*

The occupancy factor specifies the fraction of time spent in the effected area.

[1] Kis et al, 2003

3. Monetary costs

As described in the data sheets, there are many different contributions to monetary costs when implementing a countermeasure. This chapter presents generic cost equations that can be used for STRATEGY countermeasures. A table is included at the end of chapter 4 where countermeasures are attributed to an appropriate cost equation.

In general, countermeasures can be divided in two main groups, namely remedial countermeasures and product bans. Total costs connected with remedial countermeasures is here given as the cost of implementation, C_{imp}, which can be defined as follows:

$$C_{imp} = C_{manpower} + C_{equipment} + C_{consumables} \quad \textbf{(Eq. 12)}$$

The implementation cost can be calculated taking into account all details about costs specified in the data sheets. Alternatively service costs (e.g. the price a contractor would charge for implementing a specific countermeasure) can be used and will often give a more accurate estimate since it is an integrated estimate of all the aforementioned costs.

Costs of bans (C_{ban}) may be estimated using stock or crop values:

$$C_{ban} = Value\ to\ producer \quad \textbf{(Eq. 13)}$$

However, food bans will also have associated waste disposal costs.

The following paragraphs expand Eq. 12 and 13 according to different types of countermeasures.

3.1 Agricultural and semi-natural ecosystems

3.1.1 Soil-plant countermeasures

For physical countermeasures such as ploughing or removal of contaminated soil the following equation may be used to calculate implementation costs for a specified area:

$$C_{imp} = C_{area} \cdot P_{area} \quad \textbf{(Eq. 14)}$$

Costs per unit area for ploughing of pasture should include reseeding and fertilisation. For chemical countermeasures like liming or application of potassium fertilizer this equation may be expanded using:

$$C_{area} = C_{spread} \cdot R_{spread} \quad \textbf{(Eq. 15)}$$

where

C_{area} = *Implementation cost per unit area (€/ha)*
P_{area} = *Production area (ha)*
C_{spread} = *Implementation cost of spreading (€/kg)*
R_{spread} = *Spreading rate (kg/ha)*

Note that C_{spread} can depend upon R_{spread}.

Service costs of ploughing and spreading fertilizer may be found in books on farming management such as Nix, 2002 for the UK. Soil-plant measures such as ploughing might in some cases have secondary impacts that need to be included in the cost estimates. For instance, if a pasture is ploughed, replacement feed (and housing) for grazing animals is needed during the period of pasture regrowth (see Eq. 18).

3.1.2 Animal countermeasures

The primary cost equation for animal-directed countermeasures can be defined as the cost per animal times the number of animals:

$$C_{imp} = C_{animal} \cdot No^{a} \qquad \textbf{(Eq. 16)}$$

This equation may be suitable for calculating implementation cost of, for instance, AFCF boli administration to ruminants. For other countermeasures, however, more detailed equations taking into account the implementation period (T_{imp}) are more useful. In such cases, Eq. 16 could be expanded using Eq. 17 or 18, depending on the nature of the countermeasure:

$$C_{animal} = C_{time} \cdot T_{imp} \qquad \textbf{(Eq. 17)}$$

$$C_{animal} = C_{feed} \cdot FR \cdot T_{imp} \qquad \textbf{(Eq. 18)}$$

where

C_{animal} = *Implementation cost per animal (€)*
No^{a} = *Number of animals*
C_{time} = *Implementation cost per time (€/unit time)*
T_{imp} = *Implementation time (unit time)*
C_{feed} = *Cost of feed (€/kg)*
FR = *Feeding rate (kg/unit time)*

For instance, cost of housing animals may be calculated using Eq.17, whereas Eq. 18 is suitable for calculating costs of clean feeding or administration of AFCF in concentrates.

For drastic countermeasures like slaughtering dairy herds, the value of the animals and lost income to the farmer must be taken into account in addition to the implementation cost of slaughtering. The following equation can be used for the value of the animal:

$$C_{ban} = VAL \cdot No^{a} \quad \textbf{(Eq. 19)}$$

where
VAL = *Value of lost animal to the producer (€)*

There will also be associated costs of disposing of animal carcasses.

3.1.3 Food product countermeasures

Implementation costs of processing or decontaminating foodstuffs may be calculated using:

$$C_{imp} = C_{amount} \cdot W_{treated} \quad \textbf{(Eq. 20)}$$

where
C_{amount} = *Implementation cost per amount treated (€/kg)*
$W_{treated}$ = *Weight of foodstuff to be treated (kg)*

Examples might be decontamination of milk using MAG•SEP^{SM} or processing of cow's milk to cheese. Food production countermeasures will also generate wastes that need to be disposed of with associated costs.

3.1.4 Food bans

The value of a product to a producer is used to estimate costs attributed to a food ban:

$$C_{ban} = VAL \cdot W_{banned} \quad \textbf{(Eq. 21)}$$

where
VAL = *Value of product to producer (€/kg)*
W_{banned} = *Weight of banned product (kg)*

All food bans will also entail large amounts of waste that need to be disposed off with associated costs.

3.2 Aquatic environments

3.2.1 Countermeasures lowering uptake of radionuclides in fish

Implementation costs for treating lakes and catchments with potash or lime may be calculated using:

$$C_{imp} = C_{spread} \cdot R_{spread} \cdot A_{imp} \qquad \textbf{(Eq. 22)}$$

where
C_{spread} = *Implementation cost of spreading (€/kg)*
R_{spread} = *Spreading rate (kg/ha)*
A_{imp} = *Implementation area (ha)*

Note that C_{spread} may depend upon R_{spread}.

3.2.2 Drinking water treatment and alternative supply

Implementation costs due to switching or blending of drinking water supplies or regulating flow of contaminated water may be calculated from:

$$C_{imp} = C_{volume} \cdot V \qquad \textbf{(Eq. 23)}$$

where
C_{volume} = *Implementation cost per unit volume (€/L)*
V = *Volume (L)*

The volume can either refer to the amount of water that needs to be treated or as the volume necessary to provide people with safe drinking water in the affected area. Eq. 23 can thus be expanded for the latter case to:

$$V = CR \cdot No^{p} \cdot T_{imp} \qquad \textbf{(Eq. 24)}$$

where
CR = *Consumption rate per person (L/unit time)*
No^{p} = *Number of persons*
T_{imp} = *Implementation period (unit time)*

3.3. Social countermeasures

Many of the countermeasures directed at the public such as Information/Advice Bureau, Medical check-up and Citizen's jury do not avert any dose directly or in an easily quantifiable way (information/advice for example could result in high dose aversion if people follow that advice; some if not all of the social countermeasures also work in tandem with other countermeasures, making them potentially more effective in terms of dose reduction – even a medical check-up can have implication for dose, e.g. by encouraging/discouraging different behaviour patterns). Some of these might give a secondary averted dose because people become more educated on radiation matters. This effect, however, is outside the scope of this paper and is not included. Only countermeasures where cost-effectiveness calculations are possible are included below.

3.3.1 Dietary advice

Total costs of this countermeasure are limited to administration and distribution of information and will depend on the price of printing informational leaflets, time used for giving advice and method of communication (personal, internet, telephone etc.); the general Eq. 12 can be used.

3.3.2 Free food bans

The market value of a banned product may be used when estimating the cost connected to free food bans. The following equation is applicable for free food the collection of which is controlled/licensed, such as hunted game:

$$C_{ban} = VAL \cdot W_{gathered} \qquad \textbf{(Eq. 25)}$$

where
VAL = *Market value of free food (€/kg)*
$W_{gathered}$ = *Weight of foodstuff normally gathered (kg)*

If game hunting is banned there will still be a need to maintain population numbers at a sustainable level to avoid ecosystem damage. It might be necessary to pay professional hunters for this job, incurring another monetary cost ($C_{manpower}$).

For other types of free food, like berries, mushrooms and freshwater fish, it may be difficult to estimate the gathered amount due to a lack of local data. In such cases it might not be possible to attribute a monetary cost. However, relevant data can be estimated using average consumption rates, or could be gathered in the early post-accident phase.

3.3.3 Sheltering, evacuation or relocation

Implementation costs for permanent relocation of people from a contaminated area can be estimated using:

$$C_{imp} = C_{person} \cdot No^{p} \quad \textbf{(Eq. 26)}$$

In case of sheltering or evacuation the equation above could be expanded taking into account the implementation period:

$$C_{person} = C_{time} \cdot T_{imp} \quad \textbf{(Eq. 27)}$$

where
C_{person} = *Implementation cost per person (€)*
No^{p} = *Number of persons*
C_{time} = *Implementation cost per time unit (€/unit time)*
T_{imp} = *Implementation time (unit time)*

3.4 Urban and industrial environments

Costs of urban and industrial countermeasures are usually calculated on an area basis. The following equation may be used to calculate implementation costs for specified areas such as parks, roads, walls or roofs:

$$C_{imp} = C_{area} \cdot A_{imp} \quad \textbf{(Eq. 28)}$$

where
C_{area} = *Implementation cost per unit area (€/ha)*
A_{imp} = *Implementation area (ha)*

4. Cost-effectiveness analysis

A cost-effectiveness analysis is a method to determine the best protection strategy obtainable for fixed resources (ignoring all other constraints). It considers only two variables: The direct monetary cost (C)[2] and the averted collective dose (AD^{coll}) when implementing a countermeasure. The resulting cost-effectiveness (CE) is given in €/personSv:

$$CE\ (€/personSv) = \frac{C\ (€)}{AD^{coll}(personSv)} \qquad \textbf{(Eq. 29)}$$

The cost-effectiveness of countermeasures can be estimated by combining relevant averted dose and cost equations from chapters 2 and 3 respectively. To be able to calculate AD^{coll}, an implementation period has to be specified. This period has to be linked to the cost estimates. For countermeasures with continuing costs (e.g. clean feeding) an implementation period (T_{imp}) needs to be specified. This period has to be the same for calculating both AD^{coll} and cost to give correct cost-effectiveness estimates. Single one-off costs (e.g. ploughing) are time independent.

In Table 1 to Table 4 averted dose and cost equations relevant for the various countermeasures included in STRATEGY have been specified. For some of the measures, the cost-effectiveness could not be determined for instance due to no averted collective dose. In such cases the reason for not specifying equations is given in "Comments". Some countermeasures do not avert any dose themselves (no primary averted dose), but might entail a secondary averted dose, for instance Live-monitoring or Education programme in schools. Such secondary averted doses are outside the scope of this paper, and cost-effectiveness equations are not included. The following abbreviations are used in the tables: AD = averted dose, C = cost, CM = countermeasure.

A comparative study of cost-effectiveness calculations aimed at milk production for a hypothetical accident in an area in UK is given in chapter 5.

[2] The cost (C) as given here may either represent implementation costs or cost of bans (or the sum of these costs) depending on countermeasure.

Table 1: Countermeasures for agricultural and semi-natural ecosystems

Countermeasure	Averted dose equation	Cost equation	Comments
Food bans	5 or 6	21	
Dilution	-	-	No averted collective dose
Early removal of crops	5	14	
Processing of crops for subsequent consumption	5	20	
Processing of milk for subsequent human consumption	6	20	
Salting of meat for subsequent consumption	6	20	
Feeding animals with crops/milk in excess of Intervention Levels	-	-	No averted dose
Shallow ploughing	5 or 6	14	If pasture is ploughed – cost of alternative feed and housing during the regrowth period must be included (cost eq.17 and 18).
Deep ploughing	5 or 6	14	
Skim and burial ploughing	5 or 6	14	
Topsoil removal	5 or 6	14	
Application of potassium fertilisers to arable soils and grassland	5 or 6	14 and 15	
Application of lime to arable soils and grassland	5 or 6	14 and 15	
Select edible crop that can be processed	5	14	
Select alternative land use	5 or 6	14 or 16	
Live monitoring	-	-	No primary averted dose
Decontamination techniques for milk	6	20	
Suppression of lactation before slaughter	-	-	Only used as an aid to the next cm on the list
Slaughtering dairy cows	6	16 and 19	
Ploughing, fertilising and reseeding of unimproved pastures	6	14 and 15	
Clean feeding	6	16 and 18	
Distribution of concentrates with AFCF	6	16 and 18	
Distribution of concentrates with added calcium	6	16 and 18	
Administration of clay minerals to feed	6	16 and 18	
Selective grazing regime	6	16 and 17	
Manipulation of slaughter time	6	16 (and 17)	
Change of hunting season	-	-	Too complex for general AD and C equations
Administration of AFCF boli to ruminants	6	16	
Distribution of saltlicks containing AFCF	6	16	

Table 2: Countermeasures directed at social/human/communication issues

Countermeasure	Averted dose equation	Cost equation	Comments
Dietary advice	9	12	Primarily information costs
Restrictions on gathering of free food	8 or 9	25	
Restrictions on use of recreation areas	10	12	Primarily information costs, possibly fences
Advice on use of fire ash	-	-	Collective AD calculations not possible
Information/Advice Bureau	-	-	No primary averted dose
Compensation Scheme	-	-	No averted dose
Provision of counting/monitoring equipment	-	-	No primary averted dose
Raising intervention limits	-	-	No averted dose
Do nothing	-	-	No averted dose, no monetary costs
Medical check-up	-	-	No averted dose
Citizen’s jury	-	-	No primary averted dose
Education programme in schools	-	-	No primary averted dose
Food labelling	-	-	No primary averted dose
Relocation	10 or 11	26	
Evacuation/sheltering	10 or 11	26 and 27	

Table 3: Countermeasures for aquatic ecosystems and forest industry

Countermeasure	Averted dose equation	Cost equation	Comments
Bans on drinking water consumption	9	23 and 24	
Switching or blending of drinking water supplies	9	23	
Purification of drinking water at water treatment plants	9	23	
Regulation of flow of contaminated water through reservoirs	9	23	
Construction of dykes or barriers	9	12	
Addition of potassium to lakes	9	22	
Addition of lime to lakes or catchments	9	22	
Modification in tree felling time	-	-	CMS aimed at the forest industry and collective AD calculations not possible in a general manner.
Forest soil treatment with fertilizer	-	-	
Restrictions on the use of wood	-	-	

Table 4: Urban and industrial countermeasures

Countermeasure	Averted dose equation	Cost equation	Comments
Road planing	11	28	
Vacuum sweeping roads and walkways	11	28	
Firehosing roads and walkways	11	28	
Turning flagstones	11	28	
Topsoil removal applying lignin coating	11	28	
Topsoil removal by machines (e.g., 'bobcat')	11	28	
Topsoil removal manually	11	28	
Application of clean sand/soil around dwellings and in frequently occupied areas	11	28	
Resurfacing with e.g., asphalt in frequently occupied areas	11	28	
Snow removal	11	28	
Garden digging	11	28	
Triple digging	11	28	
Skim-and-burial ploughing (park areas)	10 or 11	28	
Deep ploughing (park areas)	10 or 11	28	
Shallow ploughing (park areas)	10 or 11	28	
Turf harvesting (park areas)	10 or 11	28	
Lawn mowing	11	28	
Pruning or removal of trees and shrubs	11	28	
High pressure water hosing of walls	11	28	
Sandblasting of walls	11	28	
Ammonium treatment of walls	11	28	
Mechanical abrasion of wooden walls	11	28	
High pressure water hosing of roofs	11	28	
Roof cleaning by cleaning device	11	28	
Roof cleaning by pressurised hot water trolley	11	28	
Change of roof	11	28	
Intensive indoor surface cleaning	11	28	
Physical cleaning of contaminated metal surfaces	11	28	
Chemical cleaning of contaminated metal surfaces	11	28	
Electrochemical treatment of contaminated metal surfaces	11	28	
Application of detachable polymer paste on metal surfaces	11	28	
Ultrasound treatment with chemical decontamination	11	12	
Cleaning of contaminated industrial ventilation systems	11	28	
Cleaning of contaminated plastic and coated surfaces	11	28	
Filter removal from industrial areas	11	28	Use cost per filter instead of cost per m^2

5. Cost-effectiveness of countermeasures in connection to cow's milk production – a comparative study for ^{137}Cs

5.1 The hypothetical accident and chosen countermeasures

A case study site for a hypothetical nuclear accident was chosen in northern England for the project to test the STRATEGY model. The hypothetical accident happens in early May with substantial release of ^{137}Cs. The report of the case study will be delivered at a later stage of the project.

One of the modelled 25 km^2 pixels receiving deposition has been chosen here to take a closer look at the cost-effectiveness of different countermeasures aimed at milk production. For this hypothetical accident, the STRATEGY model predicts a radiocaesium fallout in the chosen pixel of 390 000 Bq/m^2. The area has 684 milking cows with an assumed average milk production of 6000 L/y per animal. For part of the year they will produce milk in excess of the Council Food Intervention Limit (CFIL)[3] of 1000 Bq/L for ^{137}Cs in milk. Activity concentrations of ^{137}Cs in cow's milk the first year after the accident were predicted by the STRATEGY model. The values are presented in Figure 1 as monthly averages in the absence of countermeasures.

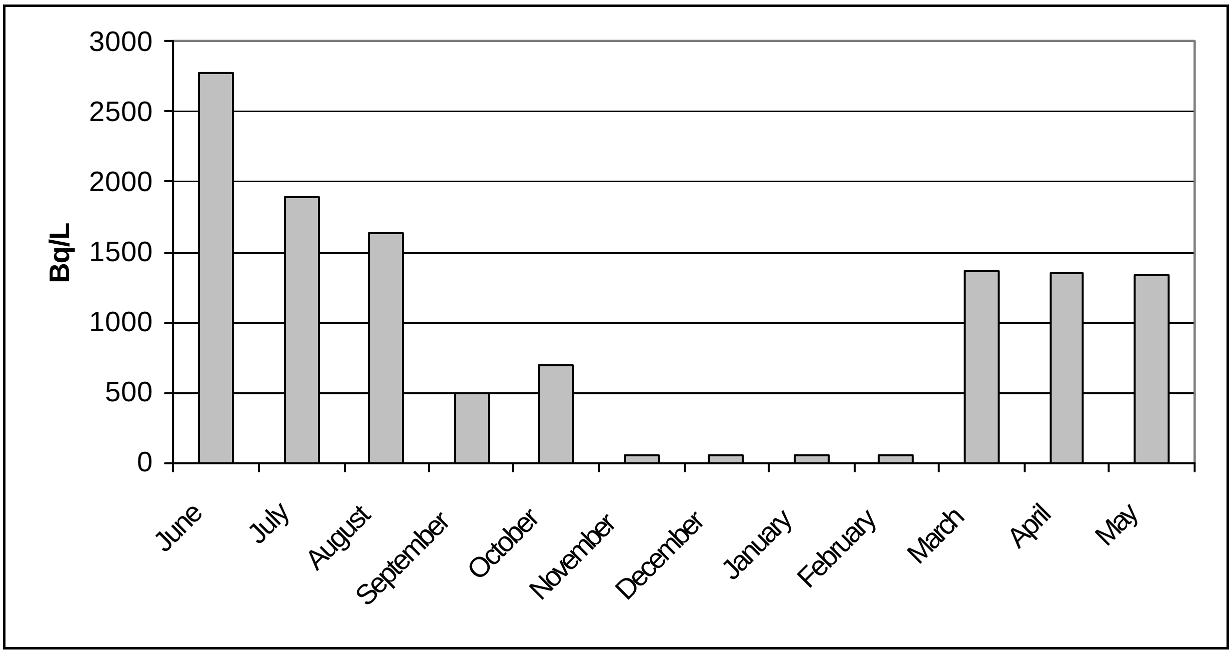

Figure 1: Activity concentration of ^{137}Cs in cow's milk (Bq/L) from the selected area in northern England the first year after the hypothetical accident[4].

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[3] In case of a new nuclear accident
[4] Predictions made using a provisional development version of the STRATEGY model.

To produce milk fit for human consumption, countermeasures need to be implemented and the measures chosen here from the STRATEGY database of countermeasures are presented in Table 5.

Table 5: Countermeasures aimed at milk production included in this example

Countermeasure	Target
Normal ploughing	Pasture
Deep ploughing	Pasture
Distribution of concentrates with AFCF	Dairy cows
Administration of AFCF boli	Dairy cows
Administration of clay minerals to feed	Dairy cows
Clean feeding 1: Replacement of all feedstuffs	Dairy cows
Clean feeding 2: Replacement of pasture grass	Dairy cows
Bans	Milk
Decontamination (MAG·SEP^{SM})	Milk
Processing (cheese production)	Milk

It is assumed that ploughing is carried out on 31 May and that other countermeasures are implemented soon after the accident. The time period considered for the cost-effectiveness investigation was 1 year (1 June - 31 May). Month 0 – the month of the hypothetical accident – has been omitted in the calculations to avoid the most pronounced early-phase effects, as this is not within the scope of STRATEGY. It is assumed that animal directed measures have reached their maximum countermeasure effectiveness at the start of the calculations.

The countermeasures can be divided in three groups according to countermeasure target:

- Pasture directed measures
- Animal directed measures
- Milk directed measures

Pasture directed countermeasures
include normal ploughing and deep ploughing of pasture land. There is an assumed four-month re-growth period of pasture after ploughing when the animals must be yarded and fed at the farm. The total pasture area (lowland grass) for the 25 km^2 area is 1536 ha. Since other animals (e.g. sheep, beef cattle) also graze on lowland grass, the pasture area required for milking cows only, has been calculated from a stocking rate of 2 cows per ha (average according to Nix, 2002). Since there are 684 cows in the area, the resulting required pasture area is 342 ha.

Animal directed countermeasures
include distribution of caesium binders and clean feeding. The caesium binder AFCF can be distributed either in concentrates or in boli. Concentrates with AFCF need to be administered daily while boli are administered every 8 weeks, three at a time. The clay mineral bentonite is another caesium binder that can be distributed in daily feed. Clean feeding can be divided in two practices: Either you replace all feedstuffs with uncontaminated fodder or you replace only pasture grass, which is the main contributor to ^{137}Cs in milk. Seasonal variations in dairy cow feeding are summarized in Appendix 1. For the sake of simplicity, it is assumed that amount and constituents of clean feed will be identical to the winter diet.

Milk directed countermeasures

include bans, decontamination techniques and processing. Banning implies that the milk is declared not fit for human consumption and will be disposed off. The decontamination technique chosen here is by using the MAG·SEP^{SM} magnetic separation process[5]. Production of cow's cheese is chosen as the processing measure since only a fraction of ^{137}Cs in milk is transferred to the cheese.

For more detailed information on the various countermeasures, please see the individual datasheets.

5.2 Dose calculations

Total ingestion doses from milk produced within the area (TD_m, personSv) are calculated using:

$$TD_m = \sum_{month}(A_m \cdot Y_a) \cdot No^a \cdot DCF_{ing} \qquad \textbf{(Eq. 30)}$$

where

A_m = *Monthly average activity concentration of* ^{137}Cs *in milk, Bq/L*
Y_a = *Monthly animal yield of milk; 500 L/month*
No^a = *Number of dairy cows in the study area; 684 animals*
DCF_{ing} = *Dose conversion factor for* ^{137}Cs *ingestion;* $1.3 \cdot 10^{-8}$ *Sv/Bq (ICRP, 1996)*

Monthly average activity concentrations have been taken from the STRATEGY model outputs (see Figure 1). To limit the study, three countermeasure implementation periods have been considered in the following. These are summarized in Table 6.

Table 6: Data for different countermeasure implementation periods

Implementation period	Months	TD_m during the period
(1) Whole year	12 (Month 1-12)	52.3 personSv
(2) Grazing periods	8 (Month 1-5 & 10-12)	51.3 personSv
(3) Periods above CFIL	6 (Month 1-3 & 10-12)	46.0 personSv

Averted collective ingestion doses from milk (AD_m^{coll}) due to countermeasure implementation are calculated using:

$$AD_m^{coll} = TD_m \cdot E_{CM} \qquad \textbf{(Eq. 31)}$$

The calculated averted doses according to implementation period are given in Table 7 along with the countermeasure effectiveness, E_{CM}. We see that the highest averted doses are achieved by banning milk for human consumption or by replacing all feedstuffs with uncontaminated

[5] http://www.anl.gov/LabDB2/Current/Ext/H102-text.002.html

fodder (clean feeding 1). Decontamination by MAG·SEP[SM] follows close behind. Adding clay minerals to feed gives the lowest averted dose.

Table 7: Countermeasure effectiveness and averted collective dose for implementation periods (1) to (3)

Countermeasure	E_{CM}	AD_m^{coll} **(1) personSv**	AD_m^{coll} **(2) personSv**	AD_m^{coll} **(3) personSv**
Normal ploughing	0.50 (0.78)§	40.7	n/a	n/a
Deep ploughing	0.70 (0.86)§	45.2	n/a	n/a
Distribution of concentrates with AFCF	0.80	41.9	41.1	36.8
Administration of AFCF boli	0.60	31.4	30.8	27.6
Administration of clay minerals to feed	0.50	26.2	25.7	23.0
Clean feeding 1: Replacement of all feedstuffs	1.00	52.3	51.3	46.0
Clean feeding 2: Replacement of pasture grass	0.90	47.1	46.2	41.4
Bans	1.00	52.3	51.3	46.0
Decontamination (MAG·SEP[SM])	0.99	51.8	50.8	45.6
Processing (cheese production)	0.93	48.7	47.7	42.8

§ Numbers in brackets indicate the increased countermeasure effectiveness the first year due to a four months non-grazing period during re-growth of ploughed pasture. These "increased" effectiveness values have been used in the subsequent calculations.

5.3 Cost estimates

Methods for estimating the costs of agricultural countermeasures are given in chapter 3.
Table 8 gives the estimated costs for performing the different countermeasures using this methodology. Most unit costs have been derived from the STRATEGY model and/or the relevant datasheets, with supplementary info taken from Nix (2002). In some cases, however, it was necessary to use additional sources; these references are stated in table 8.

Table 8: Total costs (C) for different countermeasures and implementation periods (1) to (3)

Countermeasure	C1 €	C2 €	C3 €	References
Normal ploughing	195000	n/a	n/a	NILF[1)]
Deep ploughing	202000	n/a	n/a	NILF[1)]
Distribution of concentrates with AFCF	56100	37400	28100	
Administration of AFCF boli	36900	24600	18400	
Administration of clay minerals to feed	44600	29700	22300	PermaKem[2)] AUN[3)]
Clean feeding 1: Replacement of all feedstuffs	740000	535000	401000	NILF[1)]
Clean feeding 2: Replacement of pasture grass	309000	309000	261000	NILF[1)]
Bans	1260000	838000	628000	
Decontamination (MAG·SEP^{SM})	1540000	1020000	769000	NRPB
Processing (cheese production)	546000	364000	273000	TINE[4)]

1) Norwegian Agricultural Economics Research Institute
2) PermaKem A/S, Norway
3) Agricultural University of Norway
4) TINE BA, Norway

Decontamination by MAG·SEP^{SM} is the most expensive countermeasure followed by milk bans and clean feeding 1. Distribution of AFCF boli is the cheapest option, followed by administration of clay minerals to feed.

5.4 Cost-effectiveness

The cost-effectiveness (CE) of the different countermeasures was calculated using Eq. 29. The cost-effectiveness estimates are summarized in Table 9 and comments are given below. Some of the countermeasures will also produce waste that needs to be disposed off. This is also stated in Table 9.

Table 9: Waste and Cost effectiveness of countermeasures for different implementation periods (1) to (3)

Countermeasure	CE 1 € personSv^{-1}	CE 2 € personSv^{-1}	CE 3 € personSv^{-1}	Waste
Normal ploughing	4800	n/a	n/a	No
Deep ploughing	4500	n/a	n/a	No
Distribution of concentrates with AFCF	1300	910	760	No
Administration of AFCF boli	1200	800	670	No
Administration of clay minerals to feed	1700	1200	970	No
Clean feeding 1: Replacement of all feedstuffs	14000	10000	8700	No
Clean feeding 2: Replacement of pasture grass	6600	6300	5900	No
Bans	24000	16000	14000	Yes
Decontamination (MAG·SEP^{SM})	30000	20000	17000	Yes
Processing (cheese production)	11000	7600	6400	Yes

Pasture directed countermeasures

The costs of normal and deep ploughing are the sum of the cost of ploughing and the cost of giving the animals replacement feed and associated care in the period of pasture regrowth (4 months). The cost of replacement feed and yarded keep seems to dominate - only 10-15% of the cost estimate is attributed to ploughing alone. Deep ploughing is slightly more expensive than normal ploughing, but also averts higher doses thus it seems to be slightly better cost-effectively speaking. There are, however, large uncertainties in the calculations and the actual difference between the two might be negligible. An advantage for these two countermeasure options is that they do not produce any waste (although there may be slurry occurring as a consequence of clean feeding) and they need to be performed only once. Ploughing soon after the accident will give an averted dose for all the years to come, while the cost is only incurred in the first year.

Animal directed countermeasures

The caesium binders AFCF and clay minerals incorporated in feed or boli are cheap countermeasures of comparable cost effectiveness. AFCF in boli and concentrates, though, seem to be slightly better from a cost-effective perspective than administration of clay minerals since the averted dose is much lower for the latter. These countermeasures have to be implemented on a continuous basis throughout the year and for as long as the ^{137}Cs concentration in milk is above safe drinking limits. Costs will incur for every year they are implemented. An advantage is that they do not produce any waste.

The cost-effectiveness of clean feeding depends highly on whether clean feeding 1 or clean feeding 2 is chosen, the latter being considerably more cost-effective. This is because the main dose contribution comes from milk produced during the grazing period, as was shown in Figure 1. The cost for clean feeding 1 is also substantially greater than for option 2. As for caesium binders, these countermeasures have to be implemented on a continuous basis throughout the year and for as long as the ^{137}Cs activity concentration in milk is above the CFIL, with associated costs every year. An advantage is that they usually do not produce any waste. (If, however, the animals must be housed during clean feeding while not housed under normal conditions, the slurry produced must be disposed off. This slurry can usually be disposed off at the farm.)

Milk directed countermeasures

Bans and decontamination are the least cost-effective options of all the countermeasures described, while cheese production is intermediate. At an early stage after a nuclear accident, food bans will often be an appropriate countermeasure since it takes some time to get an overview of the consequences, initiate measurements of radionuclides in milk and come up with a countermeasure strategy. The problem with continuing food bans as the only countermeasure for milk is that it is expensive and produces large amounts of waste to be disposed off. Decontamination using MAG·SEP^{SM} resins is an effective countermeasure used in the Ukraine after the Chernobyl accident. Although effective, it is expensive and does not seem attractive since it costs more than the assumed value of milk to the producer. A limited volume of waste is produced as the contaminated MAG·SEP^{SM} resins need to de disposed off. Processing the milk to cheese seems to be a good alternative to discarding the milk. Most of the radioactivity will remain in the whey, while the activity concentration in cheese per kg will be only approximately half of the activity concentration in milk per litre. Compared to the value of milk, the processing cost of cheese is not very high. In addition, one gains a valuable product. The major disadvantage compared to decontamination is the large amounts of whey produced that probably must be disposed off. In a normal situation the whey is used for feeding other animals. In a contamination situation, however, this might not be possible. All these countermeasures must be implemented on a continuing basis, with associated costs, as long as the milk is above the CFIL. Processing and decontamination of contaminated (raw) products may have a negative impact on the value of the resulting products; people may tend to avoid them and retailers will probably not buy it: General consensus of FARMING stakeholders was that processed milk would not be eaten. This opinion also applied to decontamination techniques such as MAG·SEP^{SM}.

5.5 Conclusions

Overall the countermeasures using caesium binders are the most cost-effective in this scenario. Ploughing and clean feeding 2 (replacement of pasture) are second best. Cheese production and clean feeding 1 (replacement of all feedstuffs) takes an intermediate position whilst the least cost-effective measures are milk bans and decontamination. This clearly shows that measures to reduce the uptake in pasture or animals are preferable, on a cost-effectiveness basis, to measures directed at the produced milk. The latter countermeasures will also produce considerable amounts of waste.

On a longer time perspective than one year, ploughing will become more cost-effective since the costs only incur the first year whilst there will be averted doses associated with the countermeasure for further years which are relevant in a longer assessment. For the other countermeasures, costs will be incurred every year the countermeasure is implemented. As activity concentrations in milk decline, the cost-effectiveness tends to decrease since the averted doses become smaller while the costs are similar.

6. Concluding remarks

This paper describes a generic method for calculating cost-effectiveness (comparing averted dose to implementation costs or cost of bans). Parameters to be considered in the calculations are outlined and all STRATEGY countermeasures have been attributed suitable equations for calculating averted collective doses and implementation costs where possible. In every real situation the calculations will, of course, depend on scenario and site-specific data. The example in chapter 5 demonstrates how site-specific predictions can be carried out using the STRATEGY model. Similar predictions can be performed for different countermeasures and other case-study sites or real accident situations. A combination of countermeasures may be necessary to reduce the public exposure to a safe level. This might result in an overall better cost-effectiveness.

Calculating cost-effectiveness is an essential tool in a decision making process. It can give you the least costly way of achieving a specified reduction in dose, or it can predict the maximum reduction in dose for a fixed cost. Furthermore, a cost-effectiveness analysis may be an important step in excluding available countermeasures, since measures with a low cost-effectiveness would normally not be chosen when better options are available. It is thus one of the criteria that should be used in a more holistic approach to remedial actions.

A holistic approach will include consideration of many aspects in addition to cost-effectiveness such as practicability in the affected area, waste costs, incremental doses to workers performing the countermeasure, and social and environmental side-effects. The costs of waste disposal can far outweigh the costs of the countermeasure, making comparisons between countermeasures very difficult if this is omitted. Depending on the radionuclide-countermeasure combination, incremental doses are not always trivial and could influence whether a countermeasure is implemented, irrespective of its apparent cost-effectiveness. In addition, an emergency situation might entail changes in:

- costs (rise of prices due to shortness of manpower, equipment and consumables)
- public perception (measures unacceptable in normal situations might change to acceptable)
- governmental priorities (regional affairs, emphasis on individuals or the whole population)

Each of these factors might influence the choice of remedial actions by decision makers. The method of communicating decisions to affected workers and the public is also important for a successful remedial strategy. All countermeasures will thus entail an information cost in addition to the implementation costs mentioned in this document, and most require data to refine assessments of their effectiveness and acceptability.

As clearly stated in the STRATEGY project, all these factors are important when choosing between countermeasures. Details are outlined in the data sheets. This and other documents delivered by the project give a wider perspective of important matters to consider when choosing remedial strategies after a nuclear accident.

7. References

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Appendix 1: Dairy cow feeding

(a) Normal diet assumed for dairy cow

Month		**Pasture** kg d^{-1}	**Stored grass** kg d^{-1}	**Maize silage** kg d^{-1}	**Cereal conc.** kg d^{-1}
1-3	Jun-Aug	10.725	0	5.775	0
4-5	Sep-Oct	3.3	3.3	9.075	0.825
6-9	Nov-Feb	0	3.3	10.725	2.475
10-12	Mar-May	10.725	0	5.775	0

(b) Clean feeding diet for dairy cow (winter diet, purchased amount for clean feeding 1)

Month		**Pasture** kg d^{-1}	**Stored grass** kg d^{-1}	**Maize silage** kg d^{-1}	**Cereal conc.** kg d^{-1}
1-12	Jun-May	0	3.3	9.075	2.475

(c) Replacement feed for pasture grass for dairy cow (purchased amount for clean feeding 2)

Month		**Pasture** kg d^{-1}	**Stored grass** kg d^{-1}	**Maize silage** kg d^{-1}	**Cereal conc.** kg d^{-1}
1-3	Jun-Aug	0	3.3	4.95	2.48
4-5	Sep-Oct	0	0	1.65	1.65
6-9	Nov-Feb	0	0	0	0
10-12	Mar-May	0	3.3	4.95	2.48

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