Averted dose methodology

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 or for an exposed population. Many factors, such as deposition level, exposure pathways, countermeasure target and effectiveness, agricultural management, consumption rates and behaviours, may influence the averted dose. Within the general description of different averted dose scenarios given below the different factors that should be taken into account are stated and averted dose equations presented. All abbreviations used are explained in a list given at the end of the document.

The time span for the calculations should be chosen according to the countermeasure's reduction time. Some countermeasures may be performed once, however reducing dose for all years to follow. In this case, ICRP[1] usually recommends integrating the averted dose over a time period of 50 years for adults and 70 years for children and young persons. For other countermeasures, the reduction may endure for a limited time only. In this case the averted dose should be integrated over the appropriate time period. In the following the time of countermeasure implementation is given as t_c.

1) INDIVIDUAL AVERTED INGESTION DOSE

For an individual being exposed to radiation due to consumption of foodstuffs contaminated by radionuclides, the individual averted ingestion dose due to countermeasure implementation ($AD^{ind}(t)$; Sv) can be calculated according to the following equation:

$$AD^{ind}(t) = \int_{t_c}^{t} I(t) \cdot DCF_{ing} \cdot E_{CM} \, dt$$

where

DCF_{ing} = *Nuclide dependent dose conversion factor for ingestion (Sv Bq^{-1})*

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

$I(t)$ = *Intake (Bq per unit time), calculated by summing up over all foodstuffs that the countermeasure has an effect on, given by:*

$$I(t) = \sum_{1}^{i} \left[A_i(t) \cdot CR \cdot f_{fp} \right]$$

and

$A_i(t)$ = *Activity concentration in foodstuff i (Bq kg^{-1}) at time t*

CR = *Consumption rate of foodstuff i (kg per unit time)*

f_{fp} = *Food processing retention factor (dimensionless)*

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[1] International Commission on Radiological Protection. *Age-dependent Doses to Members of the Public from Intake of Radionuclides: Part 5 Compilation of Ingestion and Inhalation Dose Coefficients*. ICRP Publication 72, Annals of the ICRP Vol. 23 No. 3/4 1996.

The activity concentration in foodstuffs can be determined by measuring samples, using mechanistic models (e.g STRATEGY model) or by empirical approaches (e.g. aggregated transfer factors and concentration rations). The calculation of $A_i(t)$ will depend on ecosystem and food production method and is described below.

1 A) SEMI-NATURAL environment.

This includes game, freshwater fish, mushrooms, berries and semi-domesticated animals like reindeer. The activity concentration (Bq kg^{-1}) in a given foodstuff *i* at time *t* is given by:

$$A_i(t) = \mathrm{DEP} \; ? \; T_{ag} \; ? \; e^{\frac{-\ln 2 \cdot t}{T_{eff,ecol}}}$$

where

DEP = *Initial deposition (Bq m^{-2})*

T_{ag} =*Aggregated transfer factor (from deposition to foodstuff) (m^2 kg^{-1})*

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

t =*Time since deposition (unit time)*

1B) AGRICULTURAL ENVIRONMENT; crops.

This includes all vegetables, cereals and fruits produced on farms. The activity concentration in a given foodstuff *i* at time *t* is given by:

$$A_i(t) = \mathrm{DEP} \; ? \; T_{ag} \; ? \; e^{\frac{-\ln 2 \cdot t}{T_{eff,ecol}}}$$

where

DEP = *Initial deposition (Bq m^{-2})*

T_{ag} = *Aggregated transfer factor (from deposition to foodstuff) (m^2 kg^{-1})*

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

t = *Time since deposition (unit time)*

1C) AGRICULTURAL ENVIRONMENT; animal produce.

This includes all animal foodstuffs produced at agricultural farms. The activity concentration in a given foodstuff *i* at time *t* is given by:

$$A_i(t) = \mathrm{DEP} \; ? \; T_{ag} \; ? \; FR \; ? \; TF \; ? \; e^{\frac{-\ln 2 \cdot t}{T_{eff,ecol}}}$$

where

T_{ag} = *Aggregated transfer factor (from deposition to animal feedstuff) (m^2 kg^{-1})*

FR = *Feeding rate of animal (kg per unit time)*

TF = *Transfer factor (from feed to animal produce) (unit time kg^{-1})*
$T_{eff,ecol}$ = *Effective ecological half time for the given nuclide in a 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:

$$\sum_{1}^{m} T_{ag}^{m} \cdot FR^{m} \cdot TF^{m}$$

NOTE:

- It is important to use the same time unit for all parameters and equations, i.e. years or months or weeks or days (t, FR, TF, $T_{eff,\ ecol}$).
- All relevant parameters should be in either fresh or dry weight. This is particularly important to be accounted for when using T_{ag}, TF, FR and CR as these may be reported on either a dry or fresh weight basis.

2) COLLECTIVE AVERTED INGESTION DOSE; crops.

For some purposes it is desirable to calculate the averted collective dose ($AD^{coll}(t)$; personSv), from crops. For instance, when implementing a countermeasure in a given field, it is possible to calculate what the averted dose would be if we assume that all the agricultural produce from the field would be eaten sometime, somewhere by someone without specifying who the affected persons would be. In this case, the following equation should be used:

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

where $A_s(t)$ = *Soil activity (Bq m^{-2}) at time t* given by:

$$A_s(t) = DEP \cdot e^{\frac{-\ln 2 \cdot t}{T_{eff,ecol}}}$$

and

P_{area} = *Production area (m^2)*
Y_p = *Production yield (kg m^{-2} per unit time)*
T_{ag} = *Aggregated transfer factor (from deposition to vegetable produce) (m^2 kg^{-1})*
f_e = *Edible fraction of crop (dimensionless) according to processing*
DCF_{ing} = *Nuclide dependent dose conversion factor for ingestion (Sv Bq^{-1})*
E_{CM} = *Countermeasure effectiveness (dimensionless), fraction as specified in data sheets*
DEP = *Initial deposition (Bq m^{-2})*
$T_{eff,ecol}$ = *Effective ecological half time for the given nuclide in a given ecosystem (unit time)*
t = *Time since deposition (unit time)*

3) COLLECTIVE AVERTED INGESTION DOSE; animal produce.

For some purposes it can be desirable to calculate the averted collective dose, $AD^{coll}(t)$, from animal produce. For instance, when implementing a countermeasure on an animal herd, it is possible to calculate what the averted dose would be if we assume that all the agricultural produce from the herd would be eaten sometime, somewhere by someone without specifying who the affected persons would be. In this case, the following equation should be used:

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

where $A_s(t)$ = *Soil activity (Bq m^{-2}) at time t* given by:

$$A_s(t) = DEP \cdot e^{\frac{-\ln 2 \cdot t}{T_{eff,ecol}}}$$

and

T_{ag} = *Aggregated transfer factor (from soil to animal feedstuff) (m^2 kg^{-1})*
FR = *Feeding rate of animal (kg per unit time)*
TF = *Transfer factor (from feed to animal produce) (unit time kg^{-1})*
Y_a = *Animal yield (kg per unit time)*
No^a = *Number of animals*
DCF_{ing} = *Nuclide dependent dose conversion factor for ingestion (Sv Bq^{-1})*
E_{CM} = *Countermeasure effectiveness (dimensionless), fraction as specified in data sheets*
DEP = *Initial deposition (Bq m^{-2})*
$T_{eff,ecol}$ = *Effective ecological half time for the given nuclide in a 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:

$$\sum_{1}^{m} T_{ag}^{m} \cdot FR^{m} \cdot TF^{m}$$

NOTE:

- It is important to use the same time unit for all parameters and equations, i.e. years or months or weeks or days (t, FR, TF, $T_{eff,\ ecol}$).
- All relevant parameters should be in either fresh or dry weight. This is particularly important to be accounted for when using T_{ag}, TF, FR and CR as these may be reported on either a dry or fresh weight basis.

4) INDIVIDUAL AVERTED EXTERNAL DOSE; recreational areas.

For a person spending time in a contaminated recreational areas (e.g. forest), the exposure will depend on the deposition level, the type of area and the time spent there. If countermeasures are implemented, the individual averted external dose, $AD^{ind}(t)$, can be calculated by:

$$AD^{ind}(t) = \int_{t_c}^{t} D_{rate}(t) \cdot DEP \cdot OF(t) \cdot E_{CM}\, dt$$

where $D_{rate}(t)$ = *Dose rate at time t normalised to unit deposition (Sv per unit time/Bq m*$^{-2}$*)* given by:

$$D_{rate}(t) = D_{rate}(t=0) \cdot e^{\frac{-\ln 2 \cdot t}{T_{eff,ecol}}}$$

and

DEP = *Initial deposition (Bq m*$^{-2}$*)*
$OF(t)$ = *Occupancy factor (dimensionless)*
E_{CM} = *Countermeasure effectiveness (dimensionless), fraction as specified in data sheets*
$T_{eff,ecol}$ = *Effective ecological half time for the given nuclide in a given Ecosystem (unit time)*
t = *Time since deposition (unit time)*

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

5) COLLECTIVE AVERTED EXTERNAL DOSES; recreational areas.

If it is desirable to calculate the collective averted dose, $AD^{coll}(t)$, due to countermeasure implementation, the number of persons spending time in recreational areas must be taken into account as well as deposition level, the type of area and the time spent there:

$$AD^{coll}(t) = \int_{t_c}^{t} D_{rate}(t) \cdot DEP \cdot OF(t) \cdot No^{p} \cdot E_{CM}\, dt$$

where $D_{rate}(t)$ = *Dose rate at time t normalised to unit deposition (Sv per unit time/Bq m*$^{-2}$*)* given by:

$$D_{rate}(t) = D_{rate}(t=0) \cdot e^{\frac{-\ln 2 \cdot t}{T_{eff,ecol}}}$$

and

DEP = *Initial deposition (Bq m*$^{-2}$*)*

$OF(t)$ = *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*

$T_{eff,ecol}$ = *Effective ecological half time for the given nuclide in a given area (unit time)*
t = *Time since deposition (unit time)*

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

6) INDIVIDUAL AVERTED EXTERNAL DOSES; urban and industrial environments.
In the urban and industrial environment external doses are modelled within STRATEGY using by Monte Carlo simulations to predict air kerma rates (Gy per unit time). The dose received by an individual depends on the kerma rate at a given location and the occupancy factor at that location. More details on this method can be found in Kis et al, 2003 (see footnote 2). If countermeasures are implemented, the individual averted external dose, $AD^{ind}(t)$, can be calculated by:

$$AD^{ind}(t) = \int_{t_c}^{t} K_{rate}(t) \cdot DEP \cdot DCF_{kerma} \cdot OF(t) \cdot E_{CM}\, dt$$

where $K_{rate}(t)$ = *Kerma rate at time t normalised to unit deposition (Gy per unit time/Bq m^{-2})* given by:

$$K_{rate}(t) = K_{rate}(t=0) \cdot e^{\frac{-\ln 2 \cdot t}{T_{1/2}}}$$

and
DEP = *Initial deposition (Bq m^{-2})*
DCF_{kerma} = *Dose conversion factor from kerma to dose (Sv per unit time/Gy per unit time)*[2]
$OF(t)$ = *Occupancy factor (dimensionless)*
E_{CM} = *Countermeasure effectiveness (dimensionless), fraction as specified in data sheets*
$T_{1/2}$ = *Half time for the given nuclide (unit time)*
t = *Time since deposition (unit time)*

7) COLLECTIVE AVERTED EXTERNAL DOSES; urban and industrial environments.
If it is desirable to calculate the collective averted dose, $AD^{coll}(t)$, due to countermeasure implementation, the number of persons spending time at the given location must be taken into account as well as kerma rate and the time spent there:

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

[2] Kis Z, Eged K, Voigt G, Meckbach R, Muller H. Guidelines for planning interventions against external exposure in industrial areas after a nuclear accident, Part II: Calculation of doses using Monte Carlo method, Neuherberg: Forschungszentrum fuer Umwelt und Gesundheit, GSF Report, 02/03, 2003.

where $K_{rate}(t)$ = *Kerma rate at time t normalised to unit deposition (Gy per unit time/Bq m*$^{-2}$*)* given by:

$$K_{rate}(t) = K_{rate}(t=0) \cdot e^{\frac{-\ln 2 \cdot t}{T_{1/2}}}$$

and

DEP = *Initial deposition (Bq m*$^{-2}$*)*

DCF_{kerma} = *Dose conversion factor from kerma to dose (Sv per uni t time/Gy per unit time) (footnote 2)*

$OF(t)$ = *Occupancy factor (dimensionless)*

No^{p} = *Number of persons spending time at the given location*

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

$T_{1/2}$ = *Half time for the given nuclide (unit time)*

t = *Time since deposition (unit time)*

Quantities and units used in this document

$AD^{coll}(t)$ = Collective averted dose, unit: personSv.

$AD^{ind}(t)$ = Individual averted dose, unit: Sievert (Sv). $A_i(t) =$ Activity concentration of a radionuclide in foodstuff i at time t, unit: Bq kg^{-1} (fresh or dry weight).

$A_i(t) =$ Activity concentration of a radionuclide in foodstuff i at time t, unit: Bq kg^{-1} (fresh or dry weight).

$A_s(t)=$ Soil activity at time t, unit: Bq m^{-2}.

$CR =$ Human consumption rate of foodstuff i, unit: kg per unit time. The time unit can be day, week, month or year, giving kg d^{-1}, kg week^{-1}, kg month^{-1}, kg a^{-1}.

$DCF_{ing} =$ Nuclide dependent dose conversion factor for ingestion, unit: Sv Bq^{-1}. Gives the dose (Sv) to a person from ingestion of 1 Bq of a given radionuclide. These values are listed in ICRP publication 72.

DCF_{kerma} = Nuclide dependent dose conversion factor for external exposure converting kerma rate to dose (Sv per unit time / Gy per unit time). Values can be found in Kis et al, 2003 where they are presented as Sv month^{-1}/pGy s^{-1}.

DEP = Amount of radioactivity (Bequerel, Bq) initially deposited per square meter after an accident, unit: Bq m^{-2}.

$D_{rate}(t) =$ Dose rate at time t normalised to unit deposition, unit: Sv per unit time/Bq m^{-2}. This parameter describes the external exposure to humans from radioactive surroundings.

$E_{CM} =$ Countermeasure effectiveness, unit: dimensionless. If the countermeasure gives a 50% reduction, the value 0.5 should be used. Likewise an 80% reduction should be given as 0.8 and so on. The percentage is specified in the data sheets.

$f_e =$ Edible fraction of crop, unit: dimensionless. Usually only part of a vegetable crop is edible. In addition, the radionuclide content can be altered during processing, see f_{fp}. The parameter f_e must thus take into account the edible fraction and possibly the food processing factor as well, thus reflecting how much of the initial activity concentration in the produce that is actually consumed.

$f_{fp} =$ Food processing retention factor, unit: dimensionless. This parameter is the ratio of the activity concentration of a given food item when ready for consumption to the activity concentration before processing and preparation. Some processing/preparation methods may increase the radionuclide content, while others may reduce the content. These values are given in, for instance, IAEA Technical Report Series No. 364: Handbook of parameter values for the prediction of radionuclide transfer in temperate environments, 1994.

$FR =$ Feeding rate of animal, unit: kg per unit time. The time unit can be day, week, month or year, giving kg d^{-1}, kg $week^{-1}$, kg $month^{-1}$, kg a^{-1}.

$I(t) =$ Intake of a radionuclide at a time *t*, unit: Bq per unit time.

$K_{rate}(t)$ = Kerma rate at time t normalised to unit deposition, unit: Gy per unit time/Bq m^{-2}. This parameter describes the external exposure in urban and industrial environments modelled by Monte Carlo simulation.

$No^a =$ Number of animals in the herd considered, unit: dimensionless.

No^p = Number of persons spending time in a contaminated area, unit: dimensionless.

$OF(t)$ = Occupancy factor unit: dimensionless. This parameter gives the fraction of time spent in a given contaminated area.

$P_{area} =$ Production area for vegetable produce, unit: m^2.

$t =$ Time since deposition, unit time. The time unit can be week, month or year.

T_{ag} = Aggregated transfer factor, unit: m^2 kg^{-1}. This parameter is the ratio of the activity concentration of a radionuclide in a foodstuff or an animal feed stuff (Bq kg^{-1} fresh or dry weight) to the soil deposition (Bq m^{-2}).

$T_{eff,ecol}$ = Effective ecological half time for the given nuclide in the given ecosystem, unit: time. The time unit can be day, week, month or year. The parameter describes how long it takes before the radioactivity in a given compartment is reduced to half. The half time can be affected by many physical, biological or ecological processes. The half time depends on the compartment considered and factors affecting the compartment such as temperature, nutrient intake, physiological status etc.

$TF =$ Transfer factor, unit: unit time kg^{-1}. This parameter describes the proportion of the activity concentration in animal feed that is transferred to animal produce by ingestion. The time unit can be day, week, month or year, giving d kg^{-1}, week kg^{-1}, month kg^{-1}, a kg^{-1}.

$Y_a =$ Animal yield, unit: kg per unit time. This parameter states how much milk, meat, eggs etc. (kg) an animal produces. The value should be given for a time period according to the time span chosen for the other parameters and equations (day, week, month, year).

$Y_p =$ Production yield for vegetable produce, unit: kg m^{-2} per unit time.

Author: Astrid Liland, NRPA