

Dose Calculations in ARGOS

Table of Contents

Introduction.....	2
Dose Pathways	2
Dose Types.....	2
Sheltering	3
Age Groups.....	3
Integration Time.....	4
Database Tables used by ARGOS Dose Calculations.....	4
Computing Details.....	5
Total Effective Dose Equivalent.....	5
Inhalation Dose.....	6
Inhalation Dose, Total.....	6
Thyroid Dose	7
External Gamma Doses.....	8
External Gamma Dose from Plume	8
External Gamma Dose from Ground.....	8
Probit.....	9
Doses used with RIMPUFF	10
Doses used with URD	10
Calculations for Long Range models	11
Doses used with FDM/AgriCP	11
Location factors.....	12
Internal dose from ingestion.....	13
Internal dose from inhalation	14
Inhalation dose from resuspended radionuclides.....	15
External dose from radionuclides in the cloud.....	16
External dose from radionuclides deposited on ground.....	17
External dose from radionuclides deposited on skin and clothes.....	18

Calculation of collective doses..... 20
 Doses used with ERMIN..... 21
 Public Doses 21
 Dose Parameters..... 21

Introduction

Dose Pathways

The ARGOS system calculates doses to man from both internal and external irradiation. Furthermore, the Probit function for Chemicals is, due to implementation details, also covered here. Currently the following doses are supported:

Dose	Calculated in	Remarks
Gamma dose from Plume (Puffs)	RIMPUFF, URD ARGOS	Calculated in ARGOS when based on time-integrated air-concentration from long range model
Gamma dose from Ground (Deposition)	RIMPUFF, URD ARGOS	Calculated in ARGOS when based on total deposition on ground from long range model
Gamma dose from Plume (Puffs) and Ground (Deposition)	URD	
External gamma dose from plume	ARGOS	based on Gamma Dose from Plume
External gamma dose from ground	ARGOS	based on Gamma Dose from Ground and Concentration of Deposited Material
Inhalation dose	ARGOS, FDM	based on Air Concentration, Time Integrated
Thyroid Organ dose	ARGOS	based on Inhalation dose
Total Effective dose	ARGOS	based on Inhalation dose, External Gamma dose from Ground, External Gamma dose from Plume
Ingestion dose	FDM	
Skin Contamination	FDM	
Resuspension	FDM	
Cloud-shine	FDM	
Ground-shine	FDM	
Probit	ARGOS	based on Air Concentration, Instantaneous. Chemical only.

Dose Types

Doses are normally calculated as an individual's *potential dose* – as if located outside, unshielded, in open air over lawn. As this is rarely the case for members of the public, an *expected dose* or *normal living dose* can be considered as a certain combination of Outdoor dose and Indoor dose, in which members of the public on average spend a fraction of time indoor and the rest of the time

outdoors. The ERMIN dose model uses the term “Normal Living dose” whereas the AGRICP model uses the term “Expected dose”.

$$D_{normal_living,expected} = C_o * D_{outdoor}$$

where:

- C_o is the occupancy factor, the average ratio of time that members of the public spend indoors to total time,
default: 0.9 for ERMIN (db field `CM_Values.FloatValue` where `CM_Values.FieldName = 'OCCUPANCY_INDOOR'`), 0.8 for AgriCP (db field `Locf_limits.rawoccfac`)

Sheltering

By actively sheltering people a reduction in received dose can be achieved due to the shielding effect of the shelter. For use with AgriCP, this is calculated by applying a ‘location factor’ (thus assuming that people spend 100% of their time either outdoor or indoor) and then looking separately at *Indoor dose* and *Outdoor dose*:

$$D_{indoor} = F_{loc} * D_{outdoor}$$

where:

- F_{loc} is the location (shielding) factor, default 0.15 (db field `system_defaults.Value` where `system_defaults.Shortname='LOF'`)

Likewise, the effect of sheltering (averted dose) can be estimated as:

$$D_{averted} = D_{outdoor} - D_{indoor}$$

or

$$D_{averted} = (1 - F_{loc}) * D_{outdoor}$$

Sheltering is considered for these pathways: Thyroid dose, External Gamma dose from Plume, External Gamma dose from Ground and Total Effective dose.

Age Groups

For inhalation dose it is relevant to consider the normal breathing rate (inhalation speed) of an individual, and this is different in various stages in the person’s life. Therefore, the concept of ‘age groups’ is used with the following definitions:

Age Group	Inhalation Speed (default)	Remarks
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1 year child	$7.0E-05 \frac{m^3}{s}$	Children up to 1 year old
5 year child	$0.00014 \frac{m^3}{s}$	Children between 1 and 5 years old
10 year child	$0.00021 \frac{m^3}{s}$	Children between 5 and 10 years old
15 year child	$0.00028 \frac{m^3}{s}$	Children between 10 and 15 years old
Adult	$0.00033 \frac{m^3}{s}$	Above 15 years of age

Inhalation speeds are defined in the table `system_defaults`.

Age groups are then considered for these pathways: Inhalation dose, Thyroid dose and Total Effective dose.

Integration Time

When radiation from ground is estimated, it is relevant to calculate time integrated values because the deposited material (if not removed) will expose people to external radiation over time. This integration is divided into two groups:

1. During deposition (plume passage), and
2. After deposition.

After the radioactive material has deposited, it can further be relevant to look at a few time periods, due to the various isotope's different half-lives.

Integration Time is considered for these pathways: External Gamma dose from Ground and Total Effective dose. External Gamma dose from Ground is calculated for 5 Integration Time periods: Deposition, 2 days, 7 days, 30 days and 1 year, whereas the Total Effective dose is calculated for 2 Integration Time periods: 2 days and 7 days.

For the 'Deposition' time period, the model output 'Gamma dose from Ground' is used, whereas for the other time periods, the 'Deposition on Ground' is used.

Database Tables used by ARGOS Dose Calculations

A number of constants are used by dose calculations in ARGOS, i.e. not including those dose calculations made by FDM/AGRICP and ERMIN. The following tables lists tables in the ARGOS N database that contain values used in these calculations.

Table	Value / Constant	Dose Calculation
<code>system_defaults</code>	Location factor	External Gamma from Plume External Gamma from Ground
<code>system_defaults</code>	Inhalation speed (by agegroup)	Inhalation dose

system_defaults	Inhalation dose reduction factor	Total Inhalation dose (only used by Total Effective Dose calc.), Thyroid dose
system_defaults	Inhalation dose reduction factor for organic iodine	Total Inhalation dose (only used by Total Effective Dose calc.), Thyroid dose
system_defaults	Thyroid dose factor	Thyroid dose
Isotopdata	Committed Effective dose coefficient (by nuclide and agegroup)	Inhalation dose

Computing Details

The Dose Calculation performed in the ARGOS system is divided into groups according to the model being used in the actual situation. When running an Atmospheric Dispersion Prognosis with RIMPUFF/URD, the dose calculations are performed by ARGOS code with the exception of “External Gamma from Ground” for integration times 2 day, 7 days, 30 days and 1 year. In the latter case, dose conversion factors are calculated by code adapted from the FDM model.

Total Effective Dose Equivalent

In ARGOS, the Total Effective Dose Equivalent (TEDE) is the total integrated gamma dose that a person may receive from the beginning of the release and until two days or 7 days (integration times) after the plume has passed the area. Therefore, there will be only one time step in the dose results, but the end-points will be calculated by nuclide, age group, integration time and sheltering.

Total effective dose avertable by sheltering is the dose that can be averted if a person stays indoors during the plume passage.

Unit: Sv.

The Total Effective dose is given as:

$$D_{TED(2days)} = D_{inhalationTotal_{[T=n-1]}} + D_{externalPlume_{[T=n-1]}} + D_{externalGround_{[Deposition]}} + D_{externalGround_{[2\ days]}}$$

for Integration time 2 days, and

$$D_{TED(7days)} = D_{inhalationTotal_{[T=n-1]}} + D_{externalPlume_{[T=n-1]}} + D_{externalGround_{[Deposition]}} + D_{externalGround_{[7\ days]}}$$

for Integration time 7 days.

Inhalation Dose

The Inhalation dose is the dose a person may receive when inhaling air with the concentrations $C_{air,i}$ while the plume is passing. The Committed Effective Inhalation dose delivered over 50 years $E_i(50)$ for isotope i , is calculated from:

$$E_i(50) = C_{air,i} \cdot I \cdot e_i(50) \cdot T [Sv]$$

where:

- I is the Inhalation Speed (different for children and adults), $[\frac{m^3}{s}]$,
- T is the Time for the Plume passage, $[s]$,
- $e_{age,i}(50)$ is the Committed Effective dose coefficient for age group 'age' for isotope 'i', $[\frac{Sv}{Bq}]$,
- $C_{air,i}$ is the Average Air Concentration of Isotope i , $[\frac{Bq}{m^3}]$.

I and $e_i(50)$ are constants (see Dose Parameters: INHALHAST_CHILD, INHALHAST_CHILD5, INHALHAST_CHILD10, INHALHAST_CHILD15, INHALHAST_ADULT, COMMEFDOSE_CHILD, COMMEFDOSE_CHILD_5, COMMEFDOSE_CHILD_10, COMMEFDOSE_CHILD_15 and COMMEFDOSE_ADULT) and are replaced in the formula by a so-called Agegroup Inhalation Factor $F_{age,i}$ defined as:

$$F_{age,i} = I_{age} \cdot e_{age,i}(50) \left[\frac{Sv \cdot m^3}{Bq \cdot s} \right]$$

The Average Air Concentration of isotope i over time T is replaced in the calculation by the Time Integrated Air Concentration over time T defined as:

$$C_{intgr,i} = C_{air,i} \cdot T \left[\frac{Bq \cdot s}{m^3} \right]$$

The Inhalation dose calculation thus becomes:

$$E_{age,i}(50) = C_{intgr,i} \cdot F_{age,i} [Sv]$$

The normal Iodine nuclides are calculated as sums of the values for all three of the corresponding extended Iodine chemical forms.

A 'Total' nuclide is calculated as the sum of all given nuclides (for Iodine only the extended are added to the total).

Inhalation Dose, Total

For using Inhalation dose within the calculation of Total Effective dose, the effect of inhaling air indoors as opposed to outdoors should be taken into account. To this end a so-called Inhalation Dose Reduction Factor (R) is defined as a constant in the system and a special calculation is performed using this constant solely for the purpose of calculating the Total dose. The calculation uses the last timestep of the Inhalation Dose results, and is performed for each nuclide and each

age group. The Inhalation Dose Total is not visible in the results tree, but only used for calculation of the Total Effective Dose.

The Inhalation Dose Reduction factor R is defined in the db field `system_defaults.Value` where `system_defaults.Shortname='IRF'`.

$$E_i(50)_{Total,Outdoor} = E_i(50) [Sv]$$

$$E_i(50)_{Total,Indoor} = E_i(50) \cdot R [Sv]$$

Also, the averted dose can be calculated:

$$E_i(50)_{Total,Averted} = E_i(50) \cdot (1 - R) [Sv]$$

Thyroid Dose

Radioactive iodine is accumulated in the Thyroid gland when a person inhales radioactive air. The iodine isotopes are treated in the system in a special way, in which so-called extended iodine isotopes are defined, representing the three chemical forms: organic, elementary (gas form) and aerosol (small particles). These extended iodine isotopes are handled separately in the dispersion models RIMPUFF and URD.

The Thyroid absorbed dose is calculated from:

$$D_{Thyroid} = F_{TD} \cdot \sum_i^{Extended\ iodines} E_i(50) \cdot F_{DCF} [Gy]$$

where:

- $D_{Thyroid}$ is the Thyroid dose, summed over all extended iodines, [Sv],
- F_{TD} is a Thyroid dose factor (TDF)
- $E_i(50)$ is the Inhalation dose for extended iodine isotopes i, [Sv]
- F_{DCF} is a dose conversion factor from Sv to Gy, = 1, $\left[\frac{Gy}{Sv}\right]$.

The thyroid dose is calculated separately for adults and children.

The Thyroid dose factor F_{TD} is defined in the db field `system_defaults.Value` where `system_defaults.Shortname='TDF'`.

Thyroid dose avertable by sheltering is the dose that can be averted if a person stays indoors during the plume passage. Similarly to Total Inhalation dose, an inhalation dose reduction factor is used for calculating the indoor inhalation, but for the Thyroid dose a separate inhalation dose reduction factor is used for organic iodine isotopes.

External Gamma Doses

The External Gamma dose is received either directly from plume or from deposited material that has been contaminated with radioactivity. In both cases, the External dose that is calculated is the Integrated Gamma dose that a person may receive during the plume passage. However, the contamination of the ground does not disappear because the plume has passed. External dose from deposit is therefore calculated for periods of 2 days, 7 days, 30 days, and 1 year after the plume has passed.

The External doses are calculated separately for adults and children.

External dose avertable by sheltering is the dose that can be averted if a person stays indoors during the plume passage.

Unit: Sv.

External Gamma Dose from Plume

This calculation uses the “gamma doses from puffs” output from RIMPUFF/URD, applying only a sheltering factor.

The following calculations are performed:

$$D_{ExtClo,outdoor} = D_{Gamma,puffs} \cdot \frac{1}{F_{DCF}} [Sv]$$

$$D_{ExtClo,indoor} = D_{Gamma,puffs} \cdot F_{LOF} \cdot \frac{1}{F_{DCF}} [Sv]$$

$$D_{ExtClo,averted} = D_{Gamma,puffs} \cdot (1 - F_{LOF}) \cdot \frac{1}{F_{DCF}} [Sv]$$

where:

- $D_{ExtClo,outdoor}$ is the Outdoor External Gamma Dose from Plume (cloud), [Sv],
- $D_{ExtClo,indoor}$ is the Indoor External Gamma Dose from Plume, [Sv],
- $D_{ExtClo,averted}$ is the External Gamma Dose from Plume averted by sheltering, [Sv],
- $D_{Gamma,puffs}$ is the Gamma Dose from Puffs, [Gy],
- F_{LOF} is a Location factor, default = 0.15,
- F_{DCF} is a dose conversion factor from Sv to Gy, = 1, $\left[\frac{Gy}{Sv}\right]$.

The Location factor F_{LOF} is defined in the db field `system_defaults.Value` where `system_defaults.Shortname='LOF'`.

External Gamma Dose from Ground

The External Gamma Dose from Ground calculation is divided into two different parts: During deposition and after deposition.

Deposition Phase

For calculating the external ground dose during the deposition phase, the “Total Gamma Dose from Deposition” output from RIMPUFF/URD is used, but only the last time step. A Sheltering factor is applied.

The following calculations are performed for the deposition phase:

$$D_{ExtGndDep,outdoor} = D_{TotGamDep} \cdot \frac{1}{F_{DCF}} [Sv]$$

$$D_{ExtGndDep,indoor} = D_{TotGamDep} \cdot F_{LOF} \cdot \frac{1}{F_{DCF}} [Sv]$$

$$D_{ExtGndDep,averted} = D_{TotGamDep} \cdot (1 - F_{LOF}) \cdot \frac{1}{F_{DCF}} [Sv]$$

where:

- $D_{ExtGndDep,outdoor}$ is the Outdoor External Gamma Dose from Ground, deposition phase, [Sv],
- $D_{ExtGndDep,indoor}$ is the Indoor External Gamma Dose from Ground, deposition phase, [Sv],
- $D_{ExtGndDep,averted}$ is the External Gamma Dose from Ground averted by sheltering, dep. [Sv],
- $D_{TotGamDep}$ is the Total Gamma Dose from Deposition, [Gy],
- F_{LOF} is a Location factor (LOF), default = 0.15,
- F_{DCF} is a dose conversion factor from Sv to Gy, = 1, $\left[\frac{Gy}{Sv}\right]$.

After Deposition

For integrating the external ground dose after the deposition phase, the “Deposition on Ground” output from RIMPUFF/URD is used. A Ground Exposure Dose Factor is calculated, based on nuclide, age group and organ. The FDM routine for calculating time integrated ground exposure dose factors is used for the selected time intervals: 2 days, 7 days, 30 days, and 1 year. See also sect. “External dose from radionuclides deposited on ground”.

Only one time step is output.

Probit

The Probit output is only for the Chemical mode. Unit: $\left(\frac{mg}{m^3}\right)^n * s$

Based on Instantaneous Air Concentration, having the unit: $\frac{mg}{m^3}$.

The Probit ‘dose’ is given by:

$$D_{T;T=0} = C_T^n$$

$$D_{T;T>0} = D_{T-1} + C_T^n$$

$$P_T = D_T \cdot t \left[\left(\frac{mg}{m^3} \right)^n * s \right]$$

where:

- T is the time step number,
- t is the time step length in seconds,
- D is the Instantaneous Probit value,
- C is the Instantaneous Air Concentration value at each point, for a given substance,
- n is a 'probit power' which is substance dependent,
- P is the Probit dose .

Doses used with RIMPUFF

Because the dose calculations in ARGOS sometimes take as input results from other dose calculations, the format RIMPUFF binary output file format was selected for the output results from the dose calculations. In this way all the files, both those produced by RIMPUFF and ARGOS, are handled in the same way.

Files produced by RIMPUFF have the prefix “Out_”, and files produced by ARGOS have the prefix “Calc_”.

Dose	Input files	Output files
Inhalation (N only)	Out_IntgrConcAir.DAT	Calc_Inhalation.DAT, Calc_InhalationTotal.DAT
Thyroid (N only)	Calc_Inhalation.DAT	Calc_Thyroid.DAT
External from Cloud (N only)	Out_GamDosePuff.DAT	Calc_Extcloud.DAT
External from Ground (N only)	Out_GamDoseDep.DAT, Out_ConcDep.DAT	Calc_Extground.DAT
Total Effective (N only)	Calc_InhalationTotal.DAT, Calc_Extcloud.DAT, Calc_Extground.DAT	Calc_TotalEff.DAT
Probit (C only)	Out_InstConcAir.DAT	Calc_Probit.DAT

Doses used with URD

The files produced by the urban release

Dose	Input files	Output files
Inhalation (N only)	Out_URD_ConcTI_Air.DAT	Calc_URD_Inhalation.DAT, Calc_URD_InhalationTotal.DAT
Thyroid (N only)	Calc_URD_Inhalation.DAT	
External from Cloud (N only)	Out_URD_GammaDosePuff.DAT	Calc_URD_Extcloud.DAT
External from Ground (N only)	Out_URD_GammaDoseDepo.DAT	Calc_URD_Extground.DAT
Total Effective (N only)	Calc_URD_InhalationTotal.DAT, Calc_URD_Extcloud.DAT, Calc_URD_Extground.DAT	Calc_URD_TotalEff.DAT

Probit (C only)	Out_URD_Conc_Air.DAT	Calc_URD_Probit.DAT
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Calculations for Long Range models

Currently the following files are produced by Long Range Atmospheric Dispersion models used by ARGOS (DERMA, MLDP0, SNAP and MATCH):

File Name	Description
<run-id>_<model>_conc	Air Concentration, Ground Level
<run-id>_<model>_depo	Deposition on Ground
<run-id>_<model>_dose	Air Concentration, Time Integrated

Some models produce some additional files, but these are not used for dose calculations.

These result files are converted into the URD file format and subsequently handled like URD output. This means that all dose calculations are made for long range runs, but performed on data converted to the URD format.

The following doses are calculated by ARGOS because they are needed by subsequent calculations:

Dose	Input files	Output files
Gamma Dose from Puffs	Out_URD_ConcTI_Air.DAT	Out_URD_GammaDosePuff.DAT
Gamma Dose from deposition	Out_URD_DepoTot.DAT	Out_URD_GammaDoseDepo.DAT

Gamma Dose from Puffs

The Gamma Dose from Puffs is calculated from:

$$D_{Gamma,puffs} = C_{intgr,i} F_{Puff,Gamma} [Gy]$$

where:

- $D_{Gamma,puffs}$ is the Gamma dose from puffs, [Gy]
- $C_{intgr,i}$ is the Time-integrated Air Concentration for a given nuclide, $\left[\frac{Bq s}{m^3}\right]$
- $F_{Puff,Gamma,i}$ is puff-gamma factor for a given nuclide, $\left[\frac{Gy m^3}{s Bq}\right]$.

A 'Total' nuclide is calculated as a sum of values for all input nuclides.

Gamma Dose from Deposition

The Gamma Dose from Deposition is calculated from:

$$D_{Gamma,dep} = A_{Soil} F_{Depo,Gamma} T [Gy]$$

where:

- $D_{Gamma,dep}$ is the Gamma dose from deposition, [Gy]

- A_{Soil} is the deposition on ground for a given nuclide, $\left[\frac{\text{Bq}}{\text{m}^2}\right]$
- $F_{\text{Depo,Gamma}}$ is depo-gamma factor, $\left[\frac{\text{Gy m}^2}{\text{s Bq}}\right]$
- T is the time interval of each timestep, [s].

A 'Total' nuclide is calculated as a sum of values for all input nuclides.

Doses used with FDM/AgriCP

The following description is taken from the FDM documentation Part 3, written by ConRad Consulting in Radioecology. Any references in this section refer to the FDM documentation, ARGOS Manual sect. 6.4.1 part 3.

Location factors

In ARGOS location factors are defined as the ratio of the average effective dose rate received at a specific location to that received outdoors on an open lawn without any shielding or filtering structures for the same air concentration of radionuclides or deposited activity (in some references the terms "shielding factors" or "modifying factors" are used for location factors). By definition location factors include occupancy factors, which give the average fraction of time spent at the specific location. These occupancy factors are simply multiplied with the location factor as given for 100% occupancy of the specific location. The same location factors are also applied for all other organ doses besides effective dose, due to a lack of knowledge for organ specific location factors.

Since the dose rate on an open lawn is time dependent because of the increasing attenuation due to the migration of radionuclides in the soil and the physical decay, location factors only contain a relative time dependence, e.g. they can decrease or increase with time.

Location factors consider different processes which determine the radiation exposure depending on the regarded exposure pathway. Therefore, the assumptions for each exposure pathway are explained separately in this section.

In FDM a simple model for calculating location factors is used since detailed information on house types and shielding properties is not available:

1. The prevailing house type (low, medium or high shielding) at one location is derived from the population density:
 - if population density < lower limit \Rightarrow low shielding houses
 - if population density > lower limit and < upper limit
 \Rightarrow medium shielding houses
 - if population density > upper limit \Rightarrow high shielding houses

The limits are stored in the data base of ARGOS and can be defined separately for each radioecological region. The population density is read in from the geographical data base of ARGOS.

2. The location factors for an occupancy factor of 100% for each exposure pathway are read in from the ARGOS data base for the according house type. The location factors are defined for each radioecological region separately to account for variations in house building standards in different countries.
3. The occupancy factors (fraction of time spent indoors on average) are read in from the data base for the according radioecological region.
4. Location factors as retrieved from the data base are multiplied with the occupancy factors to determine the location factors for the given location. Both, location factors including the appropriate occupancy factor or an occupancy factor of 100% are provided as output of Subroutine LOCATION_FACTOR.

For the occupancy factor f_{in} (average fraction of time spent indoors) a default value of 0.8 is used. For each radioecological region more appropriate occupancy factors can be applied and stored in the ARGOS data base. In future these factors could be made dependent on the age group and also on the time of the year.

Internal dose from ingestion

The intake of activity by man is calculated from the time-dependent concentrations of activity in foodstuffs and the human consumption rates:

$$A_h(t) = \sum_{k=1}^K C_k(t) \cdot V_k(t) \quad (4.1)$$

where $A_h(t)$ = human intake rate (Bq d⁻¹) of activity
 K = number of foodstuffs considered
 $C_k(t)$ = concentration of activity (Bq kg⁻¹) of foodstuff k
 $V_k(t)$ = consumption rate (kg d⁻¹) of foodstuff k .

In FDM the foodstuffs are assumed to be locally produced, i.e. the calculated ingestion doses represent potential doses for people producing all their food locally. Age-dependent consumption rates of the average population are applied.

All consumption rates can be adapted individually for each radioecological region. As a default, average German consumption rates for the age groups 1, 5, 10, 15 y and adults as given in Table 17 are applied.

The dietary habits can be assumed to be season-dependent. In the default data set, for leafy vegetables it is assumed that the consumption rate in summertime is higher than the mean annual rate, and in wintertime, only a small fraction of the consumed vegetables is harvested outdoors (the rest is produced in greenhouses or imported from abroad). From May through October, a factor of

1.5 and from November through April, a factor of 0.1 is applied to the consumption rates for leafy vegetables given in Table 17 in Appendix B.

The dose $D_{\text{Ing}}(T)$ due to ingestion of contaminated foodstuffs within the time T after deposition is given by

$$D_{\text{Ing}}(T) = \int_0^T A_h(t) g_{\text{Ing}}(t) dt \quad (4.2)$$

where $D_{\text{Ing}}(T)$ = ingestion dose (Sv)
 $g_{\text{Ing}}(t)$ = age-dependent dose factor for ingestion (Sv Bq⁻¹).

The dose factors applied in FDM were calculated using the NRPB internal dosimetry program PLEIADES, which is consistent with publications ICRP-68, ICRP-72, and IAEA BSS. They give the dose commitment for an individual from its age at ingestion until the age of 70 y. For activity intake above the age of 20 y, the 50-year dose commitment is calculated.

Internal dose from inhalation

Inhalation dose from plume

The dose D_{Inh} due to inhalation of radionuclides during the passage of the radioactive cloud is calculated from the time-integrated activity concentration in the near ground air, the inhalation rate, and the age-dependent dose factor for inhalation. In addition, a reduction factor can be applied taking into account the lower activity in air inside houses:

$$D_{\text{Inh}} = \bar{C}_{\text{air}} \cdot I_{\text{Inh}} \cdot g_{\text{Inh}} \cdot R_{\text{Inh}} \quad (4.3)$$

with D_{Inh} = inhalation dose (Sv)
 \bar{C}_{air} = time-integrated activity concentration in air (Bq·h·m⁻³)
 I_{Inh} = inhalation rate (m³·h⁻¹)
 g_{Inh} = dose factor for inhalation (Sv·Bq⁻¹)
 R_{Inh} = location factor for staying indoors.

The age-dependent inhalation rates applied for the five age-groups (average over day considering different states of corporeal activity) are given in Table 18 in Appendix B. They are based on ICRP publication 71 (1995).

In ARGOS the following location factors R_{Inh} are default values; they can be adapted for each radioecological region separately. These location factors are given for an occupancy factor of 100% in Table 19 in Appendix B.

The same criteria as described in section “Location factors” is used to derive the prevailing house type at each location.

In FDM potential (R_{inh} is set to 1.0) and expected (using the above data) dose for inhalation can be calculated.

Inhalation dose from resuspended radionuclides

The amount of radioactive material which is resuspended from the soil by wind or other processes depends on many factors, as e.g. the conditions during deposition of the radionuclides (wet/dry deposition), the size and chemical conditions of the radioactive particles, the type of surface (vegetation, soil, urban surfaces), climatic conditions, and others (Sehmel, 1980). Therefore, there is large variability in the observed amount of resuspended material. A commonly used way to describe quantitatively the resuspension process is to apply the following approach:

$$C_{air,r}(t) = A_{soil} \cdot K_R(t) \cdot \exp(-\lambda_r \cdot t) \quad (4.4)$$

with $C_{air,r}(t)$ = concentration of activity in the near ground air
(Bq m⁻³) due to resuspension
 A_{Soil} = total deposition to ground (Bq m⁻²)
 $K_R(t)$ = time dependent resuspension factor (m⁻¹)

In many approaches in the literature (e.g. Linsley, 1978; Garland et al., 1992), the resuspension factor is expressed by an exponential together with a constant term:

$$K_R(t) = R_1 \cdot \exp(-R_2 \cdot t) + R_3 \quad (4.5)$$

with R_1 = resuspension factor (m⁻¹) immediately after deposition
 R_2 = rate of exponential decrease of $K_R(t)$ after deposition (d⁻¹)
 R_3 = long term resuspension factor (m⁻¹)

Before the time of the Chernobyl accident, typical values for R_1 have been in the range of $1 \cdot 10^{-6}$ m⁻¹ to $1 \cdot 10^{-4}$ m⁻¹, where the lower values seem to be representative for vegetated surfaces in moderate humid climate while the higher values apply to urban areas with traffic. Measurements of Caesium in air after the Chernobyl accident at different locations could be fairly good fitted with an exponential using A_R values in the range $3.6 \cdot 10^{-9}$ m⁻¹ to $4.9 \cdot 10^{-8}$ m⁻¹, and values of the parameter R_2 , which specified the exponential decline, were in the range of 0.026 to 0.124 per month (Garland et al., 1992). In this study, due to the limited observation period, a constant term R_3 could not be observed. The R_1 factor showed a significant negative correlation with the total amount of deposited activity; possible explanations for this are different deposition patterns (wet resp. dry deposition) at locations with high and low deposition, or some long range transport of resuspended material.

In the dose module of ARGOS the approach as given above is used for describing resuspension. The parameters R_1 , R_2 , and R_3 can be adjusted by the user. As default values, a short term resuspension factor of $5 \cdot 10^{-8} \text{ m}^{-1}$ (representing the highest values observed after the Chernobyl accident), a decrease rate of 0.003 d^{-1} ($= 0.09 \text{ month}^{-1}$) and a long term resuspension factor of $1 \cdot 10^{-9} \text{ m}^{-1}$ (though not observed after the Chernobyl accident, this value is taken to avoid underestimation for long times) seem appropriate for caesium (the above measurements are mostly based on caesium). The concentration of activity in the resuspended soil fractions might be increased considerably compared to the mean soil contamination; this is due to the strong binding of many radionuclides to clay minerals. Therefore, the activity concentration as described by equations (4.4) and (4.5) is multiplied by the resuspension enrichment factor f_r . The applied values for f_r for different elements and soil types are given in Table 11 (Appendix B). Since caesium has an enrichment factor of 3, the following values applied for R_1 and R_3 are taken in order to meet the above default resuspension factors for caesium: $R_1 = 1.5 \cdot 10^{-8} \text{ m}^{-1}$, $R_2 = 0.003 \text{ d}^{-1}$ and $R_3 = 3 \cdot 10^{-10} \text{ m}^{-1}$.

Calculation of inhalation dose from resuspended activity is done in the same way as for inhalation from the plume (see Section 4.3.1).

External dose from radionuclides in the cloud

ARGOS is to be applied at very different distances from the source emitting radionuclides to the atmosphere: from a few hundred meters up to a European scale. While at large distances (at least several kilometres) a semi-infinite homogeneous cloud could be assumed for calculating γ -exposure due to radiation from the cloud, this is not justified for smaller distances; instead of it, the dose rate has to be calculated by 3-dimensional integration over the activity concentration in the plume. Therefore, in ARGOS the average effective dose rate from airborne radionuclides for adults for each time interval of the atmospheric dispersion time grid, $\dot{D}_c(\Delta t_i)$, has been defined as interface between the atmospheric dispersion modules and the dose module FDM. External γ -exposure from the cloud integrated over the time periods Δt_i for is calculated by:

$$D_c = \sum_i \dot{D}_c(\Delta t_i) \cdot \Delta t_i \cdot R_c \quad (4.6)$$

where

- D_c = effective dose for adults due to external radiation from the cloud (Sv)
- \dot{D}_c = effective dose rate for adults due to external radiation from the cloud (Sv/s)
- R_c = location factor

Doses and dose rates for other age groups or for specific organs are calculated from the effective doses or dose rates for adults by scaling with the respective ratio of dose conversion factors:

$$D_{c,ik} = D_c \cdot g_{c,ik} / g_c \quad (4.7)$$

- $D_{c,ik}$ = Dose (Sv) for age group i and organ k
 $g_{c,ik}$ = dose conversion factor for exposure from the cloud ($Sv\ s^{-1}\ Bq^{-1}\ m^3$) for age group i and organ k
 g_c = dose conversion factor for exposure from the cloud ($Sv\ s^{-1}\ Bq^{-1}\ m^3$) for effective dose of adults

The age-dependent dose factors $g_{c,ik}$ for exposure from the cloud are taken from Jacob et al.(1990).

The following location factors R_c are default values for; they can be adapted for each radioecological region separately. These location factors are given for an occupancy factor of 100% in Table 20 in Appendix B.

The criteria as described in section “Location factors” is used to derive the prevailing house type at each location.

In FDM potential (R_c is set to 1.0) and expected (as in the above formula) external dose from cloud can be calculated.

External dose from radionuclides deposited on ground

The dose by gamma radiation from deposited radionuclides is calculated by

$$D_g(T) = \dot{K}_g \cdot R_g \cdot \int_0^T y(t) \cdot g_g(t) \cdot \exp(-\lambda_r \cdot t) \cdot dt \quad (4.8)$$

- where $D_g(t)$ = dose (Sv) from gamma radiation of deposited nuclides from time of deposition up to time t
 \dot{K}_g = kerma rate in air ($Gy\ s^{-1}$) at time of deposition from radionuclides deposited on ground (on lawn)
 $g_g(t)$ = age-dependent dose factor for exposure from ground ($Sv\ Gy^{-1}$)
 R_g = location factor
 $y(t)$ = corrective function for shielding due to migration of the radionuclides into deeper soil layers.

The age-dependent dose factors g_g for external exposure from deposited radionuclides are gained by dividing the dose-equivalent rates per unit activity per unit area by the kerma rate in air at 1 m above ground for infinite plane sources in ground at a depth of 5mm as given in Jacob et al.(1990).

The following location factors R_g for groundshine are default values; they can be adapted for each radioecological region separately. As a first approach location factors for short and long term are

set to the same values. These location factors are given for an occupancy factor of 100% in Table 21 in Appendix B.

The criteria as described in section “Location factors” is used to derive the prevailing house type at each location.

The consideration of nuclide specific location factors due to the energy dependence of structure shielding seems not to be very reasonable due to the relatively small variations in location factors for most building types (low and medium shielding houses) compared with the uncertainties e.g. in the nuclide spectrum, the deposition, the urban environments or the occupancy times.

In FDM potential (R_g is set to 1.0) and expected (as given above) external dose from ground can be calculated.

The following approach (Jacob 1991) describes the corrective function for shielding $y(t)$:

$$y(t) = a_1 \exp(-\lambda_{m1} \cdot t) + a_2 \exp(-\lambda_{m2} \cdot t) \quad (4.9)$$

with

$$\begin{aligned} \lambda_{m1}, \lambda_{m2} &= \text{migration rates } (\lambda_1 = 1.01 \times 10^{-3} \text{ d}^{-1}, \lambda_2 = 0.0 \text{ d}^{-1}) \\ a_1, a_2 &= \text{contribution fractions of the migration rates } (a_1 = 0.6, a_2 = 0.4). \end{aligned}$$

Attention! Due to the need to use time-integrated dose factors including the corrective function for shielding and the generation of daughter nuclides, presently an older set of dose factors is used in FDM. It contains an older time-dependent shielding function given by Gale!

External dose from radionuclides deposited on skin and clothes

Sparse data were available in the beginning 1990's about calculation of external dose from contamination of skin and clothes. More recent experimental data on this topic (published from 1997 to 2005) are not yet considered in the present modelling approach of FDM. Especially calculation of deposition to these surfaces is therefore associated with high uncertainty. Calculation of doses from this pathway in FDM is based on the following assumptions:

- Dry deposition velocity $v_{g,sk}$ on skin is the same as that on clothes (Jones, 1991). This deposition velocity can be chosen by the user; a default value of $1 \cdot 10^{-3} \text{ m} \cdot \text{s}^{-1}$ is used. Reduction of dry deposition due to staying inside buildings is assumed to be equal to the reduction factor for inhalation, R_{Inh} .
- For wet deposition, the average contamination of cloth/skin is assumed to be $f_{sk,w}$ times that of the total wet deposition to ground. As a default, $f_{sk,w} = 0.1$ (Jones, 1991) is used. Wet deposition onto skin is only assumed during the fraction f_{out} ($= 1 - f_{in}$) of time when people are outdoors.

- A fraction of f_{cloth} of human skin surface is protected by clothes. This fraction can be chosen by the user; a default value of 0.8 is used.
- The time t_{sk} after which activity is removed is assumed to be the same for skin and clothes. As a default, 24 hours are taken for t_{sk} . During this time interval, reduction of radioactivity by radioactive decay only is considered.
- For skin contamination, skin dose is due to α -, β -, and γ -radiation of the nuclides, while for contamination of clothes the γ component only is efficient. The dose conversion factors, giving the dose rate in skin (averaged over depth of 50 - 100 μ m) and other organs for a unit skin contamination are taken from Jacobi et al. (1989):

$g_{sk,sk}$ is the total dose rate in skin from unit skin contamination ($Sv \cdot s^{-1}$ per $Bq \cdot cm^{-2}$)

$g_{sk,sk,\gamma}$ is the γ -component of dose rate in skin from unit skin contamination ($Sv \cdot s^{-1}$ per $Bq \cdot cm^{-2}$)

$g_{sk,k}$ is the dose rate in organ k from unit skin contamination ($Sv \cdot s^{-1}$ per Bq)

With these assumptions, the mean skin dose H_{skm} is calculated by

$$H_{skm} = (C_{air} \cdot v_{g,sk} \cdot R_{Inh} + f_{sk,w} \cdot D_{wet} \cdot f_{out}) \cdot \{g_{sk,sk,\gamma} \cdot f_{cloth} + g_{sk,sk} \cdot (1 - f_{cloth})\} \cdot \frac{1}{\lambda_r} \cdot \{1 - \exp(-\lambda_r \cdot t_{sk})\} \quad (4.10)$$

For organs other than skin the dose from skin/cloth contamination is

$$H_{sk} = (C_{air} \cdot v_{g,sk} \cdot R_{Inh} + f_{sk,w} \cdot D_{wet} \cdot f_{out}) \cdot g_{sk,k\gamma} \cdot A_{skin} \cdot \frac{1}{\lambda_r} \cdot \{1 - \exp(-\lambda_r \cdot t_{sk})\} \quad (4.11)$$

with A_{skin} = total area of skin (m^2)
and other symbols as defined above.

The location factor for the dry deposition component is the same as for the exposure from inhalation, since this factor gives the reduction of the indoor air concentration of radionuclides compared to the outdoor concentration and the dry deposition is linearly related to the air concentration. The location factor for the wet deposition component is simply zero, since wet deposition cannot occur indoors.

In FDM potential (R_{Inh} and f_{out} is set to 1.0) and expected (as in the above formula) external dose from skin/cloth contamination can be calculated.

Calculation of collective doses

The assessments of collective doses in FDM can only be regarded as rough estimations of the real collective doses since due to the limited input information several simplifying assumptions have to be made. Different approaches are used for collective doses for the ingestion pathway, and those for all other pathways. Therefore, no collective dose for the sum of all pathways is given.

Collective doses are first estimated individually for all locations (communities) defined by ARGOS by the methods described below. Then they are summed up over all locations to yield a total collective dose for the whole considered area, and a frequency distribution (giving the number of persons having a dose equal or below the respective dose) is built up. It has to be taken in mind that such a frequency distribution does not reflect the real distribution of individual doses since all people at one location are considered to have the same dose.

Ingestion pathway:

The collective dose at a location (i.e. community in ARGOS) due to consumption of contaminated foodstuffs is based on the amount of foodstuffs produced at that location. Only that part of products which is consumed by humans is considered. Collective dose is estimated as that effective dose equivalent which arises if these products are eaten by adults, no matter where they are eaten (this might be by people living at the considered location, or somewhere else). Collective doses can be calculated only for those foodstuffs for which production data are available. Since it can be expected that production data will never be available for all produced foodstuffs, summing up the collective doses for all foodstuffs considered seems to be not very useful; the result would be a more or less arbitrary number.

For a given location, collective dose from ingestion of raw product k in the time period from deposition up to time T is calculated as

$$D_{\text{Ing}}^{\text{Col}}(T) = g_{\text{Ing,a}} \cdot PR_k \cdot \exp(-\lambda_r \cdot t_{\text{pk}}) \cdot \int_0^T C_{k0}(t) \cdot dt \quad (4.12)$$

with $D_{\text{Ing}}^{\text{Col}}(t)$ = collective dose from ingestion of foodstuff (raw product) k
 $g_{\text{Ing,a}}$ = ingestion dose factor (Sv Bq⁻¹) for adults
 PR_k = production rate of foodstuff k (kg a⁻¹)
 t_{pk} = storage and processing time (d) for product k
 $C_{k0}(t)$ = activity concentration (Bq kg⁻¹) in the raw product at time t

If a certain raw product is used to process more than one foodstuff, then the shortest storage and processing time t_{pk} is used in this calculation. Further, loss of activity from the food chain during food processing and culinary preparation is not considered in this estimation since production data are given for raw foodstuffs, and there is no information on processing of them. For these reasons, the resulting collective dose for a (raw) foodstuff has to be regarded as an upper limit.

Pathways different from ingestion:

For all exposure pathways except ingestion, collective dose is roughly estimated from the expected individual dose of an adult, multiplied by the number of inhabitants living at the location:

$$D_p^{COL} = D_p \cdot N \tag{4.13}$$

- with D_p^{Col} = collective dose from pathway p for a certain location
- D_p = individual dose of an adult at the considered location
- N = number of inhabitants living at the considered location

Doses used with ERMIN

The doses calculated by the ERMIN model are called “Public Doses” and “Surface Doses”. They are calculated by ERMIN during the screening phase.

Public Doses

Total, Gamma, Beta, Resuspension.

The dose path "Total" means: the sum of effective dose from gamma radiation and committed effective dose from inhalation of resuspended material.

Sheltering: Normal Living, Outdoor, Indoor.

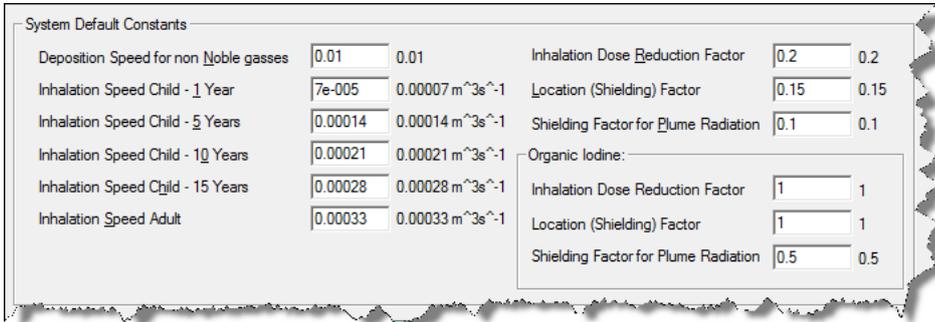
Integration times: 7, 30, 365, 3650 (days).

Dose Parameters

The ARGOS N database contains the table “system_defaults” which holds the following data related to Nuclear dose calculation:

Id	Shortname	Descr	Value
1	DEPHAST	Deposition Speed for non-Noble gasses	0.01
2	INHALHAST_CHILD	Inhalation Speed Child - 1 Year	7E-05
3	INHALHAST_CHILD5	Inhalation Speed Child - 5 Years	0.00014
4	INHALHAST_CHILD10	Inhalation Speed Child - 10 Years	0.00021
5	INHALHAST_CHILD15	Inhalation Speed Child - 15 Years	0.00028
6	INHALHAST_ADULT	Inhalation Speed Adult	0.00033
7	TDF	Thyroid Dose Factor	5
8	IRF	Inhalation Dose Reduction Factor	0.2
9	LOF	Location (Shielding) Factor	0.15
10	SHF	Shielding Factor for Plume Radiation	0.1
11	IRF_IOD	Inhalation Dose Reduction Factor - Iodine	1
12	LOF_IOD	Location (Shielding) Factor - Iodine	1
13	SHF_IOD	Shielding Factor for Plume Radiation - Iodine	0.5

Many of these values can be edited through the ARGOS UI from the “Basedata|Nuclide Data” menu:



The Thyroid Dose Factor does not have any UI – it must be changed in the database manually.

The Committed Effective Dose coefficient $e_i(50)$ is defined explicitly for each isotope i in the database table “isotopdata” for each of the age groups. These values can be edited through the ARGOS UI from the “Basedata|Nuclide Data” dialog.

The ARGOS C database contains the table “ChemAgents” which holds the following data related to Chemical Probit calculation (only some columns and only one row shown here):

Agent_index	Designation	Name	Probit
1	CH4	Methane	2