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Summary :

The objective of this report is to propose some reference exposure scenarios and parameters for performing a dose-assessment for a soil contaminated with radioactive substances.

The proposed scenarios and parameters take into account following principles :

- Ensure the consistency with the scenarios and parameters used for chemical risk-assessment in the three Belgian regions (S-Risk model);
- Ensure the consistency with existing international practices;

As radiological contamination is in most cases coupled to chemical contamination, it is particulary recommended to use consistent scenarios and parameters in the assessment of both radiological and chemical risks.

Where applicable, FANC recommends the use as baseline of S-Risk reference scenarios and parameters in the assessment of the radiological risk.

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1. Introduction

The objective of this report is to propose some reference exposure scenarios and parameters for performing a dose-assessment for a soil contaminated with radioactive substances.

The proposed scenarios and parameters take into account following principles :

- Ensure the consistency with the scenarios and parameters used for chemical risk-assessment in the three Belgian regions (S-Risk model);
- Ensure the consistency with existing international practices;

The main references used in this report are the following :

- « S-Risk : Technical guidance document » [1], [2]
- "Using RCLEA – the radioactively contaminated Land exposure assessment methodology" [3]
- "Berechnungsgrundlagen zur Ermittlung der Strahlenexposition infolge bergbaubedingter Umweltradioaktivität" [4]
- "Gestion des sites potentiellement pollués par des substances radioactives – guide méthodologique" [5]

This report is a further development of the notes AFCN 2017-08-31-SRA-7-3-1-FR et AFCN 2017-08-31-SRA-7-3-2-FR [6]. In these two notes, a comparison had been made between the parameters used in various international guides and methodologies. This intercomparison is summarized in Annex and has been published in [7].
A similar work of comparison of default parameters values in different models had also been performed by US EPA [8].

As radiological contamination is in most cases coupled to chemical contamination, it is particulary recommended to use consistent scenarios and parameters in the assessment of both radiological and chemical risks. **Therefore, where applicable, FANC recommends the use as baseline of S-Risk reference scenarios and parameters in the assessment of the radiological risk**.

The formules and equations referred to in this report must be used in combination with S-Risk Technical Guidance document [1][2] (referred to in this report as "S-Risk manual"). The context of the assessment, the appropriateness of the assumptions, the consistency of the units have to be considered with the necessary care.

2. Reference scenarios

Regional regulations regarding soil remediation (« bodemsaneringsdecreet » in Flanders and « décret-sol » in Wallonia) define five standard uses for soil. The correspondence between these standard uses and the various types of real uses is established in Annex IV art. 2 of "bodemsaneringsdecreet" and Annex II of "décret-sols".

For each of the five standard uses, the S-Risk model proposes default scenarios. They are reproduced in Table 1 below :

<table>
<tr><th colspan="2"></th><th colspan="2">Name</th><th>S-Risk default scenario</th></tr>
<tr><td colspan="2">Type I</td><td colspan="2">Natuurgebied / naturel</td><td>REC-dayout (day recreation – incl. sport)</td></tr>
<tr><td colspan="2">Type II</td><td colspan="2">Landbouw / agricole</td><td>AGR (residence with vegetable garden in agricultural area)</td></tr>
<tr><td colspan="2">Type III</td><td colspan="2">Wonen / résidentiel</td><td>RES-veg (residential with vegetable garden)
RES (residential with garden)
RES-ng (residential without garden)</td></tr>
<tr><td rowspan="2">Type IV</td><td>a</td><td>Dagrecreatie buiten</td><td rowspan="2">récréatif et commercial</td><td>REC-dayout (day recreation – incl. sport)</td></tr>
<tr><td>b</td><td>verblijfsrecreatie</td><td>REC-dayin (day recreation indoor sport scenario)</td></tr>
<tr><td rowspan="2">Type V</td><td>a</td><td colspan="2">Zware industrie / industriel léger</td><td>IND-l (light industry)</td></tr>
<tr><td>b</td><td colspan="2">Lichte industrie / industriel lourd</td><td>IND-h (heavy industry with outside activity)</td></tr>
</table>

Table 1: Default scenarios corresponding to the standard soil uses

These scenarios may also serve as reference in the assessment of radiological risk.

3. Exposure pathways

S-Risk model takes into account the following exposure pathways :

a) *Oral*
- **Ingestion of soil and indoor settled dust;**
- **Intake of vegetables from local production (home-grown);**
- **Intake of meat and milk from local production;**
- **Intake of water (drinking-water or groundwater);**

b) *Dermal*
- Absorption from soil and indoor settled dust;
- Absorption from water during showering and bathing;

c) *Inhalation*
- **Inhalation of outdoor air (gas-phase + particles);**
- **Inhalation of indoor air (gas-phase + particles);**
- Inhalation during showering (gas-phase).

In **bold**, the exposure pathways which also need to be considered in the radiological assessment. Dermal and inhalation during showering pathways are neglected[1]. One may note however that the RCLEA guide, for instance, describes the calculation method for direct skin *irradiation* through dermal contact.

External exposure needs to be added for the radiological assesment. Exposure to radon is included in the inhalation pathway (gas-phase).

[1] EPA proposes a method for calculating the dose from *ingestion* through showering with a contaminated water. This exposure pathway was relevant for instance for the case of uranium contamination in the groundwater of Uccle.

Table 2 (inspired from Table 27 of [1]) reproduces the exposure pathways to be considered for each default scenario.

	AGR	RES-veg	RES	RES-ng	REC-dayout	REC-dayin	IND-l	IND-h
External exposure indoor	X	X	X	X		X	X	X
External exposure outdoor	X	X	X	X	X		X	X
Oral								
Ingestion of soil	X	X	X	X	X		X	X
Ingestion of indoor settled dust	X	X	X	X		X	X	X
Intake of vegetables from local production	X	X						
Intake of meat and milk from local production	X							
Intake of water	X	X	X	X			X	X
Inhalation								
Inhalation of outdoor particles	X	X	X	X	X		X	X
Inhalation of outdoor gas (radon)	X	X	X	X	X		X	X
Inhalation of indoor dust	X	X	X	X		X	X	X
Inhalation of indoor air (radon)	X	X	X	X		X	X	X

Table 2: exposure pathways of reference scenarios

4. Equations and parameters

a) External exposure outdoor

External exposure outdoor is easily evaluated if measurements of the ambient dose-rate on the contaminated site are available :

$$D_{ext,\,out}\ (\mu Sv/a) = N * f_{eq/eff} * (d_{ext} - d_{ext,bkg})$$

- N = exposure duration (in hours/year) ;
- d_{ext}, the ambient equivalent dose-rate (H*(10) - µSv/h) measured by a dose-rate meter on the contaminated zone at 1m heighth;
- $d_{ext,bkg}$, the ambient equivalent dose-rate (H*(10) - µSv/h) corresponding to local background;
- $f_{eq/eff}$ is the conversion factor between equivalent and effective dose ;

Table 3 [4] gives the conversion factor $f_{eq/eff}$ for the differents age groups.

Age groups	$f_{eq/eff}$
≤ 1 a	0.8
1 – 2	0.7
2 – 7	0.7
7 – 12	0.7
12 – 17	0.6
> 17	0.6

Table 3: conversion factor equivalent dose / effective dose for each age group.

If no ambient dose-rate measurements are available, the external dose may be calculated from the activity concentrations in soil through a specific calculation code (µ-Shield, RESRAD, Normalysa, ...) or through the rules described in annex 1.

Exposure time is scenario-dependent. Section 9.6.1 "Time patterns" of S-Risk manual (tables 35 to 43) provides an estimation of exposure time (inside and outside) for each standard scenario. These tables are reproduced in annex 2.

b) External exposure indoor

External exposure indoor is calculated in a similar way by multiplying the ambient dose-rate outside by a shielding factor.

$$d_{ext,\, in}\ (\mu Sv/a) = f_e * d_{ext,\, out}$$

This shielding factor is dependent on the type of construction. Annex 1 of [4] proposes two values (building with « heavy » construction materials – bricks, concrete – and « light » construction – wooden cabin / caravan) :

	f_e
« Heavy » construction	0.1
« light » construction (cabin, caravan,...)	0.3

Table 4: shielding factor

These values are consistent with the ones of RCLEA (f_e=0.1) and the default value of RESRAD (f_e=0.3). Nuclide-specific shielding factors have also been calculated in [5] for different types and thicknesses of soil cover.

c) Ingestion of soil and of indoor settled dust

S-Risk distinguishes between direct soil ingestion and dust ingestion.

$$D_{ing} = N * IR_{soil} * \Sigma_i * a_i * h_i^{ing} + N * IR_{dust} * \Sigma_i * a_{i,settled\_dust} * h_i^{ing}$$

- N = exposure time (cf. annex 2)
- IR_{soil} = soil ingestion rate (mg/h) or (mg/day)
- IR_{dust} = dust ingestion rate (mg/h) or (mg/day)
- a_i = activity concentration of the radionuclide i in the superficial layer of contaminated soil (Bq/kg)
- h_i^{ing} = dose-coefficient by unit of incorporation of the radionuclide i (µSv/Bq). These coefficients are discussed in annex 3 for the natural radionuclides.
- $a_{i,settled\ dust}$ = activity concentration of the radionuclide i in dust.

One assumes that the concentration of a contaminant in the fine fraction (thus, in dust) is enriched compared to soil-concentration (cf. also [4] – eq. 5.1a).

$$a_{i,settled\_dust} = F_{soil/settled\_dust} * EF_{soil/settled\_dust} * a_i$$

- $a_{settled\_dust}$ = activity concentration of nuclide i in dust
- $F_{soil/settled\_dust}$ = fraction of soil in settled dust (scenario-dependent : cf. table 5 – reproduced from table 46 of [1])
- $EF_{soil/settled\_dust}$ = enrichment factor of the fine fraction (default value in S-Risk = 1.5)

Scenario	$F_{soil/settled\_dust}$
AGR	0.5
RES-veg	
RES	
RES-ng	0.25
REC-dayout	
REC-dayin	
IND-l	
IND-h	

Table 5: fraction of soil in settled dust

The ingestion rate of dust and soil, IR_{dust} and IR_{soil} , are provided by the tables 43 and 44 of S-Risk manual. They are reproduced in Table 6.

Age group	AGR/RES-veg/RES		RES-ng		IND-l		IND-h		REC-dayin/REC-dayout	
	IR_{soil}	IR_{dust}	IR_{soil}	IR_{dust}	IR_{soil}	IR_{dust}	IR_{soil}	IR_{dust}	IR_{soil}	IR_{dust}
	mg/day								mg/h	
1 - <3	68.4	83.6	40	85	0	0	0	0	26	4
3 - <6	54.9	67.1	32	68	0	0	0	0	20	3
6 - <10	41.85	51.15	18.25	54.75	0	0	0	0	13	2
10 - <15	40.05	48.95	15.64	52.36	0	0	0	0	11	2
15 - <21	38.25	46.75	12.6	50.4	5.2	20.8	30.8	7.7	9	2
21 - <61	34.65	42.35	10.6	42.4	5.2	20.8	30.8	7.7	5	1.8
≥ 61	34.65	42.35	10.6	42.4	5.2	20.8	30.8	7.7	5	1.8

Table 5: ingestion rate of dust and soil in the reference scenarios (from [1])

d) Intake of vegetables from local production

Contamination of plants and grains on a contaminated soil can result from following processes :

- Transfer of contaminants from soil to plant though the roots and translocation of the contaminants in the plant;
- Transfert of contaminants via atmospheric deposition;

For *organic* compounds, S-Risk also considers the transfer of contaminants present as gas-phase in air as well as the transfer of contaminants through soil-splash. These transfer pathways are neglected in the present document.

On the other hand, transfert of contaminants through irrigation with contaminated water may be taken into account [4][9] although it is neglected in S-Risk. The calculation of the activity concentration in plant due to irrigation is for instance described in §6.2.2 (eq. 6.4) of [4] or in § D.2.1.5.3 (ditch irrigation) and § D.2.1.5.4 (overhead irrigation) of RESRAD user's manuel [9].

i) Transfer soil-plant though the roots

Transfer of contaminants to the plant is calculated by using transfer factors.

$$(a_i)_{plant,DW} = F_{i,\ plant} \times (a_i)_{soil,DW}$$

With $(a_i)_{plant,DW}$ the activity concentration of nuclide i in the plant (in dry weight), $(a_i)_{soil,DW}$ the activity concentration of nuclide i in soil (also in dry weight) and $F_{i,\ plant}$ the transfer factor.

Default values of transfer factors may be found in the IAEA report SRS472 « *Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments* ». As the differences between minimal and maximal values cover sometimes several orders of magnitude, if no site-specific values are available, it is recommended to use the median value as basic assumption but also to carry out a sensitivity analysis.

Transfer factors of SRS472 have been derived with the convention defined by the *International Union of Radioecologists* (IUR) for root depth : 10 cm for gras and 20 cm for the other crops (including fruit trees). In order to use these transfer factors, one considers then the average contamination value in the upper 10 (resp. 20) cm soil layer.

Remark : the IUR assumption is different of the one used in S-Risk where it is considered that the transfer through the roots happens through the upper *30 cm* soil layer [1].

ii) Transfer through deposition

The contaminants concentration in plant due to dust deposition is calculated in S-Risk with following formula[2]; one finds a similar formula in [9] and [4].

$$(a_i)_{plant,DW,\ deposition} = a_{i,settled\_dust} \times I_v \times (V_d + R_n \times R_w \times W_c) \times (1 - \exp(-k_w\ t))$$

With $a_{i,settled\_dust}$ = activity concentration of nuclide i in dust
I_v = fraction of particles intercepted by plant
V_d = dry particle deposition rate
R_n = annual rainfall
R_w = fraction retained after rainfall
W_c = volumetric wash-out factor for particles (default value = $5\ 10^5$) ;
K_w = plant weathering constant
t = growth period of plant
Y_v = plant yield

The fraction of particles intercepted by plant I_v is dependent on plant yield and is calculated with S-Risk equations :

$I_v = 1 - \exp(-\ 2.88 \times Y_{v,grass} \times dm/100)$;
$I_v = 1 - \exp(-\ 0.769 \times Y_{v,silage} \times dm/100)$;
$I_v = 1 - \exp(-\ 0.0846 \times Y_{v,foliar})$;
$I_v = 1 - \exp(-\ 0.0324 \times Y_{v,other})$;

Where dm is the dry matter content of the plant (in %).
The other parameters are taken from tables 19 and 20 in S-Risk manual.

iii) Calculation of exposure

[2] Eq. 117 S-Risk manual

Assessment of exposure requires first to calculate the total activity of ingested contaminants based on the diet of the reference person.

S-Risk first groups vegetables into categories.
The quantity of vegetables for a given category is calculated through (Eq. 171-173) of S-Risk manual:

$$C_{veg,\ cat\_j} = (\Sigma\ C_{veg\_i,j} \times Q_{veg\_i,j})/(\Sigma\ Q_{veg\_i,j})$$

$$A^{yearly}_{veg\_cat\_j} = a_{veg,\ cat\_j} \times Q_{veg,cat} \times f_{veg,cat}^{\ garden}$$

With :

$A^{yearly}_{veg\_cat}$ = the total activity of ingested contaminants through the vegetables of categoy « j » ;
$a_{veg,\ cat\_j}$ = activity concentration in the vegetables of category j ;
$Q_{veg,cat}$ = total quantities of vegetables of category j ;
$f_{veg,cat}^{\ garden}$ = fraction of consumed vegetables from home-grown production;

The average consumption in Belgium of vegetable of a given category are given in table 29 of S-Risk manual. These tables are reproduced in annex.

The dose is calculated by multiplying the total ingested activity by the corresponding dose conversion factor and by summing over vegetables categories and nuclides :

$$D_{veg} = \Sigma_{\ cat}\ \Sigma_{\ nucl\_i}\ A^{yearly}_{i,veg\_cat\_j}\ h_i^{ing}$$

e) *Intake of meat and milk from local production*

One refers to chapter 8 and § 9.2.2 of S-Risk Technical Guidance.

S-Risk allows to calculate contaminants concentrations in beef and mutton meat, in milk and in eggs.

i) Calculation of contaminant concentration in animal products

The calculation of contaminant concentration in animal products is made in two steps:

- Calculation of the intake of contaminants by the animal;
- Calculation of the concentration in the animal product by multiplying the intake by the respective transfer factor;

The intake by the animal (beef or milk cattle, sheep and chicken in S-Risk) corresponds to the yearly intake of the contaminant through ingestion of pasture or silage grass, maize, soil particles and external feedstuff (concentrates). A distinction is made between summer and winter diet.

- For exposure of cattle, see Eq. (127) – (130) of S-Risk manual and the values of the corresponding parameters ;
- For exposure of chicken, see Eq. (141) – (147);

The yearly intake is calculated on basis of the activity concentrations in grass, maize (see § d), soil and water and the ingested quantities (in $kg_{,dry\ matter}$/day).

The concentration in the animal product is then calculated by multiplying the yearly intake by the transfer factor of the contaminant to animal product. Here also the IAEA Safety report SRS472 (section 6) [10] is used as reference. SRS472 does not contain value of transfer factors for all nuclides: when site-specific data are available, they should be preferred to literature data. In absence of data, a value of transfer factor may be chosen on basis of analogy of chemical properties with another contaminant.

For inorganic contaminants in milk, S-Risk considers that the concentration in butter is the same as the concentration in milk.

ii) Calculation of exposure

As for vegetables, the exposure will be assessed :

- by multiplying the concentration in the respective product (beef, chicken, etc.) by the yearly ingested quantities of that product – taking into account the proportion of intake of locally grown food: see eq. (174) – (178) of S-Risk manual and the tables (30) and (45) for the consumption data and the fraction of locally produced food: this provides the yearly intake to an individual from the consumption of animal product.
- The ingestion dose is then calculated by multiplying the yearly intake by the corresponding dose-conversion factor for ingestion:

$$D_{animal\_product} = \Sigma_{cat} \Sigma_{nucl\_i} A^{yearly}_{i,animal\_cat\_j} h_i^{ing}$$

f) Intake of water

Regarding exposure through intake of contaminated water, the principle of the calculations is the same as for other products :

- Assess (or measure) the contaminant concentration in water;
- Calculate the intake of the contaminant through intake of water;
- Calculate the dose by multiplying the contaminant intake by the dose conversion factor;

S-Risk calculates two contributions to the contamination of drinking water:

- The contamination of the local groundwater – assuming some fraction of it is used as drinking water;
- The contamination resulting from the permeation of the contaminant through the drinking water pipes; this pathway however is only relevant for organic contaminant; we will neglect it for radionuclides;

When no site-specific values for contamination of groundwater is available, S-Risk allows to calculate the concentration of the contaminant in groundwater from the concentration in the contaminated soil pore-water. See Eq. (21) to (24) and Table 7 of S-Risk manual.
To obtain the concentration in drinking water, one multiplies the concentration in groundwater by the fraction of groundwater used for drinking purpose:

$$C_{dw} = C_{gw} \text{ X } f_g$$

However, in S-Risk, the default value for the fraction of groundwater used as drinking water is zero for all standard scenarios (see Table 45), which basically means that contamination of drinking water may be discarded as exposure pathway for humans. But if local circumstances indicates that this is not the case, one can choose a non zero value for this parameter.

The intake of the contaminant through drinking water is calculated according to Eq. (180) – (181). It takes into account the quantities of drinking water ingested depending on age category and on the standard scenario considered.

g) Inhalation of outdoor and indoor dust

Concentration of contaminant in outdoor particles is due to soil resuspension. An additional contribution from volatization may be added for contaminant present in gas phase.

Concentration due to soil resuspension $C_{PM10,out}$ may be calculated from the PM_{10} fraction of the concentration of suspended particles: See Eq. (44) – (45) of S-Risk manual.

The concentration in PM10 in indoor air is calculated by multiplying the concentration in outdoor air by a reduction factor $F_{out/in}$:

$$C_{PM10,in} = F_{out/in} \times C_{PM10,out}$$

The default value of $F_{out/in}$ in S-Risk (Table 16) is 1. One considers thus conservatively that the concentration of PM10 indoor is the same as outdoor.

The way S-Risk calculates the dose due to inhalation of particle differs from what is usually done for inhalation of radionuclides. In S-Risk, inhalation risk-assessment is based on concentrations which are time-averaged and weighted on age and type of activity.

Models usually applied for radionuclides are rather based on dose-calculations: the quantity of contaminant inhaled is calculated from the concentration of contaminant in the suspended particles multiplied by an age- and activity dependent respiratory debit. Multiplying by the inhalation dose conversion factor allows to get the dose.

We recommend to use the respiratory debit defined in ICRP66 and to use the exposure time of the different scenarios defined by S-Risk.

h) Inhalation of indoor gas

S-Risk incorporates the Volasoil model which allows calculating indoor air concentration of volatile compound due to vapour intrusion from soil or groundwater into the building. The model considers three different building types: without basement (slab-on-grade), with basement and with crawl space; it takes into account both diffusive and convective transport. It also allows two options for the floor of the building: intact or with gaps and holes.

Such a model could be applied to estimate radon concentration indoor (in Bq/m^3) from the measured radon concentration in soil-gas.

The calculations are quite complex however: they necessitate to calculate the flux from soil to indoor air through the floor: (Eq. 47) of S-Risk manual.

An effective diffusion coefficient needs to be calculated for each soil layer (Eq. 36). The effective diffusion coefficient in the floor is also assessed (Eq. 54) from the diffusion coefficient of the contaminant in air D_a (Eq. 13).

The contaminant concentration in indoor air is calculated from the flux of the contaminant from soil to indoor air – taking into account floor area and volume of indoor space - See

Eq. (61). The flux of contaminant into indoor air does not only take into account diffusion but also advection through the pressure gradient between indoor space and soil. Advection process is known to be the essential contributor to radon concentration indoor.

Similar calculations may be performed for a building with basement or with crawl space.

Althoug some preliminary calculations for the "slab-on-grade" case with intact floor seem to indicate a consistent result for radon concentration indoor from an elevated radon concentration in soil-gas (3500 Bq/m^3 indoor for 800 kBq/m^3 in soil-gas), the results are not consistent anymore while testing the case with floor with gaps and holes. A generalisation of the Volasoil model to the estimation of radon indoor concentration would thus need further work.

In any case, decision about radon-risk should rather be based on measurements than on modelling. A significant increase of radon concentration in soil-gas in a contaminated area gives already a sufficient rationale to consider the contaminated site as a radon-prone area with consequently prevention measures against ingress of radon in buildings and monitoring program. For a more quantitative methodology, see for instance [12].

Annex 1 : calculation of external dose from activity concentrations in soil

- Table 4 of RCLEA guidance [3] gives a list of dose coefficient for external whole body irradiation in (Sv/yr)/(Bq/m^3) (considering a uniformly contaminated slab of 1 m depth and infinite area).

- For U-238 in secular equilibrium, [4] proposes the following conversion factor :

$$d_{ext} = g * C_{U\text{-}238}$$

  - $C_{U\text{-}238}$ = activitity concentration of U-238 (Bq/kg)
  - g = 5.3 10^{-4} (µSv/h)/(Bq/kg)

Annex 2 : default time-use patterns per scenario in S-Risk

Table 35: Time-use for landuse type agricultural residential area with vegetable garden (AGR)

Age	Sleeping (t_{sleep})	Awake Inside (t_{in})	Outside (t_{out})	Total* on site	EF_{week}	EF_{year}
	h/day	h/day	h/day	h/day	d/week	weeks/year
1 - < 3 year	12	11.5	0.5	24	7	52
3 - < 6 year	11	9.7	1.38	22.08	7	52
6 - < 10 year	10	8.7	1.57	20.27	7	52
10 - < 15 year	9	10.6	1.12	20.72	7	52
15 - < 21 year	8	8.5	0.8	17.3	7	52
21 - < 31 year	8	9.0	1.0	18	7	52
31 - < 41 year	8	11.5	1.3	20.8	7	52
41 - < 51 year	8	11.5	1.5	21	7	52
51 - < 61 year	8	11.5	1.8	21.3	7	52
≥ 61 years	8	11.5	1.7	21.2	7	52

* sum of hours 'sleeping'. 'awake' and 'outside'

Table 36: Time-use for landuse type residential with vegetable garden (RES-veg)

Age	Sleeping (t_{sleep})	Awake Inside (t_{in})	Outside (t_{out})	Total* on site	EF_{week}	EF_{year}
	h/day	h/day	h/day	h/day	d/week	weeks/year
1 - < 3 year	12	11.5	0.5	24	7	52
3 - < 6 year	11	9.7	1.38	22.08	7	52
6 - < 10 year	10	8.7	1.57	20.27	7	52
10 - < 15 year	9	10.6	1.12	20.72	7	52
15 - < 21 year	8	8.5	0.8	17.3	7	52
21 - < 31 year	8	9.0	1.0	18	7	52
31 - < 41 year	8	11.5	1.3	20.8	7	52
41 - < 51 year	8	11.5	1.5	21	7	52
51 - < 61 year	8	11.5	1.8	21.3	7	52
≥ 61 years	8	11.5	1.7	21.2	7	52

* sum of hours 'sleeping'. 'awake' and 'outside'

Table 37: Time-use for landuse type residential with garden (RES)

Age	Sleeping (t_{sleep})	Awake inside (t_{in})	Outside (t_{out})	Total* on site	EF_{week}	EF_{year}
	h/day	h/day	h/day	h/day	d/week	weeks/year
1 - < 3 year	12	11.5	0.5	24	7	52
3 - < 6 year	11	9.7	1.38	22.08	7	52
6 - < 10 year	10	8.7	1.57	20.27	7	52
10 - < 15 year	9	10.6	1.12	20.72	7	52
15 - < 21 year	8	8.5	0.4	16.9	7	52
21 - < 31 year	8	9.0	0.4	17.4	7	52
31 - < 41 year	8	11.5	0.7	20.2	7	52
41 - < 51 year	8	11.5	1.0	20.5	7	52
51 - < 61 year	8	11.5	1.3	20.8	7	52
≥ 61 years	8	11.5	1.0	20.5	7	52

* sum of hours 'sleeping'. 'awake' and 'outside'

Table 38: Time-use for landuse type residential without garden (RES-ng)

Age	Sleeping (t_{sleep})	Awake inside (t_{in})	Outside (t_{out})	Total* on site	EF_{week}	EF_{year}
	h/day	h/day	h/day	h/day	d/week	weeks/year
1 - < 3 year	12	11.5	0.5	24	7	52
3 - < 6 year	11	9.7	1.38	22.08	7	52
6 - < 10 year	10	8.7	1.57	20.27	7	52
10 - < 15 year	9	10.6	1.12	20.72	7	52
15 - < 21 year	8	8.5	0.3	16.8	7	52
21 - < 31 year	8	9.0	0.3	17.3	7	52
31 - < 41 year	8	11.5	0.4	19.9	7	52
41 - < 51 year	8	11.5	1.0	20.5	7	52
51 - < 61 year	8	11.5	1.0	20.5	7	52
≥ 61 years	8	11.5	1.0	20.5	7	52

* sum of hours 'sleeping'. 'awake' and 'outside'

Table 39: Time-use for landuse type day recreation for children and adults in indoor sport scenario (REC-dayin)

Age	Sleeping (t_{sleep})	Awake inside (t_{in})	Outside (t_{out})	Total* on site	EF_{week}	EF_{year}
	h/day	h/day	h/day	h/day	d/week	weeks/year
1 - < 3 year	0	2.1	0	2.1	2	44
3 - < 6 year	0	2.1	0	2.1	2	44
6 - < 10 year	0	1.9	0	1.9	3	44
10 - < 15 year	0	1.9	0	1.9	3	44
15 - < 21 year	0	1.9	0	1.9	3	44
21 - < 31 year	0	2.1	0	2.1	2	44
31 - < 41 year	0	2.1	0	2.1	2	44
41 - < 51 year	0	2.5	0	2.5	2	44
51 - < 61 year	0	2.5	0	2.5	2	44
≥ 61 years	0	3.1	0	3.1	2	44

* sum of hours 'sleeping'. 'awake' and 'outside'

Table 40: Time-use for landuse type day recreation for children and adults (REC-dayout)

Age	Sleeping (t_{sleep})	Awake Inside (t_{in})	Outside (t_{out})	Total* on site	EF_{week}	EF_{year}
	h/day	h/day	h/day	h/day	d/week	weeks/year
1 - < 3 year	0	0	8	8	5	8
3 - < 6 year	0	0	8	8	5	8
6 - < 10 year	0	0	8	8	5	8
10 - < 15 year	0	0	8	8	5	8
15 - < 21 year	0	0	8	8	5	8
21 - < 31 year	0	0	2.1	2.1	2	44
31 - < 41 year	0	0	2.1	2.1	2	44
41 - < 51 year	0	0	2.5	2.5	2	44
51 - < 61 year	0	0	3.1	3.1	2	44
≥ 61 years	0	0	3.1	3.1	2	44

* sum of hours 'sleeping'. 'awake' and 'outside'

Table 41: Time-use for landuse type holiday resort for children and adults for mainly indoors (REC-stay)

Age	Sleeping (t_{sleep})	Awake inside (t_{in})	Outside (t_{out})	Total* on site	EF_{week}	EF_{year}
	h/day	h/day	h/day	h/day	d/week	weeks/year
1 - < 3 year	12	9.1	2.9	24	7	8
3 - < 6 year	11	9.8	3.2	24	7	8
6 - < 10 year	10	10.4	3.6	24	7	8
10 - < 15 year	9	11.3	3.7	24	7	8
15 - < 21 year	8	12.3	3.7	24	7	8
21 - < 31 year	8	12.3	3.7	24	7	8
31 - < 41 year	8	12.3	3.7	24	7	8
41 - < 51 year	8	12.3	3.7	24	7	8
51 - < 61 year	8	12.3	3.7	24	7	8
≥ 61 years	8	12.3	3.7	24	7	8

* sum of hours 'sleeping'. 'awake' and 'outside'

Table 42: Time-use for landuse type light industry (IND-l)

Age	Sleeping (t_{sleep})	Awake inside (t_{in})	Outside (t_{out})	Total* on site	EF_{week}	EF_{year}
	h/day	h/day	h/day	h/day	d/week	weeks/year
1 - < 3 year	0	0	0	0	5	47
3 - < 6 year	0	0	0	0	5	47
6 - < 10 year	0	0	0	0	5	47
10 - < 15 year	0	0	0	0	5	47
15 - < 21 year	0	7	1	8	5	47
21 - < 31 year	0	7	1	8	5	47
31 - < 41 year	0	7	1	8	5	47
41 - < 51 year	0	7	1	8	5	47
51 - < 61 year	0	7	1	8	5	47
≥ 61 years	0	7	1	8	5	47

* sum of hours 'sleeping'. 'awake' and 'outside'

Table 43: Time-use for landuse type heavy industry with outside activity (IND-h)

Age	Sleeping (t_{sleep})	Awake inside (t_{in})	Outside (t_{out})	Total* on site	EF_{week}	EF_{year}
	h/day	h/day	h/day	h/day	d/week	weeks/year
1 - < 3 year	0	0	0	0	5	47
3 - < 6 year	0	0	0	0	5	47
6 - < 10 year	0	0	0	0	5	47
10 - < 15 year	0	0	0	0	5	47
15 - < 21 year	0	1	7	8	5	47
21 - < 31 year	0	1	7	8	5	47
31 - < 41 year	0	1	7	8	5	47
41 - < 51 year	0	1	7	8	5	47
51 - < 61 year	0	1	7	8	5	47
≥ 61 years	0	1	7	8	5	47

* sum of hours 'sleeping'. 'awake' and 'outside'

Annex 3: ingestion and inhalation dose coefficients

Age-related incorporation (ingestion and inhalation) dose-coefficients have been defined in the Recommendation N°60 of ICRP and reproduced in the euratom 1996 Basic Safety Standards directive (96/29/euratom). They have been applied in the European Commission Report "Radiation Protection 122 Part II" [11] to derive exemption and clearance levels for natural radionuclides.

Table 23 and Table 25 of this document provide respectively the inhalation and ingestion dose-coefficients for the natural radionuclides of the uranium and thorium series and for potassium-40. Dose-coefficients are provided for six age classes: < 1, 1 – 2, 2 – 7, 7 – 12, 12 – 17 and > 17 years as well as for the distinct category "worker".

Annex 4: inter-comparison of parameters in different methodologies

This annex reproduces the results of a comparison exercise which has been published in [7]. That study compares the parameters of S-Risk and of the three guides for assessing radiological risk cited in the introduction [3][4][5].

That study does not address all exposure pathways and parameters used in these references. It only focuses on some selected exposure pathways and parameters: exposure time, dust inhalation, inadvertent ingestion of contaminated soil, ingestion of food grown on a contaminated land.

1. Comparison of default values for parameters of the exposure assessment

1.1 Exposure scenarios and age classes

The models described in the study proposed envelope scenarios. The scenarios of S-Risk have been described in the main text of this report.

The German guide considers the following scenarios: residential (where consumption of home-grown foodstuff is considered as a distinct scenario), stay in open space, stay in underground workplaces.

The RCLEA guide proposes 3 reference land uses suitable for generic assessments: residential (where consumption of home grown products may or may not be considered), allotment use where the contaminated land is assumed to be a largely open space with individual plots for growing fruits and vegetables consumed by the allotment user and his/her family. Finally, the commercial or industrial land use reflects individual shops or offices or light industrial park.

The French guide does not consider reference land use but proposes a description of 11 generic scenarios, which may serve as starting point to develop a site-specific scenario: two of these scenarios are only relevant in the context of contaminated buildings, the 9 others are relevant for activities on contaminated soil: parking lot, allotment, professional activity, residential, school, sport complex, leisure park.

Regarding age classes, both German and French guide considers the 6 ages categories of (ICRP, 1994), while RCLEA only considers three categories: infant (= one-year old), child (= 10-year old) and adult (> 17-year old). S-Risk distinguishes between 10 age categories as the "adult" category is split into decades (e.g. 21-31 years old, 31-41, etc.). However, the differences in the parameters of these different "adult" subcategories are generally quite small.

1.2 Exposure time

The exposure time depends obviously on the exposure scenario considered and we focus in this section on the scenario "residential with vegetable garden". Table A.1 shows the suggested exposure time in the different guides considered. It must be noted that, while S-Risk and the French methodological guide distinguish between sleeping and awake time inside, RCLEA makes rather a distinction between "active" and "passive" activities. The German guide does not make such a distinction and rather gives global exposure time outside and inside. The values suggested as examples in the French guide are taken from ICRP66 [13].

S-Risk	FR	RCLEA	BfS

Age category	Sleeping	Awake inside	Outside	*Age category*	Sleeping	Awake inside	Outside	*Age category*	Indoor	Outdoor	Indoor	Outdoor
1 - 2	12	11.5	0.5	*1 - 2*	14	9	1	*infant*	21	4	-	-
3 - 5	11	9.7	1.38	*3 - 5*	12	9	3	*Child (10 – 11)*	18	4		
6 - 9	10	8.7	1.57	*8 - 12*	10	11	3					
10 – 15	9	10.6	1.12	*13 -17*		11 (boy) 12 (girl)	3 (boy) 2 (girl)					
15 – 21	8	8.5	0.8	*≥ 17 (living at home)*	8.5	14.5	1	*Adult (59 – 70)*	20	4	19	5
21 – 31	8	9	1									
31 – 41	8	11.5	1.3									
41 – 51	8	11.5	1.5									
51 – 61	8	11.5	1.8									
≥ 61	8	11.5	1.7									

Table A.1: exposure time (in hour per day) for different age categories (in years) referenced in the guides

Although some details may vary and some guides such as S-Risk propose more age categories, there are no fundamental differences between the different guides. The French guide proposes a slightly higher exposure time inside for the sedentary inhabitant (23 hours/day) while for the three other examples the exposure time inside is rather around 20 hours a day.

1.3 External dose: shielding factor

In a residential scenario, the external dose from the gamma radiation emitted by the radionuclides present in the underlying soil is shielded by the building. The external dose calculated from soil contamination or taken from on-site (outdoor) dose-rate measurements needs thus to be multiplied by a shielding factor which depends on the density and structure of the building basement layer.

Obviously, S-Risk does not consider external exposure and the comparison only applies to the three other guides.

In the French guide, various shielding factors (or protection factors) have been calculated with the software MicroShield® for different nuclides and different kinds of building structure (e.g. concrete). The two other guides do not make a difference between radionuclides and only suggest two types of shielding: one shielding factor for heavy construction made of concrete or bricks and another value for light construction such as a cabin made of wood.

Table A.2 summarizes the values for the shielding factors. For the sake of the comparison, we have picked in the French guide the protection factor for U-238 in secular equilibrium given by a 10 cm (resp. 15 cm) concrete layer.

FR			BfS	RCLEA
U-238+ (10 cm concrete)	0.087	*Heavy construction (concrete, bricks...)*	0.1	0.1
U-238+ (15 cm concrete)	0.037			
		Light construction (wood...)	0.3	1

Table A.2: shielding factors from external dose

There is good agreement in the shielding factors for an heavy construction where both German and British guides have selected a value close from the shielding of a 10 cm concrete layer from a soil contaminated with U-238 and its progenies – as calculated with MicroShield® in the French guide. On the other hand, the British and German guides suggest very different values in the case of a light construction.

1.4 Parameters for inhalation dose: respiratory debit and air concentration

1.4.1 Respiratory debit

Respiratory debit depends on the nature of the activity (and thus of the exposure scenario) as well as on the age group. While the French guide suggests the values of ICRP66 and considers 4 different sorts of activities (sleep, rest, heavy and light work), the German guide only considers one type of activity (stay in building or in open space) and the UK guide two classes (active and passive). S-Risk proposes values of respiratory debit for each standard exposure scenario. As for the other parameters, S-Risk and the French guide refer to all age classes while the UK methodology only considers the three categories infant, child and adult. The values cited in the French, German and British guides are summarized in Table A.3.

	FR				BfS	RCLEA		
	Sleep	*Rest*	*Light exercise*	*Heavy exercise*	*Stay in open space or building*		*Active*	*Passive*
< 1	0.09	-	-	-	0.12	-		
1 – 2	0.15	0.22	0.35	-	0.22	*Infant (1-2)*	0.339 (male) 0.32 (female)	0.124 (male) 0.117 (female)
3 – 7	0.24	0.32	0.57	-	0.36			
8 – 12	0.31	0.38	1.12	2.22 (male) 1.84 (female)	0.64	*Child (10-11)*	1.103 (male) 1.1 (female)	0.404 (male) 0.403 (female)
13– 17	0.42 (male) 0.35 (female)	0.48 (male) 0.40 (female)	1.38 (male) 1.3 (female)	2.92 (male) 2.57 (female)	0.84	-		
≥18	0.45 (male) 0.32 (female)	0.54 (male) 0.39 (female)	1.5 (male) 1.25 (female)	3 (male) 2.7 (female)	0.93	*Adult (16– 59)*	1.456 (male) 1.234 (female)	0.485 (male) 0.411 (female)
worker					1.2			

Table A.3: respiratory debit (in m^3/hour) for the different age categories and activities considered in the guides of France, Germany and UK.

Comparison with S-Risk is not straightforward as S-Risk calculates inhalation rate on basis of a default inhalation rate for adults (70 kg) of 20 m^3/day (0.83 m^3/hour) and of weighting factors for different age categories and types of activities.

Obviously, respiratory debits vary a lot in function of age and activities. This makes a direct comparison between the values of the different guides difficult as they do not categorize the activities in the same way. For instance, the value given in RCLEA for an "active" adult is essentially the same as the respiratory debit referred to in the French guide for an adult with "light exercise" activity. For "passive" activity, the RCLEA respiratory debit lies between the "sleep" and "rest" values of ICRP66 for male but for female the RCLEA respiratory debit is higher than the one of the French guide.

The value referred to in the German guide is roughly the average of "active" and "passive" activity of RCLEA for a male individual.

1.4.2 Air concentration

For typical resuspended dust concentration in air, the various guides suggest different approaches. The French guide proposes 4 typical values depending on the type of activity: very weak, weak, medium and high dust concentration corresponding respectively to e.g. sleep activity, outside activities, gardening and infrastructure works; the German guide only distinguishes between a reference air concentration value from resuspension during a stay in open space and during work activities. Both RCLEA and S-Risk consider only one value from soil resuspension. The RCLEA value corresponds to a residential scenario. These values are summarized in Table A.4.

FR				BfS		RCLEA	S-Risk
(1)	(2)	(3)	(4)	(5)	(6)		
0.001 – 0.01	0.01 – 0.1	0.1 - 10	10 - 100	0.05	0.5	0.05	0.01

Table A.4: typical values for dust concentration. The French guide distinguishes between very weak (1), weak (2), medium (3) and high (4) concentration. The German guide distinguishes between concentration during stay outside (5) and outdoor work activities (6). All values are in mg/m^3.

There is a good agreement between the French (medium concentration), German and British guide regarding typical dust concentration for outside light activity. The value suggested by S-Risk is similar to the edge between weak and medium concentration of the French guide.

1.5 Ingestion dose

1.5.1 Soil ingestion rate

In the guides, inadvertent soil ingestion rate are expressed in different units (mg/day in France and Belgium, mg/h in Germany and kg/year in RCLEA). For the sake of comparison, they have been converted in mg/day taking into account the exposure time of the relevant scenario. For the German values, two time patterns have been considered : the time pattern corresponding to the exposure in a garden (1000 hours a year for all age classes) and the pattern corresponding to a stay on an outside contaminated area (100 or 250 hours per year depending on age). Table A.5 gives an overview of the values considered in the different guides for the age classes and exposure scenario considered.

	FR	BfS		RCLEA	S-Risk				
Age category		(1)	(2)		*Age category*	AGR/RES	RES-ng	IND-l	IND-h
1 – 2	100	13.7	137	150.7	*1 -2*	68,4	40	0	0
3 – 7	100	20.5	82	-	*3 – 5*	54,9	32	0	0
8 – 12	50	4.1	16,4	101.4	*6 – 9*	41,85	18,25	0	0
13 -17	40	4.1	16,4	-	*10 – 14*	40,05	15,64	0	0
					15 – 20	38,25	12,6	5.2	30.8
Adult	40	1.6	16,4	60.3 (residential) 71.2 (allotment)	*> 20*	34,65	10,6	5.2	30.8

Table A.5: comparison of inadvertent soil ingestion rate (mg/day). For the BfS guide, two exposure patterns are considered (1) stay in a garden (1000 hours a year) (2) stay on an outside area (100 or 250 hours a year). For S-Risk, the acronyms of exposure scenario are explained in the main report.

There is a significant variability of the inadvertent ingestion rate depending on the scenario and on the guide considered. RCLEA in particular suggests values which are significantly higher than the other references.

1.5.2 Dietary habits

Dietary habits are among the parameters for which most variability is expected: they vary between and within countries, between urban and rural environment, among age groups and sex, may depend on local circumstances... In the present paper, we only focus on dietary habits of the Western European countries addressed in the guides. The dietary habits include not only the consumption of various foods (grains, vegetables, meat, dairy products, drinking water...) but also the proportion of consumed food coming from the contaminated site.

1.5.2.1 Consumption rates

For this inter-comparison, we only consider the dietary habits of adults. Table A.6 shows the different categories of vegetables considered in the different guides. All data are expressed in kg per year. For S-Risk, we take values for the age category 21 – 31 years old as S-Risk provides slightly different values depending on the adult age.

<table>
<tr><th rowspan="2"></th><th rowspan="2">FR (average individual)</th><th rowspan="2">BfS</th><th colspan="2">RCLEA</th><th rowspan="2">S-Risk</th></tr>
<tr><th>male</th><th>female</th></tr>
<tr><td>Brussels sprout</td><td colspan="2" rowspan="5">-</td><td>21</td><td>17</td><td rowspan="2">6.8</td></tr>
<tr><td>Cabbage</td><td>20</td><td>17</td></tr>
<tr><td>Carrot</td><td>19</td><td>16</td><td>24.8</td></tr>
<tr><td>Leafy salads</td><td>14</td><td>12</td><td></td></tr>
<tr><td>Onion (shallots and leeks)</td><td>13</td><td>11</td><td>7</td></tr>
<tr><td>Leafy vegetables</td><td>20</td><td>13</td><td colspan="2" rowspan="3">-</td><td>11.9</td></tr>
<tr><td>Fruits vegetables</td><td>74</td><td>-</td><td>29</td></tr>
<tr><td>Root vegetables</td><td>9</td><td rowspan="2">55</td><td>-</td></tr>
<tr><td>Potatoes</td><td>32</td><td>101</td><td>84</td><td>47.4</td></tr>
<tr><td>Other vegetables</td><td rowspan="2">-</td><td>40</td><td colspan="3" rowspan="3">-</td></tr>
<tr><td>Fruit and derived product</td><td>35</td></tr>
<tr><td>Grain and derived products</td><td>55</td><td>110</td></tr>
</table>

Table A.6: various vegetables categories and their consumption rate (in kg/year) considered in the different guides.

The different guides do not categorize the vegetables in the same manner. RCLEA for instance only focus on vegetables which will be grown in an allotment. However, all guides give values for the consumption rate of potatoes, which varies with a factor 3 between France and UK.

Table A.7 shows a similar inter-comparison for animal products. RCLEA does not provide any value for animal products. The German guide does not distinguish between different categories of meat and S-Risk only provides value for beef.

	FR (average individual)	BfS	S-Risk
Beef	19	90	11.7
Mutton	7		-
Pork	24		
Poultry	20		
Eggs	8		15
Milk	66	130	78.5
Dairy	37		1.13 (butter)
Fish	11	7.5	-

Table A.7: various animal products and their consumption rate (in kg/year)

Here also there are noticeable differences between countries. The meat consumption in Germany for instance is 25% higher than in France according to the Table while the beef consumption in Belgium is 40% lower than in France.

Finally, we compare in Table A.8 the values for water consumption per age category.

	FR	BfS	S-Risk	
Age category			*Age category*	
< 1	0.55	0.15	*1-2*	0.3
1 – 2	0.8	0.27	*3-5*	0.31
3 – 7	1.3	0.27	*6-9*	0.38
8 – 12	1.5	0.41	*10-14*	0.65
13 – 17	1.5	0.55	*15-20*	1
Adult	1.5	0.96	*21-60*	1.76 – 2.23

Table A.8: water consumption (liter per day) per age category.

The values proposed by the German guide are significantly lower than the values proposed in the French guide. The Belgian S-Risk gives values close to the German ones for the child consumption rate but closer to the French value for the adult. For some age categories, the values may vary with a factor 4 between different guides.

1.5.2.2 Fraction of consumption from home-grown products

The fraction of food derived from home-grown production is very much dependent on the selected exposure scenario: in an agricultural scenario, this fraction is often chosen close to 1 and is significantly lower in a residential scenario with garden. Table A.9 summarizes these values. Note that the German guide assumes that the fraction of food from local production is 0.5 for all categories.

	FR (average individual)	FR (rural inhabitant)	BfS	RCLEA	S-Risk (RES-veg)	S-Risk (AGR)

Brussels sprout	-			0.87	0.21	1
Cabbage				0.92		
Carrot				0.7	0.36	1
Leafy salads				0.51	-	
Onion (shallots and leeks)				0.91	0.52	1
Leafy vegetables	0.267	0.707	0.5	-	0.36	1
Fruits vegetables	0.135	0.306			0.39	1
Root vegetables	0.237	0.675		-		
Potatoes	0.237	0.767		0.66	0.39	0.5
Grain and derived products	0.001	0.001		-		

Table A.9: fraction of consumption from home-grown production for different vegetable categories. The French guide gives values both for the average individual and for a rural inhabitant. S-Risk also distinguishes between the residential with garden scenario (similar to the RCLEA scenario) and the agricultural scenario.

RCLEA and the agricultural scenario of S-Risk suggest quite conservative values for the fraction of consumption from home-grown production – except for potatoes where the value for a French rural inhabitant is higher. However, variation between guides are logically not as important as variation within a national population, e.g. between urban and rural population.

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