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Derivation of Exclusion Levels

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CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Regulatory systems for radiation protection are intended to ensure the protection of people from harm arising from exposure to ionizing radiation. However, there are some human activities involving exposure to radiation that do not warrant regulatory control. Such circumstances arise when the resources that would need to be expended in regulating the activity would be excessive in relation to any benefit that might ensue in terms of reduced risk. The scope of legal instruments for regulatory control should therefore be defined so as to include only activities for which regulation is warranted. This Safety Report supports the Safety Guide on *Radioactivity in Material not requiring Regulation for Purposes of Radiation Protection* [1].

This document deals with all material[1] to include commodities[2] for which regulatory control in accordance with the *International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (the BSS)* [2] should be applied. It includes the removal of control of material containing very low levels of radioactivity originating from regulated practices[3], i.e., industrial installations (nuclear fuel cycle and others), hospitals, and research institutes, and of material from interventions[4]. It also addresses naturally occurring radioactive material (NORM) that should be considered for regulation.

The document derives exclusion levels in terms of activity concentration[5] for deciding if a certain material should come under the regime of the BSS [2]. These exclusion levels are derived in such a way that they are valid for all types of solid and liquid material with radionuclides of artificial or natural origin except foodstuffs and drinking water. Because the exclusion levels are applicable to a whole range of materials, they have been derived on the basis of several scenarios and assumptions:

(a) The main basis for the derivation of the exclusion levels is a set of radiological scenarios referring to external irradiation, dust inhalation and ingestion (direct and secondary ingestion) which are deemed to encompass all typical exposure situations for all material types except NORM. Those scenarios relate the activity concentration in the material to individual doses.

(b) The scenarios for artificial radionuclides are determined by taking existing radiological studies (e.g. those used for deriving clearance and exemption levels) and using them to build up a framework of generalized scenarios. The approach to envelop the worldwide variety of situations that may be found in Member States necessarily requires a degree of conservatism. In order to cover various exposure scenarios, more than one scenario has been considered for each pathway to reflect the range of material characteristics and exposed individuals. Each scenario

1 The term *material* is defined as the matter from which a thing is made, the elements or constitute parts of a substance.

2 The term *commodity* is any article or raw or material that can be bought or sold.

3 A *practice* is defined as any human activity that introduces additional sources of exposure or exposure pathways or extends exposure to additional people or modifies the network of exposure pathways from existing sources, so as to increase the exposure or the likelihood of exposure to people or the number of people exposed.

4 An *intervention* is defined as any action intended to reduce or avert exposure or the likelihood of exposure to sources which are not part of a controlled practice or which are out of control as a consequence of an accident.

5 *Activity concentration* is the amount of a radionuclide per unit mass or volume of a material.

therefore contains a set of parameter values and represents a range of exposure situations.

(c) A scenario-based approach was not used in the case of naturally occurring radioactive material (NORM). Instead the exclusion levels applicable to NORM were derived using a pragmatic approach that places greater emphasis on optimization of protection. This involved consideration of the world-wide distribution of the concentration of naturally occurring radionuclides in environmental material.

2. RADIOLOGICAL BASIS FOR EXCLUSION LEVELS

For each artificial radionuclide in material, the exclusion level has been determined such that individual effective doses to the public and workers[6] would be on the order of 10 μSv/a and having only a very low probability of approaching an individual dose of 1 mSv/a. A dose of 10 μSv/a corresponds to a trivial level of risk [2].

While no exclusion levels have been derived in this Safety Report for foodstuff and drinking water, the water and food pathways have been taken into account in the scenarios for artificial radionuclides to address the radiological consequences from these pathways. Specific levels for foodstuffs have been developed by the Codex Alimentarius Commission [3] and for drinking water by the World Health Organization [4].

The calculations of exclusion levels for artificial radionuclides are based on the evaluation of a selected set of typical exposure scenarios for all material encompassing external irradiation, dust inhalation and ingestion (direct and indirect). Exclusion levels were derived based on these scenarios as the lower value obtained from:

I. The use of realistic parameter values applying an effective dose criterion of 10 μSv/a.

II. The use of low probability parameter values applying an effective dose criterion of 1mSv/a and a skin equivalent dose limit of 50 mSv/a.

The derived results from the scenario calculations are sufficient to ensure an adequate degree of protection in both occupational and public exposure situations.

If radionuclide-specific exclusion values for naturally occurring radionuclides are derived on the basis of the same radiological criteria, the values will, in many cases, be lower than concentrations that occur in many natural environmental material. Thus, many human activities previously unregulated from a radiological standpoint, such as construction of houses from natural building materials or even the use of land in many areas, could be subject to regulation. Establishing levels for natural radionuclides that invoke such widespread regulatory consideration, in circumstances where in many cases it is unlikely to achieve any improvement in protection, is not an optimum use of regulatory resources. Therefore, derivation of exclusion levels for naturally occurring radionuclides is based on a methodology that places greater emphasis on optimization of protection, including regulatory resources.

[6] Worker is taken here to mean those workers who could be inadvertently exposed to ionizing radiation while at work, such as foundry or land-fill workers.

The objective in defining naturally occurring radioactive substances that should be regulated is to identify those materials of significant radiological risk where regulation can achieve real improvements in protection. At the same time, the number of materials involved should not be so great as to make regulation essentially unmanageable. The application of a dose criterion of 10 μSv/a is not practical for NORM. In selecting levels for material that contains NORM, a major issue is that high levels that would exclude the majority of natural material in the environment would also allow a number of situations such as release of phosphate slags to be excluded without further considerations. Conversely, selecting a low value would trigger an unnecessary application of the BSS. Therefore, the exclusion levels were derived from consideration of the worldwide distribution of concentrations of naturally occurring radionuclides from an independent source (8).

Exclusion levels for naturally occurring radionuclides are the total of the background and any added radioactivity. Doses to individuals as a consequence of the use of these exclusion levels are unlikely to exceed about 1mSv in a year, excluding the emanation of radon and in situations of large volumes contaminating water pathways. This situation could require case by case evaluation of possible doses.

3. GENERAL APPROACH FOR DERIVING EXCLUSION LEVELS

3.1. CHOICE OF RADIONUCLIDES AND DOSE COEFFICIENTS

The radionuclides for which exclusion levels are calculated are those for which exemption levels exist in the BSS [2]. This set contains those nuclides that are most relevant to nuclear installations like nuclear power plants or fuel cycle facilities and the application of radionuclides in research, industry and medicine, including short-lived nuclides. A number of additional radionuclides are also considered because of their practical relevance in some cases (e.g., Ca-41, Se-79). Radionuclides of natural origin (^{40}K and the decay chains of ^{238}U, ^{235}U, ^{232}Th) are also included.

A number of radionuclides that are considered in this document decay into unstable short-lived radionuclides. The way in which decay products are treated is discussed in section 3.2. of this document.

In general, dose coefficients are used to calculate (annual) doses from a given activity. More specifically, dose coefficients are used for the following exposure pathways:

- External exposure: The dose from external irradiation is caused by photons from gamma emitting radionuclides absorbed by the human body. Therefore, the relationship between dose and radioactivity is complicated, depending not only on the radionuclide, but also on the geometry in which the radioactivity is distributed, on shielding effects, on self-absorption effects and on the distance and direction to the source. Dose coefficients for external irradiation are expressed as dose rate (μSv/h) per activity content of the source (Bq/g). In the present case, suitable dose coefficients are calculated for each radionuclide and each exposure geometry. These dose coefficients are presented in Appendix II, Table II-III.

The exposure scenarios consider adults and children of an age between one and two years, which are the most critical age groups for external exposure. A correction of the dose coefficients calculated for adults is required for children to take account of the higher effective dose as compared to adults in the same exposures situation (i.e. for the same air kerma). The factor applied is estimated from Figure 12 in [5], comparing the effective dose per unit air kerma for different age groups in an isotropic irradiation geometry. For the relevant range of photon energies above 100 keV the ratio between children of 1 year of age and adults is about 1.2. This factor is being used in the scenario calculations for children.

- Inhalation exposure: Dose coefficients for inhalation are contained in Appendix II, Table II-IV. The dose coefficients relate the individual effective dose (in Sv) to the inhaled quantity of radioactivity (in Bq).

- Ingestion exposure: Dose coefficients for ingestion are also contained in Appendix II, Table II-V. The dose coefficients relate the individual effective dose (in Sv) to the ingested quantity of radioactivity (in Bq).

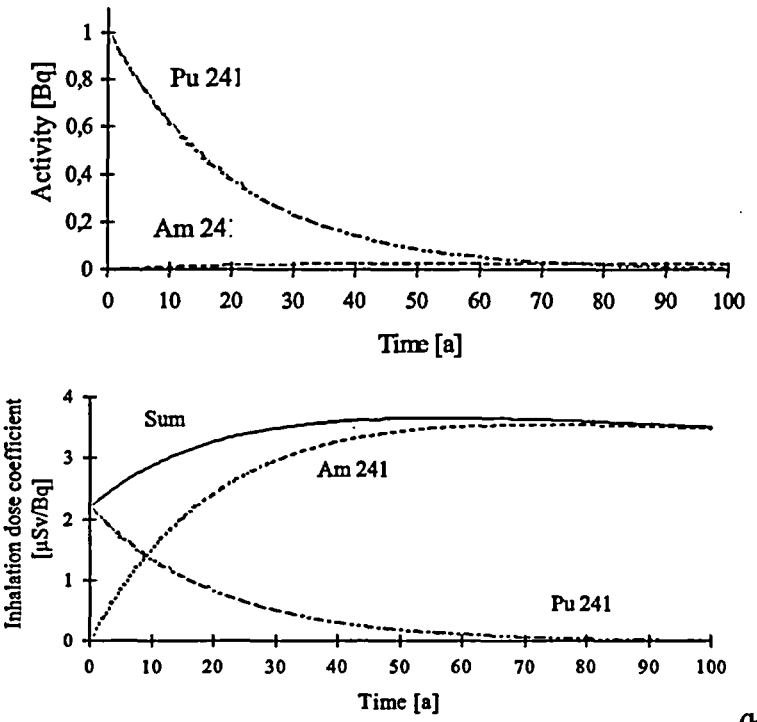
- Skin exposure: Dose coefficients for the skin relate the skin equivalent dose to the concentration of radionuclides on the skin. Skin dose coefficients are listed in [6] and are taken conservatively for a skin surface weight of 4 mg/cm^2. These dose coefficients are contained in Appendix II, Table II-VI.

3.2. DECAY CHAINS AND PROGENY INGROWTH

For radionuclides possessing daughter radionuclides that have a non-negligible dose coefficient in comparison to the parent radionuclides, dose coefficients are calculated as the weighted sum of parent and daughter radionuclides. Weighting is done by using the activity ratios given in Appendix I for the daughter radionuclides indicated. This ensures that the effect of the daughter radionuclides is properly accounted for in the dose calculations.

A number of the radionuclides that are considered in this document decay into unstable short-lived radionuclides. These daughter radionuclides also contribute to the dose caused by the parent radionuclide after release from regulatory control. For daughter radionuclides with short half-lives, an equilibrium situation with the parent nuclides is reached in a very short time, like for the pair ^{137}Cs/^{137m}Ba within 30 minutes or for the pair ^{90}Sr/^{90}Y within 20 days. However, there are some important daughter radionuclides with longer half-lives, which yield a high dose contribution, like ^{241}Pu/^{241}Am. In Fig 1. (a) the activity as a function of time is shown for an initial quantity of 1 Bq ^{241}Pu. The activity maximum of the daughter radionuclide ^{241}Am occurs at about 70 years at which time the total activity represents only a fraction of the initial activity. In Fig 1 (b) the inhalation dose coefficient is plotted for material in which the initial activity of ^{241}Pu is 1 Bq. In contrast to the activity, the dose coefficient increases over time reaching a maximum at around 60 years although at this time the total activity has decreased to less than 0.1 Bq. This demonstrates that if material containing those radionuclides remains together for a prolonged period of time, the scenarios occurring many years after being released from regulatory control can lead to higher doses than those calculated for the first year after its release due to the ingrowth of daughter radionuclides. Therefore, the relevant progeny is accounted for in the calculations.

(a)



(b)

FIG. 1. Development of activity and dose coefficient of the radionuclides pair $^{241}Pu/^{241}Am$ over time

The dose contribution from daughter radionuclides is included in the calculations in order not to underestimate doses. This is ensured by adding the dose coefficients of the daughter radionuclides to the dose coefficients of the parent radionuclides, using the appropriate weighting factors for the dose coefficients of the daughter radionuclides. The weighting factors for the daughter nuclides are taken as the maximum activity ratio that the respective daughter radionuclides will reach during a time span of 100 years as illustrated in Fig 2. where the point of maximum activity of the daughter radionuclide is marked. A time span of 100 years is necessary to ensure that material, which does not exceed the exclusion levels at a certain time, will also do so at any later point of time within a reasonable time frame.[7]

[7] This approach does not take account of the fact that in situations like the $^{241}Pu/^{241}Am$ example given in Figure 1 the parent nuclide already has decayed to a large extent when the daughter nuclide reaches its activity maximum. Consequently, the dose factor for the mixture of parent and daughter nuclide will be overestimated in such situations (by a factor of about 1.7 in the example). However, an approach avoiding this potential overestimation would be complicated in particular when several daughter nuclides are involved. Therefore, the approach presented is considered appropriate, satisfying the overall goals of the dose assessments presented here not to underestimate doses and to the extent possible use simple and concise models.

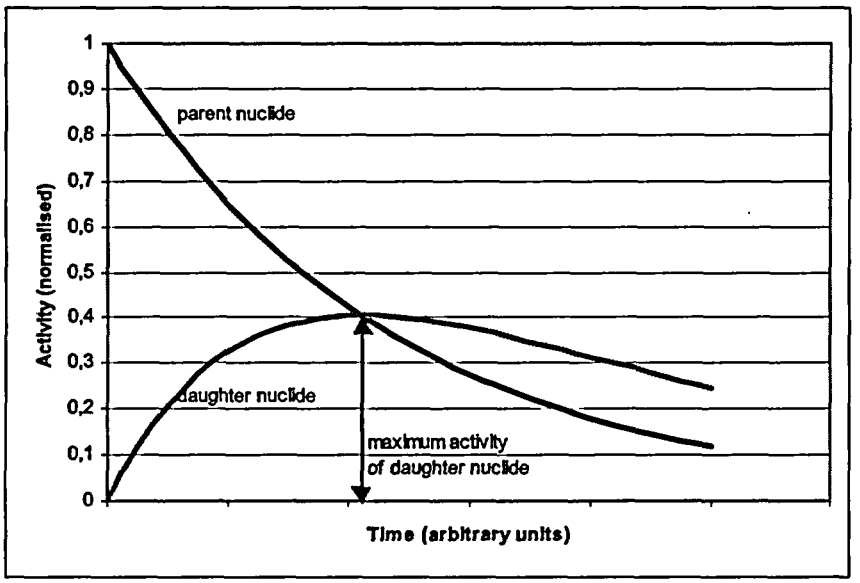


FIG. 2. Activity of arbitrary parent and daughter radionuclide with time. The point of maximum activity of the daughter radionuclide is marked.

The time at which the activity of the first decay product is at a maximum is derived as follows:

If the activity of the progeny as a function of time is designated as $A_2(t)$, then,

$$A_2(t)=A_1(0)\lambda_2\frac{(e^{-\lambda_1 t}-e^{-\lambda_2 t})B_2}{\lambda_2-\lambda_1}$$

$A_2(t)$ = activity of daughter at time t
$A_1(0)$ = initial activity of parent
λ_1 = decay constant of parent
λ_2 = Radioactive decay constant
B_2 = branching ratio of daughter

setting the derivative with respect to time to zero

$$\frac{dA_2(t)}{dt}=\frac{A_1(0)\lambda_2}{\lambda_2-\lambda_1}(\lambda_2 e^{-\lambda_2 t}-\lambda_1 e^{-\lambda_1 t})B_2=0$$

solving for t, one obtains

$$t_{max}=\frac{\log\left(\frac{\lambda_2}{\lambda_1}\right)}{\lambda_2-\lambda_1}$$

t_{max} = time of maximum

The weighting factors that are calculated in this way are provided in Appendix I of this document.

As the exclusion levels derived in this document already take into account dose contributions from daughter radionuclides, it is also possible to provide a list of those daughter radionuclides that are fully accounted for in exclusion levels of the parent radionuclide. The

following set of criteria is convenient in order to define when this is the case for a particular daughter radionuclide:

1. The half-life of the daughter radionuclide must be shorter than that of the parent radionuclide.

   AND

2. The half-life of the daughter radionuclide is less than 1 day OR
3. The half-life of the daughter radionuclide is less than 10% of the half-life of the parent radionuclide AND the half-life of the daughter radionuclide is less than 10 years.

This means that a daughter radionuclide needs not be treated separately if criterion 1 is fulfilled together with at least one of the criteria 2 and 3. Table I provides a list of parent and daughter radionuclides that fulfill the above criteria. For decay chains (i.e. more than one daughter radionuclide), the process of including daughter radionuclides in this way is carried on until a radionuclide is reached which fails to meet the criteria. All daughter radionuclides up to this one are then taken into account in the dose calculations. The parent radionuclides are marked with the sign "+" to indicate that the derived exclusion level also includes daughter radionuclides. When applying the exclusion levels, the daughter radionuclides listed in Table I need not be considered separately.

TABLE I. LIST OF DAUGHTER RADIONUCLIDES THAT ARE TAKEN INTO ACCOUNT WITH THE PARENT RADIONUCLIDE

Parent Radionuclide	Daughter Radionuclides						
Fe-52+	Mn-52m						
Zn-69m+	Zn-69						
Sr-90+	Y-90						
Sr-91+	Y-91m						
Zr-95+	Nb-95m						
Zr-97+	Nb-97m	Nb-97					
Nb-97+	Nb-97m						
Mo-99+	Tc-99m						
Mo-101+	Tc-101						
Ru-103+	Rh-103m						
Ru-105+	Rh-105m						
Ru-106+	Rh-106						
Pd-103+	Rh-103m						
Pd-109+	Ag-109m						
Ag-108m+	Ag-108						
Ag-110m+	Ag-110						
Cd-109+	Ag-109m						
Cd-113m	In-113m	Cd-113					
Cd-115+	In-115m						
Cd-115m+	In-115m						
In-114m+	In-114						
Sn-113+	In-113m						
Sn-121m	Sn-121						
Sb-125+	Te-125m						
Te-127m+	Te-127						
Te-129m+	Te-129						
Te-131m+	Te-131						
Te-132+	I-132						
Cs-137+	Ba-137m						
Ce-144+	Pr-144	Pr-144m					
Pm-146	Sm-146						
U-232sec	Th-228	Ra-224	Rn-220	Po-216	Pb-212	Bi-212	Tl-208
U-240+	Np-240m	Np-240					
Np-237+	Pa-233						
Pu-244+	U-240	Np-240m	Np-240				
Am-242m+	Np-238						
Am-243+	Np-239						
Cm-247+	Pu-243						
Es-254+	Bk-250						
Es-254m+	Fm-254						

3.3. ARTIFICIAL RADIONUCLIDES

The entire sequence of calculations for deriving the exclusion levels for all material containing artificial radionuclides, except foodstuffs and drinking water, proceeds along the following lines:

- selection of radionuclides for which the calculations are carried out;
- definition of suitable scenarios and parameter values;
- calculation of annual doses relating to the unit specific activity (i.e., 1 Bq/g) for each radionuclide;
- identification of the limiting scenario for each set of calculations, i.e., the one that gives the highest dose;
- derivation of the radionuclide specific exclusion levels by dividing the reference dose level (10 μSv/a, 1 mSv/a, or 50 mSv/a, as appropriate) by the annual dose calculated for 1 Bq/g for the limiting scenario for that nuclide; and
- application of rounding procedures to the exclusion levels.

The rounding[8] to powers of ten is similar to the approach followed for the exemption levels. It implies that the radiological models do not possess such a level of accuracy that a higher precision of the result would be justified.

For the artificial radionuclides, several evaluations were considered as described below. The scenarios described in this section serve to determine whether material should fall within the scope of the BSS [2]. They are designed to be applicable to all material types in large or small quantities. They are not, however, suitable to treat large amounts of NORM that is dealt with in section 3.4.

Examination of a large number of scenarios from around the world revealed that the limiting cases for a large number of radionuclides could be reduced to a few scenarios. Within these scenarios, different exposure pathways may account for the total exposure. These relevant exposure pathways are summed up for each scenario to yield the total dose.

On a radionuclide by radionuclide basis, the dominant scenario depends on a few parameters, such as exposure time, concentration of the radionuclide used in the exposure pathway(s), timing of the scenario with respect to radioactive decay, etc. Based on these observations from specific and detailed scenarios, the following scenarios are used in the calculation of exclusion levels:

- Scenario WL

A worker is exposed from contaminated material dumped on a landfill. Exposure pathways encompass external irradiation from the material, the inhalation of contaminated dust, and the inadvertent ingestion of contaminated (e.g. via hand-to-mouth pathway).

- Scenario WF

A worker in a foundry where contaminated metal is smelted. External exposures arise if the worker stays within the vicinity of piles of contaminated material. In addition, the

[8] If the calculated values lie between $3x10^x$ and $3x10^{x+1}$, the rounded value is 10^{x+1}. This type of near-logarithmic rounding was preferred in order to err by the same factor rather than by a factor 2 upwards and 5 downwards in conventional rounding.

worker is exposed to dust released from the material during the transport and melting process. This dust can be inhaled and inadvertently ingested.

- Scenario WO

A worker who comes into contact with contaminated material on a regular basis (e.g. a truck driver). He is exposed externally from the material (e.g. from the truckload). This scenario also covers the exposure from a large piece of equipment cleared from regulatory control and re-used in a workplace.

- Scenarios RL-C and RL-A

This scenario considers residents near a landfill or an other facility (RL-C = child, RL-A = adult), being exposed through contaminated dust released at the landfill or facility. In addition, it is assumed that the residents harvest foodstuff in a private garden on ground that has become contaminated through the deposition of contaminated material.

- Scenario RF

Since the exposure situation with respect to contaminated dust could be different near a foundry to the residential scenario (RL), another scenario of a child being exposed to contaminated dust released by a foundry is considered. Unlike scenario RL, covering a general situation including landfills, no food consumption is considered here, because the presence of contaminated material offsite is already covered by scenario RL.

- Scenario RH

Contaminated material (building rubble, slag, fly ash) may be used in the construction of buildings as concrete aggregate or cement substitute. This will lead to an external exposure of the building residents addressed in this scenario. Other possible uses of material cleared from nuclear facilities in private homes are also covered by this scenario (e.g., the use of steel plates for the cladding of walls).

- Scenario RP

If contaminated material is used for covering public places there will be external exposure and the inhalation and ingestion of contaminated dust for residents (e.g. playing children). This exposure situation is covered in this scenario.

- Scenario RW

The presence of contaminated material may lead to a release of radionuclides into a groundwater aquifer. This may affect downstream wells. As a consequence, this may lead to the ingestion of contaminated drinking water or of contaminated foodstuff produced in a private garden if the well water is used for irrigation. If the contaminated groundwater discharges into a river, the additional pathway of fish consumption has to be considered.

The identified scenarios encompass all reasonable situations worldwide without specifying a specific situation. The scenarios are not intended to account for worst-case scenarios, outlier scenarios or scenarios that apply to a very few individuals. In this way the scenarios are not bounding.

Construction of the scenarios is approached by examination of the parameters of the dominant exposure pathways, and the parameters are adapted to ensure worldwide applicability to a variety of situations. Care is taken to ensure that the parameter values are internally consistent within a particular scenario.

The limiting scenario may be different for different countries, because of different exposure geometries, working hours, sizes of transportation vehicles, etc. Thus, different sets of parameters could be chosen in different countries but the linkage of all relevant parameters needs to be taken into account in developing the scenarios. There are balancing effects between sets of parameters; while one parameter may be higher in one set than in another, other parameters may be lower and compensate for the higher parameter. The enveloping parameter set has been chosen carefully to avoid over-conservatism. The most restrictive parameters are not necessarily all gathered into the enveloping scenario.

A number of scenarios are required which cover all relevant aspects of external irradiation, inhalation, and ingestion in such a way that any exposure situation, that is reasonable to assume, would not lead to higher doses. Whereas the exact parameter values may be material specific, the general categories of scenarios and formulae are common to all material.

For each scenario, two distinct approaches have been used:

- The first one is to make the calculations with realistic scenario parameter values using an effective dose criterion of 10 μSv/a.
- The second is to use a set of low probability scenario parameter values using an effective dose criterion of 1 mSv/a and a skin equivalent dose limit of 50 mSv/a.

The approach applied differs from the derivation of clearance values or exemption levels made by other organizations [7], where only the predominant exposure pathway and not the sum of all exposures within a exposure situation is taken as the basis for comparison to the dose criterion. The reason for adopting this different approach is twofold:

- The original derivation of the 10 μSv/a criterion was based on a dose of 100 μSv/a that was considered acceptable as a trivial risk. But since an individual may be exposed to several exposure sources over different pathways the criterion was divided by ten accounting for this possible multiple exposures. The derivation of exclusion levels presented here, however, also is based on the 1 mSv/a public dose criterion for the low probability parameter assumptions. In this case, no allowance can be made for multiple exposure pathways affecting one individual because the dose criterion refers to the overall exposure of a member of the public. Therefore, the sum of all exposures affecting one individual in a specific situation has to be considered.

- The scenarios have been defined combining only those exposure pathways that will occur simultaneously in a particular situation with a high probability. For example, a landfill worker dealing with contaminated material will in most cases be affected by external exposure as well as by dust inhalation and ingestion. Therefore, it is considered prudent to base the derivation of exclusion levels on the sum of exposure pathways having a high probability of affecting an individual simultaneously.

The situation could also occur that the different defined scenarios affect one individual. For example, the landfill worker may happen to live in a house constructed with contaminated material. A further combination of these exposures to yield the hypothetical maximum exposure to an individual is not considered appropriate:

- For realistic parameters used in the scenarios, comparison is made with the 10 μSv/a criterion, allowing for possible multiple exposures as discussed above. Consequently, exclusion levels based on realistic parameters implicitly take account of the possibility of such unlikely but possible multiple exposures.

- Comparing exposures to the 1 mSv/a dose criterion, on the other hand, involves low probability assumptions for each scenario. Therefore, the assumption that one individual is exposed by two different scenarios, having only a small probability of occurrence as such, plus the further assumption that in both scenarios the low probability parameters are adequately describing the situation has only a negligible overall probability of occurrence. It is therefore reasonable to assume that for one individual, at a maximum, one exposure scenario will correspond to the low probability parameters. This scenario then dominates the assessment based on the 1 mSv/a dose criterion, and the possible simultaneous exposure through another scenario contributing only 10 μSv/a is not of consequence.

3.4. SHORT-LIVED RADIONUCLIDES

According to the overall concept outlined in the Safety Guide exclusion levels have to be lower than or equal to the exemption levels given in the BSS, because the exclusion levels define the entry level into the regime of the BSS while the exemption levels are criteria within the scope of the BSS for exemption from this regime for materials with small activity concentrations and total activities. This condition is satisfied by the results of the defined scenarios for most of the radionuclides, but not for all of them.

The calculated exclusion levels are higher than the exemption levels for a number of radionuclides with short half-lifes. The reason for this lies in the fact that the scenarios used to determine the exclusion levels are focusing on the handling (transport, trade, use, or deposition) of the material outside the facilities in which they arise (reactors, accelerators), because these facilities will be under regulatory control in any case. As a consequence, the scenarios used for the exclusion levels always consider a decay time before the start of the exposure (see Section 4.2), which is assumed to be at least one day (or considerably longer for some scenarios). The calculations on which the exemption levels in the BSS are based do not consider decay times because they also cover the direct handling of the material in the facilities where the material arises.

In order to cover the direct handling of the material in the derivation of the exclusion levels, scenarios could be added in analogy to those used for the BSS. However, this would not add any new information. Therefore, it is concluded to define the exclusion levels as the minimum of the scenario results presented and the exemption levels given in the BSS. This assures that the case of direct handling of the material is adequately reflected in the exclusion levels also for the short-lived radionuclides.

3.5 NATURAL RADIONUCLIDES

Scenarios were not used for calculating exclusion levels for naturally occurring radionuclides. Rather, they were based on consideration of world-wide distribution of concentrations of naturally occurring radionuclides.

3.6. MIXTURES

To apply the exclusion levels to a material containing a mixture of radionuclides (either artificial or naturally occurring), the concentrations should be determined as follows:

(1) artificial

$$\sum_{i=1}^{n} \frac{C_i(artificial)}{Exclusion\ level_i} \langle 1$$

(2) naturally occurring — For each radionuclide*:

$$\frac{C_{natural}}{Exclusion\ level} \langle 1$$

* In case of secular equilibrium, all $C_{natural}$ of a chain are equal.

where $C_i(artificial)$ is the concentration (Bq/g) of artificial radionuclide is in the material, $Exclusion\ level_i$ is the exclusion level for the artifical radionuclide in that material and n is the number of radionuclides in the mixture. For equation 2, $C_{natural}$ is the concentration (Bq/g) of naturally occurring radionuclide in the material or for those materials in secular equilibrium, it is the concentration of the parent nuclide, and exclusion level is the exclusion level for the naturally occurring radionuclide (or for those in secular equilibrium, the parent nuclide).

If both (1) and (2) are satisfied and are less than or equal to 1, then the material should not be attributed to radiation protection considerations. If either sum is greater than one, the requirements of the BSS [2] should be applied to the material as given in section 2 of this document. This type of relationship should be used by national regulatory body in their specific guidance on application of the BSS [2] to account for situations where multiple radionuclides are present in mixtures.

It is worth noting that this is a conservative approach since the pathways of exposure of the critical group of exposed individuals is not necessarily the same for each nuclide, because of partitioning or separation of nuclides by processes. In many cases it will be useful to identify a measurable indicator nuclide within the spectrum and apply correspondingly, a sum-index as defined above.

3.7. AVERAGING PROCEDURE

Exclusion levels have been derived in terms of activity concentrations. These values are meant to be measuring averages over a quantity of material. Averaging should be applied over the volume that is appropriate to the specific situation giving rise to the exposure of an individual. Application of averaging should also take into account areas of elevated activity in consideration of the potential dose to an individual.

Radioactivity that is confined to the surfaces of materials requires an assessment of the relationship of the surface to the mass of the materials to apply the exclusion levels that are expressed in Bq/g. Further considerations of this aspect are given in Section 3.9.

3.8. EFFECTS OF PARTICLE SIZES

The exclusion levels are based on the average activity concentration in a material. For material exhibiting a particle size distribution (e.g. building rubble, soil, ashes), the average activity concentration is not necessarily identical with the activity in certain particle size fractions. A well-known example is the distribution of the activity between ingot, slag, and fume during the smelting of contaminated metal. Depending on technical parameters and on the chemical properties of the radionuclides, a substantial enrichment of the activity concentration may be found in the slag or in the fume.

For many other material not arising from thermal processes, higher activity concentrations in fine fractions may be observed. This phenomenon can occur for material consisting of individual particles by the transfer of dissolved radionuclides into the material with a fluid phase (e.g. contamination from spills). A non-uniform activity concentration over particle size may also be caused or further enhanced by a redistribution of the activity in the material through leaching by fluids. An enhanced activity concentration of the fine fraction also obviously results when the activity is brought into the material with fine particles (e.g., deposition of dust or fumes on surfaces).

A higher activity concentration in the fine fraction has to be considered in assessments of the inhalation pathway. It is also relevant for the direct ingestion of contaminated material because this also refers to the fine fraction.

Several investigations have been performed concerning the smelting of metal. On the basis of these studies, element specific enrichment factors in the fumes between 1 and 70 have been derived [9]. These are applied in the calculations performed here for the foundry scenarios WF and RF.

For material other than metal, the situation is more complicated. The investigation of the processes that may lead to an enriched activity in the fine fraction shows that the actual activity distribution over particle size will depend on many factors, such as the type of material, its physical and chemical properties, and the origin and possible later redistribution of the contamination. This obviously causes difficulties for a generic assessment. Nevertheless, it is considered more appropriate to take account of this phenomenon even in a crude fashion rather than ignoring it in total.

On this basis, it is assumed for material other than metal, the activity concentrations in the respirable fine fraction are a factor of four higher than in the average of the material. For the dust that is subject to direct ingestion, a factor of two is used because this pathway on the average refers to coarser particles. These numbers are based on comprehensive investigations carried out on soil-like material in Germany [10]. It should be noted that the chosen factors do not correspond to the maximum values observed in these studies. But they are considered reasonable as an assumption covering the broad majority of material.

3.9 SURFACE CONTAMINATION

The activity in a material is not in all cases fully characterized by the activity concentration. Apart from particle size effects discussed above, a major portion of the activity may be concentrated on the surface of the material. This is in particular relevant for metals and buildings, but also other material may exhibit a surface contamination depending on their nature and on the origin of the contamination.

The difference between contaminants present preferentially on the surface as compared to the bulk of a material only plays a minor role for the important pathways of external irradiation and of food ingestion, and does not affect exposure estimates significantly. For the inhalation and ingestion of contaminated dust, however, this difference can become very important. A well-known example is the massive release of surface-bound radionuclides during the thermal cutting of metals, giving rise to a multiple of the doses that are to be expected if the radionuclides are evenly distributed throughout the bulk of the material.

This aspect has been intensively considered in several studies relating specifically to the clearance of material from nuclear installations [9, 11, 12]. For the purpose of the generic derivation of exclusion levels, however, such factors cannot be taken into account. Therefore, it has to be recognized that for specific situations such as the clearance of metal or the reuse of buildings from nuclear installations, additional criteria relating to the surface contamination may have to be applied which are not reflected in the derived exclusion levels. This may lead to the decision of the regulatory body not to release some material even if the exclusion levels are not exceeded for the bulk quantity.

4. EXCLUSION LEVELS FOR ARTIFICIAL RADIONUCLIDES

4.1. OVERVIEW

An overview of the scenarios considered in the derivation of exclusion limits for artificial radionuclides and the relevant pathways is given in Table II. The basis for the exposure estimates and the parameters used for the realistic and low probability cases are described in the following sections. Section 4.2 presents scenario specific assumptions on exposure and decay times as well as dilution factors. Section 4.3 discusses the specific approaches for the modeling of the relevant exposure pathways.

TABLE II. EXPOSURE SCENARIOS CONSIDERED AND RELEVANT PATHWAYS

Scenario	Description	Exposed Individual	Relevant Exposure Pathways
WL	Worker on landfill or in other facility (other than foundry)	worker	External exposure on landfill
			Inhalation on landfill
			Direct ingestion of contaminated material
WF	Worker in foundry	worker	External exposure in foundry from equipment or scrap pile
			Inhalation in foundry
			Direct ingestion of contaminated material
WO	Other worker (e.g., truck driver)	worker	External exposure from equipment or truck load
RL-C	Resident near landfill or other facility	child (1-2a)	Inhalation near landfill or other facility
			Ingestion of contaminated foodstuff grown on contaminated land
RL-A		adult (>17 a)	Inhalation near landfill or other facility
			Ingestion of contaminated foodstuff grown on contaminated land
RF	Resident near foundry	child (1-2a)	Inhalation near foundry
RH	Resident in house constructed of contaminated material	adult (>17 a)	External exposure in house
RP	Resident near public place constructed with contaminated material	child (1-2a)	External exposure on place
			Inhalation of contaminated dust
			Direct ingestion of contaminated material
RW-C	Resident using water from private well or consuming fish from contaminated river	child (1-2a)	Ingestion of contaminated drinking water, foodstuff and fish
RW-A		adult (>17 a)	

4.2. GENERAL PARAMETERS FOR SCENARIOS

For each scenario, general parameters are defined that characterize the exposure situation:

- Exposure time;
- Decay time allowed before the scenario starts; and
- Decay time during the scenario.

The decay time before the scenario addresses the period of time between the determination of compliance with the exclusion levels for the material in question and the actual start of the exposure.

The decay time during a scenario defines the time intervals at which new material is brought into a facility or used for construction purposes. Since exposures in individual years are considered, a maximum of 365 days of decay can be taken into account during a scenario, even if the deposition of material is a single event or if there is no new material used as in the case of a building after the construction is finished.

Decay times for the growing of foodstuff on contaminated land are treated separately because the material in this case has to be present in the area concerned for a considerable period of time before the growing of plants is expected to start.

The following values for these parameters for the realistic assumptions and for the low probability case (see Section 2) are used:

- Exposure time:
  - For all workplace scenarios except WO a range between a quarter of a working year (realistic assumption) and a full working year (low probability assumption) is used. For scenario WO an exposure time of 900 hours, corresponding to half a working year, is used in order to cover the case that a piece of equipment cleared from a nuclear facility is re-used.
  - The realistic time residents are exposed from a facility is set to 1000 hours per year. But since the dust within a building very close to a facility may also be impacted, a low probability assumption of a continuous exposure throughout a year is made. This covers, for example, a child spending most of the time in the house or in its vicinity.
  - With similar arguments, the low probability assumption for the scenario of living in a house constructed from the material is set to a continuous exposure (8760 hours). As a realistic assumption, 4500 hours are used.
  - For the case of children playing on a public place covered with the material, exposure times are assumed as 400 (about 1 hour per day) to 1000 hours, the upper bound being sufficient to address children playing on this place for about 3 hours every day.

- Decay times:
  - Decay times are chosen identically for all scenarios in which the exposure is due to material brought into a facility for processing or deposition. For the realistic case, a decay time before the scenario of 30 days and a decay during the scenario of 365 days is used. The latter corresponds to the assumption that the facility receives such material only once or at least infrequently. A facility processing such material on a routine basis is covered by the low probability assumptions with only one day decay time before the scenario and no decay during the scenario.
  - The two considered scenarios where the material has been used for construction purposes (building or public place) assume a decay time before the start of the scenario of 100 days. This allows for the preparation of the building material and the construction phase. Since no new material will be brought in after the construction is complete, a 365 day decay time during the scenario is assumed.
  - For the growing of foodstuff on an area contaminated by the material a decay time of 365 days before the start of the scenario is assumed. Since new material will not be added (or only a infrequent basis as, for example, in the case of wood chips), the decay time during the scenario is also set to 365 days.
  - For the water pathways, decay times are considered within the model applied (see Section 4.3.4). General assumptions are therefore not required.

The parameter values are provided in Table III.

TABLE III. GENERAL PARAMETER OF EXPOSURE SCENARIOS

Parameter	Unit	Case	Scenario						
			WL	WF	WO	RL	RF	RH	RP
			worker landfill	worker foundry	other worker	resident landfill	resident foundry	resident house	resident place
Exposure time (t_e)	h/a	realistic	450	450	900	1000	1000	4500	400
		low prob.	1800	1800	1800	8760	8760	8760	1000
Decay time before scenario (t_1)	d	realistic	30	30	30	30	30	100	100
		low prob.	1	1	1	1	1		
Decay time during scenario (t_2)	d	realistic	365	365	365	365	365	365	365
		low prob.	0	0	0	0	0		
Decay time before food scenario (t_{f1})	d	realistic	N/A	N/A	N/A	365	N/A	N/A	N/A
Decay time during food scenario (t_{f2})	d	realistic	N/A	N/A	N/A	365	N/A	N/A	N/A

4.3. MODELLING OF EXPOSURE PATHWAYS

In the following, the exposure models and the parameters used are described for all pathways relevant to the exposure scenarios considered. The results of the calculations are shown in Appendix II. The exclusion levels are shown in Table XV.

4.3.1. External Exposure

Exposure situations in which external exposure is relevant are very varied and may include exposure on a landfill or garden where waste that has been released from regulatory control is disposed (landfill worker), working near a large piece of cleared equipment and while staying in a building that is constructed using building rubble or other material (e.g. slag or fly ash) that has been released from regulatory control as aggregate for the new concrete or as substitute for cement in the concrete. The scenarios considered are defined to cover these and similar situations.

The dose from external exposure is calculated according to equation (1):

$$E_{ext,C} = \dot{e}_{ext} \cdot t_e \cdot f_d \cdot e^{-\lambda t_1} \frac{1-e^{-\lambda t_2}}{\lambda \cdot t_2} \quad (1)$$

where

$E_{ext,C}$ [(μSv/a)/(Bq/g)] individual effective dose in a year from external exposure per unit activity concentration in the material,

$\dot{e}_{ext}$ [(μSv/h)/(Bq/g)] average effective dose rate per unit activity concentration in the material, depending on geometry, distance, shielding, age group etc.,

t_e [h/a] exposure time,

f_d [-] dilution factor,

λ [1/a] radioactive decay constant,

t_1 [a] decay time before start of scenario, and

t_2 [a] decay time during scenario.

External exposures are assessed for four different situations as required by the definition of the scenarios in Table II with the following parameters:

- Dilution factor:
  - In a realistic situation, a dilution of at least 1:10 is reasonable to assume for the landfill scenario while the low probability approach assumes no dilution.
  - For the external irradiation in a foundry processing the material it is assumed that a worker is in contact with a larger piece of equipment or a pile of scrap. This also covers a truck driver bringing material to a foundry or a landfill. The same range for the dilution factor is assumed as for the landfill scenario.
  - In scenario RH it is assumed that a person spends time in a room or enclosure which is to some percentage made from the material (e.g., by using building rubble, slag or ash as aggregate or cement substitute in concrete). It is assumed that the material of which the room or enclosure is constructed, will in realistic circumstances, be mixed 1:10 with other material. Since the construction material can, for technological reasons, contain only a certain percentage of building rubble, ashes or similar material, an upper limit for the dilution of 0.5 is assumed for the low probability case.
  - The scenario RP considers playing children on a public place partially made from the material. The dilution factor for realistic parameters is assumed at 0.1. For the low probability case a factor of 0.5 is chosen, because the public place is not likely to be covered with a deep cover of the material – either the cover will consist only of a relatively thin layer of, for example, ashes or slag, or there will be some mixing with other material. A factor of 0.5 is felt to provide a sufficiently conservative upper estimate.
- Density of material:
  - The density of the material only has a relatively small effect on the results. For a higher density, more activity is present per volume of the material (with a given mass specific activity concentration). This increases the number of photons emitted; however, self-absorption of the gamma radiation by the material increases as well.
  - On these grounds, a homogeneously distributed source in the material is assumed for which a density of 1.5 g/cm³ is used for the dose calculations in all scenarios.
- Geometry:
  - In the landfill scenario and for the public place, doses are calculated for rotational exposure geometry at 1 m height above the ground.
  - To estimate exposures from a large item (equipment, pile of scrap, truckload) the exposure geometry is chosen to be a slab 5 m × 2 m × 1 m thick. The dose coefficients for this exposure situation are almost identical to those for a smaller piece of equipment (5 m × 2 m × 1 m) made of steel (density 7.8 g/cm^3) considered in other models set up for the derivation of clearance values. Thus, the scenario presented here covers both situations.
  - For the building constructed of contaminated material, exposure geometry chosen is a room[9] of 3 × 4 m² with a height of 2.5 m. The calculations are based on 2 walls and a ceiling that are 20 cm thick. It is assumed that windows and doors account for the other 2 walls and that the floor would be

[9] The actual size of the room is of minor importance. If, e.g., the room is much longer in one dimension, say 8 m instead of 3 m, the dose coefficient increases by only 10%.

made of other material. Doses are calculated for a rotational geometry in the middle of the room at a height of 1 m. Doses calculated in clearance studies for the use of steel plates cleared from nuclear facilities are considerably smaller than those in the case considered here. Thus, this scenario is covered here as well.

- Dose coefficients:
  - Doses are calculated for adults in the workplace scenarios and for the resident in the house. For the public place, dose calculations are performed for children between 1 and 2 years of age.[10]

The parameter values are provided in Table IV.

TABLE IV. PARAMETERS FOR EXTERNAL IRRADIATION SCENARIOS

Parameter	Unit	Case	WL	WF/WO	RH	RP
			worker landfill	foundry or other worker	resident house	resident place
Dilution factor (f_d)	[-]	realistic	0.1	0.1	0.1	0.1
		low prob.	1	1	0.5	0.5
Density of material	g/cm³		1.5	1.5	1.5	1.5
Geometry			1 m above ground, semi-infinite source	1 m from load or item 5x2x1 m³, no shielding	Ceiling, 2 walls, 3x4 m², 2.5 m height, 20 cm wall thickness.	1 m above ground, semi-infinite source
Dose rate coefficient ($\dot{e}_{ext}$)	µSv/h/(Bq/g)		(adult)	(adult)	(adult)	(child 1-2 a)
			Depending on radionuclide and geometry			

4.3.2. Inhalation

Inhalation of contaminated dust can occur in many exposure situations. Therefore, representative exposures for workplaces and for the general population are considered. A child (age group 1-2 a) is chosen as the reference age group in the latter case.

Doses from inhalation are calculated according to equation (2):

$$E_{inh,C} = e_{inh} \cdot t_e \cdot f_d \cdot f_c \cdot C_{dust} \cdot \dot{V} \cdot e^{-\lambda t_1} \frac{1-e^{-\lambda t_2}}{\lambda \cdot t_2} \qquad (2)$$

where

$E_{inh,C}$ [(µSv/a)/(Bq/g)] individual effective dose in a year from inhalation per unit activity concentration in the material,

e_{inh} [µSv/Bq] effective dose coefficient for inhalation (see section 3.1.),

t_e [h/a] exposure time,

[10] The inclusion of children between one and two years of age in the reference groups is consistent with a strict interpretation of the exemption criterion (10 µSv/a) as relating to any single year of exposure; in terms of radiological risk from protracted low level exposure a much longer integration period could be considered so that children of a specific age group would normally not be in the most restrictive age group.

f_d [-] dilution factor,

f_c [-] concentration factor of specific activity in the fine fraction,

C_{dust} [g/m³] effective dust concentration in the air,

$\dot{V}$ [m³/h] breathing rate,

λ [1/a] radioactive decay constant,

t_1 [a] decay time before start of scenario, and

t_2 [a] decay time during scenario.

The inhalation pathway is relevant for most of the scenarios considered. The following parameters are used:

- Dilution factor:
  - For the landfill, the same range (0.1 to 1) for the dilution factor is used as for external irradiation.
  - The dilution factor for the foundry is chosen as 0.02 in the realistic case, accounting for the fact that typical foundries process large amounts of scrap material. For the low probability case, a factor of 0.1 is used.[11]
  - For the residents living in the vicinity of a landfill or facility, the dilution factors are reduced by a factor of 10 as compared to the assumptions within the facility. This takes into account that several other sources will contribute to the airborne dust outside the facility.
  - On the public place a realistic dilution factor of 0.1 is assumed in accordance with the assumptions for the external exposure. However, the low probability assumption of the external exposure pathway of 0.5 dilution is not used for the inhalation pathway, because the material may have been used for covering the place with a thin layer (e.g. ash). Since the airborne dust in this case would be almost completely generated from the cover layer, no dilution is assumed in the low probability case.
- Dust concentration in air:
  - For the workplaces, a realistic dust concentration in air of 0.5 mg/m³ and a low probability value of 1 mg/m³ is assumed.
  - The range for the dust concentration in air for the scenarios outside the facilities are reduced to 10^{-4} for realistic assumptions and to 5×10^{-4} for low probability assumptions.
- Concentration factor of specific activity in the fine fraction:
  - The higher activity in the fine fraction as compared to the material average is taken into account according to the discussion in Section 3.7. For metal

[11] It should be noted that for the external irradiation in the foundry, a dilution factor in the range of 0.1 to 1 is used, corresponding to the landfill scenario. The reason for adopting a lower factor for the inhalation pathway is as follows: A worker in the foundry may be specialized on processing certain material types in preparation to smelting (e.g., stainless steel). Consequently, this worker may be exposed to the material of concern on a frequent basis, which is accounted for by the lower dilution considered for the external exposure as well as for the material ingestion scenarios. The radionuclide concentrations in the fumes present in the foundry, on the other hand, will be determined by the overall dilution of the material processed in the facility, which is expected to be considerably higher.

smelting an element dependent range between 1 and 70 is used, while for other materials a factor 4 is used.

- Breathing rate:
  - The breathing rate for workers and other adults is set to 1.2 m³/h (accounting for moderate physical activity). For children between one and two years of age a breathing rate of 0.22 m³/h is applied.
- Dose coefficients:
  - Dose coefficients for workers are taken from the BSS [2] for 5 μm AMAD (Activity Median Aerodynamic Diameter). For the public, dose coefficients are taken from the BSS [2] for the default lung retention class and the appropriate age group.

Parameter values are provided in Table V.

TABLE V. PARAMETERS FOR INHALATION SCENARIOS

Parameter	Unit	Case	WL	WF	RL-A	RL-C	RF	RP
			worker landfill	worker foundry	resident landfill		resident foundry	resident place
Dilution factor (f_d)	[-]	realistic	0.1	0.02	0.01	0.01	0.002	0.1
		low prob.	1	0.1	0.1	0.1	0.01	1
Dust concentration in air (C_{dust})	g/m³	realistic	5×10^{-4}	5×10^{-4}	10^{-4}	10^{-4}	10^{-4}	10^{-4}
		low prob.	10^{-3}	10^{-3}	5×10^{-4}	5×10^{-4}	5×10^{-4}	5×10^{-4}
concentration factor (f_c)	[-]		4	1 – 70	4	4	1 – 70	4
Breathing rate ($\dot{V}$)	m³/h		1.2	1.2	1.2	0.22	0.22	0.22
Dose coefficient (e_{inh})	μSv/Bq		5 μm, worker, see 3.1.	5 μm, worker, see 3.1.	adult, see 3.1.	child (1-2a), see 3.1.	child (1-2a), see 3.1.	child (1-2a), see 3.1.

4.3.3. Ingestion

Two types of exposure pathways are considered for ingestion:

- Inadvertent direct ingestion of dust (e.g. via hand-to-mouth-pathway), and
- Ingestion of crops which are grown in the material in question (e.g. soil) which the nuclides enter via the roots of the plants.

The growing of plants in soil that contains material that has been released from regulatory control might occur in the following situations: released building rubble which is present in soil in small fractions, released soil from a nuclear site which is used in a garden or which has been used for covering an old landfill site which later on is used as a recreational area, or even reuse of a former nuclear site for general purposes. The foodstuff scenario RL-A accounts for an adult who will consume vegetables grown in the material, RL-C covers the exposure of children in the same situation.

The dose from ingestion is calculated according to equation (3):

$$E_{ing,C} = e_{ing} \cdot q \cdot f_d \cdot f_c \cdot f_t \cdot e^{-\lambda t_1} \frac{1 - e^{-\lambda t_2}}{\lambda \cdot t_2} \qquad (3)$$

where$E_{ing,C}$ [(μSv/a)/(Bq/g)] individual effective dose in a year from ingestion per unit activity concentration in the material,

e_{ing} [μSv/Bq] dose coefficient for ingestion see section 3.1.,
q [g/a] ingested quantity per year,
f_d [-] dilution factor,
f_c [-] concentration factor in fine fraction,
f_t [-] root transfer factor,
λ [1/a] radioactive decay constant,
t_1 [a] decay time before start of scenario, and
t_2 [a] decay time during scenario.

The factor f describes the transfer of elements from soil to plants for those circumstances where growing of foodstuff in soil mixed with material that has been released from regulatory control is considered. This factor accounts for the fact that the uptake of radionuclides in plants depends on the element. Values for f are given in Bq/kg in the plant per Bq/kg in the soil (i.e., they are dimensionless) and are provided in Safety Report 19 [13].

The following parameters are used for the ingestion scenarios:

- Dilution factor:
  - Assumptions for the dilution of dust ingested inadvertently by a resident near a landfill are identical to those for the inhalation pathway. For the growing of foodstuff a realistic dilution of 0.01 and a low probability dilution of 0.1 is used. This dilution covers the fact that only part of the soil will consist of the material. It is also assumed that only a portion of the annual dietary intake will be grown in the garden. With the combination of these two factors, the assumed range is considered to be adequate.
- Concentration factor of specific activity in the fine fraction:
  - This factor is only relevant for the direct ingestion of material. For the particle size fraction that may be subject to direct ingestion a concentration factor of 2 is used according to the discussion in Section 3.8.
- Root transfer factor:
  - This factor is only relevant for the ingestion of foodstuff. Root transfer factors describing the transfer of radionuclides from the soil to the plants are provided in [13].
- Annually ingested quantity:
  - For the direct ingestion of a worker a quantity of 10 g/a is assumed. A low probability approach is to use 50 g/a.
  - The amount of dirt and dust which a small child may inadvertently swallow when playing on a public place covered with the material could amount under realistic assumptions to 25 g/a. The low probability approach is to assume an ingested quantity of 50 g/a.
  - For the foodstuff pathway the annual consumption of vegetables and fruits is considered that may be grown in the garden.[12] Consumption quantities used are for the realistic case 68 kg per year for children and 88 kg per year for adults. In the low probability scenarios consumption rates of 204 kg per

[12] This scenario does not consider other agricultural products like grain, meat, or milk. Such products would require substantially larger areas as compared to the growing of vegetables or fruit in a private garden. This would lead to substantially higher dilution factors because it cannot reasonably be assumed that large agricultural areas are contaminated in total with the material. Therefore, the consideration of a private garden with limited types of foodstuff produced represents the covering scenario for the food pathway.

year for children and 264 kg per year for adults are used. The derivation of these assumptions is provided in connection with other consumption parameters required for the water pathway model in Section 4.3.4. A dilution with foodstuff from other sources already has been taken into account in the assumptions for the dilution factor.

- Dose coefficients:
  - The ingestion dose coefficients are taken from the Basic Safety Standards [2] for workers or the appropriate age group of the public.

Parameter values are provided in Table VI.

TABLE VI. PARAMETERS FOR INGESTION SCENARIOS

Parameter	Unit	Case	WL/WF	RP	RL-A	RL-C
			landfill or foundry worker	resident place	resident landfill	
Dilution factor (f_d)	[-]	realistic	0.1	0.1	0.01	0.01
		low probab.	1	1	0.1	0.1
Concentration factor (f_c)	[-]		2	2	N/A	N/A
Root transfer factor (f_t)	[-]		N/A	N/A	[12]	[12]
Annually ingested quantity (q)	g/a or kg/a	realistic	10 g/a	25 g/a	88 kg/a	68 kg/a
		low probab.	50 g/a	50 g/a	264 kg/a	204 kg/a
Dose coefficient (e_{ing})	µSv/Bq		worker; see 3.1.	child (1-2a), see 3.1.	adult, see 3.1.	child (1-2a), see 3.1.

4.3.4. Water Pathway

Water pathways are included in radiological assessments in those cases where large quantities of material that has been removed from regulatory control are disposed or stored in a single place where rain can reach the material and dissolve its residual contamination that is then carried away to a groundwater layer or to surface water. The radionuclides can enter the human food chain if the water is used as drinking water or for irrigation purposes. In the case of groundwater contamination, it is conceivable that the water is taken from a private well that is not subject to any legal requirements concerning the water quality, while in the case of surface water contamination, the water might be used by municipal water works. Various investigations have demonstrated that the private well supplying groundwater to a family is the most restrictive of the various water pathways. If the contaminated water is discharged into surface water an additional exposure pathway to be taken into account is the ingestion of contaminated fish.

Modeling a water pathway requires assumptions about the quantity of material that is stored or disposed, the location (landfill site, public area, etc.) where it is placed and the characteristics of the environment (e.g., hydrogeology). These factors are highly site-specific making the generic modeling of the water pathway difficult. Nevertheless, it is considered more appropriate to include the water pathway into the assessment in spite of this difficulty than to disregard this pathway in total.

The model used for the water pathway is described in the following. In line with the overall approach a realistic case and a low probability case are considered. Assumptions for the latter

case represent unfavorable site and exposure conditions, so that the modeling results are considered to cover all situations that are reasonably to be expected.

The models developed are based on the RESRAD computer model developed for radiation dose estimates arising from residual radioactive material [14]. This computer model has been widely used for exposure assessments and has been benchmarked against other models. A direct use of RESRAD for modeling the water pathway, however, was not possible because not all of the nuclides relevant here are considered in RESRAD. Moreover, only a small subset of the models implemented in RESRAD actually are required here. Therefore, it was decided to develop a new model based on algorithms and assumptions provided in the RESRAD documentation. In order to verify the model developed, its results were checked against RESRAD results for selected radionuclides.

4.3.4.1. Model equations

The modeling of the water pathway assumes an extended source of the material present in the catchment area of a groundwater aquifer. This could be a landfill or the consequence of the use of the material in a landscape construction project.

The model assumes conservatively that the whole inventory of radionuclides in the material is available for migration. The rate at which the radionuclides are released is determined using a K_d model [14]. Within this model the leach rate of the radionuclide i from the source L_i is given as:

$$L_i = \frac{I}{\theta^{\alpha} \cdot z^{\alpha} \cdot R_i^{\alpha}} \tag{4}$$

where

I	[m/a] infiltration rate,
θ^{α}	volumetric water content of the contaminated zone (dimensionless),
z^{α}	[m] thickness of contaminated zone,
R_i^{α}	retardation factor for radionuclide i (dimensionless),

The retardation factor is given by:

$$R_i^{\alpha} = 1 + \frac{\rho^{\alpha} \cdot K_{di}}{\theta^{\alpha}} \tag{5}$$

where

ρ^{α}	[g/cm^3] density of contaminated zone, and
K_{di}	[cm^3/g] distribution coefficient for radionuclide i.

The decisive parameter determining the leaching of different radionuclides from the contaminated zone is the distribution coefficient. This quantity is dependent on the chemical characteristics of the radionuclide and the geochemical properties of the soil. Values provided for different elements in the literature vary considerably. For the purpose of the generic model developed here it is therefore necessary to select conservative estimates from the values published for different elements.

For the realistic scenario the default values used in the RESRAD model are used. These are already reasonably conservative in comparison to other values published (see Table E.4 in

[14]). For some nuclides, however, lower values are reported in this table. The low probability scenario therefore uses the minimum values for the distribution coefficients provided in Table E.4 of [14].

For some elements no measurements of distribution coefficients are available. In this case the approximation given in Appendix H of [14] is used, estimating the distribution coefficient from the root transfer factor f_i (see Section 4.3.3) as

$$\ln K_{d_i} = a + b \cdot \ln f_i \tag{6}$$

with a = 2.11 (valid for sandy soil) and b = -0.56.

The values of the distribution coefficient used for the different elements are given in Table VII. Values derived from Equation (6) are indicated. The remaining values are based on measurements.

Table VII. Distribution Coefficients (cm^3/g)

Element	realistic	low probability	Element	realistic	low probability
Ag	0	0	Nb	0	0
Am	20	20	Ni	1000	300
Ba	50	44*	Np	50	5
Bi	0	0	Pd	30	30
Bk	213*	213*	Pm	268*	240
C	0	0	Pt	12*	12*
Ca	50	5	Pu	2000	550
Cd	0	0	Rb	20*	20*
Ce	1000	500	Rh	44*	44*
Cf	109*	109*	Ru	0	0
Cl	3*	3*	Sb	0	0
Cm	395*	395*	Se	0	0
Co	1000	60	Sm	182*	182*
Cs	1000	270	Sn	0	0
Es	213*	213*	Sr	30	15
Eu	268*	240	Tb	182*	182*
Fe	1000	160	Tc	0	0
Gd	182*	182*	Te	0	0
H	0	0	Th	60000	1378
Ho	182*	182*	Tl	0	0
I	0.1	0.1	Tm	213*	213*
La	213*	213*	U	50	15
Mn	200	50	Zn	0	0
Mo	20*	10	Zr	395*	280
Na	10	10			

* *value calculated using Equation 6*

It should be noted that K_d values in concrete situations may be considerably different from the numbers given in Table VII. It may also be the case that the linear K_d model is not adequate for certain site conditions (e.g. because of the presence of other chemical substances or because of adsorption saturation effects). Therefore, it cannot be assumed that leach rates in all cases are covered by the model presented. This possibility, however, has to be seen in the overall context of relatively conservative assumptions used, so that a higher leach rate for some radionuclides under specific site conditions does not necessarily mean that eventual exposures are higher than predicted by the model.

The radionuclide concentration in the seepage C_i^s for radionuclide i can be calculated from the leach rate L_i as:

$$C_i^s = \frac{M \cdot c_i \cdot L_i}{U^s} \tag{7}$$

where

M [g] total mass of contaminated material,

c_i [Bq/g] specific activity of radionuclide i in the contaminated material,

L_i [1/a] leach rate for radionuclide i according to Equation (4), and

U^s [m^3/a] volume of seepage through contaminated zone.

The volume of the seepage through the contaminated zone U^s is given by:

$$U^s = I \cdot A^{cz} \tag{8}$$

where

I [m/a] infiltration rate,

A^{cz} [m^2] surface area of contaminated zone.

It is assumed that the seepage from the source is discharged into an aquifer. For the realistic scenario, it is assumed that there is an unsaturated zone between the contaminated material and the aquifer. Its presence will only have an effect on the eventual contaminant concentration in the seepage reaching the aquifer through radioactive decay of the radionuclides while migrating through the unsaturated zone. The transport time through this zone is given by the following equation:

$$t_i = \frac{z^{uz} \cdot R_i^{uz} \cdot p^{uz} \cdot R_s^{uz}}{I} \tag{9}$$

where

I [m/a] infiltration rate,

z^{uz} [m] thickness of contaminated zone,

p^{uz} effective porosity of the unsaturated zone (dimensionless),

R_s^{uz} saturation ratio of the unsaturated zone (dimensionless), and

R_i^{uz} retardation factor for radionuclide i in the unsaturated zone (dimensionless).

The unsaturated zone retardation factor is given by:

$$R_i^{uz} = 1 + \frac{\rho^{uz} \cdot K_{di}}{\theta^{uz}} \tag{10}$$

where

ρ^{uz} [g/cm^3] density of unsaturated zone,

K_{di} [cm^3/g] distribution coefficient for radionuclide i, and

θ^{uz} volumetric water content of the unsaturated zone (dimensionless).

Distributions coefficients are chosen identical to the contaminated zone (see Table VII).

The transport time given by Equation (9) will only be valid if the transport can be described as flow through a porous medium with the K_d concept being applicable. This will not be the case in all situations. For example, transport mechanisms like fracture flow or colloidal transport may lead to a substantially faster transport of the radionuclides through the unsaturated zone. Therefore, the low probability model does not take account of the presence of an unsaturated zone at all. This covers the situation where there is a direct contact of the contaminated zone with the groundwater aquifer as well as the presence of fast transport mechanisms through an unsaturated zone.

The exposure assessment assumes a private well downstream of the source. This well is conservatively assumed to be so close to the source that no dilution with groundwater that has not been impacted by the source takes place. The transport modeling of the radionuclides in the aquifer does not consider dispersion or diffusion effects. This is also a conservative assumption.

Within these assumptions the radionuclide concentration in the well water is given by the dilution with the groundwater volume U_{gw} flowing underneath the area of the contaminated zone:

$$U^{gw} = z^{gw} \cdot w^{gw} \cdot v^{gw} \cdot p^{gw} \tag{11}$$

where

z^{gw}	[m] thickness of aquifer,
w^{gw}	[m] width of contaminated zone perpendicular to flow rate of aquifer,
v^{gw}	[m/a] pore water velocity of groundwater, and
p^{gw}	effective porosity of aquifer (dimensionless).

From Equations (7), (8), (9), and (11) the concentration of the radionuclide i in the well water c_i^w is given by:

$$c_i^w = \frac{U^s}{U^{gw} + U^s} \cdot C_i^s \cdot e^{-\lambda_i \cdot t_i} \tag{12}$$

From this result the ingestion dose arising from the use of the well water as drinking water can be calculated.

For the assessment of the radiological impact of using this water for the irrigation of foodstuff grown in a private garden the transfer of the radionuclides from the water to the plants has to be considered. This is performed using the transfer factor given in the following equation derived in [14] assuming an overhead irrigation of the plants:

$$f_t = \frac{I_{rr} \cdot f_r \cdot T_f \cdot \left(1 - e^{-\lambda_w \cdot t_e}\right)}{Y_w \cdot \lambda_w} + \frac{I_{rr} \cdot (1 - f_r) \cdot f_i \cdot \left(1 - e^{-L_i \cdot t_e}\right)}{\rho^e \cdot L_i} \tag{13}$$

where (with default assumptions used according to [13])

I_{rr}	[m/a] irrigation rate,
f_r	fraction of deposited radionuclides retained on vegetation (0.25),
T_f	foliage-to-food transfer coefficient (0.1 for fruit and non-leafy vegetables and 1 for leafy vegetables),
λ_w	weathering removal constant for vegetation (20 a^{-1}),
t_e	time of exposure during growing season (0.17 a for fruit and non-leafy vegetables and 0.25 a for leafy vegetables),
Y_w	wet-weight crop yield (0.7 kg/m^2 for fruit and non-leafy vegetables and 1.5 kg/m^2) for leafy vegetables,
f_i	root transfer factor for radionuclide i (dimensionless, see Section 4.3.3),
L_i	[1/a] leach rate for radionuclide i according to Equation (4), and
ρ^e	effective surface density of soil (225 kg/m^2)

The eventual discharge of the groundwater into a surface water body will also give rise to exposures if the surface water is used as drinking water or for irrigation. However, because of dilution effects doses will be lower in this case as compared to the private well. Therefore, it is not necessary to consider the use of surface water explicitly in the model. An additional exposure pathway arises, however, through the ingestion of fish from this surface water body.

In analogy to Equation 12, the radionuclide concentration in the river water (c_i^r) is determined from the flow rate of the river (U^r)as:

$$c_i^r = \frac{U^s}{U^r + U^s} \cdot C_i^s \cdot e^{-\lambda_i \cdot t_i} \tag{14}$$

From this concentration the radionuclides transferred into fish can be calculated using transfer factors given in Table D.5 of [14].

4.3.4.2. Conditions at model site

For the realistic scenario, the amount of material present on the site is assumed as 25,000 m^3, and for the low probability case, a total volume of 100,000 m^3 is considered. The thickness of the contaminated zone is assumed to be 5 m in both cases. These assumptions are considered to cover all cases of material containing artificial radionuclides.[13]

In analogy to the foodstuff scenarios, a decay time before the start of the scenario of one year is assumed. During the scenario the decay depends on the migration time of the contaminant calculated according to Section 4.3.4.1. After the water reaches the well or the river, no further decay is considered because the dominating pathway is the direct ingestion of drinking water, which would occur instantaneously.

The infiltration rate is chosen as 0.2 m per year corresponding to the default assumptions in RESRAD. This value is sufficient for a moderate climate. In cases of wet regions and appropriate soil conditions, higher infiltration rates are possible. However, in this case flow rates of aquifers and surface water are to be expected to be higher too, so that the eventual dilution factor between the seepage from the contaminated material and ground or surface water should remain approximately the same.

For realistic assumptions an unsaturated zone of 2 m thickness is assumed between the contaminated zone and the top of the aquifer. The low probability scenario assumes direct contact of the contaminated zone and the aquifer.

The pore water velocity of the groundwater in the aquifer is taken as 1000 m per year in the realistic case and 500 m per year in the low probability case. Lower groundwater velocities and consequently a lower dilution may occur at some sites. However, within the overall context of the assumptions applied to the model site, this range is considered to be sufficiently conservative.

The groundwater in the private well is assumed to be used as drinking water and for irrigation purposes in a private garden. The irrigation rate is assumed as 0.2 m per year.

The river considered in the model is assumed to have a flow rate of 5 m^3/s, which is considered high enough to support a sufficient fish population to cover the annual fish consumption of the exposed persons.

The model calculations consider adults and children of the age group 1-2a in accordance with the ingestion scenarios presented in Section 4.3.3. Dietary parameters are also chosen

[13] For material with elevated levels of natural radionuclides (NORM), higher masses are possible (e.g. in connection with mining operations). However, the models developed are not applied to natural radionuclides in this report.

consistent with these scenarios. The model presented requires input parameters for the consumption of

- drinking water;
- leafy vegetables;
- non-leafy vegetables and fruits; and
- fish.

Safety Report 19 [13] provides only aggregate numbers on consumption (410 kg per year of fruits, vegetables, and grain for adults). Since this is not sufficient for the models developed here, the ingestion quantities are based on detailed parameters provided in the German Radiation Protection Ordinance [15], giving ingestion quantities for average cases and for low probability cases (approximately corresponding to 95% percentiles). These parameters are used for the realistic and the low probability scenarios, respectively. They are shown in Table VIII. Considering that the overall consumption given in [13] of 410 kg per year also includes grain, the assumptions are consistent.

TABLE VIII. INGESTION PARAMETERS

Type	consumption of children (1-2a) [kg/a]		consumption of adults (>17 a) [kg/a]	
	realistic	low prob.	realistic	low prob.
drinking water	100	200	350	700
leafy vegetables	6	18	13	39
non-leafy vegetables	17	51	40	120
fruits	45	135	35	105
total vegetables and fruits	68	204	88	264
fish	0.6	3	1.5	7.5

For the realistic scenario, it is assumed that 25 % of the annual consumption of drinking water and foodstuff are affected by the radionuclides from the contaminated material and that the remainder is obtained from other sources. In the low probability scenario, the assumption is used that the total consumption of drinking water and foodstuff as specified above is affected from the contaminated material.

A summary of the site parameters used is presented in Table IX.

TABLE IX. SITE PARAMETERS FOR WATER PATHWAY MODEL

Parameter	Unit	realistic	low probability
Contaminated zone			
decay time before scenario	a	1	1
area of contaminated zone	m^2	5000	20000
thickness of contaminated zone	m	5.00	5.00
density of contaminated area	g/cm^3	1.80	1.80
infiltration rate	m/a	0.20	0.20
irrigation rate	m/a	0.20	0.20
seepage through contaminated zone (calculated)	m^3/a	1000	4000
total porosity of contaminated area		0.40	0.40
saturated hydraulic conductivity	m/a	5000	5000
volumetric water content		0.16	0.16
Unsaturated zone			
thickness of unsaturated zone	m	2.00	0.00
density of unsaturated zone	g/cm^3	1.80	1.80
total porosity of unsaturated zone		0.40	0.40
effective porosity of unsaturated zone		0.20	0,.20
volumetric water content		0.16	0.16
Groundwater aquifer			
thickness of aquifer	m	5.00	5.00
width of contaminated zone perpendicular to aquifer	m	100	100
groundwater pore water velocity	m/a	1000	500
effective porosity of aquifer		0.25	0.25
flow rate of aquifer (calculated)	m^3/a	1.25E+05	6.25E+04
dilution factor between seepage and groundwater (calculated)		7.94E-03	6.02E-02
Surface water			
flow rate of river	m^3/s	5.00	5.00
dilution factor between seepage and river (calculated)		6.34E-06	2.54E-05
Irrigation parameter			
length of growing season for non-leafy vegetables	a	0.17	0.17
length of growing season for leafy vegetables	a	0.25	0.25
weathering removal constant for vegetation	1/a	20	20
fraction of radionuclides retained on vegetation		0.25	0.25
foliage-to-food transfer coefficient for non-leafy vegetables		0.1	0.1
foliage-to-food transfer coefficient for leafy vegetables		1	1
effective surface density of soil	kg/m^2	225	225
wet-weight crop yield for non-leafy vegetables	kg/m^2	0.7	0.7
wet-weight crop yield for leafy vegetables	kg/m^2	1.5	1.5
Ingestion parameter			
consumption of drinking water (1-2a)	kg/a	100	200
consumption of drinking water (> 17a)	kg/a	350	700
consumption of non-leafy vegetables (1-2a)	kg/a	17	51
consumption of non-leafy vegetables (> 17a)	kg/a	40	120
consumption of leafy vegetables (1-2a)	kg/a	6	18
consumption of leafy vegetables (> 17a)	kg/a	13	39
consumption of fish (1-2a)	kg/a	0.6	3
consumption of fish (> 17a)	kg/a	1.5	7.5
fraction of contaminated drinking water consumed		0.25	1
fraction of contaminated vegetables consumed		0.25	1
fraction of contaminated fish consumed		0.25	1

4.3.4.3. *Radionuclides considered*

Modeling is performed only for radionuclides with a half-life greater than 0.5 years because radionuclides with a shorter half-life will not contribute significantly to the water pathway doses. Ingestion doses incurred by these short-lived radionuclides will be dominated by the ingestion scenarios and/or other pathways presented in Section 4.3.3

The ingrowth of daughter nuclides is considered according to Section 3.2. However, for the water pathway it has to be considered that the leachability and groundwater mobility of a daughter nuclide may be higher than those of its parent nuclides. To account for this effect the following approach is used:

- Daughter nuclides with a half-life less then 0.05 years are treated in equilibrium with their parent nuclides in the water and foodstuff consumed because the processes relevant for the migration of the radionuclides and the plant uptake are slow enough to at least nearly achieve a radioactive equilibrium in this case.
- Longer-lived daughter nuclides are modeled independently and their dose contribution is added to the dose incurred by the parent nuclide. The ingrowth of daughter nuclides is considered in analogy to the other pathways using the model presented in Chapter 2.

4.3.4.4. *Time scales*

In the realistic scenario, an unsaturated zone is assumed to be present between the contaminated material and the groundwater aquifer. In this situation, migration processes of contaminants with a high K_d value are very slow. The time span between the deposition of the material and their arrival in the well or the river may be hundreds or even thousands of years. The consideration of such long-term exposures may be seen as contradicting the assumption concerning the ingrowth of daughter nuclides (see Chapter 2), where a period of 100 years has been used.

The examination of the results for those nuclides dominated by the water pathway within the realistic scenario showed, however, that the resulting exclusion levels do not change if a cut-off after 100 years is applied. Therefore, the question of which time scale to used is not of practical relevance in this case.

4.3.4.5. *Discussion of results*

The results from the water pathway model presented in Appendix II show that only for some radionuclides the exclusion level is dominated by the water pathway. These are mobile nuclides with a considerably long half-live, high ingestion dose factors and low external dose factors.

The exposures from these nuclides over the water pathway in real situations will depend on actual site conditions. As discussed already, the model used for the derivation of exclusion levels does not cover all potentially occurring individual site parameters. Nevertheless, the results are considered to be sufficiently conservative to cover the vast majority of cases:

- The volumes of contaminated material considered in the model are quite high.
- The exposure situation of residents using the contaminated groundwater downstream of the landfill without any additional dilution corresponds to unfavorable conditions.
- The model used does not take account of effects like dispersion that would lead to lower exposures.
- An intensive use of the contaminated water is assumed for drinking water and for irrigation purposes.

On this basis, the derived exclusion levels are considered appropriate also for sites where some of the relevant site factors are more unfavorable as assumed here.

4.3.5. Skin Contamination

Skin contamination by dust containing radionuclides can only occur with some significance at workplaces in dusty environments. Those workplaces may be at a scrap yard or metal recycling facility where metal is segmented or at a landfill site where workers come into contact with the dumped material.

The skin dose is calculated according to equation (15):

$$E_{skin,C} = \dot{e}_{skin} \cdot t_e \cdot L_{dust} \cdot f_d \cdot f_c \cdot \rho \cdot e^{-\lambda t_1} \frac{1-e^{-\lambda \cdot t_2}}{\lambda \cdot t_2} \qquad (15)$$

where

$E_{skin,C}$	[(μSv/a)/(Bq/g)] skin equivalent dose in a year from skin contamination with beta and gamma emitters per unit activity concentration in the material,
$\dot{e}_{skin}$	[(μSv/h)/(Bq/cm²)] sum of skin equivalent dose rate coefficients for beta emitters (4 mg/cm² skin density) and for gamma emitters [6] per surface specific unit activity,
t_e	[h/a] exposure time (time during which the skin is contaminated),
L_{dust}	[cm] layer thickness of dust loading on the skin,
f_d	[-] dilution factor,
f_c	[-] concentration factor,
ρ	[g/cm³] density of surface layer,
λ	[1/a] radioactive decay constant,
t_1	[a] decay time before start of scenario, and
t_2	[a] decay time during scenario.

Contamination of the skin is assumed to occur during the entire working year (1800 h/a). The layer thickness of the dust is assumed to 100 μm (0.01 cm) which is a thickness that would not be significantly disturbing while working and therefore would be removed by the worker only at the end of his working time.

No dilution has been assumed. This is a conservative assumption, but it is consistent with the low probability parameter used for the landfill scenario. In order to account for a higher activity concentration in the fine fraction a concentration factor 2 is used (see Section 3.7). As the material causing skin contamination might always be recently cleared, no decay before or during the scenario is assumed. The density of the dust on the skin is set to 1.5 g/cm³.

Parameter values provided in Table X.

TABLE X. SCENARIO PARAMETERS FOR SKIN CONTAMINATION

Parameter	Unit	Scenario SKIN
Exposure time (t_e)	h/a	1800
Layer thickness (L_{dust})	cm	0.01
Dust density (ρ)	g/cm³	1.5
Dilution factor (f_d)	[-]	1
Concentration factor (f_c)	[-]	2
Decay time before scenario (t_1)	d	0
Decay time during scenario (t_2)	d	0
Dose rate coefficient ($\dot{e}_{skin}$)	(μSv/h)/(Bq/cm²)	depending on radionuclide

The parameter values defined are in total quite conservative. Therefore, the estimation of the skin dose has to be seen as a low probability scenario. The resulting dose therefore could be converted into an effective dose with the skin weighting factor of 0.01 and the fraction of the total skin being exposed (choosing this fraction as 0.1 would correspond to an exposure of about 2000 cm^2, approximately equivalent to the forearms and hands). The resulting effective dose could then be compared to the 1 mSv/a dose criterion.

However, this would not yield a compliance with the skin dose limit of 50 mSv/a, corresponding only to an effective dose of 0.05 mSv/a with an assumption of an uncovered skin area of 2000 cm2. Therefore, it is necessary to use the BSS dose limit for the skin of 50 mSv/a as the criterion for the assessment of the skin dose. This limit compared to the equivalenty dose of the exposed skin area (for which size no assumptions are required) is given by equation 15.

4.4. FLUIDS

Liquids of concern for exclusion generally carry radionuclides in a water-borne or organic-liquid-borne form. Radionuclides can be in the form of suspended solids or dissolved in solution from solids, liquids or gases. Typically, liquids that are candidates for exclusion from the BSS, as liquids, can be considered on the same basis as solids for the external exposure pathway. However, ingestion and inhalation exposures require consideration of likely mechanisms of intake, for example, vaporization, drinking, etc. These mechanisms apply, in turn, to the physical-chemical properties of the specific liquid and the processes commonly associated with it. Processes that tend to concentrate the small concentrations are, for example, water processing or incineration and recycle of organic liquids. These processes can lead to concentration exceeding the exclusion level's in filters, sludges, resins, residues, ashes, and combustion gases. Finally, the volume of liquids is an unstable quantity, strongly depending on the ambient physical conditions, especially temperature. In particular, liquids evaporate and concentrate as the temperature rises. Therefore, it is necessary to adopt exclusion levels which cannot be considered as inappropriate when the ambient physical conditions are modified. For this reason, the following is recommended:

- for pure liquids, in the case the radionuclide is part of the molecule of the liquid, the exclusion level applies to the liquid as such.
- for dissolved radionuclides, i.e., in case of solutions, the exclusion level applies to the solid residue after evaporation of the liquid or, at least, to the best concentrate of the solution.

4.5. GASES

Calculations were not undertaken explicitly for gases. However, scenarios representing exposure from gas cylinders were taken into account in deriving the exemption concentrations for Schedule I in the BSS [2]. These calculations took account of exposure from a limited volume of gas whereas exposure from larger quantities of gas would, in principle, occur during transport or storage of gas cylinders. These exposures were taken into account in establishing exempt levels for purposes of the Transport Regulations [16] and it was decided to adopt the Schedule I values of the BSS [2] into the Transport Regulations [16]. Therefore it was considered appropriate to use the Schedule I values for exclusion levels.

5. EXCLUSION LEVELS FOR NATURALLY OCCURRING RADIONUCLIDES

The objective in defining material that contains naturally occurring radioactive substances that should be regulated is to identify that material of significant radiological risk where regulation can achieve real improvements in protection. At the same time, the number of materials involved should not be so great as to make regulation essentially unmanageable. The application of a dose criterion of 10 μSv/a is not practical. In selecting levels for material that contains NORM, a major issue is that high levels that would exclude the majority of natural material in the environment would also allow a number of situations such as release of phosphate slags to be excluded without further considerations. Conversely, selecting a low value would trigger an unnecessary application of the BSS [2]. Therefore, the levels should be derived from consideration of the world-wide distribution of concentrations of naturally occurring radionuclides.

In considering exclusion levels for naturally occurring radionuclides the intention is to exclude from regulation virtually all soils, but not exclude from regulation ores, mineral sands, industrial residues and wastes which are recognized as having significant activity considerations.

Tables XI present data from UNSCEAR for concentrations of naturally occurring radionuclides in normal soil material. The values for ^{238}U and ^{232}Th are for 'head of chain' assuming that daughters are in equilibrium.

TABLE XI: NATURAL RADIONUCLIDES IN SOIL [8]

Region/Country	Population in 1996 (10^6)	Concentration in soil (Bq/kg)							
		^{40}K		^{238}U		^{226}Ra		^{232}Th	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range
Africa									
Algeria	28.78	370	66-1,150	30	2-110	50	5-180	25	2-140
Egypt	63.27	320	29-650	37	6-120	17	5-64	18	2-96
North America									
Costa Rica	3.50	140	6-380	46	11-130	46	11-130	11	1-42
United States [M7]	269.4	370	100-700	35	4-140	40	8-160	35	4-130
South America									
Argentina	35.22	650	540-750						
East Asia									
Bangladesh	120.1	350	130-610			34	21-43		
China [P16,Z5]	123.2	440	9-1,800	33	2-690	32	2-440	41	1-360
- Hong Kong SAR [W12]	6.19	530	80-1,100	84	25-130	59	20-110	95	16-200
India	944.6	400	38-760	29	7-81	29	7-81	64	14-160
Japan [M5	125.4	310	15-990	29	2-59	33	6-98	28	2-88
Kazakhstan	16.82	300	100-1,200	37	12-120	35	12-120	60	10-220
Korea, Rep. of	45.31	670	17-1,500						
Malaysia	20.58	310	170-430	66	49-86	67	38-94	82	63-110
Thailand	58.70	230	7-712	114	3-370	48	11-78	51	7-120
West Asia									
Armenia	3.64	360	310-420	46	20-78	51	32-77	30	29-60
Iran (Islamic Rep. of)	69.98	640	250-980			28	8-55	22	5-42
Syrian Arab Republic	14.57	270	87-780	23	10-64	20	13-32	20	10-32
North Europe									
Denmark	5.24	460	240-610			17	9-29	19	8-30
Estonia	1.47	510	140-1,120			35	6-310	27	5-59
Lithuania	3.73	600	350-850	16	3-30			25	9-46
Norway	4.35	850		50		50		45	
Sweden	8.82	780	560-1,150			42	12-170	42	14-94
West Europe									
Belgium	10.16	380	70-900			26	5-50	27	5-50
Germany	81.92		40-1,340		11-330		5-200		7-134
Ireland [M6]	3.55	350	40-800	37	8-120	60	10-200	26	3-60
Luxembourg	0.41	620	80-1,800			35	6-52	50	7-70
Netherlands [K2]	15.58		120-730		5-53	23	6-63		8-77
Switzerland	7.22	370	40-1,000	40	10-150	40	10-900	25	4-70
United Kingdom [B2]	58.14		0-3,200		2-330	37			1-180
East Europe									
Bulgaria	8.47	400	40-800	40	8-190	45	12-210	30	7-160
Hungary	10.05	370	79-570	29	12-66	33	14-76	28	12-45
Poland [K2]	38.60	410	110-970	26	5-120	26	5-120	21	4-77
Romania [K2]	22.66	490	250-1,100	32	8-60	32	8-60	38	11-75
Russian Federation	148.1	520	100-1,400	19	0-67	27	1-76	30	2-79
Slovakia	5.35	520	200-1,380	32	15-130	32	12-120	38	12-80
South Europe									
Albania	3.40	360	15-1,115	23	6-96			24	4-160
Croatia	4.50	490	140-710	110	83-180	54	21-77	45	12-65
Cyprus	0.76	140	0-670			17	0-120		
Greece	10.49	360	12-1,570	25	1-240	25	8-65	21	1-190
Portugal	9.81	840	220-1,230	49	26-82	44	2-210	51	22-100
Slovenia	1.92	370	15-1,410			41	6-250	35	2-90
Spain	39.67	470	25-1,650			32		33	2-210
Median		400	140-850	35	16-110	35	17-60	30	11-64
Population-weighted average		420		33		32		45	

Table XII shows typical activity concentrations in various ores and mineral sands that are used in industrial processes.

TABLE XII: ACTIVITY CONCENTRATIONS IN ORES AND MINERAL SANDS IN (Bq/Kg)

Ore/mineral sand	^{238}U	^{226}Ra	^{232}Th	^{40}K
Phosphate ore	30-5000	30-5000	25-2000	3-200
Monazite sand	370		1800	160
Monazite	6000-40000		8000-900000	
Bastnaesite			400	
Xenotime	3500-500000		180000	
Thorianite			2500000-5500000	
Tin ores	1000		300	
Pyrochlore	10000		80000	
Titanium ores	70-9000		70-9000	
Ilmenite	2000		1000	
Zircon sands	10000	3000-4000	10000	
Bauxite	400-600		400-600	
Coal	soil concentrations typically			
Iron ore	15			

Residues from industrial processes may have elevated levels of natural radionuclides. Phosphogypsum, a by-product from phosphate rock processing can have activity concentrations of ^{226}Ra up to 3 Bq/g. Residues from ore processing industries generally can have elevated levels of natural radionuclides but if these industries are subject to regulation because of the activity concentration in the feedstock, this will not be an issue. Examples are given in Table XIII.

Although not explicitly considered, elevated levels of isotopes of polonium and lead can also occur in residues from industrial processes. For example, tin rich residues from metal extraction processes can contain up to 10 Bq/g of ^{210}Pb and ^{210}Po. Filter dusts from metal processing can also contain elevated concentrations of ^{210}Po due to volatilization during heating. For example, concentrations of ^{210}Po of up to 200 Bq/g have been observed in collected fumes from tin smelting.

TABLE XIII: ACTIVITY CONCENTRATIONS IN INDUSTRIAL RESIDUES AND WASTES IN (Bq/Kg)

Material	^{238}U	^{226}Ra	^{232}Th	^{40}K
Tin slag		1000-4000	230-340	
Oil scale (old process)		up to 4000		
Oil scale (new process, scale inhibition techniques)		40-100		
Rare earth extraction byproducts		3000-450000		
T_iO_2 production residues from ilmenite		up to 400,000		
Monazite processing residues		up to 450,000		
Zircon processing				
residues		2000-50,000		
sludge		200-7000		
Copper slag		500-2000		
Aluminium processing sludge	260-540	150-330		
Fly ash	400			
Blast furnace slag from steel production	150		150	

Some products from processing of natural radioactive materials may in themselves be radioactive. Examples are given in Table XIV. The main issues appear to surround thorium-containing materials.

TABLE XIV: PRODUCTS FROM PROCESSING NATURAL MATERIALS IN (Bq/Kg)

	^{238}U	^{226}Ra	^{232}Th	^{40}K
Phosphate fertilisers	300-3000	200-1000		Up to 6000
Thorium				
Thoriated welding electrodes			up to ~100,000	
Special alloys (jet engines)			35,000	
Gas mantles			500,000	
Thoriated glass			200,000	
Titanium oxide pigment			30,000	
Construction materials containing fly-ash		70-170	70-170	

Unmodified concentrations of radionuclides in most raw materials are deemed to be excluded from the Standards by the BSS [1]. In this Report, it has been taken to mean virtually all unmodified soils, but not ores or mineral sands that are recognized as having significant activity concentrations. Exclusion levels have been chosen as the optimum boundary between, on the one hand, the ubiquitous unmodified soil concentrations (Table XI) and, on the other hand, activity concentrations in ores, mineral sands, industrial residues and wastes (Tables XII, XIII, and XIV) is judged to be 0.5 Bq/g for naturally occurring radionuclides. The only exceptions are K-40 where the level is 5 Bq/g and U-235 where the level is 0.05 Bq/g based on the natural ratio between the two decay chains of U-238 and U-235.

It can be seen that these levels are around a factor of 10 higher than the population-weighted average activity concentrations in Table XI, and are therefore unlikely to result in an unwarranted regulatory burden. Scenario-based calculations done by the European Union demonstrate convergence with these numbers.

For indoor radon in air, the "action levels" established in the BSS [2], namely 1000 Bq/m^3 for work places and within the range of 200-600 Bq/m^3 for dwellings, shall apply.

6. EXCLUSION LEVELS

Table XV provides the exclusion levels for artificial and natural radionuclides.

TABLE XV. EXCLUSION LEVELS FOR RADIONUCLIDES

Radionuclide	Exclusion Level (Bq/g)	
H-3	100	
Be-7	10	
C-14	1	
F-18	10	*
Na-22	0.1	
Na-24	1	*
Si-31	1000	*
P-32	1000	
P-33	1000	
S-35	100	
Cl-36	1	
Cl-38	10	*
K-40	5	nat
K-42	100	
K-43	10	*
Ca-45	100	
Ca-47	10	
Sc-46	0.1	
Sc-47	100	
Sc-48	1	
V-48	1	
Cr-51	100	
Mn-51	10	*
Mn-52	1	
Mn-52m	10	*
Mn-53	100	
Mn-54	0.1	
Mn-56	10	*
Fe-52	10	*
Fe-55	1000	
Fe-59	1	
Co-55	10	*
Co-56	0.1	
Co-57	1	
Co-58	1	
Co-58m	10000	*
Co-60	0.1	
Co-60m	1000	*
Co-61	100	*
Co-62m	10	*
Ni-59	100	
Ni-63	100	
Ni-65	10	*
Cu-64	100	*
Zn-65	0.1	
Zn-69	1000	*
Zn-69m	10	*
Ga-72	10	*
Ge-71	10000	
As-73	1000	
As-74	10	*
As-76	10	*
As-77	1000	
Se-75	1	

Radionuclide	Exclusion Level (Bq/g)	
Br-82	1	
Rb-86	100	
Sr-85	1	
Sr-85m	100	*
Sr-87m	100	*
Sr-89	1000	
Sr-90	1	
Sr-91	10	*
Sr-92	10	*
Y-90	1000	
Y-91	100	
Y-91m	100	*
Y-92	100	*
Y-93	100	*
Zr-93	10	*
Zr-95	1	
Zr-97	10	*
Nb-93m	10	
Nb-94	0.1	
Nb-95	10	
Nb-97	10	*
Nb-98	10	*
Mo-90	10	*
Mo-93	10	
Mo-99	10	
Mo-101	10	*
Tc-96	1	
Tc-96m	1000	*
Tc-97	10	
Tc-97m	100	
Tc-99	1	
Tc-99m	100	*
Ru-97	10	
Ru-103	10	
Ru-105	10	*
Ru-106	0.1	
Rh-103m	10000	*
Rh-105	100	
Pd-103	1000	
Pd-109	100	
Ag-105	10	
Ag-110m	0.1	
Ag-111	100	
Cd-109	1	
Cd-115	10	
Cd-115m	100	
In-111	10	
In-113m	100	*
In-114m	10	
In-115m	100	*
Sn-113	1	
Sn-125	10	
Sb-122	10	
Sb-124	1	

Radionuclide	Exclusion Level (Bq/g)	
Sb-125	0.1	
Te-123m	1	
Te-125m	1000	
Te-127	1000	
Te-127m	10	
Te-129	100	*
Te-129m	100	
Te-131	100	*
Te-131m	10	
Te-132	1	
Te-133	10	*
Te-133m	10	*
Te-134	10	*
I-123	10	
I-125	1000	
I-126	10	
I-129	0.1	
I-130	10	*
I-131	10	
I-132	10	*
I-133	10	*
I-134	10	*
I-135	10	*
Cs-129	10	
Cs-131	1000	
Cs-132	10	
Cs-134	0.1	
Cs-134m	10	*
Cs-135	100	
Cs-136	1	
Cs-137	0.1	
Cs-138	10	*
Ba-131	10	
Ba-140	1	
La-140	1	
Ce-139	1	
Ce-141	100	
Ce-143	10	
Ce-144	10	
Pr-142	100	*
Pr-143	1000	
Nd-147	100	
Nd-149	100	*
Pm-147	1000	
Pm-149	1000	
Sm-151	10000	
Sm-153	100	
Eu-152	0.1	
Eu-152m	100	*
Eu-154	0.1	
Eu-155	1	
Gd-153	10	
Gd-159	100	*
Tb-160	1	

Radionuclide	Exclusion Level (Bq/g)	
Dy-165	1000	*
Dy-166	100	
Ho-166	100	
Er-169	1000	
Er-171	100	*
Tm-170	100	
Tm-171	1000	
Yb-175	100	
Lu-177	100	
Hf-181	10	
Ta-182	0.1	
W-181	10	
W-185	1000	
W-187	101000	
Re-186	1000	
Re-188	100	*
Os-185	1	
Os-191	100	
Os-191m	1000	*
Os-193	100	
Ir-190	1	
Ir-192	1	
Ir-194	100	*
Pt-191	10	
Pt-193m	1000	
Pt-197	1000	*
Pt-197m	100	*
Au-198	10	
Au-199	100	
Hg-197	100	
Hg-197m	100	
Hg-203	10	
Tl-200	10	
Tl-201	100	
Tl-202	10	
Tl-204	1	
Pb-203	10	
Pb-210	0.5	nat
Pb-212	0.5	*nat
Bi-206	1	
Bi-207	0.1	
Bi-210	0.5	nat
Bi-212	0.5	*nat
Po-203	10	*
Po-205	10	*
Po-207	10	*
Po-210	0.5	nat
At-211	1000	*
Ra-223	0.05	nat
Ra-224	0.5	nat
Ra-225	10	
Ra-226	0.5	nat
Ra-227	100	*
Ra-228	0.5	nat
Ac-227	0.05	nat
Ac-228	0.5	*nat
Th-226	1000	*

Radionuclide	Exclusion Level (Bq/g)	
Th-227	0.05	nat
Th-228	0.5	nat
Th-229	0.1	
Th-230	0.5	nat
Th-231	0.05	nat
Th-232	0.5	nat
Th-234	0.5	nat
Pa-230	10	
Pa-231	0.5	nat
Pa-233	10	
U-230	10	
U-231	100	
U-232	0.1	
U-233	10	
U-234	0.5	nat
U-235	0.05	nat
U-236	10	
U-237	100	
U-238	0.5	nat
U-239	100	*
U-240	100	*
Np-237	1	
Np-239	100	
Np-240	10	*
Pu-234	100	*
Pu-235	100	*
Pu-236	1	
Pu-237	100	
Pu-238	1	
Pu-239	1	
Pu-240	1	
Pu-241	100	
Pu-242	1	
Pu-243	1000	*
Pu-244	0.1	
Am-241	1	
Am-242	1000	*
Am-242m	1	
Am-243	1	
Cm-242	10	
Cm-243	1	
Cm-244	10	
Cm-245	1	
Cm-246	1	
Cm-247	0.1	
Cm-248	1	
Bk-249	100	
Cf-246	1000	
Cf-248	10	
Cf-249	0.1	
Cf-250	1	
Cf-251	1	
Cf-252	10	
Cf-253	100	
Cf-254	1	
Es-253	100	
Es-254	0.1	

Radionuclide	Exclusion Level (Bq/g)	
Es-254m	10	
Fm-254	10000	*
Fm-255	100	*

* indicates half life less than 1 day
nat means naturally occurring radionuclide

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APPENDIX I – WEIGHTING FACTORS

APPENDIX II – CALCULATIONS FOR REALISTIC AND LOW PROBABILITY SCENARIOS