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To cite this article before publication: Teun van Dillen et al 2018 J. Radiol. Prot. in press https://doi.org/10.1088/1361-6498/aacc0a

Manuscript version: Accepted Manuscript

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SUDOQU, a new dose-assessment methodology for radiological surface contamination

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Abstract

A new methodology has been developed for the assessment of the annual effective dose resulting from removable and fixed radiological surface contamination. It is entitled SUDOQU (SUrface DOse QUantification) and it can for instance be used to derive criteria for surface contamination related to the import of non-food consumer goods, containers and conveyances, e.g., limiting values and operational screening levels. SUDOQU imposes mass (activity)-balance equations based on radioactive decay, removal and deposition processes in indoor and outdoor environments. This leads to time-dependent contamination levels that may be of particular importance in exposure scenarios dealing with one or a few contaminated items only (usually public exposure scenarios, therefore referred to as the ‘consumer’ model). Exposure scenarios with a continuous flow of freshly contaminated goods also fall within the scope of the methodology (typically occupational exposure scenarios, thus referred to as the ‘worker model’).

In this paper we describe SUDOQU, its applications, and its current limitations. First, we delineate the contamination issue, present the assumptions and explain the concepts. We describe the relevant removal, transfer, and deposition processes, and derive equations for the time evolution of the radiological surface-, air- and skin-contamination levels. These are then input for the subsequent evaluation of the annual effective dose with possible contributions from external gamma radiation, inhalation, secondary ingestion (indirect, from hand to mouth), skin contamination, direct ingestion and skin-contact exposure. The limiting effective surface dose is introduced for issues involving the conservatism of dose calculations.

SUDOQU can be used by radiation-protection scientists/experts and policy makers in the field of e.g. emergency preparedness, trade and transport, exemption and clearance, waste management, and nuclear facilities. Several practical examples are worked out demonstrating the potential applications of the methodology.

Supplementary material for this paper is available online

Keywords: surface contamination, radiological, dose assessment, methodology, mass-balance
Article highlights

SUDOQU:

- is a new dose-assessment methodology for radiological surface contamination, both fixed and removable
- explicitly takes account of removal and deposition processes using a mass-balance approach
- deals with public and occupational exposure scenarios for indoor and outdoor environments involving the exposure either to a single, contaminated item throughout time or to a continuous flow of freshly contaminated items
- considers the conservatism of dose evaluations by use of the Limiting Effective Surface Dose
- can be used to derive criteria (limiting values, screening levels) for radiological surface contamination
1. Introduction

1.1 The need for a new surface-contamination model

In 2012, the Dutch National Institute for Public Health and the Environment (RIVM) initiated a project with the aim to develop criteria for the import of non-food (consumer) goods, containers and conveyances with radiological surface contamination as a result of e.g. deposition of atmospherically released radionuclides during a distant nuclear accident like the one in Fukushima (Japan) in 2011. The current absence of such criteria usually forces one to fall back on the internationally harmonized contamination standards laid down in the Transport Regulations of the International Atomic Energy Agency (IAEA 2012a). However, the problem is that these standards, dating back to the early 1960’s (IAEA 1961a; 1961b, pp 79-82), are in principle only applicable to the safe transport of radioactive material. These specific regulations may not guarantee an optimized level of radiation protection when dealing with imported, surface-contaminated goods and items. The Dutch competent authority, the Authority for Nuclear Safety and Radiation Protection (ANVS), commissioned RIVM to develop surface-contamination criteria that do assure protection in such exposure situations. This required a methodology that adequately assesses the effective dose from surface contamination.

First, several existing (often similar) models were considered. The RESRAD-BUILD 3.0 model, developed at Argonne National Laboratory (Yu et al 2000, 2003) with funding from the United States Department of Energy (U.S. DoE), can evaluate the dose from human activities in (surface-) contaminated buildings (Biwer et al 2002, Kamboj et al 2011). This is also the case for the building-occupancy scenario of the NUREG/CR-5512 methodology (Kennedy and Strenge 1992). Several other models focus on the reuse of equipment and the recycling of scrap after clearance from a nuclear facility (EC 1999, Cheng et al 2000, 2004, Anigstein et al 2003). In 2005, a basic model for removable surface contamination was published in IAEA-TECDOC-1449 (IAEA 2005). This work was performed within a Coordinated Research Project (CRP) - initiated by the IAEA in 2001 - with the aim to review the limits and controls prescribed by the IAEA ‘Regulations for the Safe Transport of Radioactive Material’ (IAEA 2012a). A similar study on removable surface-contamination limits for spent-fuel transportation casks was performed by Oak Ridge National Laboratory under sponsorship of the United States Nuclear Regulatory Commission (NRC) (Rawl et al 2004). This study adopted and slightly modified the basic IAEA-CRP model to calculate the effective dose for workers in handling, loading and transportation activities, as well as the doses to members of the public. Work of the CRP was followed up by Ogino and Hattori (2009), who adapted the CRP model to derive exemption levels for surface contamination. Each of these models was designed to target a specific contamination issue under specific modeling conditions. The basic IAEA-CRP model (IAEA 2005), for instance, aims at assessing the transportation activities without explicitly taking into account radioactive decay (note: radioactive progeny were considered). Other models do incorporate radioactive decay (and ingrowth of progeny) in dose assessments.

However, none of the existing models take proper account of the disappearance of activity by wipe-off and resuspension. This implies that, in the absence of radioactive decay, the level of surface contamination would be independent of time (in most models) despite the fact that surface activity is removed during the scenario. This is acceptable if one is frequently confronted with a new or fresh contamination, which typically occurs in occupational exposure scenarios. But, when dealing with the same object throughout the year, e.g., the reuse of cleared items from radiological or nuclear facilities, or the use of retail products contaminated after a nuclear accident, then account should be taken of removal and decay (and deposition). For this reason, a new methodology entitled SUDOQU (SUrface DOse QUantification) was developed. It was first introduced in Dillen (2015) and is fully described in this paper.

1.2 Description and aim of the SUDOQU methodology
The SUDOQU methodology considers a person using, handling or working with one or several surface-contaminated products or objects in an indoor or outdoor environment. This person may either be a worker (radiological or non-radiological) or a member of the public, e.g., a consumer using a contaminated product. Besides radioactive decay, the methodology explicitly considers removability of surface (and air) contamination by resuspension, wipe-off, deposition and room ventilation. This is done within a mass (or activity)-balance framework (see section 4), imposing an upper limit on the total activity. This results in surface and airborne contamination levels that become time-dependent not only because of radioactive decay. The mass-balance condition is expressed through a set of coupled ordinary differential equations for contamination levels, which can be solved analytically. Based on these levels, SUDOQU calculates the individual’s annual effective dose (μSv in a year) from the following pathways: (1) external gamma radiation from the object’s surface, (2) internal contamination by inhalation of airborne activity, (3) internal contamination by secondary ingestion of wiped-off activity (indirect ingestion via hands), (4) external radiation of the skin from transferred contamination (hands and face), (5) external radiation of the skin from direct contact with the contaminated object, and (6) direct ingestion of activity from the object (mouthing).

We introduce the concept of Limiting Effective Surface Dose (LESD) to target issues related to the conservatism of dose evaluations aimed at deriving criteria (limiting values) for surface contamination. Four hypothetical, limiting scenarios are defined for which the annual effective dose is calculated (see section 5.7). The maximum value may offer the level of conservatism that is required. Limiting values can be accompanied by screening levels for the ambient dose rate, which follows from the methodology as well.

SUDOQU was originally developed to derive surface-contamination criteria for the import of non-food consumer goods, containers and conveyances after distant nuclear accidents (Dillen 2015). Its versatility and flexibility enables dose assessments in a broader range of contamination situations, such as emergency preparedness, trade and transport, clearance and exemption, waste management and nuclear facilities. For example, in a recent pilot project with RIVM, Bel V (subsidiary of the Belgian Federal Agency for Nuclear Control, FANC) applied the SUDOQU methodology to determine the annual effective dose resulting from the reuse of surface-contaminated objects released from a nuclear facility (Russo et al. 2018a, 2018b). SUDOQU can also be a useful tool for risk assessments after radiological incidents or accidents involving surface contamination.

For an overview and brief description of the concepts of the SUDOQU methodology (without mathematical details), we refer to Dillen (2015).

1.3 Organization of the paper

In section 2 we describe the various types of surface contamination considered by SUDOQU, delineate the contamination problem and describe the general assumptions. Section 3 deals with the specific assumptions and ingredients that underlie the approach of the methodology. In section 4, mass (activity)-balance equations governing the time dependence of the surface and airborne contamination levels in indoor and outdoor environments, are derived and solved. These solutions form the basis of the effective dose calculations in section 5, with contributions from external gamma radiation, inhalation, secondary ingestion, skin contamination and several additional pathways (skin-object contact/direct ingestion). In this section we also discuss conservatism in dose evaluations and the concept of Limiting Effective Surface Dose. In section 6 example applications are worked out for Cs-137+, I-131, Co-60, Sr-90+ and Am-241. Section 7 gives some closing remarks and an outlook on further research. Several underlying, theoretical topics are addressed in the Appendices (A-D). In the supplementary material we summarize the main, analytical equations used in the SUDOQU methodology. To perform dose evaluations in accordance with SUDOQU, these equations can be implemented in a numerical computer/software code or mathematical platform.

2. Description and delineation of the radiological surface contamination problem

2.1. Radiological surface contamination
Surface contamination can be defined as the presence of radionuclides in or on a well-defined, solid surface of an object (houses, buildings and ground surface included). It arises from the physical or chemical transfer of radioactive materials onto the surface, for instance by deposition of airborne nuclides during a nuclear accident (e.g., the contamination of freight containers during the Fukushima nuclear accident) or by the spillage of a radioactive substance or solution (IAEA 1970). The level of contamination, in units of Bq/cm$^2$, is defined as the areal activity concentration, i.e., the amount of activity (Bq) per unit area (cm$^2$), which may vary over the object’s area of contamination $A_{cont}$. We discriminate between removable (loose, non-fixed) surface contamination, which is defined as one that can be completely removed by non-destructive means, e.g. by repetitively touching or wiping the surface of the object (ISO-7503 2016), and fixed surface contamination, which cannot be removed or transferred in this way due to adsorption (surface adherence). A wipe or smear test may be conducted to determine the removable surface contamination (Frame and Abelquist 1999). In this context, the wiping efficiency or removal factor $F$ plays an important role, and is defined in the international standard ISO-7503 (1988, 2016) as the ‘ratio of the activity of the radionuclides removed from the surface by one wipe sample ($q_1$ in Bq) to the activity of the radionuclides of the removable surface contamination prior to this sampling ($Q_{rem,tot}$ in Bq), i.e.,

$$F = q_1/Q_{rem,tot},$$

in which $Q_{rem,tot}$ can be determined by conducting repetitive smears (on the same, wiped area) and by adding the removed activity $q_j$ (Bq) of each smear $j$:

$$Q_{rem,tot} = \sum_{j=1}^{\infty} q_j.$$ 

Theoretically, the summation in equation (2) is over an infinitely large number of smears, but practically a large number will usually suffice. If one performs only a single smear sample, the total removable activity can be estimated by $F^{-1}q_1$ from equation (1). If the value of $F$ is not known and has not been determined experimentally, a conservative value of 0.1 should be used according to the ISO-7503 (1988, 2016) standard, by which $Q_{rem,tot}$ would be estimated as $10\times q_1$. The removable surface contamination (Bq cm$^2$) is then found by dividing $Q_{rem,tot}$ by the area wiped in the smear test. Note that, in this paper, symbol $Q$ is used to signify total activity, whereas symbol $C$ is used to signify activity concentration.

Generally, the total surface contamination consists of a removable and a fixed component. The removable fraction, $f_{rem}$, is here defined as the ratio of the total removable contamination and the total (fixed + removable) contamination. For a total surface contamination $C_{surf,tot}$, the removable component is thus $f_{rem}C_{surf,tot}$ and the fixed component is $(1-f_{rem})C_{surf,tot}$. The total surface contamination can be determined directly by measurements using surface-contamination monitors. Note that part of the removable contamination may become fixed to the surface in time, either as the result of physical or chemical processes. The opposite also occurs, in which fixed contamination becomes removable (‘sweating’).

Many quantities and parameters in this paper are nuclide dependent. In such cases, index $i$ is used as subscript to indicate the type of nuclide. The object’s removable surface contamination for nuclide $i$ will be indicated by $C_{surf,i}$, or alternatively by $f_{rem,i}C_{surf,tot,i}$.

### 2.2. Delineation of the surface-contamination problem
We here delineate the SUDOQU surface-contamination issue with some simplifications and general assumptions. This is done to make the methodology analytically tractable with simple solutions enabling its use in dose assessments and in the derivation of limiting values and screening levels. The following situational assumptions are made:

**Completely removable:** Surface contamination is completely removable by resuspension and wipe-off, i.e., \( f_{\text{rem},i} = 1 \) \( (C_{\text{surf},i} = C_{\text{surf},i,\text{tot}}) \). Hence, it may decrease to 0 Bq.cm\(^{-2}\) with time as a result of the object’s use, even in the case of long-lived nuclides. However, contamination with a fixed component is also briefly described in sections 4.3 (case 3) and 4.5.

**Homogeneous:** The surface contamination is and remains (on average) homogeneous over the contaminated area, i.e., there are no ‘hot spots’. Its level will decrease over time \( t \) (h) by several removal mechanisms, but at each moment, we assume no spatial variation over the contaminated area. For nuclide \( i \), the object’s (average) removable surface contamination, \( C_{\text{surf},i}(t) \), then follows from the ratio of the removable activity still present on the surface at time \( t \), \( Q_{\text{surf},i}(t) \) (Bq), and the contaminated area, \( A_{\text{cont}} \) (cm\(^2\)), on which this activity resides:

\[
C_{\text{surf},i}(r;t) = C_{\text{surf},i}(t) = \frac{Q_{\text{surf},i}(t)}{A_{\text{cont}}} = \lambda_{r,i} N_{\text{surf},i}(t) \times 2.78 \times 10^{-4},
\]

with vector \( r \) indicating the position on the surface, \( \lambda_{r,i} \) (h\(^{-1}\)) the physical decay (rate) constant, and \( N_{\text{surf},i}(t) \) the total number of non-fixed, unstable atoms of type \( i \) present on the surface. Since all removal constants in SUDOQU are expressed in units of h\(^{-1}\) (section 2.3), the factor \( 1/3600 = 2.78 \times 10^{-4} \) h.s\(^{-1}\) in equation (3) is required for the correct conversion to Bq. The area of contamination \( (A_{\text{cont}}) \) is treated as a time-independent quantity, indicating that we have not taken into account a spread of the contamination.

**Thin layer:** The layer of surface contamination is sufficiently thin to prevent any radiation self-shielding effect. Moreover, no additional shielding effects are involved either. In some scenarios one may wish to model the impact of these effects explicitly, and therefore optional shielding or attenuation factors can be provided in the calculations.

**Only one user:** The methodology is conservative in several aspects to prevent underestimating the resulting individual effective dose. For instance, we assume that the object is only used by the person for whom the effective dose is calculated. Use of the object by others is disregarded, since it would decrease the level of contamination faster and thereby result in a smaller effective dose for the person under consideration. In addition, surface removal processes other than radioactive decay, wipe-off and resuspension are not taken into account, with one exception: direct ingestion of activity from the object (section 5.5). This process is to be regarded when considering, for instance, children’s toys for which direct ingestion (mouthing) is a realistic and possibly dominant exposure pathway.

**Exposure only during actual use:** Only exposure during the actual use of the object is considered. This implies that, when a person stops using the object, external-radiation exposure is also discontinued, as well as exposure to and inhalation of the airborne activity (see also section 3.1).

**Only regular use, no processing:** Exposure scenarios for both workers and members of the public only consider the use or reuse of surface-contaminated objects, items or products. Special exposure scenarios involving the processing or incineration of surface-contaminated materials have not been implemented.

### 2.3. Unit convention

In this paper we adhere to the following units: activity in Bq \( (i.e., \text{s}^{-1}) \), time in h, length in cm, area in cm\(^2\), volume in cm\(^3\), removal constants (decay constant, resuspension rate, wipe-off loss rate, ventilation rate, deposition loss rate) and wipe-off and ingestion frequencies/rates in h\(^{-1}\), and
deposition velocity in cm.h\(^{-1}\) (exception: the wind speed is expressed in m.s\(^{-1}\)). The surface contamination level is expressed in Bq.cm\(^{-2}\) while the air-activity concentration is expressed in Bq.m\(^{-3}\). The resuspension factor is expressed in m\(^{-1}\), the respiratory or breathing rate in m\(^3\).h\(^{-1}\) and each contribution of an exposure pathway to the annual effective dose is expressed in \(\mu\)Sv.y\(^{-1}\). Note that, in this paper, \(\mu\)Sv.y\(^{-1}\) refers to the dose accumulated in one year (annual dose, \(\mu\)Sv in a year) and not to a dose rate. As dose conversion factors are often expressed in Sv, a conversion of \(10^6\) \(\mu\)Sv.Sv\(^{-1}\) is therefore applied.

3. SUDOQU: Ingredients and underlying model assumptions

In section 2 we formulated the general simplifications and assumptions that delineate the surface-contamination problem. In this section we focus on the model assumptions and ingredients underlying our methodology to solve the problem.

We consider the removal of surface activity in a mass (activity)-balance framework imposing a limit on the total activity to which one is exposed. This is important if, for instance, a consumer would buy a surface-contaminated product and use it throughout the year. The activity that is eventually removed by wipe-off and resuspension together with the activity that has disappeared by radioactive decay can obviously not exceed the total activity initially present on the product’s surface. This is explicitly captured by the mass-balance equations. Adherence to the mass-balance approach is represented by a parameter \(\delta\), which can have the value 0 or 1. For \(\delta = 1\), the mass-balance approach is followed which we here refer to as the ‘RIVM-SUDOQU’ model or the ‘consumer’ model. By setting \(\delta\) to 0, removal, decay and deposition processes are ignored in the governing equation for surface contamination, as in the basic model from IAEA (2005). For the aforementioned reasons (section 1.1 and Dillen (2015)), this is referred to as the ‘IAEA-CRP’ model or the ‘worker model’. Even though dose calculations will generally use \(\delta = 0\) for workers and \(\delta = 1\) for members of the public (consumers), there may of course be exceptions.

We only consider parent nuclide \(i\). Contributions to the effective dose from the possible ingrowth of daughter nuclides are accounted for via modification of the Dose Conversion (DC) factors of the parent. This approach is also employed by the Article 31 Group of Experts (Euratom Treaty) and the IAEA in dose calculations underlying derived exemption and clearance levels for the activity concentrations (EC 2000, IAEA 2004).

Many practical aspects related to the measurement of fixed or removable surface contamination, e.g., to monitor for compliance with exemption or clearance levels (IAEA 1970, 2012b), are not described in this paper. We acknowledge that these aspects are of vital importance and need also to be taken into consideration for SUDOQU-based criteria to become even more applicable and practical to a range of environments.

3.1. Object use, duty factor and the continuous model description

We consider an object homogeneously contaminated with radionuclides over an area \(A_{cont}\), which may be smaller than its total surface area. Object or product use here refers to use by a person who is in the vicinity of the object while occasionally touching it during use, involving contact of the hands, mouth or feet with the object. This is not necessarily a continuous process, but occurs at distinct times at random places of the object during its use and leads to a decrease in surface contamination. We consider the product use in a certain period of time \(\Delta T_{use}\) (h), the duration of the scenario, which is by default set at 8760 h (one year). The cumulative duration of actual product use within \(\Delta T_{tot}\) is indicated by \(\Delta T_{use}\) (h, but also written as h.y\(^{-1}\) if \(\Delta T_{tot}\) is one year). Product use for 3 hours per day, 5 days per week and 30 weeks per year would add up to \(\Delta T_{use} = 450\) h.y\(^{-1}\). Such discontinuous exposure profiles involving random contact events cannot be described in such detail by simple
analytical models and would require computational, numerical treatment. In SUDOQU, however, the
discrete and random nature of product use is replaced by a continuous one in which product use and
related contact events are assumed to be spread out uniformly over $\Delta T_{\text{tot}}$. This implies that within any
arbitrary time interval $\Delta t$ (no matter when and no matter how small), the object is used for only a
fraction of this time interval, $f_{\text{use}} \Delta t$, with $f_{\text{use}}$ the duty factor, with values between 0 and 1, defined as:

$$f_{\text{use}} = \frac{\Delta T_{\text{use}}}{\Delta T_{\text{tot}}}.$$  (4)

The concept of spreading out the object use can also be viewed as a continuous use over the entire
scenario duration $\Delta T_{\text{tot}}$, but with adapted, time-averaged values of the resuspension and wipe-off rates
as will be shown through sections 3.3 to 3.5.

The duty factor is a crucial parameter in the calculation of both the time-dependent contamination
levels and the effective dose contributions of the various exposure pathways. For the example above,
the value of $f_{\text{use}}$ is 0.051. The number of times that the object is touched (i.e., the number of contact
events) during its use depends, among other things, on the wipe-off frequency as explained in section
3.6. The default value of $\Delta T_{\text{use}}$ in SUDOQU is 2000 h.y$^{-1}$, with $f_{\text{use}} = 0.228$.

As discussed in section 2.2 (fifth assumption), the annual duration of object use, $\Delta T_{\text{use}} = f_{\text{use}} \Delta T_{\text{tot}}$, also determines the duration of direct exposure to external radiation from the object’s contaminated
surface, $\Delta T_{\text{exp}}$ (h.y$^{-1}$). If, in addition to object use, a person is also in close vicinity of the object while
not using it, the duration of exposure to external radiation extends to $\Delta T_{\text{exp}} = f_{\text{exp}} \Delta T_{\text{tot}}$, with

$$\frac{f_{\text{exp}}}{f_{\text{use}}} = \frac{\Delta T_{\text{exp}}}{\Delta T_{\text{use}}} \geq 1.$$  (5)

Since most dose assessments can be carried out without this extended period, we continue the
description of SUDOQU using $f_{\text{exp}} = f_{\text{use}}$, as in the example calculation in Dillen (2015). The same
holds for exposure to and inhalation of contaminated air, for which the annual exposure duration
$\Delta T_{\text{inh}}$ (h.y$^{-1}$) is set equal to $\Delta T_{\text{use}}$.

If the exposure scenario drastically changes or repeats itself within one year, one may consider
splitting up the year in smaller time intervals $\Delta T_{\text{tot}}$ (note: $f_{\text{use}}$ may differ per interval). After
performing a separate dose calculation for each interval, they can be summed to yield the annual dose.

3.2. Surface contamination in the continuous model

The removable surface-contamination level for nuclide $i$ is defined by equation (3) and has an initial
value of $C_{\text{surf,}i}(0) = C_{0,i}$ (Bq.cm$^{-2}$) at the start of the exposure scenario, with $Q_{\text{surf,}i}(0) = C_{0,i} \Lambda_{\text{cont}}$, the object’s initial, removable surface activity (Bq). Hence, no delay time is considered between the
measurement of the surface-contamination level and the start of the exposure scenario. Due to decay
and removal processes, this level gradually decreases with time $t$, i.e., $C_{\text{surf,}i}(t) / C_{0,i} \leq 1$ for $t \geq 0$.

Both fixed and removable surface contamination continuously decrease by radioactive decay, a
homogeneous Poisson process described by its physical decay (rate) constant $\lambda_{\text{e,}i}$ (h$^{-1}$). In case of
removable contamination, activity can also be removed by processes of resuspension (section 3.4) and
wipe-off (sections 3.5 and 3.6). Finally, part of the resuspended, airborne activity may deposit back
onto the object’s contaminated surface thereby affecting the level of contamination as well (section
3.7). Hence, $C_{\text{surf,}i}(t)$ can be viewed as the net, overall evolution (decrease) of the removable surface
contamination resulting from decay, removal and deposition processes in the context of the uniform or
continuous model structure (section 3.1). It provides the input for the evaluation of the annual effective
dose contributions from external-radiation exposure from the object’s surface, ingestion and skin
exposure. As will be shown in section 5, the relevant quantity for these dose contributions is the Time-
Integrated Surface Contamination (TISC, in Bq.h.cm\(^{-2}\)) experienced during product use, defined by:

\[ TISC_{\text{use},j}(t) = \int_{0}^{t} C_{\text{surf},j}(t')dt', \quad (6) \]

with \(0 \leq t \leq \Delta T_{\text{tot}}\) and with the annual contributions being proportional to \(TISC_{\text{use},j}(\Delta T_{\text{tot}})\).

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### 3.3. Air contamination in the continuous model

Resuspension of removable surface activity leads to a contamination of the surrounding air, which can
(1) be inhaled and thus lead to a committed effective dose from internal contamination and (2) be the
source of an effective dose from external radiation (submersion). As discussed in sections 2.2 (fifth
assumption) and 3.1, we assume that exposure to contaminated air only occurs during actual use of the
object. For the indoor exposure environment we also assume that all resuspended, airborne activity is
instantaneously well-mixed within the entire room’s volume (Shapiro 1970, IAEA 2005, section
6.4.4). The assumed homogenous air-activity concentration may lead to an underestimation of these
dose contributions, since the local contamination level at the position of the receptor could be
considerably higher. An explicit correction for this underestimation is provided in section 5.2 dealing
with the inhalation dose assessment.

As described in section 3.1, use of the object (and thus exposure) is spread out uniformly over the
entire year. The resulting model can then be visualized in two ways. This is illustrated in figure 1 for
exposure to airborne activity in an arbitrary, small time interval \([t, t+dt]\) within \(\Delta T_{\text{tot}}\).

**First interpretation:** We could divide the infinitesimally small time-interval in two separate phases,
one in which the object is used in \([t, t+f_{\text{use}}dt]\), and one in which the object is not used in
\([t+f_{\text{use}}dt, t+dt]\). In the first phase, the user experiences an increased air concentration \(\tilde{C}_{\text{air},j}(t)\)
(Bq.m\(^{-3}\)) caused by the induced, elevated resuspension rate (section 3.4). Any transient buildup and
saturation behavior of the air concentration in this phase is simply ignored, implying that one is
immediately exposed to its then maximum possible value under the prevailing ambient conditions.
This value is proportional to the product of the resuspension rate during use and the surface-contamination level (Shapiro 1970, equation 3, p 502). No air concentration (0 Bq.m$^{-3}$) is experienced in the second phase, after using the object. The concentration profile $\tilde{C}_{\text{air},i}(t)$, shown in figure 1 by the thick, solid line, is a quantity that represents the elevated air-contamination level experienced during the product-use phase around time $t$, its overall time evolution over $\Delta T_{\text{tot}}$ being determined by processes of radioactive decay, resuspension, room ventilation (indoors) or atmospheric dispersion (outdoors), and deposition.

**Second interpretation:** As object use and exposure are spread out uniformly over $\Delta T_{\text{tot}}$, it is more convenient to define a hypothetical air concentration $C_{\text{air},i}(t)$ (Bq.m$^{-3}$) to which one would be exposed continuously throughout the complete duration $\Delta T_{\text{tot}}$ of the scenario. In this alternative description, product use is considered to occur continuously with certain effective resuspension and wipe-off rates, which follow from a proper time-average: $\langle \xi \rangle$ and $\langle \lambda_{\text{wo}},i \rangle$ introduced in sections 3.4 and 3.5, respectively. The short time interval $[t, t + \Delta t]$ is therefore not divided into two phases as before, but is now considered as a single interval in which the ‘continuously experienced’ air concentration remains virtually constant, as indicated by the dashed profile in figure 1. Although being (nearly) constant within this short interval, $C_{\text{air},i}(t)$ evolves with time just like $\tilde{C}_{\text{air},i}(t)$ by decay and removal processes, as also shown in figure 1 (i.e., $C_{\text{air},i}$ varies between time intervals).

The relation between $\tilde{C}_{\text{air},i}$ and $C_{\text{air},i}$ is found by considering the Time-Integrated Air Concentration, $TIAC_{\text{use},i}$ (Bq.h.m$^{-3}$), experienced during product use, since this is the relevant quantity for dose calculations (inhalation, submersion). The shaded areas in figure 1 represent the contributions of the short time interval to $TIAC_{\text{use},i}$ and should be equal: $\int C_{\text{air},i}(t')dt' = C_{\text{air},i}(t)$. From this it follows that

$$C_{\text{air},i}(t) = f_{\text{use}}\tilde{C}_{\text{air},i}(t).$$

(7)

Similar to equation (6), and by use of equation (7), the dose assessment in section 5 will be based on:

$$TIAC_{\text{use},i}(t) = f_{\text{use}} \int_{0}^{t} \tilde{C}_{\text{air},i}(t')dt' = \int C_{\text{air},i}(t')dt',$$

(8)

with the annual contributions being proportional to $TIAC_{\text{use},i}(\Delta T_{\text{tot}})$.

**3.4. Resuspension**

Air movement around the object’s surface and externally applied mechanical stresses can remove activity from the surface. This process, in which (deposited) radionuclides, attached to fine particles, become airborne, is called particle resuspension (Healy 1980, Sehmel 1980, Kim et al 2010). We assume that the amount of resuspended activity per unit surface area and per unit time, the resuspension flux $RFL_i$ (Bq.cm$^{-2}$.h$^{-1}$), is directly proportional to the removable surface contamination $C_{\text{surf},i}$. The constant of proportionality is the instantaneous resuspension rate $\xi_i$ (h$^{-1}$), the fraction of the surface contamination that becomes airborne per unit of time, defined as (Slinn 1976, 1978, Holländer and Garger 1996, Qian and Ferro 2008a, Kim et al 2010):

$$\xi_i = \frac{RFL_i}{C_{\text{surf},i}}.$$

(9)
Even though the instantaneous resuspension rate in Slinn (1976) explicitly refers to the removable surface contamination as in equation (9), experimental values of $\xi$ from literature may often be related to the total and initial surface contamination instead (Garland and Pomeroy 1994, Kim et al 2010). These differences and possible memory effects of the resuspension process (Holländer and Garger 1996) are ignored here for simplicity. Furthermore, equation (9) implies that all contamination that could eventually be wiped off the surface is in principle also available to resuspension.


a. the characteristics of the surface (e.g., chemical composition, roughness, moisture), the properties of the particulate contaminants (e.g., chemical composition, shape, size distribution) and their interactions (adherence properties);

b. the meteorological conditions (e.g., wind, rain) or the ambient indoor conditions (ventilation);

c. other external stresses that may drive the mass-transfer process, i.e., mechanical disturbance (e.g., the use of the object or walking on a contaminated surface).

The resuspension rate is difficult to determine experimentally and ranges over several orders of magnitude. Wind-induced rates in the outdoor environment typically vary between $10^{-9}$ h$^{-1}$ and $10^{-2}$ h$^{-1}$ (Sehmel 1980). In the indoor environment, Thatcher and Layton (1995) determined resuspension rates of $10^{-7}$ h$^{-1}$ to $10^{-1}$ h$^{-1}$ for sub-micron particles and $10^{-5}$ h$^{-1}$ to $10^{-3}$ h$^{-1}$ for supermicron particles in a situation in which four residents performed normal activities. The latter values are in good agreement with values estimated earlier by Healy (1971). Qian et al (2008b) also studied residential resuspension rates from human activities: walking on a carpeted floor resulted in a rate of $(1.4 \pm 0.6) \times 10^{-4}$ h$^{-1}$, whereas in a more detailed study, also addressing environmental factors, resuspension rates between $10^{-5}$ h$^{-1}$ to $10^{-2}$ h$^{-1}$ were found (Qian et al 2008a). As also mentioned in IAEA (2005), we emphasize that one has to be careful when selecting a value for $\xi$ from literature, since many experimental data (e.g., those reviewed and presented in Sehmel (1980)) refer to mechanically or wind-induced resuspension of soil or dust over open country or on roads, and are therefore not applicable to local resuspension from surfaces of objects or packages. In other words, literature values can only be used if the underlying scenarios and conditions exhibit a certain degree of correspondence.

In IAEA (2005) relating to the surfaces of e.g. transport packages, the resuspension rate was set at a constant, conservative value of $10^{-4}$ h$^{-1}$ for all nuclides (except tritium: $10^{-1}$ h$^{-1}$). The specified upper limit is presented in Muto et al (1982) and Kennedy et al (1981). For workers frequently dealing with fresh contaminations ($\delta = 0$, worker model, section 3), the resuspension rate may be assumed to attain a relatively high, time-independent value, since each time the resuspension mechanism starts over again with a new object. However, when dealing with the same object for a large(r) period of time ($\delta = 1$, consumer model), the time dependence of this rate should in principle be taken into account.

After all, it is not likely that resuspension continues at a high rate of $10^{-4}$ h$^{-1}$ throughout the year in which the object is used; the use of the object, which is in the first place a source of resuspension, may also change local (adherence) properties of the surface contamination. Because little is known on its exact, long-term time dependence under use, and to simplify the conceptual/mathematical treatment, SUDOQU replaces the time-dependent, instantaneous resuspension rate, $\xi(t)$, by $\langle \xi \rangle$, the time-average value over $\Delta T_{tot}$. The following expression for the average resuspension rate is derived in Appendix A:

$$\langle \xi \rangle \Delta T_{tot}^{-1} \int_0^{\Delta T_{tot}} \xi(t) dt = f_{use} \overline{\xi}_{use,i} + (1 - f_{use}) \overline{\xi}_{idle,i}$$

where $\overline{\xi}_{use,i}$ and $\overline{\xi}_{idle,i}$ are the mean values during object use and non-use, respectively. Since both $\overline{\xi}_{use,i}$ and $\overline{\xi}_{idle,i}$ are time-averaged quantities (Appendix A), they may have values much smaller than the (conservative) initial values at $t = 0$. 


Next, we assume that the use of the object is the main source of resuspension, implying that \( \bar{\xi}_{\text{use},i} \gg \bar{\xi}_{\text{idle},i} \). Then, by ignoring \( \bar{\xi}_{\text{idle},i} \), the average value of the resuspension rate in equation (10) reduces to:

\[
\langle \xi_i \rangle = f_{\text{use}} \bar{\xi}_{\text{use},i}.
\]  

(11)

There is an additional, important reason for ignoring the mean resuspension rate \( \bar{\xi}_{\text{idle},i} \) in the current analysis, even if it were to have a significant value. In the exposure situation that we are considering here (sections 3.1, 3.3 and figure 1), a person is not exposed to ionizing radiation from the contaminated surface or air during \( (1 - f_{\text{use}}) \Delta T_{\text{tot}} \) for which the average resuspension rate is \( \bar{\xi}_{\text{idle},i} \).

For the calculation of the continuously experienced air-activity concentration, \( C_{\text{air},i}(t) \), the value of \( \bar{\xi}_{\text{idle},i} \) must therefore be ignored. At the same time, one could argue that a significant value of \( \bar{\xi}_{\text{idle},i} \) should in principle be taken into account when regarding the time evolution of the surface contamination. By ignoring this contribution, the net, overall decrease of \( C_{\text{surf},i}(t) \) will be smaller, and thus more activity will be left over and available for exposure during object use in \( f_{\text{use}} \Delta T_{\text{tot}} \).

Since this results in a somewhat higher total effective dose (i.e., a more conservative approach), equation (11) is used by SUDOQU as the average resuspension rate for the calculation of both \( C_{\text{surf},i}(t) \) and \( C_{\text{air},i}(t) \). The value of input parameter \( \bar{\xi}_{\text{use},i} \) may depend on how the object is handled during its use, e.g., on the contact event rate (hands touching object). The default value of \( \bar{\xi}_{\text{use},i} \) is set at a conservative value of \( 10^{-4} \text{ h}^{-1} \), the same value as the one used in IAEA (2005) for transportation packages. This rate (corresponding to \( 3 \times 10^{-8} \text{ s}^{-1} \)) is well within the range of values reported in Biwer et al (2002, table 3.2) and Yu et al (2003, table J.8).

Some models for surface contamination make use of the so-called resuspension factor \( K \) \((\text{m}^{-1})\), which is defined as the ratio of the (continuously experienced) air concentration to the surface contamination:

\[
K = \frac{C_{\text{air},i}}{C_{\text{surf},i}} \cdot 10^{-4} = f_{\text{use}} \hat{K} \quad \text{with} \quad \hat{K} = \frac{C_{\text{air},i}}{C_{\text{surf},i}} \cdot 10^{-4},
\]

(12)

where \( \hat{K} \) is the resuspension factor during actual product use and where the factor \( 10^{-4} \) results from the conversion of cm\(^2\) to m\(^2\) associated with \( C_{\text{surf},i} \). The advantage of this quantity is that its value can be determined easily from experiments. However, as explained in IAEA (2005), it is only meaningful for the specific exposure situation under consideration. More specifically, in equilibrium, the resuspension factor not only depends on the resuspension rate, but also other (environmental) quantities that define the exposure scenario. For instance, for indoor exposures, \( K \) depends on the object’s contaminated area, the room’s volume, and the ventilation and deposition loss rates, as is shown in section 4. Like the IAEA-CRP model (IAEA 2005), SUDOQU therefore describes the resuspension process using the resuspension rate instead of the resuspension factor. However, we acknowledge that there may of course be exposure scenarios for which the direct use of the resuspension factor would be preferred, especially in outdoor exposure environments.

3.5. Process and kinetics of wipe-off

Wipe-off is the process by which radiological contamination of the object’s surface is transferred to the hands (or other parts of the skin), leading to a decrease in \( C_{\text{surf},i} \). The wipe-off process is described by the dimensionless transfer efficiency \( f_{\text{oth},i} \) (oth: ‘object-to-hand’). Like the resuspension
rate (section 3.4), its value depends on properties of the surface and of the particulate contaminant (with attached nuclides $i$), and on their interaction. It also depends on the force exerted on the surface by which the contaminant is removed and the conditions of the skin (dry, moist). We define the (instantaneous) transfer efficiency $f_{\text{oth},i}$ as the ratio of the maximum attained (homogeneous) surface-contamination level of the hands $C_{\text{surf},\text{hands},i}$ (Bq.cm$^{-2}$) after a single, complete wipe-off event to the removable surface contamination level of the object before this event, i.e.,

$$f_{\text{oth},i} = \frac{C_{\text{surf},\text{hands},i}}{C_{\text{surf},i}}.$$  \hfill (13)

Like the resuspension rate, the transfer efficiency can be a time-dependent quantity, $f_{\text{oth},i} = f_{\text{oth},i}(t)$, whose evolution may be affected by the use. When the object is used, part of the activity is wiped off at random spots of its surface by transfer to the hands (press contacts, smudges). The actual process of wipe off is a complicated process due to its probabilistic, discrete and non-homogeneous nature. However, in the continuous-model approach (section 3.1), we treat the average wipe-off process as deterministic, continuous and homogenous. During prolonged use comprising many wipe-off events, the stochastic, discrete events average out resulting in a net, overall decrease in $C_{\text{surf},i}$. Each wipe-off event results in a concomitant decrease in the average contamination level $C_{\text{surf},i}$.

After a single wipe-off event, the skin-contamination level of the hands is $C_{\text{surf},\text{hands},i}$, which is here also assumed to be homogeneous over a total skin area of $A_{\text{hands}}$ (cm$^2$). By use of equation (13), the activity then transferred to the hands reads $f_{\text{oth},i}C_{\text{surf},i}A_{\text{hands}}$, which has been removed from the object’s contaminated surface of area $A_{\text{cont}}$. Next, we introduce the wipe-off frequency, $\phi_{\text{use}}$ (h$^{-1}$), as the number of wipe-off events per unit time during use of the object (wipe-off event rate). The rate at which activity is removed from the surface (Bq.h$^{-1}$) then equals $f_{\text{oth},i}C_{\text{surf},i}A_{\text{hands}}\phi_{\text{use}}$, and the wipe-off removal flux $WOFL_i$ (Bq.cm$^{-2}$.h$^{-1}$), i.e., per unit of contaminated area, is given by $f_{\text{oth},i}C_{\text{surf},i}A_{\text{hands}}\phi_{\text{use}}A_{\text{cont}}$. Similar to the definition of the resuspension rate in equation (9), we can define the wipe-off loss rate $\lambda_{\text{wo},i}$ (h$^{-1}$) for nuclide $i$ as:

$$\lambda_{\text{wo},i} = \frac{WOFL_i}{C_{\text{surf},i}}.$$  \hfill (14)

Therefore, the wipe-off loss rate during object use attains a value of

$$\lambda_{\text{wo,use},i} = f_{\text{oth},i}\phi_{\text{use}} \left( \frac{A_{\text{hands}}}{A_{\text{cont}}} \right).$$  \hfill (15)

When the object is not used, the wipe-off frequency vanishes: $\lambda_{\text{wo,Idle},i} = 0$ h$^{-1}$. Following the same approach as that for resuspension (equations (10) and (11)), the time-averaged value of the wipe-off loss rate can be written as:

$$\langle \lambda_{\text{wo},i} \rangle = \frac{1}{\Delta T_{\text{tot}}} \int_{0}^{\Delta T_{\text{tot}}} \lambda_{\text{wo},i}(t)dt = f_{\text{use}}\bar{\lambda}_{\text{wo,use},i}+(1-f_{\text{use}})\bar{\lambda}_{\text{wo,Idle},i} = f_{\text{use}}\bar{\lambda}_{\text{wo,use},i}.$$

Substituting equation (15) into equation (16) then results in
\[ \lambda_{\text{wo},i} = f_{\text{use}} \bar{\phi}_{\text{wo,use},i} = f_{\text{use}} \bar{f}_{\text{oth},i} \bar{\phi}_{\text{use}} \left( \frac{A_{\text{hands}}}{A_{\text{cont}}} \right), \]  

(17)

where \( \bar{\phi}_{\text{wo,use},i} \), \( \bar{f}_{\text{oth},i} \) and \( \bar{\phi}_{\text{use}} \) are the average quantities during use of the object, similar to \( \bar{\lambda}_{\text{use}} \) for resuspension (section 3.4 and Appendix A). We here replaced the average of the product \( f_{\text{oth},i} \phi_{\text{use}} A_{\text{hands}} \) by the product of the averages \( \bar{f}_{\text{oth},i} \bar{\phi}_{\text{use}} A_{\text{hands}} \), under the assumption that these quantities are independent. Equation (17) is used to account for the wipe-off process in the time-dependent surface-contamination level (section 4). The quantities \( \bar{\phi}_{\text{use}} \) and \( \bar{f}_{\text{oth},i} \) will be discussed in section 3.6.

If wipe-off were to be the only removal process (no radioactive decay, resuspension, deposition), the object’s net, removable surface contamination would be modeled to decrease exponentially as (Appendix B):

\[ C_{\text{surf},i}(t) = C_{0,i} \exp \left[ -f_{\text{use}} \bar{f}_{\text{oth},i} \bar{\phi}_{\text{use}} \left( \frac{A_{\text{hands}}}{A_{\text{cont}}} \right) t \right], \]  

(18)

which is plotted in figure 2 (solid line) for \( C_{0,i} = 1.0 \text{ Bq cm}^{-2} \), \( f_{\text{use}} = 0.20 \) (somewhat smaller than the default value), \( \bar{f}_{\text{oth},i} = 0.10 \), \( \bar{\phi}_{\text{use}} = 0.25 \text{ h}^{-1} \), \( A_{\text{hands}} = 400 \text{ cm}^2 \) and \( A_{\text{cont}} = 1000 \text{ cm}^2 \). The straight, dashed line indicates the initial, linear decrease of the surface-contamination level and is the tangent line of \( C_{\text{surf},i}(t) \) at \( t = 0 \). If this linear decrease were to continue, the contamination would vanish at \( t = \tau_{\text{wo},i}(\text{h}) \), the wipe-off associated mean lifetime of the contamination (see figure 2). The corresponding half-life \( T_{1/2,\text{wo},i} \) (h) of the contamination is directly related to the lifetime and the time-averaged wipe-off loss rate according to (Dillen 2015):

\[ T_{1/2,\text{wo},i} = \tau_{\text{wo},i} \ln 2 = \frac{\ln 2}{f_{\text{use}} \bar{f}_{\text{oth},i} \bar{\phi}_{\text{use}} \left( \frac{A_{\text{cont}}}{A_{\text{hands}}} \right)}. \]  

(19)

In the example of figure 2, \( \tau_{\text{wo},i} = 500 \text{ h} \) and \( T_{1/2,\text{wo},i} = 347 \text{ h} \).

The assumption of an average exponential decrease in equation (18) has its limits. For small contaminated areas, the discrete and probabilistic nature of the wipe-off process will become dominant and will determine the actual decrease of the surface contamination. It is plausible to assume that equation (18) loses its validity if the wipe-off associated mean lifetime \( \tau_{\text{wo},i} \) is in the order of (or smaller than) the average duration of a wipe-off event in the continuous model, \( t^* = \left( f_{\text{use}} \bar{\phi}_{\text{use}} \right)^{-1} \) (h), as derived in section 3.6. This occurs if the contaminated area is in the order of or smaller than a certain critical area,

\[ A_{\text{crit},i} = \bar{f}_{\text{oth},i} A_{\text{hands}}, \]  

(20)

which is found by setting \( \tau_{\text{wo},i} \) equal to \( t^* \). In the example above, \( A_{\text{crit},i} = 40 \text{ cm}^2 \), and thus with \( A_{\text{cont}} = 1000 \text{ cm}^2 >> A_{\text{crit},i} \), the exponential decrease is assumed and expected to be a valid approach.
Figure 2. Exponential decrease (solid curve) of the surface contamination $C_{\text{surf},j}(t)$ according to equation (18) for wipe off only (no other removal processes), using: $C_{0,j} = 1.0$ Bq cm$^{-2}$, $f_{\text{ase}} = 0.20$, $f_{\text{oth},j} = 0.10$, $\theta_{\text{ase}} = 0.25$ h$^{-1}$, $A_{\text{hands}} = 400$ cm$^2$ and $A_{\text{cont}} = 1000$ cm$^2$. The dashed curve represents the tangent line of $C_{\text{surf},j}(t)$ at $t = 0$ and mimics its initial, linear decrease with time. The related life time ($\tau_{\text{wo},j} = 500$ h) and half-life ($T_{1/2,\text{wo},j} = 347$ h) of the contamination are indicated as well.

3.6. Wipe-off: the transfer frequency and efficiency

A single wipe-off event can be associated with more than one contact event. With $A_{\text{hands}}$ in the order of 100 cm$^2$ or more, several contact events are needed to achieve the homogeneous level of $f_{\text{oth},j}C_{\text{surf},j}$. A wipe-off event starts with uncontaminated (clean) hands touching the object during use and ends when they are washed or wiped clean clearing them completely from their maximum (removable) contamination level of $f_{\text{oth},j}C_{\text{surf},j}$. A subsequent wipe-off event then starts when use of the object is continued. In the continuous model, the process of wipe-off is spread out over the complete year ($\Delta t_{\text{tot}}$), and with an annual amount of $N_{\text{wo}}$ wipe-off events, the average wipe-off frequency equals $\langle \phi \rangle = N_{\text{wo}} / \Delta t_{\text{tot}} = (t^* \lambda_s)^{-1}$ (h$^{-1}$), with $t^*$ (h) the overall, average duration of a wipe-off event. In case $\langle \phi \rangle$ is known, equation (17) can also be evaluated as $\langle \lambda_{\text{wo},j} \rangle = \frac{\langle \phi \rangle}{f_{\text{ase}}} A_{\text{hands}} / A_{\text{cont}}$. Since all $N_{\text{wo}}$ events actually occur in $\Delta t_{\text{ase}}$, the wipe-off frequency averaged over the duration-of-use can be written as

$$\bar{\phi}_{\text{ase}} = \frac{N_{\text{wo}}}{\Delta t_{\text{ase}}} = \frac{N_{\text{wo}}}{f_{\text{ase}} \Delta t_{\text{tot}}} = \frac{\langle \phi \rangle}{f_{\text{ase}}} = (f_{\text{ase}} t^*)^{-1} = (t^* \lambda_s)^{-1},$$

(21)

with $t^* = f_{\text{ase}} t^*$ (h) representing the average duration of a wipe-off event during use of the object, which can be seen as the average time between cleaning or washing hands. The average value $\bar{\phi}_{\text{ase}}$ may thus be estimated from either $N_{\text{wo}}$ or $t^*$. Its default value is set at 0.25 h$^{-1}$ (one wipe-off event in 4 hours of use).

The wipe-off process is described by the mean transfer efficiency $\bar{f}_{\text{oth},j}$, defined by equation (13) averaged over the time-of-use. For simplicity, we continue to use equation (13) with $f_{\text{oth},j} = f_{\text{oth},j}(t)$
replaced by $\overline{f}_{\text{oth},i}$. This parameter is similar but not identical to the removal factor (wiping efficiency) $F$ from the ISO-7503 (1988, 2016) standard, described earlier in section 2.1.

On the one hand, there is a practical difference in transfer mechanism underlying these two parameters. The average transfer efficiency $\overline{f}_{\text{oth},i}$ for wipe-off events is adopted for handling objects during their regular use, which is not the same as an experimental wipe sample for which the removal factor $F$ is defined. Hence, the values of $\overline{f}_{\text{oth},i}$ and $F_i$ will likely be different for a surface-contaminated object.

On the other hand, based on the definitions, we can show that both quantities are directly proportional. We ignore the aforementioned practical differences and treat a user’s wipe-off event as a smear sample. Suppose that during a single wipe-off event, a net area $A_{\text{touched}}$ (cm$^2$) of the object is touched by the hands, which thereby gain a total activity of $q_{\text{hands},i}$ (Bq) homogeneously distributed over $A_{\text{hands}}$. From equation (1), the removal factor is written as $F_i = q_{\text{hands},i}/Q_{\text{rem,touched},i}$, in which $Q_{\text{rem,touched},i}$ (Bq) is the object’s removable surface activity on $A_{\text{touched}}$ prior to the wipe-off event. By using equation (13), the average transfer efficiency can be written as $\overline{f}_{\text{oth},i} = (q_{\text{hands},i}/A_{\text{hands}})/(Q_{\text{rem,touched},i}/A_{\text{touched}})$, and from this we see that

$$\overline{f}_{\text{oth},i}A_{\text{hands}} = F_i A_{\text{touched}}. \quad (22)$$

From equation (22), the transfer efficiency is written as $\overline{f}_{\text{oth},i} = \eta F_i$ with $\eta = A_{\text{touched}}/A_{\text{hands}}$.

With $F_i \leq 1$ (since $q_{\text{hands},i} \leq Q_{\text{rem,touched},i}$), it follows that $\overline{f}_{\text{oth},i} \leq \eta$, from which we conclude that the transfer efficiency may attain a value larger than 1 in case $A_{\text{touched}} > A_{\text{hands}}$. Activity is then accumulated on a smaller area, possibly leading to a larger skin-contamination level than the object’s surface contamination prior to the wipe-off event. Using equation (22), an alternative expression for the average wipe-off loss rate is: $\lambda_{\text{wo},i} = f_{\text{case}} F_i A_{\text{touched}} / A_{\text{cont}}$, with $A_{\text{touched}} / A_{\text{cont}} \leq 1$. In the remainder of this paper, however, we will continue the use of $\overline{f}_{\text{oth},i}$ and keep the product $\overline{f}_{\text{oth},i}A_{\text{hands}}$.

In Appendix B, we show that for a constant removal factor $F_i = \overline{f}_{\text{oth},i}/\eta$, a simple model based on the ISO-7503 (1988, 2016) standard predicts an (almost) exponential decrease of $C_{\text{surf},i}$ with time, which is in agreement with our approach (equation (18) and figure B1).

Since quantitative information on the transfer mechanism and on the value of $\eta$ is generally unknown, the difference between parameters $\overline{f}_{\text{oth},i}$ and $F_i$ remains theoretical. Therefore, if the value of $F_i$ is known, one could consider it to be practical to use it as an estimate for $\overline{f}_{\text{oth},i}$, or vice versa.

The ISO-7503 (1988, 2016) standard recommends a default value of 0.10 for the removal factor $F_i$ if experimental information on its actual value is missing. Experimental work by Shoji et al (2010) showed that this value is indeed appropriate for polyvinyl chloride flooring wiped with foamed polystyrene pads (Appendix B). More information on wipe-sampling methods and on values of the removal factor (wiping or collection efficiency) can for instance be found in the following references: (Frame and Abelquist 1999), (Jung et al 2001), (Verkouteren et al 2008), (McArthur 1992), (U.S. EPA 2011a), (Lichtenwalner 1992), (Sugiura et al 2007), (Ichiji and Ogino 2011), (Barbieri et al 2009).
In IAEA (2005) and Rawl et al (2004) the transfer efficiency $f_{oth,i}$ is assigned a value of 0.20. In ‘Radiation Protection 101’ (EC 1999), a value of only $f_s = 0.01$ is used, where $f_s$ is defined as the skin-transfer factor. This latter value seems smaller than the former, but it is further explained that the value of $f_s$ was “chosen by assuming that 10% of the activity is removable and 10% of this activity is transferred to the hands”. Hence, the skin-transfer factor is the product of the transfer efficiency and the removable fraction, i.e., $f_{s,i} = f_{oth,i} f_{rem,i}$, with $f_{oth,i} = f_{rem,i} = 0.1$ (note the subtle difference in parameter use: $C_{surf, hands,i}$ is here $f_{oth,i} C_{surf,i}$ from equation (13), while it is $f_{s,i} C_{surf, tot,i}$ in EC (1999)).

Surface-to-skin transfer efficiencies of contaminants, usually pesticides and fluorescent tracers, have been studied experimentally, see for instance in section 7.6 of the U.S. EPA Exposure Factors Handbook (U.S. EPA 2011b). In one of these studies by Cohen Hubal et al (2005), the incremental and overall transfer efficiencies were determined by a fluorescent imaging technique. This was done for several surface types (carpet, laminate) and hand conditions (dry, moist, sticky). The study showed that the contamination level of the hands reaches a maximum within five contact events, indicating a saturation behavior of the residue-transfer mechanism. Since each contact was performed in a fresh location on the test surface, this saturation was not the result of a decrease in the available activity for transfer. Overall transfer efficiencies determined after these five contact events varied between 1.6% and 8.2%, the latter value achieved with sticky hands. Since in the definition of the overall efficiency one divides the ‘mass on the hands after final contact’ by the ‘total area contacted’ (i.e., $A_{hands}$) and not by the contaminated skin area, the resulting values are actually a measure of the removal factor $F_r$. Therefore, if one would model a wipe-off event as consisting of five hand-surface contacts, the transfer efficiency $f_{oth,i}$ as defined by equation (13) would then be five times higher, i.e., between 8% and 41% (with $\eta = 5$), assuming all applied contamination in these experiments was removable (i.e., $f_{rem,i} = 1$). In a similar study by Brouwer et al (1999), the skin adherence of contamination on a glass plate was investigated after one or more press-contact events. Even though they observed transfer efficiencies of $\leq 2\%$ for a single contact, repeated contacts result in larger efficiencies. From their data, transfer efficiencies $f_{oth,i}$ between 6% and 7% are achieved after 6 contact events. Since a wipe-off event will usually consist of several press contacts and/or smudges, a transfer efficiency of 10% or even larger is not unlikely. The default value of $f_{oth,i}$ is therefore set at 0.10.

### 3.7. Indoor environment: ventilation and deposition

The indoor environment of a house or building is schematically depicted in figure 3 and is characterized by a single room or hall (one compartment) with floor area $A_{floor}$ (cm$^2$), height $H$ (cm) and volume $V = A_{floor} H$ (cm$^3$). Default values in SUDOQU for a dwelling are $A_{floor} = 50 \times 10^4$ cm$^2$ (50 m$^2$), $H = 250$ cm (2.5 m) and thus $V = 1.25 \times 10^8$ cm$^3$ (125 m$^3$). Note that this is relatively large room and that one may need to choose a smaller room area for more conservative dose evaluations. Resuspension of activity from the contaminated surface is the source of air contamination (section 3.4). The reduction of airborne activity is not only the result of radioactive decay but also of removal by ventilation and deposition.

Ventilation is described by an air-exchange rate $\lambda_v$ (h$^{-1}$), which is the number of air changes per hour, or alternatively, by a volumetric ventilation rate $\kappa_v = \lambda_v V$ (cm$^3$.h$^{-1}$). Under the assumption that clean air from outside enters the room, and that the airborne activity is always well-mixed throughout its volume, the rate-of-change of the air-contamination level (in Bq.m$^{-3}$.h$^{-1}$) by ventilation is simply

$$\frac{dC_{air,i}}{dt} = -\lambda_v C_{air,i}.$$ (23)
For residential dwellings, the air-exchange rate has typical values between 0.2 h\(^{-1}\) and 1.0 h\(^{-1}\) with its default value set at 0.5 h\(^{-1}\) in SUDOQU, for commercial buildings this is typically between 0.5 and 2.0 h\(^{-1}\). We refer to Yu et al. (2003, section J.2.6) for an overview of experimental studies on the air-exchange rates in the United States.

For deposition of particles carrying radionuclides we can write a similar equation to equation (23) but then using the deposition-loss-rate constant \(\dot{\lambda}_d\) (h\(^{-1}\)). The value of this constant varies over 3 to 4 orders of magnitude depending on particle diameter and the conditions in/of the room. For particles with diameters between 1 and 10 \(\mu\)m \(\dot{\lambda}_d\) varies between \(10^{-3}\) h\(^{-1}\) and 10 h\(^{-1}\), as follows from several indoor experimental and modeling studies (Thatcher and Layton 1995), (Schneider et al. 1999), (Thatcher et al. 2002), (Lai and Nazaroff 2000) and (Lai 2002). This loss-rate constant may have independent contributions from deposition to horizontally and vertically oriented surfaces in and of the room. Its overall value can be written as (Lai 2002):

\[
\dot{\lambda}_d = \frac{v_{dv}A_v + v_{du}A_u + v_{dd}A_d}{V},
\]

(24)

with \(v_{dv}\), \(v_{du}\) and \(v_{dd}\) (cm.h\(^{-1}\)) the deposition velocities on vertical, upward- and downward-facing surfaces, respectively, with corresponding total surface areas of \(A_v\), \(A_u\) and \(A_d\). For supermicron size particles, it can be seen from Schneider et al. (1999) and Lai and Nazaroff (2000) that the value of \(\dot{\lambda}_d\) is dominated by deposition to horizontal, upward-facing surfaces and thus mainly depends on the particle-diameter dependent, gravitational settling velocity. The deposition-loss-rate constant is then written as (Thatcher and Layton 1995, equation (4)):

\[
\dot{\lambda}_d \approx \frac{A_u}{V}v_{du}.
\]

(25)

As demonstrated experimentally by Thatcher et al. (2002), the conditions in/of the room strongly influence the deposition-loss-rate constant given by equations (24) and (25). The presence of furniture, for instance, leads to an increase in \(\dot{\lambda}_d\), as the available area for deposition increases.

![Figure 3. Schematic illustration of the contaminated object in the indoor environment, with floor area \(A_{floor}\), height \(H\), volume \(V\) and ventilated at an air-exchange rate \(\dot{\lambda}_e\).](image)
As a modeling simplification, we here assume that there is no room furniture and that the contaminated (object’s) area covers part of the floor area, as illustrated in figure 3. In that case, $A_i = A_{\text{floor}} = V/H$ and the deposition-loss-rate constant $\lambda_{d,i}$ for nuclide $i$ is:

$$\lambda_{d,i} = \frac{v_{d,i}}{H}, \quad (26)$$

with the deposition velocity $v_{du}$ rewritten as $v_{d,i}$. Equation (26) can easily be derived as follows. In a time interval of duration $dt$, the total amount of activity deposited on the floor is $(v_{d,i} dt) A_{\text{floor}} C_{\text{air,i}}$ (Bq). This activity is removed from the room’s volume $V$, and thus the rate-of-change of the air concentration by deposition is $(v_{d,i} dt) A_{\text{floor}} C_{\text{air,i}} = -(v_{d,i} H) C_{\text{air,i}}$, from which

$$\lambda_{d,i} = \frac{v_{d,i}}{H}. \quad \text{(Using a typical indoor deposition velocity of 360 cm.h}^{-1} (1.0 \text{ mm.s}^{-1}) \text{ and a room height of 250 cm, then yields a deposition-loss-rate constant of } \lambda_{d,i} = 1.44 \text{ h}^{-1} \text{ (default value in SUDOQU).}}$$

Deposition in the indoor environment not only leads to a decrease in the air-activity concentration, but also affects the surface-contamination level $C_{\text{surf,i}}$ as activity redeposits onto the object’s surface $A_{\text{cont}}$. Deposition on and external radiation from the (floor) area surrounding the object is not considered in this paper.

In the outdoor environment, deposition of resuspended activity is neglected, since wind blows airborne activity away from the object, inhibiting redeposition onto the (relatively small) object.

3.8. Transfer of activity to skin (hands and face)

Wipe-off is modelled as a homogeneous contamination of the hands over a skin area of $A_{\text{hands}}$, accumulated after several contact events with the contaminated object. Even though activity may initially be transferred to several parts of the hands (e.g., finger tips, palms), it may gradually spread across a larger skin area. Redistribution of activity is not modeled explicitly. Instead, we assume a gradual and homogeneous transfer to $A_{\text{hands}}$ with an efficiency $f_{\text{oth}}$ as defined by equation (13). The scenario-dependent input value of $A_{\text{hands}}$ can thus be larger than the initial skin-contact area during activity transfer, but will generally be smaller than the total skin area of the hands. Note that it is also possible to study the accumulation effect by setting $A_{\text{hands}}$ to a small value (several cm$^2$) and the value of the transfer factor $f_{\text{oth}} > 1$ (with $A_{\text{touched}} > A_{\text{hands}}$, section 3.6). In addition, part of the face may become contaminated by contact with the hands. The transfer to a facial skin area of $A_{\text{face}}$ (cm$^2$) is again assumed to be gradual and homogeneous, occurring with an average efficiency $f_{\text{htf}}$ (htf: hand-to-face) defined later. The default values of $A_{\text{hands}}$ and $A_{\text{face}}$ are 400 cm$^2$ and 100 cm$^2$, respectively (IAEA 2005). Both skin-contamination levels are used to estimate the annual, local skin-equivalent doses and their contribution to the annual effective dose (section 5).

As discussed in sections 3.5 and 3.6, the hands’ skin-contamination level after a complete wipe-off event at time $t$ is $C_{\text{surf,hands,i}}(t) = f_{\text{oth,i}} C_{\text{surf,i}}(t)$, after which the hands are cleaned by washing or wiping them. A next wipe-off event starts with clean hands again. One can argue whether or not the skin is completely clean after washing it. It is likely that a fraction of the activity on the skin becomes fixed as it gets caught in its pores and slightly enters the horny layer (stratum corneum) of the epidermis. Successive wipe-off events may then lead to an initial build-up of such fixed skin contamination, which will saturate and eventually reach an equilibrium level as skin-wear and renewal processes slowly remove activity as well, the latter occurring at a typical half-life of about 5 to 10 days (Hayashi et al 1998).
If, within each single wipe-off event, activity is gradually transferred from the object to the skin of the hands, then the (annual) “effective” duration of skin contamination and exposure of the hands may be smaller than the (annual) duration of use of the object, i.e., \( \Delta T_{\text{hands},i} < \Delta T_{\text{use}} \). At the same time, the skin may remain contaminated and exposed when the object is not in use anymore, since cleaning hands may occur at some point after use. Hence, \( \Delta T_{\text{hands},i} > \Delta T_{\text{use}} \) is also possible. To take into account the net duration of skin contamination (and exposure) of the hands, we have introduced a multiplication factor \( m_{\text{hands},i} \), defined as

\[
m_{\text{hands},i} = \frac{\Delta T_{\text{hands},i}}{\Delta T_{\text{use}}} = \left( f_{\text{use}} \right)^{-1} \left( \frac{\Delta T_{\text{hands},i}}{\Delta T_{\text{tot}}} \right).
\]  \( \text{(27)} \)

The (annual) effective duration of skin contamination of the hands can thus be regulated by \( m_{\text{hands},i} \):

\[
\Delta T_{\text{hands},i} = m_{\text{hands},i} f_{\text{use}} \Delta T_{\text{tot}} \quad \text{(in h or h.y}^{-1} \text{if } \Delta T_{\text{tot}} \text{ is one year)},
\]

from which follows that \( m_{\text{hands},i} f_{\text{use}} \leq 1 \), because \( \Delta T_{\text{hands},i} \leq \Delta T_{\text{tot}} \). Effective duration should here be interpreted as the net period of time during which the skin would be constantly contaminated at its maximum level of \( J_{\text{oth},i} C_{\text{surf},j} \), achieved before or at the end of a wipe-off event. The actual time-dependence of skin contamination during transfer/wipe-off (i.e., the gradual build-up of contamination on the hands from 0 to \( J_{\text{oth},i} C_{\text{surf},j}(t) \)) and its possible continuation after object use is replaced by a simplified situation in which the skin is constantly contaminated at its maximum value of \( J_{\text{oth},i} C_{\text{surf},j}(t) \). The duration of such maximum-level skin contamination and exposure in a small time interval \([t, t+\Delta t]\) is therefore \( m_{\text{hands},i} f_{\text{use}} \Delta t \). The value of \( m_{\text{hands},i} \) is such that the time-integrated surface contamination of the hands, \( TISC_{\text{hands},j} \) (Bq.h.cm\(^{-2}\)), is equal in both situations and is proportional to the experienced time-integrated surface contamination of the object as (see Appendix C for details):

\[
TISC_{\text{hands},j}(t) = m_{\text{hands},i} J_{\text{oth},i} TISC_{\text{use},j}(t),
\]  \( \text{(28)} \)

with \( TISC_{\text{use},j}(t) \) given by equation (6). Factor \( m_{\text{hands},i} \) determines the committed effective dose from secondary ingestion (activity ingested by transfer from hands to mouth) and the equivalent and effective skin dose from external radiation emitted by radionuclides residing on the hands (section 5).

Theoretically, \( m_{\text{hands},i} \) could be calculated if one would have information on the average duration of a wipe-off event (i.e., \( t_{\text{use}} \) from section 3.6) and the time-dependence of the relative transfer behavior of contamination from the object to the hands, as is described in Appendix C.

Here we present a clarifying example: let us consider a small time interval \( \Delta t \), during which the contaminated object is used for a period of \( f_{\text{use}} \Delta t \), without a significant change in its surface contamination level \( C_{\text{surf},j} \). We assume that during use contamination is transferred linearly with time, from 0 Bq.cm\(^{-2}\) at start of use to \( J_{\text{oth},i} C_{\text{surf},j} \) at the end of a wipe-off event. We also assume that one complete wipe-off event occurs during use, and that the hands are cleaned immediately after object use, i.e., \( f_{\text{use}} = f_{\text{use}} \Delta t \). The average skin-contamination level is then \( \frac{1}{2} J_{\text{oth},i} C_{\text{surf},j} \) during use, and 0 after use, resulting in a time-integrated level of \( TISC_{\text{hands},i} = \left( \frac{1}{2} J_{\text{oth},i} C_{\text{surf},j} \right) \cdot f_{\text{use}} \Delta t \). This value would also be achieved if the hands were contaminated at the maximum level of \( J_{\text{oth},i} C_{\text{surf},j} \) for a duration of \( f_{\text{use}} \Delta t \), and therefore \( m_{\text{hands},i} = 0.5 \). This value is also obtained from equation (28) since
TISC_{use,\,i} = f_{use} C_{surf,\,i} \Delta t. \text{ This means that if a product is used for } \Delta T_{use} = 400 \text{ h.y}^{-1}, \text{ the effective duration of skin contamination and exposure of the hands is } \Delta T_{hands} = 200 \text{ h.y}^{-1}.

Since little is known about the complex object-to-hand transfer mechanism, a linear multi-contact behavior with \( m_{\text{hands,\,i}} = 0.5 \) seems practical to use, although a decrease in skin adherence is observed in several experiments (Brouwer et al 1999, Cohel Hubal et al 2005). Taking into account the possible continuation of skin contamination after object use, would then require a value (somewhat) larger than 0.5. The default value of \( m_{\text{hands,\,i}} \) is therefore set at 1.0, which in most cases is a conservative value.

As mentioned earlier, part of the skin of the face may become contaminated. A surface area of \( A_{\text{face}} \) (default value: 100 cm\(^2\)) is assumed to gradually attain a maximum homogeneous contamination level of (similar to equation (13)):

\[
C_{\text{surf,\,face,\,i}}(t) = \bar{t}_{\text{hf,\,i}} C_{\text{surf,\,hands,\,i}}(t) = \bar{t}_{\text{hf,\,i}} \bar{t}_{\text{oth,\,i}} C_{\text{surf,\,i}}(t). \tag{29}
\]

In equation (29), \( \bar{t}_{\text{hf,\,i}} \) is the average transfer efficiency from hands to face. Theoretically, like \( \bar{t}_{\text{oth,\,i}} \), \( \bar{t}_{\text{hf,\,i}} \) could attain values larger than 1 if accumulation of activity on the face occurs (i.e., \( C_{\text{surf,\,face,\,i}} > C_{\text{surf,\,hands,\,i}} \)). In the absence of data on this quantity, its default value is equated with that of \( \bar{t}_{\text{oth,\,i}} \), i.e., 0.10 (section 3.6).

The effective exposure time of the skin of the face, \( \Delta T_{\text{face,\,i}} \) (h), is regulated by the multiplication factor \( m_{\text{face,\,i}} \), with \( \Delta T_{\text{face,\,i}} = m_{\text{face,\,i}} \Delta T_{\text{use}} \) and \( m_{\text{face,\,i}} f_{\text{use}} \leq 1 \). The time-integrated surface contamination of the face (Bq.h.cm\(^{-2}\)) then reads

\[
\text{TISC}_{\text{face,\,i}}(t) = m_{\text{face,\,i}} \bar{t}_{\text{hf,\,i}} \bar{t}_{\text{oth,\,i}} \text{TISC}_{\text{use,\,i}}(t). \tag{30}
\]

Since the face is usually washed less frequently than the hands, its contamination will likely continue to be present for a longer period of time after object use. The value of \( m_{\text{face,\,i}} \) is therefore expected to be larger than that of \( m_{\text{hands,\,i}} \). Its default value is conservatively set at 2.0 if \( m_{\text{face,\,i}} f_{\text{use}} \leq 1 \), otherwise it is set at \( m_{\text{face,\,i}} = (f_{\text{use}})^{-1} \).

Finally, the total activity transferred to the face, \( \bar{t}_{\text{hf,\,i}} \bar{t}_{\text{oth,\,i}} C_{\text{surf,\,i}} A_{\text{face}} \) (Bq), is not modeled as activity being at the expense of the activity on the hands nor of the activity on the object. This approach deviates from the model’s mass-balance treatment and is followed for simplicity and conservatism.

3.9. Summary of default parameter values

Table 1 summarizes SUDOQU’s input parameters and their default values as described so far in sections 2 and 3. Note that with \( f_{\text{use}} = 0.228 \) and \( \Delta T_{\text{tot}} = 8760 \) h, the annual duration of object use is \( \Delta T_{\text{use}} = 2000 \) h (or h.y\(^{-1}\)). The default value of \( A_{\text{cont}} \) for calculations in this paper is arbitrarily set at 1000 cm\(^2\), but in section 6 its value is also varied over a large range (see figures 6, 7 and 8).
Table 1. Summary of SUDOQU’s input parameters and their default value for calculations in this paper. For more details, see relevant sections (numbers are included in Table).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Section</th>
<th>Default value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{rem,i}$</td>
<td>Removable fraction of nuclide $i$</td>
<td>2.1; 2.2</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>$A_{cont}$</td>
<td>Contaminated surface</td>
<td>2.1</td>
<td>1000</td>
<td>cm$^2$</td>
</tr>
<tr>
<td>$\Delta T_{tot}$</td>
<td>Total considered time (1 year)</td>
<td>3.1</td>
<td>8760</td>
<td>h</td>
</tr>
<tr>
<td>$f_{use}$</td>
<td>Fraction of time for object use (duty factor)</td>
<td>3.1</td>
<td>0.228</td>
<td>-</td>
</tr>
<tr>
<td>$\xi_{use,i}$</td>
<td>Time-avg. resuspension rate during object use</td>
<td>3.4</td>
<td>10$^{-4}$</td>
<td>h$^{-1}$</td>
</tr>
<tr>
<td>$\overline{\eta}_{use}$</td>
<td>Time-avg. wipe-off frequency during object use</td>
<td>3.6</td>
<td>0.25</td>
<td>h$^{-1}$</td>
</tr>
<tr>
<td>$f_{oh,i}$</td>
<td>Time-avg. transfer efficiency (object-to-hand)</td>
<td>3.6</td>
<td>0.10</td>
<td>-</td>
</tr>
<tr>
<td>$A_{floor}$</td>
<td>Total floor area room (in dwelling)</td>
<td>3.7</td>
<td>50×10$^4$</td>
<td>cm$^2$</td>
</tr>
<tr>
<td>$H$</td>
<td>Room height (dwelling)</td>
<td>3.7</td>
<td>250</td>
<td>cm</td>
</tr>
<tr>
<td>$V$</td>
<td>Room volume (dwelling)</td>
<td>3.7</td>
<td>1.25×10$^5$</td>
<td>cm$^3$</td>
</tr>
<tr>
<td>$\lambda_v$</td>
<td>Air exchange rate (room in dwelling)</td>
<td>3.7</td>
<td>0.50</td>
<td>h$^{-1}$</td>
</tr>
<tr>
<td>$\kappa_v$</td>
<td>Volumetric ventilation rate</td>
<td>3.7</td>
<td>6.25×10$^7$</td>
<td>cm$^3$.h$^{-1}$</td>
</tr>
<tr>
<td>$v_{d,i}$</td>
<td>Indoor deposition velocity</td>
<td>3.7</td>
<td>360</td>
<td>cm.h$^{-1}$</td>
</tr>
<tr>
<td>$\lambda_{d,i}$</td>
<td>Indoor deposition-loss-rate constant</td>
<td>3.7</td>
<td>1.44</td>
<td>h$^{-1}$</td>
</tr>
<tr>
<td>$A_{hands}$</td>
<td>Contaminated skin area of the hands</td>
<td>3.8</td>
<td>400</td>
<td>cm$^2$</td>
</tr>
<tr>
<td>$m_{hands,i}$</td>
<td>Time multiplication factor for hand exposure</td>
<td>3.8</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>$A_{face}$</td>
<td>Contaminated skin area of the face</td>
<td>3.8</td>
<td>100</td>
<td>cm$^2$</td>
</tr>
<tr>
<td>$m_{face,i}$</td>
<td>Time multiplication factor for face exposure</td>
<td>3.8</td>
<td>2.0</td>
<td>-</td>
</tr>
<tr>
<td>$\overline{f}_{htf,i}$</td>
<td>Average transfer efficiency (hands to face)</td>
<td>3.8</td>
<td>0.10</td>
<td>-</td>
</tr>
</tbody>
</table>

4. Mass-balance for contamination levels

4.1 Mass/activity-balance for indoor environment

In the indoor environment, we consider a room as sketched in figure 3. The scenario starts at time $t=0$ h with homogeneous, removable surface contamination $C_{surf,i}(0) = C_{0,i}$ Bq.cm$^{-2}$ for radionuclide $i$ over a total object area of $A_{cont}$. We consider the total change in surface-contamination level $dC_{surf,i}(t)$ (Bq.cm$^{-2}$) in a small time interval $[t,t+dr)$. The level of contamination may decrease by (see section 3):

- Radioactive decay at a rate of $\dot{\lambda}_{r,i}$;
- Resuspension of activity at an average rate of $\langle \xi \rangle$ (equation (11));
- Wipe-off by transfer of contamination to the hands, at an average rate of $\langle \dot{\lambda}_{wo,i} \rangle$ (equation (17)).

At the same time, the object’s surface contamination may increase by

- Deposition of (resuspended) airborne activity at a velocity of $v_{d,i} = \lambda_{d,i}H$ (equation (26)).

Radioactive decay, resuspension and wipe-off are proportional to the surface-contamination level,
\( C_{\text{surf},i}(t) \), and are expressed as: 
\[-\lambda_{r,i} C_{\text{surf},i}(t) \, \text{d}t, \quad -\langle \xi_i \rangle C_{\text{surf},i}(t) \, \text{d}t, \quad \text{and} \quad -\langle \lambda_{\text{wo},i} \rangle C_{\text{surf},i}(t) \, \text{d}t, \]
respectively. The deposition is proportional to the ‘continuously experienced’ air-activity concentration, \( C_{\text{air},i}(t) \) (section 3.3), and is written as \(+v_{d,i} C_{\text{air},i}(t) \, \text{d}t\), with the deposition velocity \( v_{d,i} \) being the constant of proportionality. The absence of the duty factor \( f_{\text{use}} \) for deposition is here related to the use of \( C_{\text{air},i} \) instead of \( \bar{C}_{\text{air},i} \). Using equations (11), (17) and (26), the rate-of-change of the surface-contamination level, \( \dot{C}_{\text{surf},i} \equiv dC_{\text{surf},i}(t)/\text{d}t \), is then written as

\[
\dot{C}_{\text{surf},i} = \left[-\lambda_{r,i} C_{\text{surf},i}(t) + \left(\lambda_{d,i} H\right) C_{\text{air},i}\right] \delta,
\]

with \( C_{\text{surf},i}(0) = C_{0,i} \). As explained in the introduction of section 3, parameter \( \delta \) is a switch for in/exclusion of the processes of surface-removal and deposition. For \( \delta = 1 \) you get the ‘consumer model’ and for \( \delta = 0 \) you get the ‘worker model’. The effective surface-removal constant \((\text{h}^{-1})\) is defined by

\[
\lambda_{\text{surf},i} = \lambda_{r,i} + \langle \xi_i \rangle + \langle \lambda_{\text{wo},i} \rangle = \lambda_{r,i} + f_{\text{use}} \left(\bar{\xi}_{\text{use},i} + \bar{\xi}_{\text{wo},\text{use},i}\right).
\]

Equation (31) should be considered within the total time interval \([0, \Delta T_{\text{tot}}]\). With \( \delta = 0 \), we have \( \dot{C}_{\text{surf},i} = 0 \) and thus \( C_{\text{surf},i}(t) = C_{0,i} \) at each time \( t \), which therefore imposes an explicit deviation from the mass/activity-balance approach. This does not mean that resuspension and wipe-off do not occur, but only that these processes do not influence the level of surface contamination.

The room’s (well-mixed, homogeneous) air-activity concentration varies as well, given by the rate-of-change \( \dot{C}_{\text{air},i} \equiv dC_{\text{air},i}(t)/\text{d}t \), which is derived as follows. At \( t = 0 \), the air concentration is \( C_{\text{air},i}(0) = 0 \, \text{Bq.cm}^{-3} \), after which it will increase by resuspension of activity from the contaminated surface of the object, at an average rate of \( \langle \xi_i \rangle \). At the same time, activity is removed from the air by radioactive decay, ventilation and deposition. We consider the total change in air-contamination level \( dC_{\text{air},i}(t) \) (Bq.cm\(^{-3}\)) in a small time interval \([t, t + \text{d}t]\). The contribution of resuspension to this total change \( dC_{\text{air},i}(t) \) is found by dividing the average, resuspended activity by the room’s volume, i.e.,

\[
\langle \xi_i \rangle C_{\text{surf},i}(t) A_{\text{cont}} \, \text{d}t / V.
\]

The contributions of radioactive decay, ventilation and deposition are 
\(-\lambda_{r,i} C_{\text{air},i}(t) \, \text{d}t\), \(-\lambda_{c,i} C_{\text{air},i}(t) \, \text{d}t\) and \(-v_{d,i} C_{\text{air},i}(t) \, \text{d}t\), respectively. Using equation (11), we can write:

\[
\dot{C}_{\text{air},i} = f_{\text{use}} \bar{\xi}_{\text{use},i} A_{\text{cont}} C_{\text{surf},i} - \left(\lambda_{r,i} \delta + \lambda_{c,i} + \lambda_{d,i} \delta\right) C_{\text{air},i},
\]

where we added switch \( \delta \) in the removal terms for radioactive decay and deposition to be compliant with the IAEA-CRP model for \( \delta = 0 \) (IAEA 2005). This equation should be considered within the total time interval \([0, \Delta T_{\text{tot}}]\). The set of equations, equations (31) and (33), is solved in section 4.3.

4.2 Mass/activity-balance for the outdoor environment

The outdoor situation differs from the indoor situation. One could argue that the average, idle resuspension rate \( \bar{\xi}_{\text{idle},i} \) (object not used, section 3.4) cannot be ignored anymore, since its value may be dominated by atmospheric conditions. The values of \( \bar{\xi}_{\text{use},i} \) and \( \bar{\xi}_{\text{idle},i} \) may be similar, say \( \bar{\xi}_i \), thus
yielding an effective surface-removal constant of $\lambda_{\text{surf}, i} = \lambda_{r,i} + \xi_i + f_{\text{use}}\bar{\lambda}_{\text{wo,use}, i}$. This leads to lower contamination levels during use of the object and thereby to a smaller individual, annual effective dose. To keep the calculation conservative, $\xi_i$ is therefore also ignored for outdoor exposure. The surface-contamination level then develops as follows (deposition is ignored, see section 3.7):

$$\dot{C}_{\text{surf}, i} = -\delta \cdot \lambda_{\text{surf}, i} C_{\text{surf}, i} = -\delta \cdot \left( \lambda_{r,i} + f_{\text{use}} \left( \bar{\xi}_{\text{use}, i} + \bar{\lambda}_{\text{wo,use},i} \right) \right) C_{\text{surf}, i}.$$  (34)

For the ‘continuously experienced’ air-contamination level $C_{\text{air}, i}$, we follow the approach of IAEA-TECDOC-1449 (IAEA 2005). The activity released from the surface in time interval $[t, t+dt]$ is $f_{\text{use}} \bar{\xi}_{\text{use}, i} C_{\text{surf}, i}(t) A_{\text{cont}} dt$ (Bq). This is assumed to be dispersed into a volume with cross-sectional area $A_{\text{out}}$ (cm$^2$) (perpendicular to the dispersive wind) and length $v_w dt$ (cm), where $v_w$ is the prevailing wind speed (cm.h$^{-1}$). The air concentration, $C_{\text{air}, i}(t)$, is thus proportional to the surface contamination:

$$C_{\text{air}, i}(t) = \frac{f_{\text{use}} \bar{\xi}_{\text{use}, i} A_{\text{cont}}}{v_w A_{\text{out}}} C_{\text{surf}, i}(t).$$  (35)

Within 3 meters of the object, the area $A_{\text{out}}$ is assumed to be 10 times the cross-sectional area of the contaminated object. At distances of 5, 10, 30 and 50 m, this factor is 15, 20, 60 and 100, respectively (see Table 8 in IAEA (2005)).

### 4.3. Solution of the mass/activity-balance equations, indoor environment

The development of the concentrations for the indoor environment, equations (31) and (33), can be written as a matrix equation:

$$\begin{pmatrix} \dot{C}_{\text{surf}, i} \\ C_{\text{air}, i} \end{pmatrix} = \begin{pmatrix} -a_i & b_i \\ c_i & -d_i \end{pmatrix} \begin{pmatrix} C_{\text{surf}, i} \\ C_{\text{air}, i} \end{pmatrix} \quad \text{with} \quad \begin{pmatrix} C_{\text{surf}, i}(0) \\ C_{\text{air}, i}(0) \end{pmatrix} = \begin{pmatrix} C_{0,i} \\ 0 \end{pmatrix},$$  (36)

where

$$a_i = \lambda_{\text{surf}, i} \delta, \quad b_i = \lambda_{d,i} \delta, \quad c_i = \frac{f_{\text{use}} \bar{\xi}_{\text{use}, i} A_{\text{cont}}}{V}, \quad \text{and} \quad d_i = \lambda_{\text{v,w}} + \left( \lambda_{r,i} + \lambda_{d,i} \right) \delta.$$  (37)

Equation (36) is solved in Appendix D. If we define the following characteristic rate constants (h$^{-1}$)

$$\lambda_1 = \frac{1}{2} \left( (a_i + d_i) + \lambda_i^* \right) \quad \text{and} \quad \lambda_2 = \frac{1}{2} \left( (a_i + d_i) - \lambda_i^* \right),$$  (38)

with

$$\lambda_i^* = \lambda_{a,i} - \lambda_{2,i} = \sqrt{4b_i c_i + (a_i - d_i)^2},$$  (39)

then the solution of the surface-contamination level (Bq.cm$^{-2}$) can be written as

$$C_{\text{surf}, i}(t) = \frac{C_{0,i}}{\lambda_i^*} \left( (\lambda_1 - d_i) \exp[-\lambda_1 t] + (d_i - \lambda_2) \exp[-\lambda_2 t] \right).$$  (40)
The solution of the air-activity concentration (Bq.m\(^{-3}\)) reads

\[ C_{\text{air},i}(t) = \frac{c_i}{\lambda_i} C_{0,i} \left( \exp\left[-\lambda_{2,i} t\right] - \exp\left[-\lambda_{1,i} t\right]\right) \cdot 10^6 \]

\[ = \frac{c_i}{\lambda_i} C_{0,i} \exp\left[-\lambda_{2,i} t\right] \left(1 - \exp\left[-\lambda_{1,i} t\right]\right) \cdot 10^6. \]  

The resuspension factor (m\(^{-1}\)), defined by equation (12), can be worked out using equations (40) and (41) to give (for \(d_i \neq \lambda_{2,i}\)):

\[ K_i(t) = K_{\infty,i} \frac{1 - \exp\left[-\lambda_i^* t\right]}{1 + \frac{\lambda_{d,i} - d_i}{d_i - \lambda_{2,i}} \exp\left[-\lambda_i^* t\right]}, \]

where

\[ K_{\infty,i} = \frac{c_i}{d_i - \lambda_{2,i}} \cdot 10^2 = \frac{f_{\text{use}} \bar{A}_{\text{use,i}} \lambda_{\text{cont}}}{V} \cdot \frac{2 \cdot 10^5}{\lambda_{i} + \left(\lambda_{d,i} - d_i \cdot f_{\text{use}} \bar{A}_{\text{use,i}} + \bar{F}_{\text{use,i}} + \bar{F}_{\text{use,i}}\right) \cdot \delta + \lambda_i^*}. \]

The factor \(10^2\) converts cm\(^{-1}\) to m\(^{-1}\) (resulting from the product of conversion factors in equations (12) and (41)). The time-integrated contamination levels, \(TIS_{\text{use,i}}\) and \(TIAC_{\text{use,i}}\) (sections 3.2 and 3.3), can now be worked-out. Substitution of equation (40) into equation (6) and equation (41) into equation (8), gives

\[ TIS_{\text{use,i}}(t) = f_{\text{use}} \frac{C_{0,i}}{\lambda_i} \cdot t \left(\lambda_{d,i} - d_i\right) \Psi\left(\lambda_{1,i} t\right) + \left(d_i - \lambda_{2,i}\right) \Psi\left(\lambda_{2,i} t\right), \]

and

\[ TIAC_{\text{use,i}}(t) = c_i \frac{C_{0,i}}{\lambda_i} \cdot t \left(\Psi\left(\lambda_{2,i} t\right) - \Psi\left(\lambda_{1,i} t\right)\right) \cdot 10^6, \]

where we have introduced the dimensionless removal function \(\Psi\) as

\[ \Psi(x) = \begin{cases} 1 & \text{for } x = 0 \\ \frac{1}{x} \int_0^x \exp[-s] \, ds = \frac{1 - \exp[-x]}{x} & \text{for } x > 0. \end{cases} \]

Our general indoor model is thus characterized by equations (40-45). For three limiting cases, these solutions will be worked out below.

**Case-1: The worker model**

When \(\delta\) is set to 0, the surface-contamination level is constant (at \(C_{0,i}\)). This is referred to as the ‘IAEA-CRP’ model (IAEA 2005) or the ‘worker model’ (see section 3). Then we see that \(a_i = 0\) h\(^{-1}\), \(b_i = 0\) cm.h\(^{-1}\) and \(d_i = \lambda_{2,i}\), resulting in \(\lambda_{d,i} = \lambda_{1,i}^* = \lambda_{i}\) and \(\lambda_{2,i} = 0\) h\(^{-1}\). For this case, we therefore write:
\[
C_{\text{surf},i}(t) = C_{0,i}, \quad (47)
\]
\[
C_{\text{air},i}(t) = \frac{f_{\text{use,air}} A_{\text{cont}}}{V \lambda_v} C_{0,i} (1 - \exp[-\lambda_v t]) \cdot 10^6, \quad (48)
\]
\[
K_i(t) = \frac{f_{\text{use,air}} A_{\text{cont}}}{V \lambda_v} (1 - \exp[-\lambda_v t]) \cdot 10^2, \quad (49)
\]
\[
\text{TISC}_{\text{use},i}(t) = f_{\text{use}} C_{0,i} \cdot t, \quad (50)
\]
\[
\text{TIACT}_{\text{use},i}(t) = \frac{f_{\text{use}} A_{\text{cont}} C_{0,i} \cdot t}{V \lambda_v} (1 - \Psi(\lambda_v t)) \cdot 10^6. \quad (51)
\]

Even for a relatively small value of \( \lambda_v = 0.5 \) h\(^{-1} \) (for laboratories, the air exchange rate is in the range between 2 h\(^{-1} \) and 8 h\(^{-1} \)), the time dependence of the air concentration and resuspension factor, determined by \( \exp[-\lambda_v t] \), vanish after several hours and reach their steady-state values. Since \( \Psi(\lambda_v t) \) also vanishes quickly, the value of \( \text{TIACT}_{\text{use},i} \) then increases linearly with time, as seen from equation (51). Since dose contributions are proportional to either \( \text{TISC}_{\text{use},i} \) or \( \text{TIACT}_{\text{use},i} \) (section 5), they will increase linearly with time. The total annual effective dose will therefore be proportional to \( f_{\text{use}} \Delta T_{\text{tot}} = \Delta T_{\text{use}} \), as confirmed by reference to IAEA (2005).

**Case-2: No deposition**

In the absence of deposition, we have \( \lambda_{d,i} = 0 \) h\(^{-1} \). From this we get \( b_i = 0 \) cm.h\(^{-1} \). Thus, in the case in which we choose \( d_i \geq a_i \), then equation (39) gives us \( \lambda_i = |a_i - d_i| = d_i - a_i \). Using equation (38), we find \( \lambda_{1,i} = d_i \) and \( \lambda_{2,i} = a_i \). This results in (with \( \lambda_i^* = \lambda_v - f_{\text{use}} (\xi_v + \xi_{\text{wo,use},i}) \cdot \delta \)):

\[
C_{\text{surf},i}(t) = C_{0,i} \exp[-a_i t] = C_{0,i} \exp[-\lambda_{\text{surf},i} t \cdot \delta \cdot t], \quad (52)
\]
\[
C_{\text{air},i}(t) = \frac{f_{\text{use,air}} A_{\text{cont}}}{V \lambda_i} (1 - \exp[-\lambda_i^* t]) \cdot 10^6 \cdot C_{\text{surf},i}(t), \quad (53)
\]
\[
K_i(t) = \frac{f_{\text{use,air}} A_{\text{cont}}}{V \lambda_i} (1 - \exp[-\lambda_i^* t]) \cdot 10^2, \quad (54)
\]
\[
\text{TISC}_{\text{use},i}(t) = f_{\text{use}} C_{0,i} \Psi(\lambda_{\text{surf},i} t) \cdot t, \quad (55)
\]
\[
\text{TIACT}_{\text{use},i}(t) = \frac{f_{\text{use}} A_{\text{cont}} C_{0,i} \cdot t}{V \lambda_i} (\Psi(\lambda_{\text{surf},i} t) - \Psi((\lambda_{r,i} + \lambda_v) t)) \cdot 10^6. \quad (56)
\]

The case with \( d_i < a_i \) can only occur for \( \delta = 1 \). We then have \( \lambda_i^* = a_i - d_i \) and thus \( \lambda_{1,i} = a_i \) and \( \lambda_{2,i} = d_i \). The solutions of \( C_{\text{surf},i} \) and \( \text{TISC}_{\text{use},i} \) are still given by equation (52) and equation (55), respectively. However, the solution of \( C_{\text{air},i} \) and \( K_i \) change and get an extra factor \( \exp[\lambda_i^* t] \):
\[ C_{\text{air},i}(t) = \frac{f_{\text{use}} \overline{A}_{\text{use},i} A_{\text{cont}}}{V_{i}^{\lambda_i^*}} \exp\left[\lambda_i^* t \right] \left(1 - \exp\left[-\lambda_i^* t \right]\right) \cdot 10^6 \cdot C_{\text{surf},i}(t), \]  
(57)

\[ K_i(t) = \frac{f_{\text{use}} \overline{A}_{\text{use},i} A_{\text{cont}}}{V_{i}^{\lambda_i^*}} \exp\left[\lambda_i^* t \right] \left(1 - \exp\left[-\lambda_i^* t \right]\right) \cdot 10^2 , \]  
(58)

with \( \lambda_i^* = f_{\text{use}} (\overline{A}_{\text{use},i} + \overline{A}_{\text{wo,use},i}) - \lambda_v \).

Finally, the value of \( TIAC_{\text{use},i} \) reads

\[ TIAC_{\text{use},i}(t) = f_{\text{use}} \overline{A}_{\text{use},i} A_{\text{cont}} C_{0,i} \cdot t \left(\psi \left(\lambda_{r,i} + \lambda_v\right) t\right) - \psi \left(\lambda_{\text{surf},i} t\right) \cdot 10^6 . \]  
(59)

\section*{Case-3: Fixed contamination}

A fixed contamination can be modeled as a limiting case of a removable contamination, by assuming absence of resuspension and wipe-off: \( \overline{A}_{\text{use},i} \rightarrow 0 \) and \( \overline{A}_{\text{wo,use},i} \rightarrow 0 \). The latter can be achieved by setting the transfer efficiency \( \overline{A}_{\text{oth},i} \) to 0. No air-activity concentration builds up (hence, \( C_{\text{air},i} = 0 \) Bq.m\(^{-3}\), \( K_i = 0 \) m\(^{-1}\), and \( TIAC_{\text{use},i} = 0 \) Bq.h.m\(^{-3}\)) and the surface-contamination level decreases by radioactive decay only. Therefore, with \( \delta = 1 \) and writing \( C_{\text{surf,fixed},i} \) instead of \( C_{\text{surf},i} \), we have

\[ C_{\text{surf,fixed},i}(t) = C_{0,i} \exp\left[-\lambda_{r,i} t \right] , \]  
(60)

with its time-integrated value of

\[ TISC_{\text{use,fixed},i}(t) = f_{\text{use}} C_{0,i} \psi \left(\lambda_{r,i} t\right) \cdot t . \]  
(61)

Note that \( C_{0,i} \) is now of course the initial level of fixed surface contamination.

\section*{4.4. Solution of the mass/activity-balance equations, outdoor environment}

Since we ignore deposition in the outdoor model (i.e., \( \lambda_{d,i} = 0 \) h\(^{-1}\)), the surface-contamination level \( C_{\text{surf},i} \) (Bq.cm\(^{-2}\)) and its integrated counterpart \( TISC_{\text{use},i} \) (Bq.h.cm\(^{-2}\)) are given by equations (52) and (55), respectively. The air-contamination level \( C_{\text{air},i} \) (Bq.m\(^{-3}\)) then simply follows from \( C_{\text{surf},i} \) by applying equation (55):

\[ C_{\text{air},i}(t) = 2.78 \frac{f_{\text{use}} \overline{A}_{\text{use},i} A_{\text{cont}} C_{0,i}}{v_w A_{\text{bat}}} \exp\left[-\lambda_{\text{surf},i} d \cdot t \right] , \]  
(62)

with \( \lambda_{\text{surf},i} \) from equation (32) and with the wind speed \( v_w \) now expressed in m.s\(^{-1}\). The conversion factor 2.78 results from a conversion of the wind speed, \( 3.6 \cdot 10^5 \) cm.h\(^{-1}\) per m.s\(^{-1}\) (in denominator), and from \( 10^6 \) cm\(^2\).m\(^{-3}\) (section 2.3). The constant resuspension factor (m\(^{-1}\)) is given by
and the time-integrated air contamination (Bq.h.m⁻³) by:

\[
TIA_{\text{use},j}(t) = 2.78 \cdot \frac{f_{\text{use}} \bar{Z}_{\text{use},j}}{v_{\text{w}}} \cdot \frac{A_{\text{cont}} C_{0,j} \cdot t}{v_{\text{w}}} \cdot \psi \left( \lambda_{\text{surf},j} \delta \cdot t \right) = 2.78 \cdot \frac{Z_{\text{use},j} A_{\text{cont}}}{v_{\text{w}}} \cdot TISC_{\text{use},j}(t).
\]

4.5. Dealing with fixed and removable contamination

So far, we have only considered completely removable contaminations with \( f_{\text{rem},i} = 1 \) (section 2.2) and completely fixed contaminations as a limiting case (section 4.3). If one deals with a total surface contamination \( C_{\text{surf,tot},i} \) consisting of a removable and a fixed component (\( 0 < f_{\text{rem},i} < 1 \)), both levels follow their own time dependence. If the total surface-contamination is initially given by \( C_{\text{surf,tot},i}(0) = C_{0,i} \), these components evolve with time as (\( \delta = 1 \)):

\[
C_{\text{surf,fixed},i}(t) = (1 - f_{\text{rem},i}) C_{0,i} \exp \left[ -\lambda_{\text{rem},i} t \right],
\]

which is equation (60) multiplied by its fixed fraction \( 1 - f_{\text{rem},i} \), and

\[
C_{\text{surf},i}(t) = f_{\text{rem},i} C_{0,i} \left( \left( \lambda_{\text{rem},i} - \lambda_{\text{surf},i} \right) \exp \left[ -\lambda_{\text{rem},i} t \right] + \left( 1 - e^{-\lambda_{\text{surf},i} t} \right) \exp \left[ -\lambda_{\text{surf},i} t \right] \right),
\]

which is equation (40) multiplied by its removable fraction \( f_{\text{rem},i} \). The total surface contamination \( C_{\text{surf,tot},i}(t) \) at time \( t \) is then found by summing equations (65) and (66). Note that from equations (13) and (66) it follows that \( C_{\text{surf,hand},i}(t) \) is now proportional to \( f_{s,i} C_{\text{surf,tot},i}(0) = f_{\text{rem},i} f_{\text{oth},i} C_{0,i} \), where \( f_{s,i} \) is the skin-transfer factor used in EC (1999), as described in section 3.6.

The air concentration is then given by:

\[
C_{\text{air},i}(t) = \frac{c_i}{\lambda_{\text{rem}}} \cdot f_{\text{rem},i} C_{0,i} \left( \exp \left[ -\lambda_{\text{rem},i} t \right] - \exp \left[ -\lambda_{\text{surf},i} t \right] \right) \cdot 10^6
\]

Equations (65-67) can be used for dose evaluations. Parameter \( f_{\text{rem},i} \) is usually unknown or uncertain. The concept of the ‘limiting effective surface dose’ (LESD) (Dillen 2015), guarantees a conservative approach of the problem. It is described in section 5.7.

5. Dose-assessment methodology for exposure pathways

In the assessment of the individual effective dose from exposure to radiological surface contamination, we consider the following pathways:

- External exposure from surface contamination residing on the object’s surface (section 5.1);
- Internal exposure from inhalation of resuspended activity (section 5.2);
- Internal exposure from secondary, hand-to-mouth ingestion (section 5.3);
- External exposure from skin contamination by transfer from the object to hands or other parts of the body (section 5.4).
Other exposure pathways are described in section 5.5. We do not consider external exposure from submersion or cloudshine and from deposition of resuspended activity onto the surroundings (floor/ground, other objects), skin or clothing (section 6.4.7 of IAEA (2005)).

In the following sections, the increment of the individual effective dose $dE^{\text{pathway,}i}_{\text{d}}$ in a time interval $[t, t + dt]$ is derived for each exposure pathway. The annual dose contributions ($\mu$Sv·y$^{-1}$) are evaluated by time integration as $E^{\text{pathway,}i}_{\text{d}}(\Delta T_{\text{tot}})$ for $\Delta T_{\text{tot}} = 8760$ h (1 year) and summed. In section 5.7 we discuss the limiting effective surface dose (Dillen 2015). In section 5.8 we present an overview of all parameters (table 2) and their default values.

5.1. External exposure to gamma radiation from the object’s surface (external gamma radiation)

External exposure to radiation from the object’s contaminated surface is described here for gamma-emitting nuclides only, using the ambient-dose-equivalent-rate approach. For nuclides emitting beta particles below 0.6 MeV, the external-radiation field will mostly lead to exposure of the skin, as a result of their short range in soft tissue (ICRP 2010). Even though the skin equivalent dose may then be elevated locally, its contribution to the effective dose will usually be relatively small due to (1) the low tissue-weighting factor of $w_{\text{skin}} = 0.01$, (2) the probably small fraction of the total skin that is exposed, and (3) shielding by clothing. Moreover, external exposure of the skin is described separately by two pathways: skin contamination from transfer (section 5.4) and contact with the contaminated object (section 5.5). These pathways can be used to include the external-radiation exposure for low-energy beta-emitting nuclides. Beta particles with energies larger than 0.6 MeV also contribute to the effective dose of deeper organs. For irradiation with 1 MeV monoenergetic electrons in the anteroposterior (AP) irradiation geometry, the contribution of the skin to the effective dose is only 24% (ICRP 2010). The aforementioned skin-dose contributions can therefore not serve as a proxy for the external-radiation dose from nuclides emitting highly energetic beta-particles, e.g., Y-90 with energies up to 2.3 MeV.

![Figure 4](image)

**Figure 4.** Schematic illustration of the exposure geometry for external radiation from a contaminated surface $S$ (here a disc-shaped area of radius $R$). The ambient dose rate is calculated at the receptor point (exposed individual) located at a distance $L$ from the center of the surface. The total dose rate is found by point-kernel integration, in which point-source contributions of surface elements $dS$ (with activity $C_{\text{surf,}i,\text{d}}dS$) at a distance $\rho$ from the receptor are added.

We assume that a person, modeled as a point receptor, is located at a distance $L$ (cm) from the center of a surface $S$ (area $A_{\text{cont}}$), homogeneously contaminated with radionuclide $i$ ($C_{\text{surf,}i,\text{d}}$, Bq·cm$^{-2}$), as
illustrated in figure 4. In vacuum, the uncollided ambient dose equivalent rate, \( \hat{H}^\ast (10)_i \) (Sv.h\(^{-1}\)), from the object’s surface can be written as

\[
\hat{H}^\ast (10)_i = h(10)_i C_{\text{surf},i} \int_S \frac{1}{\rho^2} dS \cdot 10^4. \tag{68}
\]

where \( h(10)_i \) is the nuclide’s ambient-dose-equivalent-rate constant (Sv.h\(^{-1}\).m\(^2\).Bq\(^{-1}\)) and \( \rho \) (cm) is the distance of surface-area element \( dS \) (cm\(^2\)) of \( S \) to the receptor (exposed individual). The factor \( 10^4 \text{cm}^2\cdot\text{m}^{-2} \) is included to convert the unit of surface-contamination level to Bq.m\(^{-2}\). We refer to the surface integral in equation (68) as the (dimensionless) geometrical factor \( g(D;L) \)

\[
g(D;L) = \int_S \frac{1}{\rho^2} dS, \tag{69}
\]

which depends on the surface’s dimensions \( D \) and the distance \( L \), with \( \rho = L \) at the center of \( S \). The integrand of equation (69), \( \rho^{-2} \), describes the geometric, inverse-square attenuation and is called the uncollided dose point kernel in vacuum (Shultis and Faw 2000). In case an intermediate, attenuating medium is present between the surface source and the receptor, the point kernel should also include an exponential, material-attenuation factor (shielding) and a dose-buildup factor accounting for scattered radiation. For exposure in air at short distance, the latter can be neglected and thus equations (68) and (69) are used for the evaluation of the external gamma-radiation dose. If, however, a shielding material (e.g., a slab) is present between the source and the receptor and the source is sufficiently far from this material, this dose could be modified by a dimensionless, broad-beam attenuation factor \( f_{\text{att},i} \), as for instance described in Shultis and Faw (2000, pp 229-235). Its value depends on the thickness and type of the shielding material, the characteristics of the emitted radiation and the angle of incidence. The default value of \( f_{\text{att},i} \) in SUDOQU is 1.

Depending on the irradiation geometry (AP, PA, LAT, ISO, ROT) and the energy of the emitted photons, a factor \( f_{\text{conv}} \equiv E_{\text{ext},i}/H^\ast (10)_i \) converts the ambient dose \( H^\ast (10)_i \) to effective dose \( E_{\text{ext},i} \), see ICRP (1996, 2010) and ICRU (1997). For a given irradiation geometry, the mean value \( f_{\text{conv},i} \) for nuclide \( i \) is found by averaging over all emitted photon energies using the emission probabilities as weight factors. Since most photon energies are well below 3 MeV, \( f_{\text{conv},i} \) will usually attain a value smaller than 1 (ICRP 2010, figure 5.2), implying that \( H^\ast (10)_i \) is a conservative estimator of \( E_{\text{ext},i} \).

The default value of \( f_{\text{conv},i} \) is therefore set to 1 (see also Russo et al (2018b)).

Based on these ingredients and equations (68) and (69), the increase in the effective dose from external exposure to gamma radiation in time interval \([t, t+dt]\) is given by

\[
dE_{\text{ext},i}(t) = f_{\text{use}} f_{\text{conv},i} f_{\text{att},i} g(D;L) h(10)_i C_{\text{surf},i}(t) dt \cdot 10^4 \text{(Sv)},
\]

where \( f_{\text{use}} \) is included since exposure occurs during \( f_{\text{use}} \cdot dt \). The effective dose from external gamma-radiation exposure (\( \mu \text{Sv} \)) is then:

\[
E_{\text{ext},i}(t) = g(D;L) h(10)_i f_{\text{conv},i} f_{\text{att},i} T\text{ISC}_{\text{use},i}(t) \cdot 10^{10}. \tag{70}
\]
In equation (70), the product \( g(D; L)h(10)_{\text{conv,i}} \) (Sv.h\(^{-1}\).m\(^2\).Bq\(^{-1}\)) is the effective dose rate conversion coefficient \( DC_{\text{ext,i}}(D; L) \) for the surface geometry under consideration. The source constant \( h(10)_{\text{i}} \) can be found in (Tschurlovits et al. 1992), (SSK 2000) and (Keverling-Buisman 2015).

The default geometry of the object’s surface is assumed to be a disc of radius \( R \), as drawn in figure 4. The geometrical factor from equation (69) at a perpendicular distance \( L \) from its center is (Johnson and Birky 2012):

\[
g_{\text{disc}}(R; L) = \pi \ln \left[ 1 + \left( \frac{R}{L} \right)^2 \right] = \pi \ln \left[ 1 + \frac{A_{\text{cont}}}{\pi L^2} \right].
\]  

(71)

For distances \( L \gg R \), this approaches the geometrical factor of a point source, \( \pi R^2/L^2 = A_{\text{cont}}/L^2 \).

For calculations in this paper, the default value of \( R \) is 17.8 cm \( (A_{\text{cont}} = 1000 \text{ cm}^2, \text{table 1}) \), and of \( L \) is 60 cm, resulting in a geometrical factor of 0.266. For many other geometries, equation (71) will usually give a fair approximation (or proxy) providing a conservative value of the actual geometrical factor, with \( R = \sqrt{A_{\text{cont}}/\pi} \). Deviations from the disc-geometry are represented by a geometrical correction factor \( g_{\text{cor}} \), such that \( g_{\text{disc}}(R; L) \approx g_{\text{cor}} \cdot g_{\text{disc}}(R; L) \). The default value of \( g_{\text{cor}} \) is 1.

5.2. Internal exposure from inhalation of resuspended activity

Inhalation of resuspended activity leads to internal contamination and thus to a committed effective dose. In a time interval \( [t, t+dt] \), the inhaled activity (Bq) is \( C_{\text{air,i}}(t) f_{\text{resp,i}} \text{cor}_{\text{air,i}} I \cdot dt \), where \( C_{\text{air,i}}(t) \) is the air-contamination level (Bq.m\(^{-3}\)) described in section 3.3, \( f_{\text{resp,i}} \) is the respirable fraction (fraction of airborne activity for inhalation) and \( I \) the breathing rate (m\(^3\).h\(^{-1}\)). An optional correction factor \( \text{cor}_{\text{air,i}} \geq 1 \) can take account of the inhomogeneity of the air concentration as discussed in section 3.3. A value of \( \text{cor}_{\text{air,i}} < 1 \) can be chosen if protective breathing equipment is used. The default values of \( f_{\text{resp,i}} \) and \( \text{cor}_{\text{air,i}} \) are 1, and the breathing rate is set to 1.2 m\(^3\).h\(^{-1}\), the average respiratory rate of a reference worker during an 8-hour working day (ICRP 1994). Other values may be chosen depending on the gender, age and physical activity and can be found in ICRP Publication 89 (ICRP 2002). The increase in the committed effective inhalation dose is thus \( dE_{\text{inh,i}}(t) = DC_{\text{inh,i}} C_{\text{air,i}}(t) f_{\text{resp,i}} \text{cor}_{\text{air,i}} I \cdot dt \) (Sv), where \( DC_{\text{inh,i}} \) is the nuclide’s effective dose coefficient for inhalation. A compilation of dose coefficients \( DC_{\text{inh,i}} \) for both workers and members of the public is published in ICRP Publication 119 (ICRP 2012). These coefficients are based on the Publication 60 recommendations (ICRP 1991) and will be replaced in due course by new coefficients based on the Publication 103 recommendations (ICRP 2007). The committed effective dose from inhalation, \( E_{\text{inh,i}}(t) \) (μSv), is

\[
E_{\text{inh,i}}(t) = DC_{\text{inh,i}} f_{\text{resp,i}} \text{cor}_{\text{air,i}} I \cdot \text{TIC}_{\text{use,i}}(t) \cdot 10^6,
\]

(72)

where we used equation (8).

5.3. Internal exposure from secondary, hand-to-mouth ingestion

Part of the surface contamination can enter the body by secondary ingestion. First, the hands get contaminated by touching the object. In a time interval \( [t, t+dt] \), this leads to a homogeneous skin-
contamination level of \( \bar{C}_{\text{surf},i}(t) \) over an area of \( A_{\text{hands}} \) for an effective duration of \( m_{\text{hands},i} \cdot f_{\text{use}} \cdot dt \) as discussed in section 3.8. Per secondary ingestion event, the amount of activity ingested (Bq) is a fraction of the activity on the hands: \( \bar{C}_{\text{surf},i} \cdot (A_{\text{hands}} \cdot f_{\text{ing}}) \cdot F_{\text{hm},i} \). Here, \( f_{\text{ing}} \) is the fraction of the area of the hands from which ingestion occurs (i.e., \( f_{\text{ing}} \cdot A_{\text{hands}} \) is the hands’ area for ingestion) and \( F_{\text{hm},i} \) is the average transfer factor from the hands to the mouth, with values always \( \leq 1 \) (\( F_{\text{hm},i} \) is comparable to the average transfer factor \( F_{\text{i}} \) for wipe-off). With \( \Phi_{\text{ing}} \) (h\(^{-1}\)) being the secondary ingestion frequency, the increase in the committed effective dose reads:

\[
E_{\text{ing},i}(t) = D_{\text{ing},i} \cdot \bar{C}_{\text{surf},i} \cdot f_{\text{hm},i} \cdot f_{\text{ing}} \cdot m_{\text{hands},i} \cdot A_{\text{hands}} \cdot \Phi_{\text{ing}} \cdot TISC_{\text{use},i}(t) \cdot 10^6, \tag{73}
\]

which can, by use of equation (28), be written as:

\[
E_{\text{ing},i}(t) = D_{\text{ing},i} \cdot F_{\text{hm},i} \cdot f_{\text{ing}} \cdot A_{\text{hands}} \cdot \Phi_{\text{ing}} \cdot TISC_{\text{hands},i}(t) \cdot 10^6. \tag{74}
\]

The following values are used for the additional parameters: \( F_{\text{hm},i} = 1.0, f_{\text{ing}} = 0.01 \) (see IAEA (2005)) and \( \Phi_{\text{ing}} = \bar{\Phi}_{\text{use}} = 0.25 \text{ h}^{-1} \). As for inhalation (section 5.2), dose coefficients \( D_{\text{ing},i} \) for both workers and members of the public are also published in ICRP Publication 119 (ICRP 2012). If the value of \( m_{\text{hands},i} \cdot \Phi_{\text{ing}} \) is larger than that of \( \bar{\Phi}_{\text{use}} \), a single wipe-off event is associated with more than one secondary ingestion event and care should then be taken that not more activity is (modeled to be) ingested than actually transferred to the hands. The ratio of both frequencies (event rates), \( \Phi_{\text{ing}} / \bar{\Phi}_{\text{use}} \), should therefore not exceed a certain maximum value, given by:

\[
\Phi_{\text{ing}} / \bar{\Phi}_{\text{use}} \leq \left( m_{\text{hands},i} \cdot F_{\text{hm},i} \cdot f_{\text{ing}} \right)^{-1}. \tag{75}
\]

Based on the default values used here (\( m_{\text{hands},i} = 1.0, F_{\text{hm},i} = 1.0 \) and \( f_{\text{ing}} = 0.01 \)), the ratio should remain below 100. Since we use \( \Phi_{\text{ing}} = \bar{\Phi}_{\text{use}} \), equation (75) is satisfied in our calculations.

5.4. External exposure from skin contamination by transfer

The transfer of contamination from the object to the hands not only leads to a committed effective dose from secondary ingestion (section 5.3), but also directly leads to external exposure of skin tissue. To protect the skin from harmful, tissue-reaction (deterministic) effects, the local skin-equivalent dose should not exceed the corresponding annual dose limit (ICRP 2007): 50 mSv.y\(^{-1}\) for public exposure and 500 mSv.y\(^{-1}\) for occupational exposure. These limits apply to the dose averaged over 1 cm\(^2\) (i.e., local) irrespective of the area exposed, and they refer to the skin area of highest exposure.

In a time interval \([t, t + dt]\), we model the skin of the hands to be exposed to its maximum level of contamination after a wipe-off event, \( \bar{C}_{\text{surf},i}(t) \), for a duration of \( m_{\text{hands},i} \cdot f_{\text{use}} \cdot dt \) as discussed in section 3.8. The increase in the local skin-equivalent dose (Sv) is given by

\[
dH_{\text{skin,hand},i}(t) = D_{\text{skin},i} \cdot \bar{C}_{\text{surf},i}(t) \cdot (m_{\text{hands},i} \cdot f_{\text{use}}) \cdot 3600, \tag{76}
\]

with \( D_{\text{skin},i} \) (Sv.s\(^{-1}\).cm\(^2\).Bq\(^{-1}\)) the
local skin-equivalent dose rate conversion coefficient (and 3600 s.h\(^{-1}\) a conversion factor). The local skin-equivalent dose of the hands (\(\mu \text{Sv}\)) is:

\[
H_{\text{skin, hands}, i}(t) = DC_{\text{skin, } i} \cdot T_{\text{other, } i} \cdot m_{\text{hands, } i} \cdot TISC_{\text{use, } i}(t) \cdot 3.6 \cdot 10^9 \\
= DC_{\text{skin, } i} \cdot TISC_{\text{hands, } i}(t) \cdot 3.6 \cdot 10^9,
\]

where we used a conversion factor of \(10^6 \mu \text{Sv.Sv}^{-1}\). For the local skin-equivalent dose of the face (\(\mu \text{Sv}\)) we can write a similar equation:

\[
H_{\text{skin, face}, i}(t) = DC_{\text{skin, } i} \cdot T_{\text{other, } i} \cdot m_{\text{face, } i} \cdot TISC_{\text{use, } i}(t) \cdot 3.6 \cdot 10^9 \\
= DC_{\text{skin, } i} \cdot TISC_{\text{face, } i}(t) \cdot 3.6 \cdot 10^9,
\]

where we used equation (30). Both annual equivalent doses should remain below the public or occupational dose limit. The local skin-equivalent dose rate conversion coefficients are taken from the German Commission on Radiological Protection (SSK 1989, 1992). These coefficients include contributions from beta and gamma radiation, the latter calculated under the assumption that the entire skin surface is contaminated. They are calculated by averaging the absorbed dose over the sensitive basal layer between 50 \(\mu\)m and 100 \(\mu\)m (nominal depth of 70 \(\mu\)m or 7 mg.cm\(^{-2}\) (ICRP 1991, para 173)). For nuclides emitting alpha particles with energies larger than 6 MeV, a significant contribution can be expected as well (SSK 2000, ICRP 2010). New coefficients for beta contamination (generally the most relevant component) based on ICRP Publication 116 (ICRP 2010, Annex G) have recently become available (Bourgois et al 2017). The skin tissue weighting factor for stochastic effects is \(w_{\text{skin}} = 0.01\). For a uniform, full-body skin contamination (and exposure), the contribution to the effective dose \(E_{\text{skin}}\) is evaluated as the product of \(H_{\text{skin}}\) (the local skin-equivalent dose) and \(w_{\text{skin}}\). To calculate \(E_{\text{skin}}\) from partial skin contamination, we use the methodology described in NRPB (1997), which is closely related to ICRP Publication 59 (ICRP 1992). According to this method, the radiosensitivity varies with the skin area. UVR-exposed sites (face, neck, outer aspects of hands and arms) are about thousand times more radiosensitive than UVR-shielded sites, because of already accumulated DNA-damage. This characteristic is included as modifying factor \(m_{\text{f, skin}}\), which is 1 for UVR-exposed skin of total area \(A_{\text{skin, total}} = 3000 \text{ cm}^2\) and \(10^{-3}\) for UVR-shielded skin of total area \(A_{\text{skin, total}} = 15000 \text{ cm}^2\). The effective dose (\(\mu\text{Sv}\)) from partial skin contamination by transfer is:

\[
E_{\text{skin}} = m_{\text{f, skin}} \cdot H_{\text{skin, } i} \cdot w_{\text{skin}} \cdot A_{\text{skin, cont}} / A_{\text{skin, total}},
\]

with \(A_{\text{skin, cont}} \text{ (cm}^2\) the radioactively contaminated area of UVR-exposed or UVR-shielded skin. For the same value of \(A_{\text{skin, cont}}\), the contribution from UVR-shielded skin is thus 5000 times smaller than that from UVR-exposed skin. For conservative dose calculations we treat the palm-side of the hands as UVR-exposed, similar to the approach in IAEA (2005). The contributions to the effective dose by transfer of contamination from object to hands \((A_{\text{skin, cont}} = A_{\text{hands}})\) and from hands to face \((A_{\text{skin, cont}} = A_{\text{face}})\) are

\[
E_{\text{skin, hands, } i}(t) = DC_{\text{skin, } i} \cdot T_{\text{other, } i} \cdot m_{\text{hands, } i} \cdot w_{\text{skin}} \cdot A_{\text{hands}} / A_{\text{skin, total}} \cdot TISC_{\text{use, } i}(t) \cdot 3.6 \cdot 10^9
\]

and
respectively. In contrast to the method applied here, one may decide to ignore the distinction between UVR-exposed and UVR-shielded skin areas, as in EC (1993, 1999). Equations (79) and (80) remain valid but should then employ a value of $A_{skin,total} = 18000 \text{ cm}^2$. Finally, if the skin is protected by clothes (e.g., gloves) one may need to apply an attenuation factor resulting from the shielding of alpha and beta particles.

5.5. Additional exposure pathways

We describe two additional pathways:
- Exposure of the skin by direct contact with the object;
- Direct ingestion of activity from the object (mouthing).

During use of the object, the skin will be in direct contact with the contaminated object. The evaluation of the direct, skin-object contact dose contribution is in line with the approach in section 5.4. Similar to equation (27), we write the duration of direct contact (in h or h.y$^{-1}$) as $\Delta T_{use} = m_{use}$ where the value of $m_{use}$ should be $\leq 1$. Since the skin is directly exposed to the object’s contamination $C_{surf,i}$, its time-integrated value is now $TISC_{use,i} = m_{use} TISC_{total}$. For the local skin-equivalent dose and its contribution to the effective dose ($\mu$Sv), we therefore have

$$H_{skin,contact,i}(t) = DC_{skin,i} m_{skin,contact} TISC_{use,i}(t) \cdot 3.6 \cdot 10^9,$$

(81)

$$E_{skin,contact,i}(t) = DC_{skin,i} m_{skin,contact} w_{skin} A_{skin,contact} A_{skin,total} TISC_{use,i}(t) \cdot 3.6 \cdot 10^9,$$

(82)

respectively. $A_{skin,contact}$ (cm$^2$) is the area of direct contact which is assumed to be UVR-exposed (and thus $A_{skin,total} = 3000 \text{ cm}^2$ as used). Equations (81) and (82) are relevant for exposure scenarios in which one holds the object or leans on or against it for a significant amount of time. Note that this skin-contact exposure is also relevant for fixed surface contaminations (i.e., for $f_{rem,i} = 0$).

Ingestion of radionuclides may also occur directly when the object is brought in contact with the mouth. Mouthing may be the case for children’s toys. Per direct ingestion event, the object’s area contacted by the mouth is denoted as $A_{dir,ing}$ (cm$^2$) and the average transfer factor of contamination as $F_{otm,i}$ (otm: object-to-mouth). Note that $A_{dir,ing}$ and $F_{otm,i}$ compare with $A_{touched}$ and $F_1$ for wipe-off, respectively (section 3.6). The product $A_{dir,ing} F_{otm,i}$ thus compares with $A_{touched} F_1$ and thus with $A_{hands} F_{oth,i}$ as seen from equation (22). With $f_{dir,ing}$ (h$^{-1}$) being the direct-ingestion frequency, the corresponding time-averaged removal constant becomes (see equation (17) for wipe-off with the aforementioned replacements):
\[
\langle A_{\text{dir,ing}} \rangle = f_{\text{use}} \bar{A}_{\text{dir,ing}} = f_{\text{use}} F_{\text{om,dir}} \bar{A}_{\text{dir,ing}} \left( \frac{A_{\text{dir,ing}}}{A_{\text{cont}}} \right),
\]

(83)

with \( \bar{A}_{\text{dir,ing}} \) its mean value during use. For the calculation of contamination levels, equation (83) should be incorporated into \( \lambda_{\text{surf},i} \), i.e., \( \lambda_{\text{surf},i} = \lambda_{\text{r},i} + f_{\text{use}} \left( \bar{x}_{\text{use},i} + \bar{x}_{\text{wo,use},i} + \bar{x}_{\text{dir,ing},i} \right) \). Direct ingestion leads to an additional committed effective dose (\( \mu \text{Sv} \)), given by:

\[
E_{\text{dir,ing}}(t) = DC_{\text{ing},i} F_{\text{om,dir}} \bar{A}_{\text{dir,ing}} \cdot TISC_{\text{use},i} (t) \cdot 10^6.
\]

(84)

Further details on mouthing behavior (mostly of young children) can for instance be found in U.S. EPA (2011b).

5.6. Total (annual) effective dose

At each time \( t \), the total effective dose (\( \mu \text{Sv} \)) is the sum of all dose contributions of the relevant pathways. Hence, at the end of the scenario, at \( t = \Delta T_{\text{tot}} \), it is given by (for nuclide \( i \)):

\[
E_{\text{tot},i} (\Delta T_{\text{tot}}) = f_{\text{cont}} \cdot \sum_{\text{pathways}} E_{\text{pathway},i} (\Delta T_{\text{tot}}),
\]

(85)

where \( f_{\text{cont}} \) is the fraction of items that is contaminated. For the worker model (\( \delta = 0 \)), the default value of \( f_{\text{cont}} \) is 1, and for the consumer (\( \delta = 1 \)), who uses only one item, \( f_{\text{cont}} \) is 1 by definition. For \( \Delta T_{\text{tot}} = 1 \text{ year} \), the total annual dose from equation (85) can be compared with the annual dose criterion to estimate a (nuclide-specific) ‘derived limiting value’ for radiological surface contamination.

5.7. Conservatism and the limiting effective surface dose (LESD)

Dose evaluations should be sufficiently conservative to guarantee adequate protection. A too conservative dose estimate, however, leads to unrealistically overprotective and impracticable implementation of protection measures. One should therefore carefully choose a suitable dose criterion and a proper level of conservatism to ensure an optimized level of radiation protection.

In the IAEA-CRP model (\( \delta = 0 \)), more conservatism is achieved by simply increasing the exchange parameters (surface-to-human, surface-to-air, air-to-human), because the surface-contamination level is assumed to remain unchanged and the exposure pathways to be independent. In contrast with this, in the RIVM-SUDOQU model (\( \delta = 1 \)), the adoption of larger (stronger) exchange parameters does not guarantee a more conservative approach. This is because, via the mass-balance equations, the relative dose incurred by the use of the contaminated object is merely redistributed over the model’s interdependent pathways. The absolute, total dose can then even decrease, since the increase in a certain dose contribution could be at the expense of another, more dominant contribution (Russo et al. 2018a, 2018b). Consequently, it is not straightforward to judge and guarantee the level of conservatism that is required when one is deriving criteria for surface contamination. A similar reasoning applies to (the consequences of) modification of the removable fraction \( f_{\text{rem},i} \), which was set to 1 (section 2.2).

To target these issues of conservatism, the concept of Limiting Effective Surface Dose (LESD) was introduced in Dillen (2015). Four limiting exposure scenarios are defined and analyzed by the RIVM-SUDOQU model (with \( \delta = 1 \)). Each scenario is constructed such that one or two constituents of the total effective dose are amplified. In this way, four conservative values of the total effective dose (\( \text{LESD}_1 \) to \( \text{LESD}_4 \), in \( \mu \text{Sv} \), or in \( \mu \text{Sv} \cdot \text{y}^{-1} \) as described in section 2.3) can be found. Based on the
exposure pathways from sections 5.1 to 5.4, the limiting scenarios are defined as follows (dose contributions in parentheses, amplified exposure pathways in *italics*): all surface contamination is

1. fixed (external radiation);
2. removable, but only by resuspension (external radiation, inhalation);
3. removable, but only by wipe-off (external radiation, secondary ingestion, skin contamination);
4. removable, by resuspension and wipe-off (external radiation, inhalation, secondary ingestion, skin contamination).

The fourth scenario, with both resuspension and wipe-off, corresponds to the full RIVM-SUDOQU model as described earlier, including all pathways. These scenarios are evaluated as follows:

**Limiting scenario 1:** a fixed surface contamination can be modeled as a removable one without resuspension \((\bar{\xi}_{\text{use},i} = 0 \ h^{-1})\) and wipe-off \((\bar{\lambda}_{\text{oth},i} = 0, \text{and thus } \bar{\xi}_{\text{wo,use},i} = 0 \ h^{-1})\). The only remaining dose contribution is that of exposure to external radiation, *i.e.*,

\[
\text{LESD}_{1,j} = E_{\text{tot},j}(\Delta T_{\text{tot}})\hat{\xi}_{\text{use},i} = 0, \bar{\lambda}_{\text{oth},i} = 0 = E_{\text{ext},j}(\Delta T_{\text{tot}})_{\hat{\xi}_{\text{use},i} = 0, \bar{\lambda}_{\text{oth},i} = 0} \tag{86}
\]

which can be written as:

\[
\text{LESD}_{1,j} = g(D;L)h(10)^{1} f_{\text{conv},i} f_{\text{att},i} C_{0,i} \Psi(\lambda_{\text{tot}}) \Delta T_{\text{tot}} 10^{10}, \tag{87}
\]

as follows from equation (70) with \(TISC_{\text{use, fixed},i}(\Delta T_{\text{tot}}) = C_{0,i} \Psi(\lambda_{\text{tot}}) \Delta T_{\text{tot}} \text{TISC}_{\text{use}}\) from equation (61).

Since surface activity only decreases by radioactive decay, this external-radiation dose is larger than that in the other limiting scenarios.

**Limiting scenario 2:** in this scenario no wipe-off occurs \((\bar{\xi}_{\text{wo,use},i} = 0 \ h^{-1})\), and thus no indirect ingestion and no skin contamination. This scenario reflects the use of the object without touching it, such that resuspension can still occur. It could be described by setting the wipe-off frequency \(\bar{\xi}_{\text{use}}\) to 0 \ h^{-1}, as well as the time-multiplication factors \(m_{\text{hands},i} = m_{\text{face},i} = 0\), the latter forcing the ingestion and skin dose contributions to 0 \(\mu\text{Sv}.\text{y}^{-1}\) (note: for \(\bar{\xi}_{\text{use}} \to 0 \ h^{-1}\), the average duration of wipe-off event during use is \(\to \infty\) from equation (21)). This implies that a contamination level on the skin does not build up in time and thus that \(m_{\text{hands},i} \text{ and } m_{\text{face},i} \text{ are 0})\). Numerically, the same can be achieved by only setting transfer efficiency \(\bar{\lambda}_{\text{oth},i} \to 0\), and thus we write

\[
\text{LESD}_{2,j} = E_{\text{tot},j}(\Delta T_{\text{tot}})_{\bar{\lambda}_{\text{oth},i} = 0} = \left( E_{\text{ext},j} + E_{\text{inh},i} \right)(\Delta T_{\text{tot}})_{\bar{\lambda}_{\text{oth},i} = 0} \tag{88}
\]

Since only resuspension is considered, the air-activity concentration will be highest among the four scenarios and will lead to the highest effective inhalation dose.

**Limiting scenario 3:** there is no resuspension \((\bar{\xi}_{\text{use},i} = 0 \ h^{-1})\) and therefore no inhalation dose. The LESD of this scenario is

\[
\text{LESD}_{3,j} = E_{\text{tot},j}(\Delta T_{\text{tot}})_{\bar{\xi}_{\text{use},i} = 0} = \left( E_{\text{ext},j} + E_{\text{ing},i} + E_{\text{skin},i} \right)(\Delta T_{\text{tot}})_{\bar{\xi}_{\text{use},i} = 0} \tag{89}
\]
with \( E_{\text{skin},i} (\Delta T_{\text{tot}}) = E_{\text{hands},i} (\Delta T_{\text{tot}}) + E_{\text{face},i} (\Delta T_{\text{tot}}) \) as described in section 5.4. With respect to the other limiting scenarios, wipe-off related contributions of secondary ingestion and skin contamination will be largest in this scenario.

Limiting scenario 4: is the full RIVM-SUDOQU model with:

\[
LES_{D,4,i} = E_{\text{tot},i} (\Delta T_{\text{tot}}) \delta_{\text{ext}} = \left\{ E_{\text{ext},i} + E_{\text{inh},i} + E_{\text{ing},i} + E_{\text{skin},i} \right\} (\Delta T_{\text{tot}})^{\delta_{\text{ext}}} \, , \tag{90}
\]

with \( E_{\text{skin},i} (\Delta T_{\text{tot}}) = E_{\text{hands},i} (\Delta T_{\text{tot}}) + E_{\text{face},i} (\Delta T_{\text{tot}}) \).

If direct skin-contact exposure is an additional pathway to consider, each scenario would also contain an extra contribution \( E_{\text{skin,contact},i} \), of which the contribution would be largest in the first scenario.

Based on the description of scenario 2 one could decide to ignore the skin-contact exposure in the second, limiting scenario (more realistic), but for reasons of conservatism it could be included as well. If direct ingestion is relevant, then a contribution \( E_{\text{dir,ing}} \) should be included. The limiting scenarios need to be slightly redefined and the set of scenario’s has to be complemented with a fifth one in which surface contamination is only removed by direct ingestion.

The conservatism that is needed for the derivation of limiting values can be found by taking the maximum value of these limiting effective surface doses (\( \mu Sv \cdot y^{-1} \)), i.e.,

\[
MLES_{D,i} = \max \left[ LES_{D,k,i}, k \in \{1,2,3,4\} \right] . \tag{91}
\]

We recommend considering these scenarios, even though they may not always be realistic.

5.8. Summary of default parameter values for dose calculations

In addition to the default parameter values summarized in section 3.9, table 2 is a continuation of table 1 listing all default values of the parameters introduced in section 5. They are used for dose calculations in section 6.

**Table 2.** Summary of input parameters of the dose-assessment and default values for calculations in this paper. For more details, see relevant sections.

\* This amounts to a default area of 1000 cm² (table 1)

\** Per secondary ingestion event

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Sect.</th>
<th>Default value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_{\text{att},i} )</td>
<td>Attenuation factor from shielding</td>
<td>5.1</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>( f_{\text{conv},i} )</td>
<td>Conversion factor from ( H^*(10) ) to ( E_{\text{ext},i} )</td>
<td>5.1</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>( R )</td>
<td>Radius of (disk-shaped) object</td>
<td>5.1</td>
<td>17.8</td>
<td>cm</td>
</tr>
<tr>
<td>( L )</td>
<td>Distance to center of (disk-shaped) object</td>
<td>5.1</td>
<td>60</td>
<td>cm</td>
</tr>
<tr>
<td>( \text{cor}_{g} )</td>
<td>Geometrical correction factor</td>
<td>5.1</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>( f_{\text{resp},i} )</td>
<td>Respirable fraction</td>
<td>5.2</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>( \text{cor}_{\text{pdc},i} )</td>
<td>Correction factor for local air-contamination</td>
<td>5.2</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>( I )</td>
<td>Breathing rate</td>
<td>5.2</td>
<td>1.2</td>
<td>m³/h</td>
</tr>
<tr>
<td>( f_{\text{ing}} )</td>
<td>Fraction of area of hands for ingestion</td>
<td>5.3</td>
<td>0.01**</td>
<td>-</td>
</tr>
<tr>
<td>( F_{\text{hbm},i} )</td>
<td>Average transfer factor (hands-to-mouth)</td>
<td>5.3</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>( \Phi_{\text{ing}} )</td>
<td>Secondary ingestion frequency</td>
<td>5.3</td>
<td>0.25</td>
<td>h⁻¹</td>
</tr>
</tbody>
</table>
6. Examples for indoor exposure

In this section, our methodology is demonstrated for a set of indoor exposure situations (see table 1 and 2 for input-parameter values). We used the Mathematica environment (Wolfram Research, Inc. Mathematica Version 11.0.1.0, Champaign, IL, 2016) for evaluations and graphs in this paper. Some calculations were verified using a Microsoft Excel spreadsheet. For a convenient overview of the implemented equations (sections 2 through 5), we refer to the supplementary material.

In section 6.1 we list the nuclides and their dose (rate) coefficients used for these calculations. In section 6.2, we study the long-lived radionuclide Cs-137 (the dominant, remaining radionuclide long after an accident at a nuclear power plant). This is compared with similar evaluations for other nuclides in section 6.3. Calculations are shown for both the RIVM-SUDOQU model (\(\delta=1\)) and for the IAEA-CRP model (\(\delta=0\)).

6.1. Nuclides and their dose (rate) coefficients

In table 3 we list the nuclides used in the example calculations in sections 6.2 and 6.3 and their characteristics.

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Main type of emission</th>
<th>(T_{1/2,j})</th>
<th>(h(10))</th>
<th>(DC_{inh,j})</th>
<th>(DC_{ing,j})</th>
<th>(DC_{skin,j})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cs-137+</td>
<td>(\beta,\gamma)</td>
<td>30.0 y</td>
<td>9.3×10^{-12}</td>
<td>4.6×10^{-9} (F)</td>
<td>1.3×10^{-8}</td>
<td>4.5×10^{-10}</td>
</tr>
<tr>
<td>I-131</td>
<td>(\beta,\gamma)</td>
<td>8.04 d</td>
<td>6.6×10^{-14}</td>
<td>7.4×10^{-9} (F)</td>
<td>2.2×10^{-8}</td>
<td>4.0×10^{-10}</td>
</tr>
<tr>
<td>Co-60</td>
<td>(\beta,\gamma)</td>
<td>5.271 y</td>
<td>3.6×10^{-13}</td>
<td>1.0×10^{-9} (M)</td>
<td>3.4×10^{-9}</td>
<td>3.0×10^{-10}</td>
</tr>
<tr>
<td>Sr-90+</td>
<td>(\beta)</td>
<td>29.12 y</td>
<td>-</td>
<td>3.7×10^{-9} (M)</td>
<td>3.1×10^{-9}</td>
<td>9.0×10^{-10}</td>
</tr>
<tr>
<td>Am-241</td>
<td>(\alpha,\gamma)</td>
<td>432.2 y</td>
<td>1.7×10^{-14}</td>
<td>4.2×10^{-5} (M)</td>
<td>2.0×10^{-1}</td>
<td>5.0×10^{-12}</td>
</tr>
</tbody>
</table>

Cs-137 is assumed to be in secular equilibrium with its daughter nuclide Ba-137m (half-life of 2.55 min), and Sr-90 with its daughter Y-90 (half-life of 64 h), which is indicated by the “+”. The half-lives are converted to physical decay constants by \(\lambda_j = \ln(2)/T_{1/2,j}\) in h^{-1}. Values of \(h(10)\) are taken from Keverling-Buisman (2015), and values of \(DC_{inh,j}\) and \(DC_{ing,j}\) from ICRP (2012). For inhalation and ingestion we used values for an adult member of the public. Values of \(DC_{skin,j}\) are taken from SSK (1989, 1992). In secular equilibrium, the dose coefficients should be summed using a weighting factor equal to the branching ratio (0.946 for Cs-137+ and 1 for Sr-90+). Hence, for Cs-137+ and Sr-90+, values in table 3 are the resulting values after summation. For Cs-137 a summation is only required for \(DC_{skin,j}\), because for the other pathways the contribution of progeny is already included in the DC of the parent.

6.2. Example calculations for Cs-137+ (results and discussion)
In this example, an adult member of the public uses an object for 2000 h.y⁻¹ in a square ventilated room as illustrated in figure 3. The disk-shaped object is homogeneously contaminated with 1 Bq.cm⁻² Cs-137⁺ over a surface area of 1000 cm² (radius of 17.8 cm). This example is similar to the one described in Dillen (2015), but yields slightly different results due to small differences in input parameters (see tables 1, 2 and 3). With these input-parameter values, the components of the surface-removal constant are: \( \lambda_{s,s} = 2.6 \times 10^{-6} \text{ h}^{-1} \), \( f_{\text{use},s} = 2.3 \times 10^{-5} \text{ h}^{-1} \) and \( f_{\text{use},w} = 2.3 \times 10^{-3} \text{ h}^{-1} \). From this it follows that wipe-off is the dominant surface-removal mechanism. Results are shown in figure 5. The total activity wiped off the object’s surface (as a fraction of the initial surface activity \( C_{0,s}A_{\text{cont}} = 1000 \text{ Bq} \)) is calculated as

\[
\frac{f_{\text{other}} \phi_{\text{use},s} A_{\text{hands}} TISC_{\text{use},s}(t)}{C_{0,s} A_{\text{cont}}} = \lambda_{\text{wo,use},s} TISC_{\text{use},s}(t) / C_{0,s} \tag{92}
\]

Its time dependence is plotted in figure 5(a).

**Figure 5.** Time evolution of (a) the fraction of activity wiped off, (b) the object’s surface-contamination level, (c) the room’s air-contamination level and (d), the total effective dose from all exposure pathways (external gamma radiation, inhalation, ingestion and skin contamination) incurred by the person using the object. Results are shown for the RIVM-SUDOQU consumer model (solid lines) and the IAEA-CRP worker model (dashed lines).

In the IAEA-CRP model (dashed curves) the fraction of the activity wiped off increases linearly until the activity of exactly one object is completely wiped off, which is after 18.25 d (438 h). Due to the absence of mass-balance requirements, this fraction continues to increase linearly and reaches a value of 20 after one year. Hence, after a year the total (initial) surface activity of 20 objects is wiped off.
This is only possible when one continuously deals with a fresh contamination each time the object is used or handled. If, in addition, the exposure duration per item is relatively short, the level of contamination \( C_{\text{surf},i} \) one deals with is more or less constant (i.e., at \( C_{0,i} = 1 \, \text{Bq/cm}^2 \)), as illustrated in figure 5(b). For the RIVM-SUDOQU-model (solid curves), which deals with only one contaminated item, figure 5(a) shows that the activity wiped off the object’s surface does not exceed the initial, total activity. The fraction evaluated by equation (92) now saturates at a value slightly smaller than 1 since part of the activity has become airborne by resuspension (note: radioactive decay can be neglected here due to the relatively long half-life of 30 years compared to the 60 days of object use in figure 5). The surface contamination, starting at its initial value of 1.0 Bq.cm\(^{-2}\), now decreases exponentially with an effective, wipe-off dominated half-life of 12.7 d (304 h) as calculated by equation (19). After about 60 days, most of the surface activity has been removed by wipe-off and the object is effectively clean.

Figure 5(c) shows the air-contamination level \( C_{\text{air},i} \) in the room. For the IAEA-CRP model it rapidly increases and reaches a steady-state saturation value of \( f_{\text{use,}0} \bar{F}_{\text{use,i}} C_{0,i}^{\text{cond}} \frac{10^6}{(V \lambda_i)} = 3.7 \times 10^{-4} \, \text{Bq.m}^{-3} \) (see equation (48)) after about \( 5 \cdot \ln 2 / \lambda_i = 7 \) h (5 air-change cycles), which is maintained throughout the year. In the SUDOQU-RIVM model, the air-contamination level also increases rapidly, but now reaches a maximum value of \( 0.93 \times 10^{-4} \, \text{Bq.m}^{-3} \) at about 3.5 h, after which it decreases exponentially with the same effective half-life as that of the surface contamination (12.6 d). During this exponential decrease, the ratio of \( C_{\text{air},i} \) and \( C_{\text{surf},i} \), the resuspension factor, therefore remains constant. The fact that the maximum level of \( 0.93 \times 10^{-4} \, \text{Bq.m}^{-3} \) is smaller than the steady-state saturation value in the IAEA-CRP model is related to the absence of deposition in the latter model.

Figure 5(d) shows the evolution of the total effective dose (all pathways included) incurred by the person using the object. Since the contamination levels in the IAEA-CRP model remain constant throughout the year, the individual contributions and thus the resulting total effective dose increase linearly with time. As can be seen from figure 5(d), it attains a value of 0.59 \( \mu \text{Sv} \) after 60 d and thus a value of 3.57 \( \mu \text{Sv.y}^{-1} \). In the SUDOQU-RIVM model, the dose initially increases linearly with time, similar to the IAEA-CRP model, but quickly levels off and reaches a (maximum) saturation value of 0.18 \( \mu \text{Sv} \). The dose saturates because the object is clean after 60 days. The annual total effective dose in the IAEA-CRP model is about 20 times larger than that in the RIVM-SUDOQU model. The fact that this dose-ratio is the same as the ratio found earlier for the annual fraction of activity wiped off, implies that the relative behavior of the curves in figures 5(a) and 5(d) is similar. The total effective dose in this example is therefore dominated by contributions that are proportional to \( TIS_{\text{use,i}} \).

The right, two columns of table 4 list the annual effective dose results of both models as presented in figure 5(d), together with a specification of the contributions of the exposure pathways. The contribution of secondary ingestion is dominant, accounting for 73% of the annual total effective dose in both models.
Table 4. Annual effective dose results for a homogeneous surface contamination with 1.0 Bq cm\(^{-2}\) Cs-137\(^+\) over a disk-shaped area of 1000 cm\(^2\). Values are in \(\mu\)Sv y\(^{-1}\). Listed are contributions of the limiting effective surface doses (\(LESD_{4}\) with \(\delta=1\)), where \(LESD_4\) refers to the RIVM-SUDOQU model. Results are also listed for the IAEA-CRP model (\(\delta=0\)).

<table>
<thead>
<tr>
<th>pathway</th>
<th>(LESD_1)</th>
<th>(LESD_2)</th>
<th>(LESD_3)</th>
<th>(LESD_4)_RIVM-SUDOQU</th>
<th>(E_{pathway})_{IAEA-CRP}</th>
</tr>
</thead>
<tbody>
<tr>
<td>External</td>
<td>0.489</td>
<td>0.444</td>
<td>0.025</td>
<td>0.024</td>
<td>0.495</td>
</tr>
<tr>
<td>Inhalation</td>
<td>-</td>
<td>0.004</td>
<td>-</td>
<td>0.000</td>
<td>0.018</td>
</tr>
<tr>
<td>Secondary ingestion</td>
<td>-</td>
<td>-</td>
<td>0.130</td>
<td>0.129</td>
<td>2.600</td>
</tr>
<tr>
<td>Skin contamination</td>
<td>-</td>
<td>-</td>
<td>0.023</td>
<td>0.022</td>
<td>0.454</td>
</tr>
<tr>
<td>Total</td>
<td>0.489</td>
<td>0.448</td>
<td>0.177</td>
<td>0.176</td>
<td>3.566</td>
</tr>
</tbody>
</table>

Table 4 also shows the four limiting effective surface doses as introduced in section 5.7. For this example, the first scenario yields the largest dose (for \(\delta=1\)): \(LESD_1\) is 2.8 times larger than the dose in the fourth scenario (RIVM-SUDOQU model), but still considerably smaller than the total dose in the IAEA-CRP model. The values of both \(LESD_2\) and \(LESD_3\) are smaller than that of \(LESD_1\). In the second scenario, resuspension of activity leads to a decrease in the (time-integrated) surface contamination and thus to a reduced contribution of the external gamma-radiation dose. The additional contribution from inhalation is not sufficient to compensate for this reduction. Similar arguments hold when comparing \(LESD_3\) with \(LESD_1\): here, the even larger reduction in the external-radiation dose by (dominant) wipe-off is not compensated by the additional contributions from secondary ingestion and skin contamination. Results of the fourth, RIVM-SUDOQU scenario are comparable to those of the third scenario. The additional contribution from inhalation is negligible because most activity is wiped off of the surface of the object and is thereby not available for resuspension.

As a conclusion for the present example, the most conservative limiting scenario with \(\delta=1\) is the first one in which all contamination is assumed to be fixed to the surface. Since Cs-137 has a physical half-life of 30 years, radioactive decay within a year is negligible (2.3%) and the surface contamination remains virtually constant. The resulting effective dose from exposure to external gamma radiation is then larger than the dose in any other limiting scenario. It may seem counterintuitive that the dose obtained in the fourth scenario is dominated by the contribution from secondary ingestion. This is a result of the effectiveness of wipe-off in combination with a rather small contaminated area of 1000 cm\(^2\). Wipe-off then results in an effective decrease of the surface-contamination level (figure 5(b)), thereby (strongly) reducing the contribution from external radiation, here to a level even below that of secondary ingestion.

The larger the area of contamination with Cs-137\(^+\), the more dominant the pathway of external-radiation in the RIVM-SUDOQU model (i.e., in \(LESD_4\)). This is demonstrated by repeating the above calculation for varying values of \(A_{cont}\). In figure 6(a), the size dependence of the annual total effective dose is plotted, including the separate contributions from the pathways. The total dose increases from \(1.5 \times 10^4 \ \mu\text{Sv.y}^{-1}\) for \(A_{cont} = 1\) cm\(^2\) (note: this is below the critical area of 40 cm\(^2\), section 3.5) to 26.1 \(\mu\text{Sv.y}^{-1}\) for \(A_{cont} = A_{floor} = 50 \times 10^4\) cm\(^2\) (50 m\(^2\)). Below \(6.3 \times 10^3\) cm\(^2\), secondary ingestion has the largest contribution to the total dose, in the example calculation for \(LESD_4\) (as in table 4), but for larger areas the external-radiation contribution dominates the total dose, as expected for strong gamma emitters like Cs-137\(^+\) (with gamma rays from Ba-137m).

In figure 6(b), we compare the size dependence of the total dose in the RIVM-SUDOQU model (solid line) with that of the IAEA-CRP model (dashed line). For small values of \(A_{cont}\), the dose in the RIVM-SUDOQU model is several orders of magnitude smaller than that in the IAEA-CRP model. However, as \(A_{cont}\) increases, the SUDOQU-RIVM model approaches the IAEA-CRP model. With increasing area of contamination, the wipe-off removal constant (equation (17)) decreases and thus has a smaller impact on the level of surface contamination. A smaller decrease in \(C_{surf,i}\) means that the...
RIVM-SUDOQU model more closely resembles the IAEA-CRP model with the constant level of surface contamination (Dillen 2015). Note that this resemblance would not be observed for short-lived nuclides. Figure 6(b) also shows the maximum limiting effective surface dose, \( MLESD \). At small areas, it is 3.3 times larger than the dose in the SUDOQU-RIVM model \( (LESD_a) \), whereas the difference vanishes for large areas. The most conservative scenarios are: scenario 1 for \( A_{cont} < 2.5 \text{ m}^2 \), scenario 3 for \( A_{cont} \) between 2.5 m\(^2\) and 28 m\(^2\) and scenario 4 for \( A_{cont} > 28 \text{ m}^2 \). For these large areas, the curves of the SUDOQU-RIVM model and \( MLESD \) overlap.

![Figure 6](image.png)

**Figure 6.** The annual effective dose (\( \mu Sv.y^{-1} \) per Bq.cm\(^{-2}\)) as a function of the contaminated area \( A_{cont} \) (cm\(^2\)). Figure (a) shows the contributions from the different exposure pathways in the RIVM-SUDOQU model. Figure (b) shows the total dose in both the RIVM-SUDOQU and the IAEA-CRP model, as well as the maximum limiting effective surface dose, \( MLESD \), as defined by equation (91).

In figure 7 we present a contour plot of the annual total effective dose with isocurves of \( E_{tot} (\Delta T_{tot}) \) as a function of \( A_{cont} \) and \( f_{use} \). We assume that only \( A_{cont} \) and \( f_{use} \) vary, while all other input parameters have their default values listed in tables 1 and 2, except for \( m_{face} \), which is set to 1.0, to ensure that \( m_{face}f_{use} \) does not exceed the value of 1. With figure 7, one can perform a quick conservative dose estimation, which may be useful in the field of nuclear and radiological emergency.
preparedness and response. An example: the effective dose for an item of 6 m$^2$ homogeneously contaminated with 4.0 Bq.cm$^{-2}$ Cs-137+ that one would use for 3150 hours per year ($f_{use} = 0.36$) is estimated as: 15 μSv.y$^{-1}$.Bq$^{-1}$.cm$^{-2}$ (taken from figure 7) × 4.0 Bq.cm$^{-2}$ = 60 μSv.y$^{-1}$.

![Figure 7](image)

**Figure 7.** Dose contour plot: isocurves of the annual total effective dose $E_{tot} (\Delta T_{tot}, \delta = 1)$ as a function of the contaminated area $A_{cont}$ (cm$^2$) and the duty factor $f_{use}$. Contour values are shown for 1,5,10,…,35 μSv.y$^{-1}$ per Bq.cm$^{-2}$.

6.3. Example calculations for various nuclides (results and discussion)

The example calculations of section 6.2 (exposure to a disk-shaped object of 1000 cm$^2$ homogeneously contaminated with 1.0 Bq.cm$^{-2}$) were repeated for several other nuclides: I-131, Co-60, Sr-90+ and Am-241. Based on the radiological properties listed in table 3, the results are presented in table 5.

**Table 5.** Total annual effective dose results for a homogeneous surface contamination with 1.0 Bq.cm$^{-2}$ over an area of 1000 cm$^2$ for several nuclides. Values are in μSv.y$^{-1}$. Listed are the limiting effective surface doses ($LESD_{1-4}$ with $\delta = 1$), where $LESD_4$ refers to the RIVM-SUDOQU model. The value of $MLESD$ is shown in boldface. Results are also listed for the IAEA-CRP model ($\delta = 0$).

<table>
<thead>
<tr>
<th>Nuclide</th>
<th>$LESD_1$</th>
<th>$LESD_2$</th>
<th>$LESD_3$</th>
<th>$LESD_4$ RIVM-SUDOQU</th>
<th>$E_{tot} (\Delta T_{tot}, \delta = 0)$ IAEA-CRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cs-137+</td>
<td>0.489</td>
<td>0.448</td>
<td>0.177</td>
<td>0.176</td>
<td>3.566</td>
</tr>
<tr>
<td>I-131</td>
<td>0.011</td>
<td>0.011</td>
<td>0.100</td>
<td>0.100</td>
<td>5.183</td>
</tr>
<tr>
<td>Co-60</td>
<td>1.796</td>
<td>1.640</td>
<td>0.144</td>
<td>0.143</td>
<td>2.937</td>
</tr>
<tr>
<td>Sr-90+</td>
<td>-</td>
<td>0.033</td>
<td>0.352</td>
<td>0.350</td>
<td>7.191</td>
</tr>
<tr>
<td>Am-241</td>
<td>0.090</td>
<td>37.73</td>
<td>2.005</td>
<td>4.042</td>
<td>201.3</td>
</tr>
</tbody>
</table>

The results of the RIVM-SUDOQU model ($LESD_4$) are similar for the beta/gamma emitters (Cs-137+, I-131 and Co-60) as they are all in the range between 0.1 and 0.2 μSv.y$^{-1}$. The most conservative
scenario is not always \( \text{LESD}_1 \) (fixed surface contamination). For I-131, the third scenario is the most conservative one. This can be attributed to the relatively short physical half-life of 8 days, which greatly reduces the value of \( \text{TISC}_{\text{use},1} \) in the first scenario, and thus the value of \( \text{LESD}_1 \). The relatively large value of \( DC_{\text{ing},1} \) for I-131 then causes the value of \( \text{LESD}_2 \) (which is also proportional to \( \text{TISC}_{\text{use},1} \)) to exceed that of \( \text{LESD}_1 \).

The results for Sr-90+, a pure beta emitter (including its daughter Y-90), are in the same order of magnitude as those for the beta/gamma emitters. As discussed in section 5.1, no external radiation dose is calculated for pure beta emitters, which explains the absence of a value for \( \text{LESD}_1 \). The relatively large value of \( DC_{\text{ing},1} \) again causes the third scenario to be the most conservative one.

A completely different result is obtained for Am-241, the only alpha emitter studied here. It is mainly characterized by its very large inhalation dose coefficient \( DC_{\text{inh},1} \), which is 3 to 4 orders of magnitude larger than that of the other nuclides in table 3. This explains why the second scenario, highlighting the inhalation pathway, is the most conservative scenario, i.e., \( M\text{LESD} = \text{LESD}_3 \), and why its value is much larger than that of the other nuclides.

The dose ratio IAEA-CRP/RIVM-SUDOQU is about 20 for long-lived nuclides Cs-137+, Co-60 and Sr-90+, whose total dose is dominated by contributions proportional to \( \text{TISC}_{\text{use},1} \). The dose ratio is then simply equal to \( \frac{\text{TISC}_{\text{use},1}(\Delta T_{\text{tot}}, \delta = 0)}{\text{TISC}_{\text{use},1}(\Delta T_{\text{tot}}, \delta = 1)} \approx 20 \). For I-131 the ratio is even larger: 52. This can be attributed to radioactive decay, which leads to a further reduction of the RIVM-SUDOQU dose value with respect to that of the IAEA-CRP model. For long-lived radionuclide Am-241 the dose ratio is also larger, 50, since the total dose now has a large contribution from inhalation.

The dependence of the total annual effective dose on the area of contamination is shown in figure 8 for the five nuclides in table 5.

![Figure 8](image_url)

Figure 8. The total annual total effective dose (\( \mu \text{Sv.y}^{-1} \) per Bq.cm\(^{-2} \)) in the RIVM-SUDOQU model as a function of the area of contamination \( A_{\text{cont}} \) (cm\(^2 \)). Results are shown for the five studied nuclides. The black solid line for Cs-137+ is taken from figure 6 as a reference.

For small areas \( A_{\text{cont}} \) contaminated with I-131, the impact of radioactive decay on the annual dose is small, because removal of surface contamination is dominated by wipe-off, i.e., \( \langle \lambda_{\text{woj}} \rangle \gg \lambda_{r,j} \). With the secondary ingestion dose dominating at small areas (see figure 6(a) for Cs-137+) and with a larger \( DC_{\text{ing},1} \)-value, the dose of I-131 is even higher than that of the other beta/gamma emitters, Cs-137+ and Co-60. For areas larger than \( \left( f_{\text{use}} f_{\text{oth}, \phi_{\text{use}} A_{\text{hands}}} \right) \lambda_{r,j} = 636 \text{ cm}^2 \), wipe-off parameter \( \langle \lambda_{\text{woj}} \rangle \)
becomes smaller than $\lambda_{\nu,i}$ and radioactive decay significantly affects the annual total effective dose. The dose for I-131 therefore becomes smaller than that of Cs-137+ and Co-60, as seen in figure 8. For each area $A_{\text{cont}}$, Am-241 results in the highest dose values, thereby showing its large radiotoxicity. For areas below 1000 cm$^2$, the total dose comes mainly from secondary ingestion (as for the other nuclides), while at larger areas it is dominated by the contribution from inhalation.

7. Conclusion

We described the SUDOQU “consumer” methodology from Dillen (2015) for dose assessments involving the (re)use of single items with removable (and fixed) radioactive surface contamination in indoor or outdoor environments. The method incorporates mass-balance equations related to removal, decay and deposition processes. In this way, it distinguishes itself from the classical, usually “worker”-based models that often consider the manipulation of a continuous flow of (many) contaminated items, e.g., IAEA’s basic model from TECDOC-1449 (IAEA 2005). This IAEA-CRP model follows from our approach as a limiting case, and therefore serves as an internal benchmark. We observed that the total effective dose in the SUDOQU consumer model can be several orders of magnitude smaller than that in the IAEA-CRP worker model. This emphasizes the need for our mass-balance approach in surface-contamination scenarios involving the prolonged use only one or a few items.

Many particular exposure situations not explicitly addressed in this study can be found as limiting cases of our general methodology. For example, dose evaluations for individuals never using the object but who are merely in its close vicinity for some period of time can be carried out by setting the wipe-off frequency to zero: $\overline{\phi}_{\text{wce}} = 0$ h$^{-1}$ and thus $m_{\text{hands},i} = m_{\text{face},i} = 0$ (i.e., use of the object without contact events). Furthermore, the methodology can easily be extended to include additional removal mechanisms and exposure pathways (see e.g. section 5.5).

The concept of the limiting effective surface dose (section 5.7) was introduced to deal with the level of conservatism of the underlying dose evaluation. Such evaluations for the derivation of limiting values should be sufficiently conservative to offer protection against ionizing radiation, but not too conservative to hinder its practical implementation. Clearly, optimization is necessary to best balance these issues. The real challenges in deriving criteria are (1) determining and agreeing on the exposure scenarios that serve as input for the calculations, (2) choosing proper dose criteria and (3) ensuring that optimization is satisfied, taking into account practical, economical and societal factors as well. Harmonization of criteria among countries, though very desirable, will require considerable efforts and should be stimulated, supported and guided by international radiation-protection agencies.

The SUDOQU methodology may be of interest to radiation-protection specialists, experts and policy makers, and we kindly invite them to supply us with feedback on the methodology to further improve and extend it.

Acknowledgments

The authors thank Astrid Kloosterman (RIVM) for her help in preparing and reviewing the manuscript and for validations, and they thank the reviewers for their comments and suggestions. The authors also express their gratitude to Chantal Mommaert and Federica Russo (Bel V, Brussels, Belgium) for the many fruitful discussions. This work was financially supported by the Dutch Authority for Nuclear Safety and Radiation Protection (ANVS).

Appendix A. The average resuspension rate

The instantaneous resuspension rate, defined by equation (9), is time-dependent because of:
a. use of the product versus non-use of the product (use versus idle: $\xi_{\text{use},t}$ versus $\xi_{\text{idle},t}$);

b. changes in physical and chemical properties of the surface and/or the particulate contaminants during the aforementioned phases (use, idle).

The resuspension rate is therefore explicitly written as:

$$\xi_i(t) = \begin{cases} 
\xi_{\text{use},i}(t) & \text{during use} \\
\xi_{\text{idle},i}(t) & \text{during idle} 
\end{cases}, \quad (A.1)$$

with $t \in [0, \Delta T_{\text{surf}}]$. Object use itself will have an impact on the value and time-dependence of $\xi_{\text{idle},i}$.

The instantaneous resuspension flux is the removable activity (Bq) that becomes airborne per unit of contaminated area and per unit of time. It therefore determines the rate-of-change of the removable surface-contamination level solely due to resuspension. Hence, we can write (Holländer and Garger 1996, Slinn 1976):

$$RFL_i(t) = -\frac{dC_{\text{surf},i}(t)}{dt}. \quad (A.2)$$

Combining equations (9) and (A.2) yields:

$$dC_{\text{surf},i}(t) = -\xi_i(t)C_{\text{surf},i}(t)dt. \quad (A.3)$$

In a time interval $[t, t + dt]$, the object is used for a duration of $f_{\text{use}}dt$ (with $\xi_i(t) = \xi_{\text{use},i}(t)$) and is not used for a duration of $(1 - f_{\text{use}})dt$ (with $\xi_i(t) = \xi_{\text{idle},i}(t)$), so that equation (A.3) becomes:

$$\frac{dC_{\text{surf},i}(t)}{dt} = \dot{C}_{\text{surf},i}(t) = -\left[f_{\text{use}}\xi_{\text{use},i}(t) + (1 - f_{\text{use}})\xi_{\text{idle},i}(t)\right]C_{\text{surf},i}(t), \quad (A.4)$$

where $\dot{C}_{\text{surf},i}$ denotes the time rate-of-change of $C_{\text{surf},i}$. The solution of this differential equation is

$$C_{\text{surf},i}(t) = C_{0,i}e^{-\int \left[f_{\text{use}}\xi_{\text{use},i}(t') + (1 - f_{\text{use}})\xi_{\text{idle},i}(t')\right]dt'}. \quad (A.5)$$

The resuspension rate is, for simplicity and absence of detailed information on the time-dependent behavior of $\xi_i(t)$, replaced by a constant, annual average $\langle \xi_i \rangle$, such that the level of surface contamination decreases exponentially as well and reaches the exact same value as equation (A.5) at the end of the year ($t = \Delta T_{\text{tot}}$), i.e.,

$$C_{\text{surf},i}(\Delta T_{\text{tot}}) = C_{0,i}e^{-\int_0^{\Delta T_{\text{tot}}} \langle \xi_i \rangle dt'} = C_{0,i}e^{-\langle \xi_i \rangle \Delta T_{\text{tot}}}. \quad (A.6)$$

Equating equation (A.5) at $t = \Delta T_{\text{tot}}$ to equation (A.6) yields (note: integration-dummy $t'$ is replaced by $t$):

$$\langle \xi_i \rangle = \frac{1}{\Delta T_{\text{tot}}} \int_0^{\Delta T_{\text{tot}}} \left[f_{\text{use}}\xi_{\text{use},i}(t) + (1 - f_{\text{use}})\xi_{\text{idle},i}(t)\right]dt, \quad (A.7)$$
which can also be written as

\[ \langle \xi_i \rangle = f_{\text{use}} \bar{\xi}_{\text{use},i} + (1 - f_{\text{use}}) \bar{\xi}_{\text{idle},i}. \quad (A.8) \]

In equation (A.8), we have defined

\[ \bar{\xi}_{\text{use},i} = \frac{1}{\Delta T_{\text{tot}}} \int_0^{\Delta T_{\text{tot}}} \xi_{\text{use},i}(t) \, dt \quad \text{and} \quad \bar{\xi}_{\text{idle},i} = \frac{1}{\Delta T_{\text{tot}}} \int_0^{\Delta T_{\text{tot}}} \xi_{\text{idle},i}(t) \, dt \quad (A.9) \]

as the mean values during object use and non-use, respectively. Within the framework of the continuous model structure as described in sections 3.1 to 3.3, the integrand \( f_{\text{use}} \bar{\xi}_{\text{use},i}(t) \) in equation (A.7) can be viewed of as the ‘spread-out’ resuspension rate from object use, as if it were continuously occurring.

An alternative and more direct approach to arrive to equation (A.8) is

\[ \langle \xi_i \rangle = \frac{1}{\Delta T_{\text{tot}}} \int_0^{\Delta T_{\text{tot}}} \xi_i(t) \, dt = \frac{1}{\Delta T_{\text{tot}}} \left[ \int_{\text{use in } \Delta T_{\text{tot}}} \xi_{\text{use},i}(t) \, dt + \int_{\text{no use in } \Delta T_{\text{tot}} - \Delta T_{\text{use}}} \xi_{\text{idle},i}(t) \, dt \right] \]

\[ = \frac{1}{\Delta T_{\text{tot}}} \left[ \Delta T_{\text{use}} \bar{\xi}_{\text{use},i} + (\Delta T_{\text{tot}} - \Delta T_{\text{use}}) \bar{\xi}_{\text{idle},i} \right] - f_{\text{use}} \bar{\xi}_{\text{use},i} + (1 - f_{\text{use}}) \bar{\xi}_{\text{idle},i} \]

Here, the mean values \( \bar{\xi}_{\text{use},i} \) and \( \bar{\xi}_{\text{idle},i} \) are written in an alternative manner, e.g.,

\[ \bar{\xi}_{\text{use},i} = (\Delta T_{\text{use}})^{-1} \int_{\text{use in } \Delta T_{\text{tot}}} \xi_{\text{use},i}(t) \, dt. \quad (A.10) \]

The integration in equation (A.10) is over all phases within \([0, \Delta T_{\text{tot}}]\) in which the product is used (adding up to a total time of \( \Delta T_{\text{use}} \)). Theoretically, the spread-out of object use should be carried out such that both integrals of equations (A.9) and (A.10) are equal (similar arguments hold for the ‘idle’ parts).

The general time-dependence of the removable surface-contamination level by resuspension is modeled by the following, governing equation:

\[ \frac{dC_{\text{surf},j}(t)}{dt} = -\langle R E_i \rangle = -\langle \xi_i \rangle C_{\text{surf},j}(t), \quad (A.11) \]

with \( \langle \xi_i \rangle \) from equation (A.8). In SUDOQU, equation (A.11) replaces equations (A.2) and (A.3).

**Appendix B. A model for wipe-off based on ISO-7503 and a comparison with SUDOQU**

Let us consider a smear test on a fixed area \( A_{\text{smear}} \) (cm\(^2\)) with a constant removal factor \( F \) as defined by equation (1) in section 2.1. For simplicity, we here temporarily omit the index \( i \) identifying the specific nuclide. We assume that the activity removed in wipe/smear \( j \) (\( q_j \) in Bq) relates directly to that removed in wipe \( j - 1 \), by the following recurrence relation:
\[ q_j = (1 - F)q_{j-1} \quad j = 2, 3, \ldots \] (B.1)

The idea behind this relation is that a larger removal factor \( F \) will result in a smaller activity that will be picked up in a subsequent smear. We therefore use the factor \( 1 - F \), which is to be applied for each subsequent smear. Equation (B.1) can be rewritten as:

\[ q_j = (1 - F)^{j-1} q_1 \quad j = 1, 2, 3, \ldots \] (B.2)

The cumulative activity removed after \( n \) smears, \( Q_{\text{rem},n} \) (Bq), from area \( A_{\text{smear}} \) is

\[ Q_{\text{rem},n} = \sum_{j=1}^{n} q_j = \left[ 1 - (1 - F)^n \right] \frac{q_1}{F} \quad n = 0, 1, 2, \ldots \] (B.3)

which after substitution of equation (1) from section 2.1 leads to:

\[ Q_{\text{rem},n} = \sum_{j=1}^{n} q_j = \left[ 1 - (1 - F)^n \right] Q_{\text{rem, tot}} \quad n = 0, 1, 2, \ldots \] (B.4)

where \( Q_{\text{rem, tot}} \) (Bq) is the total removable activity on area \( A_{\text{smear}} \) prior to the first smear. Equation (B.4) satisfies the condition \( \lim_{n \to \infty} Q_{\text{rem},n} = Q_{\text{rem, tot}} \) for \( F \in (0, 1] \). After \( n \) smears, the removable activity still present on the smear’s surface area \( A_{\text{smear}} \) is then:

\[ Q_{\text{pres,rem},n} = Q_{\text{rem, tot}} - Q_{\text{rem},n} = (1 - F)^n Q_{\text{rem, tot}} \] (B.5)

With \( q_{n+1} = (1 - F)^n q_1 \) from equation (B.2) and with the result in equation (B.5), we can write:

\[ \frac{q_{n+1}}{Q_{\text{pres,rem},n}} = \frac{q_1}{Q_{\text{rem, tot}}} \equiv F \] (B.6)

where we have used the definition of the removal factor, equation (1) from section 2.1. Equation (B.6) states that the removed activity of smear \( n + 1 \left( q_{n+1} \right) \) is directly proportional to the remaining removable activity (still) present on the surface prior to this smear \( Q_{\text{pres,rem},n} \), with the constant of proportionality being the removal factor \( F \). Dividing both sides of equation (B.5) by the area \( A_{\text{smear}} \) of the smear, results in the remaining removable surface contamination (Bq.cm\(^{-2}\)) present within this area:

\[ C_{\text{surf,smear,n}} = (1 - F)^n C_0 \] (B.7)

where \( C_0 = \frac{Q_{\text{rem, tot}}}{A_{\text{smear}}} \) is the initial, removable level of contamination in Bq.cm\(^{-2}\). The idea behind the wipe-off process in SUDOQU is that it can be viewed as a smear test on a total contaminated area of \( A_{\text{smear}} = A_{\text{cont}} \), with the wiping cloth replaced by the hands. For an intuitive translation of the simple ISO-7503-based model above (ISO-7503 1988, 2016) to the actual problem of wipe-off considered by SUDOQU, we simplify it by assuming that one needs on average \( A_{\text{cont}}/A_{\text{touched}} \) wipe-off events for one single smear of total area \( A_{\text{cont}} \) (\( A_{\text{touched}} \) is the object’s area
touched by the hands during a single wipe-off event, see section 3.6). At time \( t \), the average number of wipe-off events, \( f_{\text{use}} \bar{\phi}_{\text{use}} t \), results in a number of total-area smears equal to:

\[
n = n(t) = \frac{f_{\text{use}} \bar{\phi}_{\text{use}} t}{A_{\text{cont}} / A_{\text{touched}}} = f_{\text{use}} \bar{\phi}_{\text{use}} \left( \frac{A_{\text{touched}}}{A_{\text{cont}}} \right) t,
\]

and equation (B.7) is thus rewritten as:

\[
C_{\text{surf}}(t) = C_0 (1 - F) f_{\text{use}} \bar{\phi}_{\text{use}} (A_{\text{touched}} / A_{\text{cont}}) t.
\]

Equation (B.9) is thus the simple result of the wipe-off process by treating it as a smear test according to the ISO-7503 methodology and by assuming that the removal factor remains constant throughout the experiment. In the SUDOQU methodology, the net/overall decrease of the surface contamination by wipe-off is governed by the average removal flux \( \langle WOFL \rangle = \langle \lambda_{\text{wo}} \rangle \cdot C_{\text{surf}} \) (equation (14), with the applied time average, similar to equation (A.11) for resuspension) and results in following differential equation:

\[
\frac{dC_{\text{surf}}}{dt} = -\langle WOFL \rangle = -\langle \lambda_{\text{wo}} \rangle C_{\text{surf}} = -f_{\text{use}} \bar{\phi}_{\text{use}} \left( \frac{A_{\text{hands}}}{A_{\text{cont}}} \right) C_{\text{surf}},
\]

where we have made use of equation (17) in section 3.5 (nuclide index \( i \) omitted). Equation (B.10) holds if there are no other removal processes such as radioactive decay or resuspension. After replacing the product \( \bar{\phi}_{\text{use}} A_{\text{hands}} \) by \( FA_{\text{touched}} \) (equation (22), section 3.6), the solution becomes

\[
C_{\text{surf}}(t) = C_0 \exp \left[ -f_{\text{use}} F \bar{\phi}_{\text{use}} \left( \frac{A_{\text{touched}}}{A_{\text{cont}}} \right) \cdot t \right],
\]

with \( C_0 \) the initial level of surface contamination, i.e., \( C_{\text{surf}}(0) = C_0 \). As imposed by the construction of the SUDOQU model, both approaches (leading to equation (B.9) and to equation (B.11)) should more or less yield identical results for the same value of the removal factor \( F \). This is verified by two simple, example calculations presented in figure B1, showing the evolution of \( C_{\text{surf}}(t) \) using (a) \( F = 0.20 \) and (b) \( F = 0.01 \). Furthermore, we used the following parameter values in both calculations: \( C_0 = 1.0 \text{ Bq.cm}^{-2} \), \( f_{\text{use}} = 1.0 \), \( \bar{\phi}_{\text{use}} = 1.0 \text{ h}^{-1} \), \( A_{\text{touched}} = 400 \text{ cm}^2 \) and \( A_{\text{cont}} = 1000 \text{ cm}^2 \) (note: with \( A_{\text{hands}} \) also having a value of 400 cm\(^2\), we would here have \( A_{\text{touched}} = F \)). In figure B1, the dashed curves refer to \( C_{\text{surf}}(t) \) according to equation (B.9), the ISO-7503 approach, and the solid curves to its SUDOQU counterpart given by equation (B.11). Since the removal factor is 20 times smaller in calculation (b) than that in (a), the corresponding time scale for graph (b) is extended by a factor 20 (i.e., \( t_{\text{max}} = 1000 \) h in (b) instead of \( t_{\text{max}} = 50 \) h in (a)) to yield the exact same value of the surface-contamination level at the end of the plotted time interval (\( t = t_{\text{max}} \)) according to the exponential behavior in equation (B.11), i.e.,

\[
C_{\text{surf}}(t_{\text{max}} = 50)\bigg|_{F = 0.20} = C_{\text{surf}}(t_{\text{max}} = 1000)\bigg|_{F = 0.01} = 1.0 \cdot \exp[-4.0] = 1.8 \times 10^{-2} \text{ Bq.cm}^{-2}.
\]

As can be seen in figure B1(a), there is a difference between both approaches in case the removal factor has a significant value of \( F = 0.20 \). The ratio of these levels (SUDOQU/ISO-7503) gradually increases from 1 at \( t = 0 \) h to 1.6 at \( t = 50 \) h. This is not clear from figure B1(a) and can best be
viewed on a logarithmic scale (not shown here). This ratio continues to increase with time, e.g., at \( t = 100 \) h, the ratio has increased to 2.5. However, both dose calculations will be dominated by their contribution attained in time regime for which \( C_{\text{surf}}(t) \) deviates significantly from zero, which is the regime plotted in figure B1(a). The effective dose contributions from external radiation, ingestion and skin contamination (see section 5) are proportional to the time-integrated surface contamination \( TISC(\Delta T_{\text{tot}}) \), which is calculated by equation (6) in section 3.2 and yields values of 12.5 Bq.h.cm\(^{-2}\) based on equation (B.11) and 11.2 Bq.h.cm\(^{-2}\) based on equation (B.9), a difference of less than 12%. This clearly indicates the similarity of both approaches even at significant values of the removal factor \( F \).

![Figure B1](image)

**Figure B1.** Time evolution of the surface contamination \( C_{\text{surf}}(t) \) according to equation (B.9) (dashed curves, ISO-7503 based model) and equation (B.11) (solid curves, SUDOQU) for a removal factor of (a) \( F = 0.20 \) and of (b) \( F = 0.01 \) (more details in text).

Figure B1(b) shows that both approaches yield identical curves of \( C_{\text{surf}}(t) \) in case the removal factor is decreased by a factor of 20 to 0.01, a value much closer to 0. The two curves collapse, and equation (B.9) thus converges to equation (B.11) in the limit for small removal factors \( F \). Mathematically, this can be seen by rewriting the power in equation (B.7) as:
\[ (1 - F)^n = \left(1 + \left(\frac{-nF}{n}\right)^n\right) = \left(1 + \frac{x}{n}\right)^n, \]

with \( x = -nF \). For \( F \rightarrow 0 \), one can simply state that \( n \gg |x| \) and since

\[
\lim_{n \to \infty} \left(1 + \frac{x}{n}\right)^n = \exp[x],
\]

we can write the following approximation for small values of \( F \):

\[
(1 - F)^n \approx \exp[-F \cdot n]. \tag{B.12}
\]

Applying equation (B.12) to equation (B.9) then indeed results in equation (B.11), confirming the observed overlap in figure B1(b).

Shoji et al (2010) performed experimental work on the removal characteristics of polyvinyl chloride flooring contaminated with radioactive \(^{14}\text{C}-\text{thymidine}\). For surfaces without a wax coating they find that the activity of the eighth wipe is about 46% of that of the first wipe, i.e., \( q_8 = 0.46q_1 \). Then, using the model presented above (equation (B.2)), we can write:

\[
q_8 = (1 - F)^7 q_1 = 0.46q_1,
\]

resulting in a predicted removal factor of \( F = 1 - \sqrt{0.46} \approx 0.11 \), as also estimated in Shoji et al (2010). This value is close to the default value of 0.1 recommended in the ISO-7503 (1988, 2016) standard.

**Appendix C. Transfer of activity from object to hands**

The transfer of activity from the surface-contaminated object to the skin of the hands is a complicated process of which not many details are known, especially in the case of long-term use of the same object. We here focus on the multiplication factor \( m_{\text{hands},d} \) introduced in section 3.8. We consider a small time interval \([t, t + \Delta t]\) during which the object’s surface contamination is assumed to be (almost) constant at a level of \( C_{\text{surf},d}(t) \). After a complete wipe-off event in this interval, the surface contamination of the hands is given by \( C_{\text{surf, hands},d}(t) = \mathcal{F}_{\text{oth},d} C_{\text{surf},d}(t) \), as defined by equation (13) and where we have replaced the time-dependent value of the transfer efficiency by its time-averaged counterpart, \( \mathcal{F}_{\text{oth},d} \). The time-dependence of the transfer process of contamination is described by a dimensionless, relative transfer function \( r_{\text{hands},d}(s) \) with values between 0 and 1 and with \( s \in [0; \Delta t] \) as the internal time scale. The (removable) surface contamination on the skin of the hands is now defined by its maximum value after a complete wipe-off and the relative transfer function as:

\[
C_{\text{surf, hands},d}(t; s) = \mathcal{F}_{\text{oth},d} C_{\text{surf},d}(t) r_{\text{hands},d}(s). \tag{C.1}
\]

Function \( r_{\text{hands},d}(s) \) thus describes the instantaneous surface-contamination level of the hands as a fraction of its maximum value. It can be visualized as follows. The function is treated as being independent of the global time scale \( t \) and of the object’s surface-contamination level \( C_{\text{surf},d}(t) \), and, on average, it repeats itself in each new time interval \( \Delta t \). With object use for instance occurring in the
first part of the interval, \([t, t + f_{use} \Delta t]\), and with clean hands at start of use, \(r_{hands,i}(0) = 0\) the relative transfer function starts to increase to its maximum value of 1. If a wipe-off event during use is completed at time \(s^*\) (e.g., \(t_{use}^*, 2t_{use}^*, \ldots\)), then \(r_{hands,i}(s^*) = \lim_{s \to s^*} r_{hands,i}(s) = 1\), and \(\lim_{s \to s^*} r_{hands,i}(s) = 0\) since the hands are cleaned just after \(s^*\). Next, the average behavior of \(r_{hands,i}(s)\) is assumed to be similar during consecutive wipe-off events and when object use is discontinued, \(r_{hands,i}(s)\) remains at its value of \(r_{hands,i}(f_{use} \Delta t)\) either until the next cleaning event of the hands occurs (at which \(r_{hands,i}\) reduces to 0) or until object use is continued (\(r_{hands,i}\) continues to increase), whichever comes first.

An example to visualize this: we choose \(\Delta t\) to be 10 hours in which the object is used for the first 6 hours (\(f_{use} = 0.60\)). The average time of a wipe-off event (between two consecutive cleaning events) during object use is set at \(t_{use}^* = 2.5\) hours, during which the skin contamination grows as e.g., \(\left(\frac{s - n \cdot t_{use}^*}{t_{use}^*}\right)^k\), with \(n = 0, 1, 2, \ldots\) the number of already completed wipe-off events and with exponent \(k\) set at a value of 2 in this example (parabolic growth from 0 to 1). The resulting behavior of \(r_{hands,i}(s)\) is shown in figure C1.

During use of the object, there are two full wipe-off events terminating at 2.5 h and 5.0 h (\(t_{use}^*\) and \(2t_{use}^*\)). The third wipe-off event is incomplete since the use of the object is discontinued at 6 h. The function \(r_{hands,i}\) remains at a value of \((6.0 - 2 \times 2.5)/2.5) = 0.16\) until the next cleaning event at \(s = 3t_{use}^* = 7.5\) h. Since hands are also cleaned at the end of the interval (\(s = \Delta t = 4t_{use}^* = 10\) h), the subsequent interval \([t + \Delta t, t + 2\Delta t]\) is identical to the one shown in figure C1.

**Figure C1.** Example of the relative transfer function, \(r_{hands,i}\), as function of the internal time \(s\) (h). Used for the calculation: \(\Delta t = 10\) h, \(f_{use} = 0.60\), \(t_{use}^* = 2.5\) h and a parabolic growth behavior (from 0 to 1) during wipe off: \(\left(\frac{s - n \cdot t_{use}^*}{t_{use}^*}\right)^k\), with \(n = 0, 1, 2, \ldots\) the number of already completed wipe-off events.

Based on this ‘transfer-of-contamination’ description, SUDOQU considers the time-dependent surface contamination of the hands averaged over the interval \(\Delta t\):
\[ \left\langle C_{\text{surf, hands}, i} \right\rangle_{\Delta t}(t) = \frac{1}{\Delta t} \int_{0}^{\Delta t} C_{\text{surf, hands}, i}(t; s) ds = \tilde{f}_{\text{other}, i} C_{\text{surf}, i}(t) \left[ \frac{1}{\Delta t} \int_{0}^{\Delta t} r_{\text{hands}, i}(s) ds \right], \quad (C.2) \]

with \( \left\langle r_{\text{hands}, i} \right\rangle_{\Delta t} \) the average value of \( r_{\text{hands}, i} \) in \([0; \Delta t] \). In equation (C.2), the time-integrated value of \( r_{\text{hands}, i} \) can be seen as the effective contamination and exposure time of the hands, \( \Delta t_{\text{hands}, i} \), as introduced in section 3.8. With this, we can also write

\[ \left\langle r_{\text{hands}, i} \right\rangle_{\Delta t} = \frac{1}{\Delta t} \int_{0}^{\Delta t} r_{\text{hands}, i}(s) ds = \frac{\Delta t_{\text{hands}, i}}{\Delta t}, \quad (C.3) \]

with values \( \leq 1 \). From the definition of \( m_{\text{hands}, i} \) by equation (27) it follows that

\[ \Delta t_{\text{hands}, i} = m_{\text{hands}, i} f_{\text{use}} \Delta t. \quad (C.4) \]

By substituting equations (C.3) and (C.4) into equation (C.2), we get

\[ \left\langle C_{\text{surf, hands}, i} \right\rangle_{\Delta t}(t) = m_{\text{hands}, i} f_{\text{use}} \tilde{f}_{\text{other}, i} C_{\text{surf}, i}(t). \quad (C.5) \]

For dose assessments (secondary ingestion and skin contamination) the time-integrated surface contamination (Bq.h.cm\(^{-2}\)) of the hands is required:

\[ TISC_{\text{hands}, i}(t) = \int_{0}^{t} \left\langle C_{\text{surf, hands}, i} \right\rangle_{\Delta t}(t') dt'. \quad (C.6) \]

This quantity follows from equation (C.5) by integration over the global time:

\[ TISC_{\text{hands}, i}(t) = m_{\text{hands}, i} \tilde{f}_{\text{other}, i} \left[ f_{\text{use}} \int_{0}^{t} C_{\text{surf}, i}(t') dt' \right] = m_{\text{hands}, i} f_{\text{use}} \tilde{f}_{\text{other}, i} TISC_{\text{use}, i}(t), \quad (C.7) \]

where we made use of equation (6). This completes our proof of equation (28).

The value of \( m_{\text{hands}, i} \) could thus be calculated from relative transfer functions \( r_{\text{hands}, i} \), if this information were available, with

\[ m_{\text{hands}, i} = \frac{1}{f_{\text{use}} \Delta t} \int_{0}^{\Delta t} r_{\text{hands}, i}(s) ds. \quad (C.8) \]

It attains a value of 0.33 for the function plotted in figure C1. In figure C2 (solid curve), we plotted the resulting value of \( m_{\text{hands}, i} \) for the example of figure C1 (with \( \Delta t = 4 t_{\text{use}}^* = 10 \) h and \( f_{\text{use}} = 0.60 \)), as a function of the exponent \( k \) of the growth function during wipe-off. For small values of the exponent \( k \) (\(< 0.22 \)), \( m_{\text{hands}, i} \) attains values larger than 1.0 in which case the effective duration of skin contamination is larger than that of object use. The maximum value of \( m_{\text{hands}, i} \) is achieved for \( k \) approaching 0 and has a value of 1.25 in this example. The hands are then continuously contaminated.
at the maximum level of $\int_0^\infty C_{\text{surf},i}(t)$ during the 6.0 h of object use as well as for the following 1.5 hours after use. Therefore, $m_{\text{hands},i} = \Delta t_{\text{hands},i}/\Delta t_{\text{use}} = (6.0+1.5)/6.0 = 1.25$. The dotted curve in figure C2 is the function $(1+k)^{-1}$, which would be the result of $m_{\text{hands},i}$ in case an integer number of wipe-off events fits into the duration of use $f_{\text{use}}\Delta t$: in the example above this would occur at e.g. $t_{\text{use}}^* = 0.5$ h, 1.0 h, 2.0 h, 3.0 h, or 6.0 h (12, 6, 3, 2, or 1 wipe-off events in $f_{\text{use}}\Delta t = 6.0$ h, respectively). The maximum value of $m_{\text{hands},i}$ is then calculated as $\lim_{k \to 0} (1+k)^{-1} = 1.0$. Since the skin is not contaminated after object use, we have $\Delta t_{\text{hands},i} = \Delta t_{\text{use}}$ and thus $m_{\text{hands},i} = 1.0$. For a linear transfer curve during wipe off ($k = 1$), the value of $m_{\text{hands},i}$ results in 0.50 (dotted curve for $f_{\text{use}}\Delta t / t_{\text{use}}^* = 1, 2, ...$), as derived in section 3.8.

Figure C2. Multiplication factor $m_{\text{hands},i}$ as a function of the exponent $k$ of the transfer function during wipe-off, with $f_{\text{use}} = 0.60$ and $\Delta t = 10$ h. Solid curve: $t_{\text{use}}^* = 2.5$ h. Dotted curve: $t_{\text{use}}^*$ is such that an integer number of wipe-off events occurs in $f_{\text{use}}\Delta t = 6.0$ h, e.g., $t_{\text{use}}^* = 2.0$ or 3.0 h. This curve is given by $m_{\text{hands},i} = (1+k)^{-1}$.

Appendix D. Solution of the mass/activity-balance equations in the indoor environment

The original, coupled set of differential equations in SUDOQU is given by (equation (36), section 4.3):

$$\begin{pmatrix} \dot{C}_{\text{surf}} \\ \dot{C}_{\text{air}} \end{pmatrix} = \begin{pmatrix} a & b \\ c & -d \end{pmatrix} \begin{pmatrix} C_{\text{surf}} \\ C_{\text{air}} \end{pmatrix}$$

with

$$\begin{pmatrix} C_{\text{surf}}(0) \\ C_{\text{air}}(0) \end{pmatrix} = \begin{pmatrix} C_0 \\ 0 \end{pmatrix}.$$  \hspace{1cm} (D.1)

with:

$$a = \lambda_{\text{surf}} \delta, \quad b = \lambda_d H \delta, \quad c = \frac{f_{\text{use}} \bar{C}_{\text{use}} A_{\text{cont}}}{V}, \quad d = \lambda_c + \left( \lambda_c + \lambda_d \right) \delta.$$  \hspace{1cm} (D.2)

We drop index $i$ indicating the nuclide in equations (D.1) and (D.2). Equation (D.1) can be written as
\[ \dot{C} = MC, \]  
(D.3)

with

\[ M = \begin{pmatrix} -a & b \\ c & -d \end{pmatrix} \quad \text{and} \quad C = \begin{pmatrix} C_{\text{surf}} \\ C_{\text{air}} \end{pmatrix}. \]  
(D.4)

If matrix \( M \) is a diagonalizable matrix, any solution can be written in the form of:

\[ C = \beta_1 \exp[\eta_1 t]v_1 + \beta_2 \exp[\eta_2 t]v_2, \]  
(D.5)

in which \( \eta_1 \) and \( \eta_2 \) are the eigenvalues of \( M \) and \( v_1 \) and \( v_2 \) the corresponding eigenvectors. The constants \( \beta_1 \) and \( \beta_2 \) are determined from the initial condition

\[ C(0) = \begin{pmatrix} C_0 \\ 0 \end{pmatrix}. \]  
(D.6)

For convenience, we write

\[ C = \beta_1 \exp[-\lambda_1 t]v_1 + \beta_2 \exp[-\lambda_2 t]v_2, \]  
(D.7)

where \( \lambda_j = -\eta_j \) (\( j = 1, 2 \)). The eigenvalues \( \eta_j \) of \( M \) are found by solving the equation \( \det[M - \eta I] = 0 \) (with \( I \) the identity matrix), that is \( \eta^2 + (a + d)\eta + ad - bc = 0 \). This leads to the following values for \( \lambda_j \):

\[ \lambda_1 = \frac{(a + d) + \sqrt{4bc + (a - d)^2}}{2}, \quad \lambda_2 = \frac{(a + d) - \sqrt{4bc + (a - d)^2}}{2}. \]  
(D.8)

Equation (D.8) can be rewritten as

\[ \lambda_1 = \frac{1}{2} ((a + d) + \lambda^*), \quad \text{and} \quad \lambda_2 = \frac{1}{2} ((a + d) - \lambda^*), \]  
(D.9)

with:

\[ \lambda^* = \lambda_1 - \lambda_2 = \sqrt{4bc + (a - d)^2}. \]  
(D.10)

The eigenvectors \( v_j \) of \( M \) can now be found by solving \( (M - \eta_j I)v_j = (M + \lambda_j I)v_j = 0 \), i.e.,

\[ \begin{pmatrix} \lambda_j - a & b \\ c & \lambda_j - d \end{pmatrix} \begin{pmatrix} v_{j,1} \\ v_{j,2} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}. \]  
(D.11)

Using for instance the second equation, \( cv_{j,1} + (\lambda_j - d)v_{j,2} = 0 \), leads to \( v_{j,1} = \left( (d - \lambda_j)/c \right) v_{j,2} \), from which the eigenvectors are:
\[ v_j = \begin{pmatrix} v_{j,1} \\ v_{j,2} \end{pmatrix} = \begin{pmatrix} (d - \lambda_j) \\ c \\ l \end{pmatrix} v_{j,2} . \] (D.12)

The value of \( v_{j,2} \) is arbitrary and can be taken as 1, inasmuch as the constants \( \beta_1 \) and \( \beta_2 \) are to be determined from the initial conditions anyway. Our solution thus becomes:

\[ \begin{pmatrix} C_{\text{surf}} \\ C_{\text{air}} \end{pmatrix} = \beta_1 \begin{pmatrix} (d - \lambda_1) \\ c \\ l \end{pmatrix} \exp[-\lambda_1 t] + \beta_2 \begin{pmatrix} (d - \lambda_2) \\ c \\ l \end{pmatrix} \exp[-\lambda_2 t]. \] (D.13)

Finally, from the initial condition we have:

\[ C(0) = \beta_1 \begin{pmatrix} (d - \lambda_1) \\ c \\ l \end{pmatrix} + \beta_2 \begin{pmatrix} (d - \lambda_2) \\ c \\ l \end{pmatrix} = \begin{pmatrix} C_0 \\ 0 \end{pmatrix}. \] (D.14)

Solving equation (D.14) and by using the fact that \( \lambda^* = \lambda_1 - \lambda_2 \), the following values for \( \beta_1 \) and \( \beta_2 \) can be found:

\[ \beta_1 = -\beta_2 = -\frac{c}{\lambda^*} C_0. \] (D.15)

The final solution becomes:

\[ \begin{pmatrix} C_{\text{surf}} \\ C_{\text{air}} \end{pmatrix} = -\frac{c}{\lambda^*} C_0 \begin{pmatrix} (d - \lambda_1) \\ c \\ l \end{pmatrix} \exp[-\lambda_1 t] + \frac{c}{\lambda^*} C_0 \begin{pmatrix} (d - \lambda_2) \\ c \\ l \end{pmatrix} \exp[-\lambda_2 t]. \] (D.16)

For the surface contamination we can write:

\[ C_{\text{surf}}(t) = \frac{C_0}{\lambda^*} \left( (\lambda_1 - d) \exp[-\lambda_1 t] + (d - \lambda_2) \exp[-\lambda_2 t] \right), \] (D.17)

and for the air activity concentration we have:

\[ C_{\text{air}}(t) = \frac{c}{\lambda^*} C_0 \exp[-\lambda_2 t] - \exp[-\lambda_1 t] = \frac{c}{\lambda^*} C_0 \exp[-\lambda_2 t] \times \left( 1 - \exp[-\lambda^* t] \right). \] (D.18)
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