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Comparison of external dose coefficients used by the European Model for Inhabited Areas (ERMIN) and ICRP Publication 144

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Comparison of external dose coefficients used by the European Model for Inhabited Areas (ERMIN) and ICRP Publication 144

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Abstract

The recent ICRP publication of dose coefficients for external exposures to environmental sources, ICRP Publication 144, provided an opportunity to evaluate and improve the dose coefficients and dose conversion factors used by the European Model for Inhabited Areas (ERMIN). ERMIN contains several idealised built environments with the “open area” environment being very similar to the ICRP Publication 144 “planar sources on and within the ground” situation. The ICRP dataset includes many radionuclides, organs, and age-groups. In contrast the ERMIN's “open area” dataset includes only effective and skin doses to adults, and only radionuclides considered of concern for the recovery after an accident. Both datasets were generated using Monte Carlo codes, but ICRP uses more modern ones than those that were used for ERMIN’s creation over 20 years ago. The study compares the values given in ERMIN with those derived from ICRP Publication 144 for the external gamma dose coefficients, the dose conversion factors to convert from air kerma to effective dose, and the beta skin dose coefficients.

The comparison between ICRP Publication 144 and ERMIN external dose coefficients for gamma-emitting radionuclides were in reasonable agreement, with most being within a factor of 2. However, the ICRP Publication 144 and ERMIN’s external dose coefficients for transuranic (those which are generally alpha emitters, with low gamma energies and emissions), beta, and low energy gamma-emitting radionuclides were in less agreement. ERMIN’s dose coefficients tend to be higher than those in ICRP Publication 144, except for radionuclides where there is a significant bremsstrahlung component as these are not included in ERMIN’s calculations. The agreement between the two decreased with soil depth, because of differences in the modelling approaches.

To convert the air kerma rates to adult effective dose, ERMIN uses dose conversion factors derived from ICRP Publication 74. In this approach there is a single dose conversion factor for each radionuclide, which is applied to the dose rates from every surface for locations both indoors and outdoors. With the issuing of ICRP Publication 144, these can be replaced with nine radionuclide specific dose conversion factors: one for the ground surface (and other surfaces including trees and buildings) and one for each of the eight soil layers used in ERMIN. Comparison of the ERMIN dose conversion factors based on ICRP Publication 74 with those in ICRP Publication 144 found that that the ones at the surface were mostly in reasonable agreement but that there was greater difference at deeper soil depths. Again, the transuranic, beta and lower energy gamma-emitting radionuclides showed the greatest differences. This reflects an acknowledged weakness in the creation of the original ERMIN dose conversion factors which are based on an assumed field of a mix of photon energies from radionuclides at

the surface. The presence of layers of soil will change the proportions of different energies and skew it to higher energies, and this effect is greatest for radionuclides that emit a mix that is dominated by lower energy photons.

Beta skin dose coefficients in ERMIN are derived from a 1989 Canadian publication. The comparison between the datasets found that beta dose rate from the soil surface is mostly in reasonable agreement except for transuranic and low energy beta-emitting radionuclides

This study has enabled ERMIN to be improved in several ways. A new “open area” environment has been created based on ICRP Publication 144 “planar sources on and within the ground” situation. New dose conversion factors to convert from air kerma to effective dose have been developed so that the depth in the soil can be taken into account. Other existing built environments have been improved by using a correction factor for external gamma dose coefficients derived from ICRP Publication 144 to account for bremsstrahlung for those radionuclides where it is important. These include ^{137}Cs, ^{143}Pr, ^{144}Pr, ^{106}Ru, ^{89}Sr, ^{90}Sr, ^{90}Y and ^{91}Y. Additionally beta skin dose coefficients have been replaced by those derived from ICRP Publication 144.

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Report version 0.m

Version history

Version	Release date	Notes
1.0	15th December 2023	JAEA editorial notes and report number added

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Contents

1 Introduction

The International Commission on Radiological Protection (ICRP) recently issued Publication 144 which provides a comprehensive set of dose coefficients (DC) for estimating external exposure to environmental sources of radiation. The coefficients were developed using modern Monte Carlo particle transport codes (ICRP, 2020b) and were given for three broad categories of exposure:

- Soil contamination, including contamination at the surface and at depth.
- Immersion in contaminated air.
- Immersion in contaminated water.

The ERMIN model (European Model for Inhabited Areas) (Charnock et al, 2016), uses older libraries of DC, to estimate long-term doses to people in urban areas contaminated by radioactivity deposited on surfaces from air-borne contamination. The libraries were developed from existing studies that used older, less powerful Monte Carlo codes. The new publication of soil contamination dose coefficients affords the opportunity to review the existing DC in ERMIN and to improve the ERMIN modelling approach.

The contaminated soil exposure situation of ICRP Publication 144 is much simpler than many of the urban environments in the ERMIN library. However, the ERMIN "open area" environment is similar in that it represents an area with no buildings and was developed in a similar, albeit simpler, way.

Section 2 of this report compares ERMIN's "open area" external gamma dose coefficients with those derived from ICRP Publication 144. It compares the dose conversion factors (DCF), to convert from air kerma to effective dose currently used in ERMIN with new DCFs derived from ICRP Publication 144. Lastly it compares the beta dose coefficients used in ERMIN with those in ICRP Publication 144.

ERMIN models remediation options such as ploughing that can move significant amounts of radioactivity to depths e.g. 50 g cm^{-2} whereas the ICRP Publication 144 standard planar source goes down to 10 g cm^{-2}. Fortunately, additional, consistent data sets were obtained from the Japan Atomic Energy Agency (JAEA) researchers who generated the ICRP Publication 144 datasets that gave greater depths and also gave components of dose from photons and from bremsstrahlung separately. Section 3 describes how the new DC and DCF were derived from these.

A new version of ERMIN, version 2.3, was developed to use the new DC and DCF and examples of the differences between the use of old and new values are presented in Section 4. Section 5 describes the changes made to develop the new version of ERMIN and further changes that could be incorporated.

1.1 Background to ERMIN and the ERMIN external dose coefficients

ERMIN has been developed through the course of several collaborative European projects since 2006. It is a tool for providing data to inform recovery decisions following an accident involving airborne radioactivity contaminating a settlement or inhabited area.

Functionally the model proceeds in the following steps:

1. The input is an initial deposition of radionuclides onto a reference surface which is usually short grass away from buildings and trees.
2. The initial deposition is then used to predict the deposition onto other surfaces using particle, scenario, and weather dependent empirical ratios in the ERMIN database. Surfaces include paved areas (roads, paved and other paved areas), external walls of buildings, roofs, trees, plants, and internal surfaces.
3. The subsequent weathering of material from those surfaces is modelled using empirical retention functions. The migration of radionuclides down the soil column is modelled with a convection-dispersion model (Bunzl et al, 2000).
4. ERMIN has a database (unit dose-rate library (UDL)) of external dose rate coefficients from surfaces to locations, both indoors and outdoors, in different idealised built environments. From these, dose-rates and doses from surfaces to locations indoors and outdoors in the environments can be calculated and then summed to calculate total doses.
5. Different kinds of clean-up and other recovery operations can be represented by removing radioactivity from surfaces, moving radioactivity from surfaces, changing weathering rates and changing shielding parameters.

Outputs from ERMIN include estimates of doses to the resident population and to workers undertaking the operations, waste quantities and radioactive concentrations in the waste, and costs and effort to undertake recovery operations.

For this document it is the UDL of Step 4 that is of most interest and its development, features and weaknesses are described below.

The UDL has remained largely unchanged since it was first created under the EURANOS collaborative project (Raskob et al, 2010) . It was developed from existing studies and datasets, so it is limited to the types of environments that previous researchers chose to analyse. Various manipulations, conversions and compromises were applied to make the environments as consistent as was possible given their disparate sources. Table 1 gives a summary of the development of the idealised environments in the ERMIN UDL.

Table 1 Summary of development of Idealised environments in ERMIN UDL up to this project (Numbers refer to environment labelling in UDL).

Environment	Source	Notes
1. Street of detached prefabricated houses 2. Street of semi-detached houses with basement 4. Street of terrace houses 5. Multi-storey block of flats amongst other house blocks 6. Multi-storey block of flats opposite parkland	GSF[a]	Based on Monte Carlo calculations of air kerma from contaminated exterior surfaces and the top one cm of soil, performed at GSF, using source energies of 0.3, 0.662 and 3 MeV which are interpolated and extrapolated to give DC for radionuclides. Different locations both inside and outside the target house or apartment were used. The supplementary subsurface - soil dose rates were taken from Eckerman and Ryman (1993), corrected to allow for the finite area of soil and for the shielding effects of soil on the dose rates from material at depths in the soil. The supplementary interior surface dose rates were derived from the HPA/PHE street of semi-detached houses without basement (Jones et al, 2006). Beta skin dose rates are derived from Holford (1989).
3. Street of semi-detached houses without basement 8. Open area	HPA/PHE, Jones et al (2006)	Based on Monte Carlo calculations of adult effective dose from contaminated interior and exterior surfaces and 9 soil layers, using source energies of 0.01, 0.015, 0.02, 0.03, 0.05, 0.1, 0.2, 0.5, 1, 1.5, 2, 4 MeV. DC for specific radionuclides generated with a binning approach, converted to air kerma using a set of radionuclide specific dose conversion factors derived from ICRP Publication 74. Beta skin dose rates are derived from Holford (1989).
7. Industrial site	GSF, Kis et al (2003)	Incomplete with only $^{137}Cs/^{137m}Ba$ provided. The missing subsurface - soil dose rates were taken from Eckerman and Ryman (1993), corrected to allow for the finite area of soil and for the shielding effects of soil on the dose rates from material at depths in the soil. There are no beta skin dose rates.

a Under the original EURANOS project in which ERMIN was first developed, unpublished datasets were supplied by GSF (National Research Centre for Environment and Health, now called Helmholtz Zentrum München) to populate the UDL. Publications that used these results include Meckbach et al (1988) and Meckbach and Jacob (1988).

The DC for idealised environments from Germany's GSF-National Research Centre, were provided as air kerma (Gy per Bq m^{-2} per m^2 of surface), whereas those provided by HPA (a predecessor organisation to UKHSA) were provided as effective adult dose (Sv per Bq m^{-2} per m^2 of surface). Rerunning either set of environments for consistency was not a practical option and therefore it was necessary to convert one set to match the other using an appropriate set of dose conversion factors (DCF). The environments used in the HPA study (Jones et al, 2006), were converted to air kerma because there is a clear advantage in the UDL not being tied to any one set of ICRP recommendations and therefore making future revisions easier. However, dose conversion factors are then also required to convert air kerma to the adult effective dose value required when ERMIN is used operationally. The dose conversion factors used were derived from ICRP Publication 74 (ICRP, 1996b).

The practical constraints of the project meant that only a single dose conversion factor for each radionuclide was derived. It was recognised that this would introduce inaccuracies that would not necessarily be conservative, particularly for dose from lower layers of the soil. As radionuclides migrate down the soil column, different energies are attenuated and scattered to different degrees. Therefore, the dose rate characteristics change because a radiation field from a radionuclide on the surface is different from a radiation field from a radionuclide buried at some depth. This is also true for radiation fields in indoor locations from outdoor sources.

The justification was that this limitation of the modelling would only be significant for radionuclides that emit a large proportion of lower energy photons, and these radionuclides are generally less important when making decisions about recovery options. Other inaccuracies will be introduced because of the assumptions made about geometry in the ICRP calculations and their appropriateness or different ERMIN surfaces. However, these inaccuracies were not practical to resolve.

The formula for deriving the radionuclide dependent dose coefficients was:

$$DCF_n = \sum_e DCF_e \times N_e$$

Where:

DCF_n is the dose conversion factor for the radionuclide (Sv/Gy) for a given age group and organ;

DCF_e is the dose conversion factor for photon of energy *e* (Sv/Gy) for a given age group and organ from ICRP Publication 74, Table A.17 for rotational geometry;

N_e is the proportion of the photons emitted by the radionuclide of energy *e*.

The beta DC in ERMIN are for skin and are derived from Holford (1989). They are assumed to apply in all environments. The coefficients assume deposition on an infinite uniformly contaminated surface. When incorporating them into ERMIN the following assumptions were made:

- The beta dose outdoors from material on paved surfaces is the dose rate in tissue one metre above an infinite, uniformly contaminated surface.
- The beta dose outdoors from material on walls and roofs is zero. This is an assumption that reflects that the range in air of particles emitted by most beta-emitting radionuclides is small compared to the average distance between walls and people and the paucity of data available.
- The beta dose outdoors from the top layer of soil makes no allowance for attenuation by the soil and in effect assumes that the material in this layer is on the surface of the soil.
- The beta dose outdoors from material deeper in the soil is not considered, as the attenuation caused by the soil above the activity significantly reduces the exposure.
- Material deposited outdoors does not contribute to beta dose rates indoors.
- The indoor beta dose will be greatly affected by the presence of interior walls, and the position and material of furnishing. Therefore simplifying assumptions are made that the dose rate comes only from material deposited on the floor, and it is assumed that this is a smooth surface of infinite extent.

1.2 Background to ICRP Publication 144

The International Commission on Radiological Protection (ICRP) has calculated age-dependent dose coefficients for internal exposures (ICRP, 1990; ICRP, 1993; ICRP, 1995a; ICRP, 1995b; ICRP, 1996a; ICRP, 2015; ICRP, 2016; ICRP, 2017; ICRP, 2019). Recently ICRP calculated age-dependent dose coefficients for external exposures to radionuclides in ICRP Publication 144 (ICRP, 2020b).

ICRP Publication 144 provides the dose coefficients for external exposures calculated in the following three conditions: soil (ground) contamination simulated as fully infinite planar sources on the ground surface and at selected depths below the ground surface; air submersion simulated as a semi-infinite volume source of radionuclides in air; and water immersion simulated as a fully infinite volume source of radionuclides in water. The radionuclide distribution on the ground, air, and water was assumed to be uniform. The nuclide-specific dose coefficients for ICRP Publication 144 include the dose contribution of bremsstrahlung photons generated by electron interactions in soil, as well as of photons and electrons.

The dose coefficients in ICRP Publication 144 were computed using the ICRP voxel-based adult phantoms and paediatric voxelised phantoms. These models are male and female ones for new-borns, 1 year old, 5 years old, 10 years old, 15 years old, and adults. For skin doses in ICRP 144, the ICRP tetrahedral-mesh phantoms were used to calculate the dose in the target sensitive layer within the skin at depths of 50–100 μm in adults (ICRP, 2020a).

Dose (organ absorbed dose (Gy), equivalent dose (Sv), effective dose (Sv), and air kerma (Gy)) per unit radioactivity concentration (Bq m^{-2} or Bq m^{-3}) were summarized as the dose coefficients in ICRP Publication 144. The values of the weighting factors for calculating the equivalent dose and effective dose are given in ICRP Publication 103 (ICRP, 2007).

ICRP Publication 144 states that the particle transport calculations for estimating dose coefficients were performed with the Monte Carlo simulation code “Particle and Heavy Ion Transport code System (PHITS) version 2.66” (Sato et al, 2013). The calculations used a two-step approach. The first step involved the radiation transport from the contaminated environment to a virtual cylinder surrounding the exposed individual. The second step involved the transport of the primary and secondary radiation into the phantom.

2 Comparison of ERMIN and ICRP Publication 144

2.1 Dose coefficients from soil contamination at different depths

The comparison of dose coefficients for soil layers between ERMIN (“Open area” environment) and ICRP Publication 144 are shown in Table 2 to Table 5. In this report, the dose coefficient is given as the air kerma normalised to source activity (nGy h^{-1} Bq^{-1} m^2). The relationship between the effective gamma energy[1] and the ratio of dose coefficients for ERMIN and ICRP Publication 144 at different depths[2] is shown in Figure 1. In ERMIN, the air kerma from activity in soil was calculated using the assumption that radionuclides exist uniformly in each soil layer (0–1, 1–2,

[1] Effective gamma energy is the sum of the product of gamma energy and its emission rate.

[2] In this report, depth indicates mass depth (g m^{-2}) multiplied by depth (m) and soil density (g m^{-3}).

2–4, 4–6, 6–8, 8–10, 10–15, 15–20, and 20–40 g cm^{-2}). In contrast, the air kerma from ICRP Publication 144 was calculated from the activity concentration in a planar source at specified depths (including the additional JAEA data, these are 0, 0.5, 3, 10, 12, 15, 20, 25, 30, 40, 50, 75 and 100 g cm^{-2}). In this study, to compare the dose coefficients between ERMIN and ICRP Publication 144, a suitable ICRP depth was chosen that was close to the middle of the ERMIN layer. For example, the DC for ERMIN layer 2-4 g cm^{-2} was compared with the ICRP Publication 144 DC at 3 g cm^{-2}.

The dose coefficients of most radionuclides agreed within 20% between ERMIN and ICRP Publication 144. However, there were some radionuclides which differed by a factor of more than ten and these are shown in Table 2 to Table 5 and Figure 1. These radionuclides have the following characteristics:

1. Transuranic radionuclides (^{241}Am, ^{242}Cm, ^{244}Cm, ^{238}Pu, ^{239}Pu, ^{240}Pu, and ^{241}Pu), generally alpha emitters, with low gamma energies and emission rates.
2. Beta-emitting radionuclides (^{137}Cs, ^{143}Pr, ^{106}Ru, ^{89}Sr, ^{90}Sr, and ^{90}Y) where beta exposure is the principal hazard.
3. Radionuclides with low gamma energies and emissions rates (^{103m}Rh, ^{127m}Te, ^{129}Te, ^{129m}Te, and ^{97}Zr) as shown in Figure 1.

Notably, the dose coefficients of some beta-emitting radionuclides (^{137}Cs, ^{106}Ru, ^{90}Sr, and ^{90}Y) differed by a factor of more than 100 between ERMIN and ICRP Publication 144. One of the reasons for this difference is the bremsstrahlung photons via electrons deceleration. The environments within the ERMIN database do not include this component, while ICRP Publication 144 does. Table 6 shows the contribution of bremsstrahlung to the ICRP Publication 144 dose coefficients at the depth of 0.5 g cm^{-2}, indicating that the bremsstrahlung contributes to most of the dose coefficient for ^{137}Cs, ^{143}Pr,^{144}Pr, ^{106}Ru, ^{89}Sr, ^{90}Sr, ^{90}Y, and ^{91}Y.

Additional data files provided by JAEA to supplement the ICRP Publication 144 ones give the dose-rates from photons and bremsstrahlung separately, Using ^{90}Y as an example, the additional data files show that the air kerma rate from photons at the depth of 0.5 g cm^{-2} is 4.83×10^{-10} nGy h^{-1} Bq^{-1} m^2, which is similar to the value of ERMIN (6.50×10^{-9} nGy h^{-1} Bq^{-1} m^2). However, the air kerma rate from bremsstrahlung for ^{90}Y at the depth of 0.5 g cm^{-2} is a much larger 1.56×10^{-5} nGy h^{-1} Bq^{-1} m^2.

For all radionuclides, the difference in dose coefficients between ERMIN and ICRP Publication 144 is greater at deeper depths of contamination as shown in Figure 2.

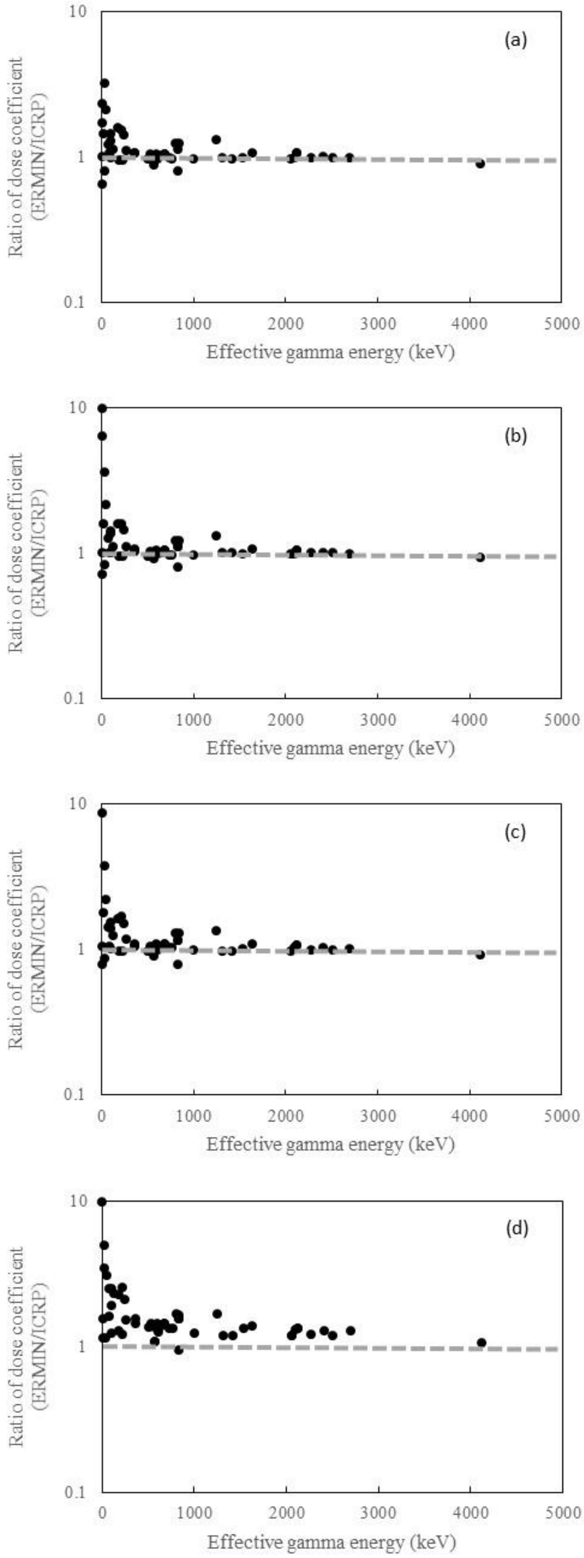


Figure 1 Relationship between the effective gamma energy and the ratio of dose coefficients for ERMIN and ICRP Publication 144 excluding transuranic and beta-emitting radionuclides at (a) depth of 0.5 g cm^{-2}, (b) depth of 3 g cm^{-2}, (c) depth of 10 g cm^{-2}, (d) depth of 30 g cm^{-2}.

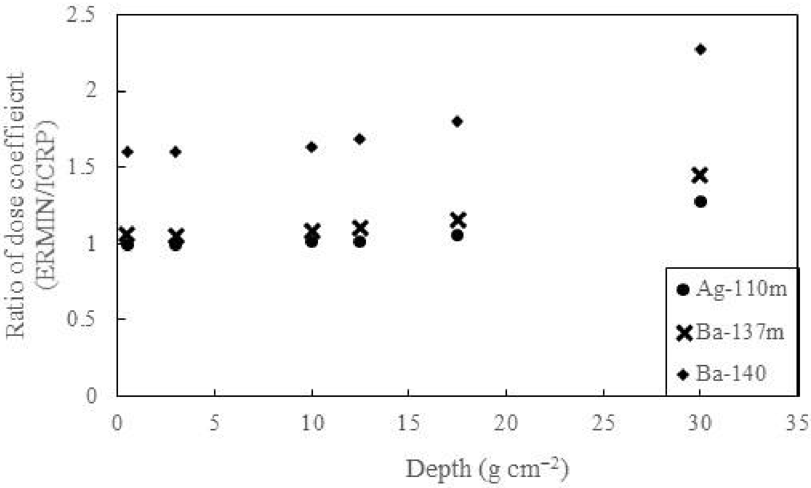


Figure 2 Examples of the relationship between the depth of contamination and the ratio of dose coefficients for ERMIN and ICRP Publication 144.

Table 2 Comparison of dose coefficients (nGy h^{-1} Bq^{-1} m^2) between ERMIN and ICRP Publication 144. The dose coefficient in ERMIN chosen was the value for the soil layer of 0–1 g cm^{-2} in ERMIN "open area" environment. The dose coefficient in ICRP Publication 144 chosen was for the sources uniformly distributed at the depth of 0.5 g cm^{-2}.

Radionuclide	ERMIN	ICRP144	ERMIN/ICRP	Radionuclide	ERMIN	ICRP144	ERMIN/ICRP
Ag-110m	8.21E-03	8.25E-03	0.99	Pu-240	1.08E-05	8.88E-07	12.21
Am-241	1.61E-04	6.26E-05	2.57	Pu-241	2.09E-08	4.10E-09	5.09
Ba-137m	1.96E-03	1.85E-03	1.06	Rb-86	2.74E-04	2.74E-04	1.00
Ba-140	8.99E-04	5.60E-04	1.60	Rb-88	1.65E-03	1.86E-03	0.89
Ce-141	2.67E-04	2.18E-04	1.22	Rh-103m	1.59E-05	2.31E-06	6.90
Ce-143	1.22E-03	8.57E-04	1.43	Rh-105	2.53E-04	2.36E-04	1.07
Ce-144	7.93E-05	5.46E-05	1.45	Rh-106	6.37E-04	6.64E-04	0.96
Cm-242	1.22E-05	1.26E-06	9.71	Ru-103	1.50E-03	1.53E-03	0.98
Cm-244	2.58E-05	1.12E-06	23.06	Ru-105	2.43E-03	2.29E-03	1.06
Co-58	3.74E-03	2.98E-03	1.26	Ru-106	0.00E+00	1.36E-10	0.00
Co-60	7.06E-03	7.10E-03	0.99	Sb-127	2.19E-03	2.14E-03	1.02
Cs-134	4.76E-03	4.78E-03	1.00	Sb-129	4.24E-03	4.31E-03	0.98
Cs-136	6.69E-03	6.28E-03	1.06	Sr-89	2.53E-07	6.59E-06	0.04
Cs-137	0.00E+00	7.93E-07	0.00	Sr-90	0.00E+00	7.69E-07	0.00
Cs-138	6.53E-03	6.71E-03	0.97	Sr-91	2.08E-03	2.11E-03	0.98
I-129	1.32E-04	7.61E-05	1.73	Sr-92	3.74E-03	3.79E-03	0.99
I-131	1.25E-03	1.17E-03	1.07	Tc-99m	3.95E-04	3.49E-04	1.13
I-132	6.89E-03	6.87E-03	1.00	Te-127	1.64E-05	1.60E-05	1.02
I-133	1.90E-03	1.87E-03	1.01	Te-127m	7.28E-05	3.10E-05	2.35
I-134	7.82E-03	7.72E-03	1.01	Te-129	4.11E-04	1.94E-04	2.12
I-135	4.42E-03	4.50E-03	0.98	Te-129m	3.76E-04	1.15E-04	3.27
La-140	6.54E-03	6.63E-03	0.99	Te-131	1.35E-03	1.25E-03	1.08
Mn-54	3.16E-03	2.54E-03	1.24	Te-131m	4.62E-03	4.33E-03	1.07
Mo-99	5.13E-04	4.56E-04	1.13	Te-132	1.08E-03	6.94E-04	1.55
Na-24	1.00E-02	1.12E-02	0.90	Te-133	2.82E-03	3.51E-03	0.80
Nb-95	2.33E-03	2.36E-03	0.99	Te-133m	7.24E-03	5.48E-03	1.32
Nb-97m	2.25E-03	2.06E-03	1.09	Te-134	3.01E-03	2.66E-03	1.13
Nd-147	5.48E-04	4.24E-04	1.29	Y-90	6.50E-09	1.56E-05	0.00
Np-239	7.14E-04	4.93E-04	1.45	Y-91	1.03E-05	1.56E-05	0.66
Pr-143	2.72E-11	1.96E-06	0.00	Y-91m	1.72E-03	1.63E-03	1.05
Pr-144	8.66E-05	1.08E-04	0.80	Y-92	7.37E-04	7.74E-04	0.95
Pu-238	1.07E-05	9.28E-07	11.49	Zr-95	2.25E-03	2.26E-03	1.00
Pu-239	1.45E-04	5.60E-07	259.81	Zr-97	5.28E-04	2.70E-03	0.20

Table 3 Comparison of dose coefficients (nGy h^{-1} Bq^{-1} m^2) between ERMIN and ICRP Publication 144. The dose coefficient in ERMIN chosen was the value for the soil layer of 2–4 g cm^{-2} in ERMIN “open area” environment. The dose coefficient in ICRP Publication 144 chosen was for the sources uniformly distributed at the depth of 3 g cm^{-2}.

Radionuclide	ERMIN	ICRP144	ERMIN/ICRP	Radionuclide	ERMIN	ICRP144	ERMIN/ICRP
Ag-110m	4.58E-03	4.61E-03	0.99	Pu-240	1.15E-06	2.32E-08	49.55
Am-241	6.18E-05	1.84E-05	3.36	Pu-241	1.07E-08	2.07E-09	5.18
Ba-137m	1.08E-03	1.03E-03	1.05	Rb-86	1.53E-04	1.52E-04	1.01
Ba-140	4.95E-04	3.10E-04	1.60	Rb-88	9.38E-04	1.02E-03	0.92
Ce-141	1.41E-04	1.11E-04	1.27	Rh-103m	6.29E-07	9.88E-09	63.61
Ce-143	6.54E-04	4.48E-04	1.46	Rh-105	1.40E-04	1.37E-04	1.02
Ce-144	3.94E-05	2.45E-05	1.61	Rh-106	3.55E-04	3.73E-04	0.95
Cm-242	1.03E-06	1.86E-08	55.53	Ru-103	8.35E-04	8.72E-04	0.96
Cm-244	8.31E-06	3.74E-08	222.15	Ru-105	1.35E-03	1.29E-03	1.05
Co-58	2.07E-03	1.68E-03	1.24	Ru-106	0.00E+00	3.18E-13	0.00
Co-60	4.00E-03	3.92E-03	1.02	Sb-127	1.22E-03	1.20E-03	1.01
Cs-134	2.65E-03	2.68E-03	0.99	Sb-129	2.37E-03	2.41E-03	0.98
Cs-136	3.71E-03	3.51E-03	1.06	Sr-89	1.40E-07	3.01E-06	0.05
Cs-137	0.00E+00	2.75E-07	0.00	Sr-90	0.00E+00	2.53E-07	0.00
Cs-138	3.71E-03	3.70E-03	1.00	Sr-91	1.15E-03	1.17E-03	0.99
I-129	1.82E-05	2.82E-06	6.47	Sr-92	2.13E-03	2.09E-03	1.02
I-131	6.94E-04	6.73E-04	1.03	Tc-99m	2.13E-04	1.92E-04	1.11
I-132	3.83E-03	3.84E-03	1.00	Te-127	9.07E-06	8.92E-06	1.02
I-133	1.06E-03	1.06E-03	1.00	Te-127m	9.22E-06	9.31E-07	9.90
I-134	4.36E-03	4.31E-03	1.01	Te-129	2.23E-04	1.02E-04	2.19
I-135	2.51E-03	2.49E-03	1.01	Te-129m	1.93E-04	5.27E-05	3.66
La-140	3.72E-03	3.67E-03	1.01	Te-131	7.45E-04	6.92E-04	1.08
Mn-54	1.75E-03	1.42E-03	1.23	Te-131m	2.57E-03	2.41E-03	1.07
Mo-99	2.83E-04	2.55E-04	1.11	Te-132	5.69E-04	3.58E-04	1.59
Na-24	5.76E-03	6.09E-03	0.95	Te-133	1.58E-03	1.96E-03	0.81
Nb-95	1.29E-03	1.33E-03	0.97	Te-133m	4.03E-03	3.05E-03	1.32
Nb-97m	1.25E-03	1.15E-03	1.08	Te-134	1.66E-03	1.49E-03	1.11
Nd-147	2.86E-04	2.07E-04	1.38	Y-90	0.00E+00	7.62E-06	0.00
Np-239	3.85E-04	2.68E-04	1.44	Y-91	5.80E-06	8.00E-06	0.72
Pr-143	1.51E-11	7.69E-07	0.00	Y-91m	9.55E-04	9.23E-04	1.04
Pr-144	4.91E-05	5.85E-05	0.84	Y-92	4.12E-04	4.30E-04	0.96
Pu-238	8.21E-07	2.08E-08	39.46	Zr-95	1.25E-03	1.27E-03	0.98
Pu-239	4.50E-05	9.40E-08	479.07	Zr-97	2.97E-04	1.51E-03	0.20

Table 4 Comparison of dose coefficients (nGy h^{-1} Bq^{-1} m^2) between ERMIN and ICRP Publication 144. The dose coefficient in ERMIN chosen was the value for the soil layer of 8–15 g cm^{-2} in ERMIN "open area" environment. The dose coefficient in ICRP Publication 144 chosen was for the sources uniformly distributed at the depth of 10 g cm^{-2}.

Radionuclide	ERMIN	ICRP144	ERMIN/ICRP	Radionuclide	ERMIN	ICRP144	ERMIN/ICRP
Ag-110m	2.13E-03	2.11E-03	1.01	Pu-240	2.83E-07	4.08E-09	69.41
Am-241	1.23E-05	1.93E-06	6.39	Pu-241	3.56E-09	5.92E-10	6.01
Ba-137m	5.01E-04	4.61E-04	1.09	Rb-86	7.20E-05	7.11E-05	1.01
Ba-140	2.22E-04	1.36E-04	1.63	Rb-88	4.59E-04	5.07E-04	0.91
Ce-141	5.29E-05	3.73E-05	1.42	Rh-103m	2.65E-08	7.66E-11	346.27
Ce-143	2.85E-04	1.88E-04	1.52	Rh-105	6.15E-05	5.82E-05	1.06
Ce-144	1.35E-05	7.58E-06	1.79	Rh-106	1.63E-04	1.67E-04	0.97
Cm-242	2.73E-07	4.35E-09	62.67	Ru-103	3.78E-04	3.89E-04	0.97
Cm-244	3.53E-06	1.49E-08	236.99	Ru-105	6.20E-04	5.71E-04	1.09
Co-58	9.65E-04	7.46E-04	1.29	Ru-106	0.00E+00	0.00E+00	-
Co-60	1.87E-03	1.89E-03	0.99	Sb-127	5.58E-04	5.34E-04	1.05
Cs-134	1.23E-03	1.20E-03	1.02	Sb-129	1.11E-03	1.11E-03	1.00
Cs-136	1.72E-03	1.60E-03	1.08	Sr-89	6.59E-08	1.07E-06	0.06
Cs-137	0.00E+00	7.61E-08	0.00	Sr-90	0.00E+00	6.57E-08	0.00
Cs-138	1.76E-03	1.82E-03	0.97	Sr-91	5.40E-04	5.38E-04	1.00
I-129	8.86E-07	9.00E-09	98.49	Sr-92	9.93E-04	1.02E-03	0.97
I-131	3.10E-04	2.92E-04	1.06	Tc-99m	8.06E-05	6.45E-05	1.25
I-132	1.78E-03	1.74E-03	1.03	Te-127	4.04E-06	3.84E-06	1.05
I-133	4.83E-04	4.77E-04	1.01	Te-127m	1.05E-06	1.21E-07	8.66
I-134	2.04E-03	1.97E-03	1.04	Te-129	1.01E-04	4.54E-05	2.22
I-135	1.18E-03	1.20E-03	0.99	Te-129m	8.79E-05	2.32E-05	3.79
La-140	1.75E-03	1.77E-03	0.99	Te-131	3.29E-04	2.98E-04	1.10
Mn-54	8.19E-04	6.35E-04	1.29	Te-131m	1.20E-03	1.09E-03	1.10
Mo-99	1.29E-04	1.10E-04	1.17	Te-132	2.38E-04	1.39E-04	1.71
Na-24	2.89E-03	3.16E-03	0.91	Te-133	7.26E-04	9.18E-04	0.79
Nb-95	6.01E-04	5.86E-04	1.03	Te-133m	1.89E-03	1.41E-03	1.34
Nb-97m	5.80E-04	5.17E-04	1.12	Te-134	7.49E-04	6.41E-04	1.17
Nd-147	1.17E-04	8.29E-05	1.41	Y-90	0.00E+00	2.87E-06	0.00
Np-239	1.48E-04	9.52E-05	1.55	Y-91	2.71E-06	3.44E-06	0.79
Pr-143	7.01E-12	2.35E-07	0.00	Y-91m	4.36E-04	4.14E-04	1.05
Pr-144	2.38E-05	2.73E-05	0.87	Y-92	1.93E-04	1.99E-04	0.97
Pu-238	1.65E-07	3.82E-09	43.21	Zr-95	5.80E-04	5.63E-04	1.03
Pu-239	1.63E-05	3.11E-08	523.49	Zr-97	1.38E-04	6.77E-04	0.20

Table 5 Comparison of dose coefficients (nGy h^{-1} Bq^{-1} m^2) between ERMIN and ICRP Publication 144. The dose coefficient in ERMIN chosen was the value for the soil layer of 20–40 g cm^{-2} in ERMIN "open area" environment. The dose coefficient in ICRP Publication 144 chosen was for the sources uniformly distributed at the depth of 30 g cm^{-2}.

Radionuclide	ERMIN	ICRP144	ERMIN/ICRP	Radionuclide	ERMIN	ICRP144	ERMIN/ICRP
Ag-110m	6.26E-04	4.91E-04	1.28	Pu-240	4.57E-08	2.92E-10	156.44
Am-241	8.48E-07	6.75E-09	125.57	Pu-241	3.57E-10	2.60E-11	13.74
Ba-137m	1.36E-04	9.44E-05	1.44	Rb-86	2.19E-05	1.78E-05	1.23
Ba-140	5.45E-05	2.39E-05	2.28	Rb-88	1.56E-04	1.45E-04	1.08
Ce-141	6.58E-06	2.61E-06	2.52	Rh-103m	0.00E+00	0.00E+00	-
Ce-143	6.57E-05	3.11E-05	2.11	Rh-105	1.29E-05	7.98E-06	1.62
Ce-144	1.55E-06	4.49E-07	3.46	Rh-106	4.34E-05	3.35E-05	1.29
Cm-242	5.78E-08	5.42E-10	106.61	Ru-103	9.56E-05	7.07E-05	1.35
Cm-244	1.03E-06	3.53E-09	290.52	Ru-105	1.65E-04	1.14E-04	1.45
Co-58	2.70E-04	1.62E-04	1.67	Ru-106	0.00E+00	0.00E+00	-
Co-60	6.04E-04	5.02E-04	1.20	Sb-127	1.48E-04	1.06E-04	1.40
Cs-134	3.39E-04	2.54E-04	1.33	Sb-129	3.31E-04	2.67E-04	1.24
Cs-136	4.90E-04	3.67E-04	1.34	Sr-89	1.91E-08	1.33E-07	0.14
Cs-137	0.00E+00	5.99E-09	0.00	Sr-90	0.00E+00	4.35E-09	0.00
Cs-138	5.79E-04	4.89E-04	1.18	Sr-91	1.57E-04	1.25E-04	1.26
I-129	0.00E+00	6.61E-12	0.00	Sr-92	3.28E-04	2.74E-04	1.20
I-131	7.15E-05	4.62E-05	1.55	Tc-99m	9.90E-06	4.29E-06	2.31
I-132	5.08E-04	3.86E-04	1.32	Te-127	9.41E-07	6.07E-07	1.55
I-133	1.29E-04	9.43E-05	1.36	Te-127m	1.59E-07	1.61E-08	9.86
I-134	5.98E-04	4.64E-04	1.29	Te-129	2.55E-05	8.31E-06	3.07
I-135	3.81E-04	3.19E-04	1.20	Te-129m	2.42E-05	4.84E-06	5.00
La-140	5.64E-04	4.63E-04	1.22	Te-131	8.00E-05	5.57E-05	1.44
Mn-54	2.34E-04	1.43E-04	1.63	Te-131m	3.44E-04	2.49E-04	1.38
Mo-99	3.38E-05	2.21E-05	1.53	Te-132	3.85E-05	1.51E-05	2.55
Na-24	1.04E-03	9.73E-04	1.07	Te-133	2.01E-04	2.13E-04	0.94
Nb-95	1.69E-04	1.27E-04	1.33	Te-133m	5.51E-04	3.30E-04	1.67
Nb-97m	1.62E-04	1.06E-04	1.53	Te-134	1.86E-04	1.19E-04	1.56
Nd-147	2.65E-05	1.38E-05	1.92	Y-90	0.00E+00	4.08E-07	0.00
Np-239	2.22E-05	8.89E-06	2.50	Y-91	8.64E-07	7.48E-07	1.15
Pr-143	1.96E-12	2.10E-08	0.00	Y-91m	1.14E-04	7.87E-05	1.44
Pr-144	7.82E-06	6.84E-06	1.14	Y-92	5.80E-05	4.80E-05	1.21
Pu-238	1.28E-08	1.97E-10	64.84	Zr-95	1.62E-04	1.21E-04	1.34
Pu-239	2.89E-06	3.54E-09	815.67	Zr-97	4.09E-05	1.48E-04	0.28

Table 6 Dose coefficients (nGy h^{-1} Bq^{-1} m^2) in ICRP Publication 144 at the depth of 0.5 g cm^{-2}. The column of Total is the dose coefficient from all radiation, and that of B is only from bremsstrahlung radiation.

Radionuclide	Total	B	B/Total	Radionuclide	Total	B	B/Total
Ag-110m	8.25E-03	2.17E-07	0.00	Pu-240	8.88E-07	8.46E-12	0.00
Am-241	6.26E-05		0.00	Pu-241	4.10E-09	3.88E-13	0.00
Ba-137m	1.85E-03		0.00	Rb-86	2.74E-04	8.47E-06	0.03
Ba-140	5.60E-04	1.76E-06	0.00	Rb-88	1.86E-03	8.06E-05	0.04
Ce-141	2.18E-04	4.55E-07	0.00	Rh-103m	2.31E-06		0.00
Ce-143	8.57E-04	3.30E-06	0.00	Rh-105	2.36E-04	5.23E-07	0.00
Ce-144	5.46E-05	1.46E-07	0.00	Rh-106	6.64E-04	3.48E-05	0.05
Cm-242	1.26E-06	4.48E-12	0.00	Ru-103	1.53E-03		0.00
Cm-244	1.12E-06	1.60E-10	0.00	Ru-105	2.29E-03	3.30E-06	0.00
Co-58	2.98E-03	1.05E-07	0.00	Ru-106	1.36E-10	1.36E-10	1.00
Co-60	7.10E-03	1.97E-07	0.00	Sb-127	2.14E-03	1.98E-06	0.00
Cs-134	4.78E-03	6.47E-07	0.00	Sb-129	4.31E-03	4.06E-06	0.00
Cs-136	6.28E-03	3.26E-07	0.00	Sr-89	6.59E-06	6.33E-06	0.96
Cs-137	7.93E-07	7.88E-07	0.99	Sr-90	7.69E-07	7.69E-07	1.00
Cs-138	6.71E-03	2.72E-05	0.00	Sr-91	2.11E-03	9.52E-06	0.00
I-129	7.61E-05	4.20E-08	0.00	Sr-92	3.79E-03	1.07E-06	0.00
I-131	1.17E-03	7.04E-07	0.00	Tc-99m	3.49E-04	1.04E-11	0.00
I-132	6.87E-03	5.12E-06	0.00	Te-127	1.60E-05	1.03E-06	0.06
I-133	1.87E-03	3.35E-06	0.00	Te-127m	3.10E-05	3.12E-08	0.00
I-134	7.72E-03	6.45E-06	0.00	Te-129	1.94E-04	5.11E-06	0.03
I-135	4.50E-03	2.68E-06	0.00	Te-129m	1.15E-04	2.36E-06	0.02
La-140	6.63E-03	5.28E-06	0.00	Te-131	1.25E-03	9.07E-06	0.01
Mn-54	2.54E-03	4.54E-12	0.00	Te-131m	4.33E-03	8.38E-07	0.00
Mo-99	4.56E-04	3.10E-06	0.01	Te-132	6.94E-04	8.95E-08	0.00
Na-24	1.12E-02	5.43E-06	0.00	Te-133	3.51E-03	9.90E-06	0.00
Nb-95	2.36E-03	3.29E-08	0.00	Te-133m	5.48E-03	3.67E-06	0.00
Nb-97	2.06E-03	4.07E-06	0.00	Te-134	2.66E-03	7.52E-07	0.00
Nd-147	4.24E-04	1.18E-06	0.00	Y-90	1.56E-05	1.56E-05	1.00
Np-239	4.93E-04	2.91E-07	0.00	Y-91	1.56E-05	6.74E-06	0.43
Pr-143	1.96E-06	1.96E-06	1.00	Y-91m	1.63E-03		0.00
Pr-144	1.08E-04	2.56E-05	0.24	Y-92	7.74E-04	3.84E-05	0.05
Pu-238	9.28E-07	1.76E-13	0.00	Zr-95	2.26E-03	2.99E-07	0.00
Pu-239	5.60E-07		0.00	Zr-97	2.70E-03	9.25E-06	0.00

2.2 Dose conversion factors from soil contamination at different depths

The comparison of dose conversion factors (Sv Gy^{-1}) for soil layers between ERMIN and ICRP Publication 144 is shown in Table 7 and Figure 3. The dose conversion factor in ICRP Publication 144 was calculated by dividing the effective dose of adults by the air kerma because ICRP Publication 144 does not provide the dose conversion factor. The dose conversion factor in ERMIN is independent of the depth, whilst that in ICRP Publication 144 depends on the depth

(Figure 4). The dose conversion factors for most radionuclides at the depth of 0.5 g cm^{-2} agreed within 20% between ERMIN and ICRP Publication 144. Those in ERMIN tended to be higher than those in ICRP Publication 144 as shown in Figure 3. However, for some radionuclides, the ratio differed by a factor of more than two. Those radionuclides are transuranic and beta-emitting ones, and radionuclides with low gamma energies and emission rates, as mentioned previously. Additionally, the ratio of dose conversion factor of ERMIN to ICRP tended to be larger for deeper soil layers because the dose conversion factor of ICRP Publication 144 tended to decrease with depth as shown in Figure 4.

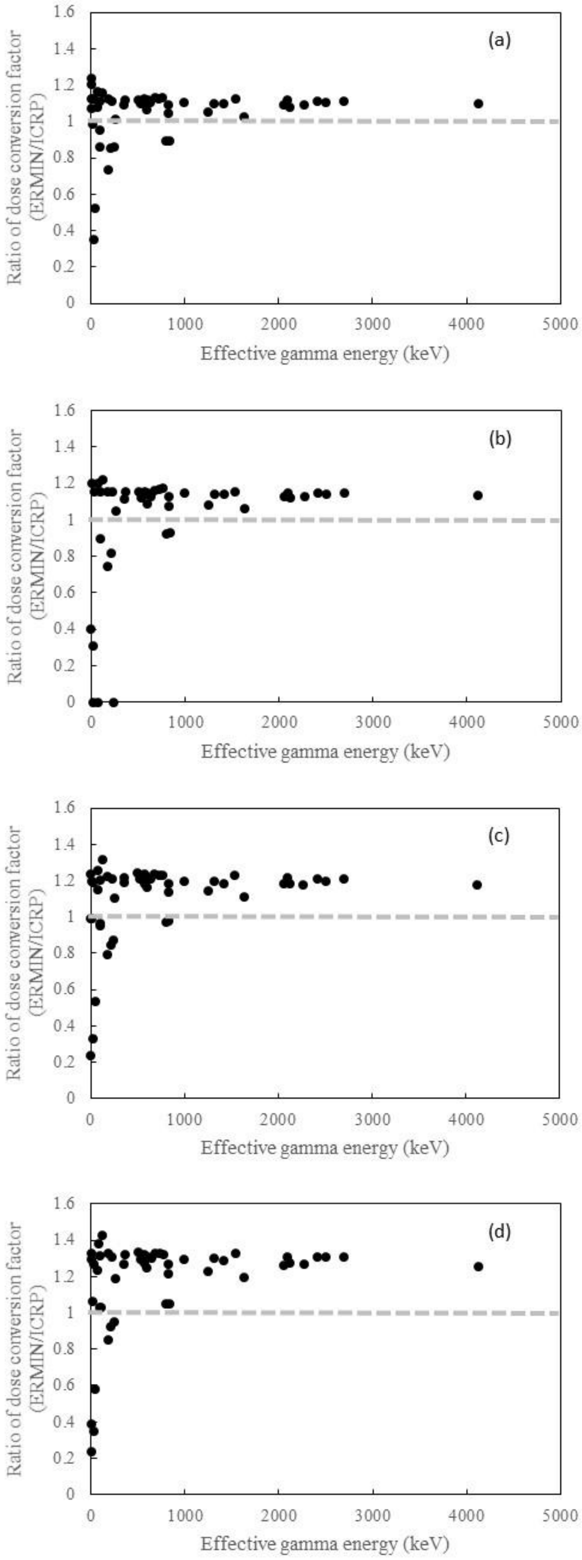


Figure 3 Relationship between the effective gamma energy and the ratio of dose conversion factors for ERMIN and ICRP Publication 144 at (a): depth of 0.5 g cm^{-2}, (b): depth of 3 g cm^{-2}, (c): depth of 10 g cm^{-2}, (d): depth of 30 g cm^{-2}.

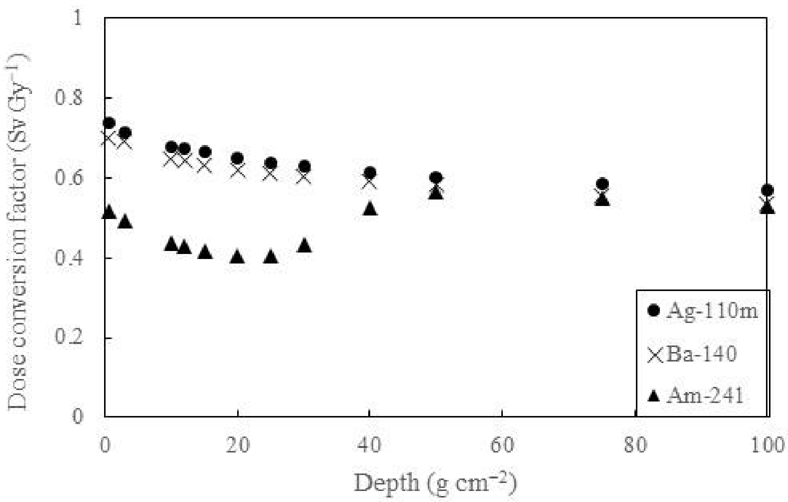


Figure 4 Examples of relationship between the dose conversion factor and the depth of contamination for ICRP Publication 144.

Table 7 Comparison of dose conversion factors (Sv Gy^{-1}) between ERMIN and ICRP Publication 144.

Radionuclide	ERMIN	ICRP Publication 144				ERMIN/ICRP			
		Depth (g cm^{-2})				Depth (g cm^{-2})			
		0.5	3	10	30	0.5	3	10	30
Ag-110m	0.821	0.739	0.714	0.678	0.629	1.11	1.15	1.21	1.30
Am-241	0.307	0.519	0.493	0.438	0.431	0.59	0.62	0.70	0.71
Ba-137m	0.766	0.719	0.705	0.657	0.613	1.06	1.09	1.16	1.25
Ba-140	0.514	0.698	0.690	0.648	0.603	0.74	0.74	0.79	0.85
Ce-141	0.729	0.674	0.679	0.635	0.590	1.08	1.07	1.15	1.24
Ce-143	0.573	0.665	0.676	0.654	0.601	0.86	0.85	0.88	0.95
Ce-144	0.621	0.630	0.665	0.628	0.584	0.99	0.93	0.99	1.06
Cm-242	0.029	0.056	0.543	0.632	0.618	0.52	0.05	0.05	0.05
Cm-244	0.028	0.080	0.671	0.691	0.660	0.35	0.04	0.04	0.04
Co-58	0.649	0.728	0.702	0.666	0.617	0.89	0.92	0.97	1.05
Co-60	0.843	0.765	0.737	0.704	0.645	1.10	1.14	1.20	1.31
Cs-134	0.815	0.726	0.705	0.663	0.614	1.12	1.16	1.23	1.33
Cs-136	0.798	0.739	0.712	0.675	0.627	1.08	1.12	1.18	1.27
Cs-137	0.000	0.518	0.615	0.619	0.588	0.00	0.00	0.00	0.00
Cs-138	0.837	0.768	0.743	0.709	0.663	1.09	1.13	1.18	1.26
I-129	0.203	0.164	0.170	0.206	0.525	1.24	1.20	0.99	0.39
I-131	0.788	0.705	0.682	0.647	0.595	1.12	1.16	1.22	1.32
I-132	0.818	0.732	0.711	0.672	0.624	1.12	1.15	1.22	1.31
I-133	0.810	0.722	0.702	0.656	0.612	1.12	1.15	1.23	1.32
I-134	0.822	0.740	0.715	0.680	0.629	1.11	1.15	1.21	1.31
I-135	0.838	0.764	0.735	0.708	0.652	1.10	1.14	1.18	1.29
La-140	0.831	0.762	0.736	0.706	0.654	1.09	1.13	1.18	1.27
Mn-54	0.655	0.732	0.704	0.671	0.624	0.89	0.93	0.98	1.05
Mo-99	0.733	0.721	0.698	0.664	0.615	1.02	1.05	1.10	1.19
Na-24	0.869	0.790	0.767	0.741	0.693	1.10	1.13	1.17	1.25
Nb-95	0.819	0.725	0.698	0.666	0.620	1.13	1.17	1.23	1.32
Nb-97m	0.808	0.723	0.707	0.658	0.614	1.12	1.14	1.23	1.31
Nd-147	0.622	0.653	0.676	0.644	0.602	0.95	0.92	0.97	1.03
Np-239	0.602	0.702	0.672	0.633	0.584	0.86	0.90	0.95	1.03
Pr-143	0.817	0.561	0.633	0.626	0.586	1.46	1.29	1.31	1.39
Pr-144	0.838	0.744	0.726	0.703	0.661	1.13	1.15	1.19	1.27
Pu-238	0.025	0.065	0.529	0.605	0.589	0.38	0.05	0.04	0.04
Pu-239	0.001	0.250	0.640	0.630	0.593	0.01	0.00	0.00	0.00

Table 7 Comparison of dose conversion factors (Sv Gy^{-1}) between ERMIN and ICRP Publication 144 (Continued)

Radionuclide	ERMIN	ICRP Publication 144				ERMIN/ICRP			
		Depth (g cm^{-2})				Depth (g cm^{-2})			
		0.5	3	10	30	0.5	3	10	30
Pu-240	0.025	0.071	0.517	0.608	0.623	0.35	0.05	0.04	0.04
Pu-241	0.196	0.705	0.671	0.617	0.573	0.28	0.29	0.32	0.34
Rb-86	0.834	0.752	0.724	0.692	0.635	1.11	1.15	1.21	1.31
Rb-88	0.853	0.774	0.749	0.722	0.668	1.10	1.14	1.18	1.28
Rh-103m	0.038	0.052	0.239	0.197	-*	0.74	0.16	0.19	-*
Rh-105	0.808	0.695	0.672	0.643	0.586	1.16	1.20	1.26	1.38
Rh-106	0.812	0.721	0.702	0.665	0.612	1.13	1.16	1.22	1.33
Ru-103	0.804	0.719	0.695	0.648	0.604	1.12	1.16	1.24	1.33
Ru-105	0.813	0.721	0.700	0.658	0.611	1.13	1.16	1.23	1.33
Ru-106	0.000	0.049	0.090	-*	-*	0.00	0.00	-*	-*
Sb-127	0.793	0.720	0.702	0.657	0.610	1.10	1.13	1.21	1.30
Sb-129	0.823	0.745	0.718	0.687	0.637	1.10	1.15	1.20	1.29
Sr-89	0.822	0.619	0.658	0.636	0.599	1.33	1.25	1.29	1.37
Sr-90	0.000	0.503	0.609	0.612	0.584	0.00	0.00	0.00	0.00
Sr-91	0.825	0.739	0.718	0.678	0.630	1.12	1.15	1.22	1.31
Sr-92	0.845	0.770	0.742	0.708	0.650	1.10	1.14	1.19	1.30
Tc-99m	0.837	0.722	0.688	0.636	0.587	1.16	1.22	1.32	1.42
Te-127	0.772	0.688	0.682	0.643	0.595	1.12	1.13	1.20	1.30
Te-127m	0.144	0.134	0.362	0.603	0.609	1.07	0.40	0.24	0.24
Te-129	0.351	0.670	0.696	0.654	0.606	0.52	0.50	0.54	0.58
Te-129m	0.216	0.610	0.696	0.659	0.616	0.35	0.31	0.33	0.35
Te-131	0.786	0.721	0.704	0.661	0.619	1.09	1.12	1.19	1.27
Te-131m	0.753	0.734	0.710	0.679	0.631	1.03	1.06	1.11	1.19
Te-132	0.544	0.638	0.665	0.642	0.589	0.85	0.82	0.85	0.92
Te-133	0.814	0.746	0.719	0.688	0.643	1.09	1.13	1.18	1.27
Te-133m	0.778	0.741	0.718	0.681	0.633	1.05	1.08	1.14	1.23
Te-134	0.743	0.711	0.691	0.655	0.611	1.05	1.08	1.13	1.22
Y-90	0.019	0.647	0.668	0.645	0.603	0.03	0.03	0.03	0.03
Y-91	0.840	0.699	0.705	0.680	0.634	1.20	1.19	1.24	1.33
Y-91m	0.787	0.718	0.700	0.652	0.607	1.10	1.12	1.21	1.30
Y-92	0.828	0.744	0.719	0.683	0.633	1.11	1.15	1.21	1.31
Zr-95	0.818	0.726	0.702	0.664	0.616	1.13	1.17	1.23	1.33
Zr-97	0.824	0.730	0.702	0.668	0.621	1.13	1.17	1.23	1.33

*The effective dose and air kerma are zero.

2.3 Beta dose rates from the soil surface

The beta skin dose rates coefficients in ERMIN are derived from Holford (1989) using the assumptions given in Section 1.1. These were compared to the ICRP Publication 144 dose coefficients for beta radiations on soil surfaces at a depth of 0 g cm^{-2}. The comparison of the dose coefficients from beta radiation between ERMIN and ICRP Publication 144 is shown in

Table 8. The dose coefficient differed depending on the beta energy as shown in Figure 5. For most radionuclides, the dose coefficient for skin in ERMIN is smaller than that in ICRP Publication 144. The ratio of the dose coefficient in ERMIN to ICRP was approximately one for radionuclides with a beta energy of approximately 1000 keV, whilst it tended to be less than one for radionuclides with beta energies less or more than 1000 keV. The beta dose coefficients for transuranic radionuclides in ICRP Publication 144 were approximately 100 times larger than those in ERMIN.

Table 8 Comparison of dose coefficient (nSv h^{-1} Bq^{-1} m^2) from beta radiations between ERMIN and ICRP Publication 144. The dose coefficient in ERMIN shown is the value for the soil layer of 0–1 g cm^{-2} in the ERMIN "open area" environment. The ICRP Publication 144 dose coefficient for electrons shown is the one for uniform contamination at a depth of 0 g cm^{-2} averaged between the sexes.

	Dose coefficient				Dose coefficient		
Radionuclide	ERMIN	ICRP	ERMIN/ICRP	Radionuclide	ERMIN	ICRP	ERMIN/ICRP
Ag-110m	2.77E-03	3.48E-03	0.80	Pu-240	3.82E-08	1.57E-06	0.02
Am-241	4.65E-07	5.04E-06	0.09	Pu-241	1.12E-08	3.35E-08	0.33
Ba-137m	4.67E-03	3.93E-03	1.19	Rb-86	3.86E-02	3.72E-02	1.04
Ba-140	1.70E-02	1.74E-02	0.98	Rb-88	6.06E-02	7.46E-02	0.81
Ce-141	6.53E-03	8.77E-03	0.74	Rh-103m	0.00E+00	3.32E-07	0.00
Ce-143	2.62E-02	2.51E-02	1.05	Rh-105	7.16E-03	8.51E-03	0.84
Ce-144	1.88E-03	3.16E-03	0.60	Rh-106	5.65E-02	6.35E-02	0.89
Cm-242	1.67E-07	8.43E-07	0.20	Ru-103	1.75E-03	1.83E-03	0.95
Cm-244	0.00E+00	8.88E-07	0.00	Ru-105	2.59E-02	2.62E-02	0.99
Co-58	1.54E-03	1.84E-03	0.84	Ru-106	0.00E+00	4.12E-08	0.00
Co-60	2.67E-03	3.96E-03	0.67	Sb-127	1.96E-02	1.93E-02	1.02
Cs-134	8.74E-03	9.55E-03	0.92	Sb-129	2.32E-02	2.24E-02	1.03
Cs-136	4.39E-03	6.97E-03	0.63	Sr-89	3.60E-02	3.37E-02	1.07
Cs-137	9.00E-03	1.11E-02	0.81	Sr-90	1.04E-02	1.19E-02	0.88
Cs-138	5.34E-02	5.87E-02	0.91	Sr-91	3.57E-02	3.54E-02	1.01
I-129	3.96E-05	6.89E-04	0.06	Sr-92	9.90E-03	1.18E-02	0.84
I-131	9.79E-03	1.12E-02	0.87	Tc-99m	2.32E-04	5.93E-04	0.39
I-132	2.99E-02	2.85E-02	1.05	Te-127	1.27E-02	1.38E-02	0.92
I-133	2.65E-02	2.50E-02	1.06	Te-127m	3.62E-04	1.08E-03	0.34
I-134	3.70E-02	3.30E-02	1.12	Te-129	3.31E-02	3.07E-02	1.08
I-135	2.28E-02	2.07E-02	1.10	Te-129m	1.21E-02	1.33E-02	0.91
La-140	3.37E-02	3.13E-02	1.08	Te-131	4.01E-02	3.90E-02	1.03
Mn-54	1.31E-05	1.16E-05	1.14	Te-131m	8.71E-03	9.41E-03	0.93
Mo-99	2.49E-02	2.35E-02	1.06	Te-132	1.45E-03	2.93E-03	0.50
Na-24	3.56E-02	3.27E-02	1.09	Te-133	4.38E-02	3.71E-02	1.18
Nb-95	1.63E-04	5.68E-04	0.29	Te-133m	3.87E-02	2.19E-02	1.77
Nb-97m	1.04E-03	2.82E-02	0.04	Te-134	1.67E-02	1.23E-02	1.36
Nd-147	1.37E-02	1.44E-02	0.95	Y-90	4.74E-02	4.81E-02	0.99
Np-239	7.17E-03	1.01E-02	0.71	Y-91	3.68E-02	3.45E-02	1.07
Pr-143	2.00E-02	1.96E-02	1.02	Y-91m	1.98E-03	1.74E-03	1.14
Pr-144	5.34E-02	5.75E-02	0.93	Y-92	5.52E-02	6.33E-02	0.87
Pu-238	1.29E-07	1.56E-06	0.08	Zr-95	4.12E-03	5.69E-03	0.72
Pu-239	5.30E-07	1.37E-06	0.39	Zr-97	4.01E-02	3.98E-02	1.01

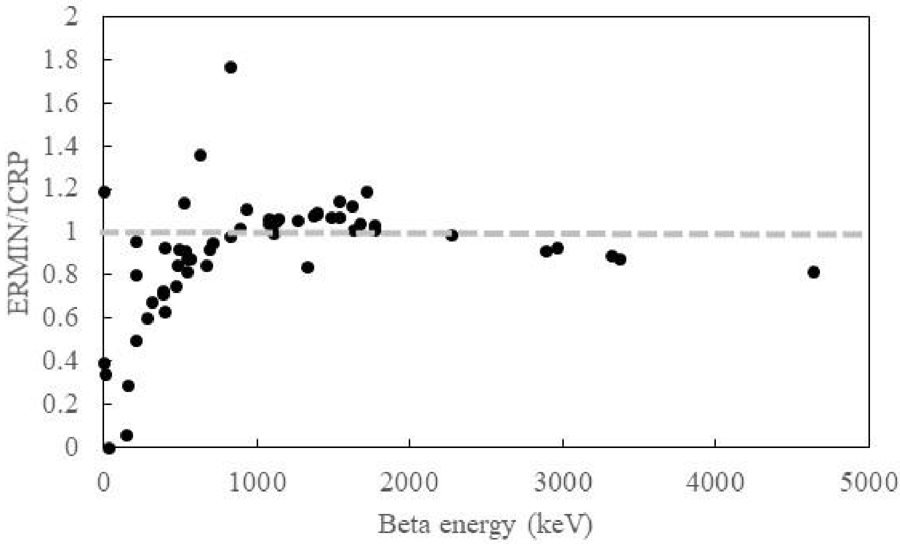


Figure 5 Relationship between the beta energy and the ratio of dose coefficient from beta radiation between ERMIN and ICRP Publication 144.

3 New dose coefficients and dose conversion factors for ERMIN

This section describes how dose coefficients for a new ERMIN open area environment were developed based on ICRP Publication 144. It also describes how dose conversion factors that can be applied to all environments in ERMIN were developed.

The new open area environment needs dose coefficients for each of the nine soil layers. However, the depths of the dose coefficients are not consistent between ERMIN and ICRP Publication 144. Furthermore, ERMIN DC are based on soil layers with volumes, whereas ICRP are planar sources. However, the investigation in Section 2 shows that these volumetric layers can be reasonably approximated by using a planar source from a depth, central to the layer.

As mentioned, ERMIN currently uses a single radionuclide-specific dose conversion factor that is applied to every surface. ICRP Publication 144 affords the opportunity to improve on this by developing additional DCF that can account for the effect of soil depth. Here again there is the problem that ERMIN soil layer depths are not consistent with those in ICRP Publication 144.

To interpolate dose coefficients and dose conversion factors at appropriate depths for ERMIN, the relationships between the depth of contamination and dose coefficient and between the depth and dose conversion factor provided by ICRP Publication 144 were investigated and are described in Sections 3.1 and 3.2 respectively.

For beta radiation, the dose coefficients at the depth of 0 g cm^{-2} in ICRP Publication 144 replace the existing coefficients from Holford (1989) used in ERMIN.

3.1 New dose coefficients from soil contamination at different depths

The relationship between the depth of contamination and dose coefficient for most of the radionuclides can be expressed by the combination of logarithmic and exponential functions (Figure 6a). However, some radionuclides, such as transuranic and beta-emitting ones, and radionuclides with low gamma energies and emission rates, cannot be expressed logarithmically (Figure 6b). For these radionuclides, the relationship between the depth and logarithm of dose coefficient can be expressed by logarithmic function (Figure 6c). In this study, the relationship between the depth and dose coefficient was expressed in the following equations and the proportional constants (*a*, *b*, *c*, and *d*) were determined to reproduce the relationship for each radionuclide.

For gamma radionuclides except those with low gamma energies and emission rates,

$DC = a \cdot \ln(depth) + b \;\; (depth < 15\ g\ cm^{-2}),$

$DC = c \cdot \exp(d \cdot depth) \;\; (depth \geq 15\ g\ cm^{-2}),$

Equation I

for transuranic and beta-emitting radionuclides, and those with low gamma energies and emission rates,

$\ln(DC) = a \cdot \ln(depth) + b \; (depth \;\leq 10\ g\ cm^{-2}),$

$DC = c \cdot \exp(d \cdot depth) \;\; (depth \geq 10\ g\ cm^{-2}),$

Equation II

where *DC* is dose coefficient (nGy h^{-1} Bq^{-1} m^2), *depth* is the mass depth (g cm^{-2}). The proportional constants (*a*, *b*, *c*, and *d*) for each radionuclide are summarized in Table 9. The new dose coefficients for ERMIN were calculated using equations obtained above and are summarized in Table 10. The comparison of the dose coefficients between ERMIN and ICRP Publication 144 is shown in Table 11. The new ERMIN dose coefficients for most radionuclides agreed within 5%, whilst that of some radionuclides (such as transuranic and beta-emitting radionuclides, and ones with low gamma energies and emission rates) differed by a factor of less than four.

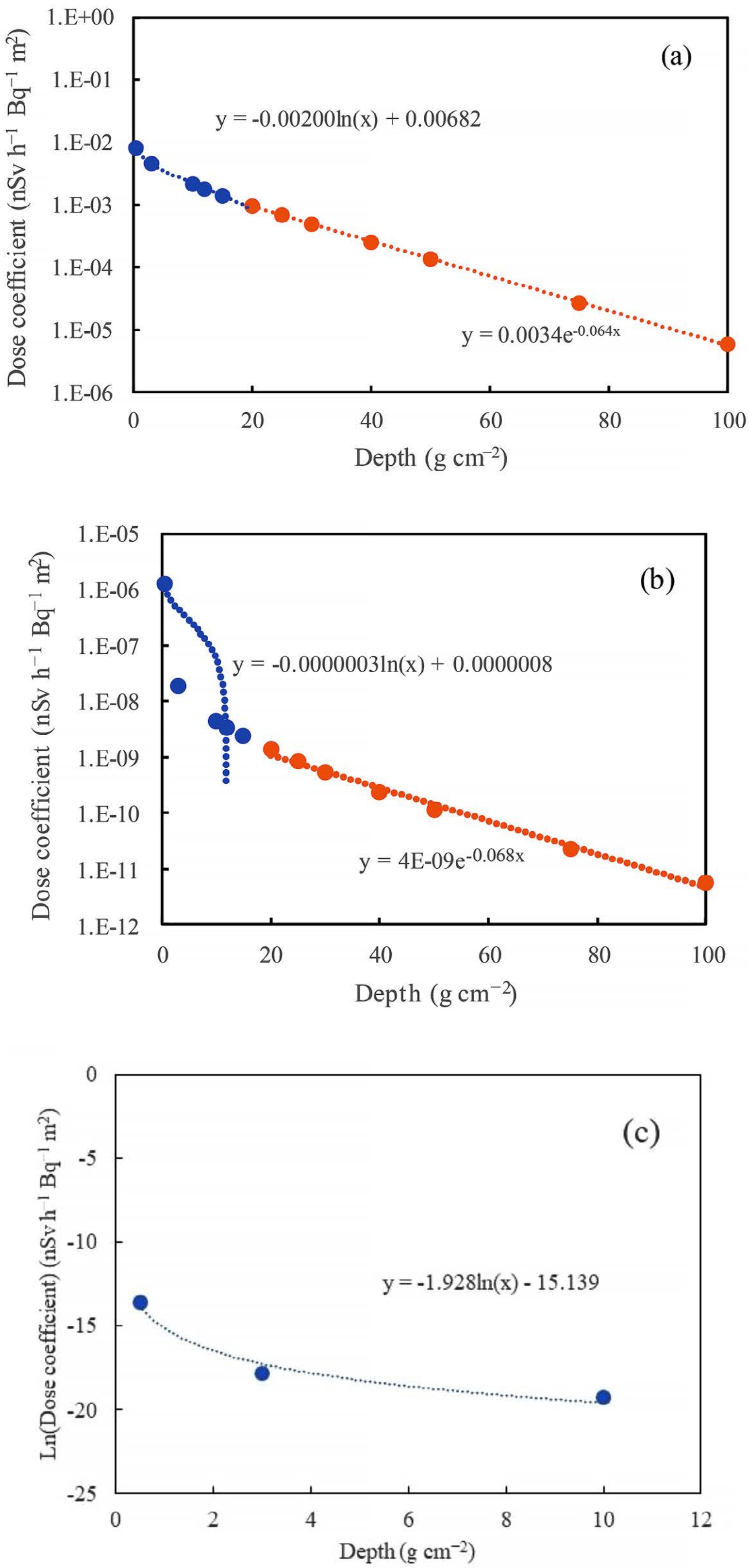


Figure 6 Examples of the relationship between the dose coefficient and depth of contamination in ICRP Publication 144. (a): ^{110}Ag, (b): ^{242}Cm, (c): ^{242}Cm (logarithm)

Table 9 Proportional constants in the equation giving the relationship between the dose coefficient and depth of contamination.

Radionuclide	Equation[a]	a	b	c	d
Ag-110m	I	-2.00E-03	6.83E-03	3.48E-03	-6.83E-02
Am-241	II	-1.12E+00	-1.02E+01	3.12E-05	-2.84E-01
Ba-137m	I	-4.53E-04	1.53E-03	8.90E-04	-7.43E-02
Ba-140	I	-1.39E-04	4.62E-04	2.80E-04	-8.16E-02
Ce-141	I	-5.80E-05	1.76E-04	1.30E-04	-1.32E-01
Ce-143	I	-2.16E-04	6.98E-04	3.50E-04	-7.93E-02
Ce-144	I	-1.50E-05	4.30E-05	2.80E-05	-1.38E-01
Cm-242	II	-1.93E+00	-1.51E+01	1.16E-08	-1.04E-01
Cm-244	II	-1.48E+00	-1.49E+01	2.93E-08	-7.18E-02
Co-58	I	-7.30E-04	2.47E-03	1.33E-03	-6.93E-02
Co-60	I	-1.69E-03	5.86E-03	2.99E-03	-5.85E-02
Cs-134	I	-1.17E-03	3.96E-03	2.19E-03	-7.11E-02
Cs-136	I	-1.53E-03	5.20E-03	2.68E-03	-6.52E-02
Cs-137	II	-7.68E-01	-1.45E+01	2.58E-07	-1.27E-01
Cs-138	I	-1.59E-03	5.54E-03	2.52E-03	-5.35E-02
I-129	II	-2.93E+00	-1.10E+01	1.42E-07	-3.53E-01
I-131	I	-2.92E-04	9.74E-04	6.10E-04	-8.57E-02
I-132	I	-1.67E-03	5.68E-03	2.93E-03	-6.66E-02
I-133	I	-4.58E-04	1.55E-03	8.80E-04	-7.39E-02
I-134	I	-1.87E-03	6.39E-03	3.20E-03	-6.35E-02
I-135	I	-1.07E-03	3.72E-03	1.79E-03	-5.65E-02
La-140	I	-1.58E-03	5.48E-03	2.52E-03	-5.53E-02
Mn-54	I	-6.20E-04	2.10E-03	1.12E-03	-6.77E-02
Mo-99	I	-1.13E-04	3.77E-04	2.00E-04	-7.15E-02
Na-24	I	-2.61E-03	9.23E-03	3.99E-03	-4.59E-02
Nb-95	I	-5.79E-04	1.96E-03	1.06E-03	-6.98E-02
Nb-97m	I	-5.04E-04	1.70E-03	9.68E-04	-7.32E-02
Nd-147	I	-1.08E-04	3.40E-04	1.60E-04	-8.13E-02
Np-239	I	-1.30E-04	4.04E-04	2.10E-04	-1.03E-01
Pr-143	II	-6.94E-01	-1.35E+01	7.53E-07	-1.21E-01
Pr-144	I	-2.60E-05	8.90E-05	3.60E-05	-5.37E-02
Pu-238	II	-1.86E+00	-1.53E+01	1.60E-08	-1.48E-01
Pu-239	II	-9.67E-01	-1.51E+01	8.89E-08	-1.09E-01

a Equation I indicates gamma-emitting radionuclides except those with low effective gamma energy; Equation II indicates transuranic and beta-emitting radionuclides, and ones with low effective gamma energy

Table 9 Proportional constants in the equation giving the relationship between the dose coefficient and depth of contamination.(Continued).

Radionuclide	Equation[a]	a	b	c	d
Pu-240	II	-1.82E+00	-1.53E+01	1.41E-08	-1.32E-01
Pu-241	I	-1.12E-09	3.29E-09	1.94E-09	-1.42E-01
Rb-86	I	-6.60E-05	2.26E-04	1.20E-04	-6.26E-02
Rb-88	I	-4.39E-04	1.54E-03	6.80E-04	-5.05E-02
Rh-103m	II	-3.41E+00	-1.52E+01	7.12E-08	-6.85E-01
Rh-105	I	-5.90E-05	1.97E-04	1.40E-04	-9.42E-02
Rh-106	I	-1.63E-04	5.50E-04	2.90E-04	-7.20E-02
Ru-103	I	-3.77E-04	1.27E-03	8.10E-04	-8.14E-02
Ru-105	I	-5.63E-04	1.90E-03	1.05E-03	-7.32E-02
Ru-106	II	-3.38E+00	-2.51E+01	0.00E+00	0.00E+00
Sb-127	I	-5.26E-04	1.77E-03	1.00E-03	-7.41E-02
Sb-129	I	-1.04E-03	3.57E-03	1.73E-03	-6.13E-02
Sr-89	I	-1.70E-06	5.20E-06	1.77E-06	-8.44E-02
Sr-90	I	-2.00E-07	6.00E-07	2.43E-07	-1.35E-01
Sr-91	I	-5.11E-04	1.74E-03	9.20E-04	-6.56E-02
Sr-92	I	-9.01E-04	3.13E-03	1.55E-03	-5.67E-02
Tc-99m	I	-9.30E-05	2.86E-04	2.40E-04	-1.34E-01
Te-127	I	-4.00E-06	1.32E-05	8.00E-06	-8.71E-02
Te-127m	II	-1.86E+00	-1.17E+01	3.04E-07	-1.00E-01
Te-129	I	-4.80E-05	1.58E-04	8.20E-05	-7.65E-02
Te-129m	I	-2.90E-05	9.10E-05	4.30E-05	-7.22E-02
Te-131	I	-3.11E-04	1.03E-03	4.80E-04	-7.00E-02
Te-131m	I	-1.06E-03	3.58E-03	1.75E-03	-6.38E-02
Te-132	I	-1.79E-04	5.63E-04	3.70E-04	-1.06E-01
Te-133	I	-8.49E-04	2.91E-03	1.28E-03	-5.83E-02
Te-133m	I	-1.33E-03	4.53E-03	2.17E-03	-6.17E-02
Te-134	I	-6.61E-04	2.20E-03	1.16E-03	-7.49E-02
Y-90	I	-4.00E-06	1.25E-05	4.66E-06	-7.94E-02
Y-91	I	-3.90E-06	1.26E-05	5.15E-06	-6.27E-02
Y-91m	I	-4.00E-04	1.35E-03	8.50E-04	-7.91E-02
Y-92	I	-1.87E-04	6.40E-04	3.20E-04	-6.20E-02
Zr-95	I	-5.54E-04	1.87E-03	1.03E-03	-7.07E-02
Zr-97	I	-6.60E-04	2.23E-03	1.17E-03	-6.82E-02

a Equation I indicates gamma-emitting radionuclides except those with low effective gamma energy; Equation II indicates transuranic and beta-emitting radionuclides, and ones with low effective gamma energy

Table 10 New dose coefficients (nGy h^{-1} Bq^{-1} m^2) for ERMIN

	Depth (g cm^{-2})								
Radionuclide	0.5	1.5	3	5	7	9	12.5	17.5	30
Ag-110m	8.21E-03	6.01E-03	4.63E-03	3.60E-03	2.93E-03	2.43E-03	1.77E-03	1.05E-03	4.49E-04
Am-241	7.85E-05	2.28E-05	1.05E-05	5.90E-06	4.04E-06	3.05E-06	8.96E-07	2.17E-07	6.22E-09
Ba-137m	1.84E-03	1.35E-03	1.03E-03	8.00E-04	6.48E-04	5.34E-04	3.85E-04	2.42E-04	9.58E-05
Ba-140	5.58E-04	4.06E-04	3.09E-04	2.38E-04	1.92E-04	1.57E-04	1.11E-04	6.72E-05	2.42E-05
Ce-141	2.16E-04	1.52E-04	1.12E-04	8.27E-05	6.31E-05	4.86E-05	2.95E-05	1.29E-05	2.48E-06
Ce-143	8.48E-04	6.10E-04	4.61E-04	3.50E-04	2.78E-04	2.23E-04	1.52E-04	8.74E-05	3.25E-05
Ce-144	5.34E-05	3.69E-05	2.65E-05	1.89E-05	1.38E-05	1.00E-05	5.11E-06	2.52E-06	4.50E-07
Cm-242	1.01E-06	1.22E-07	3.20E-08	1.20E-08	6.25E-09	3.85E-09	3.16E-09	1.88E-09	5.12E-10
Cm-244	9.02E-07	1.78E-07	6.40E-08	3.01E-08	1.83E-08	1.26E-08	1.19E-08	8.34E-09	3.40E-09
Co-58	2.97E-03	2.17E-03	1.67E-03	1.29E-03	1.05E-03	8.65E-04	6.25E-04	3.96E-04	1.66E-04
Co-60	7.04E-03	5.18E-03	4.00E-03	3.14E-03	2.57E-03	2.15E-03	1.59E-03	1.07E-03	5.17E-04
Cs-134	4.77E-03	3.48E-03	2.67E-03	2.07E-03	1.68E-03	1.39E-03	1.00E-03	6.31E-04	2.59E-04
Cs-136	6.25E-03	4.58E-03	3.52E-03	2.74E-03	2.22E-03	1.84E-03	1.34E-03	8.57E-04	3.79E-04
Cs-137	8.68E-07	3.73E-07	2.19E-07	1.48E-07	1.14E-07	9.43E-08	5.27E-08	2.80E-08	5.71E-09
Cs-138	6.65E-03	4.90E-03	3.79E-03	2.98E-03	2.44E-03	2.04E-03	1.52E-03	9.89E-04	5.07E-04
I-129	1.33E-04	5.34E-06	7.02E-07	1.57E-07	5.88E-08	2.82E-08	1.72E-09	2.95E-10	3.57E-12
I-131	1.18E-03	8.56E-04	6.53E-04	5.04E-04	4.06E-04	3.32E-04	2.36E-04	1.36E-04	4.66E-05
I-132	6.84E-03	5.00E-03	3.85E-03	2.99E-03	2.43E-03	2.01E-03	1.46E-03	9.13E-04	3.97E-04
I-133	1.87E-03	1.37E-03	1.05E-03	8.15E-04	6.61E-04	5.46E-04	3.95E-04	2.41E-04	9.59E-05
I-134	7.68E-03	5.63E-03	4.33E-03	3.37E-03	2.74E-03	2.27E-03	1.65E-03	1.05E-03	4.77E-04
I-135	4.46E-03	3.28E-03	2.54E-03	1.99E-03	1.63E-03	1.36E-03	1.01E-03	6.66E-04	3.29E-04
La-140	6.58E-03	4.84E-03	3.74E-03	2.93E-03	2.40E-03	2.00E-03	1.48E-03	9.58E-04	4.80E-04
Mn-54	2.53E-03	1.85E-03	1.42E-03	1.10E-03	8.94E-04	7.38E-04	5.34E-04	3.43E-04	1.47E-04
Mo-99	4.55E-04	3.31E-04	2.53E-04	1.95E-04	1.57E-04	1.29E-04	9.16E-05	5.72E-05	2.34E-05
Na-24	1.10E-02	8.17E-03	6.37E-03	5.04E-03	4.16E-03	3.50E-03	2.65E-03	1.79E-03	1.01E-03
Nb-95	2.36E-03	1.72E-03	1.32E-03	1.02E-03	8.28E-04	6.83E-04	4.93E-04	3.12E-04	1.30E-04
Nb-97m	2.05E-03	1.50E-03	1.15E-03	8.92E-04	7.23E-04	5.96E-04	4.30E-04	2.69E-04	1.08E-04
Nd-147	4.15E-04	2.96E-04	2.21E-04	1.66E-04	1.30E-04	1.03E-04	6.72E-05	3.85E-05	1.39E-05
Np-239	4.94E-04	3.51E-04	2.61E-04	1.95E-04	1.51E-04	1.18E-04	7.57E-05	3.45E-05	9.49E-06
Pr-143	2.14E-06	9.99E-07	6.18E-07	4.33E-07	3.43E-07	2.88E-07	1.66E-07	9.06E-08	2.00E-08
Pr-144	1.07E-04	7.85E-05	6.04E-05	4.72E-05	3.84E-05	3.19E-05	2.33E-05	1.41E-05	7.18E-06
Pu-238	8.11E-07	1.06E-07	2.91E-08	1.13E-08	6.05E-09	3.79E-09	2.52E-09	1.20E-09	1.89E-10
Pu-239	5.51E-07	1.91E-07	9.75E-08	5.95E-08	4.3E-08	3.37E-08	2.28E-08	1.32E-08	3.38E-09

Table 10 New dose coefficients (nGy h⁻¹ Bq⁻¹ m2) for ERMIN (Continued)

	Depth (g cm^{-2})								
Radionuclide	0.5	1.5	3	5	7	9	12.5	17.5	30
Pu-240	7.93E-07	1.08E-07	3.07E-08	1.21E-08	6.60E-09	4.18E-09	2.71E-09	1.40E-09	2.69E-10
Pu-241	4.07E-09	2.84E-09	2.06E-09	1.49E-09	1.12E-09	8.36E-10	4.69E-10	1.62E-10	2.74E-11
Rb-86	2.72E-04	1.99E-04	1.53E-04	1.20E-04	9.76E-05	8.10E-05	5.93E-05	4.02E-05	1.84E-05
Rb-88	1.84E-03	1.36E-03	1.05E-03	8.28E-04	6.81E-04	5.70E-04	4.26E-04	2.81E-04	1.49E-04
Rh-103m	2.79E-06	6.57E-08	6.18E-09	1.08E-09	3.43E-10	1.45E-10	1.36E-11	4.43E-13	8.47E-17
Rh-105	2.38E-04	1.73E-04	1.32E-04	1.02E-04	8.22E-05	6.74E-05	4.80E-05	2.69E-05	8.29E-06
Rh-106	6.63E-04	4.84E-04	3.71E-04	2.88E-04	2.33E-04	1.92E-04	1.38E-04	8.23E-05	3.35E-05
Ru-103	1.53E-03	1.12E-03	8.58E-04	6.65E-04	5.38E-04	4.44E-04	3.20E-04	1.95E-04	7.05E-05
Ru-105	2.29E-03	1.67E-03	1.28E-03	9.91E-04	8.01E-04	6.60E-04	4.75E-04	2.92E-04	1.17E-04
Ru-106	1.36E-10	3.31E-12	3.18E-13	5.66E-14	1.81E-14	7.75E-15	0.00E+00	0.00E+00	0.00E+00
Sb-127	2.14E-03	1.56E-03	1.19E-03	9.24E-04	7.47E-04	6.15E-04	4.42E-04	2.73E-04	1.08E-04
Sb-129	4.29E-03	3.14E-03	2.42E-03	1.89E-03	1.54E-03	1.28E-03	9.33E-04	5.91E-04	2.75E-04
Sr-89	6.38E-06	4.51E-06	3.33E-06	2.46E-06	1.89E-06	1.46E-06	9.06E-07	4.04E-07	1.41E-07
Sr-90	7.39E-07	5.19E-07	3.80E-07	2.78E-07	2.11E-07	1.61E-07	9.49E-08	2.29E-08	4.23E-09
Sr-91	2.10E-03	1.54E-03	1.18E-03	9.21E-04	7.49E-04	6.20E-04	4.52E-04	2.92E-04	1.29E-04
Sr-92	3.75E-03	2.76E-03	2.14E-03	1.68E-03	1.38E-03	1.15E-03	8.54E-04	5.75E-04	2.83E-04
Tc-99m	3.50E-04	2.48E-04	1.84E-04	1.36E-04	1.05E-04	8.17E-05	5.11E-05	2.31E-05	4.34E-06
Te-127	1.60E-05	1.16E-05	8.81E-06	6.76E-06	5.42E-06	4.41E-06	3.10E-06	1.74E-06	5.86E-07
Te-127m	2.95E-05	3.83E-06	1.05E-06	4.08E-07	2.18E-07	1.37E-07	8.71E-08	5.28E-08	1.51E-08
Te-129	1.91E-04	1.39E-04	1.05E-04	8.07E-05	6.46E-05	5.25E-05	3.68E-05	2.15E-05	8.26E-06
Te-129m	1.11E-04	7.92E-05	5.91E-05	4.43E-05	3.46E-05	2.73E-05	1.78E-05	1.22E-05	4.93E-06
Te-131	1.25E-03	9.05E-04	6.89E-04	5.30E-04	4.26E-04	3.48E-04	2.45E-04	1.41E-04	5.88E-05
Te-131m	4.31E-03	3.15E-03	2.42E-03	1.88E-03	1.53E-03	1.26E-03	9.13E-04	5.73E-04	2.58E-04
Te-132	6.87E-04	4.90E-04	3.66E-04	2.75E-04	2.15E-04	1.70E-04	1.11E-04	5.75E-05	1.52E-05
Te-133	3.49E-03	2.56E-03	1.97E-03	1.54E-03	1.25E-03	1.04E-03	7.61E-04	4.62E-04	2.23E-04
Te-133m	5.45E-03	3.99E-03	3.07E-03	2.39E-03	1.95E-03	1.61E-03	1.18E-03	7.37E-04	3.41E-04
Te-134	2.66E-03	1.93E-03	1.47E-03	1.14E-03	9.14E-04	7.48E-04	5.30E-04	3.13E-04	1.23E-04
Y-90	1.53E-05	1.09E-05	8.11E-06	6.06E-06	4.72E-06	3.71E-06	2.40E-06	1.16E-06	4.30E-07
Y-91	1.53E-05	1.10E-05	8.32E-06	6.32E-06	5.01E-06	4.03E-06	2.75E-06	1.72E-06	7.85E-07
Y-91m	1.63E-03	1.19E-03	9.14E-04	7.09E-04	5.75E-04	4.74E-04	3.43E-04	2.13E-04	7.91E-05
Y-92	7.70E-04	5.64E-04	4.35E-04	3.39E-04	2.76E-04	2.29E-04	1.68E-04	1.08E-04	4.98E-05
Zr-95	2.26E-03	1.65E-03	1.26E-03	9.79E-04	7.93E-04	6.54E-04	4.72E-04	2.99E-04	1.23E-04
Zr-97	2.69E-03	1.97E-03	1.51E-03	1.17E-03	9.49E-04	7.83E-04	5.66E-04	3.55E-04	1.51E-04

Table 11 Comparison of new ERMIN dose coefficients (nGy h^{-1} Bq^{-1} m^2) with ICRP Publication 144 (ERMIN/ICRP)

	Depth (g cm^{-2})					Depth (g cm^{-2})			
Radionuclide	0.5	3	10	30	Radionuclide	0.5	3	10	30
Ag-110m	1.00	1.00	1.05	0.91	Pu-240	0.89	1.32	0.92	0.92
Am-241	1.25	0.57	0.94	0.92	Pu-241	0.99	1.00	1.21	1.05
Ba-137m	1.00	1.00	1.05	1.01	Rb-86	0.99	1.01	1.04	1.03
Ba-140	1.00	1.00	1.04	1.01	Rb-88	0.99	1.03	1.03	1.03
Ce-141	0.99	1.01	1.14	0.95	Rh-103m	1.21	0.63	0.98	-
Ce-143	0.99	1.03	1.07	1.04	Rh-105	1.01	0.96	1.05	1.04
Ce-144	0.98	1.08	1.12	1.00	Rh-106	1.00	0.99	1.05	1.00
Cm-242	0.80	1.72	0.94	0.95	Ru-103	1.00	0.98	1.04	1.00
Cm-244	0.81	1.71	0.96	0.96	Ru-105	1.00	0.99	1.05	1.03
Co-58	1.00	0.99	1.06	1.03	Ru-106	1.00	1.00	-	-
Co-60	0.99	1.02	1.04	1.03	Sb-127	1.00	0.99	1.05	1.02
Cs-134	1.00	1.00	1.05	1.02	Sb-129	1.00	1.00	1.05	1.03
Cs-136	1.00	1.00	1.05	1.03	Sr-89	0.97	1.11	1.20	1.06
Cs-137	1.10	0.80	0.95	0.95	Sr-90	0.96	1.50	2.12	0.97
Cs-138	0.99	1.02	1.03	1.04	Sr-91	0.99	1.01	1.05	1.03
I-129	1.75	0.25	0.46	0.54	Sr-92	0.99	1.02	1.03	1.03
I-131	1.01	0.97	1.03	1.01	Tc-99m	1.00	0.96	1.11	1.01
I-132	1.00	1.00	1.05	1.03	Te-127	1.00	0.99	1.04	0.97
I-133	1.00	0.99	1.04	1.02	Te-127m	0.95	1.13	0.92	0.94
I-134	1.00	1.00	1.05	1.03	Te-129	0.99	1.03	1.05	0.99
I-135	0.99	1.02	1.04	1.03	Te-129m	0.97	1.12	1.04	1.02
La-140	0.99	1.02	1.04	1.04	Te-131	1.00	1.00	1.06	1.06
Mn-54	1.00	1.00	1.06	1.03	Te-131m	1.00	1.00	1.05	1.04
Mo-99	1.00	0.99	1.06	1.06	Te-132	0.99	1.02	1.09	1.01
Na-24	0.99	1.05	1.02	1.03	Te-133	1.00	1.01	1.03	1.05
Nb-95	1.00	0.99	1.06	1.03	Te-133m	0.99	1.01	1.04	1.03
Nb-97m	1.00	1.00	1.05	1.02	Te-134	1.00	0.99	1.06	1.03
Nd-147	0.98	1.07	1.10	1.01	Y-90	0.98	1.06	1.15	1.05
Np-239	1.00	0.97	1.10	1.07	Y-91	0.98	1.04	1.05	1.05
Pr-143	1.09	0.80	0.96	0.95	Y-91m	1.00	0.99	1.04	1.01
Pr-144	0.99	1.03	1.07	1.05	Y-92	0.99	1.01	1.05	1.04
Pu-238	0.87	1.40	0.95	0.96	Zr-95	1.00	0.99	1.06	1.02
Pu-239	0.98	1.04	0.96	0.95	Zr-97	1.00	1.00	1.05	1.02

3.2 New dose conversion factors from soil contamination at different depths

For all the radionuclides, the relationship between the depth of contamination and the dose conversion factor can be expressed by various logarithmic functions (Figure 7). This is necessary because ICRP does not provide all the depths needed by ERMIN. Unfortunately, the approximation curves did not reproduce the ICRP values sufficiently closely for some radionuclides, such as alpha- and beta-emitting ones, and those with low energy and low gamma-emission rates (Figure 7b). In this study, the relationship between the depth and dose conversion factor was expressed by following equations and the proportional constants (*a*, *b*, *c*, and *d*) were determined in order reproduce the relationship for each radionuclide.

$$DCF = a \cdot \ln(depth) + b \ \ (depth \leq 10\ g\ cm^{-2}),$$

$$DCF = c \cdot \ln(depth) + d \ \ (depth > 10\ g\ cm^{-2}).$$

where *DCF* is dose conversion factor (Sv Gy^{-1}), and *depth* is mass depth (g cm^{-2}) corresponding to the middle depth of soil layer in ERMIN. The proportional constants (*a*, *b*, *c*, and *d*) for each radionuclide are summarized in Table 12. The new dose conversion factors for ERMIN were calculated using equations obtained above and are summarized in Table 13. The comparison of the dose conversion factors between ERMIN and ICRP Publication 144 is shown in Table 14. For most radionuclides, the new dose conversion factor agreed within 5%, whilst that of some radionuclides (such as transuranic and beta-emitting ones, and those with low energy and low gamma-emission rates) differed by almost 50%.

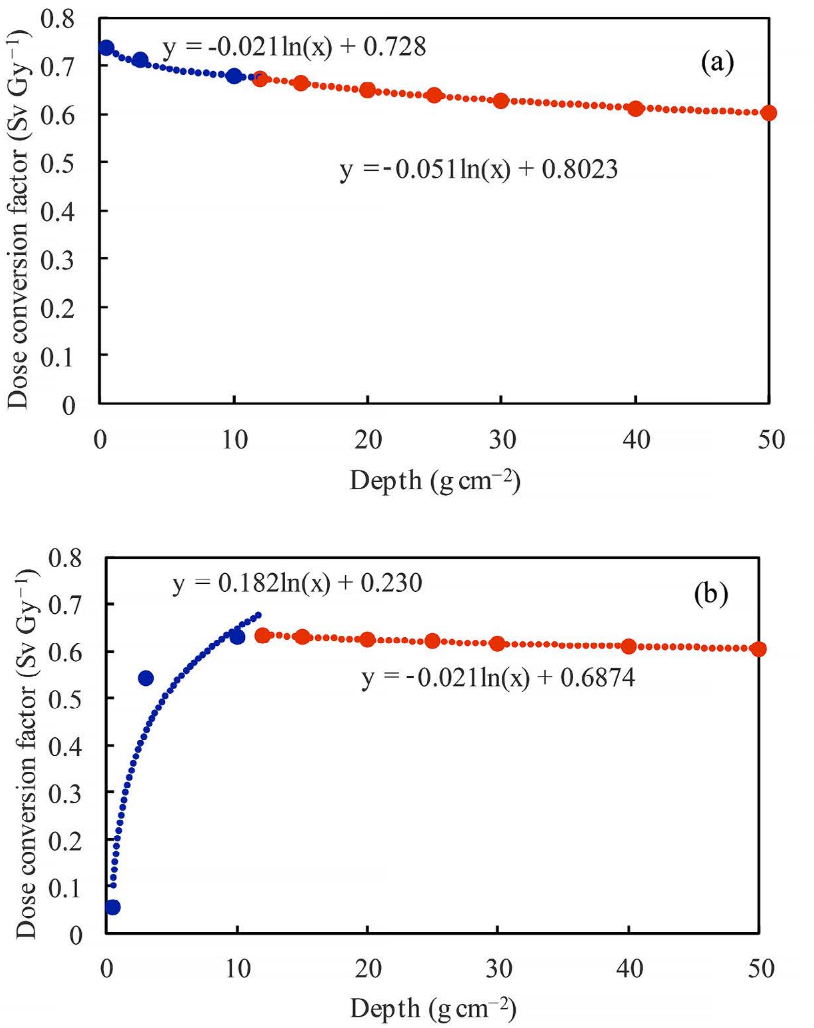


Figure 7 Examples of the relationship between the dose conversion factor and depth from ICRP Publication 144. (a) ^{110m}Ag, (b) ^{242}Cm.

Table 12 Proportional constants in the equation between the dose conversion factor and depth

Radionuclide	a	b	c	d	Radionuclide	a	b	c	d
Ag-110m	-0.021	0.728	-0.050	0.798	Pu-240	0.171	0.231	0.005	0.605
Am-241	-0.029	0.506	-0.029	0.506	Pu-241	-0.030	0.690	-0.070	0.800
Ba-137m	-0.022	0.711	-0.046	0.767	Rb-86	-0.021	0.740	-0.049	0.803
Ba-140	-0.018	0.693	-0.049	0.769	Rb-88	-0.018	0.764	-0.055	0.855
Ce-141	-0.013	0.665	-0.079	0.843	Rh-103m	0.041	0.114	-0.100	0.440
Ce-143	-0.005	0.662	-0.055	0.786	Rh-105	-0.018	0.685	-0.087	0.869
Ce-144	-0.001	0.629	-0.079	0.839	Rh-106	-0.021	0.713	-0.038	0.744
Cm-242	0.182	0.230	-0.021	0.687	Ru-103	-0.025	0.708	-0.051	0.774
Cm-244	0.191	0.286	-0.039	0.791	Ru-105	-0.022	0.711	-0.053	0.790
Co-58	-0.021	0.717	-0.062	0.823	Ru-106	0.000	0.694	0.000	0.000
Co-60	-0.021	0.753	-0.052	0.824	Sb-127	-0.022	0.711	-0.050	0.789
Cs-134	-0.022	0.716	-0.053	0.793	Sb-129	-0.021	0.734	-0.047	0.796
Cs-136	-0.021	0.727	-0.052	0.803	Sr-89	0.004	0.631	-0.049	0.760
Cs-137	0.031	0.552	-0.043	0.728	Sr-90	0.033	0.540	-0.069	0.804
Cs-138	-0.021	0.757	-0.050	0.830	Sr-91	-0.021	0.730	-0.049	0.794
I-129	0.016	0.168	0.357	-0.648	Sr-92	-0.022	0.758	-0.055	0.839
I-131	-0.021	0.695	-0.064	0.808	Tc-99m	-0.030	0.707	-0.078	0.840
I-132	-0.022	0.722	-0.046	0.779	Te-127	-0.015	0.677	-0.070	0.824
I-133	-0.023	0.712	-0.044	0.760	Te-127m	0.154	0.227	-0.018	0.667
I-134	-0.021	0.729	-0.050	0.801	Te-129	-0.007	0.666	-0.046	0.763
I-135	-0.020	0.753	-0.051	0.827	Te-129m	0.013	0.638	-0.054	0.794
La-140	-0.019	0.751	-0.051	0.828	Te-131	-0.021	0.712	-0.042	0.761
Mn-54	-0.021	0.721	-0.063	0.831	Te-131m	-0.020	0.724	-0.049	0.797
Mo-99	-0.021	0.711	-0.059	0.812	Te-132	-0.001	0.646	-0.077	0.840
Na-24	-0.017	0.781	-0.059	0.888	Te-133	-0.020	0.735	-0.042	0.788
Nb-95	-0.021	0.713	-0.063	0.825	Te-133m	-0.020	0.731	-0.047	0.793
Nb-97m	-0.023	0.715	-0.039	0.749	Te-134	-0.020	0.702	-0.056	0.795
Nd-147	-0.004	0.651	-0.047	0.760	Y-90	-0.001	0.647	-0.045	0.755
Np-239	-0.024	0.689	-0.081	0.847	Y-91	-0.007	0.694	-0.044	0.783
Pr-143	0.018	0.586	-0.061	0.786	Y-91m	-0.024	0.709	-0.043	0.752
Pr-144	-0.015	0.736	-0.044	0.806	Y-92	-0.020	0.733	-0.049	0.803
Pu-238	0.170	0.231	-0.026	0.676	Zr-95	-0.021	0.715	-0.060	0.813
Pu-239	0.117	0.385	-0.066	0.806	Zr-97	-0.021	0.718	-0.054	0.800

Table 13 New dose conversion factors (Sv Gy^{-1}) for ERMIN

Radionuclide	Depth (g cm^{-2})								
	0.5	1.5	3	5	7	9	12.5	17.5	30
Ag-110m	0.74	0.72	0.70	0.69	0.69	0.68	0.67	0.65	0.63
Am-241	0.53	0.49	0.47	0.46	0.45	0.44	0.43	0.42	0.41
Ba-137m	0.73	0.70	0.69	0.68	0.67	0.66	0.65	0.64	0.61
Ba-140	0.71	0.69	0.67	0.66	0.66	0.65	0.65	0.63	0.60
Ce-141	0.67	0.66	0.65	0.64	0.64	0.64	0.64	0.62	0.57
Ce-143	0.67	0.66	0.66	0.65	0.65	0.65	0.65	0.63	0.60
Ce-144	0.63	0.63	0.63	0.63	0.63	0.63	0.64	0.61	0.57
Cm-242	0.10	0.30	0.43	0.52	0.58	0.63	0.63	0.63	0.62
Cm-244	0.15	0.36	0.50	0.59	0.66	0.71	0.69	0.68	0.66
Co-58	0.73	0.71	0.69	0.68	0.68	0.67	0.67	0.65	0.61
Co-60	0.77	0.74	0.73	0.72	0.71	0.71	0.69	0.68	0.65
Cs-134	0.73	0.71	0.69	0.68	0.67	0.67	0.66	0.64	0.61
Cs-136	0.74	0.72	0.70	0.69	0.69	0.68	0.67	0.65	0.63
Cs-137	0.53	0.56	0.59	0.60	0.61	0.62	0.62	0.60	0.58
Cs-138	0.77	0.75	0.73	0.72	0.72	0.71	0.70	0.69	0.66
I-129	0.16	0.17	0.19	0.19	0.20	0.20	0.25	0.37	0.57
I-131	0.71	0.69	0.67	0.66	0.65	0.65	0.65	0.62	0.59
I-132	0.74	0.71	0.70	0.69	0.68	0.67	0.66	0.65	0.62
I-133	0.73	0.70	0.69	0.67	0.67	0.66	0.65	0.63	0.61
I-134	0.74	0.72	0.71	0.70	0.69	0.68	0.67	0.66	0.63
I-135	0.77	0.74	0.73	0.72	0.71	0.71	0.70	0.68	0.65
La-140	0.76	0.74	0.73	0.72	0.71	0.71	0.70	0.68	0.65
Mn-54	0.74	0.71	0.70	0.69	0.68	0.67	0.67	0.65	0.62
Mo-99	0.73	0.70	0.69	0.68	0.67	0.66	0.66	0.64	0.61
Na-24	0.79	0.77	0.76	0.75	0.75	0.74	0.74	0.72	0.69
Nb-95	0.73	0.70	0.69	0.68	0.67	0.67	0.67	0.64	0.61
Nb-97m	0.73	0.71	0.69	0.68	0.67	0.66	0.65	0.64	0.62
Nd-147	0.65	0.65	0.65	0.64	0.64	0.64	0.64	0.63	0.60
Np-239	0.71	0.68	0.66	0.65	0.64	0.64	0.64	0.62	0.57
Pr-143	0.57	0.59	0.61	0.61	0.62	0.63	0.63	0.61	0.58
Pr-144	0.75	0.73	0.72	0.71	0.71	0.70	0.69	0.68	0.66
Pu-238	0.11	0.30	0.42	0.50	0.56	0.60	0.61	0.60	0.59
Pu-239	0.30	0.43	0.51	0.57	0.61	0.64	0.64	0.62	0.58

Table 13 New dose conversion factors (Sv Gy^{-1}) for ERMIN (Continued)

Radionuclide	Depth (g cm^{-2})								
	0.5	1.5	3	5	7	9	12.5	17.5	30
Pu-240	0.11	0.30	0.42	0.51	0.56	0.61	0.62	0.62	0.62
Pu-241	0.71	0.68	0.66	0.64	0.63	0.62	0.62	0.60	0.56
Rb-86	0.75	0.73	0.72	0.71	0.70	0.69	0.68	0.66	0.64
Rb-88	0.78	0.76	0.74	0.74	0.73	0.72	0.72	0.70	0.67
Rh-103m	0.09	0.13	0.16	0.18	0.19	0.20	0.19	0.15	0.10
Rh-105	0.70	0.68	0.67	0.66	0.65	0.65	0.65	0.62	0.57
Rh-106	0.73	0.70	0.69	0.68	0.67	0.67	0.65	0.64	0.61
Ru-103	0.73	0.70	0.68	0.67	0.66	0.65	0.65	0.63	0.60
Ru-105	0.73	0.70	0.69	0.68	0.67	0.66	0.66	0.64	0.61
Ru-106	0.07	0.07	0.07	0.07	0.07	0.07	0.00	0.00	0.00
Sb-127	0.73	0.70	0.69	0.68	0.67	0.66	0.66	0.65	0.62
Sb-129	0.75	0.73	0.71	0.70	0.69	0.69	0.68	0.66	0.64
Sr-89	0.63	0.63	0.64	0.64	0.64	0.64	0.64	0.62	0.59
Sr-90	0.52	0.55	0.58	0.59	0.60	0.61	0.63	0.61	0.57
Sr-91	0.74	0.72	0.71	0.70	0.69	0.68	0.67	0.65	0.63
Sr-92	0.77	0.75	0.73	0.72	0.72	0.71	0.70	0.68	0.65
Tc-99m	0.73	0.69	0.67	0.66	0.65	0.64	0.64	0.62	0.57
Te-127	0.69	0.67	0.66	0.65	0.65	0.64	0.65	0.62	0.59
Te-127m	0.12	0.29	0.40	0.47	0.53	0.57	0.62	0.62	0.61
Te-129	0.67	0.66	0.66	0.65	0.65	0.65	0.65	0.63	0.61
Te-129m	0.63	0.64	0.65	0.66	0.66	0.67	0.66	0.64	0.61
Te-131	0.73	0.70	0.69	0.68	0.67	0.67	0.65	0.64	0.62
Te-131m	0.74	0.72	0.70	0.69	0.69	0.68	0.67	0.66	0.63
Te-132	0.65	0.65	0.64	0.64	0.64	0.64	0.65	0.62	0.58
Te-133	0.75	0.73	0.71	0.70	0.70	0.69	0.68	0.67	0.65
Te-133m	0.74	0.72	0.71	0.70	0.69	0.69	0.67	0.66	0.63
Te-134	0.72	0.69	0.68	0.67	0.66	0.66	0.65	0.63	0.60
Y-90	0.65	0.65	0.65	0.65	0.65	0.64	0.64	0.63	0.60
Y-91	0.70	0.69	0.69	0.68	0.68	0.68	0.67	0.66	0.63
Y-91m	0.73	0.70	0.68	0.67	0.66	0.66	0.64	0.63	0.61
Y-92	0.75	0.72	0.71	0.70	0.69	0.69	0.68	0.66	0.64
Zr-95	0.73	0.71	0.69	0.68	0.67	0.67	0.66	0.64	0.61
Zr-97	0.73	0.71	0.69	0.68	0.68	0.67	0.66	0.65	0.62

Table 14 Ratio of new dose conversion factors (Sv Gy^{-1}) derived for ERMIN and ICRP Publication 144 (ERMIN/ICRP)

	Depth (g cm^{-2})					Depth (g cm^{-2})			
Radionuclide	0.5	3	10	30	Radionuclide	0.5	3	10	30
Ag-110m	1.00	0.99	1.00	1.00	Pu-240	1.58	0.81	1.03	1.00
Am-241	1.01	0.96	1.00	0.94	Pu-241	1.01	0.98	1.01	0.98
Ba-137m	1.01	0.97	1.00	1.00	Rb-86	1.00	0.99	1.00	1.00
Ba-140	1.01	0.98	1.01	1.00	Rb-88	1.00	0.99	1.00	1.00
Ce-141	1.00	0.96	1.00	0.97	Rh-103m	1.66	0.67	1.06	-
Ce-143	1.00	0.97	0.99	1.00	Rh-105	1.00	0.99	1.00	0.98
Ce-144	1.00	0.94	1.00	0.98	Rh-106	1.01	0.98	1.00	1.00
Cm-242	1.86	0.79	1.03	1.00	Ru-103	1.01	0.98	1.00	0.99
Cm-244	1.93	0.74	1.05	1.00	Ru-105	1.01	0.98	1.00	1.00
Co-58	1.00	0.99	1.00	0.99	Ru-106	1.41	0.77	-	-
Co-60	1.00	0.99	1.00	1.00	Sb-127	1.01	0.98	1.00	1.01
Cs-134	1.01	0.98	1.00	1.00	Sb-129	1.01	0.99	1.00	1.00
Cs-136	1.00	0.99	1.01	1.00	Sr-89	1.01	0.97	1.01	0.99
Cs-137	1.02	0.95	1.01	0.99	Sr-90	1.03	0.95	1.01	0.98
Cs-138	1.01	0.99	1.00	1.00	Sr-91	1.01	0.98	1.00	1.00
I-129	0.96	1.09	1.00	1.08	Sr-92	1.00	0.99	1.00	1.00
I-131	1.01	0.99	1.00	0.99	Tc-99m	1.01	0.98	1.00	0.98
I-132	1.01	0.98	1.00	1.00	Te-127	1.00	0.97	1.00	0.99
I-133	1.01	0.98	1.00	1.00	Te-127m	0.90	1.09	0.96	0.99
I-134	1.01	0.99	1.00	1.00	Te-129	1.00	0.95	0.99	1.00
I-135	1.00	0.99	1.00	1.00	Te-129m	1.03	0.94	1.01	0.99
La-140	1.00	0.99	1.00	1.00	Te-131	1.01	0.98	1.00	1.00
Mn-54	1.00	0.99	1.00	0.99	Te-131m	1.00	0.99	1.00	1.00
Mo-99	1.01	0.99	1.00	0.99	Te-132	1.01	0.97	1.00	0.98
Na-24	1.00	0.99	1.00	0.99	Te-133	1.00	0.99	1.00	1.00
Nb-95	1.00	0.99	1.00	0.98	Te-133m	1.01	0.99	1.01	1.00
Nb-97m	1.01	0.98	1.01	1.00	Te-134	1.01	0.98	1.00	0.99
Nd-147	1.00	0.96	1.00	1.00	Y-90	1.00	0.97	1.00	1.00
Np-239	1.01	0.99	1.00	0.98	Y-91	1.00	0.97	1.00	1.00
Pr-143	1.02	0.96	1.00	0.99	Y-91m	1.01	0.98	1.00	1.00
Pr-144	1.00	0.99	1.00	0.99	Y-92	1.00	0.99	1.01	1.00
Pu-238	1.74	0.79	1.03	1.00	Zr-95	1.01	0.99	1.00	0.99
Pu-239	1.22	0.80	1.04	0.98	Zr-97	1.00	0.99	1.00	0.99

3.3 Incidental corrections for other ERMIN environments

The ERMIN UDL database of environments as described in Table 1, is derived from several different studies that predate the creation of ERMIN and consequently there are weaknesses. For example, the HPA environments were originally calculated as adult effective doses, whereas the GSF environments were calculated as air kerma requiring that the HPA values were converted. The GSF environments are missing dose coefficients for deposition on internal surfaces and for sub surface layers of soil. The GSF environments were created by interpolating and extrapolating from Monte-Carlo particle transport modelling results performed for a limited number of energies and there are likely large discrepancies when extrapolating to low energies. The HPA environments had a larger range of energies and used a binning approach.

Because these environments include buildings it is not possible to directly replace the surface dose coefficients that make up these environments with the factors from ICRP Publication 144 to mitigate these weaknesses. However, improvements to these environments were identified and implemented during the study as describes below.

3.3.1 Bremsstrahlung component

Table 6 demonstrates that, for a few radionuclides, the bremsstrahlung component is a significant or dominant part of the overall dose. Bremsstrahlung was omitted from the particle transport modelling of the original open area environment, and it was also omitted from the other built environments in the ERMIN library. For these radionuclides, the coefficients in all the environments are either zero or some very small value representing just the photon component of the exposure.

A simple approach was developed to modify the dose coefficients for these target radionuclides using the ICRP Publication 144 dataset. For each of the identified radionuclides, a suitable surrogate radionuclide was identified. For example, ^{144}Ce was chosen as a surrogate for ^{137}Cs. Figure 8a is a plot of the total (photon and bremsstrahlung) dose coefficients for both ^{137}Cs and ^{144}Ce and Figure 8b shows normalised DC. It is clear that from 0.5 g cm^{-2} downwards, the ratio of dose coefficients is reasonably constant. This ratio can be used as a factor to scale the DC of the surrogate to provide an estimate of the missing DC of all subsurface layers in all the ERMIN environments.

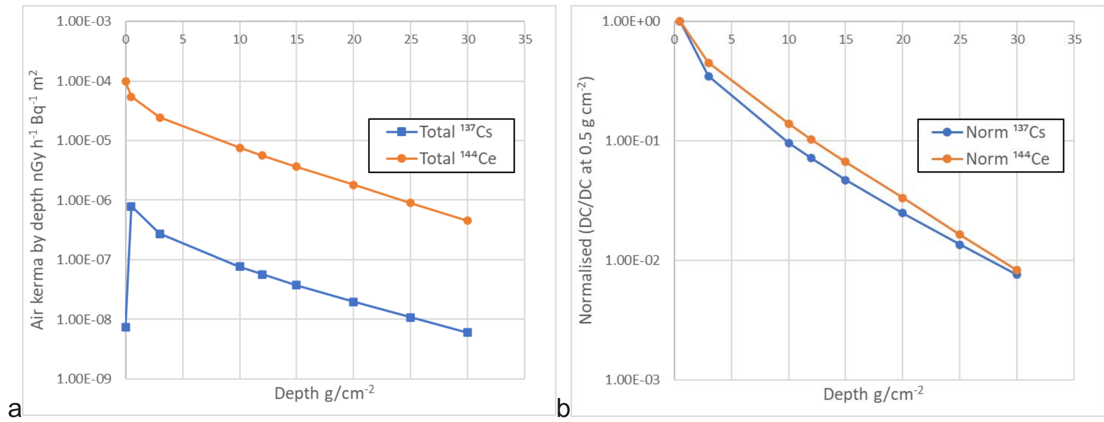


Figure 8 a) Total (photon and bremsstrahlung) air kerma dose coefficients of ^{137}Cs and ^{144}Ce extracted from ICRP publication 144. b) Normalised total DC from 0.5 g cm^{-2} downwards (DC at depth/DC at 0.5 g cm^{-2}).

A striking feature of the plot in Figure 8a is the increase in dose coefficient for ^{137}Cs between 0.0 and 0.5 g cm^{-2}. This means a very different factor is required for material on the surface, which is taken to be the ratio of DC of target and surrogate at the surface.

Since in ERMIN the top surface of soil is a layer 0.0 to 0.5 g cm^{-2}, it is appropriate to use the factor derived for subsurface layers. Similarly, the factor derived from the 0.5 g cm^{-2} DC was used for the paved surface. This is appropriate as the paved surface is never completely smooth but is pitted and rough whereas a value of 0.0 g cm^{-2} DC would mean the assumption of a completely smooth surface. However, for other surfaces such as leaves, and internal surfaces it is most appropriate to use a factor derived from the 0.0 g cm^{-2} DC. For roofs and walls, it is considered appropriate to apply the subsurface factor since neither surface is smooth and the radiation must pass through the material to reach the receptor.

Target radionuclides, surrogates, and the top surface and subsurface factors used are given in Table 15.

Table 15 Correction factors for radionuclides with significant bremsstrahlung components missing from ERMIN environments

Target	Surrogate	Top-surface factor	Subsurface factor
^{137}Cs	^{144}Ce	0.0000755	0.0115
^{143}Pr	^{144}Ce	0.000000406	0.0359
^{144}Pr	^{92}Y	0.109	0.1382
^{106}Ru	^{103m}Rh	0	0.0000455
^{89}Sr	^{132}Te	0.000287	0.0083
^{90}Sr	^{144}Ce	0	0.0097
^{90}Y	^{132}Te	0.0000448	0.0227
^{91}Y	^{129}Te	0.0367	0.0805

3.3.2 Conversion of HPA environments to Air Kerma

As indicated in Table 1, the HPA environments (the street of semi-detached houses without basement and the original open area environment) were originally calculated as adult effective doses, whereas the GSF environments were calculated as air kerma. To keep the ERMIN database consistent, the HPA environments were converted to air kerma using dose conversion factors derived from ICRP Publication 74.

To support the new dose conversion factors described in Section 3.2, it was deemed necessary to undo the original conversion and reapply the conversion with the new dose factors. This introduces an inconsistency since the original HPA calculations were performed with the ICRP Publication 60 definition of effective dose whereas the new dose conversion factors use the ICRP Publication 103 definition. However, it was decided this inconsistency was more than compensated for by a much-improved scheme that involved 9 DCFs that account for depth in soil instead of one DCF.

3.3.3 Improved internal surface to outdoor receptor DC in GSF environments

The GSF environments are missing DC for radiation from deposition on internal surfaces to receptors both indoors and outdoors as these calculations were never performed for these environments in the original studies. When the UDL was original created, DCs from the HPA semi-detached brick house environment, suitably adjusted for relative amounts of internal surfaces in the different environments were used as a surrogate. This is not ideal as this represents too much shielding in the prefabricated house environment and too little in the multi-storey block of flats. Furthermore, the DC from different locations indoors to outdoor receptors are the same whereas one would expect the DC from a basement or an upper floor to an outdoor location to be less from the ground floor to an outdoor location.

Unfortunately for the DC from internal surface to indoor receptors this approach cannot be improved in a simple way. However, it was noted that a better approach for radiation from internal surfaces to outdoor receptors was possible, as this situation is nearly the reverse of radiation from an external surface (e.g. paved) to an indoor receptor, and so the same DC can be used, again suitably adjusted for relative surface area, and furthermore DC for external surface to internal locations are available in all the GSF environments, having been undertaken in the original studies.

The proposition can be tested using the HPA environment which contained DCs for both internal surface to outdoor receptors and external surface to indoor receptors and Figure 9 demonstrates that there is a very close relationship.

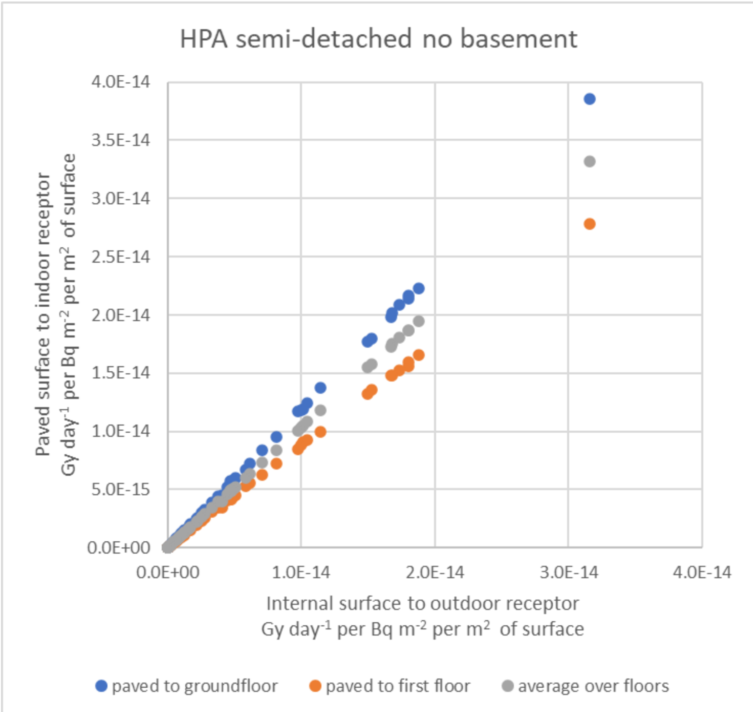
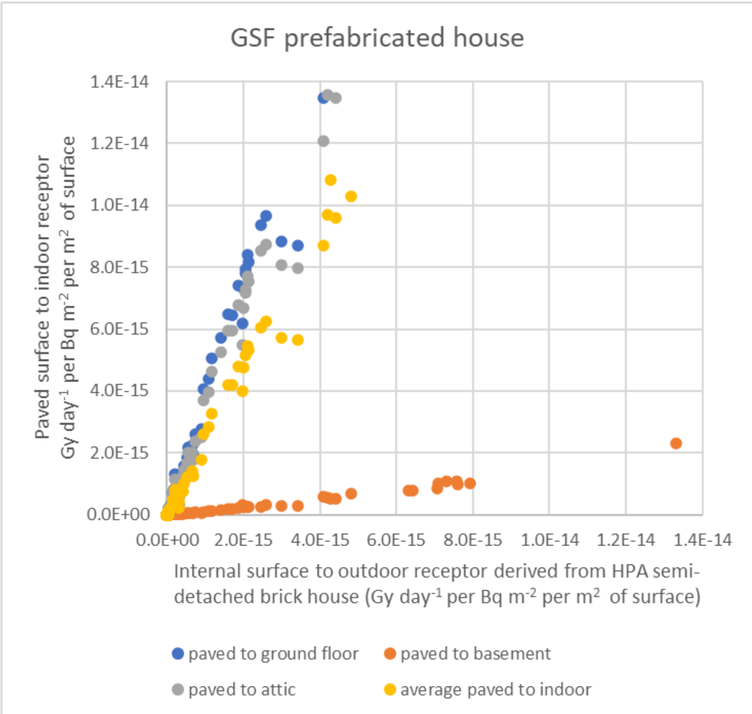
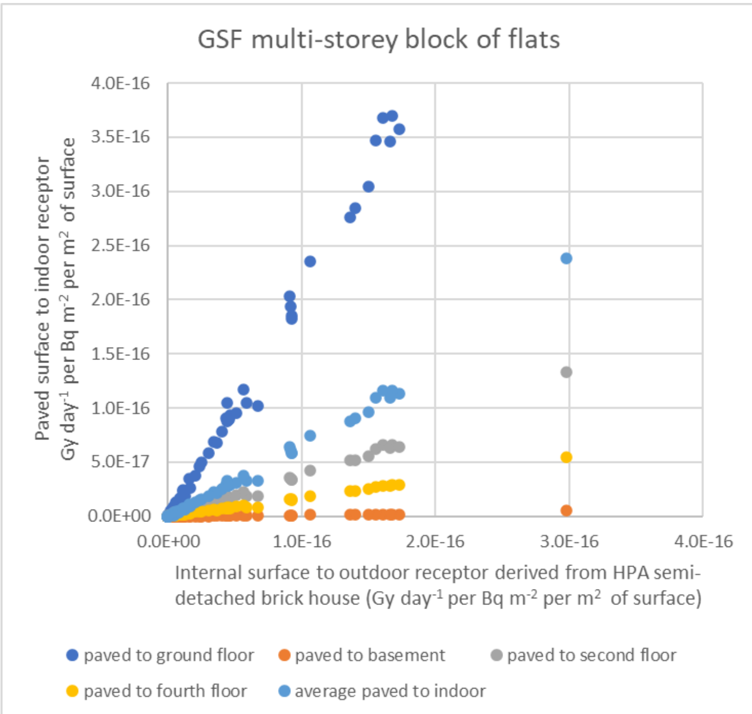


Figure 9 Comparison of dose rate coefficient of indoor surface to outdoor receptors with outdoor paved surface to indoor receptors

Using this approach, new internal surface to external receptor DC were derived for each of the GSF environments. Figure 10 shows a comparison of the old DC of internal surface to outdoor receptors with DC of paved surface to indoor receptors in both the GSF prefabricated building and multi-storey environments. The strong correlation is apparent, but DC derived from paved surfaces account for shielding and distance properties of the indoor location surfaces much more satisfactorily, for example consider the basement location in either environment, the paved DC are much lower than the paved DC to the above ground locations and very much lower than the DC generated from the HPA semi-detached environment.



(a)



(b)

Figure 10 Comparison of DC indoor surface to outdoor receptors derived from HPA semi-detached brick house environment, with DC from paved surface to indoor locations in (a) prefabricated environment and (b) multi-storey environment.

4 Illustrative ERMIN runs

To illustrate the impact of these changes, ERMIN was run with both the old and new dose coefficients and new dose conversion factors, as well as with and without the modifications described in Section 3.3.

The radionuclides selected for the runs are ^{137}Cs (along with the progeny ^{137m}Ba) as a gamma-emitting radionuclide in the middle of the energy range and one that is often important in recovery, ^{60}Co as gamma-emitter with high energy, ^{131}I as gamma-emitter with low energy, ^{89}Sr as a beta-emitter with energy in the middle of the energy range, ^{90}Y as beta-emitter with high energy, ^{143}Pr as beta-emitter with low energy, and ^{238}Pu as transuranic alpha-emitter. In addition, the radionuclide composition of the Fukushima Daiichi nuclear power station accident was selected as a mixed composition as shown in Table 16.

Table 16 Selected radionuclide composition for the Fukushima Daiichi example

Radionuclide	Concentration ratio
^{137}Cs	1.0
^{137m}Ba	1.0
^{134}Cs	1.0
^{131}I	11.5
^{132}Te	4.0
^{132}I	4.0
^{136}Cs	0.17
^{140}Ba	0.10
^{110m}Ag	0.003
^{129}Te	1.1

ERMIN runs were performed for five ERMIN environments, the HPA semi-detached brick house environment without basement, the GSF prefabricated house, the GSF terrace house, the GSF multistorey block of flats and the large open area environment. For each environment the default proportions of outdoor surfaces were used, except the open area which was assumed to be all grass.

Two sets of runs were performed, an ‘old’ run using old DCF and DC, and without modifications, and a ‘new’ run using the new DC and DCF available and with modifications as summarised in Table 17.

Table 17 Summary of differences between inputs of old and new runs of ERMIN

'Old' run	'New' run
HPA Semi-detached house environment	
Old set of dose conversion factors, one per radionuclide derived from ICRP Publication 74.	New set of dose conversion factors, nine per radionuclide to account for soil depth (see Section 3.1).
Old set of dose coefficients from particle transport modelling undertaken by HPA (see Table 1)	Old set of dose coefficients from particle transport modelling undertaken by HPA (see Table 1) but reconverted to air kerma using new set of dose conversion factors (3.3.2)
Dose coefficients account only for photon exposure and no bremsstrahlung	Dose coefficients account for photon exposure only except for selected radionuclides where a correction factor for bremsstrahlung derived from ICRP Publication 144 has been applied, see Section 3.3.1.
GSF Prefabricated house, Terrace house, Multistorey block of flats	
Old set of dose conversion factors, one per radionuclide derived from ICRP Publication 74.	New set of dose conversion factors, nine per radionuclide to account for soil depth (see Section 3.1).
Old set of dose coefficients from particle transport modelling undertaken by GSF (see Table 1)	Old set of dose coefficients from particle transport modelling undertaken by GSF (see Table 1), except for internal surface to outdoor receptors that have been improved see Section 3.3.3.
Dose coefficients account only for photon exposure and no bremsstrahlung	Dose coefficients account for photon exposure only except for selected radionuclides where a correction factor for bremsstrahlung derived from ICRP Publication 144 has been applied see Section 3.3.1.
Open-area environments (calculated by HPA and derived from ICRP Publication 144)	
Old set of dose conversion factors, one per radionuclide derived from ICRP Publication 74.	New set of dose conversion factors, nine per radionuclide to account for soil depth (see Section 3.1)
Old set of dose coefficients from particle transport modelling undertaken by HPA (see Table 1)	New set of dose coefficients derived and interpolated from ICRP Publication 144 and supplementary files provided by JAEA (See section 3.2)
Dose coefficients account only for photon exposure and no bremsstrahlung.	Dose coefficients account for both emitted photons and bremsstrahlung.

The ratios of doses calculated between the old and new runs are shown in Table 18. The biggest differences are for those corrected for a bremsstrahlung component (^{89}Sr, ^{90}Y, ^{143}Pr). ^{137}Cs was also corrected but shows only a small change in Table 18 because this is masked by the much larger contribution from its progeny ^{137m}Ba. The other radionuclides show only small changes, much less than a factor of 2. The Fukushima composition also shows little change because it is dominated by dose from ^{137}Cs/^{137m}Ba and ^{131}I.

Ignoring ^{89}Sr, ^{90}Y, ^{143}Pr where the difference is dominated by the bremsstrahlung modification, it is observed that generally differences increase with time, either with the ratio getting larger or smaller. This reflects migration into the soil and the bigger differences between the new DCF with increasing depth and the old constant DCF as identified in Section 2.2. The effect is slight since migration is slow and much of the radioactivity is in the top surface for a long time and all the doses are integrated from time zero.

Figure 11 to Figure 14 show the surface contribution to annual normal living doses for some of the radionuclides, for the built environments. Figure 11 shows ^{137}Cs/^{137m}Ba and Figure 12 shows ^{60}Co. These plots show the total doses are very similar and the relative contributions between different surfaces have not changed discernibly. There are differences caused by improving the internal surface to outdoor location DC, but these are not visually detectable since the internal surface is such a small contributor to dose outdoors and in the normal-living calculation 10% of time is spent outdoors.

Figure 13 shows ^{89}Sr and, as indicated in Table 18, the doses differ by a factor of around 5-10 with the new results being larger. ^{89}Sr is a radionuclide to which a bremsstrahlung correction was applied, so an increase is expected. The relative contribution of different surfaces has also changed with the importance of internal surfaces and trees decreasing while the importance of roofs increases. This is due in part to the choice of applying a subsurface or surface factor (see Section 3.3.1) to these surfaces.

Figure 14 shows ^{90}Y and, as indicated in Table 18, the doses are different by several orders of magnitude. An obvious feature is that for the GSF environments only the internal surface appears to contribute to dose. This is unrealistic and simply an artifact of their derivation. Originally, none of the GSF environments included ^{90}Y, but those environments were also missing all DC for the internal surface. The DC for the internal surface in the GSF environments had to be derived from the old HPA environment (see Table 1) which did include ^{90}Y, hence only the internal surfaces in the GSF environments include ^{90}Y. This is misleading and other surfaces may be equally or more important. In the corrected predictions, the internal surface is not important and is barely visible, but again this may reflect the choice of whether to apply a subsurface or surface correction factor (see Section 3.3.1) to these surfaces.

It is important not to overstate the importance of the correction factor to account for the bremsstrahlung component. The radionuclides to which it is necessary to apply the correction factor, are not usually significant dose contributors to external doses for reactor accident scenarios. Similarly, the change to the internal surface to external receptor, make little practical difference when compared to the larger contributions from other surfaces. The Fukushima mix indicates the cumulative effect of the changes made to the unit dose library are likely to be with the 10 to 15% range.

Table 18 New/old ratios of external dose without decontamination. Doses are given for normal living except for the open area which assumes outdoor living. All doses are integrated from time zero to the given time.

	Integration period	HPA Semi-detached house	GSF Prefabricated house	GSF Terrace house	GSF multi-storey building	ICRP144/HPA Open area all grass
^{137}Cs	30 d	1.00	0.96	0.98	0.98	0.89
	1 y	0.99	0.95	0.96	0.98	0.86
	10 y	0.99	0.97	0.92	0.92	0.85
^{60}Co	30 d	1.00	0.91	0.91	0.93	0.89
	1 y	0.99	0.90	0.89	0.90	0.88
	10 y	0.98	0.92	0.85	0.84	0.86
^{131}I	30 d	1.00	0.93	0.95	0.97	0.84
	1 y	1.00	0.92	0.95	0.97	0.84
	10 y	1.00	0.92	0.95	0.97	0.84
^{89}Sr	30 d	9.64	7.52	7.43	4.28	19.43
	1 y	10.66	9.95	8.49	5.02	19.30
	10 y	10.68	9.96	8.49	5.03	19.28
^{90}Y	30 d	2.73E+04	1.28E+05	6.81E+04	1.49E+04	7.89E+04
	1 y	2.73E+04	1.28E+05	6.81E+04	1.49E+04	7.90E+04
	10 y	2.73E+04	1.28E+05	6.81E+04	1.49E+04	7.90E+04
143Pr	30 d	3.69E+04	2.45E+04	2.84E+04	2.35E+04	5.56E+04
	1 y	3.78E+04	2.63E+04	2.95E+04	2.45E+04	5.53E+04
	10 y	3.78E+04	2.63E+04	2.95E+04	2.45E+04	5.53E+04
238Pu	30 d	1.02	1.24	1.08	1.02	0.60
	1 y	1.07	1.35	1.09	1.02	0.87
	10 y	1.17	1.95	1.25	1.08	0.89
Fukushima	30 d	1.00	0.93	0.96	0.97	0.87
	1 y	0.99	0.92	0.94	0.96	0.86
	10 y	0.99	0.93	0.90	0.92	0.85

Figure 11 New (a,c,e,g) and old (b,d,f,h) predictions of annual normal-living dose in each environment from $^{137}Cs/^{137m}Ba$, a,b) HPA semi-detached, c,d) GSF prefabricated, e,f) GSF Terrace and g,h) GSF multi-storey.

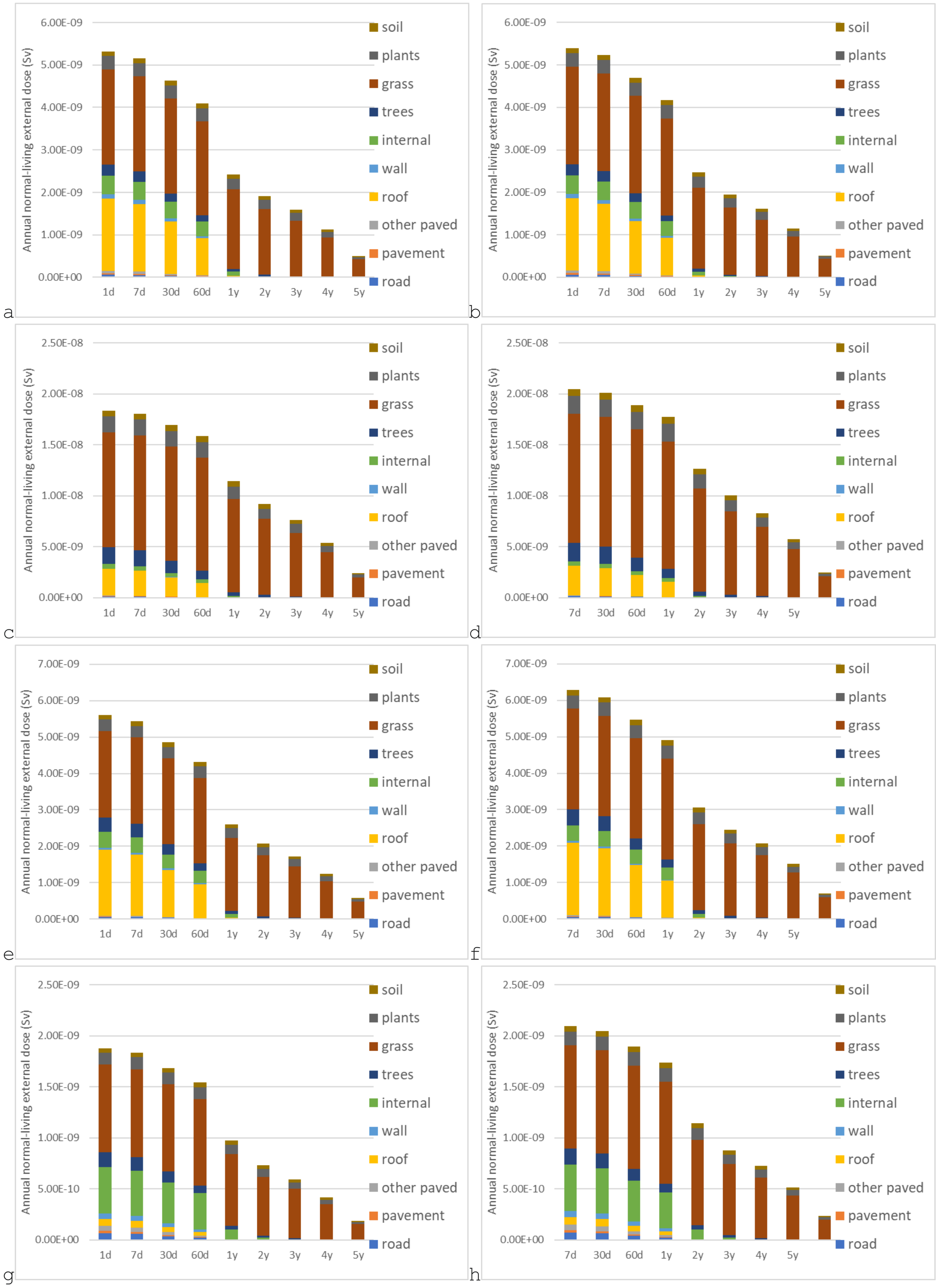


Figure 12 New (a,c,e,g) and old (b,d,f,h) predictions of annual normal-living dose in each environment from ^{60}Co, a,b) HPA semi-detached, c,d) GSF prefabricated, e,f) GSF Terrace and g,h) GSF multi-storey.

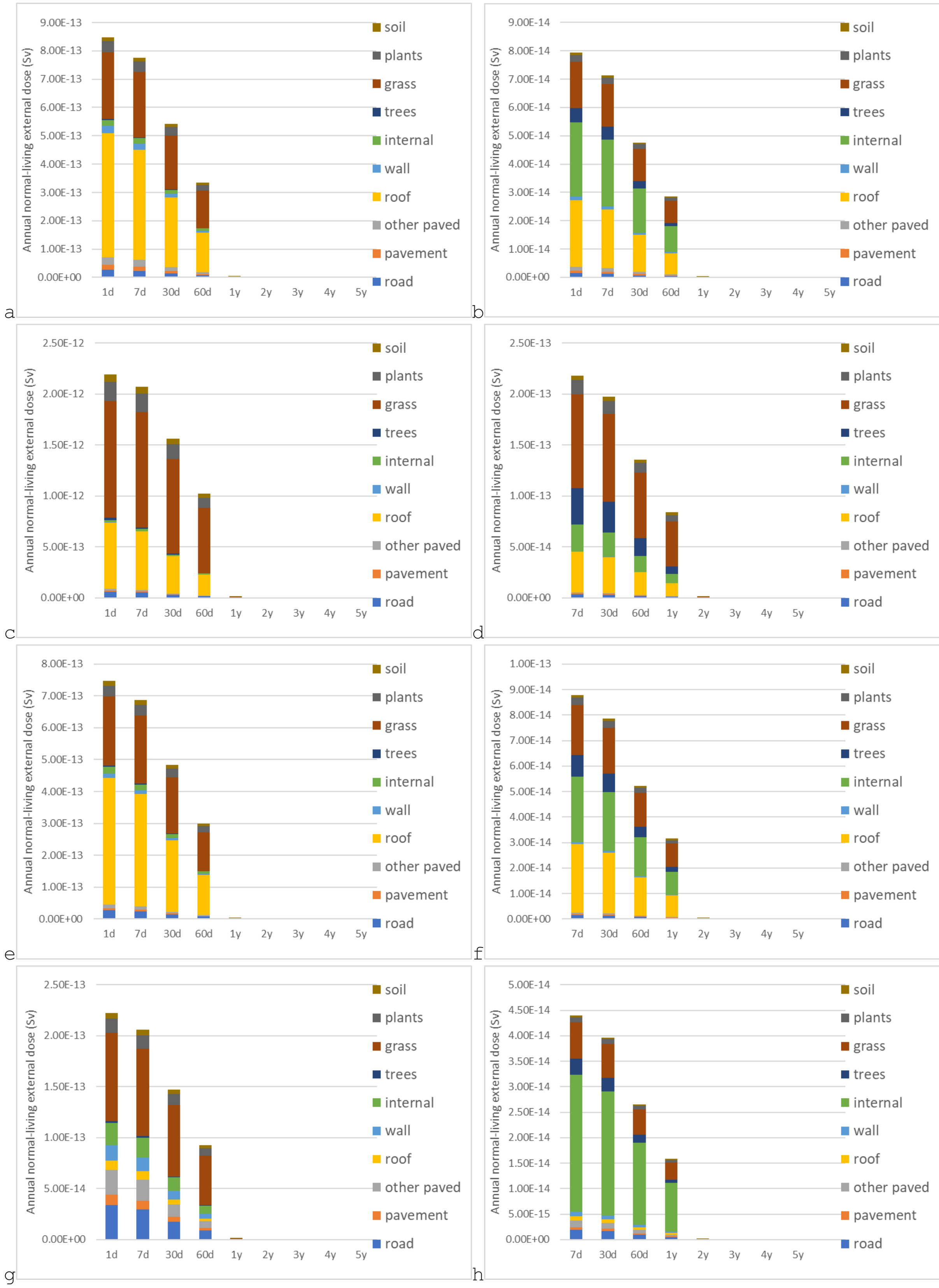


Figure 13 New (a,c,e,g) and old (b,d,f,h) predictions of annual normal-living dose in each environment from ^{89}Sr, a,b) HPA semi-detached, c,d) GSF prefabricated, e,f) GSF Terrace and g,h) GSF multi-storey.

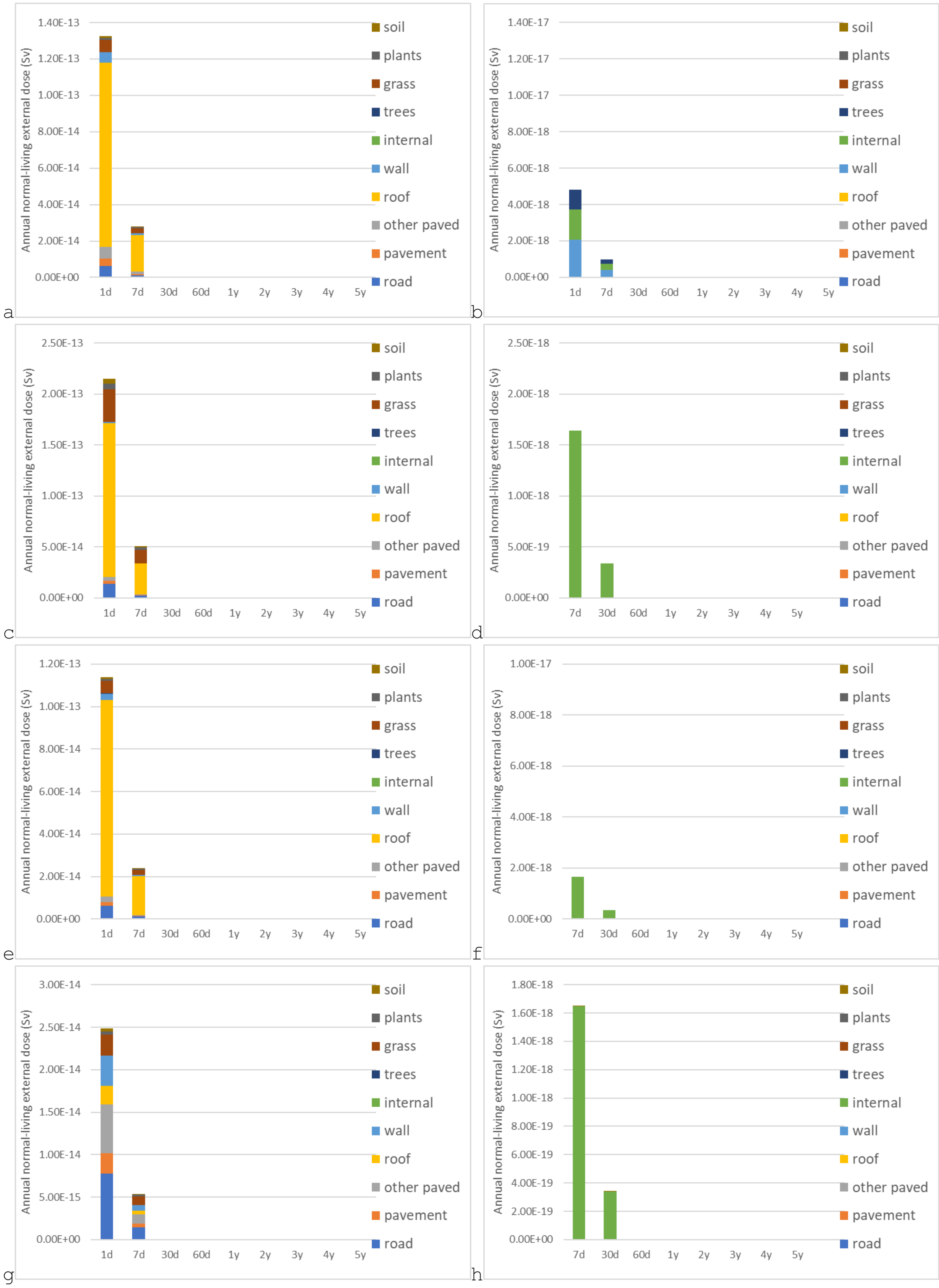


Figure 14 New (a,c,e,g) and old (b,d,f,h) predictions of annual normal-living dose in each environment from ^{90}Y, a,b) HPA semi-detached, c,d) GSF prefabricated, e,f) GSF Terrace and g,h) GSF multi-storey.

5 Conclusions

5.1 Comparison of external gamma dose coefficients

The recent ICRP Publication 144 of dose coefficients (DC) for external exposures to environmental sources (ICRP, 2020b) provides a useful opportunity to evaluate and improve the dose coefficients and factors used by ERMIN. ERMIN contains several idealised built environments in its Unit Dose Library (UDL), and the “open area” environment is very similar to the ICRP Publication 144 “planar sources on and within the ground” situation. The ICRP dataset is comprehensive and includes many radionuclides, organs, and age-groups. In contrast the “open area” dataset only includes those radionuclides considered of concern for accident recovery and only effective doses to adults.

The comparison between ICRP Publication 144 DC and the ERMIN open area DC found that the dose coefficients for gamma emitters are in reasonable agreement with most being within a factor of 2, except for low-energy gamma emitters. The dose coefficients for transuranic, beta, and low energy gamma-emitting radionuclides are not in such good agreement, with the DCs for ERMIN “open area” tending to be the larger than those in ICRP Publication 144. The exception are radionuclides, where there is a significant bremsstrahlung component that is not included in the ERMIN DC (for example the ^{137}Cs dose coefficients in ERMIN are zero for all environments and surfaces, whereas ICRP Publication 144 gives a gamma dose rate). For all radionuclides the agreement becomes worse when contamination is assumed to be present at lower soil layers.

5.2 Dose conversion factors

For each radionuclide, ERMIN uses a single DCF to calculate the dose from air kerma, derived from ICRP Publication 74 (ICRP, 1996b). ICRP Publication 144 has allowed a more sophisticated scheme to be developed for ERMIN with nine DCF, one for the top layer of soil and 8 for subsurface layers. The new ERMIN DCF scheme is not perfect since the top layer DCF is applied to all non-soil surfaces as well and all the DCF are applied to indoor and outdoor locations, but it is a considerable improvement on the single DCF scheme. The comparison between the ERMIN DCF and those of ICRP Publication 144 showed that the difference was greater for deeper soil layers which was expected.

5.3 Comparison of external beta dose coefficients

None of the ERMIN environments had specific beta particle modelling performed for them. Instead beta dose rates were derived from Holford (1989) using the assumptions outlined in Section 1.1. The comparison between ERMIN and ICRP Publication 144 found that beta dose rate from the soil surface is mostly in reasonable agreement except for transuranic and low energy beta-emitting radionuclides.

5.4 Changes made to ERMIN and UDL

During this study the following changes were made to the ERMIN model, the Unit Dose Library (UDL) and to other components of ERMIN.

- The radionuclide data file was modified to incorporate the newly derived DCF
- The ERMIN code was modified to apply the new nine DCF scheme.
- A new “open area” environment was added to the UDL based on ICRP Publication 144.
- Existing built environments were improved by applying a correction factor derived from ICRP Publication 144 to approximate the missing bremsstrahlung component for those radionuclides where its absence was significant. These include ^{137}Cs, ^{143}Pr, ^{144}Pr, ^{106}Ru, ^{89}Sr, ^{90}Sr, ^{90}Y and ^{91}Y as described in Section 3.3.1
- Beta skin dose DC in ERMIN are now derived from ICRP Publication 144 instead of Holford (1989).
- An improved approach to deriving the missing internal surfaces to external locations DC in the GSF environments was developed by scaling the available external ground surface to interior locations DC as described in Section 3.3.3.

Following this study, Table 19 replaces Table 1 as a summary of the derivation of the built environments within the ERMIN UDL.

Table 19 Summary of development of idealised environments in ERMIN UDL from this project onwards replacing summary in Table 1 (Numbers refer to environment labelling in UDL).

Environment	Source	Notes
1. Street of detached prefabricated houses 2. Street of semi-detached houses with basement 4. Street of terrace houses 5. Multi-storey block of flats amongst other house blocks 6. Multi-storey block of flats opposite parkland	GSF[a]	Based on Monte Carlo calculations of air kerma from contaminated exterior surfaces and the top one cm of soil, performed at GSF, using source energies of 0.3, 0.662 and 3 MeV which are interpolated and extrapolated to give DC for radionuclides. Different locations both inside and outside the target house or apartment were used. The supplementary subsurface soil dose rates were taken from ICRP Publication 144 and corrected to allow for the finite area of soil and for the shielding effects of soil on the dose rates from material at depths in the soil. The supplementary internal surface to interior location dose rates were derived from the HPA/PHE Street of semi-detached houses. Missing internal surface to external location have been derived from the corresponding external ground surface to interior location dose-rates. Gamma dose rates for selected radionuclides (^{137}Cs, ^{143}Pr, ^{106}Ru, ^{89}Sr, ^{90}Sr, ^{90}Y, ^{91}Y, ^{144}Pr) have been modified using factors derived from ICRP Publication 144 to account for bremsstrahlung. Beta skin dose rates are derived from ICRP Publication 144.
3. Street of semi-detached houses without basement	HPA/PHE, Jones et al (2006)	Based on Monte Carlo calculations of adult effective dose from contaminated interior and exterior surfaces and 9 soil layers, using source energies of 0.01, 0.015, 0.02, 0.03, 0.05, 0.1, 0.2, 0.5, 1, 1.5, 2, 4 MeV. DC for specific radionuclides generated with a binning approach, converted to air kerma using a set of radionuclide specific dose conversion factors derived from ICRP Publication 144. Gamma dose rates for selected radionuclides (^{137}Cs, ^{143}Pr, ^{106}Ru, ^{89}Sr, ^{90}Sr, ^{90}Y, ^{91}Y, ^{144}Pr) have been modified using factors derived from ICRP Publication 144 to account for bremsstrahlung. Beta skin dose rates are derived from ICRP Publication 144.
8. Open area	HPA/PHE, Jones et al (2006)	Based on Monte Carlo calculations of adult effective dose from 9 soil layers, using source energies of 0.01, 0.015, 0.02, 0.03, 0.05, 0.1, 0.2, 0.5, 1, 1.5, 2, 4 MeV. DC for specific radionuclides generated with a binning approach, converted to air kerma using a set of radionuclide specific dose conversion factors derived from ICRP Publication 144. Gamma dose rates for selected radionuclides (^{137}Cs, ^{143}Pr, ^{106}Ru, ^{89}Sr, ^{90}Sr, ^{90}Y, ^{91}Y, ^{144}Pr) have been modified using factors derived from ICRP Publication 144 to account for bremsstrahlung.
9. Open area ICRP144	ICRP (2020b)	Beta skin dose rates are derived from ICRP Publication 144.
7. Industrial site	GSF Kis et al (2003)	Incomplete with only ^{137}Cs/^{137m}Ba provided. The supplementary subsurface soil dose rates were taken from Eckerman and Ryman (1993), corrected to allow for the finite area of soil and for the shielding effects of soil on the dose rates from material at depths in the soil. There are no beta skin dose rates.

a Under the original EURANOS project in which ERMIN was first developed, unpublished datasets were supplied by GSF (National Research Centre for Environment and Health, now called Helmholtz Zentrum München) to populate the UDL. Publications that used these results include Meckbach et al (1988) and Meckbach and Jacob (1988).

5.5 Further improvements for ERMIN

Two areas of further potential improvement for ERMIN are discussed below.

The changes to the ERMIN environments that include buildings as outlined in Table 19 involve adjusting, scaling, and modifying existing Monte Carlo results using values derived from ICRP Publication 144. Ideally, to improve the DC and DCF, to include bremsstrahlung radiations and to understand the depth dependence of DCF of the ERMIN environments, the Monte-Carlo calculations would be repeated and would include bremsstrahlung radiations. This is because the energy of bremsstrahlung radiations depends on the atomic number of target materials such as soil and building materials.

Currently ERMIN provides only adult effective doses whereas ICRP Publication 144 provides the equivalent dose coefficients for each organ, and also considers the sex- and age-dependence of DC and equivalent dose coefficients; that is, male and female for adult, 15-year-old, 10-year-old, 5-year-old, 1-year-old, and new-born. It should be possible to modify the UDL to include DC for all organs and age groups and both sexes. The new open area environment can simply be extended from ICRP Publication 144 using the approaches in this document. For the other built environments, it may be possible to scale the existing DC using age, sex and organ specific factors derived from ICRP Publication 144.

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