



UK Health  
Security  
Agency

# **Methodology to assess health risks from the reuse of a building internally contaminated with radioactivity**

## Executive summary

Radioactive contamination of internal building surfaces arising from historical industrial practices presents ongoing safety and regulatory compliance challenges, including decommissioning. This report describes a methodology that can be used to assess the dose to both current and possible future users of a building from exposure to such contamination.

The methodology can be used to estimate the effective dose to a representative person in seven scenarios, representing a combination of various contamination profiles and reasonably foreseeable future room uses. As it is likely that most contamination would have arisen as a result of minor spills, several contamination profiles relate to localised wall or floor contamination where radioactivity is fixed to the exposed surface. The methodology also includes worst-case contamination profiles such as whole-wall and deeply embedded contamination. These latter profiles are intended to be used to estimate the upper magnitude of potential doses where there is extensive contamination present or where there are significant levels of uncertainty in how the contamination may be distributed within a room.

The methodology assumes the contaminated room was repurposed as an office. It is assumed that surfaces would be wiped prior to use removing any loose contamination and leaving only fixed contamination. In addition to assessing doses from fixed surfaces, the methodology considers exposure to dusts raised through renovation of the room in the future, for example drilling into the contamination when putting up wall-mounted shelving or removal of interior walls. To account for uncertainties in how the room would be used in the future, cautious but reasonably plausible parameter values were used.

Screening levels calculated using this methodology, expressed as activity per unit mass ( $\text{Bq g}^{-1}$ ), are presented. These screening levels can be compared to monitoring results to determine whether any reasonable future use of an internally contaminated room could result in doses that exceed a specified dose criterion. The criterion used in this publication is  $10 \mu\text{Sv y}^{-1}$ , the level used by the Office of Nuclear Regulation to represent no danger for the purposes of sections 3(12)(b) and 5(15)(a) of the Nuclear Installations Act 1965.

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## 1. Introduction

Use of radioactivity is highly controlled to keep any exposures as low as reasonably practicable. However, historical use of radioactivity in liquid or gaseous form, for example in radiochemical laboratories, was often less controlled. As a result, contamination of internal surfaces such as walls and floors has occasionally occurred. Although such contamination may not pose an unacceptable level of risk to the health of people using the building in its current form, future changes in how the space is used may alter occupancy patterns and result in unacceptable risks.

In order to help assess whether reuse of a contaminated room may result in an unacceptable level of risk to health, a simple dose assessment methodology is described.

Using this methodology screening levels, expressed as activity per unit mass ( $\text{Bq g}^{-1}$ ) that correspond to a specific dose criterion, were calculated and are presented. These levels can be compared to monitoring data to determine whether any reasonable future use of the contaminated room is likely to result in doses exceeding the selected dose criterion. The dose criterion used to calculate the presented screening levels is  $10 \mu\text{Sv y}^{-1}$ , the level defined by the Office of Nuclear Regulation (ONR) as representing no danger for the purposes of sections 3 (12) (b) and 5 (15) (a) of the Nuclear Installations Act 1965 [1].

Section 2 describes the radionuclides covered in this report and identifies those for which progeny radionuclides are assumed to be in secular equilibrium. Section 3 gives the exposure scenarios, while Section 4 describes the methodology for calculating doses that may arise when the contaminated room is reused. Section 5 presents the estimated dose per unit activity present and calculated screening levels for each radionuclide presented in Section 2.

## 2. Source term

Table 1 lists the radionuclides for which doses and screening levels were estimated. These radionuclides were selected based on their relevance to historical radiochemistry laboratory practices. Since the methodology is intended to assess the radiological impact from exposure to historical contamination rather than contamination due to recent incidents, only radionuclides with radioactive half-lives of more than 30 days are included. This is because short-lived radionuclides would have decayed to levels that would not pose a significant risk to health by the time the room is reused. The exception is for short-lived radionuclides whose activity is

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supported through the decay of a longer-lived radionuclide. Where a radioactive decay chain is present, it was cautiously assumed that all progeny radionuclides are in secular equilibrium with their parent.

**Table 1. Radionuclides for which screening levels were estimated**

<b>Radionuclide</b>	<b>Progeny radionuclides assumed to be in secular equilibrium with the parent radionuclide*</b>
<sup>14</sup> C	
<sup>90</sup> Sr+	<sup>90</sup> Y
<sup>99</sup> Tc	
<sup>99m</sup> Tc+	<sup>99</sup> Tc
<sup>137</sup> Cs+	<sup>137m</sup> Ba
<sup>210</sup> Pb+	<sup>210</sup> Bi, <sup>210</sup> Po
<sup>210</sup> Po	
<sup>226</sup> Ra+	<sup>222</sup> Rn, <sup>218</sup> Po, <sup>214</sup> Pb, <sup>214</sup> Bi, <sup>214</sup> Po, <sup>210</sup> Pb, <sup>210</sup> Bi, <sup>210</sup> Po
<sup>232</sup> Th+	<sup>228</sup> Ra, <sup>228</sup> Ac, <sup>228</sup> Th, <sup>224</sup> Ra, <sup>220</sup> Rn, <sup>216</sup> Po, <sup>212</sup> Pb, <sup>212</sup> Bi, <sup>212</sup> Po
<sup>234</sup> U+	<sup>230</sup> Th, <sup>226</sup> Ra, <sup>222</sup> Rn, <sup>218</sup> Po, <sup>214</sup> Pb, <sup>214</sup> Bi, <sup>214</sup> Po, <sup>210</sup> Pb, <sup>210</sup> Bi, <sup>210</sup> Po
<sup>235</sup> U+	<sup>231</sup> Th, <sup>231</sup> Pa, <sup>227</sup> Ac, <sup>227</sup> Th, <sup>223</sup> Ra, <sup>219</sup> Rn, <sup>215</sup> Po, <sup>211</sup> Pb, <sup>211</sup> Bi, <sup>207</sup> Tl
<sup>238</sup> U+	<sup>234</sup> Th, <sup>234m</sup> Pa, <sup>234</sup> Pa, <sup>234</sup> U, <sup>230</sup> Th, <sup>226</sup> Ra, <sup>222</sup> Rn, <sup>218</sup> Po, <sup>214</sup> Pb, <sup>214</sup> Bi, <sup>214</sup> Po, <sup>210</sup> Pb, <sup>210</sup> Bi, <sup>210</sup> Po
<sup>237</sup> Np	<sup>233</sup> Pa, <sup>233</sup> U, <sup>229</sup> Th, <sup>225</sup> Ra, <sup>225</sup> Ac, <sup>221</sup> Fr, <sup>217</sup> At, <sup>213</sup> Bi, <sup>213</sup> Po, <sup>209</sup> Pb
<sup>238</sup> Pu	<sup>234</sup> U, <sup>230</sup> Th, <sup>226</sup> Ra, <sup>222</sup> Rn, <sup>218</sup> Po, <sup>214</sup> Pb, <sup>214</sup> Bi, <sup>214</sup> Po, Pb-210, <sup>210</sup> Bi, <sup>210</sup> Po
<sup>239</sup> Pu	<sup>235</sup> U, <sup>231</sup> Th, <sup>231</sup> Pa, <sup>227</sup> Ac, <sup>227</sup> Th, <sup>223</sup> Ra, <sup>219</sup> Rn, <sup>215</sup> Po, <sup>211</sup> Pb, <sup>211</sup> Bi, <sup>207</sup> Tl
<sup>240</sup> Pu	<sup>236</sup> U, <sup>236</sup> Th, <sup>232</sup> Th, <sup>228</sup> Ra, <sup>228</sup> Ac, <sup>228</sup> Th, <sup>224</sup> Ra, <sup>220</sup> Rn, <sup>216</sup> Po, <sup>212</sup> Pb, <sup>212</sup> Bi, <sup>212</sup> Po
<sup>241</sup> Am	<sup>237</sup> Np, <sup>233</sup> Pa, <sup>233</sup> U, <sup>229</sup> Th, <sup>225</sup> Ra, <sup>225</sup> Ac, <sup>221</sup> Fr, <sup>217</sup> At, <sup>213</sup> Bi, <sup>213</sup> Po, <sup>209</sup> Pb
<sup>242</sup> Cm	<sup>238</sup> Pu, <sup>234</sup> U, <sup>230</sup> Th, <sup>226</sup> Ra, <sup>222</sup> Rn, <sup>218</sup> Po, <sup>214</sup> Pb, <sup>214</sup> Bi, <sup>214</sup> Po, <sup>210</sup> Pb, <sup>210</sup> Bi, <sup>210</sup> Po
<sup>244</sup> Cm	<sup>240</sup> Pu, <sup>236</sup> U, <sup>236</sup> Th, <sup>232</sup> Th, <sup>228</sup> Ra, <sup>228</sup> Ac, <sup>228</sup> Th, <sup>224</sup> Ra, <sup>220</sup> Rn, <sup>216</sup> Po, <sup>212</sup> Pb, <sup>212</sup> Bi, <sup>212</sup> Po
* No loss of radioactivity via emanation of radon was assumed to occur	

### 3. Overview of the exposure scenarios

The exposure scenarios describe how the radioactive contamination is distributed on or within surfaces of a room, and how representative persons may use that room and be exposed to any contamination present. The contaminated room was assumed to be a cube with walls measuring 3 m by 3 m by 3 m high. The walls of the room were assumed to be 11.5 cm thick, representing standard UK brick thickness, and covered by a 0.01 cm paint layer. Any radioactivity present was assumed to be evenly distributed within the contaminated volumes defined below.

Four wall contamination profiles were considered:

**Profile A** assumes contamination was present within a single patch measuring 0.3 m by 0.5 m, representing a total area of 0.15 m<sup>2</sup> or around 2% of the surface area of a single wall. This profile represents, for example, contamination arising from material being spilt or splashed against a wall located at the end of a workbench in a laboratory.

**Profile B** assumes contamination is present over the entire surface area of a wall as a bounding case.

Profiles A and B assume any contamination has not penetrated into the walls to any significant degree and is present only within the paint layer.

**Profile C** assumes the same surface area as Profile A but contamination present throughout the underlying brickwork.

**Profile D** assumes the same surface area as Profile B but contamination present throughout the underlying brickwork.

With respect to the representative persons, two types of future users of the room were considered reasonable. The first representative worker, an office worker, is someone who spends their entire working time sitting at a desk placed against the contaminated wall. The second representative worker, a maintenance worker, was assumed to conduct activities included minor work, such as drilling holes into the wall to put up shelving, or major renovation work that includes knocking down walls.

In addition to contamination being present on or in the walls, floor contamination may also be present. Although some kind of protective floor surface was likely to have been present when the room was used, it may not have been fully effective for example, due to small tears. After removal of the protective floor covering, some contamination may remain in the underlying concrete. As the protective flooring

would limit the penetration of liquids, contamination was assumed to extend to an average depth of 0.01 cm. Where a patch of contamination exists on the floor it was cautiously assumed to be located at the point of maximum occupancy in the room, for example in an area where someone sat at a desk.

Before the room is reused, the walls and the floor were assumed to be wiped, leaving only fixed contamination. As such, the office worker was assumed to be exposed only to contamination from external irradiation from gamma-emitting radionuclides. In addition to being externally irradiated from radioactivity present in walls and the floor, the maintenance worker was also assumed to inhaled and ingested dust created during drilling or hammering. Once any drilling or restructuring of the room had been completed, it was assumed that the majority of dust would be removed prior to the room being used as an office. So subsequent exposure are the same as for the office workers. A summary of the exposure scenarios is given below.

**Scenario 1** involves an office worker exposed to contamination distributed as described in Profile A.

**Scenario 2** involves an office worker exposed to contamination distributed as described in Profile B.

**Scenario 3** involves an office worker exposed to contamination distributed as described in Profile C.

**Scenario 4** involves an office worker exposed to contamination distributed as described in Profile D.

**Scenario 5** involves an office worker exposed to radioactivity present only within the surface layers of the floor.

**Scenario 6** involves a maintenance worker engaged in minor work such as drilling into a wall in order to put up shelving, an activity that would take a limited quantity of time and create relatively small quantities of dust. As all drilling was cautiously assumed to be carried out within the contaminated area of the wall, the estimated dose from inhaling or ingesting dust is only determined by the depth of contamination within the wall rather than its surface area.

**Scenario 7** involves a maintenance worker engaged in major work such as knocking down one or more internal walls. This process would both take a significant period of time and create a significant amount of dust.

In scenarios 1 to 4, the office worker was assumed to be sat at a distance of 0.5 m from the contaminated wall, representing the depth of a typical desk. Desk equipment like computers and miscellaneous office items were assumed to offer no shielding.

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Scenario 5 assumed that the representative person sat on a chair that was located directly above the contamination. To model this, a dose rate at a standard height of 1 m was used. It is noted that, where contamination is present on both walls and the floor, the calculated dose from exposure to each source should be summed.

In Scenarios 6 and 7, it was assumed that the worker was not wearing any personal protective equipment (PPE) that could reduce the inhalation or ingestion of dust, for example a dust mask. This approach was taken as there is no guarantee such equipment would be used or how effective it would be.

## 4. Assessment methodology

The total effective dose to a representative person using the room in the future,  $E_{total}$  (Sv  $y^{-1}$ ), was calculated using Equation 1:

$$E_{total} = E_{ext} + E_{inh} + E_{ing} \quad \text{Equation 1}$$

Where  $E_{ext}$  is the dose from exposure to gamma radiation emitted by radionuclides located in the wall or floor (Sv  $y^{-1}$ ),  $E_{inh}$  is the dose from inhalation of contaminated dust (Sv  $y^{-1}$ ), and  $E_{ing}$  is the dose from inadvertent ingestion of contaminated dust (Sv  $y^{-1}$ ). The following sections describe how the dose from each of these pathways was calculated.

### 4.1. Dose from external irradiation

The dose (Sv  $y^{-1}$ ) from exposure to gamma radiation emitted by radionuclides located in or on the walls and floor,  $E_{ext}$  was calculated using Equation 2:

$$E_{ext} = \sum_{i=r}^n C_i t R_i \quad \text{Equation 2}$$

Where  $C_i$  is the activity concentration of radionuclide  $i$  on or in the wall or floor (Bq  $g^{-1}$ ),  $t$  is the time the person spends annually working in the contaminated room (h  $y^{-1}$ ), and  $R_i$  is the effective dose rate from gamma radiation per unit activity concentration in the wall or floor from radionuclide  $i$  and any progeny radionuclides (Sv  $h^{-1}$  per Bq  $g^{-1}$ ).

The external dose rate for each scenario was calculated using the Monte Carlo particle transport software MCNP [2]. Those dose rates were estimated assuming a room measuring 3 m by 3 m by 3 m, representing a typical office. The walls of that

room were assumed to be constructed of concrete breeze blocks 11.5 cm thick [3]. The floor and ceiling were assumed to be composed of concrete with thicknesses of 20 cm and 3 cm, respectively. Effective dose rates and air kerma were calculated using 15 cm radius spherical air detectors positioned 1 m above the floor and, where applicable, 0.5 m from the contaminated wall. The calculated radiation fluence was converted to dose rates using coefficients presented by the International Commission on Radiological Protection (ICRP) in Publication 116 [4].

## 4.2. Dose from inhaling resuspended dusts

The dose ( $\text{Sv y}^{-1}$ ) from inhaling resuspended dust particles contaminated with radioactivity,  $E_{inh}$ , was calculated using Equation 3:

$$E_{inh} = \sum_{i=r}^n C_i I_{inh} e_{inh,e} F (t_{amb}L_{am} + t_{enh}L_h) \quad \text{Equation 3}$$

Where  $C_i$  is the activity concentration of radionuclide  $i$  in the paint layer or wall ( $\text{Bq g}^{-1}$ ),  $I_{inh}$  is the inhalation rate of the worker ( $\text{m}^3 \text{h}^{-1}$ ),  $e_{inh,i}$  is the committed effective dose coefficient for inhalation for radionuclide  $i$  recommended by ICRP in Publication 119 [5] ( $\text{Sv Bq}^{-1}$ ), and  $F$  denotes the fraction of created dust that is contaminated. Finally,  $t_{amb}$  and  $t_{enh}$  represent the amount of time the representative person respectively spends in ambient or enhanced dust loading conditions ( $\text{h y}^{-1}$ ) while  $L_{am}$  and  $L_h$  respectively represent ambient and enhanced dust loading levels ( $\text{g m}^{-3}$ ).

In Scenario 6, the worker was assumed to spend 4 hours in the room performing maintenance work. Of that time, 30 minutes was assumed to be spent in an enhanced dust loading of  $10 \text{ mg m}^{-3}$  when drilling or cleaning up dust. For context, COSHH (Control of Substances Hazardous to Health) defines levels of inhalable dust exceeding  $10 \text{ mg m}^{-3}$  or respirable dust exceeding  $4 \text{ mg m}^{-3}$ , averaged over a working day, to be hazardous to health and requiring adequate control measures [6]. For the remaining 3.5 hours, the worker was assumed to perform tasks that would not significantly resuspend dust. However, as contaminated dust was still assumed to be present, some inhalation would still occur. During that time, an ambient dust loading of  $0.1 \text{ mg m}^{-3}$ , was assumed. For perspective, this level of dust loading is of the same magnitude as typical outdoors dust levels due to resuspension of soil by wind [7].

During all tasks, the worker in Scenario 6 was assumed not to engage in any strenuous activities so their inhalation rate is that of a sedentary adult as recommended in NRPB-W41 [8], namely  $1.2 \text{ m}^3 \text{h}^{-1}$ . These dust loadings and inhalation rates were also used to estimate the dose to the worker in Scenario 7. However, to reflect the more extensive renovation work being performed, it was

assumed that, out of a total time of 80 hours spent working in the room, the representative worker was exposed to enhanced dust loading conditions for 16 hours.

For Scenario 6, where contamination was assumed to have penetrated the brickwork, the value of  $F$  was assumed to be 1, implying that all resuspended dust was contaminated. Where contamination was only present on the surface of the wall,  $F$  was assumed to have a value of  $2 \cdot 10^{-3}$ . This is equal to the ratio between the thickness of the contaminated layer (0.01 cm) and the drilling depth (nominally selected to be 5 cm). It was recognised that these values of  $F$  are cautious when contamination exists as patches. In such cases, some drilling would likely to occur in uncontaminated areas of the wall, leading to a greater proportion of the resuspended dust being uncontaminated.

Since it is not possible to predict the extent of any future renovations of the room, Scenario 7 assumed that only a single wall, with a volume of  $1.035 \text{ m}^3$ , would be demolished. In Scenario 7,  $F$  therefore represents the ratio of the volume of contamination present in the removed wall to the total volume of that wall. This is a cautious approach, as no dilution of contamination was considered from dust generated by the removal of other uncontaminated walls.

For contamination profiles A and C, the values of  $F$ , derived using the respective volumes of contamination present on or in the wall of  $1.5 \cdot 10^{-5} \text{ m}^3$  or  $1.7 \cdot 10^{-2} \text{ m}^3$ , are  $1 \cdot 10^{-5}$  and  $2 \cdot 10^{-2}$ , respectively. Where the entire wall was assumed to be contaminated,  $F$  has values of  $9 \cdot 10^{-4}$  and 1 for surface and penetrating contamination (profiles B and D) respectively. The value of  $F$  for profile B was estimated assuming the contaminated material had a volume of  $9 \cdot 10^{-4} \text{ m}^3$ .

## 4.3. Dose from inadvertently ingesting dusts

The dose ( $\text{Sv y}^{-1}$ ) from inadvertently ingesting dust particles contaminated with radionuclide  $i$ ,  $E_{\text{ing}}$ , was calculated using Equation 4:

$$E_{\text{ing}} = \sum_{i=r}^n C_i t e_{\text{ing},i} F I_{\text{ing}} \quad \text{Equation 4}$$

Where  $C_i$  is the activity concentration of radionuclide  $i$  in the wall ( $\text{Bq g}^{-1}$ ),  $t$  is the time the worker spends in the room when contaminated dust is present ( $\text{h y}^{-1}$ ),  $e_{\text{ing},i}$  is the committed effective dose coefficient for ingestion for radionuclide  $i$  recommended by ICRP in Publication 119 [5] ( $\text{Sv Bq}^{-1}$ ), and  $I_{\text{ing}}$  is the ingestion rate of dust by an adult, of  $0.005 \text{ g h}^{-1}$  [8]. The value  $F$  denotes the fraction of ingested dust that was contaminated and was assumed to have the same values described in Section 4.2. It

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was cautiously assumed that inadvertent ingestion of dust by the maintenance worker occurred at this rate for all time spent in the room, namely 4 and 80 h y<sup>-1</sup> for Scenarios 6 and 7, respectively.

## 4.4. Determining screening levels

The screening level represents the activity concentration (Bq g<sup>-1</sup>) below which the representative person's dose would remain lower than the specified dose,  $A_{N,D}$ , was calculated using Equation 5:

$$A_{N,D} = \frac{E_{N,D}}{E_{u,n}} \quad \text{Equation 5}$$

Where  $E_{N,D}$  is the dose criterion (Sv y<sup>-1</sup>) and  $E_{u,n}$  is the effective dose per unit activity concentration (Sv y<sup>-1</sup> per Bq g<sup>-1</sup>), calculated for each scenario as previously described. The dose criterion used is 10 μSv y<sup>-1</sup>. This dose criterion is used by the Office of Nuclear Regulation to represent no danger for the purposes of sections 3(12)(b) and 5(15)(a) of the Nuclear Installations Act 1965 [1].

In line with exemption and clearance values recommended by the International Atomic Energy Agency (IAEA) [9], the screening levels estimated in this report have been rounded. If the calculated value lies between  $3 \times 10^x$  and  $3 \times 10^{x+1}$ , it is rounded to  $10^{x+1}$ . This type of near logarithmic rounding was chosen in order to err up or down by the same factor rather than by a factor of 2 upwards and 5 downwards as in conventional rounding.

## 5. Results and discussion

Estimated dose per unit activity concentration for each exposure scenario and contamination profile, as defined in Section 3, are given in Tables 2, 3 and 4. The doses can be used directly with measured activity concentrations to estimate the potential dose from reusing of a room where contamination is present either on or within a wall or the floor. However, doses estimated to representative persons in any scenario except Scenario 5 should not be summed together as each of those scenarios assumes a specific contamination profile or representative person. It is, however, reasonable to sum the dose estimated in Scenario 5 (given in Table 2) with to the dose from one of the other scenarios (given in Tables 2, 3 and 4) if both wall and floor contamination is present. Where multiple radionuclides are present, the total dose can be estimated by summing the individual dose contribution for each radionuclide.

Tables 5, 6 and 7 present the screening levels obtained using the corresponding dose per unit activity concentrations shown in Tables 2, 3 and 4 with an assumed dose criterion of  $10 \mu\text{Sv y}^{-1}$ . Where only a single radionuclide is present as a contaminant, monitoring data can be compared directly to the appropriate screening level to determine whether future use of the room is likely to result in an annual dose exceeding  $10 \mu\text{Sv}$ . Where multiple radionuclides are present, exceedance of the dose criterion should be determined by use of the summation rule as shown in Equation 6:

$$\sum_{i=1}^n \frac{C_i}{L_i} \leq 1 \quad \text{Equation 6}$$

Where  $C_i$  is the activity concentration ( $\text{Bq g}^{-1}$ ) of the  $i^{\text{th}}$  radionuclide in the material,  $L_i$  is the screening level corresponding to radionuclide  $i$ , and  $n$  is the number of radionuclides present.

The inhalation and ingestion dose coefficients used to calculate the effective dose were sourced from ICRP Publication 119 [5]. At the time of publication, these values are being updated. A preliminary comparison between current and proposed dose coefficient values shows any potential change would not exceed a factor of 2.5 (inhalation) and 3.5 (ingestion). Although such changes are likely to have only a minimal impact on the presented doses and screening levels, UKHSA intend to reissue this report once the updated dose coefficients become available.

**Table 2: Effective dose per unit activity concentration for scenarios 1 to 5**

Radionuclide	Effective dose ( $\mu\text{Sv y}^{-1}$ per $\text{Bq g}^{-1}$ )				
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
$^{14}\text{C}$	n/a	n/a	n/a	n/a	n/a
$^{90}\text{Sr}+$	$4.1 \times 10^{-11}$	$1.9 \times 10^{-10}$	$7.7 \times 10^{-10}$	$5.6 \times 10^{-9}$	$8.3 \times 10^{-11}$
$^{99}\text{Tc}$	$2.0 \times 10^{-11}$	$1.5 \times 10^{-10}$	$7.7 \times 10^{-9}$	$5.5 \times 10^{-8}$	$8.0 \times 10^{-11}$
$^{99\text{m}}\text{Tc}+$	$3.1 \times 10^{-6}$	$2.8 \times 10^{-5}$	$1.3 \times 10^{-5}$	$1.5 \times 10^{-2}$	$1.5 \times 10^{-5}$
$^{137}\text{Cs}+$	$1.1 \times 10^{-5}$	$1.1 \times 10^{-4}$	$7.7 \times 10^{-3}$	$8.0 \times 10^{-2}$	$5.5 \times 10^{-5}$
$^{210}\text{Pb}+$	$1.3 \times 10^{-7}$	$7.5 \times 10^{-7}$	$1.4 \times 10^{-5}$	$8.0 \times 10^{-5}$	$3.4 \times 10^{-7}$
$^{210}\text{Po}$	$1.8 \times 10^{-10}$	$1.8 \times 10^{-9}$	$1.3 \times 10^{-7}$	$1.4 \times 10^{-6}$	$9.2 \times 10^{-10}$
$^{226}\text{Ra}+$	$3.0 \times 10^{-5}$	$3.1 \times 10^{-4}$	$2.1 \times 10^{-2}$	$2.3 \times 10^{-1}$	$1.5 \times 10^{-4}$
$^{232}\text{Th}+$	$2.1 \times 10^{-5}$	$2.1 \times 10^{-4}$	$1.3 \times 10^{-2}$	$1.5 \times 10^{-1}$	$1.1 \times 10^{-4}$
$^{234}\text{U}+$	$6.0 \times 10^{-5}$	$6.1 \times 10^{-4}$	$4.2 \times 10^{-2}$	$4.6 \times 10^{-1}$	$3.1 \times 10^{-4}$
$^{235}\text{U}+$	$1.6 \times 10^{-5}$	$1.4 \times 10^{-4}$	$5.4 \times 10^{-3}$	$8.2 \times 10^{-2}$	$7.5 \times 10^{-5}$
$^{238}\text{U}+$	$1.2 \times 10^{-4}$	$1.2 \times 10^{-3}$	$8.0 \times 10^{-2}$	$9.0 \times 10^{-1}$	$6.0 \times 10^{-4}$
$^{237}\text{Np}$	$1.3 \times 10^{-5}$	$1.1 \times 10^{-4}$	$6.1 \times 10^{-3}$	$6.3 \times 10^{-2}$	$5.9 \times 10^{-5}$
$^{238}\text{Pu}$	$9.0 \times 10^{-5}$	$9.2 \times 10^{-4}$	$6.2 \times 10^{-2}$	$7.0 \times 10^{-1}$	$4.6 \times 10^{-4}$
$^{239}\text{Pu}$	$3.2 \times 10^{-5}$	$2.8 \times 10^{-4}$	$1.1 \times 10^{-2}$	$1.6 \times 10^{-1}$	$1.5 \times 10^{-4}$
$^{240}\text{Pu}$	$4.3 \times 10^{-5}$	$4.3 \times 10^{-4}$	$2.6 \times 10^{-2}$	$3.1 \times 10^{-1}$	$2.2 \times 10^{-4}$
$^{241}\text{Am}$	$1.4 \times 10^{-5}$	$1.2 \times 10^{-4}$	$6.3 \times 10^{-3}$	$6.4 \times 10^{-2}$	$6.2 \times 10^{-5}$
$^{242}\text{Cm}$	$1.2 \times 10^{-4}$	$1.2 \times 10^{-3}$	$8.3 \times 10^{-2}$	$9.3 \times 10^{-1}$	$6.1 \times 10^{-4}$
$^{244}\text{Cm}$	$6.6 \times 10^{-5}$	$6.5 \times 10^{-4}$	$3.9 \times 10^{-2}$	$4.6 \times 10^{-1}$	$3.3 \times 10^{-4}$

**Table 3: Effective dose per unit activity concentration for each contamination profile assumed in scenario 6**

Radionuclide	Effective dose ( $\mu\text{Sv y}^{-1}$ per $\text{Bq g}^{-1}$ )			
	Contamination profile A	Contamination profile B	Contamination profile C	Contamination profile D
$^{14}\text{C}$	$2.6 \times 10^{-6}$	$2.6 \times 10^{-6}$	$1.3 \times 10^{-2}$	$1.3 \times 10^{-2}$
$^{90}\text{Sr}+$	$4.8 \times 10^{-5}$	$4.8 \times 10^{-5}$	$2.4 \times 10^{-1}$	$2.4 \times 10^{-1}$
$^{99}\text{Tc}$	$5.1 \times 10^{-6}$	$5.1 \times 10^{-6}$	$2.6 \times 10^{-2}$	$2.6 \times 10^{-2}$
$^{99\text{m}}\text{Tc}+$	$5.2 \times 10^{-6}$	$5.2 \times 10^{-6}$	$2.6 \times 10^{-2}$	$2.6 \times 10^{-2}$
$^{137}\text{Cs}+$	$5.9 \times 10^{-6}$	$6.1 \times 10^{-6}$	$3.0 \times 10^{-2}$	$3.0 \times 10^{-2}$
$^{210}\text{Pb}+$	$5.8 \times 10^{-3}$	$5.8 \times 10^{-3}$	$2.9 \times 10^{+1}$	$2.9 \times 10^{+1}$
$^{210}\text{Po}$	$4.2 \times 10^{-3}$	$4.2 \times 10^{-3}$	$2.1 \times 10^{+1}$	$2.1 \times 10^{+1}$
$^{226}\text{Ra}+$	$1.0 \times 10^{-2}$	$1.0 \times 10^{-2}$	$5.1 \times 10^{+1}$	$5.1 \times 10^{+1}$
$^{232}\text{Th}+$	$9.1 \times 10^{-2}$	$9.1 \times 10^{-2}$	$4.5 \times 10^{+2}$	$4.5 \times 10^{+2}$
$^{234}\text{U}+$	$3.3 \times 10^{-2}$	$3.3 \times 10^{-2}$	$1.6 \times 10^{+2}$	$1.6 \times 10^{+2}$
$^{235}\text{U}+$	$4.9 \times 10^{-1}$	$4.9 \times 10^{-1}$	$2.4 \times 10^{+3}$	$2.4 \times 10^{+3}$
$^{238}\text{U}+$	$3.7 \times 10^{-2}$	$3.7 \times 10^{-2}$	$1.8 \times 10^{+2}$	$1.8 \times 10^{+2}$
$^{237}\text{Np}$	$1.4 \times 10^{-1}$	$1.4 \times 10^{-1}$	$7.1 \times 10^{+2}$	$7.1 \times 10^{+2}$
$^{238}\text{Pu}$	$9.2 \times 10^{-2}$	$9.2 \times 10^{-2}$	$4.6 \times 10^{+2}$	$4.6 \times 10^{+2}$
$^{239}\text{Pu}$	$5.5 \times 10^{-1}$	$5.5 \times 10^{-1}$	$2.8 \times 10^{+3}$	$2.8 \times 10^{+3}$
$^{240}\text{Pu}$	$1.6 \times 10^{-1}$	$1.6 \times 10^{-1}$	$8.0 \times 10^{+2}$	$8.0 \times 10^{+2}$
$^{241}\text{Am}$	$2.0 \times 10^{-1}$	$2.0 \times 10^{-1}$	$9.8 \times 10^{+2}$	$9.8 \times 10^{+2}$
$^{242}\text{Cm}$	$9.9 \times 10^{-2}$	$9.9 \times 10^{-2}$	$4.9 \times 10^{+2}$	$4.9 \times 10^{+2}$
$^{244}\text{Cm}$	$1.9 \times 10^{-1}$	$1.9 \times 10^{-1}$	$9.7 \times 10^{+2}$	$9.7 \times 10^{+2}$

**Table 4: Effective dose per unit activity concentration for each contamination profile assumed in scenario 7**

Radionuclide	Effective dose ( $\mu\text{Sv y}^{-1}$ per $\text{Bq g}^{-1}$ )			
	Contamination profile A	Contamination profile B	Contamination profile C	Contamination profile D
$^{14}\text{C}$	$4.0 \times 10^{-6}$	$3.6 \times 10^{-4}$	$8.0 \times 10^{-3}$	$4.0 \times 10^{-1}$
$^{90}\text{Sr}+$	$7.5 \times 10^{-5}$	$6.7 \times 10^{-3}$	$1.5 \times 10^{-1}$	$7.5 \times 10^{+0}$
$^{99}\text{Tc}$	$8.0 \times 10^{-6}$	$7.2 \times 10^{-4}$	$1.6 \times 10^{-2}$	$8.0 \times 10^{-1}$
$^{99\text{m}}\text{Tc}+$	$8.2 \times 10^{-6}$	$7.2 \times 10^{-4}$	$1.6 \times 10^{-2}$	$8.0 \times 10^{-1}$
$^{137}\text{Cs}+$	$9.6 \times 10^{-6}$	$8.3 \times 10^{-4}$	$1.9 \times 10^{-2}$	$9.2 \times 10^{-1}$
$^{210}\text{Pb}+$	$9.0 \times 10^{-3}$	$8.1 \times 10^{-1}$	$1.8 \times 10^{+1}$	$9.0 \times 10^{+2}$
$^{210}\text{Po}$	$6.6 \times 10^{-3}$	$5.9 \times 10^{-1}$	$1.3 \times 10^{+1}$	$6.6 \times 10^{+2}$
$^{226}\text{Ra}+$	$1.6 \times 10^{-2}$	$1.4 \times 10^{+0}$	$3.2 \times 10^{+1}$	$1.6 \times 10^{+3}$
$^{232}\text{Th}+$	$1.4 \times 10^{-1}$	$1.3 \times 10^{+1}$	$2.8 \times 10^{+2}$	$1.4 \times 10^{+4}$
$^{234}\text{U}+$	$5.1 \times 10^{-2}$	$4.6 \times 10^{+0}$	$1.0 \times 10^{+2}$	$5.1 \times 10^{+3}$
$^{235}\text{U}+$	$7.6 \times 10^{-1}$	$6.8 \times 10^{+1}$	$1.5 \times 10^{+3}$	$7.6 \times 10^{+4}$
$^{238}\text{U}+$	$5.7 \times 10^{-2}$	$5.1 \times 10^{+0}$	$1.1 \times 10^{+2}$	$5.7 \times 10^{+3}$
$^{237}\text{Np}$	$2.2 \times 10^{-1}$	$2.0 \times 10^{+1}$	$4.4 \times 10^{+2}$	$2.2 \times 10^{+4}$
$^{238}\text{Pu}$	$1.4 \times 10^{-1}$	$1.3 \times 10^{+1}$	$2.9 \times 10^{+2}$	$1.4 \times 10^{+4}$
$^{239}\text{Pu}$	$8.6 \times 10^{-1}$	$7.7 \times 10^{+1}$	$1.7 \times 10^{+3}$	$8.6 \times 10^{+4}$
$^{240}\text{Pu}$	$2.5 \times 10^{-1}$	$2.2 \times 10^{+1}$	$5.0 \times 10^{+2}$	$2.5 \times 10^{+4}$
$^{241}\text{Am}$	$3.1 \times 10^{-1}$	$2.8 \times 10^{+1}$	$6.1 \times 10^{+2}$	$3.1 \times 10^{+4}$
$^{242}\text{Cm}$	$1.5 \times 10^{-1}$	$1.4 \times 10^{+1}$	$3.1 \times 10^{+2}$	$1.5 \times 10^{+4}$
$^{244}\text{Cm}$	$3.0 \times 10^{-1}$	$2.7 \times 10^{+1}$	$6.0 \times 10^{+2}$	$3.0 \times 10^{+4}$

**Table 5: Screening levels for scenarios 1 through 5 assuming a dose criterion of 10  $\mu\text{Sv y}^{-1}$**

Radionuclide	Screening level ( $\text{Bq g}^{-1}$ )				
	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
$^{14}\text{C}$	$1 \times 10^{+11}$	$1 \times 10^{+11}$	$1 \times 10^{+10}$	$1 \times 10^{+09}$	$1 \times 10^{+11}$
$^{90}\text{Sr}+$	$1 \times 10^{+12}$	$1 \times 10^{+11}$	$1 \times 10^{+9}$	$1 \times 10^{+8}$	$1 \times 10^{+11}$
$^{99}\text{Tc}$	$1 \times 10^{+7}$	$1 \times 10^{+6}$	$1 \times 10^{+6}$	$1 \times 10^{+3}$	$1 \times 10^{+6}$
$^{99\text{m}}\text{Tc}+$	$1 \times 10^{+6}$	$1 \times 10^{+5}$	$1 \times 10^{+3}$	$1 \times 10^{+2}$	$1 \times 10^{+5}$
$^{137}\text{Cs}+$	$1 \times 10^{+8}$	$1 \times 10^{+7}$	$1 \times 10^{+6}$	$1 \times 10^{+5}$	$1 \times 10^{+7}$
$^{210}\text{Pb}+$	$1 \times 10^{+11}$	$1 \times 10^{+10}$	$1 \times 10^{+8}$	$1 \times 10^{+7}$	$1 \times 10^{+10}$
$^{210}\text{Po}$	$1 \times 10^{+6}$	$1 \times 10^{+5}$	$1 \times 10^{+3}$	$1 \times 10^{+2}$	$1 \times 10^{+5}$
$^{226}\text{Ra}+$	$1 \times 10^{+6}$	$1 \times 10^{+5}$	$1 \times 10^{+3}$	$1 \times 10^{+2}$	$1 \times 10^{+5}$
$^{232}\text{Th}+$	$1 \times 10^{+5}$	$1 \times 10^{+4}$	$1 \times 10^{+2}$	$1 \times 10^{+1}$	$1 \times 10^{+5}$
$^{234}\text{U}+$	$1 \times 10^{+6}$	$1 \times 10^{+5}$	$1 \times 10^{+3}$	$1 \times 10^{+2}$	$1 \times 10^{+5}$
$^{235}\text{U}+$	$1 \times 10^{+5}$	$1 \times 10^{+4}$	$1 \times 10^{+2}$	$1 \times 10^{+1}$	$1 \times 10^{+4}$
$^{238}\text{U}+$	$1 \times 10^{+6}$	$1 \times 10^{+5}$	$1 \times 10^{+3}$	$1 \times 10^{+2}$	$1 \times 10^{+5}$
$^{237}\text{Np}$	$1 \times 10^{+5}$	$1 \times 10^{+4}$	$1 \times 10^{+2}$	$1 \times 10^{+1}$	$1 \times 10^{+4}$
$^{238}\text{Pu}$	$1 \times 10^{+6}$	$1 \times 10^{+5}$	$1 \times 10^{+3}$	$1 \times 10^{+2}$	$1 \times 10^{+5}$
$^{239}\text{Pu}$	$1 \times 10^{+5}$	$1 \times 10^{+4}$	$1 \times 10^{+3}$	$1 \times 10^{+2}$	$1 \times 10^{+5}$
$^{240}\text{Pu}$	$1 \times 10^{+6}$	$1 \times 10^{+5}$	$1 \times 10^{+3}$	$1 \times 10^{+2}$	$1 \times 10^{+5}$
$^{241}\text{Am}$	$1 \times 10^{+5}$	$1 \times 10^{+4}$	$1 \times 10^{+2}$	$1 \times 10^{+1}$	$1 \times 10^{+4}$
$^{242}\text{Cm}$	$1 \times 10^{+5}$	$1 \times 10^{+4}$	$1 \times 10^{+2}$	$1 \times 10^{+1}$	$1 \times 10^{+5}$
$^{244}\text{Cm}$	$1 \times 10^{+11}$	$1 \times 10^{+11}$	$1 \times 10^{+10}$	$1 \times 10^{+9}$	$1 \times 10^{+11}$

**Table 6: Screening levels for each contamination profile assumed in scenario 6, assuming a dose criterion of  $10 \mu\text{Sv y}^{-1}$**

Radionuclide	Screening level ( $\text{Bq g}^{-1}$ )			
	Contamination profile A	Contamination profile B	Contamination profile C	Contamination profile D
$^{14}\text{C}$	$1 \times 10^{+7}$	$1 \times 10^{+7}$	$1 \times 10^{+3}$	$1 \times 10^{+3}$
$^{90}\text{Sr}+$	$1 \times 10^{+5}$	$1 \times 10^{+5}$	$1 \times 10^{+2}$	$1 \times 10^{+2}$
$^{99}\text{Tc}$	$1 \times 10^{+6}$	$1 \times 10^{+6}$	$1 \times 10^{+3}$	$1 \times 10^{+3}$
$^{99\text{m}}\text{Tc}+$	$1 \times 10^{+6}$	$1 \times 10^{+6}$	$1 \times 10^{+3}$	$1 \times 10^{+3}$
$^{137}\text{Cs}+$	$1 \times 10^{+6}$	$1 \times 10^{+6}$	$1 \times 10^{+3}$	$1 \times 10^{+3}$
$^{210}\text{Pb}+$	$1 \times 10^{+3}$	$1 \times 10^{+3}$	$1 \times 10^{+0}$	$1 \times 10^{+0}$
$^{210}\text{Po}$	$1 \times 10^{+3}$	$1 \times 10^{+3}$	$1 \times 10^{+0}$	$1 \times 10^{+0}$
$^{226}\text{Ra}+$	$1 \times 10^{+3}$	$1 \times 10^{+3}$	$1 \times 10^{-1}$	$1 \times 10^{-1}$
$^{232}\text{Th}+$	$1 \times 10^{+2}$	$1 \times 10^{+2}$	$1 \times 10^{-2}$	$1 \times 10^{-2}$
$^{234}\text{U}+$	$1 \times 10^{+3}$	$1 \times 10^{+3}$	$1 \times 10^{-1}$	$1 \times 10^{-1}$
$^{235}\text{U}+$	$1 \times 10^{+1}$	$1 \times 10^{+1}$	$1 \times 10^{-2}$	$1 \times 10^{-2}$
$^{238}\text{U}+$	$1 \times 10^{+2}$	$1 \times 10^{+2}$	$1 \times 10^{-1}$	$1 \times 10^{-1}$
$^{237}\text{Np}$	$1 \times 10^{+2}$	$1 \times 10^{+2}$	$1 \times 10^{-2}$	$1 \times 10^{-2}$
$^{238}\text{Pu}$	$1 \times 10^{+2}$	$1 \times 10^{+2}$	$1 \times 10^{-2}$	$1 \times 10^{-2}$
$^{239}\text{Pu}$	$1 \times 10^{+1}$	$1 \times 10^{+1}$	$1 \times 10^{-2}$	$1 \times 10^{-2}$
$^{240}\text{Pu}$	$1 \times 10^{+2}$	$1 \times 10^{+2}$	$1 \times 10^{-2}$	$1 \times 10^{-2}$
$^{241}\text{Am}$	$1 \times 10^{+2}$	$1 \times 10^{+2}$	$1 \times 10^{-2}$	$1 \times 10^{-2}$
$^{242}\text{Cm}$	$1 \times 10^{+2}$	$1 \times 10^{+2}$	$1 \times 10^{-2}$	$1 \times 10^{-2}$
$^{244}\text{Cm}$	$1 \times 10^{+2}$	$1 \times 10^{+2}$	$1 \times 10^{-2}$	$1 \times 10^{-2}$

**Table 7: Screening levels for each contamination profile assumed in scenario 7 assuming a dose criterion of  $10 \mu\text{Sv y}^{-1}$**

Radionuclide	Screening level ( $\text{Bq g}^{-1}$ )			
	Contamination profile A	Contamination profile B	Contamination profile C	Contamination profile D
$^{14}\text{C}$	$1 \times 10^{+6}$	$1 \times 10^{+4}$	$1 \times 10^{+3}$	$1 \times 10^{+1}$
$^{90}\text{Sr}+$	$1 \times 10^{+5}$	$1 \times 10^{+3}$	$1 \times 10^{+2}$	$1 \times 10^{+0}$
$^{99}\text{Tc}$	$1 \times 10^{+6}$	$1 \times 10^{+4}$	$1 \times 10^{+3}$	$1 \times 10^{+1}$
$^{99\text{m}}\text{Tc}+$	$1 \times 10^{+6}$	$1 \times 10^{+4}$	$1 \times 10^{+3}$	$1 \times 10^{+1}$
$^{137}\text{Cs}+$	$1 \times 10^{+6}$	$1 \times 10^{+4}$	$1 \times 10^{+3}$	$1 \times 10^{+1}$
$^{210}\text{Pb}+$	$1 \times 10^{+3}$	$1 \times 10^{+1}$	$1 \times 10^{+0}$	$1 \times 10^{-2}$
$^{210}\text{Po}$	$1 \times 10^{+3}$	$1 \times 10^{+1}$	$1 \times 10^{+0}$	$1 \times 10^{-2}$
$^{226}\text{Ra}+$	$1 \times 10^{+3}$	$1 \times 10^{+1}$	$1 \times 10^{+0}$	$1 \times 10^{-2}$
$^{232}\text{Th}+$	$1 \times 10^{+2}$	$1 \times 10^{+0}$	$1 \times 10^{-1}$	$1 \times 10^{-3}$
$^{234}\text{U}+$	$1 \times 10^{+2}$	$1 \times 10^{+0}$	$1 \times 10^{-1}$	$1 \times 10^{-3}$
$^{235}\text{U}+$	$1 \times 10^{+1}$	$1 \times 10^{-1}$	$1 \times 10^{-2}$	$1 \times 10^{-4}$
$^{238}\text{U}+$	$1 \times 10^{+2}$	$1 \times 10^{+0}$	$1 \times 10^{-1}$	$1 \times 10^{-3}$
$^{237}\text{Np}$	$1 \times 10^{+2}$	$1 \times 10^{+0}$	$1 \times 10^{-2}$	$1 \times 10^{-3}$
$^{238}\text{Pu}$	$1 \times 10^{+2}$	$1 \times 10^{+0}$	$1 \times 10^{-1}$	$1 \times 10^{-3}$
$^{239}\text{Pu}$	$1 \times 10^{+1}$	$1 \times 10^{-1}$	$1 \times 10^{-2}$	$1 \times 10^{-4}$
$^{240}\text{Pu}$	$1 \times 10^{+2}$	$1 \times 10^{+0}$	$1 \times 10^{-2}$	$1 \times 10^{-3}$
$^{241}\text{Am}$	$1 \times 10^{+2}$	$1 \times 10^{+0}$	$1 \times 10^{-2}$	$1 \times 10^{-3}$
$^{242}\text{Cm}$	$1 \times 10^{+2}$	$1 \times 10^{+0}$	$1 \times 10^{-1}$	$1 \times 10^{-3}$
$^{244}\text{Cm}$	$1 \times 10^{+2}$	$1 \times 10^{+0}$	$1 \times 10^{-2}$	$1 \times 10^{-3}$

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