Correction factors for the ISO rod phantom, a cylinder phantom, and the ICRU sphere for reference beta radiation fields of the BSS 2

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ABSTRACT: The International Organization for Standardization (ISO) requires in its standard ISO 6980 that beta reference radiation fields for radiation protection be calibrated in terms of absorbed dose to tissue at a depth of 0.07 mm in a slab phantom (30 cm x 30 cm x 15 cm). However, many beta dosemeters are ring dosemeters and are, therefore, irradiated on a rod phantom (1.9 cm in diameter and 30 cm long), or they are eye dosemeters possibly irradiated on a cylinder phantom (20 cm in diameter and 20 cm high), or area dosemeters irradiated free in air with the conventional quantity value (true value) being defined in a sphere (30 cm in diameter, made of ICRU tissue (International Commission on Radiation Units and Measurements)). Therefore, the correction factors for the conventional quantity value in the rod, the cylinder, and the sphere instead of the slab (all made of ICRU tissue) were calculated for the radiation fields of $^{147}$Pm, $^{85}$Kr, $^{90}$Sr/$^{90}$Y, and, $^{106}$Ru/$^{106}$Rh sources of the beta secondary standard BSS 2 developed at PTB. All correction factors were calculated for 0° up to 75° (in steps of 15°) radiation incidence. The results are ready for implementation in ISO 6980-3 and have recently been (partly) implemented in the software of the BSS 2.

KEYWORDS: Models and simulations; Dosimetry concepts and apparatus
1 Introduction

Reference beta radiation fields for radiation protection are calibrated in terms of absorbed dose to tissue using primary extrapolation ionization chambers [1–3]. Such extrapolation chambers are usually embedded in a slab phantom (often made of polymethyl methacrylate (PMMA)) to determine the reference absorbed dose, \( D_R \), which is defined as the “personal absorbed dose, \( D_p(0.07) \), in a slab phantom made of ICRU tissue” [2] (International Commission on Radiation Units and Measurements). To account for the phantom material deviating from ICRU tissue, correction factors are applied [2]. As the quality factor for electrons is \( Q = 1 \) Sv/Gy, \( D_p(0.07) \) is equivalent to the operational quantity personal dose equivalent at 0.07 mm depth in ICRU tissue, \( H_p(0.07)_{\text{slab}} \).

Utilising the measurement of depth dose curves [5, 6] provides the quantity \( H_p(3)_{\text{slab}} \) which is (like \( H_p(0.07)_{\text{slab}} \)) implemented in the beta secondary standard BSS 2 [7–9]. For both \( H_p(0.07)_{\text{slab}} \) and \( H_p(3)_{\text{slab}} \) the index “slab” denotes the definition (and measurement) in a slab phantom.

Personal dosemeters, such as ring dosemeters, are irradiated on a rod phantom (1.9 cm in diameter and 30 cm long, made of PMMA) [3], or eye dosemeters are possibly irradiated on a cylinder phantom (20 cm in diameter and 20 cm high, water-filled cylinder made of PMMA) [10],
if not on a slab (30 cm x 30 cm x 15 cm, water-filled slab made of PMMA) [3]. The phantoms are used for irradiations to replace the person usually wearing the dosemeter in order to produce a (nearly) realistic backscatter field. However, the conventional quantity value (true value) of the personal dose equivalent is defined in a phantom of the same size but made of ICRU tissue [11, 12]. According to ISO 6980-3 [3] there is no phantom dependence of the conventional quantity value of H_p(0.07) for angles of incidence \( \alpha \leq 60^\circ \). In order to investigate the correctness of this statement for both H_p(0.07) and H_p(3), the dose was calculated at 0.07 mm depth in a rod, H_p(0.07)_{rod}, at 3 mm depth in a cylinder, H_p(3)_{cyl}, as well as at 0.07 mm and at 3 mm depth in a slab, H_p(0.07)_{slab} and H_p(3)_{slab}; — all phantoms were made of ICRU tissue. Calculations were carried out for the radiation fields of \(^{147}\)Pm, \(^{85}\)Kr, \(^{90}\)Sr/\(^{90}\)Y, and, \(^{106}\)Ru/\(^{106}\)Rh sources of the BSS 2 (the dose at 3 mm depth was only calculated for the last two sources). From the results, the following correction factors for the corresponding conventional quantity values were deduced for personal dosimetry:

\[
k_{\text{rod}}(\alpha) = \frac{H_p(0.07; \alpha)_{\text{rod}}}{H_p(0.07; \alpha)_{\text{slab}}} \tag{1.1}
\]

and

\[
k_{\text{cyl}}(\alpha) = \frac{H_p(3; \alpha)_{\text{cyl}}}{H_p(3; \alpha)_{\text{slab}}} \tag{1.2}
\]

According to ISO 6980-3 [3] and ICRU 57 [4], in beta dosimetry the conventional quantity values of the directional and personal dose equivalent (the latter in a slab) are practically equal, i.e. \( H'(d; \alpha) = H_p(d; \alpha)_{\text{slab}} \), at depths \( d = 0.07 \text{ mm} \) and \( 3 \text{ mm} \), and for angles of radiation incidence \( \alpha \leq 85^\circ \). The correctness of this statement, especially at \( d = 3 \text{ mm} \), was investigated by calculating the dose in both the slab phantom (30 cm x 30 cm x 15 cm) and the ICRU sphere (30 cm in diameter, in which the directional dose equivalent is defined [11, 12]), both made of ICRU tissue. Their ratio is the corresponding correction factor for the conventional quantity value for area dosimetry:

\[
k'(0.07; \alpha) = \frac{H'(0.07; \alpha)_{\text{sphere}}}{H_p(0.07; \alpha)_{\text{slab}}} \tag{1.3}
\]

and

\[
k'(3; \alpha) = \frac{H'(3; \alpha)_{\text{sphere}}}{H_p(3; \alpha)_{\text{slab}}} \tag{1.4}
\]

These two correction factors were, like \( k_{\text{rod}}(\alpha) \) and \( k_{\text{cyl}}(\alpha) \), calculated for radiation fields of \(^{147}\)Pm, \(^{85}\)Kr, \(^{90}\)Sr/\(^{90}\)Y, and, \(^{106}\)Ru/\(^{106}\)Rh sources of the BSS 2 (again, the dose at 3 mm depth was only calculated for the last two sources).

2 Simulation and verification

2.1 Simulation

2.1.1 Method of simulation

The simulations were carried out using the Monte Carlo particle transport code package EGSnrc [13] / BEAMnrc [14, 15] utilising EGSpp [16].\(^1\) The transport parameters were chosen as follows: the cross-sectional data for the electron transport (where the condensed history technique

\(^1\)EGSpp has been programmed in C++ (pp stands for plus-plus) and offers an almost arbitrary geometry construction which is not the case in most of the other user codes coming with EGSnrc / BEAMnrc.
is applied are: standard EGSnrc (based on the Bethe-Bloch theory) for collision stopping power and Bethe-Heitler cross sections for radiative stopping power. For photons, the XCOM cross sections are used. The maximum energy loss per electron step is 25 % (ESTEPE = 0.25) and photons and electrons are followed down to an (kinetic) energy of 1 keV for the $^{147}$Pm source and 10 keV for the others.

To make the simulations efficient, the sources were not simulated directly but phase space files produced in earlier simulations were used as input [17]. These files contain the full information of a radiation field in a certain cross-sectional plane, e.g. 15 cm in front of the source, by storing the position, direction, energy, and type of particle (electron or photon) of millions of particles.

### 2.1.2 Geometry and substances

Figure 1 shows the geometry of the simulations for $\alpha = 0^\circ$ angle of radiation incidence. The scoring volumes were located at 0.07 mm and at 3 mm depth in the slab and sphere, at 0.07 mm in the rod, and at 3 mm in the cylinder phantom. In the slab, these volumes were 10 mm high (perpendicular to the sheet level), 0.411 mm wide (from left to right on the sheet), and 0.02 mm deep (from top to bottom on the sheet, i.e. the main direction of the radiation), i.e. for $H_p(0.07)$ from a depth of 0.06 to 0.08 mm and for $H_p(3)$ from a depth of 2.99 to 3.01 mm. In the sphere, rod, and cylinder they were practically of the same size but bent according to the surface of the respective phantom. The phantoms consist of 4element ICRU tissue ($\rho = 1.0 \text{ g/cm}^3$; 10.12 % H, 11.1 % C, 2.6 % N, and 76.18 % O — percentages per weight) surrounded by dry air ($\rho = 1.1974 \times 10^{-3} \text{ g/cm}^3$; 0.01 % C, 75.53 % N, 23.18 % O, and 1.28 % Ar — again percentages per weight). As shown earlier, at least up to 50 % air humidity has no significant effect on the results [17]. The dimensions of the surrounding air are 1.2 m x 1.2 m x 1.2 m with the surface of the phantom in the geometrical centre of the air volume.

Table 1 shows the radiation field geometries of the BSS 2 for which the simulations were performed. The full information of a source including the geometry is, for example, stated by
Table 1. Radiation field geometries of the BSS 2 for which the simulations were performed.

| Radionuclide (source) | 11 cm, without filter | 20 cm, without filter | 20 cm, with filter | 30 cm, without filter | 30 cm, with filter | 50 cm, without filter | 50 cm, with filter |
|-----------------------|------------------------|------------------------|-------------------|-----------------------|-------------------|-----------------------|-------------------|
| \(^{147}\)Pm          | x                      | x                      | x                 | x                     | x                 | x                     | x                 |
| \(^{85}\)Kr           | x                      | x                      | x                 | x                     | x                 | x                     | x                 |
| \(^{90}\)Sr/\(^{90}\)Y| x                      | x                      | x                 | x                     | x                 | x                     | x                 |
| \(^{106}\)Ru/\(^{106}\)Rh | x                    | x                      | x                 | x                     | x                 | x                     | x                 |

Distance of the phase space file plane from the front of the source

| 2 cm                  | 15 cm                  |

Distance of the phase space file plane from the phantom surface

| 9 cm                  | 18 cm                  | 5 cm                  | 15 cm                  | 35 cm                  |

"\(^{147}\)Pm, 20 cm, with filter" which means the radiation field of a \(^{147}\)Pm source at a distance of 20 cm with a beam flattening filter. The filter assures that the radiation field is more homogeneous in the irradiation plane than without it. It is located at a distance of 10 cm from the radiation source [7]. In the last two lines of table 1 the position of the phase space file planes (location where the simulation starts) is given. It varies, depending on the distance from the source.

2.1.3 Uncertainty of calculations

The non-statistical standard uncertainty of the calculated dose values is assumed to be in the order of 2% with the main contribution attributed to the uncertainty of the radiative stopping power of electrons [18]. However, the correction factors are ratios of two doses which are highly correlated as the simulation program and materials are the same for all calculated doses (only the phantoms are different). Therefore, the non-statistical uncertainty of the correction factors is assumed to be negligible and only the uncertainty due to statistics supplied by EGSnrc is taken into account. The simulation times were chosen so that the statistical standard uncertainty of the correction factors for 0.07 mm depth is less or equal to 0.5%; at 3 mm depth 0.5% up to 2% resulted (the larger the angle of incidence the larger the uncertainty).

2.2 Verification of the simulations

Measurements have only been performed in a slab phantom. Therefore, measured and calculated angular dependence factors for the slab phantom, \(R(d; \alpha)_{\text{slab}}\), are compared in figures 2 and 3 for the quantities \(H_p(0.07)_{\text{slab}}\) and \(H_p(3)_{\text{slab}}\), respectively. The angular factor is given by

\[
R(d; \alpha)_{\text{slab}} = \frac{H(d; \alpha)_{\text{slab}}}{H(d; 0^\circ)_{\text{slab}}} \tag{2.1}
\]
with the depth, \( d \), the dose, \( H \), and the angle of radiation incidence, \( \alpha \). Measured data were taken from ISO [3] (for \( R(0.07; \alpha)_{\text{slab}} \) for \(^{147}\text{Pm}, ^{85}\text{Kr}, \) and \(^{90}\text{Sr}^{90}\text{Y} \)) and from Behrens and Buchholz [8] (for \( R(0.07; \alpha)_{\text{slab}} \) for \(^{106}\text{Ru}^{106}\text{Rh} \) and for \( R(3; \alpha)_{\text{slab}} \) for \(^{90}\text{Sr}^{90}\text{Y} \) and \(^{106}\text{Ru}^{106}\text{Rh} \)). Several data points for the same radionuclide represent different source geometries, see table 1. Those data points for the same radionuclide are located at slightly different beta mean energies as a different amount of material is located between the source and the phantom (different air path and the beam flattening filter being present or not). This results in slightly more or less energy loss of the beta particles and, consequently, in slightly different mean energies. The standard uncertainty is in the order of 2 % for the measurements and 0.5 % up to 2 % for the calculations. Uncertainty bars are not shown for the sake of clarification. It can be seen that measured and calculated values follow each other quite well. Only at a depth of 0.07 mm (figure 2) are the calculated values slightly below the measured ones (especially at \( \alpha \geq 45^\circ \)), which is not the case at 3 mm depth (figure 3). Thus, the simulation method is considered to be appropriate for the determination of the correction factors.

The behaviour of \( R(d; \alpha)_{\text{slab}} \) (e.g. below or above 1.0) can be explained by the effective depth in the slab phantom which increases with increasing values of \( \alpha \):

- 0.07 mm depth (figure 2): for \(^{147}\text{Pm} \) and \(^{85}\text{Kr} \) (for all values of \( \alpha \)) and for \(^{90}\text{Sr}^{90}\text{Y} \) (for \( \alpha = 75^\circ \)) the angular factor, \( R(0.07; \alpha)_{\text{slab}} \), is below 1.0 as the absorption of betas on their longer path length through the phantom dominates, whereas for \(^{90}\text{Sr}^{90}\text{Y} \) (for \( \alpha < 75^\circ \)) and for \(^{106}\text{Ru}^{106}\text{Rh} \) the dose build-up dominates. The reason is the form of the corresponding depth dose curves (for \( \alpha = 0^\circ \)) at depths slightly above 0.07 mm [17]: for \(^{147}\text{Pm} \) and \(^{85}\text{Kr} \) no dose build-up is present (but absorption), while it is for \(^{90}\text{Sr}^{90}\text{Y} \) and \(^{106}\text{Ru}^{106}\text{Rh} \). Accordingly, \( R(0.07; \alpha)_{\text{slab}} \) decreases with increasing values of \( \alpha \) for \(^{147}\text{Pm} \) and \(^{85}\text{Kr} \), while it increases with increasing values of \( \alpha \) for \(^{90}\text{Sr}^{90}\text{Y} \) and \(^{106}\text{Ru}^{106}\text{Rh} \) up to \( \alpha = 60^\circ \). For \( \alpha = 75^\circ \), the effective path length through the phantom is so large that even for \(^{90}\text{Sr}^{90}\text{Y} \) and \(^{106}\text{Ru}^{106}\text{Rh} \) the absorption dominates (decrease of the corresponding depth dose curve for \( \alpha = 0^\circ \)) [17].

- 3 mm depth (figure 3): here, it is obvious that no dose build-up is present in the depth dose curves for \( \alpha = 0^\circ \) above 3 mm phantom depth for \(^{90}\text{Sr}^{90}\text{Y} \) and \(^{106}\text{Ru}^{106}\text{Rh} \), but absorption dominates [17]. Therefore, the angular factor \( R(3; \alpha)_{\text{slab}} \) decreases with increasing values of \( \alpha \) for \(^{90}\text{Sr}^{90}\text{Y} \) and \(^{106}\text{Ru}^{106}\text{Rh} \) due to the longer path length through the phantom.

- It shall, however, be noted that the effective depth in the phantom is not simply given by the geometry. For example, for \( \alpha = 60^\circ \) the effective depth is not twice the reference depth (3 mm / \( \cos(60^\circ) \) = 6 mm according to the cosine rule), but rather shorter. The reason is illustrated in figure 4. Path 1 shows an extremely simplified path of a beta particle coming from the radiation source penetrating directly to the active volume at 3 mm depth (in reality, several scattering events occur resulting in a “zigzag path” as beta particles (electrons) are direct ionising radiation). For this path 1 the effective path length through the phantom is approximately 6 mm (or more). However, other particles will come along path 2 (again extremely simplified) and, therefore, only have to penetrate an effective path length of approximately 3 mm (or slightly more) through the phantom. On average, the effective path length will be in between these two extremes. This is confirmed by the measured and calculated values:
Figure 2. Measured and calculated angular dependence factors for a slab phantom at 0.07 mm depth.

Figure 3. Measured and calculated angular dependence factors for a slab phantom at 3 mm depth.

for example, $R(3; ^{90}\text{Sr}^{90}\text{Y})$, at 30 cm, with filter; $60^\circ$, $\alpha_{\text{slab}} = 0.23$, see figure 3. However, the depth dose curve, $T(d)$ which is the transmission at a depth $d$ in tissue, suggests a value of $T(6 \text{ mm})/T(3 \text{ mm}) \approx 0.1$ [17] which is less than 0.23. (The transmission of 0.23 is present at $d \approx 5 \text{ mm}$: $T(5 \text{ mm})/T(3 \text{ mm}) \approx 0.23$.) From this it is obvious that the effective path length through the phantom is shorter than suggested by the cosine rule, i.e. shorter than 6 mm.
3 Results

3.1 Results for each single source geometry

3.1.1 Results from this work

Figures 5 to 8 show the calculated values for the four correction factors. Again, several data points for the same radionuclide represent the different source geometries, see table 1. As for the angular dependence factors, the behaviour of the correction factors can be explained by the effective path lengths through the different phantoms and values of $\alpha$. The following features can be seen:

- For large angles of incidence ($\alpha \geq 60^\circ$) $k_{\text{rod}}(\alpha)$, $k_{\text{cyl}}(\alpha)$, and $k'(3; \alpha)$ are above 1.0 and increase with increasing values of $\alpha$. For $k_{\text{cyl}}(\alpha)$ and $k'(3; \alpha)$ this is even the case for all values of $\alpha$. The reason is that in these cases the effective path length through the rod, cylinder, and sphere is shorter than the one through the slab and, therefore, the absorption of beta particles is less compared to the slab phantom — this is the case in the deeper parts of the depth dose curves where the dose build-up is finished [17]. Only in very few cases, especially for $^{106}\text{Ru}/^{106}\text{Rh}$, some values of $k_{\text{cyl}}(\alpha)$ and $k'(3; \alpha)$ are slightly below 1.0 — but these are consistent with 1.0 considering their two sigma uncertainty. Also for $^{106}\text{Ru}/^{106}\text{Rh}$ some values for $k_{\text{rod}}(75^\circ)$ are below 1.0 — the reason is as explained below in the third bullet.

- For smaller angles of incidence ($\alpha \leq 45^\circ$) all four correction factors come close to 1.0 except for $k_{\text{rod}}(\alpha)$ of $^{90}\text{Sr}/^{90}\text{Y}$ and $^{106}\text{Ru}/^{106}\text{Rh}$, see below. The reason is that the effective path length through all three phantoms becomes similar and is nearly the same for $\alpha = 0^\circ$. 

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**Figure 4.** Detail of the slab phantom (blue) at an angle of incidence of $\alpha = 60^\circ$. The scoring volumes at 0.07 mm and at 3 mm depth are indicated in black (to scale). The red arrows indicate two extremely simplified paths of beta particles to the scoring volume at 3 mm depth.
Figure 5. Calculated correction factors $k_{rod}(\alpha)$ for the rod phantom. The ordinate omits the range between 1.05 and 1.13 in order to have a larger scale for the remaining ranges. The uncertainty bars show the statistical standard uncertainties.

Figure 6. Calculated correction factors $k_{cyl}(\alpha)$ for the cylinder phantom. The uncertainty bars show the statistical standard uncertainties.
Figure 7. Calculated correction factors $k'(0.07; \alpha)$ for the sphere. The uncertainty bars show the statistical standard uncertainties.

Figure 8. Calculated correction factors $k'(3; \alpha)$ for the sphere. The uncertainty bars show the statistical standard uncertainties.
Figure 9. Calculated angular dependence factors for a rod phantom at 0.07 mm depth: comparison of data from this work and Faw and Swinth [20]. The uncertainty bars are not shown as the symbols are much larger than the corresponding statistical standard uncertainties: less than 1% for this work and 1% for Faw and Swinth who did not state a non-statistic contribution to the uncertainty.

- For $^{90}\text{Sr}/^{90}\text{Y}$ and $^{106}\text{Ru}/^{106}\text{Rh}$ and $\alpha \leq 45^\circ$, $k_{\text{rod}}(\alpha)$ decreases with increasing $\alpha$, the stronger the larger the beta energy is, i.e. stronger for $^{106}\text{Ru}/^{106}\text{Rh}$ than for $^{90}\text{Sr}/^{90}\text{Y}$. The reason is the build-up effect: due to the shorter path length through the rod compared to the slab phantom the dose build-up is not finished in the rod and, therefore, the dose is smaller than in the slab — resulting in $k_{\text{rod}}(\alpha) \leq 1.0$. As the dose build-up effect is stronger for higher energies, $k_{\text{rod}}(\alpha)$ becomes smaller for $^{106}\text{Ru}/^{106}\text{Rh}$ than for $^{90}\text{Sr}/^{90}\text{Y}$.

- Finally, practically all values of $k'(0.07; \alpha)$ do not statistically significantly deviate from 1.0. The reason is the quite large diameter of the sphere (30 cm). This results in a very small curvature of its surface resulting, in turn, in only very slightly smaller effective path lengths through the sphere compared to the slab.

3.1.2 Comparison with literature data

For some radiation fields of the BSS 2 angular dependence factors for the rod phantom, $R(0.07; \alpha)_{\text{rod}}$, were published by Faw and Swinth [19, 20]. Among others, values were calculated for the realistic spectral distributions of the radiation fields of $^{147}\text{Pm}$, $^{85}\text{Kr}$, and $^{90}\text{Sr}/^{90}\text{Y}$ sources. However, the calculations were performed for a phantom in vacuum, i.e. all electrons impinge at the same nominal angle of incidence $\alpha$ on the phantom. This is, however, not the case in reality as the electrons undergo scattering events in the air (and the beam flattening filter) on their path from the source to the phantom. Therefore, the impinging electrons in reality have an angular distribution, which is the broader the smaller their mean energy is (details are given elsewhere [17]). Consequently, some electrons can penetrate more directly through the phantom to
Figure 10. Combined results for $k_{\text{rod}}(\alpha)$ and $k_{\text{cyl}}(\alpha)$, left and right part, respectively. The uncertainty bars show the statistical standard uncertainties.

the reference depth (here 0.07 mm). Thus, it is expected that the values of $R(0.07; \alpha)_{\text{rod}}$ from this work are larger than the data from Faw and Swinth [20], as in this work the full angular distribution is available as the full geometry including the air (and the beam flattening filter) was simulated. This effect is the stronger the smaller the electron mean energy is (as low energy electrons undergo more scattering events than electrons with higher energies), i.e. the largest differences are expected for $^{147}\text{Pm}$. From figure 9 it can be seen that the expected trend is present. As in this work, the full geometry was simulated, i.e. a much more realistic scenario compared to the simulation of Faw and Swinth [20], and as the results of this work are confirmed by measurements (only small deviations are present between the results of this work and the measurements), see section 2.2, the results of this work are considered to be more reliable than the data of Faw and Swinth [20]. Finally, it shall be noted that Faw and Swinth did not provide any information on the non-statistical contribution to the uncertainty, e.g. the fact that the electrons impinge directly on the phantom without any interaction in the surrounding air.

3.2 Combined results for each radionuclide

The dependence of all four correction factors on the beta mean energy for the same radionuclide, i.e. different radiation field geometries, does not reveal any significant trends, see subsection 3.1. Therefore, all values of the correction factor for the same radionuclide and the same angle of incidence were combined: their mean value and the corresponding standard uncertainty were determined. The results are shown in figures 10 and 11.

From figure 10 it can be seen that the practice suggested by ISO 6980-3 [3] to assume $H_{\rho}(0.07; \alpha)_{\text{rod}} = H_{\rho}(0.07; \alpha)_{\text{slab}}$ is justified only for $\alpha \leq 45^\circ$ for $^{147}\text{Pm}$ and $^{85}\text{Kr}$ as $k_{\text{rod}}(\alpha)$ does not deviate from 1.0 by more than their standard uncertainty. This is also the case for $k_{\text{cyl}}(\alpha)$ for $\alpha = 0^\circ$ for $^{90}\text{Sr}/^{90}\text{Y}$ and $^{106}\text{Ru}/^{106}\text{Rh}$. The reasons are explained above (subsection 3.1).
Figure 11. Combined results for $k'(0.07; \alpha)$ and $k'(3; \alpha)$, left and right part, respectively. The uncertainty bars show the statistical standard uncertainties.

Table 2. Values and their standard uncertainty for $k_{\text{rod}}(\alpha)$.

| Radionuclide | $0^\circ$ | $15^\circ$ | $30^\circ$ | $45^\circ$ | $60^\circ$ | $75^\circ$ |
|--------------|----------|-----------|-----------|-----------|-----------|-----------|
| $^{147}$Pm   | 1.000 ± 0.005 | 1.000 ± 0.005 | 1.000 ± 0.005 | 1.000 ± 0.006 | 1.008 ± 0.005 | 1.026 ± 0.009 |
| $^{85}$Kr    | 1.000 ± 0.005 | 1.000 ± 0.005 | 1.000 ± 0.005 | 1.000 ± 0.009 | 1.011 ± 0.008 | 1.032 ± 0.005 |
| $^{90}$Sr/$^{90}$Y | 0.987 ± 0.005 | 0.986 ± 0.005 | 0.983 ± 0.005 | 0.984 ± 0.005 | 1.014 ± 0.005 | 1.156 ± 0.008 |
| $^{106}$Ru/$^{106}$Rh | 0.987 ± 0.005 | 0.982 ± 0.006 | 0.978 ± 0.005 | 0.973 ± 0.005 | 0.996 ± 0.006 | 1.153 ± 0.006 |

1) The values for each radionuclide are valid for all respective source geometries, see table 1.

From figure 11 it can be concluded that the assumption $H'(d; \alpha) = H_\text{p}(d; \alpha)_{\text{slab}}$ stated by ISO 6980-3 [3] and ICRU 57 [4] can be confirmed for $d = 0.07$ mm for $\alpha \leq 75^\circ$, but for $d = 3$ mm this is only the case for $\alpha \leq 15^\circ$.

These findings should be taken into account in future revisions of ISO 6980-3 and ICRU 57.

Tables 2 to 5 contain the values for the four correction factors and their standard uncertainty. In those cases where the calculated values did not statistically significantly deviate from 1.0, the correction factors are stated to be 1.0 with their respective standard uncertainty. The values for $k_{\text{rod}}(\alpha)$ for $\alpha \leq 60^\circ$ given in table 2 replace the former one of 1.00 ± 0.03 stated earlier [8]. As can be seen, the old value of 1.00 with its quite large uncertainty of 0.03 was consistent with the new ones.
Table 3. Values and their standard uncertainty for $k_{cyl}(\alpha)$.

| Radio- | 0°     | 15°    | 30°    | 45°    | 60°    | 75°    |
| nuclide (1) |       |        |        |        |        |        |
| $^{90}$Sr/$^{90}$Y | 1.000 ± 0.007 | 1.012 ± 0.008 | 1.017 ± 0.010 | 1.032 ± 0.011 | 1.070 ± 0.016 | 1.161 ± 0.025 |
| $^{106}$Ru/$^{106}$Rh | 1.000 ± 0.006 | 1.000 ± 0.006 | 1.013 ± 0.007 | 1.030 ± 0.008 | 1.083 ± 0.010 | 1.203 ± 0.021 |

1) The values for each radionuclide are valid for all respective source geometries, see table 1.

Table 4. Values and their standard uncertainty for $k'(0.07; \alpha)$.

| Radio- | 0°     | 15°    | 30°    | 45°    | 60°    | 75°    |
| nuclide (1) |       |        |        |        |        |        |
| $^{147}$Pm | 1.000 ± 0.006 | 1.000 ± 0.007 | 1.000 ± 0.011 | 1.000 ± 0.007 | 1.000 ± 0.006 | 1.000 ± 0.007 |
| $^{85}$Kr | 1.000 ± 0.006 | 1.000 ± 0.007 | 1.000 ± 0.008 | 1.000 ± 0.009 | 1.000 ± 0.017 | 1.000 ± 0.014 |
| $^{90}$Sr/$^{90}$Y | 1.000 ± 0.005 | 1.000 ± 0.005 | 1.000 ± 0.007 | 1.000 ± 0.005 | 1.000 ± 0.005 | 1.000 ± 0.009 |
| $^{106}$Ru/$^{106}$Rh | 1.000 ± 0.007 | 1.000 ± 0.008 | 1.000 ± 0.007 | 1.000 ± 0.008 | 1.000 ± 0.005 | 1.000 ± 0.007 |

1) The values for each radionuclide are valid for all respective source geometries, see table 1.

Table 5. Values and their standard uncertainty for $k'(3; \alpha)$.

| Radio- | 0°     | 15°    | 30°    | 45°    | 60°    | 75°    |
| nuclide (1) |       |        |        |        |        |        |
| $^{90}$Sr/$^{90}$Y | 1.000 ± 0.008 | 1.000 ± 0.008 | 1.014 ± 0.009 | 1.024 ± 0.011 | 1.053 ± 0.016 | 1.101 ± 0.024 |
| $^{106}$Ru/$^{106}$Rh | 1.000 ± 0.007 | 1.000 ± 0.006 | 1.010 ± 0.008 | 1.023 ± 0.010 | 1.056 ± 0.010 | 1.130 ± 0.021 |

1) The values for each radionuclide are valid for all respective source geometries, see table 1.

3.3 Dissemination of the results

3.3.1 Implementation in ISO 6980-3

According to ISO 6980-3 [3] the dose equivalent, $H$, is obtained from the reference absorbed dose, $D_R$, via multiplication with the conversion coefficient

$$h_D = H/D_R$$

i.e. the dose equivalent is obtained from the reference absorbed dose via

$$H = h_D \cdot D_R$$

3.3 Dissemination of the results

3.3.1 Implementation in ISO 6980-3

According to ISO 6980-3 [3] the dose equivalent, $H$, is obtained from the reference absorbed dose, $D_R$, via multiplication with the conversion coefficient

$$h_D = H/D_R$$

i.e. the dose equivalent is obtained from the reference absorbed dose via

$$H = h_D \cdot D_R$$
As $D_R$ is defined at 0.07 mm depth in a tissue equivalent slab phantom at $\alpha = 0^\circ$ radiation incidence it is

$$H_p(0.07; 0^\circ)_{\text{slab}} = D_R, \quad \text{i.e. } h_{p,D}(0.07; 0^\circ)_{\text{slab}} = 1.0^2$$

(3.3)

Values of $h_{p,D}(0.07; \alpha)_{\text{slab}}$ for $\alpha \neq 0^\circ$ have been measured earlier [3, 8], they are given in Annex A. From these measured values the conversion coefficients for the different dose equivalents follow:

the definition

$$h_{p,D}(0.07; \alpha)_{\text{rod}} = h_{p,D}(0.07; \alpha)_{\text{slab}} \cdot k_{\text{rod}}(\alpha)$$

(3.4)

leads via equation (3.2) to the personal dose equivalent at 0.07 mm depth in a rod phantom, $H_p(0.07; \alpha)_{\text{rod}}$.

The definition

$$h'_{p,D}(0.07; \alpha) = h_{p,D}(0.07; \alpha)_{\text{slab}} \cdot k'(0.07; \alpha)$$

(3.5)

leads via equation (3.2) to the directional dose equivalent at 0.07 mm depth, $H'(0.07; \alpha)$. As $k'(0.07; \alpha)$ does not deviate significantly from 1.0, it is $h'_{p,D}(0.07; \alpha) = h_{p,D}(0.07; \alpha)_{\text{slab}}$. Accordingly, the uncertainty of $h'_{p,D}(0.07; \alpha)$ is assumed to be equal to that of $h_{p,D}(0.07; \alpha)_{\text{slab}}$, i.e. no contribution of $k'(0.07; \alpha)$ is added. This is justified by the consideration that the shapes of the sphere and the slab are — over the volume of a few cm$^3$ (according to the maximum range of the electrons involved) — almost equivalent due to the rather small curvature of the sphere.

The definition

$$h_{p,D}(3; \alpha)_{\text{cyl}} = T(3; 0^\circ)_{\text{slab}} \cdot R(3; \alpha)_{\text{slab}} \cdot k_{\text{cyl}}(\alpha)$$

(3.6)

leads via equation (3.2) to the personal dose equivalent at 3 mm depth in a cylinder phantom, $H_p(3; \alpha)_{\text{cyl}}$. The depth dependence factor is given by $T(3; 0^\circ)_{\text{slab}} = H_p(3; 0^\circ)_{\text{slab}} / H_p(0.07; 0^\circ)_{\text{slab}}$ and the angular dependence factor is given by $R(3; \alpha)_{\text{slab}} = H_p(3; \alpha)_{\text{slab}} / H_p(3; 0^\circ)_{\text{slab}}$, all to be measured in the slab phantom; data are available [8].

The definition

$$h'_{p,D}(3; \alpha) = T'(3; 0^\circ)_{\text{slab}} \cdot R(3; \alpha)_{\text{slab}} \cdot k'(3; \alpha)$$

(3.7)

leads via equation (3.2) to the directional dose equivalent at 3 mm depth, $H'(3; \alpha)$.

In Annex A, values for the coefficients calculated according to equations (3.4) to (3.7) are given as well as measured values for $h_{p,D}(0.07; \alpha)_{\text{slab}}$, $T(3; 0^\circ)_{\text{slab}}$, and $R(3; \alpha)_{\text{slab}}$.

### 3.3.2 Implementation in the BSS 2 software

Up to now, the software of the BSS 2 allows irradiations in terms of $H_p(0.07)_{\text{slab}}$, $H_p(0.07)_{\text{rod}}$, $H'(0.07)$, and $H_p(3)_{\text{slab}}$. The conversion coefficients $h_D$ for these quantities are implemented in the software via the ini file “BetaFakt.ini”, version 7.4 [8]. According to ISO 6980-3, the phantom dependence was assumed to be negligible for angles of incidence $\alpha \leq 60^\circ$, see section 1. Thus, values for $h_{p,D}(0.07; \alpha)_{\text{rod}}$ and $h'_{p,D}(0.07; \alpha)$ were contained in “BetaFakt.ini” only up to $\alpha = 60^\circ$ and assumed to be equal to $h_{p,D}(0.07; \alpha)_{\text{slab}}$ with a rather large standard uncertainty of 3 % for the rod [8]. The reason was the lack of knowledge of the correction factors $k_{\text{rod}}(\alpha)$ and $k'(0.07; \alpha)$. As they are known by now, see tables 2 and 4, values for $h_{p,D}(0.07; \alpha)_{\text{rod}}$ and $h'_{p,D}(0.07; \alpha)$ up to $\alpha = 75^\circ$.

\[2\] In ISO 6980-3 the source geometry, see table 1, is given as another parameter in the conversion coefficients, e.g. $h_{p,D}(0.07; \text{source})_{\text{slab}}$ instead of $h_{p,D}(0.07; \alpha)_{\text{slab}}$. As it is trivial that $h$ depends on the source and geometry, it is omitted in this paper for the sake of brevity.
have recently been implemented in the new version 7.5 of “BetaFakt.ini” accompanied by their smaller uncertainties, see respective tables in Annex A. The new version of the file “BetaFakt.ini” is available for downloading at PTB’s website [21]. Using this new version enables all users of the BSS 2 to perform irradiations using the new conversion coefficients and, accordingly, to obtain reduced uncertainties. Software version 4.0 (or higher) which has been distributed to all users of the BSS 2 is necessary — no further software update is required.

Up to now, the quantities $H'(3)$ and $H_p(3)_cyl$ have not yet been implemented in the software of the BSS 2. This requires a software modification and is foreseen for the future. Then, the corresponding correction factors will also be implemented in the ini file “BetaFakt.ini”.

4 Summary

In this work, for the first time, correction factors for the personal dose equivalents $H_p(0.07)_rod$ and $H_p(3)_cyl$ for the rod and cylinder calibration phantom, respectively, and for the directional dose equivalents $H'(0.07)$ and $H'(3)$ have been presented for reference beta-particle radiation fields. The results show that in contrast to an earlier statement made by ICRU [4] and ISO [3], the shape of reference phantoms is not negligible for all angles of radiation incidence, $\alpha$. For small values of $\alpha$ the statements are true, but for larger angles correction factors deviate significantly from unity, the largest being 1.2 for $\alpha = 75^\circ$ for the quantity $H_p(3)_cyl$.

The implementation in the respective ISO standard for reference beta-particle radiation fields [3] is planned; the implementation in the software of PTB’s beta secondary standard BSS 2 is finished for the quantities $H_p(0.07)_rod$ and $H'(0.07)$ and is foreseen for the quantities $H_p(3)_cyl$ and $H'(3)$.

A Tables of absorbed-dose-to-dose-equivalent conversion coefficients, $h_D$

Tables 6 to 10 contain values for the absorbed-dose-to-dose-equivalent conversion coefficients, $h_D$, for the operational quantities.\(^3\) For the sake of completeness, tables 11 and 12 contain values for $T(3; 0^\circ)_\text{slab}$ and $R(3; \alpha)_\text{slab}$ which have been measured previously [8].

\(^3\)In ISO 6980-3 the source geometry, see table 1, is given as another parameter in the conversion coefficients, e.g. $h_{p,D}(0.07; \text{source; } \alpha)_\text{slab}$ instead of $h_{p,D}(0.07; \alpha)_\text{slab}$. As it is trivial that $h$ depends on the source and geometry, it is omitted in this paper for the sake of brevity.
Table 6. Conversion coefficients $h_{p,D}(0.07; \alpha_{\text{slab}})$ and their relative standard uncertainty for the slab phantom for sources of the BSS 2. The values have been measured previously [3, 8]; the uncertainties have been adopted from [8].

| Source | Conversion coefficient $h_{p,D}(0.07; \alpha_{\text{slab}})$ and its relative standard uncertainty for a value of $\alpha$ of | 
|---|---|
| | cm | 0° $u_{\text{rel}}(0°)$ | 15° $u_{\text{rel}}(15°)$ | 30° $u_{\text{rel}}(30°)$ | 45° $u_{\text{rel}}(45°)$ | 60° $u_{\text{rel}}(60°)$ | 75° $u_{\text{rel}}(75°)$ |
| $^{147}$Pm | no | 11 | 1.00 0.0% | n.a. | n.a. | n.a. | n.a. |
| yes | 20 | 1.00 0.0% | 0.96 0.20% | 0.87 0.80% | 0.72 1.76% | 0.53 3.00% | n.a. |
| $^{85}$Kr | yes | 30 | 1.00 0.0% | 0.99 0.14% | 0.96 0.54% | 0.88 1.17% | 0.72 2.00% | 0.49 2.96% |
| yes | 50 | 1.00 0.0% | n.a. | n.a. | n.a. | n.a. | n.a. |
| $^{90}$Sr/$^{90}$Y | no | 11 | 1.00 0.0% | 1.02 0.14% | 1.06 0.54% | 1.14 1.17% | 1.21 2.00% | n.a. |
| yes | 30 | 1.00 0.0% | 1.01 0.14% | 1.06 0.54% | 1.13 1.17% | 1.16 2.00% | 0.91 2.96% |
| yes | 50 | 1.00 0.0% | 1.01 0.14% | 1.05 0.54% | 1.10 1.17% | 1.10 2.00% | 0.84 2.96% |
| $^{106}$Ru/$^{106}$Rh | no | 11 | 1.00 0.0% | n.a. | n.a. | n.a. | n.a. |
| yes | 30 | 1.00 0.0% | 1.01 0.14% | 1.06 0.54% | 1.12 1.17% | 1.14 2.00% | 0.86 2.96% |
| yes | 50 | 1.00 0.0% | n.a. | n.a. | n.a. | n.a. | n.a. |

1) The uncertainty of $h_{p,D}(0.07; 0°)_{\text{slab}}$ is zero as $H_{p}(0.07; 0°)$ is directly given by the reference dose rate, $D_{R}$, see equation (3.3).

2) These values have not yet been measured.
Table 7. Conversion coefficients $h_{p,D}(0.07; \alpha)_{\text{rod}}$ and their relative standard uncertainty for the rod phantom for sources of the BSS 2 — calculated according to equation (3.4).

| Source | Nuclide | Beam flattening filter | Distance | Conversion coefficient $h_{p,D}(0.07; \alpha)_{\text{rod}}$ and its relative standard uncertainty for a value of $\alpha$ of |
|--------|---------|-------------------------|----------|--------------------------------------------------------------------------------------------------------------------------------|
|        |         | cm                      | 0° $u_{\text{rel}}(0°)$ | 15° $u_{\text{rel}}(15°)$ | 30° $u_{\text{rel}}(30°)$ | 45° $u_{\text{rel}}(45°)$ | 60° $u_{\text{rel}}(60°)$ | 75° $u_{\text{rel}}(75°)$ |
| 147Pm  | no      | 11                      | 1.000    | 0.50 % | n.a. | n.a. | n.a. | n.a. |
| 147Pm  | yes     | 20                      | 1.000    | 0.50 % | 0.960 | 0.55 % | 0.870 | 0.96 % | 0.720 | 1.86 % | 0.534 | 3.04 % | n.a. |
| 85Kr   | yes     | 30                      | 1.000    | 0.50 % | 0.990 | 0.52 % | 0.960 | 0.76 % | 0.880 | 1.47 % | 0.728 | 2.15 % | 0.506 | 3.01 % |
| 85Kr   | yes     | 50                      | 1.000    | 0.50 % | n.a.  | n.a.  | n.a.  | n.a.  | n.a.  |
| 90Sr/90Y | no | 11                      | 0.987    | 0.51 % | n.a.  | n.a.  | n.a.  | n.a.  | n.a.  |
| 90Sr/90Y | no | 20                      | 0.987    | 0.51 % | 1.006 | 0.53 % | 1.042 | 0.74 % | 1.122 | 1.28 % | 1.227 | 2.06 % | n.a.  |
| 90Sr/90Y | no | 30                      | 0.987    | 0.51 % | 0.996 | 0.53 % | 1.042 | 0.74 % | 1.112 | 1.28 % | 1.176 | 2.06 % | 1.052 | 3.03 % |
| 90Sr/90Y | no | 50                      | 0.987    | 0.51 % | 0.996 | 0.53 % | 1.032 | 0.74 % | 1.082 | 1.28 % | 1.115 | 2.06 % | 0.971 | 3.03 % |
| 90Sr/90Y | yes | 30                      | 0.987    | 0.51 % | 0.996 | 0.53 % | 1.042 | 0.74 % | 1.102 | 1.28 % | 1.156 | 2.06 % | 0.994 | 3.03 % |
| 90Sr/90Y | yes | 50                      | 0.987    | 0.51 % | n.a.  | n.a.  | n.a.  | n.a.  | n.a.  |
| 106Ru/106Rh | no | 11                      | 0.987    | 0.55 % | n.a.  | n.a.  | n.a.  | n.a.  | n.a.  |
| 106Ru/106Rh | no | 20                      | 0.987    | 0.55 % | 0.993 | 0.58 % | 1.037 | 0.77 % | 1.120 | 1.28 % | 1.251 | 2.10 % | n.a.  |
| 106Ru/106Rh | yes | 30                      | 0.987    | 0.55 % | 0.988 | 0.58 % | 1.016 | 0.77 % | 1.097 | 1.28 % | 1.190 | 2.10 % | 1.156 | 3.01 % |
| 106Ru/106Rh | yes | 50                      | 0.987    | 0.55 % | n.a.  | n.a.  | n.a.  | n.a.  | n.a.  |

1) These values are not available as the corresponding values for $h_{p,D}(0.07; \alpha)_{\text{slab}}$ have not yet been measured, see table 6.
Table 8. Conversion coefficients $h_D'(0.07; \alpha)$ and their relative standard uncertainty for sources of the BSS 2 — calculated according to equation (3.5)\(^1\).

| Source          | Beam flattening filter | Conversion coefficient $h_D'(0.07; \alpha)$ and its relative standard uncertainty for a value of $\alpha$ of |
|-----------------|------------------------|--------------------------------------------------------------------------------------------------|
| Nuclide         | cm                     | $0^\circ$ $u_{rel}(0^\circ)$ | $15^\circ$ $u_{rel}(15^\circ)$ | $30^\circ$ $u_{rel}(30^\circ)$ | $45^\circ$ $u_{rel}(45^\circ)$ | $60^\circ$ $u_{rel}(60^\circ)$ | $75^\circ$ $u_{rel}(75^\circ)$ |
| $^{147}$Pm      | no                     | 1.00 0.64 % n.a.\(^2\) | n.a. | n.a. | n.a. | n.a. | n.a. |
| $^{147}$Pm      | yes                    | 1.00 0.64 % 0.96 0.73 % 0.87 1.39 % 0.72 1.88 % 0.53 3.06 % n.a. |
| $^{85}$Kr       | yes                    | 1.00 0.63 % 0.99 0.74 % 0.96 0.98 % 0.88 1.45 % 0.72 2.59 % 0.49 3.28 % |
| $^{85}$Kr       | yes                    | 1.00 0.63 % n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| $^{90}$Sr/$^{90}$Y | no                     | 1.00 0.50 % n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| $^{90}$Sr/$^{90}$Y | no                    | 1.00 0.50 % 1.02 0.52 % 1.06 0.75 % 1.14 1.37 % 1.21 2.06 % n.a. |
| $^{90}$Sr/$^{90}$Y | no                    | 1.00 0.50 % 1.01 0.52 % 1.06 0.75 % 1.13 1.37 % 1.16 2.06 % 0.91 3.10 % |
| $^{90}$Sr/$^{90}$Y | no                    | 1.00 0.50 % 1.01 0.52 % 1.05 0.75 % 1.10 1.37 % 1.10 2.06 % 0.84 3.10 % |
| $^{90}$Sr/$^{90}$Y | yes                   | 1.00 0.50 % 1.01 0.52 % 1.06 0.75 % 1.12 1.37 % 1.14 2.06 % 0.86 3.10 % |
| $^{90}$Sr/$^{90}$Y | yes                   | 1.00 0.50 % n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| $^{106}$Ru/$^{106}$Rh | no                    | 1.00 0.71 % n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| $^{106}$Ru/$^{106}$Rh | no                  | 1.00 0.71 % 1.011 0.81 % 1.060 0.92 % 1.151 1.40 % 1.256 2.06 % n.a. |
| $^{106}$Ru/$^{106}$Rh | yes                 | 1.00 0.71 % 0.998 0.81 % 1.039 0.92 % 1.127 1.40 % 1.195 2.06 % 1.003 3.04 % |
| $^{106}$Ru/$^{106}$Rh | yes                | 1.00 0.71 % n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |

\(^1\) According to section 3.3.1, these values are equivalent to the values stated in table 6. Only the uncertainties are slightly larger (due to the additional contribution from $k'(0.07; \alpha)$).

\(^2\) These values are not available as the corresponding values for $h_{p,D}(0.07; \alpha)_{\text{slab}}$ have not yet been measured, see table 6.
Table 9. Conversion coefficients $h_{p,D}(3; \alpha)_{cyl}$ and their relative standard uncertainty for the cylinder phantom for sources of the BSS 2 — calculated according to equation (3.6). The values for $T(3; 0^\circ)_{slab}$ and $R(3; \alpha)_{slab}$ are given in tables 11 and A.7, respectively.

| Source | Conversion coefficient $h_{p,D}(3; \alpha)_{cyl}$ and its relative standard uncertainty for a value of $\alpha$ of |  |
|---|---|---|---|---|---|---|---|
|  | Nuclide | Beam flattening filter | Distance cm | $0^\circ$ $u_{rel}(0^\circ)$ | $15^\circ$ $u_{rel}(15^\circ)$ | $30^\circ$ $u_{rel}(30^\circ)$ | $45^\circ$ $u_{rel}(45^\circ)$ | $60^\circ$ $u_{rel}(60^\circ)$ | $75^\circ$ $u_{rel}(75^\circ)$ |
|  | Sr/90Y | no | 11 | 0.501 | 0.88% | n.a. | n.a. | n.a. | n.a. |
|  | Sr/90Y | no | 20 | 0.495 | 0.89% | n.a. | n.a. | n.a. | n.a. |
|  | Sr/90Y | no | 30 | 0.476 | 0.88% | n.a. | n.a. | n.a. | n.a. |
|  | Sr/90Y | no | 50 | 0.440 | 0.89% | n.a. | n.a. | n.a. | n.a. |
|  | Sr/90Y | yes | 30 | 0.431 | 0.89% | 0.407 | 0.95% | 0.321 | 1.33% | 0.210 | 2.10% | 0.105 | 3.38% | 0.037 | 4.99% |
|  | Sr/90Y | yes | 50 | 0.384 | 0.89% | n.a. | n.a. | n.a. | n.a. |
|  | Ru/106Rh | no | 11 | 0.760 | 0.77% | n.a. | n.a. | n.a. | n.a. |
|  | Ru/106Rh | no | 20 | 0.771 | 0.77% | 0.743 | 0.83% | 0.659 | 1.16% | 0.500 | 1.99% | 0.291 | 3.19% | n.a. |
|  | Ru/106Rh | yes | 30 | 0.757 | 0.76% | 0.716 | 0.82% | 0.641 | 1.16% | 0.486 | 1.99% | 0.284 | 3.19% | 0.114 | 4.80% |
|  | Ru/106Rh | yes | 50 | 0.715 | 0.77% | n.a. | n.a. | n.a. | n.a. |

1) These values are not available as the corresponding values for $h_{p,D}(0.07; \alpha)_{slab}$ and $R(3; \alpha)_{slab}$ have not yet been measured, see table 6 and [8].
Table 10. Conversion coefficients $h_D'(3; \alpha)$ and their relative standard uncertainty for sources of the BSS 2 — calculated according to equation (3.7). The values for $T(3; 0^\circ)_{\text{slab}}$ and $R(3; \alpha)_{\text{slab}}$ are given in tables 11 and 12, respectively.

| Source | Conversion coefficient $h_D'(3; \alpha)$ and its relative standard uncertainty for a value of $\alpha$ of | Nuclide | Beam flattening filter | Distance | 0° | $u_{ref}(0°)$ | 15° | $u_{ref}(15°)$ | 30° | $u_{ref}(30°)$ | 45° | $u_{ref}(45°)$ | 60° | $u_{ref}(60°)$ | 75° | $u_{ref}(75°)$ |
|--------|-----------------------------------------------------------------------------------------------------|---------|------------------------|----------|-----|---------------|-----|---------------|-----|---------------|-----|---------------|-----|---------------|-----|---------------|
| 90Sr/90Y | no                                                                                                       | 11      | 0.501 0.90 % n.a. 1) | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| 90Sr/90Y | no                                                                                                       | 20      | 0.495 0.91 % n.a.      | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| 90Sr/90Y | no                                                                                                       | 30      | 0.476 0.90 % n.a.      | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| 90Sr/90Y | no                                                                                                       | 50      | 0.440 0.91 % n.a.      | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| 90Sr/90Y | yes                                                                                                       | 30      | 0.431 0.91 % 0.402 1.00 % | 0.320 1.31 % | 0.208 2.12 % | 0.104 3.40 % | 0.035 4.99 % | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| 90Sr/90Y | yes                                                                                                       | 50      | 0.384 0.91 % n.a.      | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| 106Ru/106Rh | no                                                                                                       | 11      | 0.760 0.87 % n.a.      | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| 106Ru/106Rh | no                                                                                                       | 20      | 0.771 0.87 % 0.743 0.85 % | 0.657 1.24 % | 0.496 2.06 % | 0.284 3.20 % | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| 106Ru/106Rh | yes                                                                                                       | 30      | 0.757 0.87 % 0.716 0.84 % | 0.639 1.24 % | 0.483 2.05 % | 0.277 3.20 % | 0.107 4.84 % | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |
| 106Ru/106Rh | yes                                                                                                       | 50      | 0.715 0.87 % n.a.      | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. |

1) These values are not available as the corresponding values for $h_{p,D}(0.07; \alpha)_{\text{slab}}$ and $R(3; \alpha)_{\text{slab}}$ have not yet been measured, see table 6 and [8].
Table 11. Depth dependence factor $T(3; 0^+)_\text{slab} = H_p(3; 0^+)_\text{slab} / H_p(0.07; 0^+)_\text{slab}$ and its relative standard uncertainty for sources of the BSS 2. The values have been measured previously [8].

| Nuclide   | Beam flattening filter | Distance (cm) | $T(3; 0^+)_\text{slab}$ | $u_{rel}(T)$ |
|-----------|------------------------|---------------|-------------------------|--------------|
| $^{90}\text{Sr}/^{90}\text{Y}$ | no                     | 11            | 0.5008                  | 0.50 %       |
| $^{90}\text{Sr}/^{90}\text{Y}$ | no                     | 20            | 0.4949                  | 0.51 %       |
| $^{90}\text{Sr}/^{90}\text{Y}$ | no                     | 30            | 0.4759                  | 0.50 %       |
| $^{90}\text{Sr}/^{90}\text{Y}$ | no                     | 50            | 0.4397                  | 0.50 %       |
| $^{90}\text{Sr}/^{90}\text{Y}$ | yes                    | 30            | 0.4311                  | 0.51 %       |
| $^{90}\text{Sr}/^{90}\text{Y}$ | yes                    | 50            | 0.3838                  | 0.51 %       |
| $^{106}\text{Ru}/^{106}\text{Rh}$ | no                     | 11            | 0.7603                  | 0.51 %       |
| $^{106}\text{Ru}/^{106}\text{Rh}$ | no                     | 20            | 0.7710                  | 0.51 %       |
| $^{106}\text{Ru}/^{106}\text{Rh}$ | yes                    | 30            | 0.7572                  | 0.50 %       |
| $^{106}\text{Ru}/^{106}\text{Rh}$ | yes                    | 50            | 0.7150                  | 0.51 %       |
Table 12. Angular dependence factor $R(3; \alpha)_{\text{slab}} = H_p(3; \alpha)_{\text{slab}} / H_p(3; 0^\circ)_{\text{slab}}$ and its relative standard uncertainty for sources of the BSS 2. The values have been measured previously [8].

| Source | Distance | $\mu_{\text{rel}}(0^\circ)$ | $\mu_{\text{rel}}(15^\circ)$ | $\mu_{\text{rel}}(30^\circ)$ | $\mu_{\text{rel}}(45^\circ)$ | $\mu_{\text{rel}}(60^\circ)$ | $\mu_{\text{rel}}(75^\circ)$ |
|--------|----------|----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| $^{90}\text{Sr}/^{90}\text{Y}$ yes | 30 | 1.000 | 0.933 | 0.733 | 0.472 | 0.228 | 0.0744 |
| $^{106}\text{Ru}/^{106}\text{Rh}$ no | 20 | 1.000 | 0.964 | 0.844 | 0.629 | 0.349 | n.a. 1) |
| $^{106}\text{Ru}/^{106}\text{Rh}$ yes | 30 | 1.000 | 0.945 | 0.836 | 0.623 | 0.346 | 0.125 |

1) This value is not available as the corresponding values for $h_{p,D}(0.07; \alpha)_{\text{slab}}$ and $R(3; \alpha)_{\text{slab}}$ have not yet been measured, see table 6 and [8].
References

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