Extensions to the Beta Secondary Standard BSS 2
Consolidated version from www.ptb.de

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The original version of this paper is published and freely available in the Journal of Instrumentation. This consolidated version combines

- the original paper: 2011 JINST 6 P11007,
- its erratum which describes a few minor typing errors and an update of the references: 2012 JINST 7 E04001, and
- its addendum which contains four minor additions regarding some equations, data values of the reference air density, data for additional irradiation geometries, information regarding the implementation of the checksum on the calibration data, and finally a detailed addition regarding the uncertainty in the measurement of dose and dose rate: 2012 JINST 7 A05001.

After publication of the three parts mentioned above a few further corrections and additions have been introduced in this consolidated version. They are marked with a vertical line besides the new text (as in this paragraph).

The data presented in this paper are contained in the file "BetaFakt.ini" which is available for the users of the BSS 2.

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[2] Version history of this consolidated paper:

Comment to version 1.6:

a) Data for source geometry "^{106}Ru/^{106}Rb at 50 cm with filter" updated in tables 2, 3 and 5.
b) Subsection 2.4.3 added (overview of depth dose curves).
c) Reference 7 updated

Comment to version 1.5:

a) References for two new radiation fields added, see [15],[16]: ^{90}Sr/^{90}Y at 20 cm with 3 mm or 4 mm PMMA absorber: Sr, 20 cm, 3P and Sr, 20 cm, 4P. The corresponding data were not added as those radiation qualities are not contained in the BSS 2 software.
b) Data for source geometry "^{85}Kr at 30 cm without filter" added. This radiation quality is not yet contained in the BSS 2 software.
c) Slab phantom added in subsection 2.7.
d) Subsection 2.8 added (use of an embedded mini-PC instead of a PC).
e) Screenshot of the software and photograph of the BSS 2 in appendix B updated (new software version 5 and photograph with the embedded mini-PC and slab phantom).

Comment to version 1.4:

a) Link to the manufacturer's website added.
b) Reference 6 updated.
c) Angular factors for the source geometry "^{106}Ru/^{106}Rh at 20 cm without filter" added. These data are not contained in the JINST papers but in version 7.5 and higher of the file "BetaFakt.ini" as of 2015-02-12.

Comment to version 1.3:

a) Data for source geometries "^{147}Pm at 11 cm without filter", "^{90}Sr/^{90}Y at 50 cm with filter", and "^{106}Ru/^{106}Rh at 50 cm with filter" added. These new data are not contained in the JINST papers but in version 7.3 and higher of the file "BetaFakt.ini" as of 2012-11-07.
b) References 9 and 13 updated.

Comment to version 1.2: Link to Addendum was added on cover page.
Comment to version 1.1: Link to Erratum was added on cover page.

ABSTRACT: Since several years, the irradiation facility for beta radiation, the Beta Secondary Standard BSS 2 developed at PTB, has been in worldwide use for the performance of irradiations with calibrated beta sources. Due to recent developments in eye tumor therapy, in eye lens dosimetry, and in soft- and hardware technology, several extensions have been added to the BSS 2.

These extensions are described in this paper:

1. The possibility of using a ^{106}Ru/^{106}Rh beta source was added as this radionuclide is often used in tumor therapy.
2. The (small) contribution due to photon radiation was included in the dose (rate) reported by the BSS 2, as this was missing in the past.
3. The quantity personal dose equivalent at a depth of 3 mm, $H_p(3)$, was implemented due to recent findings on the radio sensitivity of the eye lens regarding cataract induction and the subsequent lowering of the dose limit from 150 mSv down to 20 mSv per year;
4. The correction for ambient conditions (air temperature, pressure, and relative humidity) was improved in order to adequately handle the quantity $H_p(3)$ and in order to extend the range of use beyond 25°C.
5. A checksum test was added to the software to secure the calibration data against (un)intended changes.
6. The connection of the PC and the BSS 2 has been changed to a network interface (TCP/IP) in order to be able to use up-to-date computers not containing a parallel and a serial port.
7. A rod phantom was added in order to make sure the mechanical set-up is of high quality.

All these extensions have been implemented in the PTB's BSS 2 model. The routine implementation of extension 1 is still under investigation by the manufacturer. The commercially available BSS 2 will contain extensions 2 to 6 starting approximately in 2012, while extension 7 has already been incorporated since 2011. Extensions 2 to 5 will also be available for old BSS 2 versions via a software update, starting approximately at the beginning of 2012. Extension 6 will be available via hardware change by the manufacturer.

KEYWORDS: Dosimetry concepts and apparatus; Radiation monitoring.

Contents

1 Introduction

For several years, the Beta Secondary Standard BSS 2 developed at PTB has been in worldwide use for the performance of irradiations with calibrated beta sources [1] according to ISO 6980 [2],[3],[4] and is available commercially from a German manufacturer [5]. Several extensions have become advisable due to new developments in eye tumor therapy, in eye lens dosimetry, and in soft- and hardware technology. The background and realization of each extension are described in detail in section 2. The total dose calculation is presented in section 3. Appendix A contains a complete list of symbols used in this paper; appendix B shows a screen shot of the new software version and a photograph of the BSS 2.

At this point, some technical details of the BSS 2 are explained, as reference will be made to them later on in this work. The software of the BSS 2 is organized as follows:

1. The main program is distributed as an executable file. Versions 4.0 and higher contain the extensions described in this paper.
2. A driver necessary to control the parallel port accompanies the software. It has to be installed manually prior to installing the BSS 2 software. With the new hard- and software version described in this paper this driver will no longer be necessary.
3. The ASCII file “BetaFakt.ini” contains all parameters which are equivalent to all devices of the BSS 2, for example, the half-lives of the radio nuclides. Versions 7.0 and higher include the extensions described in this paper. This file is the same for all BSS 2 devices.
4. A second ASCII file “BetaSek2.ini” contains the source-specific parameters, like reference dose rates of the sources delivered with the individual BSS 2 (each radiation source is calibrated at the Physikalisch-Technische Bundesanstalt (PTB)). This file is individual for each BSS 2 device.

To operate the new software version it is necessary to use the new “BetaFakt.ini” file; on the other hand, it is possible to use old software versions with new files: “BetaFakt.ini”.

2 Extensions to the BSS 2

2.1 Possibility to use a ^{106}Ru/^{106}Rh beta source

2.1.1 Background

^{106}Ru/^{106}Rh beta sources are broadly used in eye tumor therapy. In addition, this radionuclide is implemented in the standard ISO 6890 [2],[3],[4]. Its mean beta energy is higher than that of ^{90}Sr/^{90}Y (about 1.2 MeV instead of 0.8 MeV); thus, it extends the energy range formerly covered by BSS 2 sources. Therefore, a ^{106}Ru/^{106}Rh source (an eye applicator usually used for tumor therapy comprising a layer of ^{106}Ru/^{106}Rh encapsulated in 1 mm pure silver [6]) was mounted into a BSS 2 source holder, and corresponding calibration measurements were performed to obtain the data and parameters described in this and the following subsections. The beam flattening filter used for the ^{106}Ru/^{106}Rh source was chosen to be equivalent to the one used for ^{90}Sr/^{90}Y sources. The reason is that simulation transport calculations showed that quite a flat beam profile results [7].

The basic physical quantity in beta dosimetry is the absorbed dose in tissue at a depth of 0.07 mm in a tissue phantom, $D_t(0.07)$. According to the nomenclature used in ISO 6980-2 [3], this is the reference absorbed dose, D_R. According to ISO 6980-3 [4], the personal dose equivalent at a depth of 0.07 mm, $H_p(0.07)$, results from the reference absorbed dose by

$$H_p(0.07) = h_{p,D}(0.07; source; \alpha) \cdot D_R, \qquad (2.1)$$

with the conversion coefficient $h_{p,D}(0.07; source; \alpha)$. The term *source* represents the source type including the radionuclide, the beam flattening filter, and the distance of the radiation source from the point of irradiation. The values of $h_{p,D}(0.07; source; \alpha)$ are available in ISO 6980-3 for ^{147}Pm, ^{85}Kr, and ^{90}Sr/^{90}Y radionuclides, for different distances, and for angles of incidence between 0° and 75° in steps of 5°. In order to obtain these data for ^{106}Ru/^{106}Rh, measurements were performed using the primary extrapolation chamber at PTB and the new ^{106}Ru/^{106}Rh BSS 2 radiation source. Absorbers of different thicknesses were placed in front of the extrapolation chamber and the ionization current was measured at a fixed chamber depth of 1 000 µm. An interpolation to the tissue-equivalent depth of 0.07 mm led to the corresponding ionization current $I(0.07)$. Those measurements were performed at different angles of incidence α between the beam axis and the extrapolation chamber. All ionization currents were corrected so as to be valid for reference air conditions ($T = 20°C$, $p = 1013.25$ hPa, $r = 0.65$) according to ISO 6980-2 [3]. From these corrected ionization currents $I(0.07; source; \alpha)$ the angular dependence was deduced according to

$$\begin{aligned} h_{p,D}(0.07; source; \alpha) &= H_p(0.07; source; \alpha) / H_p(0.07; source; 0°) \\ &= H_p(0.07; source; \alpha) / D_R \qquad (2.2) \\ &= I(0.07; source; \alpha) / I(0.07; source; 0°). \end{aligned}$$

Equation (2.2) implies that all corrections to obtain the dose from the ionization current are independent of the angle of radiation incidence (besides the correction to reference conditions). This method was already applied earlier [8] for the determination of the values for $h_{p,D}(0.07; source; \alpha)$ contained in ISO 6980-3. The results for the source type ^{106}Ru/^{106}Rh are given in table 1.

Table 1. Measured conversion coefficients $h_{p,D}(0.07; source; \alpha)$ for ^{106}Ru/^{106}Rh. Their standard uncertainty is on the order of 2 to 4 %.

Nuclide	Source Beam flattening filter	Distance	Conversion coefficient, $h_{p,D}(0.07; source; \alpha)$, for a value of α of					
		cm	0°	15°	30°	45°	60°	75°
^{106}Ru/^{106}Rh	with	30	1.000	0.998	1.039	1.127	1.195	1.003
^{106}Ru/^{106}Rh	w/o	20	1.000	1.011	1.060	1.151	1.256	---

2.1.2 Implementation

The source-specific parameters (like reference dose rate and reference date) are contained in the source-specific ASCII file “BetaSek2.ini”. The half-life used to correct for the radioactive decay since the reference date ($t_{1/2} = (373.59 \pm 0.015)$ d) is contained in the general ASCII file “BetaFakt.ini” as well as the data given in table 1 and the parameters necessary for further corrections, see below.

This implementation was performed in the software; a prototype of a ^{106}Ru/^{106}Rh source was manufactured at PTB. The possibility to produce these types of sources routinely is currently under investigation by the manufacturer of the BSS 2.

2.2 Inclusion of the contribution due to photon radiation

2.2.1 Background

In beta dosimetry, the main contribution to the dose comes, of course, from beta radiation. Therefore, in ISO 6980-2 [3] the determination of the reference beta-particle absorbed dose,

$D_{R,ß} = D_t(0.07)_{beta}$, is described. Its dose rate is used in the BSS 2 software as a basic reference value which is stored in the source-specific ASCII file “BetaSek2.ini”. In the past, this value was given by the BSS 2 as the value for the personal dose equivalent at a depth of 0.07 mm, $H_p(0.07)$, not including the contribution due to photon radiation. Therefore, the correct assignment would have been $H_p(0.07)_{beta}$.

The photon contribution can be estimated from extrapolation chamber measurements by placing absorbers of polymethyl metacrylate (PMMA) in front of the extrapolation chamber, thick enough to stop the beta radiation. The remaining ionization current, I_{phot}, can be taken as a measure of the photon contribution [3] to the ionization current at a tissue equivalent thickness of 0.07 mm, $I(0.07)$. The value at the exact depth of 0.07 mm can be obtained via interpolation of ionization currents measured using absorbers with tissue equivalent thicknesses smaller and larger than 0.07 mm. All ionization currents were corrected to reference conditions. This ratio is interpreted as the dose due to photons relative to the total dose [3]:

$$\tau_{br} = I_{phot} / I(0.07) = H_p(0.07)_{phot} / H_p(0.07).\ [1] \qquad (2.3)$$

Consequently, the total dose results from the summation of the two components:

$$H_p(0.07) = H_p(0.07)_{beta} + H_p(0.07)_{phot} = D_{R,ß} / (1 - \tau_{br}) = D_R. \qquad (2.4)$$

This is equivalent to the total reference absorbed dose, D_R [3]. The two components are given by the contribution due to beta radiation,

$$H_p(0.07)_{beta} = D_{R,ß} \qquad (2.5)$$

and the contribution due to photons, which is assumed to be independent of the depth in tissue, d, as the photons are nearly unattenuated by tissue depths relevant in a beta dosemeter (between 0 and about 10 mm):

$$H_p(d)_{phot} = \tau_{br} \cdot D_{R,ß} / (1 - \tau_{br}). \qquad (2.6)$$

Values for τ_{br} are given for different source types in table 2.

With these two dose components indicated separately by the new BSS 2 software, the contribution of a dosemeter’s indication due to the photon contamination can be taken into account. This is of special importance if the dosemeter only has a small sensitivity to beta radiation.

Table 2. Measured contribution τ_{br} to the total dose due to photon radiation and its one sigma uncertainty u (k = 1) for different radiation fields with or without a beam flattening filter.

Parameter	^{147}Pm 20 cm, with filter	^{85}Kr 30 cm, with filter	$^{90}Sr/^{90}Y$ 30 cm, with filter	$^{90}Sr/^{90}Y$ 11 cm, w/o filter	$^{90}Sr/^{90}Y$ 20 cm, w/o filter	$^{90}Sr/^{90}Y$ 30 cm, w/o filter	$^{90}Sr/^{90}Y$ 50 cm, w/o filter	$^{106}Ru/^{106}Rh$ 30 cm, with filter	$^{106}Ru/^{106}Rh$ 20 cm, w/o filter
τ_{br}	0.005 5	0.000 25	0.000 62	0.000 4	0.000 4	0.000 4	0.000 5	0.001 7	0.002 3
$u\{\tau_{br}\}$	0.002 3	0.000 09	0.000 23	0.000 2	0.000 2	0.000 2	0.000 3	0.000 9	0.001 2

Parameter	^{147}Pm 11 cm, w/o filter	^{85}Kr 50 cm, with filter	^{85}Kr 30 cm, w/o filter	$^{90}Sr/^{90}Y$ 50 cm, with filter	$^{106}Ru/^{106}Rh$ 11 cm, w/o filter	$^{106}Ru/^{106}Rh$ 50 cm, with filter
τ_{br}	0.000 1	0.000 28	0.000 07	0.001 0	0.002 0	0.002 9
$u\{\tau_{br}\}$	0.000 05	0.000 14	0.000 07	0.000 5	0.001 0	0.007 7

[1] From this, the correction factor for bremsstrahlung used in ISO 6980-2 results in $k_{br} = 1 - \tau_{br}$.

2.2.2 Implementation

The contribution due to photon radiation relative to the total dose at reference depth, τ_{br}, is contained in the general ASCII file “BetaFakt.ini”. As these values are nearly equal for all radiation sources of the same type sold so far [9], they are used by the software for all individual radiation sources of the same type.

In the past, in the software and in the irradiation protocols, only the dose due to beta radiation, e.g. $H_p(0.07)_{beta}$, was given. The new software version reports the total dose, e.g. $H_p(0.07) = H_p(0.07)_{beta} + H_p(0.07)_{phot}$. In addition, the dose due to photons, e.g. $H_p(0.07)_{phot}$, is given in the protocol file but not in the software window as its contribution is quite small (always less than one percent), see table 2.

2.3 Implementation of the quantity personal dose equivalent at a depth of 3 mm, $H_p(3)$

2.3.1 Background

In beta dosimetry, the personal dose equivalent at a depth of 0.07 mm, $H_p(0.07)$, is commonly in use as reference quantity. The reason is that in beta radiation fields, the dose in the skin is usually much larger than the effective dose (the radiation-sensitive epidermis lies about 0.07 mm below the surface). On the other hand, in recent years it has become obvious that the lens of the human eye is more radiation sensitive than assumed in the past. Therefore, the International Commission of Radiation Protection (ICRP) has lowered the annual dose limit for the eye lens from 150 mSv down to 20 mSv [10]. Thus, protecting the eye and monitoring the lens dose to prevent exceeding the dose limit is more necessary than formerly assumed. Therefore, the appropriate dose quantity, especially in beta dosimetry, is the personal dose equivalent at a depth of 3 mm, $H_p(3)$, as the radiation-sensitive part of the lens lies about 3 mm within the eye [11],[12]. In order to make possible irradiations and calibrations of dosemeters in terms of $H_p(3)$, this quantity was implemented in the BSS 2.

Among the three radionuclides used in the BSS 2 so far (^{147}Pm, ^{85}Kr, and ^{90}Sr/^{90}Y), only radiation from ^{90}Sr/^{90}Y contributes significantly to $H_p(3)$ – the beta particles emitted from the two other radionuclides are too low in energy to penetrate 3 mm of tissue. Fortunately, it has turned out that the ratio $H_p(3)/D_R$ is nearly equal for all ^{90}Sr/^{90}Y radiation sources sold so far with the BSS 2 [9]. The ratio only depends on the distance from the radiation source and on whether or not a beam flattening filter is in place. As the reference beta-particle absorbed dose, $D_{R,ß}$, has been used in the past as a basis for the BSS 2 software, this shall remain unchanged. Therefore, equation (2.1) reduces with the aid of equation (2.4) to

$$H_p(0.07) = h_{p,D}(0.07; \mathit{source}; \alpha) \cdot D_{R,ß} \,/\, (1 - \tau_{br}). \qquad (2.7)$$

According to this nomenclature $H_p(3)$ is given by

$$H_p(3) = h_{p,D}(3; \mathit{source}; \alpha) \cdot D_{R,ß} \,/\, (1 - \tau_{br}). \qquad (2.8)$$

As $H_p(3)$ has not yet been implemented in ISO 6980, no values have as yet been available for $h_{p,D}(3; \mathit{source}; \alpha)$ in that standard. Therefore, these values were determined in this work. The values for $\alpha = 0°$ and $\alpha \neq 0°$ are treated separately in the BSS 2 software, therefore, this is also done in this work, and $h_{p,D}(3; \mathit{source}; \alpha)$ results in:

$$h_{p,D}(3; \mathit{source}; \alpha) = T(3; \mathit{source}; 0°) \cdot R(3; \mathit{source}; \alpha) \qquad (2.9)$$

with the depth dependence factor $T(3; \mathit{source}; 0°)$ and the angular dependence factor $R(3; \mathit{source}; \alpha)$. In order to obtain the two components, measurements were performed again using the primary extrapolation chamber of PTB and BSS 2 radiation sources. Absorbers of different thickness were placed in front of the extrapolation chamber and the ionization current was measured at a fixed chamber depth of 1 000 µm. In addition, the measurements were performed at different angles of incidence α between the beam axis and the extrapolation chamber. Subsequently, interpolations to tissue equivalent depths of 0.07 mm and 3 mm were performed in order to obtain the corresponding ionization currents, $I(0.07; source; \alpha)$ and $I(3; source; \alpha)$, respectively. Besides the corrections to reference air conditions according to ISO 6980-2, the ionization currents were corrected to account for the depth dependence of the stopping power ratio of the beta radiation [13]. As in equation (2.2), the ratio of the corrected ionization currents can be assumed to represent the corresponding dose ratios:

$$T(3; source; 0°) = H_p(3; source; 0°) / H_p(0.07; source; 0°) = H_p(3; source; 0°) / D_R = I(3; source; 0°) / I(0.07; source; 0°) \quad (2.10)$$

valid for 0° angle of incidence, and

$$R(3; source; \alpha) = H_p(3; source; \alpha) / H_p(3; source; 0°) = I(3; source; \alpha) / I(3; source; 0°). \quad (2.11)$$

The values for $T(3; source; 0°)$ were determined for all BSS 2 radiation fields; the results are given in table 3. The values given for ^{147}Pm and ^{85}Kr are equivalent to the corresponding photon contributions τ_{br} which are assumed to be independent of the depth in tissue d and are, consequently, also valid for $d = 3$ mm, see section 2.2.1. As quite a lot of measurements are necessary to determine the values of $R(3; source; \alpha)$, they were only determined for the two radiation fields $^{90}Sr/^{90}Y$ and $^{106}Ru/^{106}Rh$, each with a beam flattening filter and at a distance of 30 cm; the results are given in table 4.

Table 3. Measured ratios $T(3; source; 0°)$ and their standard uncertainties u (k = 1).

Parameter	^{147}Pm 20 cm, with filter	^{85}Kr 30 cm, with filter	$^{90}Sr/^{90}Y$ 30 cm, with filter	$^{90}Sr/^{90}Y$ 11 cm, w/o filter	$^{90}Sr/^{90}Y$ 20 cm, w/o filter	$^{90}Sr/^{90}Y$ 30 cm, w/o filter	$^{90}Sr/^{90}Y$ 50 cm, w/o filter	$^{106}Ru/^{106}Rh$ 30 cm, with filter	$^{106}Ru/^{106}Rh$ 20 cm, w/o filter
$T(3,0°)$	0.005 5	0.000 25	0.431 1	0.500 8	0.494 9	0.475 9	0.439 7	0.757 2	0.771 0
$u\{T(3,0°)\}$	0.002 3	0.000 09	0.002 2	0.002 5	0.002 5	0.002 4	0.002 2	0.003 8	0.003 9

Parameter	^{147}Pm 11 cm, w/o filter	^{85}Kr 50 cm, with filter	^{85}Kr 30 cm, w/o filter	$^{90}Sr/^{90}Y$ 50 cm, with filter	$^{106}Ru/^{106}Rh$ 11 cm, w/o filter	$^{106}Ru/^{106}Rh$ 50 cm, with filter
$T(3; 0°)$	0.000 1	0.000 28	0.000 07	0.383 8	0.760 3	0.694 3
$u\{T(3; 0°)\}$	0.000 05	0.000 14	0.000 07	0.002 0	0.003 9	0.003 5

Note The values for ^{147}Pm and ^{85}Kr represent photon radiation as their beta particles have too small energies to contribute to $H_p(3)$, see text for details.

Table 4. Measured ratios $R(3; source; \alpha)$. Their standard uncertainty is on the order of 2 to 4 %.

Nuclide	Source Beam flattening filter	Distance cm	Angular dependence factors, $R(3; source; \alpha)$, for a value of α of 0°	15°	30°	45°	60°	75°
$^{90}Sr/^{90}Y$	with	30	1.000	0.933	0.733	0.472	0.228	0.0744
$^{106}Ru/^{106}Rh$	with	30	1.000	0.945	0.836	0.623	0.346	0.125
$^{106}Ru/^{106}Rh$	w/o	20	1.000	0.964	0.844	0.629	0.349	---

The uncertainty of these ratios is quite large, especially for large angles of incidence. The reason is that the ratios $R(3; source; \alpha)$ (determined using the ionization currents at an extrapolation chamber depth of 1 000 µm) differ from the ratios determined using extrapolation chamber depths between 250 µm and 2 500 µm and a subsequent extrapolation to zero chamber depth (as is usually done in beta dosimetry). The two methods to determine the ratios

$R(3; source; \alpha)$ deliver different results. A reason could be the following: The correction factor to account for the perturbation of the beta radiation by the side walls of the extrapolation chamber, k_{pe}, is taken from ISO 6980-2 [3]. This value is appropriate for $\alpha = 0°$ and thin absorbers in front of the extrapolation chamber (below 0.1 mm in thickness). However, the correction factor (k_{pe}) probably takes different values for non-perpendicular radiation incidence ($\alpha \neq 0°$) and thicker absorbers resulting in the discrepancies described above. Therefore, further investigations will be necessary in the future.

The contribution due to photons, $H_p(d)_{phot}$, is assumed to be independent of the quantity as most of the photons have sufficient energy to penetrate both 0.07 mm and 3 mm of tissue; therefore, this contribution is again given by equation (2.6). The contribution due to betas is given by

$$H_p(3)_{beta} = H_p(3) - H_p(3)_{phot} = \{h_{p,D}(3; source; \alpha) - \tau_{br}\} \cdot \{D_{R,ß} / (1 - \tau_{br})\}. \qquad (2.12)$$

This equation is in an analogous way valid for the quantity $H_p(0.07)$.

2.3.2 Implementation

The software was modified so that the quantity $H_p(3)$ can be chosen instead of the formerly used quantity absorbed dose in tissue at the phantom surface, $D_t(0)$, which is no longer in use in beta dosimetry. In case $D_t(0)$ is of interest anyway, it can be obtained from the value of $H_p(0.07)$ by multiplication with the depth dependence factor at a tissue depth of $d = 0$ mm, $T(0)$. It can be obtained from equation (2.14), see next subsection.

Both the ratio of the dose rate at 3 mm and at 0.07 mm tissue depth (reference depth) for zero degrees angle of radiation incidence, $T(3; source; 0°)$, and the angular dependence factor, $R(3; source; \alpha)$, are contained in the general ASCII file “BetaFakt.ini” for the different source types. They are used by the software for radiation sources calibrated before 2011. For radiation sources calibrated in 2011 and later, the source-specific ratios $T(3; source; 0°)$ are contained in the source specific ASCII file “BetaSek2.ini”. No source-specific ratios $R(3; source; \alpha)$ will be determined in the future, therefore, they are always used from the general ASCII file “BetaFakt.ini”.

2.4 Improvement of the correction for ambient conditions

2.4.1 Background

The absorption and scattering of beta radiation in air are significant; even a different air density affects the betas significantly. Therefore, the BSS 2 is accompanied by a thermometer, a hygrometer, and a barometer. From their values, the ambient air density is calculated during irradiations. The correction factor for the dose was calculated in the past according to a procedure described in ISO 6980-2 [3]: The deviation of the ambient air density, ρ, from reference air density, ρ_{a0} (for which the reference dose rate given in the source-specific file “BetaSek2.ini” is valid) is interpreted as a small amount of ICRU tissue being added (for $\rho_a > \rho_{a0}$) or subtracted (for $\rho_a < \rho_{a0}$) in front of the object to be irradiated. The thickness of the layer is given by

$$\Delta d = y_0 \cdot \eta_{a,t} (\rho_a - \rho_{a0}) / \rho_t, \qquad (2.13)$$

with the distance y_0 between the source and the object to be irradiated usually being 20 or 30 cm, the scaling factor from air to tissue, $\eta_{a,t} = 0.915$, the density of ICRU tissue, $\rho_t = 1.0$ g/cm^3, and the reference air density $\rho_{a,0}$. The value of $\rho_{a,0}$ is given in the “BetaFak.ini” file. The method to calculate the air density is different in the new software version, namely according to equation (2.16), see below, and, thus, also different to the method used in

ISO 6980-2 [3]. For the reference condition of $p = 1013$ hPa, $T = 20$°C, and $r = 0.65$, the reference air density results in $\rho_{a,0}(65\,\%) = 1.1970$ kg/m³. In the past, the reference dose rate was given for a reference air humidity of $r = 0.45$ resulting in $\rho_{a,0}(45\,\%) = 1.1991$ kg/m³. These two values are given in the new version of the "BetaFakt.ini" file. The former values were 1.1974 and 1.1995 kg/m³ for 65 % and 45 %, respectively, both resulting from equation (C.5) in ISO 6980-2. The differences are below 0.03 %.

The corresponding correction factor c_{abs} is calculated from a mean depth dose curve, $T(d)$ via $c_{abs} = T(70\ \mu m + \Delta d) / T(70\ \mu m)$. In ISO 6980-2, $T(d)$ is approximated by exponential polynomial fits which are valid for Δd between 6 and 167 µm depth in ICRU tissue and, therefore, cannot be used for the reference depth of 3 mm, corresponding to the quantity $H_p(3)$. Brunzendorf showed that the measured depth dose curves due to beta radiation can be approximated up to much larger depths via Chebyshev fits [9]:

$$T(d) = \frac{\sum_{i=0}^{8}\left(T_i \cdot \cos\left[i \cdot \arccos\left\{X(d)\right\}\right]\right) - \tau_{br}}{1 - \tau_{br}} \quad \text{with} \quad X(d) = 2 \cdot \frac{\log_{10}\left(\dfrac{d + d_{shift}}{d_{min} + d_{shift}}\right)}{\log_{10}\left(\dfrac{d_{max} + d_{shift}}{d_{min} + d_{shift}}\right)} - 1, \qquad (2.14)$$

with $d \in [d_{min}, d_{max}]$. The values for d_{min}, d_{shift}, d_{max}, and T_i, $i = 0..8$, are given in table 5; the values for τ_{br} are given in table 2. They were obtained from measurements of depth dose curves as described in section 2.3.1, the Chebychev fits were performed as described by Brunzendorf [9]. The correction for ambient conditions is then given for the quantity $H_p(d)$ with $d \in [d_{min}, d_{max}]$ via

$$c_{abs}(d) = \frac{T(d + \Delta d)}{T(d)}. \qquad (2.15)$$

The equation used in the past in the BSS 2 to calculate the actual air density is only valid in the temperature range between 15 °C and 25 °C [3]. Therefore, the following equation is used in the new BSS 2 software to calculate the air density ρ_a from the air temperature, T in °C, the air pressure, p in Pa, and the relative air humidity, r, according to Brunzendorf [13]:

$$\rho_a = \frac{1}{\left[T + 273.15\,°\mathrm{C}\right] \cdot 287.05\,\dfrac{\mathrm{J}}{\mathrm{kg \cdot K}}} \cdot \left\{ p - \left(1 - \frac{287.05}{461.495}\right) \cdot r \cdot 611.213\,\mathrm{Pa} \cdot \exp\left(\frac{17.5043 \cdot T}{241.2\,°\mathrm{C} + T}\right) \right\}. \qquad (2.16)$$

Equation (2.16) results in air densities as precise as 0.03 % and 0.2 % up to 30 °C and 50 °C, respectively [13], and can, therefore, serve to extend the temperature range of validity of ISO 6980-2.

2.4.2 Implementation

The parameters given in tables 2 and 5 are contained in the general ASCII file "BetaFakt.ini" and are used by the software to calculate c_{abs} for the required depth d in tissue of $d = 0.07$ mm and 3 mm for $H_p(0.07)$ and $H_p(3)$, respectively.

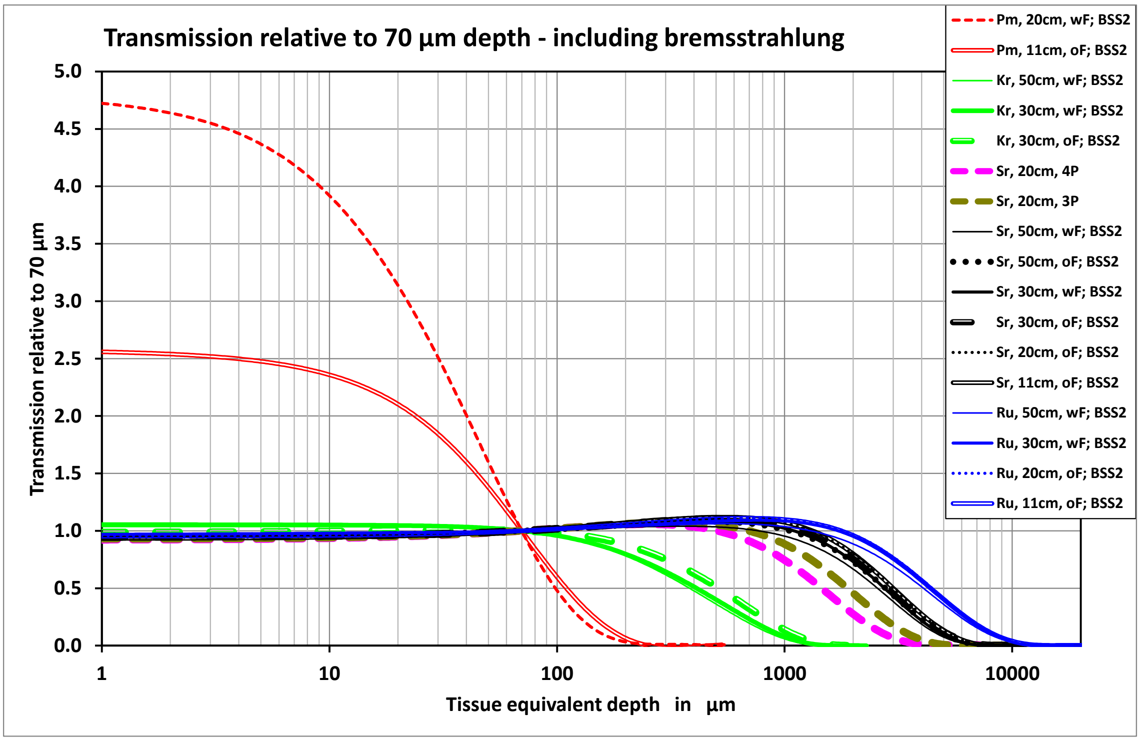
Table 5. Parameters of the mean source-specific depth-dose curves $T(d)$.

Parameter	^{147}Pm 20 cm, with filter	^{85}Kr 30 cm, with filter	$^{90}Sr/^{90}Y$ 30 cm, with filter	$^{90}Sr/^{90}Y$ 11 cm, w/o filter	$^{90}Sr/^{90}Y$ 20 cm, w/o filter	$^{90}Sr/^{90}Y$ 30 cm, w/o filter	$^{90}Sr/^{90}Y$ 50 cm, w/o filter	$^{106}Ru/^{106}Rh$ 30 cm, with filter	$^{106}Ru/^{106}Rh$ 20 cm, w/o filter
d_{min}	−1 µm	−2 µm	−4 µm	0 µm	0 µm	0 µm	−2 µm	−1 µm	−1 µm
d_{shift}	25 µm	585 µm	1090 µm	710 µm	910 µm	985 µm	985 µm	60 µm	910 µm
d_{max}	558 µm	2 315 µm	11 460 µm	11 411 µm	11 409 µm	11 409 µm	11 409 µm	18 676 µm	18 676 µm
T_0	1.672 20	0.405 05	0.524 85	0.576 90	0.560 35	0.547 70	0.532 07	0.683 18	0.574 95
T_1	-2.509 59	-0.574 59	-0.626 44	-0.625 35	-0.631 20	-0.629 73	-0.623 87	-0.534 88	-0.627 70
T_2	0.920 46	0.157 18	-0.027 25	-0.115 87	-0.082 08	-0.061 56	-0.040 86	-0.294 39	-0.101 74
T_3	0.053 96	0.042 94	0.172 43	0.179 45	0.181 87	0.177 49	0.168 04	0.017 12	0.171 07
T_4	-0.161 66	-0.032 92	-0.015 23	0.019 67	0.002 25	-0.004 74	-0.007 28	0.112 69	0.017 84
T_5	0.014 17	0.003 69	-0.030 18	-0.023 65	-0.025 63	-0.025 59	-0.026 04	0.055 04	-0.024 46
T_6	0.015 64	-0.004 23	-0.004 41	-0.016 08	-0.011 18	-0.008 79	-0.007 96	-0.007 18	-0.013 23
T_7	0.008 89	0.002 70	0.005 89	0.003 68	0.004 32	0.004 46	0.004 63	-0.021 01	0.003 63
T_8	-0.007 05	0.000 49	0.000 96	0.001 52	0.001 57	0.001 08	0.001 71	-0.011 69	0.001 04

Parameter	^{147}Pm 11 cm, w/o filter	^{85}Kr 50 cm, with filter	^{85}Kr 30 cm, w/o filter	$^{90}Sr/^{90}Y$ 50 cm, with filter	$^{106}Ru/^{106}Rh$ 11 cm, w/o filter	$^{106}Ru/^{106}Rh$ 50 cm, with filter
d_{min}	0 µm	0 µm	0 µm	-3 µm	0 µm	-8 µm
d_{shift}	110 µm	1 135 µm	685 µm	1085 µm	860 µm	1785 µm
d_{max}	11 408 µm	3 880 µm	4 901 µm	11 398 µm	21 457 µm	21 459 µm
T_0	0.483 50	0.307 01	0.345 12	0.502 26	0.559 02	0.488 55
T_1	-0.890 62	-0.496 81	-0.535 77	-0.614 08	-0.633 64	-0.619 21
T_2	0.690 86	0.272 56	0.221 17	0.001 42	-0.076 61	0.037 69
T_3	-0.430 61	-0.060 98	0.017 28	0.152 08	0.182 64	0.149 43
T_4	0.193 70	-0.027 10	-0.069 14	-0.015 92	0.005 71	-0.040 91
T_5	-0.026 82	0.025 47	0.027 86	-0.027 62	-0.031 13	-0.021 12
T_6	-0.049 24	-0.012 10	0.000 98	-0.005 24	-0.013 30	0.000 00
T_7	0.056 50	-0.001 58	-0.001 49	0.006 71	0.006 81	0.006 91
T_8	-0.032 76	-0.006 63	-0.005 99	0.001 22	0.001 77	0.000 00

2.4.3 Overview of depth dose curves

Figure A shows and overview of the depth dose curves in a in a tissue equivalent phantom described in equation 2.14 and table 5: The higher the beta mean energy, the deeper the electrons penetrate the tissue. Especially, the depth dose curves for ^{147}Pm show a steep decrease with increasing tissue depth due to its rather small beta mean energy of approximately $\bar{E}_{betea} \approx 0.07$ MeV and 0.08 MeV, for ^{147}Pm 20 cm with beam-flattening filter and ^{147}Pm 11 cm without beam-flattening filter, respectively. For ^{85}Kr with $\bar{E}_{betea} \approx 0.25$ MeV, the dose continuously decreases with increasing tissue depth due to the continuous slowing down and absorption of the electrons on their path through the phantom. Finally, the rather large beta mean energies of the $^{90}Sr/^{90}Y$ and $^{106}Ru/^{106}Rh$ sources, $\bar{E}_{betea} \approx 0.8$ MeV and $\bar{E}_{betea} \approx 1.2$ MeV, respectively, result in dose build-up effect, i.e., at medium tissue depth of 500 µm to 1000 µm, increases before it decreases further down at larger depths.



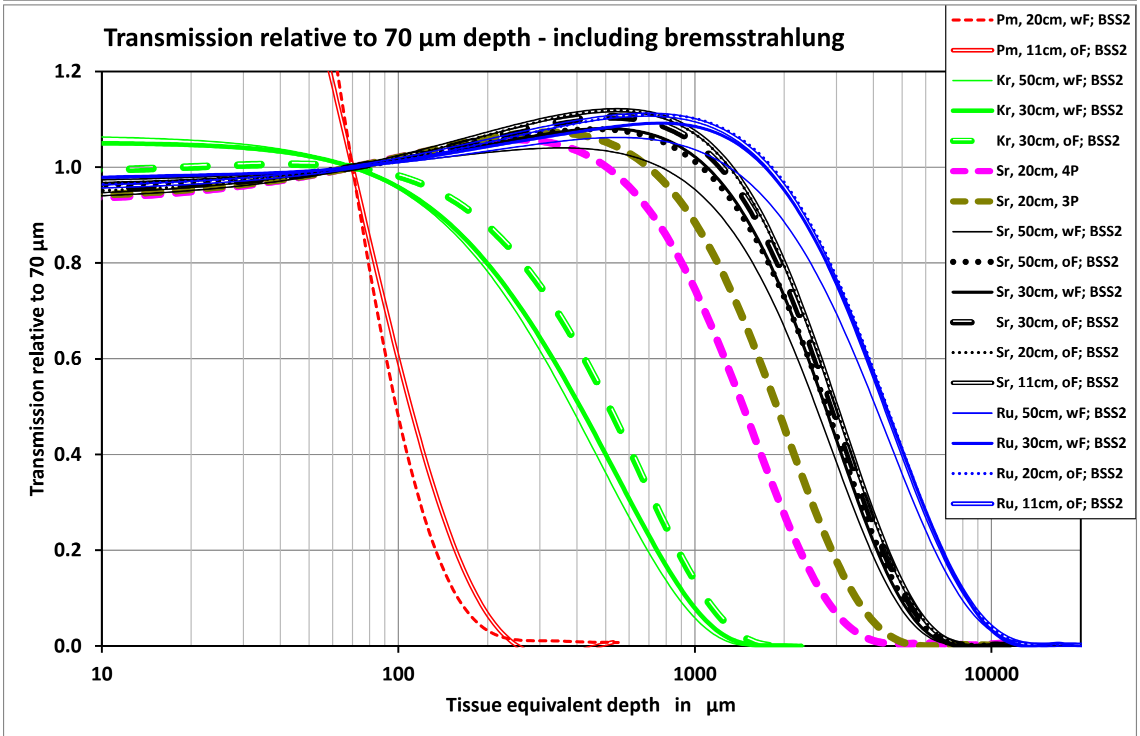


Figure A. Transmission relative to 70 µm depending on the depth in a tissue equivalent phantom. Top: Full depth dose curves; Bottom: Depth dose curves with limited ordinate and tissue depth.

2.5 Checksum test to secure the calibration data

2.5.1 Background

The software and the *.ini-files are essential parts of the BSS 2. Therefore, the simplest measure to protect them from (un)intentional changes will be applied in the future: The main program and the driver are distributed as executable files. The *.ini-files are ASCII files which in the past were located in the Windows directory. In the future, the *.ini-files cannot be located in the Windows directory any longer, as newer versions of Windows (above XP) do not allow an ordinary program (as the BSS 2 software) to save files in the Windows directory. Therefore, the place of the *.ini-files will be in the same directory as the software itself. As this directory is more public, all data affecting the dose value (reference dose rate, reference date, correction factors, and others) are secured by a simple checksum which is recalculated during every start up of the program.

2.5.2 Implementation

A checksum is calculated on the basis of all relevant data contained in the two files “BetaFakt.ini” and “BetaSek2.ini”. “Relevant data” are all data needed for the determination of the irradiation conditions, like correction factors and dose. The checksum is stored in the ini files (outside the area of the relevant data). During each program start the checksums are recalculated and compared to the sums stored in the files. If the sums are not the same, the program stops with an error message. The reference checksum of the “BetaFakt.ini” file (Version 7.0 and above) is stored in that file, however, old “BetaSek2.ini” files do not contain a checksum. Therefore, the special program “BetaSek2Chk.exe” will be distributed together with the BSS 2 software itself. Once that program is used to open a “BetaSek2.ini” file it automatically inserts the reference checksum into the user specific file “BetaSek2.ini”. In addition the uncertainties of the reference dose rates are enlarged (see below). The original version of the “BetaSek2.ini” file will be stored in a backup file.

2.6 Connection of the PC and the BSS 2 via network interface (TCP/IP)

2.6.1 Background

In the past, the BSS 2 was connected with the controlling PC via the serial (RS232) and parallel (printer) port. Most current PCs are delivered without these ports; instead USB and Ethernet ports are available.

2.6.2 Implementation

The serial and parallel ports of the BSS 2 control electronics were replaced by an Ethernet port enabling the complete data transfer between PC and BSS 2. The control electronics of old devices can be upgraded to the Ethernet port by the manufacturer. This could be of interest in case the PC of an old BSS 2 broke down and had to be replaced by a newer PC, not supplying the serial (RS232) and parallel port.

2.7 Distribution with rod and slab phantom

2.7.1 Background

In the past, the BSS 2 was distributed without any phantom. As mounting a rod or slab of more than 50 cm length exactly perpendicular to the beam axis is mechanically not trivial, new BSS 2s are delivered with a rod and slab phantom according to ISO.

2.7.2 Implementation

New BSS 2s are delivered with a rod and slab phantom. They can be mounted onto a small ground plate which enables the subsequent adjustment of the irradiation distance and the angle of radiation incidence. In contrast to old BSS 2 devices this table must no longer be demounted, but other set-ups than the rod or slab phantom can still be mounted on it. For old BSS 2s, the new rod and slab phantom can be obtained from the manufacturer. They will be accompanied by a new ground plate which can be installed by the user. Both new phantoms are in line with to the corresponding ISO phantoms [3]. Appendix B contains an up-to-date photograph of the BSS 2.

2.8 Distribution with an embedded mini-PC

2.8.1 Background

In the past, the BSS 2 was connected with a controlling PC via the serial (RS232) and parallel (printer) port or Ethernet. However, PCs usually obtain every now and then hard- or software updates possibly leading to connection problems.

2.8.2 Implementation

Since 2017, new BSS 2s are delivered together with an embedded mini-PC (with the operating system Linux) implemented in the control electronics – instead of a PC. Accordingly, the BSS 2 software was rewritten to a Linux version. Appendix B shows a screen shot of the updated software of the BSS 2. To replace the former PC, an up-to-date control electronic including the embedded mini-PC and the new software can be obtained from the manufacturer [5].

3 Determination of the total dose (rate)

All equations in section 2 containing dose values are accordingly valid for the corresponding dose rate values by division with the respective irradiation time. The reference beta-particle absorbed dose rate, $\dot{D}_{\mathrm{R,ß}}$, is given in the ASCII file "BetaSek2.ini". From $\dot{D}_{\mathrm{R,ß}}$ and the correction factors and conversion coefficients described in section 2, the dose rate during an irradiation is determined by the BSS 2 software via

$$\dot{H}_{\mathrm{p}}(d)_{\mathrm{irr}} = \left\{\dot{H}_{\mathrm{p}}(d)_{\mathrm{beta}} \cdot c_{\mathrm{abs}}(d) + \dot{H}_{\mathrm{p,phot}}\right\} \cdot k_{\mathrm{de}}, \tag{3.1}$$

see equations (2.5), (2.6), (2.12), and (2.15). The correction factor due to ambient conditions, $c_{\mathrm{abs}}(d)$, only applies to the beta contribution of the dose rate, $\dot{H}_{\mathrm{p}}(d)_{\mathrm{beta}}$, as the photons' absorption in air is negligible. The correction for the exponential decay is obtained via

$$k_{\mathrm{de}} = \exp\left[-(t_{\mathrm{m}} - t_0) \cdot \ln 2 / t_{1/2}\right] \tag{3.2}$$

with t_{m}, the irradiation date, t_0, the reference date given in the calibration certificate (given in the ASCII file "BetaSek2.ini"), and $t_{1/2}$, the half-life of the radionuclide used (given in the ASCII file "BetaFakt.ini"). All other variables and their determination are described in section 2.

To obtain the dose rate only due to beta and photon radiation, $H_{\mathrm{p}}(d)_{\mathrm{beta,irr}}$ and $H_{\mathrm{p,phot,irr}}$, respectively, the following additional equations, directly deduced from equation (3.1), can be used:

$$\begin{aligned}\dot{H}_{\mathrm{p}}(d)_{\mathrm{beta,irr}} &= \dot{H}_{\mathrm{p}}(d)_{\mathrm{beta}} \cdot c_{\mathrm{abs}}(d) \cdot k_{\mathrm{de}} \\ &= \left\{h_{\mathrm{p},D}(d; source; \alpha) - \tau_{\mathrm{br}}\right\} \cdot \left\{\dot{D}_{\mathrm{R,ß}} / (1 - \tau_{\mathrm{br}})\right\} \cdot c_{\mathrm{abs}}(d) \cdot k_{\mathrm{de}}\end{aligned} \tag{3.3}$$

and

$$\dot{H}_{\text{p,phot,irr}} = \dot{H}_{\text{p,phot}} \cdot k_{\text{de}} \\ = \tau_{\text{br}} \cdot \left\{ \dot{D}_{\text{R,ß}} / (1 - \tau_{\text{br}}) \right\} \cdot k_{\text{de}} \tag{3.4}$$

resulting in the total dose rate during an irradiation (equivalent to equation (3.1)):

$$\dot{H}_{\text{p}}(d)_{\text{irr}} = \dot{H}_{\text{p}}(d)_{\text{beta,irr}} + \dot{H}_{\text{p,phot,irr}} \tag{3.5}$$

For the determination of the dose value, the BSS 2 software uses the dose rate as given in equation (3.1)) and multiplies it by the irradiation time. This is done continuously during an irradiation and the BSS 2 software calculates the accumulated dose repeatedly using all the correction factors as mean values (time weighted) over the irradiation time elapsed so far, and closes the shutter on the operators' demand or when a preset dose value is reached. If a dose rate was preselected, the total dose determined as described above is divided by the irradiation time to obtain the mean dose rate for a (short or long) irradiation [1].

4 Conclusions

The extensions to the BSS 2 described in this paper render the BSS2 well suited to serve another long period of time as a reliable irradiation facility delivering doses and dose rates traceable to PTB.

In addition, extensions 1 to 4 may serve as a basis for a revision of the ISO standard ISO 6980 [2][3][4] in order to implement the quantity $H_{\text{p}}(3)$.

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A List of symbols and their meanings in alphabetical order

Symbol	Meaning
α	(mean) angle of beta-particle incidence under calibration conditions
c_{abs}	correction factor for variations in the attenuation and scattering of beta particles between the source and the point of test due to variations from reference conditions to correct from reference dose to the dose under the ambient conditions
d	depth in ICRU tissue
Δd	effective layer of tissue between source and point of test due to the deviation of the air density from reference air density
d_{min}	minimal value of d for which $T(d)$ can be calculated
d_{shift}	parameter for the calculation of $T(d)$
d_{max}	maximal value of d for which $T(d)$ can be calculated

Symbol	Meaning
D_R	reference absorbed dose
$D_{R,ß}$	reference beta-particle absorbed dose
$D_t(d)$	absorbed dose at a depth of *d* in ICRU tissue
$D_t(0.07)_{beta} = D_{R,ß}$	$D_t(0.07)$ due to beta radiation
$h_{p,D}(d; source; \alpha)$	conversion coefficient from D_R to $H_p(d)$ for angle α and *source* type (the subscript "$_{p,D}$" denotes "conversion from absorbed dose *D* to personal dose")
$H_p(d)$	personal dose equivalent at a depth *d* in ICRU tissue
$H_p(d)_{beta}$	$H_p(d)$ due to beta radiation
$H_p(d)_{phot}$	personal dose equivalent in ICRU tissue due to photons
i	number
I	ionization current
$I(d; source; \alpha)$	ionization current interpolated to depth *d* for angle α and *source* type
I_{phot}	ionization current caused by photon radiation
k_{de}	correction factor for radioactive decay of the beta particle source
$\eta_{a,t}$	beta-particle attenuation scaling factor of air relative to tissue
p	air pressure
ρ_a	density of air at ambient conditions
ρ_{a0}	density of air at reference conditions
ρ_t	density of tissue
r	relative air humidity
$R(3; source; \alpha)$	angular dependence factor of $h_{p,D}(3; source; \alpha)$
source	a *source* type specifies the radionuclide, the beam flattening filter, and the distance of the radiation source from the point of irradiation, e.g. *source* may represent '^{147}Pm with a beam flattening filter and at a 20 cm distance'
τ_{br}	photon contribution to the total dose
$t_{1/2}$	half-life of a radioisotope
t_0	reference time for which the given reference dose rate is valid (according to calibration certificate of specific radiation source)
t_m	time at which an irradiation is performed
T	air temperature
$T(3; source; 0°)$	conversion coefficient from D_R to $H_p(3)$ for angle 0° and *source* type
$T(d)$	transmission factor $D_t(d)/ D_t(0.07)$ in tissue for angle 0°
$X(d)$	intermediate function with values between −1 and 1 to calculate $T(d)$
y_0	distance from the source to the point of test

B Screenshot of the software and photograph of the current BSS 2 model

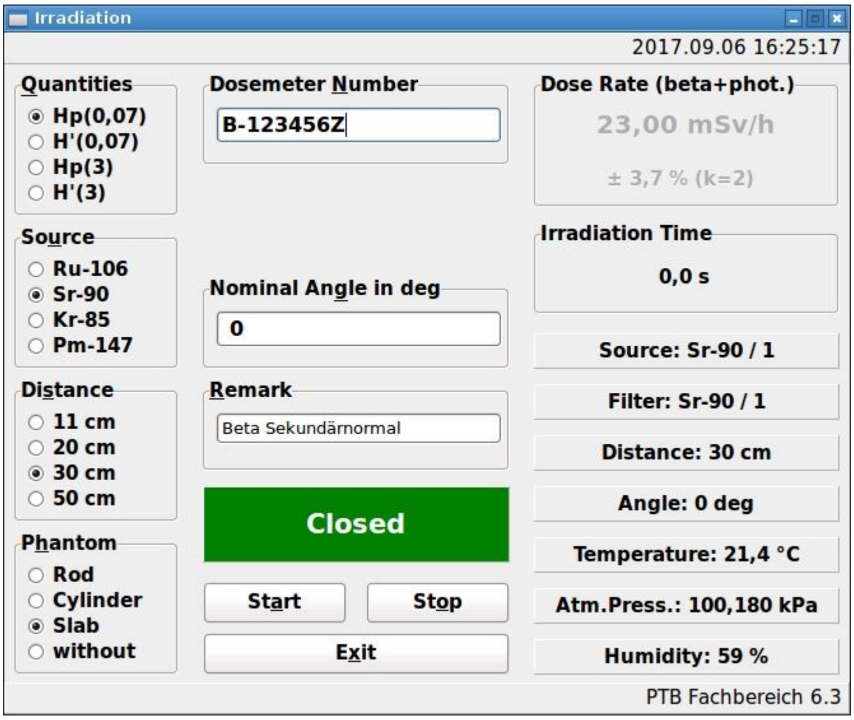

Figure 1. Screen shot of the new software version with the options to choose the quantity $H_p(3)$ and the ^{106}Ru/^{106}Rh radiation source. The dose (upper right) contains the contributions due to betas and photons.

Figure 2. Photograph of the current BSS 2 model including the new ISO rod and ISO-equivalent slab phantom and an embedded mini-PC inside the control electronics.

C Uncertainty in measurement

In this section the method used in the BSS 2 software to determine the uncertainty is described: After every irradiation (dose or dose rate), first the uncertainty of the dose rate is determined and subsequently the uncertainty of the dose (in case a dose irradiation was performed).

The method to calculate the dose rate due to betas and photons is given in equation (3.3) and (3.4), respectively. To take into account all relevant uncertainty contributions, these equations are extended to the following model functions:

$$\dot{H}_{\mathrm{p}}(d)_{\mathrm{beta,irr}} = \{T(d;source,0°)\cdot R(d;source,\alpha)-\tau_{\mathrm{br}}\}\cdot\{\dot{D}_{\mathrm{R,ß}}/(1-\tau_{\mathrm{br}})\}\cdot c_{\mathrm{absDist}}\cdot c_{\mathrm{absMeas}}\cdot c_{\mathrm{absFit}}\cdot k_{\mathrm{de}}\cdot k_{\mathrm{Dist}} \quad \text{(C.1)}$$

and

$$\dot{H}_{\mathrm{p,phot,irr}} = \tau_{\mathrm{br}}\cdot\{\dot{D}_{\mathrm{R,ß}}/(1-\tau_{\mathrm{br}})\}\cdot k_{\mathrm{de}}\cdot k_{\mathrm{Dist}} \quad \text{(C.2)}$$

The correction for the ambient conditions, see equations (2.15), (3.1), and (3.3), is represented here by $c_{\mathrm{abs}}(d) = c_{\mathrm{absDist}}\cdot c_{\mathrm{absMeas}}\cdot c_{\mathrm{absFit}}$. Here c_{absDist} has the same value as $c_{\mathrm{abs}}(d)$ and takes its uncertainty due to the uncertainty in the distance into account, c_{absMeas} is unity but takes the uncertainty contribution due to the measurement uncertainty of the current air temperature, air pressure, and relative humidity of $c_{\mathrm{abs}}(d)$ into account, c_{absFit} is also unity but takes the uncertainty contribution due to the uncertainty of the fit function of $T(d)$ of $c_{\mathrm{abs}}(d)$ into account, see equation (2.14), and k_{Dist} is unity but takes the uncertainty of the dose rate due to the quadratic distance law into account. Further explanations of the variables are given in table 6. The total dose rate due to betas and photons, $\dot{H}_{\mathrm{p}}(d)_{\mathrm{irr}}$, is given in equation (3.5).

With the irradiation time given by

$$\Delta t_{\mathrm{dose}} = (t_{\mathrm{stop}} - t_{\mathrm{start}}) + \frac{\Delta t_{\mathrm{open}} - \Delta t_{\mathrm{close}}}{2} \quad \text{(C.3)}$$

(see also equation (4.1) in Ambrosi et al. [1]), the model function for the total dose results in

$$H_{\mathrm{p}}(d)_{\mathrm{irr}} = \dot{H}_{\mathrm{p}}(d)\cdot\Delta t_{\mathrm{dose}} \quad \text{(C.4)}$$

In tables 7 to 12 examples of the uncertainty budgets for the resulting quantities are given for an irradiation performed in terms of $H_{\mathrm{p}}(0.07)$ with ^{147}Pm at an angle of radiation incidence of $\alpha = 45°$. Each time the complete uncertainty budget is given in order to show the impact of the uncertainty of each input variable on the final result. For example, it can be seen in table 12 that the uncertainties of the reference dose rate and the angular factor are dominant.

All final results are listed in table 13 presenting only the appropriate number of digits.

In tables 14 to 17 the standard uncertainties of the input variables are given, these values are contained in the new version of the "BetaFakt.ini" file accompanying the BSS 2 software. The values were deduced as follows:

1. The standard uncertainty of $T(0.07;source;0°)$ is zero as the reference calibration is performed at a depth of 0.07 mm.
2. The standard uncertainty of $T(3;source;0°)$, τ_{br}, and c_{absFit} was deduced from the uncertainty of the fit of the depth dose curve measurement, see Brunzendorf [8].
3. The standard uncertainty of c_{absDist} was deduced via the following method: A maximum uncertainty of the distance from the source of 0.5 mm was assumed; with the assumption of a rectangular distribution, a standard uncertainty of 0.29 mm results. This additional layer of air was converted via equation (2.13) to a tissue equivalent thickness Δd and the resulting change in the depth dose curve due to beta radiation was calculated,

$1 - T(d+\Delta d) / T(d)$, and taken as the standard uncertainty of c_{absDist}. The value of 0.5 mm maximum uncertainty of the distance from the source was assumed for $\alpha = 0°$, for $\alpha \neq 0°$ larger maximum uncertainties were assumed, e.g. for $\alpha = 60°$, a value of 1 mm. The angular dependence is significant only for ^{147}Pm, see table 14.

4. The standard uncertainty of c_{absMeas} was deduced in a similar way to the one of c_{absDist}: The maximum uncertainties of the measured values for the ambient conditions, 1 hPa air pressure, 0.3 K temperature, and 5 % relative air humidity, as well as rectangular distributions were assumed. The resulting effect on $T(d)$ was again interpreted as standard uncertainty.
5. The standard uncertainty of k_{Dist} was simply calculated using the quadratic distance law with the same assumptions of the uncertainty of the distance from the source as stated above (see calculation of the uncertainty of c_{absDist}).
6. The standard uncertainty of $R(d;source;\alpha)$ was deduced as described in section 2.1.1. Of course, for the slab phantom and $\alpha = 0°$ the uncertainty is zero (as the reference calibration is performed in a slab phantom) and this increases for larger values of α. This also applies for the quantity $H'(0.07)$ as the ICRU slab and sphere have quite similar absorption and backscatter effects for beta radiation as already stated in section 4.5.5, § 268, of ICRU report 57 [13]. However, the uncertainty of $R(d;source;\alpha)$ for $H_p(0.07)$ on a rod phantom is also, for $\alpha = 0°$, larger than zero for high energetic beta radiation (radionuclides ^{90}Sr/^{90}Y and ^{106}Ru/^{106}Rh) as the slab and rod phantom may have different absorption and backscatter effects for beta radiation. Finally, the uncertainty of $R(d;source;\alpha)$ for $H_p(3)$ on a slab phantom is assumed to be larger than for $H_p(0.07)$ as the reference calibration is performed at a depth of 0.07 mm.
7. The standard uncertainty of the reference dose rate, $\dot{D}_{\text{R,ß}}$, is given in the “BetaSek2.ini” file accompanying each calibrated radiation source. A revision of the uncertainty budget of the primary calibration measurements performed at PTB showed that uncertainties stated before 2011 were too small (standard uncertainty below 1 %). Therefore, the “BetaSek2Chk.exe” program accompanying the new BSS 2 software version (see correction 3 in this addendum) modifies the “BetaSek2.ini” files in such a way, that the uncertainty of the reference dose rate is changed to a standard uncertainty of about 2 %.

Table 6. List of quantities for the uncertainty determination.

Quantity	Unit	Definition
k_{de}		Correction for radioactive decay
t_m	d	Date of irradiation
t_0	d	Date for which the reference dose rate is valid (calibration of source; from “BetaSek2.ini”)
t_{12}	d	Half-life of source (from “BetaFakt.ini”)
$\dot{H}_p(d)_{beta,irr}$	mSv/h	Dose rate due to betas at depth *d*
$T(d;source;0°)$		Depth factor for depth *d* (from “BetaFakt.ini”)
$R(d;source;\alpha°)$	Sv/Gy	Angular factor for depth *d* (from “BetaFakt.ini”)
τ_{br}		Photon dose divided by total dose (from “BetaFakt.ini”)
$\dot{D}_{R,ß}$	mGy/s	Reference dose rate due to betas (from “BetaSek2.ini”)
$c_{absDist}$		Correction due to absorption and scattering in air (calculated via equation (2.15); uncertainty contribution due to uncertainty in the distance is taken into account here, value taken from “BetaFakt.ini”)
$c_{absMeas}$		Correction due to absorption and scattering in air (always unity but an uncertainty contribution due to uncertainty in measurement of ambient conditions is taken into account here, value taken from “BetaFakt.ini”)
c_{absFit}		Correction due to absorption and scattering in air (always unity but an uncertainty contribution due to the fit of the depth dose curve, see equation (2.14), is taken into account here, value taken from “BetaFakt.ini”)
k_{Dist}		Correction due to uncertainty in the distance (always unity but an uncertainty contribution due to quadratic distance law is taken into account here, value taken from “BetaFakt.ini”)
$\dot{H}_{p,phot,irr}$	mSv/h	Dose rate due to photons at depth *d*
$\dot{H}_p(d)_{irr}$	mSv/h	Total dose rate (due to betas and photons) during an irradiation
Δt_{dose}	s	Irradiation time for a certain dose
t_{stop}	s	Time of end of irradiation
t_{start}	s	Time of beginning of irradiation
Δt_{open}	s	Time to open the shutter (measured via proximity switches)
Δt_{close}	s	Time to close the shutter (measured via proximity switches)
$H_p(d)_{irr}$	mSv	Total dose (due to betas and photons) at an irradiation

Table 7. Example of the uncertainty budget for the correction due to the radioactive decay, $k_{de} = \exp[-(t_m - t_0) \cdot \ln 2/t_{1/2}]$.

Quantity	Value	Standard Uncertainty	Distribution	Sensitivity Coefficient	Uncertainty Contribution	Index
t_m	2598.00 d	0.58 d	rectangular	-0.00011	$-6.4 \cdot 10^{-5}$	87.5 %
t_0	0.000 d	0.024 d	rectangular	0.00011	$2.7 \cdot 10^{-6}$	0.2 %
t_{12}	958.20 d	0.08 d	normal	0.00030	$2.4 \cdot 10^{-5}$	12.4 %
k_{de}	0.15269	0.00007				

Table 8. Example of the uncertainty budget for the dose rate due to betas,

$$\dot{H}_{\mathrm{p}}(0.07)_{\mathrm{beta,irr}} = \left\{h_{\mathrm{p},D}\left(0.07;\ ^{147}\mathrm{Pm\ at\ 20\ cm\ with\ filter;\ 45°}\right) - \tau_{\mathrm{br}}\right\} \cdot \left\{\dot{D}_{\mathrm{R,ß}} / \left(1-\tau_{\mathrm{br}}\right)\right\} \cdot c_{\mathrm{abs}}(0.07) \cdot k_{\mathrm{de}}\ .$$

Quantity	Value	Standard Uncertainty	Distribution	Sensitivity Coefficient	Uncertainty Contribution	Index
t_{m}	2598.00 d	0.58 d	rectangular	$-8.6\cdot10^{-5}$ mSv/(h·d)	$-5.0\cdot10^{-5}$ mSv/h	0.0 %
t_0	0.000 d	0.024 d	rectangular	$8.6\cdot10^{-5}$ mSv/(h·d)	$2.1\cdot10^{-6}$ mSv/h	0.0 %
t_{12}	958.20 d	0.08 d	normal	0.00023 mSv/(h·d)	$1.9\cdot10^{-5}$ mSv/h	0.0 %
$T(0.07;source;0°)$	1	0	normal	0.12 mSv/h	0 mSv/h	0.0 %
$R(0.07;source;45°)$	0.720 Sv/Gy	0.013 Sv/Gy	normal	0.17 mGy/h	0.0021 mSv/h	30.8 %
τ_{br}	0.0055	0.0023	normal	-0.047 mSv/h	-0.00011 mSv/h	0.0 %
$\dot{D}_{\mathrm{R,ß}}$	0.0002884 mGy/s	0.0000063 mGy/s	normal	410 (Sv/Gy)·(s/h)	0.0026 mSv/h	47.3 %
c_{absDist}	1.046	0.013	normal	0.11 mSv/h	0.0015 mSv/h	15.8 %
c_{absMeas}	1.0000	0.0050	normal	0.12 mSv/h	0.00060 mSv/h	2.4 %
c_{absFit}	1.0000	0.0040	normal	0.12 mSv/h	0.00048 mSv/h	1.6 %
k_{Dist}	1.0000	0.0046	normal	0.12 mSv/h	0.00055 mSv/h	2.1 %
$\dot{H}_{\mathrm{p}}(0.07)_{\mathrm{beta,irr}}$	0.1191 mSv/h	0.0038 mSv/h				

Table 9. Example of the uncertainty budget for the dose rate due to photons,

$$\dot{H}_{\mathrm{p,phot,irr}} = \tau_{\mathrm{br}} \cdot \left\{\dot{D}_{\mathrm{R,ß}} / \left(1-\tau_{\mathrm{br}}\right)\right\} \cdot k_{\mathrm{de}} \cdot k_{\mathrm{Dist}}\ .$$

Quantity	Value	Standard Uncertainty	Distribution	Sensitivity Coefficient	Uncertainty Contribution	Index
t_{m}	2598.00 d	0.58 d	rectangular	$-6.3\cdot10^{-7}$ mSv/(h·d)	$-3.7\cdot10^{-7}$ mSv/h	0.0 %
t_0	0.000 d	0.024 d	rectangular	$6.3\cdot10^{-7}$ mSv/(h·d)	$1.5\cdot10^{-8}$ mSv/h	0.0 %
t_{12}	958.20 d	0.08 d	normal	$1.7\cdot10^{-6}$ mSv/(h·d)	$1.4\cdot10^{-7}$ mSv/h	0.0 %
τ_{br}	0.0055	0.0023	normal	0.16 mSv/h	0.00037 mSv/h	99.7 %
$\dot{D}_{\mathrm{R,ß}}$	0.0002884 mGy/s	0.0000063 mGy/s	normal	3.0 (Sv/Gy)·(s/h)	$1.9\cdot10^{-5}$ mSv/h	0.3 %
k_{Dist}	1.0000	0.0046	normal	0.00088	$4.0\cdot10^{-6}$ mSv/h	0.0 %
$\dot{H}_{\mathrm{p,phot,irr}}$	0.00088 mSv/h	0.00037 mSv/h				

Table 10. Example of the uncertainty budget for the total dose rate,

$$\dot{H}_{\mathrm{p}}(0.07)_{\mathrm{irr}} = \dot{H}_{\mathrm{p}}(0.07)_{\mathrm{beta,irr}} + \dot{H}_{\mathrm{p,phot,irr}} .$$

Quantity	Value	Standard Uncertainty	Distribution	Sensitivity Coefficient	Uncertainty Contribution	Index
t_{m}	2598.00 d	0.58 d	rectangular	$-8.7\cdot10^{-5}$ mSv/(h·d)	$-5.0\cdot10^{-5}$ mSv/h	0.0 %
t_0	0.000 d	0.024 d	rectangular	$8.7\cdot10^{-5}$ mSv/(h·d)	$2.1\cdot10^{-6}$ mSv/h	0.0 %
t_{12}	958.20 d	0.08 d	normal	0.00024 mSv/(h·d)	$1.9\cdot10^{-5}$ mSv/h	0.0 %
$T(0.07;source;0°)$	1	0	normal	0.12 mSv/h	0 mSv/h	0.0 %
$R(0.07;source;45°)$	0.720 Sv/Gy	0.013 Sv/Gy	normal	0.17 mGy/h	0.0021 mSv/h	30.4 %
τ_{br}	0.0055	0.0023	normal	0.11 mSv/h	0.00026 mSv/h	0.5 %
$\dot{D}_{\mathrm{R,ß}}$	0.0002884 mGy/s	0.0000063 mGy/s	normal	420 (Sv/Gy)·(s/h)	0.0026 mSv/h	47.5 %
c_{absDist}	1.046	0.013	normal	0.11 mSv/h	0.0015 mSv/h	15.6 %
c_{absMeas}	1.0000	0.0050	normal	0.12 mSv/h	0.00060 mSv/h	2.4 %
c_{absFit}	1.0000	0.0040	normal	0.12 mSv/h	0.00048 mSv/h	1.5 %
k_{Dist}	1.0000	0.0046	normal	0.12 mSv/h	0.00055 mSv/h	2.1 %
$\dot{H}_{\mathrm{p}}(0.07)_{\mathrm{irr}}$	0.1200 mSv/h	0.0038 mSv/h				

Table 11. Example of the uncertainty budget for irradiation time,

$$\Delta t_{\mathrm{dose}} = \left(t_{\mathrm{stop}} - t_{\mathrm{start}}\right) + \frac{\Delta t_{\mathrm{open}} - \Delta t_{\mathrm{close}}}{2} .$$

Quantity	Value	Standard Uncertainty	Distribution	Sensitivity Coefficient	Uncertainty Contribution	Index
t_{stop}	50.000 s	0.013 s	rectangular	1.0	0.0130 s	28.2 %
t_{start}	0.000 s	0.013 s	rectangular	-1.0	-0.0130 s	28.2 %
Δt_{open}	0.050 s	0.010 s	triangular	0.50	0.0051 s	4.4 %
$\Delta t_{\mathrm{close}}$	0.150 s	0.031 s	triangular	-0.50	-0.0150 s	39.2 %
Δt_{dose}	49.950 s	0.025 s				

Table 12. Example of the uncertainty budget for the total dose,
$H_{\mathrm{p}}(0.07)_{\mathrm{irr}} = \dot{H}_{\mathrm{p}}(0.07) \cdot \Delta t_{\mathrm{dose}}$.

Quantity	Value	Standard Uncertainty	Distribution	Sensitivity Coefficient	Uncertainty Contribution	Index
t_{m}	2598.00 d	0.58 d	rectangular	$-1.2\cdot10^{-6}$ mSv/d	$-7.0\cdot10^{-7}$ mSv	0.0 %
t_0	0.000 d	0.024 d	rectangular	$1.2\cdot10^{-6}$ mSv/d	$2.9\cdot10^{-8}$ mSv	0.0 %
t_{12}	958.20 d	0.08 d	normal	$3.3\cdot10^{-6}$ mSv/d	$2.6\cdot10^{-7}$ mSv	0.0 %
$T(0.07;source;0°)$	1	0	normal	0.0017 mSv	0 mSv	0.0 %
$R(0.07;source;45°)$	0.720 Sv/Gy	0.013 Sv/Gy	normal	0.0023 mGy	$2.9\cdot10^{-5}$ mSv	30.4 %
τ_{br}	0.0055	0.0023	normal	0.0016 mSv	$3.6\cdot10^{-6}$ mSv	0.5 %
$\dot{D}_{\mathrm{R,ß}}$	0.0002884 mGy/s	0.0000063 mGy/s	normal	5.8 (Sv/Gy)·s	$3.7\cdot10^{-5}$ mSv	47.4 %
c_{absDist}	1.046	0.013	normal	0.0016 mSv	$2.1\cdot10^{-5}$ mSv	15.6 %
c_{absMeas}	1.0000	0.0050	normal	0.0017 mSv	$8.3\cdot10^{-6}$ mSv	2.4 %
c_{absFit}	1.0000	0.0040	normal	0.0017 mSv	$6.6\cdot10^{-6}$ mSv	1.5 %
k_{Dist}	1.0000	0.0046	normal	0.0017 mSv	$7.7\cdot10^{-6}$ mSv	2.1 %
t_{stop}	50.000 s	0.013 s	rectangular	$3.3\cdot10^{-5}$ mSv/s	$4.3\cdot10^{-7}$ mSv	0.0 %
t_{start}	0.000 s	0.013 s	rectangular	$-3.3\cdot10^{-5}$ mSv/s	$-4.3\cdot10^{-7}$ mSv	0.0 %
Δt_{open}	0.050 s	0.010 s	triangular	$1.7\cdot10^{-5}$ mSv/s	$1.7\cdot10^{-7}$ mSv	0.0 %
$\Delta t_{\mathrm{close}}$	0.150 s	0.031 s	triangular	$-1.7\cdot10^{-5}$ mSv/s	$-5.1\cdot10^{-7}$ mSv	0.0 %
$H_{\mathrm{p}}(0.07)_{\mathrm{irr}}$	0.001665 mSv	0.000053 mSv				

Table 13. Summary of final results.

Quantity	Value	Expanded Uncertainty	Coverage Factor	Coverage Probability
k_{de}	0.15269	0.00014	2.00	95%
$\dot{H}_{\mathrm{p}}(0.07)_{\mathrm{beta,irr}}$	0.119 mSv/h	0.008 mSv/h	2.00	95%
$\dot{H}_{\mathrm{p,phot,irr}}$	0.0009 mSv/h	0.0008 mSv/h	2.00	95%
$\dot{H}_{\mathrm{p}}(0.07)_{\mathrm{irr}}$	0.120 mSv/h	0.008 mSv/h	2.00	95%
Δt_{dose}	49.95 s	0.05 s	2.00	95%
$H_{\mathrm{p}}(0.07)_{\mathrm{irr}}$	0.00166 mSv	0.00011 mSv	2.00	95%

Table 14. Standard uncertainty in % of the input variables $T(3;source;0°)$, τ_{br}, $c_{absDist}$, $c_{absMeas}$, and c_{absFit} for different sources.

Input Variable	Standard uncertainty in % for ^{147}Pm at 11 cm with filter	^{147}Pm at 20 cm with filter	^{85}Kr at 30 cm with filter	^{85}Kr at 50 cm with filter	^{85}Kr at 30 cm w/o filter	$^{90}Sr/^{90}Y$ at 30 cm with filter	$^{90}Sr/^{90}Y$ at 50 cm with filter	$^{90}Sr/^{90}Y$ at 11 cm w/o filter	$^{90}Sr/^{90}Y$ at 20 cm w/o filter	$^{90}Sr/^{90}Y$ at 30 cm w/o filter	$^{90}Sr/^{90}Y$ at 50 cm w/o filter	$^{106}Ru/^{106}Rh$ at 30 cm with filter	$^{106}Ru/^{106}Rh$ at 50 cm with filter	$^{106}Ru/^{106}Rh$ at 11 cm w/o filter	$^{106}Ru/^{106}Rh$ at 20 cm w/o filter
$T(3;source;0°)$	50	42	36	50	100	0.51	0.51	0.50	0.51	0.50	0.50	0.50	0.51	0.51	0.51
τ_{br}	50	42	36	50	100	37	50	50	50	50	50	50	50	50	50
$c_{absDist}$	0.60 1)	0.80 1)	0.10	0.10	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$c_{absMeas}$	0.50	0.50	0.08	0.08	0.08	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01
c_{absFit}	0.40	0.40	0.39	0.40	0.40	0.22	0.60	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40

1) Value valid for zero degree angle of radiation incidence, for $\alpha \neq 0°$, see table 15.

Table 15. Standard uncertainty in % of the input variable $c_{absDist}$ for the radiation source ^{147}Pm.

Input Variable	Standard uncertainty in % for an angle of radiation incidence α of 0°	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°
$c_{absDist}$ (^{147}Pm at 20 cm with filter)	0.80	0.81	0.82	0.85	0.90	0.95	1.01	1.09	1.17	1.27	1.37	1.48	1.60
$c_{absDist}$ (^{147}Pm at 11 cm w/o filter)	0.60	0.60	0.61	0.63	0.65	0.67	0.71	0.74	0.79	0.83	0.89	0.94	1.00

Table 16. Standard uncertainty in % of the input variable k_{Dist} for different distances from the radiation source.

Input Variable	Standard uncertainty in % for an angle of radiation incidence α of 0°	5°	10°	15°	20°	25°	30°	35°	40°	45°	50°	55°	60°	65°	70°	75°
k_{Dist} (11 cm)	0.53	0.53	0.54	0.56	0.59	0.62	0.67	0.72	0.77	0.83	0.90	0.97	1.05	1.13	1.22	1.31
k_{Dist} (20 cm)	0.29	0.29	0.30	0.31	0.32	0.34	0.37	0.39	0.42	0.46	0.50	0.54	0.58	0.62	0.67	0.72
k_{Dist} (30 cm)	0.19	0.19	0.20	0.21	0.22	0.23	0.24	0.26	0.28	0.31	0.33	0.36	0.39	0.42	0.45	0.48
k_{Dist} (50 cm)	0.12	0.12	0.12	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.20	0.21	0.23	0.25	0.27	0.29

Table 17. Standard uncertainty in % of the input variable $R(d;source;\alpha)$ for the quantities $H_p(0.07)$ on the slab and rod phantom, $H_p(0.07)_{slab}$ and $H_p(0.07)_{rod}$, respectively, $H_p(3)$ on the slab phantom, $H_p(3)_{slab}$, and $H'(0.07)$ for different sources.

Angle of Radiation Incidence α	Standard uncertainty in % for						
	^{147}Pm at 20 cm with filter	^{85}Kr at 30 cm with filter	^{90}Sr/^{90}Y and ^{106}Ru/^{106}Rh at 30 cm with filter			^{90}Sr/^{90}Y at 20 cm, 30 cm, and 50 cm without filter	
	$H_p(0.07)_{slab}$, $H_p(0.07)_{rod}$, $H'(0.07)$	$H_p(0.07)_{slab}$, $H_p(0.07)_{rod}$, $H'(0.07)$	$H_p(0.07)_{slab}$, $H'(0.07)$	$H_p(0.07)_{rod}$	$H_p(3)_{slab}$	$H_p(0.07)_{slab}$, $H'(0.07)$	$H_p(0.07)_{rod}$
0°	0.00	0.00	0.00	3.00	0.00	0.00	3.00
5°	0.02	0.02	0.02	3.00	---	0.02	3.00
10°	0.09	0.06	0.06	3.00	---	0.06	3.00
15°	0.20	0.14	0.14	3.00	0.20	0.14	3.00
20°	0.36	0.24	0.24	3.00	---	0.24	3.00
25°	0.56	0.37	0.37	3.00	---	0.37	3.00
30°	0.80	0.54	0.54	3.00	0.80	0.54	3.00
35°	1.09	0.72	0.72	3.00	---	0.72	3.00
40°	1.40	0.94	0.94	3.00	---	0.94	3.00
45°	1.76	1.17	1.17	3.00	1.76	1.17	3.00
50°	2.14	1.43	1.43	3.00	---	1.43	3.00
55°	2.56	1.71	1.71	3.00	---	1.71	3.00
60°	3.00	2.00	2.00	3.00	3.00	2.00	3.00
65°	---	2.31	2.31	3.00	---	2.31	3.00
70°	---	2.63	2.63	3.00	---	2.63	3.00
75°	---	2.96	2.96	3.00	4.45	2.96	3.00

For all other source geometries (*source*), data for $R(d;source;\alpha)$ are only available for $\alpha = 0°$ with a trivial uncertainty of zero except for the quantity $H_p(0.07)_{rod}$ and ^{90}Sr/^{90}Y and ^{106}Ru/^{106}Rh sources the uncertainty is 3.00 %.

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