Procedure for determining the specific activities of radionuclides in marine sediment and suspended particulate matter by gamma spectrometry

D-γ-SPEKT-MSEDI-01

Authors:

S. Schmied

A. Meyer

I. Bendler

A. Gottschalk

J. Hermann†

Federal coordinating office for seawater, marine suspended particulate matter and marine sediment

(Leitstelle für Meerwasser, Meeresschwebstoff und -sediment)

ISSN 1865-8725

Version November 2025

Procedures' Manual for monitoring of radioactive substances in the environment and of external radiation

(Messanleitungen für die „Überwachung radioaktiver Stoffe in der Umwelt und externer Strahlung")

Procedure for determining the specific activities of radionuclides in marine sediment and suspended particulate matter by gamma spectrometry

1 Scope

The procedure outlined in the following is suitable for determining the specific activities of fission and activation products as well as naturally occurring radionuclides in marine sediment and suspended particulate matter according to the Radiation Protection Act (Strahlenschutzgesetz, StrlSchG) [1] in the IMIS routine operation mode [2]. In particular, the determination of Cs-137 as a reference nuclide allows recording and evaluating the chronological trend of the long-term contamination.

Note:
The procedure is also applicable in the IMIS intensive operation mode after the occurrence of higher activities for marine sediment and suspended particulate matter as well as seawater [2].

2 Sampling

Depending on the type of sediment, samples are taken with the appropriate sampling device:

— the Gemini corer for soft, muddy sediment (see Figure 1),

— the large box corer and the small box corer (Reineck corer) for solid sediment, also with high sand content (see Figures 2 and 3) and

— the cheeks corer (see Figure 4) for sediments from which samples cannot be taken with the devices mentioned above, because they consist of gravel and coarse sand, for example, or if only the sediment surface is of interest

The Gemini Corer takes two sediment cores directly parallel from the seabed. Relatively undisturbed surfaces can be obtained with this corer.

Sediment cores, usually two parallel cores, are taken from the sediment in the corer boxes aboard using Perspex stabbing tubes. The surfaces of the cores should be kept undisturbed as far as possible, so a few centimetres of seawater must remain above the sample.

The sediment cores are cut horizontally into slices of one to five centimetres thickness – usually two centimetres – and transferred to polyethylene boxes as mixed samples of the same horizons, so that the vertical profile of the sediment cores can later be determined by gamma spectrometry.

In the case of samples obtained with the cheeks corer without a defined layer structure, it only makes sense to take the top two to three centimetres.

Fig. 1: Gemini Corer

Fig. 2: Large box corer

Fig. 3: Small box corer

Fig. 4: Cheeks corer

Marine suspended particulate matter is obtained aboard from at least ten cubic metres of seawater using a high-speed tube centrifuge connected to a seawater main. Other filtration methods are too time-consuming to obtain enough sample material because of the low concentration of suspended particulate matter in the seawater.

Both the marine sediment samples taken as well as the marine suspended particulate matter obtained from the tube centrifuge are frozen at -5 °C to -20 °C as soon as possible after sampling.

3 Analysis

3.1 Principle of the procedure

The marine sediment or suspended particulate matter samples are measured directly by gamma spectrometry after sample preparation. From the impulse height spectra obtained, the specific activities of a variety of gamma-emitting radionuclides can be determined:

- natural occurring radionuclides such as Pb-210, Ra-226, Ra-228, Th-228, U-238,
- the primordial radionuclide K-40,
- the cosmogenic radionuclide Be-7,

artificial radionuclides such as Cs-137, Cs-134, Ru-106, Co-60, Sb-125, Am-241.

Note:
In the IMIS intensive operation mode, also seawater samples are measured directly

3.2 Sample preparation

In order to obtain as homogeneous a sample as possible in a defined geometry, the frozen marine sediment or suspended particulate matter samples are then freeze-dried. Obvious foreign bodies such as shell parts or stones are removed from the sediment samples. The dry samples are then homogenized using a ball mill and weighed into suitable plastic measuring containers. The filling level is determined. Experience has shown that the bulk density of the counting sources is about 1 $g \cdot cm^{-3}$. The specific activity is referred to the dry mass.

Note:
In the IMIS intensive operation mode, the result must be available quickly. Therefore, the marine sediment or suspended particulate matter samples are not frozen after sampling. The wet samples are transferred into suitable measuring containers and later measured directly in the laboratory. Drying is not necessary.

3.3 Radiochemical separation

A radiochemical separation is not required.

4 Measuring the activity

4.1 General

In the General Chapter γ-SPEKT/GRUNDL of this Procedures' Manual, the fundamentals of gamma spectrometry and technical designs of suitable gamma spectrometry measuring devices are described [3].

4.2 Background

By a regular, e. g. monthly, recording of background spectra, disturbing contributions from the surroundings or the detector are recorded. In the case of natural radionuclides, gamma lines also occur in the background spectrum, which must be taken into account when determining activity.

Further considerations on natural radionuclides can be found in the General Chapter γ-SPEKT/NATRAD, on the determination of the background in the General Chapter γ-SPEKT/NULLEF of this Procedures' Manual [4, 5].

4.3 Calibration

The calibration of the measuring system is carried out with calibration samples, which contain different radionuclides whose activities are traceable to a national primary standard. For the calibration of the detection efficiency, measurements are carried out in all required geometries and the durations of measurement are selected in such a way that the counting rates of the radionuclides are in the range of one percent of the relative counting uncertainty. For the energy calibration as well as for continuous checking of the detection efficiencies, a europium-152 source is measured weekly.

The calculations of the detection efficiencies for the measuring geometries of the respective gamma spectrometry measuring devices as well as their energy calibrations are carried out with a commercial evaluation software for gamma spectrometry.

4.4 Measurement

For the measurement, the counting sources are placed centrally on the detector, if necessary also by means of centering rings. Depending on the specific activity of the radionuclides to be determined, the duration of measurement is usually between 24 hours and 48 hours.

5 Calculation of the results

5.1 Output quantity

The specific activity a_r of a single nuclide r at the time of sampling is calculated according to Equation (1):

$$a_\mathrm{r} = \frac{f_\mathrm{A}}{\varepsilon_\mathrm{r} \cdot p_\gamma \cdot f_\mathrm{m} \cdot m_\mathrm{DM}} \cdot R_\mathrm{n,r} = \varphi \cdot R_\mathrm{n,r} \tag{1}$$

with

$$f_\mathrm{A} = \mathrm{e}^{\lambda_\mathrm{r} \cdot t_\mathrm{A}} \tag{2}$$

$$f_\mathrm{m} = \frac{1 - \mathrm{e}^{-\lambda_\mathrm{r} \cdot t_\mathrm{m}}}{\lambda_\mathrm{r} \cdot t_\mathrm{m}} \tag{3}$$

The calculation of the net count rate depends on the type of radionuclides:

a) Is the radionuclide in question of artificial or cosmogenic origin, Equation (4) is applied:

$$R_\mathrm{n,r} = R_\mathrm{g,r} - R_\mathrm{T,r} \tag{4}$$

b) For radionuclides of natural or primordial origin, Equation (5) is used:

$$R_\mathrm{n,r} = R_\mathrm{g,r} - R_\mathrm{T,r} - (R_\mathrm{g,0,r} - R_\mathrm{T,0,r}) = R_\mathrm{g,r} - R_\mathrm{T,r} - -R_\mathrm{n,0,r} \tag{5}$$

In the Equations (1) to (5) are:

a_r specific activity of the radionuclide r, in $\mathrm{Bq \cdot kg^{-1}}$;

f_A decay correction factor related to the sampling;

f_m decay correction factor related to the measurement duration;

m_DM dry mass of the sediment or particulate suspended matter sample, in kg;

Note:
If seawater is measured in the intensive operation mode, the mass of seawater is used for m_DM.

p_γ absolute emission intensity for the gamma emission;

$R_\mathrm{g,r}$ gross count rate of the considered gamma line of the radionuclide r, in $\mathrm{s^{-1}}$;

$R_\mathrm{g,0,r}$ gross count rate of the background line of the radionuclide r, in $\mathrm{s^{-1}}$;

$R_\mathrm{n,r}$ net count rate of the considered gamma line of the radionuclide r, in $\mathrm{s^{-1}}$;

$R_\mathrm{n,0,r}$ net count rate of the background line of the radionuclide r, in $\mathrm{s^{-1}}$:

$R_\mathrm{T,r}$ background count rate of the gamma line of the radionuclide r, e. g. the trapezium background count rate, in $\mathrm{s^{-1}}$;

$R_{\mathrm{T,0,r}}$ background count rate of the background line of the radionuclide r, e. g. the trapezium background count rate, in s^{-1};

t_{A} time period between sampling and beginning of measurement, in s;

t_{m} duration of measurement of the counting source, in s;

ε_{r} detection efficiency of the radionuclide r, in $Bq^{-1} \cdot s^{-1}$;

λ_{r} decay constant of the radionuclide r, in s^{-1};

φ procedural calibration factor, in $Bq \cdot s \cdot kg^{-1}$.

5.2 Standard uncertainty of the output quantity

Uncertainty contributions arising from sampling are not taken into account in the framework of this Procedures' Manual, as these can depend on many different and often not quantifiable factors.

For calculating the standard uncertainty of the specific activity $u(a_{\mathrm{r}})$, the relative variance of the procedural calibration factor $u_{\mathrm{rel}}^2(\varphi)$ is necessary which is determined by Equation (6).

$$u_{\mathrm{rel}}^2(\varphi) = u_{\mathrm{rel}}^2(f_{\mathrm{A}}) + u_{\mathrm{rel}}^2(\varepsilon_{\mathrm{r}}) + u_{\mathrm{rel}}^2(p_{\gamma}) + u_{\mathrm{rel}}^2(f_{\mathrm{m}}) + u_{\mathrm{rel}}^2(m_{\mathrm{DM}}) \tag{6}$$

Furthermore, the kind of origin of the radionuclide under consideration is important for calculating the standard uncertainty of the specific activity. In case of artificial and the cosmogenic radionuclide Be-7 the calculation is carried out according to Equation (7):

$$u(a_{\mathrm{r}}) = \sqrt{a_{\mathrm{r}}^2 \cdot u_{\mathrm{rel}}^2(\varphi) + \varphi^2 \cdot \left[\frac{1}{t_{\mathrm{m}}} \cdot \left(R_{\mathrm{g,r}} + R_{\mathrm{T,r}} \cdot \frac{b_{\mathrm{r}}}{2 \cdot L_{\mathrm{r}}}\right)\right]} \tag{7}$$

while in case of natural and primordial radionuclides, Equation (8) is used:

$$\begin{aligned} u(a_{\mathrm{r}}) = \Bigg\{ a_{\mathrm{r}}^2 \cdot u_{\mathrm{rel}}^2(\varphi) + \varphi^2 \cdot \Bigg[\frac{R_{\mathrm{n,r}}}{t_{\mathrm{m}}} + \frac{R_{\mathrm{T,r}}}{t_{\mathrm{m}}} \cdot \left(1 + \frac{b_{\mathrm{r}}}{2 \cdot L_{\mathrm{r}}}\right) + \frac{R_{\mathrm{n,0,r}}}{t_{\mathrm{m}}} + \\ + \frac{1}{t_0} \cdot \left(R_{\mathrm{g,0,r}} + R_{\mathrm{T,0,r}} \cdot \frac{b_{\mathrm{0,r}}}{2 \cdot L_{\mathrm{0,r}}}\right) \Bigg] \Bigg\}^{\frac{1}{2}} \end{aligned} \tag{8}$$

In the Equations (6) to (8), following applies:

b_{r} base width of the gamma line of the radionuclide r in the counting source;

$b_{\mathrm{0,r}}$ base width of the gamma line of the background;

L_{r} number of channels to the left and right of the gamma line of the radionuclide r in the counting source used for determining the background, in keV or channels;

$L_{0,\mathrm{r}}$ number of channels to the left and right of the gamma line of the background used for background determination, in keV or channels;

t_0 duration of background measurement, in s;

$u(a_{\mathrm{r}})$ standard uncertainty of the specific activity of the radionuclide r, in $\mathrm{Bq \cdot kg^{-1}}$;

$u_{\mathrm{rel}}(f_{\mathrm{A}})$ relative standard uncertainty of the decay correction factor related to sampling;

$u_{\mathrm{rel}}(f_{\mathrm{m}})$ relative standard uncertainty of the decay correction factor related to the measurement duration;

$u_{\mathrm{rel}}(m_{\mathrm{DM}})$ relative standard uncertainty of the dry mass, in kg;

$u_{\mathrm{rel}}(p_{\gamma})$ relative standard uncertainty of the absolute emission intensity;

$u_{\mathrm{rel}}(\varepsilon_{\mathrm{r}})$ relative standard uncertainty of the detection efficiency of the radionuclide r;

$u_{\mathrm{rel}}(\varphi)$ relative standard uncertainty of the procedural calibration factor.

The standard uncertainty of the analysis result includes the standard uncertainties of the statistical counting, of the calibration, of the emission intensities and of the mass of the sample. The standard uncertainties of the duration of measurement, of the decay constant, of the position of the peak maximum and of the full width at half maximum h as well as the relative standard uncertainties of the decay correction factors $u_{\mathrm{rel}}(f_{\mathrm{A}})$ and $u_{\mathrm{rel}}(f_{\mathrm{m}})$ are neglected.

6 Characteristic limits of the procedure

The calculation of the characteristic limits follows the standard series ISO 11929 [6]. For further considerations, it is referred to the General Chapters CHAGR-ISO-01 and CHAGR-ISO-02 of this Procedures' Manual [7, 8].

6.1 Decision threshold

The decision threshold for the specific activity a_{r}^* is determined for artificial and cosmogenic radionuclides according to Equation (9), for natural and primordial radionuclides according to Equation (10):

$$a_{\mathrm{r}}^* = k_{1-\alpha} \cdot \varphi \cdot \sqrt{\frac{R_{\mathrm{T,r}}}{t_{\mathrm{m}}} \cdot \left(1 + \frac{b_{\mathrm{r}}}{2 \cdot L_{\mathrm{r}}}\right)} \tag{9}$$

$$a_{\mathrm{r}}^{*} = k_{1-\alpha} \cdot \varphi \cdot \sqrt{\frac{1}{t_{\mathrm{m}}} \cdot \left[R_{\mathrm{T,r}} \cdot \left(1 + \frac{b_{\mathrm{r}}}{2 \cdot L_{\mathrm{r}}} \right) + R_{\mathrm{n0,r}} + R_{\mathrm{g0,r}} + R_{\mathrm{T0,r}} \cdot \frac{b_{0,\mathrm{r}}}{2 \cdot L_{0,\mathrm{r}}} \right]} \quad (10)$$

Herein are:

a_{r}^{*} decision threshold for the specific activity of the radionuclide r, in Bq·kg^{-1};

$k_{1\text{-}\alpha}$ quantile of the normal distribution for α = 0,0014.

6.2 Detection limit

The detection limit for the specific activity $a_{\mathrm{r}}^{\#}$ is given by Equation (11):

$$a_{\mathrm{r}}^{\#} = \frac{a_{\mathrm{r}}^{*} \cdot \Psi}{\theta} \cdot \left\{ 1 + \sqrt{1 - \frac{\theta}{\Psi^2} \cdot \left(1 - \frac{k_{1-\beta}^2}{k_{1-\alpha}^2} \right)} \right\} \quad (11)$$

with the auxiliary quantities Ψ and θ calculated according the Equations (12) and (13):

$$\theta = 1 - k_{1-\beta}^2 \cdot u_{\mathrm{rel}}^2(\varphi) \quad (12)$$

$$\Psi = 1 + \frac{k_{1-\beta}^2}{2 \cdot a_{\mathrm{r}}^{*}} \cdot \varphi \cdot \frac{1}{t_{\mathrm{m}}} \quad (13)$$

Herein are:

$a_{\mathrm{r}}^{\#}$ detection limit for the specific activity of the radionuclide r, in Bq·kg^{-1};

$k_{1\text{-}\beta}$ quantile of the normal distribution for β = 0,05.

6.3 Limits of the coverage interval

The calculation of limits of the coverage interval is not required.

7 Worked examples

The evaluation can be carried out either manually (see Section 7.1) or software supported by the software UncertRadio (see Section 7.2). A project file for the software UncertRadio is available on the website of this Procedures' Manual.

In the case that no interfering gamma line is present at the energy to be analysed, the base width b is set equal to 1,7 times the full width at half maximum h from calibration measurements. However, the number of channels L should not be set greater than $b/2$.

7.1 Manual evaluation

In the manual evaluation, the interim results and the result are given rounded with four significant digits.

7.1.1 Artificial radionuclides using Cs-137 as an example

The following input values are used for the worked example:

$R_{\mathrm{g,Cs\text{-}137}}$	=	0,06 s^{-1};	$b_{\mathrm{Cs\text{-}137}}$	=	2,363 keV;
$R_{\mathrm{T,Cs\text{-}137}}$	=	0,01 s^{-1};	$L_{\mathrm{Cs\text{-}137}}$	=	1,183 keV;
t_{A}	=	$15{,}8 \cdot 10^{6}$ s;	$\lambda_{\mathrm{Cs\text{-}137}}$	=	$0{,}73 \cdot 10^{-9}$ s^{-1};
t_{m}	=	86 400 s;			
m_{DM}	=	0,100 kg;	$u_{\mathrm{rel}}(m_{\mathrm{DM}})$	=	0,02;
$\varepsilon_{\mathrm{Cs\text{-}137}}$	=	0,025 $Bq^{-1} \cdot s^{-1}$;	$u_{\mathrm{rel}}(\varepsilon_{\mathrm{Cs\text{-}137}})$	=	0,05;
p_{γ}	=	0,851;	$u_{\mathrm{rel}}(p_{\gamma})$	=	0,002;

The values of the decay correction factors f_{A} and f_{m} are calculated with the Equations (2) and (3):

$$f_{\mathrm{A}} = \mathrm{e}^{0{,}73 \cdot 10^{-9}\ \mathrm{s}^{-1} \cdot 15{,}8 \cdot 10^{6}\ \mathrm{s}} \approx 1{,}012$$

$$f_{\mathrm{m}} = \frac{1 - \mathrm{e}^{-0{,}73 \cdot 10^{-9}\ \mathrm{s}^{-1} \cdot 86{,}4 \cdot 10^{3}\ \mathrm{s}}}{0{,}73 \cdot 10^{-9}\ \mathrm{s}^{-1} \cdot 86{,}4 \cdot 10^{3}\ \mathrm{s}} \approx 1{,}000$$

The value of the procedural calibration factor is determined from Equation (1):

$$\varphi \approx \frac{1{,}012}{0{,}025\ \mathrm{Bq}^{-1} \cdot \mathrm{s}^{-1} \cdot 0{,}851 \cdot 1{,}000 \cdot 0{,}1\ \mathrm{kg}} \approx 0{,}4755 \cdot 10^{3}\ \mathrm{Bq} \cdot \mathrm{s} \cdot \mathrm{kg}^{-1}$$

In case of artificial radionuclides, the net count rate is calculated using Equation (4):

$$R_{\mathrm{n,Cs-137}} = 0{,}06\ \mathrm{s}^{-1} - 0{,}01\ \mathrm{s}^{-1} = 0{,}05\ \mathrm{s}^{-1}$$

The specific activity $a_{\mathrm{Cs\text{-}137}}$ of Cs-137 is calculated with Equation (1):

$$a_{\mathrm{Cs-137}} \approx 0{,}4755 \cdot 10^{3} \cdot 0{,}05\ \mathrm{s}^{-1} \approx 23{,}77\ \mathrm{Bq} \cdot \mathrm{kg}^{-1}\ (\mathrm{DM})$$

The relative variance of the procedural calibration factor $u_{\mathrm{rel}}^{2}(\varphi)$ is determined by Equation (6):

$$u_{\mathrm{rel}}^{2}(\varphi) = 0^{2} + 0{,}05^{2} + 0{,}002^{2} + 0^{2} + 0{,}02^{2} = 2{,}904 \cdot 10^{-3}$$

The standard uncertainty of the specific Cs-137 activity $u(a_{\mathrm{Cs\text{-}137}})$ is calculated with Equation (7):

$$u(a_{\mathrm{Cs-137}}) \approx \{(23{,}77\ \mathrm{Bq \cdot kg^{-1}})^2 \cdot 2{,}904 \cdot 10^{-3} + (0{,}4755 \cdot 10^3\ \mathrm{Bq \cdot s \cdot kg^{-1}})^2 \cdot$$

$$\cdot \frac{1}{86{,}4\ \cdot 10^3\ \mathrm{s}} \cdot \left(0{,}06\ \mathrm{s^{-1}} + \frac{0{,}01\ \mathrm{s^{-1}} \cdot 2{,}363\ \mathrm{keV}}{2 \cdot 1{,}183\ \mathrm{keV}}\right)\Bigg\}^{\frac{1}{2}} \approx$$

$$\approx 1{,}351\ \mathrm{Bq \cdot kg^{-1}\ (DM)}$$

The measurement result of the specific activity of Cs-137 is thus:

$$a_{\mathrm{Cs-137}} = (23{,}77 \pm 1{,}351)\ \mathrm{Bq \cdot kg^{-1}\ (DM)}$$

With the values for the quantiles $k_{1\text{-}\alpha}$ of 3 and $k_{1\text{-}\beta}$ of 1,645, the decision threshold of the specific activity $a^*_{\text{Cs-137}}$ is calculated using Equation (9)

$$a^*_{\mathrm{Cs-137}} \approx 3 \cdot 0{,}4755 \cdot 10^3\ \mathrm{Bq \cdot s \cdot kg^{-1}} \cdot \sqrt{\frac{0{,}01\ \mathrm{s^{-1}}}{86{,}4\ \cdot 10^3\ \mathrm{s}} \cdot \left(1 + \frac{2{,}363\ \mathrm{keV}}{2 \cdot 1{,}183\ \mathrm{keV}}\right)} \approx$$

$$\approx 0{,}6861\ \mathrm{Bq \cdot kg^{-1}\ (DM)}$$

For calculating the detection limit of the specific activity $a^{\#}_{\text{Cs-137}}$, the auxiliary quantities are determined with the Equations (12) and (13):

$$\theta = 1 - 1{,}645^2 \cdot 0{,}0029 \approx 0{,}9921$$

$$\Psi \approx 1 + \frac{1{,}645^2}{2 \cdot 0{,}6861\ \mathrm{Bq \cdot kg^{-1}}} \cdot 0{,}4755 \cdot 10^3\ \mathrm{Bq \cdot s \cdot kg^{-1}} \cdot \frac{1}{86{,}4\ \cdot 10^3\ \mathrm{s}} \approx 1{,}011$$

The value of the detection limit is calculated using Equation (11):

$$a^{\#}_{\mathrm{Cs-137}} \approx \frac{0{,}6861\ \mathrm{Bq \cdot kg^{-1}} \cdot 1{,}011}{0{,}9921} \cdot \left\{1 + \sqrt{1 - \frac{0{,}9921}{1{,}011^2} \cdot \left(1 - \frac{1{,}645^2}{3^2}\right)}\right\} \approx$$

$$\approx 1{,}095\ \mathrm{Bq \cdot kg^{-1}\ (DM)}$$

7.1.2 Natural radionuclides using K-40 as an example

The following numerical values are used for the calculation:

$R_{\text{g,K-40}}$	=	0,096 s^{-1};	$R_{\text{T,K-40}}$	=	0,004 s^{-1};
$b_{\text{K-40}}$	=	14 channels;	$L_{\text{K-40}}$	=	6 channels;
$R_{\text{g,0,K-40}}$	=	0,0021 s^{-1};	$R_{\text{T,0,K-40}}$	=	0,0006 s^{-1};
$b_{\text{0,K-40}}$	=	19 channels;	$L_{\text{0,K-40}}$	=	8 channels;
t_{m}	=	$0{,}26 \cdot 10^6$ s;	t_{A}	=	$15{,}8 \cdot 10^6$ s;

t_0	=	0,26·10^6 s;	$\lambda_{\text{K-40}}$	=	17,2·10^-18 s^-1;
m_{DM}	=	0,100 kg;	$u_{\text{rel}}(m_{\text{DM}})$	=	0,02;
$\varepsilon_{\text{K-40}}$	=	0,012 Bq^-1·s^-1;	$u_{\text{rel}}(\varepsilon_{\text{K-40}})$	=	0,05;
p_γ	=	0,107;	$u_{\text{rel}}(p_\gamma)$	=	0,002;

The values of the decay correction factors f_{A} and f_{m} are calculated with the Equations (2) and (3):

$$f_{\text{A}} = \mathrm{e}^{17{,}2\cdot 10^{-18}\ \mathrm{s}^{-1}\cdot 15{,}8\cdot 10^{6}\ \mathrm{s}} \approx 1{,}000$$

$$f_{\text{m}} = \frac{1 - \mathrm{e}^{-17{,}2\cdot 10^{-18}\ \mathrm{s}^{-1}\cdot 0{,}26\cdot 10^{6}\ \mathrm{s}}}{17{,}2\ \cdot 10^{-18}\ \mathrm{s}^{-1}\ \cdot 0{,}26\ \cdot 10^{6}\ \mathrm{s}} \approx 1{,}000$$

The value of the procedural calibration factor is determined from Equation (1):

$$\varphi \approx \frac{1{,}000}{0{,}012\ \mathrm{Bq}^{-1}\cdot \mathrm{s}^{-1}\cdot 0{,}107\cdot 1{,}000\cdot 0{,}1\ \mathrm{kg}} \approx 7{,}788\cdot 10^{3}\ \mathrm{Bq}\cdot \mathrm{s}\cdot \mathrm{kg}^{-1}$$

For the natural radionuclide K-40, the net count rate is calculated using Equation (5)

$$R_{\text{n,K}-40} = 0{,}096\ \mathrm{s}^{-1} - 0{,}004\ \mathrm{s}^{-1} - (0{,}0021\ \mathrm{s}^{-1} - 0{,}0006\ \mathrm{s}^{-1})\ = 0{,}0905\ \mathrm{s}^{-1}$$

The specific activity $a_{\text{K-40}}$ is calculated using Equation (1):

$$a_{\text{K}-40} = 7{,}788\cdot 10^{3}\ \mathrm{Bq}\cdot \mathrm{s}\cdot \mathrm{kg}^{-1}\cdot 0{,}0905\ \mathrm{s}^{-1} = 0{,}7048\cdot 10^{3}\ \mathrm{Bq}\cdot \mathrm{kg}^{-1}\ (\mathrm{DM})$$

The relative variance of the procedural calibration factor is determined by Equation (6):

$$u_{\text{rel}}^{2}(\varphi) = 0^2 + 0{,}05^2 + 0{,}002^2 + 0^2 + 0{,}02^2 = 2{,}904\cdot 10^{-3}$$

The standard uncertainty of the specific K-40 activity $u(a_{\text{K-40}})$ is calculated with Equation (8):

$$\begin{aligned} u(a_{\text{K}-40}) = \Big\{ & \left(0{,}7048\cdot 10^{3}\ \mathrm{Bq}\cdot \mathrm{kg}^{-1}\right)^2\cdot 2{,}904\cdot 10^{-3} + \left(7{,}788\cdot 10^{3}\ \mathrm{Bq}\cdot \mathrm{s}\cdot \mathrm{kg}^{-1}\right)^2\cdot \\ & \cdot\Bigg[\frac{0{,}092\ \mathrm{s}^{-1}}{0{,}26\ \cdot 10^{6}\ \mathrm{s}} + \frac{0{,}004\ \mathrm{s}^{-1}}{0{,}26\ \cdot 10^{6}\ \mathrm{s}}\cdot\left(1 + \frac{14\ \text{channels}}{2\cdot 6\ \text{channels}}\right) + \frac{0{,}0015\ \mathrm{s}^{-1}}{0{,}26\ \cdot 10^{6}\ \mathrm{s}} + \\ & + \frac{1}{0{,}26\ \cdot 10^{6}\ \mathrm{s}}\cdot\left(0{,}0021\ \mathrm{s}^{-1} + 0{,}0006\ \mathrm{s}^{-1}\cdot\frac{19\ \text{channels}}{2\cdot 8\ \text{channels}}\right)\Bigg]\Big\}^{\frac{1}{2}} = \\ & = 38{,}30\ \mathrm{Bq}\cdot \mathrm{kg}^{-1}\ (\mathrm{DM}) \end{aligned}$$

The specific activity $a_{\text{K-40}}$ of K-40 is thus:

$$a_{\mathrm{K-40}} = (704{,}8 \ \pm 38{,}30)\ \mathrm{Bq \cdot kg^{-1}}\ (\mathrm{DM})$$

With the values for the quantiles $k_{1\text{-}\alpha}$ of 3 and $k_{1\text{-}\beta}$ of 1,645, the decision threshold of the specific activity $a^{*}_{\text{K-40}}$ is calculated using Equation (10):

$$a^{*}_{\mathrm{K-40}} \approx 3 \cdot 7{,}788 \cdot 10^{3}\ \mathrm{Bq \cdot s \cdot kg^{-1}} \cdot \left[\frac{0{,}004\ \mathrm{s^{-1}}}{0{,}26\ \cdot 10^{6}\ \mathrm{s}} \cdot \left(1 + \frac{14\ \text{channels}}{2 \cdot 6\ \text{channels}}\right) + \right.$$

$$\left. + \frac{0{,}0015\ \mathrm{s^{-1}}}{0{,}26\ \cdot 10^{6}\ \mathrm{s}} + \frac{0{,}0021\ \mathrm{s^{-1}}}{0{,}26\ \cdot 10^{6}\ \mathrm{s}} + \frac{0{,}0006\ \mathrm{s^{-1}}}{0{,}26\ \cdot 10^{6}\ \mathrm{s}} \cdot \frac{19\ \text{channels}}{2 \cdot 8\ \text{channels}}\right]^{\frac{1}{2}} \approx$$

$$\approx 5{,}220\ \mathrm{Bq \cdot kg^{-1}}\ (\mathrm{DM})$$

For calculating the detection limit of the specific activity $a^{\#}_{\text{K-40}}$, the auxiliary quantities are determined with the Equations (12) and (13):

$$\theta = 1 - 1{,}645^{2} \cdot 0{,}0029 \approx 0{,}9921$$

$$\Psi \approx 1 + \frac{1{,}645^{2}}{2 \cdot 5{,}220\ \mathrm{Bq \cdot kg^{-1}}} \cdot 7{,}788 \cdot 10^{3}\ \mathrm{Bq \cdot s \cdot kg^{-1}} \cdot \frac{1}{0{,}26\ \cdot 10^{6}\ \mathrm{s}} \approx 1{,}008$$

The value of the detection limit is calculated using Equation (11):

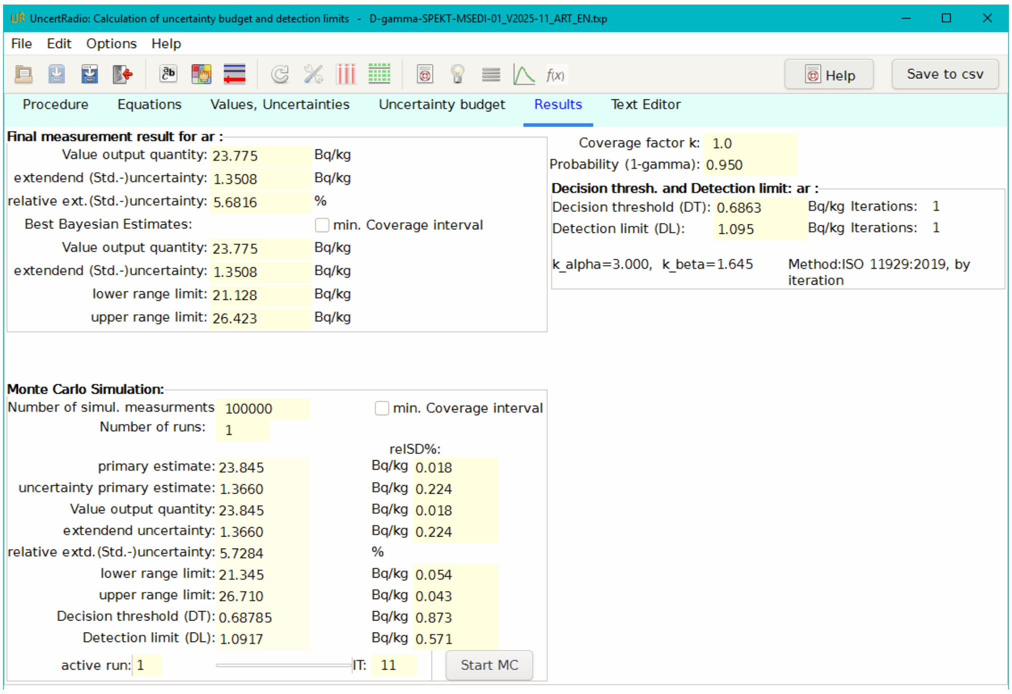
$$a^{\#}_{\mathrm{K-40}} \approx \frac{5{,}220\ \mathrm{Bq \cdot kg^{-1}} \cdot 1{,}008}{0{,}9921} \cdot \left\{1 + \sqrt{1 - \frac{0{,}9921}{1{,}008^{2}} \cdot \left(1 - \frac{1{,}645^{2}}{3^{2}}\right)}\right\} \approx$$

$$\approx 8{,}291\ \mathrm{Bq \cdot kg^{-1}}\ (\mathrm{DM})$$

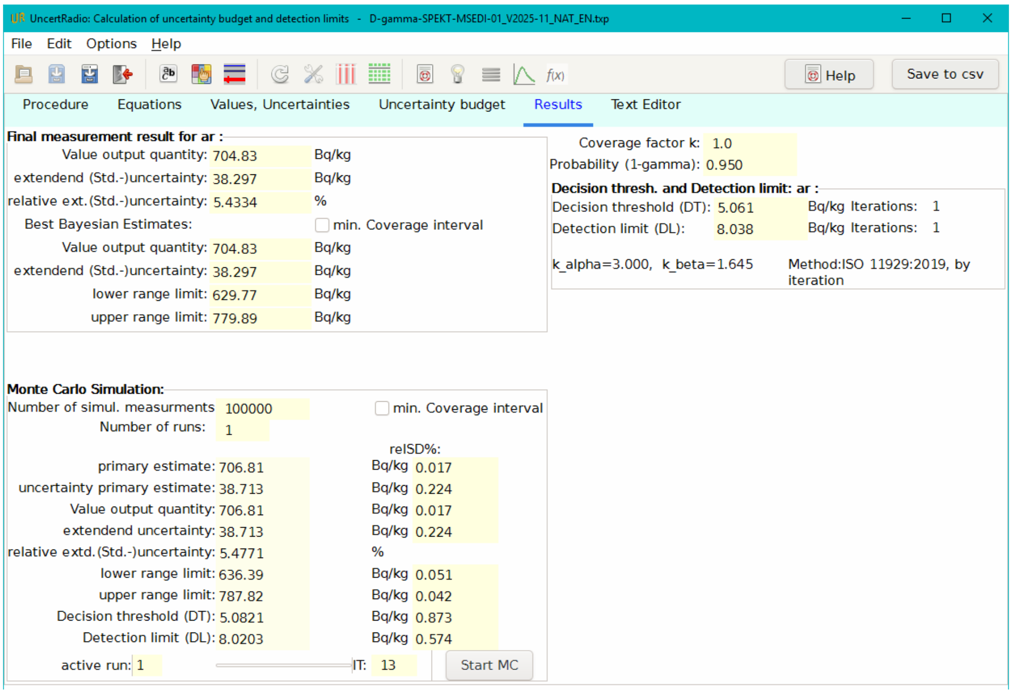
7.2 Software supported evaluation

In the following, the result page of the UncertRadio project file corresponding to this procedure is shown. The files themselves are available on the website of this Procedures' Manual.

7.2.1 For artificial radionuclides with Cs-137 as an example



7.2.2 For natural radionuclides with K-40 as an example



8 Catalogue of the chemicals und equipment

8.1 Chemicals

In this procedure, chemicals are not required.

8.2 Equipment

Besides the usual equipment of a radiochemical laboratory, the following equipment is used for the procedure:

— plastic boxes made of polyethylene (PE);

— freezer;

— freeze dryer;

— ball mill;

— plastic measuring containers with volume graduation made of polypropylene (PP);

— gamma spectrometry measuring device.

References

[1] *Act on Protection against the Harmful Effects of Ionising Radiation (Radiation Protection Act - StrlSchG)*
Available at: https://www.bundesumweltministerium.de/GE241-1.

[2] *Allgemeine Verwaltungsvorschrift zum integrierten Mess- und Informationssystem zur Überwachung der Radioaktivität in der Umwelt (IMIS) nach dem Strahlenschutz-vorsorgegesetz (AVV-IMIS)*. Bundesanzeiger Nr. 244a, p. 4-80.

[3] Arnold, D., Debertin, K., Heckel, A., et al.: *Fundamentals of gamma spectrometry*. γ-SPEKT/GRUNDL. In: Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety (ed.): Procedures' Manual for monitoring of radioactive substances in the environment and of external radiation. ISSN 1865-8725. Available at: https://www.bundesumweltministerium.de/WS1517-1.

[4] Schkade, U.-K., Heckel, A., Wershofen, H., et al.: *Gamma spectrometric determination of the activities of natural radionuclides*. γ-SPEKT/NATRAD. In: Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety (ed.): Procedures' Manual for monitoring of radioactive substances in the environment and of external radiation. ISSN 1865-8725.
Available at: https://www.bundesumweltministerium.de/WS1517-1.

[5] Wershofen, H., Heckel, A., Arnold, D., et al.: *Background contributions in gamma spectrometry*. γ-SPEKT/NULLEF. In: Federal Ministry for the Environment, Climate Action, Nature Conservation and Nuclear Safety (ed.): Procedures' Manual for monitoring of radioactive substances in the environment and external radiation.

ISSN 1865-8725.
Available at: https://www.bundesumweltministerium.de/WS1517-1.

[6] Standard series ISO 11929:2019-02, *Determination of the characteristic limits (decision threshold, detection limit and limits of the coverage interval) for measurements of ionizing radiation – Fundamentals and application (Parts 1 to 3)*.

[7] Kanisch, G., Aust, M.-O., Bruchertseifer, F., et al.: *Bestimmung der charakteristischen Grenzen bei der Aktivitätsbestimmung radioaktiver Stoffe – Teil 1: Grundlagen*. CHAGR-ISO-01. In: Bundesministerium für Umwelt, Klimaschutz, Naturschutz und nukleare Sicherheit (ed.): Messanleitungen für die Überwachung radioaktiver Stoffe in der Umwelt und externer Strahlung. ISSN 1865-8725.
Available at: https://www.bundesumweltministerium.de/WS1517.

[8] Kanisch, G., Aust, M.-O., Bruchertseifer, F., et al.: *Bestimmung der charakteristischen Grenzen bei der Aktivitätsbestimmung radioaktiver Stoffe – Teil 2: Anwendungsbeispiele*. CHAGR-ISO-02. In: Bundesministerium für Umwelt, Klimaschutz, Naturschutz und nukleare Sicherheit (ed.): Messanleitungen für die Überwachung radioaktiver Stoffe in der Umwelt und externer Strahlung. ISSN 1865-8725. Available at: https://www.bundesumweltministerium.de/WS1517.