Procedure for determining the specific activity of strontium-90 in food by liquid scintillation spectrometry (Dicyclohexyl-18-crown-6 method)

E-Sr-90-LEBM-04

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Procedures' Manual for monitoring of radioactive substances in the environment and of external radiation
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Procedure for determining the specific activity of strontium-90 in food by liquid scintillation spectrometry (Dicyclohexyl-18-crown-6 method)

1 Scope

The procedure is suitable for monitoring the specific activity of strontium-90 (Sr-90) in food according to the German Radiation Protection Act (StrlSchG) [1] and the Guideline concerning Emission and Immission Monitoring of Nuclear Facilities (REI) [2]. With this procedure, the detection limits required in the General Administrative Regulation on the Integrated Measurement and Information System for the Monitoring of Environmental Radioactivity (AVV-IMIS) [3] can be achieved within a measurement duration of about three hours to four hours.

Note:

In the context of an IMIS proficiency test [4], the mean value of the specific activity of Sr-90 in a spinach powder sample using this procedure was (102 ± 6,7) $Bq \cdot kg^{-1}$; this is in good agreement with the total mean value of the proficiency test of (103 ± 19) $Bq \cdot kg^{-1}$. In the proficiency test [5] of the Joint Research Centre of the European Commission with wild berries as sample material, a mean value for the specific activity of Sr-90 of (159 ± 12) $Bq \cdot kg^{-1}$ was determined using this procedure. This value is in good agreement with the reference value of (153 ± 8) $Bq \cdot kg^{-1}$.

2 Sampling

The sampling of food is carried out according to Procedure E-γ-SPEKT-LEBM-01.

3 Analysis

3.1 Principle of the procedure

The principle of this procedure is described in the Procedure F-Sr-90-BODEN-03.

3.2 Sample preparation

The sample preparation is carried out according to Procedure E-Sr-90-LEBM-03.

3.3 Radiochemical separation

Most ashes of food samples are almost completely dissolved after only two minutes when strontium is extracted conventionally with boiling diluted nitric acid. If a residue remains after conventional extraction, a subsequent microwave-assisted extraction at 10 bar may

be necessary. Up to 10 g of ash are transferred for extraction into a 250 ml pressure vessel.

Note:
Depending on the kind of yield determination:

a) For external determination, 5 Bq of Sr-85 tracer which is traceable to a national standard are added to the ash contained **in one of the pressure vessels used per analysis charge.**
b) For internal determination, 2 Bq to 5 Bq of Sr-85 tracer are generally added to **each pressure vessel**.

The radiochemical separation is carried out according to procedure F-Sr-90-BODEN-02.

Note:
In the liquid-liquid extraction described in the Procedure F-Sr-90-BODEN-02, the phases occasionally separate only slowly. In such cases, the addition of a maximum of 5 ml of methanol leads to a rapid phase separation.

4 Measuring the activity

The calibration, yield determination and the measurement of the background and of the counting source are described in Procedure F-Sr-90-MILCH-05.

If Sr-85 is used as an internal yield tracer, the total counting rate is increased. In order to keep this contribution low, the energy range for Sr-90 and Y-90 must be chosen in such a way that the contribution of Sr-85 in this is minimized. As a result, the detection efficiency decreases and the detection limit increases with the same measurement time. The detection limit of the specific activity required in the routine measurement program according to AVV-IMIS [3] is reached after a measurement period of approximately 48 hours.

5 Calculation of the results

The calculation of the results is based on the Procedure F-Sr-90-MILCH-05.

5.1 Output quantity

The activity concentration of Sr-90 is generally calculated according to Equation (1):

$$a = \varphi \cdot R_{\mathrm{n}} \tag{1}$$

The procedural calibration factor φ is determined by Equation (2):

$$\varphi = f_2 \cdot \frac{\varphi_{A,\mathrm{Sr-90}}}{\eta_{\mathrm{Sr}} \cdot m} \tag{2}$$

The net count rate R_n is calculated

a) **without using strontium-85** as internal tracer according to Equation (3) or

$$R_\mathrm{n} = R_\mathrm{g} - R_0 \tag{3}$$

b) **using strontium-85** as an internal tracer according to Equation (4):

$$R_\mathrm{n} = R_\mathrm{g} - (R_0 + R_{\mathrm{Sr-85}}) \tag{4}$$

In addition, when using the yield tracer Sr-85, the expected Sr-85 contribution in the energy range for the determination of the specific activity of (Sr-90 + Y-90) is determined at the time of this measurement in accordance with Equation (5):

$$R_{\mathrm{Sr-85}} = \frac{A_{\mathrm{Sr-85}}}{\varphi_{A,\mathrm{Sr-85}}} \cdot \eta_\mathrm{Sr} \cdot f_\mathrm{b} \tag{5}$$

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

$A_{\mathrm{Sr\text{-}85}}$ activity of the Sr-85 yield tracer added to the analytical sample, in Bq;

a specific activity of Sr-90, in Bq·kg^{-1}, related to fresh mass (FM);

f_b correction factor for the decay of the activity of Sr-85 for the time span between addition of the yield tracer and start of measurement:
$f_\mathrm{b} = \mathrm{e}^{-\lambda_{\mathrm{Sr-85}} \cdot t_\mathrm{b}}$

f_2 correction factor for the decay of the activity of Sr-90 for the time span between sampling and start of measurement if the time span t_A is greater than 0,5 years:
$f_2 = \mathrm{e}^{\lambda_{\mathrm{Sr-90}} \cdot t_\mathrm{A}}$

m mass of the sample, in kg,
related to dry mass (DM): $m = m_\mathrm{DM} = m_\mathrm{a} \cdot q_1$
related to fresh mass (FM): $m = m_\mathrm{FM} = m_\mathrm{a} \cdot q_1 \cdot q_2$

m_a mass of sample ash used, in kg;

q_1 ratio of dry mass to ash mass;

q_2 ratio of fresh mass to dry mass;

R_g gross count rate the Sr-90 counting source, in s^{-1};

R_n net count rate of the Sr-90 counting source, in s^{-1};

$R_{\mathrm{Sr\text{-}85}}$ count rate of strontium-85, in s^{-1};

R_0 background count rate, in s^{-1};

t_A time span between sampling and the start of the measurement, in s;

t_b time span between the addition of the yield tracer and the start of the measurement, in s;

$t_{\text{Sr-85}}$ half-life of Sr-85, in s;

$t_{\text{Sr-90}}$ half-life of Sr-90, in s;

$\lambda_{\text{Sr-85}}$ decay constant for Sr-85, in s^{-1}:

$$\lambda_{\text{Sr}-85} = \frac{\ln 2}{t_{\text{Sr}-85}}$$

$\lambda_{\text{Sr-90}}$ decay constant for Sr-90, in s^{-1}:

$$\lambda_{\text{Sr}-90} = \frac{\ln 2}{t_{\text{Sr}-90}}$$

η_{Sr} chemical yield for strontium;

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

$\varphi_{A,\text{Sr-85}}$ activity-related calibration factor of strontium-85 in the considered energy range, in Bq·s;

$\varphi_{A,\text{Sr-90}}$ activity-related calibration factor of strontium-90 in the considered energy range, in Bq·s.

Note:

In addition to the calculation, the sum of the contributions of the background and of Sr-85, (R_0 + $R_{\text{Sr-85}}$), can be determined empirically. For this purpose, the activity of Sr-85 in the counting source is determined by gamma-ray spectrometry. The same activity of Sr-85 is added to the counting vials used for the background determination of the scintillation measurements. It is assumed that the same measuring conditions are maintained.

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.

The standard uncertainty includes not only the standard statistical uncertainty but also the standard uncertainties of mass, decay correction factors, yield determination and calibration.

The relative standard uncertainty of the specific activity $u(a) \cdot a^{-1}$ is calculated

a) **without using Sr-85** as an internal yield tracer according to Equation (6)

$$\frac{u(a)}{a} = \sqrt{\frac{1}{R_{\text{n}}^2} \cdot \left(\frac{R_{\text{g}}}{t_{\text{m}}} + \frac{R_0}{t_0}\right) + u_{\text{rel}}^2(\varphi)} \tag{6}$$

b) **when using Sr-85** as internal yield tracer according to Equation (7)

$$\frac{u(a)}{a} = \sqrt{\frac{1}{R_{\text{n}}^2} \cdot \left[\frac{R_{\text{g}}}{t_{\text{m}}} + \frac{R_0}{t_0} + u^2(R_{\text{Sr}-85})\right] + u_{\text{rel}}^2(\varphi) + 2 \cdot u_{\text{rel}}^2(\eta_{\text{Sr}}) \cdot \frac{R_{\text{Sr}-85}}{R_{\text{n}}}} \tag{7}$$

The relative standard uncertainty of the procedural calibration factor φ used in the Equations (6) and (7) is determined by Equation (8):

$$u_{\mathrm{rel}}^2(\varphi) = u_{\mathrm{rel}}^2(f_2) + u_{\mathrm{rel}}^2\left(\varphi_{A,\mathrm{Sr-90}}\right) + u_{\mathrm{rel}}^2(\eta_{\mathrm{Sr}}) + u_{\mathrm{rel}}^2(m) \quad (8)$$

The standard uncertainty of the Sr-85 count rate additionally required in Equation (7) is calculated according to Equation (9):

$$u^2(R_{\mathrm{Sr-85}}) = R_{\mathrm{Sr-85}}^2 \cdot \left[u_{\mathrm{rel}}^2(A_{\mathrm{Sr\text{-}85}}) + u_{\mathrm{rel}}^2\left(\varphi_{\mathrm{A,\ Sr\text{-}85}}\right) + u_{\mathrm{rel}}^2(\eta_{\mathrm{Sr}}) + u_{\mathrm{rel}}^2(f_{\mathrm{b}})\right] \quad (9)$$

In the Equations (6) to (9) mean:

t_{m}	duration of counting source measurement, in s;
t_0	duration of background measurement, in s;
$u(a)$	standard uncertainty of the specific activity of Sr-90 at the time of sampling, in Bq·kg^{-1};
$u(R_{\mathrm{Sr\text{-}85}})$	standard uncertainty of the Sr-85 count rate, in s^{-1};
$u_{\mathrm{rel}}(A_{\mathrm{Sr\text{-}85}})$	relative standard uncertainty of the added yield tracer Sr-85;
$u_{\mathrm{rel}}(f_{\mathrm{b}})$	relative standard uncertainty of the decay correction factor for Sr-85 for the time period between addition of the yield tracer and start of measurement;
$u_{\mathrm{rel}}(f_2)$	relative standard uncertainty of the decay correction factor for Sr-90 for the time period between sampling and start of measurement;
$u_{\mathrm{rel}}(m)$	relative standard uncertainty of the sample mass; related to dry mass: $u_{\mathrm{rel}}^2(m) = u_{\mathrm{rel}}^2(m_{\mathrm{DM}}) = u_{\mathrm{rel}}^2(m_{\mathrm{a}}) + u_{\mathrm{rel}}^2(q_1)$ related to fresh mass: $u_{\mathrm{rel}}^2(m) = u_{\mathrm{rel}}^2(m_{\mathrm{FM}}) = u_{\mathrm{rel}}^2(m_{\mathrm{a}}) + u_{\mathrm{rel}}^2(q_1) + u_{\mathrm{rel}}^2(q_2)$
$u_{\mathrm{rel}}(m_{\mathrm{a}})$	relative standard uncertainty of the mass of sample ash used;
$u_{\mathrm{rel}}(\eta_{\mathrm{Sr}})$	relative standard uncertainty of chemical yield for strontium;
$u_{\mathrm{rel}}(\varphi_{A,\mathrm{Sr\text{-}85}})$	relative standard uncertainty of the activity-related calibration factor for strontium-85;
$u_{\mathrm{rel}}(\varphi_{A,\mathrm{Sr\text{-}90}})$	relative standard uncertainty of the activity-related calibration factor for strontium-90.

Usually, the contributions of the relative standard uncertainties of the correction factor $u_{\mathrm{rel}}(f_2)$ and of the ash mass $u_{\mathrm{rel}}(m_{\mathrm{a}})$ as well as the conversion factors $u_{\mathrm{rel}}(q_1)$ and $u_{\mathrm{rel}}(q_2)$ are generally neglected. Due to the low Sr-85 activity used in the procedure, this also applies to the standard uncertainty of the Sr-85 count rate $u(R_{\mathrm{Sr\text{-}85}})$.

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

In order to calculate the characteristic limits of this procedure, the decision threshold a^* is first determined

a) according to Equation (10) **without using Sr-85** as internal yield tracer

$$a^* = k_{1-\alpha} \cdot \varphi \cdot \sqrt{R_0 \cdot \left(\frac{1}{t_\mathrm{m}} + \frac{1}{t_0}\right)} \tag{10}$$

b) according to Equation (11) **using Sr-85** as internal yield tracer

$$a^* = k_{1-\alpha} \cdot \varphi \cdot \sqrt{\frac{R_0 + R_{\mathrm{Sr-85}}}{t_\mathrm{m}} + \frac{R_0}{t_0} + u^2(R_{\mathrm{Sr-85}})} \tag{11}$$

In the Equations (10) and (11):

a^* decision threshold of specific Sr-90 activity, in Bq·kg^{-1};

$k_{1-\alpha}$ quantile of the normal distribution for the probability of the type I error α.

6.2 Detection limit

The detection limit $a^\#$ is calculated

a) according to the implicit Equation (12) **using a control source**:

$$a^\# = a^* + k_{1-\beta} \cdot \sqrt{a^{\#2} \cdot u_{\mathrm{rel}}^2(\varphi) + \varphi^2 \cdot \left(\frac{a^\#}{t_\mathrm{m} \cdot \varphi} + \frac{R_0}{t_\mathrm{m}} + \frac{R_0}{t_0}\right)} \tag{12}$$

b) approximately by Equation (13) **using Sr-85** as yield tracer:

$$a^\# = a^* + k_{1-\beta} \cdot \sqrt{a^{\#2} \cdot u_{\mathrm{rel}}^2(\varphi) + \varphi^2 \cdot \left(\frac{a^\#}{t_\mathrm{m} \cdot \varphi} + \frac{R_0 + R_{\mathrm{Sr-85}}}{t_\mathrm{m}} + \frac{R_0}{t_0} + u^2(R_{\mathrm{Sr-85}})\right)} \tag{13}$$

After resolution and simplification of the Equations (12) and (13), the detection limit for both methods is calculated according to Equation (14):

$$a^{\#} = \frac{a^{*} \cdot \psi}{\theta} \cdot \left[1 + \sqrt{1 - \frac{\theta}{\psi^{2}} \cdot \left(1 - \frac{k_{1-\beta}^{2}}{k_{1-\alpha}^{2}}\right)}\right] \tag{14}$$

with the auxiliary quantities

$$\theta = 1 - k_{1-\beta}^{2} \cdot u_{\mathrm{rel}}^{2}(\varphi) \tag{15}$$

$$\psi = 1 + \frac{k_{1-\beta}^{2}}{2 \cdot a^{*}} \cdot \frac{\varphi}{t_{\mathrm{m}}} \tag{16}$$

This means:

$a^{\#}$ detection limit of the specific Sr-90 activity, in $Bq \cdot kg^{-1}$;

$k_{1\text{-}\beta}$ quantile of the standard normal distribution for the probability of the type II error β.

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.

Using the example of a pasture vegetation sample, the calculation of the specific activity of Sr-90 related to fresh mass is presented here, in which two cases are outlined: no yield tracer (Section 7.1.1 or Section 7.2.1) was used or Sr-85 was used as yield tracer (Section 7.1.2 or Section 0).

7.1 Manual evaluation

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

7.1.1 Without using strontium-85 as yield tracer

In this worked example, in which no yield tracer was used, the energy range between 20 keV and 1000 keV was evaluated for the calculation of the specific activity of the radionuclide Sr-90 in the pulse height spectrum.

The following values were determined:

R_b	=	191,2·10^{-3} s^{-1};	t_m	=	60·10^3 s;
R_0	=	79,0·10^{-3} s^{-1};	t_0	=	60·10^3 s;
t_A	=	3,456·10^6 s;	$t_{\mathrm{Sr\text{-}90}}$	=	0,9088·10^9 s;
m_a	=	0,010 kg;	$u_\mathrm{rel}(m_\mathrm{a})$	=	0,0;
q_1	=	10,0;	$u_\mathrm{rel}(q_1)$	=	0,0;
q_2	=	5,88;	$u_\mathrm{rel}(q_2)$	=	0,0;
η_Sr	=	0,750;	$u_\mathrm{rel}(\eta_\mathrm{Sr})$	=	0,05;
$\varphi_{A,\mathrm{Sr\text{-}90}}$	=	0,585 Bq·s;	$u_\mathrm{rel}(\varphi_{A,\mathrm{Sr\text{-}90}})$	=	0,04.

The relative standard uncertainties for the correction factor f_2, the mass m_a and for the time periods can be neglected.

The net count rate R_n is calculated with Equation (3):

$$R_\mathrm{n} = 191{,}2 \cdot 10^{-3}\ \mathrm{s}^{-1} - 79{,}0 \cdot 10^{-3}\ \mathrm{s}^{-1} \approx 112{,}2 \cdot 10^{-3}\ \mathrm{s}^{-1}$$

The procedural calibration factor φ is obtained with Equation (2):

$$\varphi = \frac{0{,}585\ \mathrm{Bq \cdot s}}{0{,}750 \cdot 0{,}010\ \mathrm{kg} \cdot 10{,}0 \cdot 5{,}88} \cdot \mathrm{e}^{\frac{\ln 2 \cdot 3{,}456 \cdot 10^6\ \mathrm{s}}{0{,}9088 \cdot 10^9\ \mathrm{s}}} \approx 1{,}330\ \ \mathrm{Bq \cdot s \cdot kg^{-1}} \cdot 1{,}00 \approx$$

$$\approx 1{,}330\ \mathrm{Bq \cdot s \cdot kg^{-1}}$$

The specific activity of the radionuclide Sr-90 with Equation (1):

$$a = 1{,}330\ \mathrm{Bq \cdot s \cdot kg^{-1}} \cdot 112{,}2 \cdot 10^{-3}\ \mathrm{s}^{-1} \approx 0{,}1492\ \mathrm{Bq \cdot kg^{-1}}\ (\mathrm{FM})$$

The variance of the procedural calibration factor $u_\mathrm{rel}(\varphi)$ is determined by Equation (8):

$$u_\mathrm{rel}^2(\varphi) = 0^2 + 0{,}04^2 + 0{,}05^2 + 0^2 = 4{,}1 \cdot 10^{-3}$$

The value of the relative standard uncertainty of the specific activity $u_\mathrm{rel}(a)$ is obtained with Equation (6):

$$\frac{u(a)}{a} = \sqrt{\frac{1}{(112{,}2 \cdot 10^{-3}\ \mathrm{s}^{-1})^2} \cdot \left(\frac{191{,}2 \cdot 10^{-3}\ \mathrm{s}^{-1}}{60 \cdot 10^3\ \mathrm{s}} + \frac{79{,}0 \cdot 10^{-3}\ \mathrm{s}^{-1}}{60 \cdot 10^3\ \mathrm{s}}\right) + 4{,}1 \cdot 10^{-3}} \approx$$

$$\approx \sqrt{0{,}3577 \cdot 10^{-3} + 4{,}1 \cdot 10^{-3}} \approx 66{,}77 \cdot 10^{-3}$$

For this example, the specific activity of radionuclide Sr-90 in the pasture vegetation sample at the time of sampling is:

$$a = (0{,}149 \pm 0{,}010)\ \mathrm{Bq \cdot kg^{-1}}\ (\mathrm{FM})$$

With the above values as well as the value 3 for the quantile of the standard normal distribution $k_{1\text{-}\alpha}$ and the value 1,645 for the quantile of the standard normal distribution $k_{1\text{-}\beta,}$ the detection limit a^* is calculated with Equation (10):

$$a^* = 3 \cdot 1{,}327\ \mathrm{Bq \cdot s \cdot kg^{-1}} \cdot \sqrt{79{,}0 \cdot 10^{-3}\ \mathrm{s^{-1}} \cdot \left(\frac{1}{60 \cdot 10^3\ \mathrm{s}} + \frac{1}{60 \cdot 10^3\ \mathrm{s}}\right)} \approx$$

$$\approx 3{,}981\ \mathrm{Bq \cdot s \cdot kg^{-1}} \cdot \sqrt{2{,}633 \cdot 10^{-6}\ \mathrm{s^{-2}}} \approx 6{,}460 \cdot 10^{-3}\ \ \mathrm{Bq \cdot kg^{-1}}\ (\mathrm{FM})$$

For the calculation of the value for the detection limit $a^{\#}$, the auxiliary quantities θ and ψ are first determined using the Equations (15) and (16):

$$\theta = 1 - 1{,}645^2 \cdot 4{,}1 \cdot 10^{-3} \approx 0{,}9889$$

$$\psi = 1 + \frac{1{,}645^2}{2 \cdot 6{,}460 \cdot 10^{-3}\ \ \mathrm{Bq \cdot kg^{-1}}} \cdot \frac{1{,}327\ \mathrm{Bq \cdot s \cdot kg^{-1}}}{60 \cdot 10^3\ \mathrm{s}} \approx 1{,}005$$

The value of detection limit $a^{\#}$ is obtained with Equation (14):

$$a^{\#} = \frac{6{,}460 \cdot 10^{-3}\ \ \mathrm{Bq \cdot kg^{-1}}\ (\mathrm{FM})\ \cdot 1{,}005}{0{,}9889} \cdot \left[1 + \sqrt{1 - \frac{0{,}9889}{1{,}005^2} \cdot \left(1 - \frac{1{,}645^2}{3^2}\right)}\right] \approx$$

$$\approx 6{,}565 \cdot 10^{-3}\ \mathrm{Bq \cdot kg^{-1}}\ (\mathrm{FM}) \cdot 1{,}562 \approx 10{,}25 \cdot 10^{-3}\ \ \mathrm{Bq \cdot kg^{-1}}\ (\mathrm{FM})$$

7.1.2 Using strontium-85 as a yield tracer

In this worked example, 5,0 Bq Sr-85 was added to the kale sample 20 days prior to the start of the measurement. To calculate the specific activity of Sr-90, the energy range between 350 keV and 1000 keV was used in the pulse height spectrum.

Furthermore, the following values were obtained:

R_g	=	41,67·10^{-3} s^{-1};	t_m	=	60·10^3 s;
R_0	=	16,0·10^{-3} s^{-1};	t_0	=	60·10^3 s;
t_A	=	3,456·10^6 s;	t_b	=	1,728·10^6 s;
$t_{\mathrm{Sr\text{-}85}}$	=	5,603·10^6 s;	$t_{\mathrm{Sr\text{-}90}}$	=	0,9088·10^9 s;

$A_{\text{Sr-85}}$	=	5,00 Bq;	$u_{\text{rel}}(A_{\text{Sr-85}})$	=	0,02;
m_{a}	=	0,010 kg;	$u_{\text{rel}}(m_{\text{a}})$	=	0,0;
q_1	=	10,0;	$u_{\text{rel}}(q_1)$	=	0,0;
q_2	=	5,88;	$u_{\text{rel}}(q_2)$	=	0,0;
η_{Sr}	=	0,750;	$u_{\text{rel}}(\eta_{\text{Sr}})$	=	0,05;
$\varphi_{A,\text{Sr-85}}$	=	$4{,}167 \cdot 10^3$ Bq·s;	$u_{\text{rel}}(\varphi_{A,\text{Sr-85}})$	=	0,04;
$\varphi_{A,\text{Sr-90}}$	=	2,632 Bq·s;	$u_{\text{rel}}(\varphi_{A,\text{Sr-90}})$	=	0,04.

The relative standard uncertainties for the correction factors f_{b} and f_2, for the mass m_{a} and for the time periods can be neglected. This also applies to the standard uncertainty of the Sr-85 count rate $u(R_{\text{Sr-85}})$.

First, the count rate of the radionuclide Sr-85 is determined with Equation (5):

$$R_{\text{Sr}-85} = \frac{5{,}0\ \text{Bq}}{4{,}167 \cdot 10^3\ \text{Bq} \cdot \text{s}} \cdot 0{,}750 \cdot \text{e}^{-\frac{\ln 2 \cdot 1{,}728 \cdot 10^6\ \text{s}}{5{,}603 \cdot 10^6\ \text{s}}} \approx 0{,}8999 \cdot 10^{-3}\ \text{s}^{-1} \cdot 0{,}808 \approx$$

$$\approx 0{,}7267 \cdot 10^{-3}\ \text{s}^{-1}$$

The net count rate R_{n} is calculated with Equation (4):

$$R_{\text{n}} = 41{,}67 \cdot 10^{-3}\ \text{s}^{-1} - (16{,}0 \cdot 10^{-3}\ \text{s}^{-1} + 0{,}7267 \cdot 10^{-3}\ \text{s}^{-1}) \approx 24{,}94 \cdot 10^{-3}\ \text{s}^{-1}$$

The procedural calibration factor φ is obtained with Equation (2):

$$\varphi = \frac{2{,}632\ \text{Bq} \cdot \text{s}}{0{,}750 \cdot 0{,}010\ \text{kg} \cdot 10{,}0 \cdot 5{,}88} \cdot \text{e}^{\frac{\ln 2 \cdot 3{,}456 \cdot 10^6\ \text{s}}{0{,}9088 \cdot 10^9\ \text{s}}} \approx 5{,}984\ \text{Bq} \cdot \text{s} \cdot \text{kg}^{-1} \cdot 1{,}00 \approx$$

$$\approx 5{,}984\ \text{Bq} \cdot \text{s} \cdot \text{kg}^{-1}$$

The specific activity of the radionuclide Sr-90 is with Equation (1):

$$a = 5{,}984\ \text{Bq} \cdot \text{s} \cdot \text{kg}^{-1} \cdot 24{,}94 \cdot 10^{-3}\ \text{s}^{-1} \approx 0{,}1493\ \text{Bq} \cdot \text{kg}^{-1}\ (\text{FM})$$

The variance of the prodedural calibration factor $u_{\text{rel}}(\varphi)$ is determined by Equation (8):

$$u_{\text{rel}}^2(\varphi) = 0^2 + 0{,}04^2 + 0{,}05^2 + 0^2 = 4{,}1 \cdot 10^{-3}$$

The value of the relative standard uncertainty of the specific activity $u_{\text{rel}}(a)$ is obtained with Equation (7):

$$\frac{u(a)}{a} = \left\{ \frac{1}{(24{,}94 \cdot 10^{-3}\ \mathrm{s}^{-1})^2} \cdot \left[\frac{41{,}67 \cdot 10^{-3}\ \mathrm{s}^{-1}}{60 \cdot 10^3\ \mathrm{s}} + \frac{16{,}0 \cdot 10^{-3}\ \mathrm{s}^{-1}}{60 \cdot 10^3\ \mathrm{s}} + 0 \right] + \right.$$

$$\left. + 4{,}1 \cdot 10^{-3} + 2 \cdot 0{,}05^2 \cdot \frac{0{,}7271 \cdot 10^{-3}\ \mathrm{s}^{-1}}{24{,}94 \cdot 10^{-3}\ \mathrm{s}^{-1}} \right\}^{\frac{1}{2}} \approx$$

$$\approx \sqrt{1{,}545 \cdot 10^{-3} + 4{,}1 \cdot 10^{-3} + 0{,}1458 \cdot 10^{-3}} \approx 76{,}12 \cdot 10^{-3}$$

For this example, the specific activity of radionuclide Sr-90 in the pasture vegetation sample at the time of sampling is:

$$a = (0{,}149 \pm 0{,}011) \cdot 10^{-3}\ \mathrm{Bq \cdot kg^{-1}}\ (\mathrm{FM})$$

With the above values as well as the value 3 for the quantile of the standard normal distribution $k_{1\text{-}\alpha}$ and the value 1,645 for the quantile of the standard normal distribution $k_{1\text{-}\beta,}$ the detection limit a^* is calculated with Equation (11):

$$a^* = 3 \cdot 5{,}984\ \mathrm{Bq \cdot s \cdot kg^{-1}} \cdot$$

$$\cdot \sqrt{\frac{16{,}0 \cdot 10^{-3}\ \mathrm{s}^{-1} + 0{,}7271 \cdot 10^{-3}\ \mathrm{s}^{-1}}{60 \cdot 10^3\ \mathrm{s}} + \frac{16{,}0 \cdot 10^{-3}\ \mathrm{s}^{-1}}{60 \cdot 10^3\ \mathrm{s}} + 0^2} \approx$$

$$\approx 17{,}95\ \mathrm{Bq \cdot s \cdot kg^{-1}} \cdot 0{,}7385 \cdot 10^{-3}\ \mathrm{s}^{-1} \approx 13{,}26 \cdot 10^{-3}\ \mathrm{Bq \cdot kg^{-1}}\ (\mathrm{FM})$$

For the calculation of the value for the detection limit $a^{\#}$, the auxiliary quantities θ and ψ are first determined using the Equations (15) and (16):

$$\theta = 1 - 1{,}645^2 \cdot 4{,}1 \cdot 10^{-3} \approx 0{,}9889$$

$$\psi = 1 + \frac{1{,}645^2}{2 \cdot 13{,}26 \cdot 10^{-3}\ \mathrm{Bq \cdot kg^{-1}}} \cdot \frac{5{,}984\ \mathrm{Bq \cdot s \cdot kg^{-1}}}{60 \cdot 10^3\ \mathrm{s}} \approx 1{,}010$$

The value of detection limit $a^{\#}$ is obtained with Equation (14):

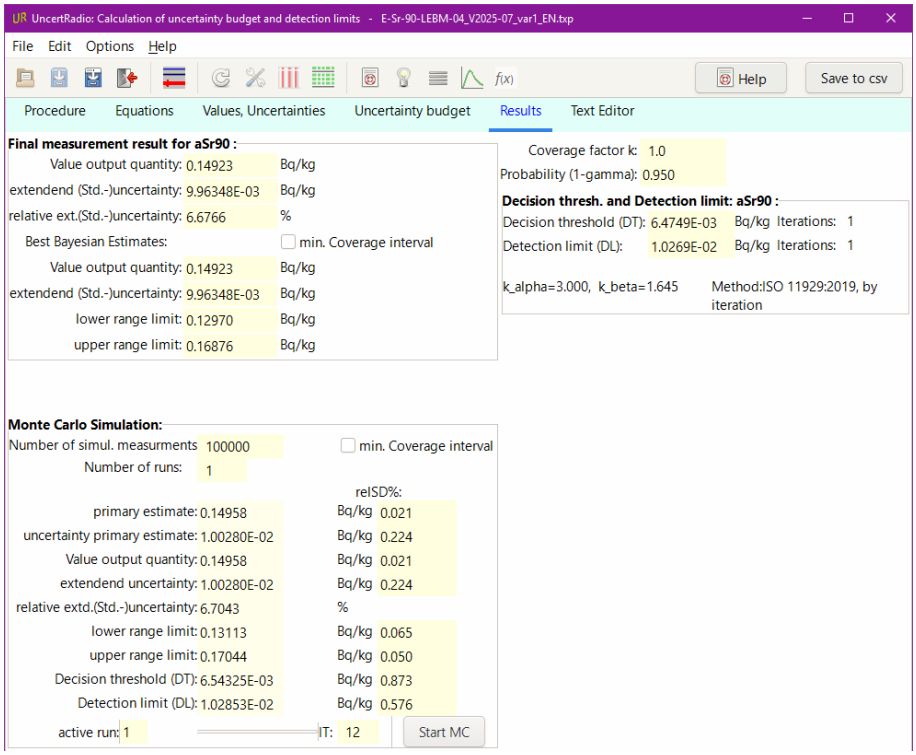
$$a^{\#} = \frac{13{,}26 \cdot 10^{-3}\ \mathrm{Bq \cdot kg^{-1}}\ (\mathrm{FM})\ \cdot 1{,}010}{0{,}9889} \cdot \left[1 + \sqrt{1 - \frac{0{,}9889}{1{,}010^2} \cdot \left(1 - \frac{1{,}645^2}{3^2} \right)} \right] \approx$$

$$\approx 13{,}54 \cdot 10^{-3}\ \mathrm{Bq \cdot kg^{-1}}\ (\mathrm{FM}) \cdot 1{,}568 \approx 21{,}28 \cdot 10^{-3}\ \mathrm{Bq \cdot kg^{-1}}\ (\mathrm{FM})$$

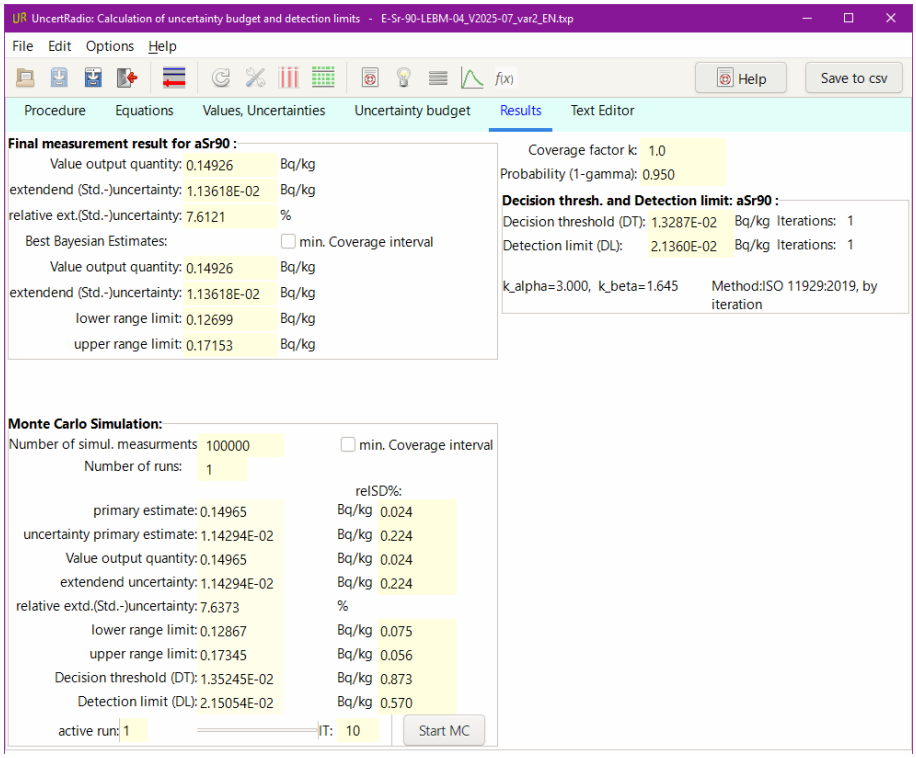
7.2 Software supported evaluation

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

7.2.1 Without using strontium-85 as yield tracer



7.2.2 Using strontium-85 as a yield tracer



8 Catalogue of the chemicals und equipment

8.1 Chemicals

The chemicals used shall be of analytically pure quality.

- ammonium carbamate;
- dicyclohexyl-18-crown-6 in chloroform: 0,05 $mol \cdot l^{-1}$;
- sodium acetate-acetic acid solution: 0,05 $mol \cdot l^{-1}$ sodium acetate in 0,05 $mol \cdot l^{-1}$ acetic acid;
- sodium dichromate solution, $Na_2Cr_2O_7$: 1,31 $mol \cdot l^{-1}$;
- sodium hydroxide solution, NaOH: 3 $mol \cdot l^{-1}$, 10 $mol \cdot l^{-1}$;
- nitric acid, HNO_3: 6 $mol \cdot l^{-1}$;
- scintillation cocktail: e.g. InstantScintGelPlus, UltimaGold LLT;
- toluene sulfonic acid in aqueous solution: 100 ml:
  25 g of toluene sulfonic acid in 75 ml of deionized water

Carrier solutions

- Barium carrier solution: 2 mg Ba^{2+} per ml solution:
  dissolve 0,356 g of barium chloride dihydrate ($BaCl_2 \cdot 2\ H_2O$) in entioni-settledwater, add 1 ml of hydrochloric acid (3 $mol \cdot l^{-1}$), then fill up to 100 ml with deionized water;
- Strontium carrier solution: 20 mg Sr^{2+} per ml solution:
  dissolve 6,086 g of strontium chloride hexahydrate ($SrCl_2 \cdot 6\ H_2O$) in deionized water, add 1 ml of hydrochloric acid (3 $mol \cdot l^{-1}$), then fill up to 100 ml with deionized water;
- Yttrium carrier solution: 20 mg Y^{3+} per ml solution:
  Dissolve 6,83 g of yttrium chloride hexahydrate ($YCl_3 \cdot 6\ H_2O$) in deionized water, add 1 ml of hydrochloric acid (3 $mol \cdot l^{-1}$), then fill up to 100 ml with deionized water.

8.2 Equipment

This procedure requires an ordinary laboratory equipment.

Additionally, further equipment is necessary:

— cutting mill with sieves for particle size less than 2 mm or 1 mm and sample suction;
— centrifugal mill with a sieve for particle size less than 1 mm;
— ash trays, e. g. made of quartz or fused silica, 55 mm high, 145 mm wide, 205 mm long and a wall thickness of 4 mm to 5 mm;
— chamber furnace with air inlet slots and catalytic exhaust gas cleaning, e. g. chamber furnace type N150 from Nabertherm;
— optional: microwave oven with 250 ml pressure vessels, e. g. from MLS;
— fine quantitative paper filters with a pore diameter of less than 2 µm, e. g. blue band filter grade 589/3, or nitrocellulose filters with a pore diameter of 0,45 µm;
— liquid scintillation measurement vials made of low potassium glass;
— liquid scintillation spectrometer, if possible low-level version with multi-channel analyzer;
— laboratory centrifuge

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] *Richtlinie zur Emissions- und Immissionsüberwachung kerntechnischer Anlagen (REI)*. Gemeinsames Ministerialblatt Nr. 6-9, p. 102.

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

[4] Roos, N., Tait, D.: *Vergleichsprüfung mit Spinatpulver als Probenart für umweltrelevante Radionuklide* In: Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit sowie Universität Bremen, Institut für Umweltphysik (ed.): 15. Fachgespräch zur Überwachung der Umweltradioaktivität: Daten – Modelle – Information, Freiburg, 05. – 07. März 2013. Bonn: Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit, 2014, p. 258-267. ISSN 1869-585X. Available at: https://www.bmuv.de/fileadmin/Daten_BMU/Download_PDF/Strahlenschutz/umweltradioaktivitaet_tagungsband_15_fachgespraech_bf.pdf. [Last access 03.06.2025].

[5] Gemeinsame Forschungsstelle – Geel, Merešová, J., Wätjen, U.: *Evaluation of EC comparison on the determination of ^{40}K, ^{90}Sr and ^{137}Cs in bilberry powder*. Luxemburg (Luxemburg): Publications Office, 2013, 66 p. ISBN 978-92-79-33427-6. DOI: 10.2787/81392.

[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: Anwendungs-beispiele*. 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.