

**Procedure for determining the specific activity of
strontium-90 in animal feed and vegetation samples
by liquid scintillation spectrometry
(Dicyclohexyl-18-crown-6 method)**

F-Sr-90-FUMI-04

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Procedure for determining the specific activity of strontium-90 in animal feed and vegetation samples 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 animal feed and vegetation 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:

The mass reference of the specific activity of Sr-90 according to AVV-IMIS is dry mass for animal feed and feed raw materials, and fresh mass for pasture and meadow vegetation. In a few cases, it is necessary to refer the specific activity to dry mass. These different mass references are considered when calculating the results in Section 5.

2 Sampling

The sampling of animal feed and vegetation is carried out according to Procedure F- γ -SPEKT-FUMI-01.

3 Analysis

3.1 Principle of the procedure

The principle of this procedure is described in the Procedure F-Sr-90-BODEN-02.

3.2 Sample preparation

The sample preparation is carried out according to Procedure F-Sr-90-FUMI-03.

3.3 Radiochemical separation

Most ashes of animal feed and vegetation 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-FUMI-03 of this Procedures' Manual. However, count rates and activity-related calibration factor φ_A shall be determined

- in the same energy window and
- under the same quench conditions, i. e. the same quench factor when measured.

If, for determining the chemical yield, the Sr-85 tracer was given to the analytical sample, possible contributions of the tracer to the count rate must be taken into account. In this case, the expected Sr-85 contribution in the energy range used to determine the specific activity of Sr-90 and of Y-90 shall be calculated at the time of this measurement and subtracted from the gross count rate R_g .

5.1 Output quantity

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

$$a = \varphi \cdot R_n \quad (1)$$

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

$$\varphi = f_2 \cdot \frac{\varphi_{A, \text{Sr-90}}}{\eta_{\text{Sr}} \cdot m} \quad (2)$$

The net count rate R_n is calculated

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

$$R_n = R_g - R_0 \quad (3)$$

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

$$R_n = R_g - (R_0 + R_{\text{Sr-85}}) \quad (4)$$

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):

$$R_{\text{Sr-85}} = \frac{A_{\text{Sr-85}}}{\varphi_{A, \text{Sr-85}}} \cdot \eta_{\text{Sr}} \cdot f_b \quad (5)$$

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

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

a specific activity of Sr-90, in $\text{Bq} \cdot \text{kg}^{-1}$, related to fresh mass (FM) or dry mass (DM);

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:

$$f_b = e^{-\lambda_{\text{Sr-85}} \cdot t_b}$$

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:

$$f_2 = e^{\lambda_{\text{Sr-90}} \cdot t_A}$$

mass of the sample used, in kg,

m for fresh mass: $m = m_{\text{FM}} = m_a \cdot q_1 \cdot q_2$

for dry mass: $m = m_{\text{DM}} = m_a \cdot q_1$

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 of the Sr-90 counting source, in s^{-1} ;
R_n	net count rate of the Sr-90 counting source, in s^{-1} ;
R_{Sr-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_{Sr-85}	half-life of Sr-85, in s;
t_{Sr-90}	half-life of Sr-90, in s;
λ_{Sr-85}	decay constant for Sr-85, in s^{-1} :
	$\lambda_{Sr-85} = \frac{\ln 2}{t_{Sr-85}}$
λ_{Sr-90}	decay constant for Sr-90, in s^{-1} :
	$\lambda_{Sr-90} = \frac{\ln 2}{t_{Sr-90}}$
η_{Sr}	chemical yield for strontium;
φ	procedural calibration factor, in $Bq \cdot s \cdot kg^{-1}$;
$\varphi_{A,Sr-85}$	activity-related calibration factor of strontium-85 in the considered energy range, in $Bq \cdot s$;
$\varphi_{A,Sr-90}$	activity-related calibration factor of strontium-90 in the considered energy range, in $Bq \cdot s$.

Note:

In addition to the calculation, the sum of the contributions of the background and of Sr-85, $(R_0 + R_{Sr-85})$, 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)

$$\frac{u(a)}{a} = \sqrt{\frac{1}{R_n^2} \cdot \left(\frac{R_g}{t_m} + \frac{R_0}{t_0} \right) + u_{\text{rel}}^2(\varphi)} \quad (6)$$

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

$$\frac{u(a)}{a} = \sqrt{\frac{1}{R_n^2} \cdot \left[\frac{R_g}{t_m} + \frac{R_0}{t_0} + u^2(R_{\text{Sr-85}}) \right] + u_{\text{rel}}^2(\varphi) + 2 \cdot u_{\text{rel}}^2(\eta_{\text{Sr}}) \cdot \frac{R_{\text{Sr-85}}}{R_n}} \quad (7)$$

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

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

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

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

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 ;
$u(R_{\text{Sr-85}})$	standard uncertainty of the Sr-85 count rate, in s ⁻¹ ;
$u_{\text{rel}}(A_{\text{Sr-85}})$	relative standard uncertainty of the added yield tracer Sr-85;
$u_{\text{rel}}(f_b)$	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;
$u_{\text{rel}}(f_2)$	relative standard uncertainty of the decay correction factor for Sr-90 for the time period between sampling and start of measurement;
$u_{\text{rel}}(m)$	relative standard uncertainty of the mass of the sample used related to: dry mass: $u_{\text{rel}}^2(m) = u_{\text{rel}}^2(m_{\text{DM}}) = u_{\text{rel}}^2(m_a) + u_{\text{rel}}^2(q_1)$ fresh mass: $u_{\text{rel}}^2(m) = u_{\text{rel}}^2(m_{\text{FM}}) = u_{\text{rel}}^2(m_a) + u_{\text{rel}}^2(q_1) + u_{\text{rel}}^2(q_2)$
$u_{\text{rel}}(m_a)$	relative standard uncertainty of the mass of sample ash used;
$u_{\text{rel}}(\eta_{\text{Sr}})$	relative standard uncertainty of chemical yield for strontium;

- $u_{\text{rel}}(\varphi_{A,\text{Sr-85}})$ relative standard uncertainty of the activity-related calibration factor for strontium-85;
- $u_{\text{rel}}(\varphi_{A,\text{Sr-90}})$ relative standard uncertainty of the activity-related calibration factor for strontium-90.

Usually, the contributions of the relative standard uncertainties of the correction factor $u_{\text{rel}}(f_2)$ and of the mass of the sample used $u_{\text{rel}}(m_a)$ as well as the conversion factors $u_{\text{rel}}(q_1)$ and $u_{\text{rel}}(q_2)$ 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 $u(R_{\text{Sr-85}})$.

6 Characteristic limits of the procedure

The calculation of the characteristic limits follows the standard series ISO 11929 [4]. For further considerations, it is referred to the General Chapters CHAGR-ISO-01 and CHAGR-ISO-02 of this Procedures' Manual [5, 6].

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

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

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

$$a^* = k_{1-\alpha} \cdot \varphi \cdot \sqrt{\frac{R_0 + R_{\text{Sr-85}}}{t_m} + \frac{R_0}{t_0} + u^2(R_{\text{Sr-85}})} \quad (11)$$

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**:

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

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

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

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

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

with the auxiliary quantities

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

$$\psi = 1 + \frac{k_{1-\beta}^2}{2 \cdot a^*} \cdot \frac{\varphi}{t_m} \quad (16)$$

This means:

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

$k_{1-\beta}$ 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 and Section 7.2.1) was used or Sr-85 was used as yield tracer (Section 7.1.2 and Section 7.2.2).

7.1 Manual evaluation

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

7.1.1 Without using strontium-85 as yield tracer

In this worked example, 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_g	=	$130,3 \cdot 10^{-3} \text{ s}^{-1}$;	t_m	=	$60 \cdot 10^3 \text{ s}$;
R_0	=	$79,0 \cdot 10^{-3} \text{ s}^{-1}$;	t_0	=	$60 \cdot 10^3 \text{ s}$;
t_A	=	$3,456 \cdot 10^6 \text{ s}$;	$t_{\text{Sr-90}}$	=	$0,9088 \cdot 10^9 \text{ s}$;
m_a	=	$0,010 \text{ kg}$;	$u_{\text{rel}}(m_a)$	=	$0,0$;
q_1	=	$11,11$;	$u_{\text{rel}}(q_1)$	=	$0,0$;
q_2	=	$5,00$;	$u_{\text{rel}}(q_2)$	=	$0,0$;
η_{Sr}	=	$0,750$;	$u_{\text{rel}}(\eta_{\text{Sr}})$	=	$0,05$;
φ_A	=	$0,585 \text{ Bq} \cdot \text{s}$;	$u_{\text{rel}}(\varphi_A)$	=	$0,04$.

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):

$$R_n = 130,3 \cdot 10^{-3} \text{ s}^{-1} - 79,0 \cdot 10^{-3} \text{ s}^{-1} \approx 51,3 \cdot 10^{-3} \text{ s}^{-1}$$

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

$$\begin{aligned} \varphi &= \frac{0,585 \text{ Bq} \cdot \text{s}}{0,750 \cdot 0,010 \text{ kg} \cdot 11,11 \cdot 5,00} \cdot e^{\frac{\ln 2 \cdot 3,456 \cdot 10^6 \text{ s}}{0,9088 \cdot 10^9 \text{ s}}} \approx 1,404 \text{ Bq} \cdot \text{s} \cdot \text{kg}^{-1} \cdot 1,00 \approx \\ &\approx 1,408 \text{ Bq} \cdot \text{s} \cdot \text{kg}^{-1} \end{aligned}$$

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

$$a = 1,408 \text{ Bq} \cdot \text{s} \cdot \text{kg}^{-1} \cdot 51,3 \cdot 10^{-3} \text{ s}^{-1} \approx 72,03 \cdot 10^{-3} \text{ Bq} \cdot \text{kg}^{-1} \text{ (FM)}$$

The variance of the procedural 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 (6):

$$\begin{aligned} \frac{u(a)}{a} &= \sqrt{\frac{1}{(51,3 \cdot 10^{-3} \text{ s}^{-1})^2} \cdot \left(\frac{130,3 \cdot 10^{-3} \text{ s}^{-1}}{60 \cdot 10^3 \text{ s}} + \frac{79,0 \cdot 10^{-3} \text{ s}^{-1}}{60 \cdot 10^3 \text{ s}} \right) + 4,1 \cdot 10^{-3}} \approx \\ &\approx \sqrt{1,326 \cdot 10^{-3} + 4,1 \cdot 10^{-3}} \approx 0,0737 \end{aligned}$$

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

$$a = (72,22 \pm 5,32) \cdot 10^{-3} \text{ Bq} \cdot \text{kg}^{-1} \text{ (FM)}$$

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

$$\begin{aligned} a^* &= 3 \cdot 1,408 \text{ Bq} \cdot \text{s} \cdot \text{kg}^{-1} \cdot \sqrt{79,0 \cdot 10^{-3} \text{ s}^{-1} \cdot \left(\frac{1}{60 \cdot 10^3 \text{ s}} + \frac{1}{60 \cdot 10^3 \text{ s}} \right)} \approx \\ &\approx 4,212 \text{ Bq} \cdot \text{s} \cdot \text{kg}^{-1} \cdot \sqrt{2,633 \cdot 10^{-6} \text{ s}^{-2}} \approx 6,854 \cdot 10^{-3} \text{ Bq} \cdot \text{kg}^{-1} \text{ (FM)} \end{aligned}$$

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):

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

$$\psi = 1 + \frac{1,645^2}{2 \cdot 6,835 \cdot 10^{-3} \text{ Bq} \cdot \text{kg}^{-1}} \cdot \frac{1,404 \text{ Bq} \cdot \text{s} \cdot \text{kg}^{-1}}{60 \cdot 10^3 \text{ s}} \approx 1,005$$

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

$$\begin{aligned} a^\# &= \frac{6,854 \cdot 10^{-3} \text{ Bq} \cdot \text{kg}^{-1} \text{ (FM)} \cdot 1,005}{0,9889} \cdot \left[1 + \sqrt{1 - \frac{0,9889}{1,005^2} \cdot \left(1 - \frac{1,645^2}{3^2} \right)} \right] \approx \\ &\approx 6,946 \cdot 10^{-3} \text{ Bq} \cdot \text{kg}^{-1} \text{ (FM)} \cdot 1,562 \approx 10,87 \cdot 10^{-3} \text{ Bq} \cdot \text{kg}^{-1} \text{ (FM)} \end{aligned}$$

7.1.2 Using strontium-85 as a yield tracer

In this worked example, 5,0 Bq Sr-85 was added to the 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	=	$28,13 \cdot 10^{-3} \text{ s}^{-1}$;	t_m	=	$60 \cdot 10^3 \text{ s}$;
R_0	=	$16,0 \cdot 10^{-3} \text{ s}^{-1}$;	t_0	=	$60 \cdot 10^3 \text{ s}$;
t_A	=	$3,456 \cdot 10^6 \text{ s}$;	t_b	=	$1,728 \cdot 10^6 \text{ s}$;
$t_{\text{Sr-85}}$	=	$5,603 \cdot 10^6 \text{ s}$;	$t_{\text{Sr-90}}$	=	$0,9088 \cdot 10^9 \text{ s}$;

$A_{\text{Sr-85}}$	=	5,00 Bq;	$u_{\text{rel}}(A_{\text{Sr-85}})$	=	0,02;
m_a	=	0,010 kg;	$u_{\text{rel}}(m_a)$	=	0,0;
q_1	=	11,11;	$u_{\text{rel}}(q_1)$	=	0,0;
q_2	=	5,0;	$u_{\text{rel}}(q_2)$	=	0,0;
η_{Sr}	=	0,750;	$u_{\text{rel}}(\eta_{\text{Sr}})$	=	0,05;
$\varphi_{A,\text{Sr-85}}$	=	$4,167 \cdot 10^3 \text{ Bq} \cdot \text{s};$	$u_{\text{rel}}(\varphi_{A,\text{Sr-85}})$	=	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):

$$R_{\text{Sr-85}} = \frac{5,0 \text{ Bq}}{4,167 \cdot 10^3 \text{ Bq} \cdot \text{s}} \cdot 0,750 \cdot e^{-\frac{\ln 2 \cdot 1,728 \cdot 10^6 \text{ s}}{5,603 \cdot 10^6 \text{ s}}} \approx 0,8999 \cdot 10^{-3} \text{ s}^{-1} \cdot 0,808 \approx 0,7267 \cdot 10^{-3} \text{ s}^{-1}$$

The net count rate R_n is calculated with Equation (4):

$$R_n = 28,13 \cdot 10^{-3} \text{ s}^{-1} - (16,0 \cdot 10^{-3} \text{ s}^{-1} + 0,7267 \cdot 10^{-3} \text{ s}^{-1}) \approx 11,40 \cdot 10^{-3} \text{ s}^{-1}$$

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

$$\varphi = \frac{2,632 \text{ Bq} \cdot \text{s}}{0,750 \cdot 0,010 \text{ kg} \cdot 11,11 \cdot 5,00} \cdot e^{\frac{\ln 2 \cdot 3,456 \cdot 10^6 \text{ s}}{0,9088 \cdot 10^9 \text{ s}}} \approx 6,317 \text{ Bq} \cdot \text{s} \cdot \text{kg}^{-1} \cdot 1,00 \approx 6,334 \text{ Bq} \cdot \text{s} \cdot \text{kg}^{-1}$$

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

$$a = 6,334 \text{ Bq} \cdot \text{s} \cdot \text{kg}^{-1} \cdot 11,40 \cdot 10^{-3} \text{ s}^{-1} \approx 72,23 \cdot 10^{-3} \text{ Bq} \cdot \text{kg}^{-1} \text{ (FM)}$$

The variance of the procedural 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):

$$\begin{aligned} \frac{u(a)}{a} &= \left\{ \frac{1}{(11,40 \cdot 10^{-3} \text{ s}^{-1})^2} \cdot \left[\frac{28,13 \cdot 10^{-3} \text{ s}^{-1}}{60 \cdot 10^3 \text{ s}} + \frac{16,0 \cdot 10^{-3} \text{ s}^{-1}}{60 \cdot 10^3 \text{ s}} + 0 \right] + \right. \\ &\quad \left. + 4,1 \cdot 10^{-3} + 2 \cdot 0,05^2 \cdot \frac{0,7271 \cdot 10^{-3} \text{ s}^{-1}}{11,40 \cdot 10^{-3} \text{ s}^{-1}} \right\}^{\frac{1}{2}} \approx \\ &\approx \sqrt{5,659 \cdot 10^{-3} + 4,1 \cdot 10^{-3} + 0,3189 \cdot 10^{-3}} \approx 0,100 \end{aligned}$$

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

$$a = (72,23 \pm 7,26) \cdot 10^{-3} \text{ Bq} \cdot \text{kg}^{-1} \text{ (FM)}$$

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

$$\begin{aligned} a^* &= 3 \cdot 6,334 \text{ Bq} \cdot \text{s} \cdot \text{kg}^{-1} \cdot \\ &\cdot \sqrt{\frac{16,0 \cdot 10^{-3} \text{ s}^{-1} + 0,7267 \cdot 10^{-3} \text{ s}^{-1}}{60 \cdot 10^3 \text{ s}} + \frac{16,0 \cdot 10^{-3} \text{ s}^{-1}}{60 \cdot 10^3 \text{ s}} + 0^2} \approx \\ &\approx 18,95 \text{ Bq} \cdot \text{s} \cdot \text{kg}^{-1} \cdot 0,7385 \cdot 10^{-3} \text{ s}^{-1} \approx 14,06 \cdot 10^{-3} \text{ Bq} \cdot \text{kg}^{-1} \text{ (FM)} \end{aligned}$$

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):

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

$$\psi = 1 + \frac{1,645^2}{2 \cdot 14,06 \cdot 10^{-3} \text{ Bq} \cdot \text{kg}^{-1}} \cdot \frac{6,334 \text{ Bq} \cdot \text{s} \cdot \text{kg}^{-1}}{60 \cdot 10^3 \text{ s}} \approx 1,010$$

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

$$\begin{aligned} a^\# &= \frac{14,06 \cdot 10^{-3} \text{ Bq} \cdot \text{kg}^{-1} \text{ (FM)} \cdot 1,010}{0,9889} \cdot \left[1 + \sqrt{1 - \frac{0,9889}{1,010^2} \cdot \left(1 - \frac{1,645^2}{3^2} \right)} \right] \approx \\ &\approx 14,37 \cdot 10^{-3} \text{ Bq} \cdot \text{kg}^{-1} \text{ (FM)} \cdot 1,568 \approx 22,52 \cdot 10^{-3} \text{ Bq} \cdot \text{kg}^{-1} \text{ (FM)} \end{aligned}$$

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

UncertRadio: Calculation of uncertainty budget and detection limits - F-Sr-90-FUMI-04_V2025-07_var1_EN.tbp

File Edit Options Help

Procedure Equations Values, Uncertainties Uncertainty budget **Results** Text Editor

Final measurement result for aSr90 :

Value output quantity: 7.22225E-02	Bq/kg
extendend (Std.-)uncertainty: 5.31977E-03	Bq/kg
relative ext.(Std.-)uncertainty: 7.3658	%

Best Bayesian Estimates: ☐ min. Coverage interval

Value output quantity: 7.22225E-02	Bq/kg
extendend (Std.-)uncertainty: 5.31977E-03	Bq/kg
lower range limit: 6.17960E-02	Bq/kg
upper range limit: 8.26491E-02	Bq/kg

Monte Carlo Simulation:

Number of simul. measurements: 100000 ☐ min. Coverage interval

Number of runs: 1

primary estimate: 7.23978E-02	Bq/kg	reISD%: 0.023
uncertainty primary estimate: 5.33132E-03	Bq/kg	0.224
Value output quantity: 7.23978E-02	Bq/kg	0.023
extendend uncertainty: 5.33132E-03	Bq/kg	0.224
relative extd.(Std.-)uncertainty: 7.3639	%	
lower range limit: 6.25249E-02	Bq/kg	0.072
upper range limit: 8.34546E-02	Bq/kg	0.054
Decision threshold (DT): 6.93932E-03	Bq/kg	0.873
Detection limit (DL): 1.09151E-02	Bq/kg	0.575

active run: 1 JT: 11 Start MC

Coverage factor k: 1.0
Probability (1-gamma): 0.950

Decision thresh. and Detection limit: aSr90 :

Decision threshold (DT): 6.8538E-03	Bq/kg	Iterations: 1
Detection limit (DL): 1.0869E-02	Bq/kg	Iterations: 1

k_alpha=3.000, k_beta=1.645 Method:ISO 11929:2019, by iteration

7.2.2 Using strontium-85 as a yield tracer

UncertRadio: Calculation of uncertainty budget and detection limits - F-Sr-90-FUMI-04_V2025-07_var2_EN.tbp

File Edit Options Help

Procedure Equations Values, Uncertainties Uncertainty budget **Results** Text Editor

Final measurement result for aSr90 :

Value output quantity: 7.22296E-02	Bq/kg
extendend (Std.-)uncertainty: 7.25650E-03	Bq/kg
relative ext.(Std.-)uncertainty: 10.046	%

Best Bayesian Estimates: ☐ min. Coverage interval

Value output quantity: 7.22296E-02	Bq/kg
extendend (Std.-)uncertainty: 7.25650E-03	Bq/kg
lower range limit: 5.80071E-02	Bq/kg
upper range limit: 8.64521E-02	Bq/kg

Monte Carlo Simulation:

Number of simul. measurements: 100000 ☐ min. Coverage interval

Number of runs: 1

primary estimate: 7.24173E-02	Bq/kg	reISD%: 0.032
uncertainty primary estimate: 7.32742E-03	Bq/kg	0.224
Value output quantity: 7.24173E-02	Bq/kg	0.032
extendend uncertainty: 7.32742E-03	Bq/kg	0.224
relative extd.(Std.-)uncertainty: 10.118	%	
lower range limit: 5.87943E-02	Bq/kg	0.105
upper range limit: 8.74944E-02	Bq/kg	0.071
Decision threshold (DT): 1.44404E-02	Bq/kg	0.873
Detection limit (DL): 2.28075E-02	Bq/kg	0.574

active run: 1 JT: 11 Start MC

Coverage factor k: 1.0
Probability (1-gamma): 0.950

Decision thresh. and Detection limit: aSr90 :

Decision threshold (DT): 1.4065E-02	Bq/kg	Iterations: 1
Detection limit (DL): 2.2609E-02	Bq/kg	Iterations: 1

k_alpha=3.000, k_beta=1.645 Method:ISO 11929:2019, by iteration

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·l⁻¹;
- sodium acetate-acetic acid solution: 0,05 mol·l⁻¹ sodium acetate in 0,05 mol·l⁻¹ acetic acid;
- sodium dichromate solution, Na₂Cr₂O₇: 1,31 mol·l⁻¹;
- sodium hydroxide solution, NaOH: 3 mol·l⁻¹, 10 mol·l⁻¹;
- nitric acid, HNO₃: 6 mol·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 Ba²⁺ per ml solution:
dissolve 0,356 g of barium chloride dihydrate (BaCl₂·2 H₂O) in deionized water, add 1 ml of hydrochloric acid (3 mol·l⁻¹), then fill up to 100 ml with deionized water;
- Strontium carrier solution: 20 mg Sr²⁺ per ml solution:
dissolve 6,086 g of strontium chloride hexahydrate (SrCl₂·6 H₂O) in deionized water, add 1 ml of hydrochloric acid (3 mol·l⁻¹), then fill up to 100 ml with deionized water;
- Yttrium carrier solution: 20 mg Y³⁺ per ml solution:
Dissolve 6,83 g of yttrium chloride hexahydrate (YCl₃·6 H₂O) in deionized water, add 1 ml of hydrochloric acid (3 mol·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 smaller than 2 mm or 1 mm and sample extraction;
- centrifugal mill with a sieve for particle size less than 1 mm;
- ashtray shells, e. g. of quartz or quartz material, 55 mm high, 145 mm wide, 205 mm long and a wall thickness of 4 mm to 5 mm;
- incineration furnace with air inlet slots and catalytic exhaust gas purification, e.g. chamber furnace type N150 of the company Nabertherm;
- optional: microwave oven with 250 ml pressure vessels, e.g. MLS;
- fine, quantitative paper filters with a pore diameter of less than 2 µm, e. g. blueband-filter grade 589/3, or filters of cellulosenitrate with a pore diameter of 0,45 µm;
- liquid scintillation measuring vials made of low potassium glass;
- liquid scintillation spectrometer, if possible low-level version with multi-channel analyzer;
- laboratory centrifuge.

References

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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] 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)*.
- [5] 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>.

- [6] 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>.