Procedure for determining the specific activities of radionuclides in fish and fishery products by gamma spectrometry

G-γ-SPEKT-FISCH-02

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ISSN 1865-8725 Version November 2015 / verified March 2020

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 fish and fishery products by gamma spectrometry

1 Scope

The procedure described in the following is suitable for gamma-ray-spectrometric analysis fish samples in case of higher releases of radioactive substances to get a rapid overview on the extent of contamination (IMIS-intensive measurement programme). It offers the main advantage to determine the specific activities of iodine isotopes, which is not possible with the procedure G-γ-SPEKT-FISCH-01 due to the volatility of iodine.

The procedure described in the following may also be used for gamma spectrometric analysis of samples of fish that have to be monitored in the IMIS-routine measurement programme according to the German Precautionary Radiation Protection Act (StrlSchG) and the Guideline for the Monitoring of Emissions and Immissions of Nuclear Installations during Regular Operation.

2 Sampling

The basic sampling is described in the procedure G-γ-SPEKT-FISCH-01. The sample mass has to be dimensioned large enough that 1,5 kg fresh mass is available for the analysis, which is filled into a 1-liter-Marinelli-beaker (reentrant beaker).

Special care must be taken if fish is sampled in higher contaminated regions. The freshly collected fish are killed quickly at the point of sampling and packed into plastic bags, which are stored on ice inside a suitable container. Freezing of the sample should be avoided as they should be measured as direct after sampling as possible. If freezing of the sample cannot be avoided, special care must be taken to include tissue fluids that may be liberated during the defrosting process in the sample. Furthermore, it must be distributed homogenously in the sample during the measurement process.

In case of import goods, crustaceans and shellfish and also tinned fish (fish commodities) are sampled besides fish. Samples are obtained from importers operating in the respective Federal State. Only the consumable parts considered as generally consumed by the public are analysed.

For correct labeling of samples, it is referred to procedure G-γ-SPEKT-FISCH-01 and the literature (1).

3 Analysis

3.1 Principle of the procedure

Fresh fish is filleted first. Fillets and tinned fish is chopped and homogenized. The specific activity is of gamma-ray emitting radionuclides including iodine is determined inside a 1-liter-Marinelli-beaker using a gamma-spectrometer.

3.2 Sample preparation

All items used for sample preparation, e. g. cutting boards, knives and Marinelli-beakers, must be cleaned using cleaning solution prior each use.

Fish are cleaned like in common household. Afterwards, they are filleted and bones and skin are removed as much as possible. The fish flesh obtained is finely cubed, a preserving agent, e. g. sodium azide is added and both are thoroughly mixed (see below). The use of a mixer or meat grinder must be avoided in cases of higher contamination.

In case of tinned fishery products it is recommended that the included liquids (e. g. sauces) are processed according to their generally consumption by the public. When they are not consumed, they may be discarded; otherwise they must be uniformly distributed inside the sample. The filling is not cleaned, but the texture may require mincing. The addition of preserving agents takes place before homogenization of the sample.

Generally the preparation is only stable for a short time. The addition of preserving agents like sodium azide decelerates microbial processes inside the preparation by which gases are released that lead to a swelling of the preparation. During measurement it is strictly advised that the cap is only loosely placed on top of the beaker. Additionally, the measurement chamber should be coated with foil or the beaker should be placed inside a large plastic bag.

At longer idle times before analysis, the preparation must be stored in the fridge.

3.3 Radiochemical separation

A radiochemical separation is not required.

4 Measuring the activity

4.1 General

The basics of gamma spectrometry and safety measures in case of higher levels of radiation are discussed in the basic chapter γ-SPEKT/GRUNDL of this procedures manual and in the literature (1, 2, 3, 4).

4.2 Calibration

4.2.1 Calibration in solution

For determining the energy-dependency of the detection efficiency, reference is made to the basic chapter γ-SPEKT/GRUNDL of this procedures manual.

The calibration is carried out with a suitable calibration preparation, e. g. an aqueous solution of a traceable standard or a resin containing traceable amounts of radioactive compounds.

4.2.2 Correction for self-attenuation

Because of the small difference in densities between water and fish flesh, a density correction for fish flesh may be omitted. This is due to the fact the density of the aqueous calibration solution is close to that of water (1 $g\cdot cm^{-3}$) and fish flesh contains from water by approx. 80 %.

4.3 Background

The basics of measuring the background effects are described in the procedure G-γ-SPEKT-FISCH-01.

In cases of specific activities two orders larger compared to the routine measuring program, the background effect must be determined with smaller measurement duration but higher frequency, e. g. each working day.

For samples of fish, reliably determining the K-40 background count rate of the background effect is important in order to be able to use the K-40 activity determined in fish for verifying the correctness of the subsequent sample spectrum analysis.

4.4 Measurement

For the detailed measurement procedure it is referred to section 4.4 of the procedure G-γ-SPEKT-FISCH-01. Instead of the cylindrical beaker described there, a 1-liter-Marinelli-beaker is used.

5 Calculation of the results

5.1 Equations

When determining specific activities of radionuclides in fish flesh, the gamma lines of different radionuclides may interfere. Therefore, determining specific activities of radionuclides from a single gamma line may not always be possible by easy-to-use methods.

If interferences occur or multiple-line radionuclides need to be analyzed, least squares fitting algorithms or, in the interference-free case, weighted means of the single line activities have to be used for calculation of the specific activities and measurement uncertainties. In this case, reference is made to the basic chapters γ-SPEKT/INTERF and γ-SPEKT/GRUNDL of this procedures manual.

For calculation of specific activities from single gamma lines it is referred the procedure G-γ-SPEKT-FISCH-01.

If a net count rate $R_{\mathrm{n,r}}$ associated with the gamma-ray energy of the radionuclide r has been detected, the resulting specific activity a_{r}, relative to fresh mass (FM) and the date and time of sampling, is calculated according to equation (1):

$$a_{\mathrm{r}} = \varphi \cdot R_{\mathrm{n,r}} = \frac{f_1 \cdot f_2 \cdot f_3 \cdot \mathrm{e}^{\lambda_{\mathrm{r}} \cdot t_{\mathrm{A}}}}{\varepsilon \cdot p_{\gamma} \cdot m_{\mathrm{F}}} \cdot R_{\mathrm{n,r}} \quad (1)$$

with:

$$f_3 = \frac{\lambda_{\mathrm{r}} \cdot t_{\mathrm{m}}}{1 - \mathrm{e}^{-\lambda_{\mathrm{r}} \cdot t_{\mathrm{m}}}}$$

Herein are:

- $R_{\mathrm{n,r}}$ net count rate of the gamma line of the regarded radionuclide r, in s^{-1};
- φ procedural calibration factor, in $Bq \cdot s \cdot kg^{-1}$;
- ε detection efficiency for water, depending on energy and fill level, in $Bq^{-1} \cdot s^{-1}$;
- f_1 correction factor for coincidence summing;
- f_2 self-attenuation correction factor for fish flesh relative to water, $f_2 = 1$;
- f_3 correction factor for the decay of the activity of the radionuclide r during the measurement;
- p_{γ} emission intensity of the gamma line of the radionuclide r;
- m_{F} mass of fresh fish flesh used for measurement, in kg;
- t_{A} time period between sampling and beginning of the measurement, in s;
- t_{m} duration of measurement, in s;
- λ_{r} decay constant of the radionuclide r, in s^{-1}.

The net count rate of the gamma-line of the radionuclide r is calculated according to equation (2):

$$R_{\mathrm{n,r}} = R_{\mathrm{b,r}} - R_{\mathrm{T,r}} - R_{0,\mathrm{r}} \quad (2)$$

Herein are:

- $R_{\mathrm{b,r}}$ gross count rate of the gamma line of the radionuclide r, in s^{-1};
- $R_{\mathrm{T,r}}$ background count rate underneath the gamma line of the radionuclide r, e. g. as count rate of a trapezoidal background, in s^{-1};
- $R_{0,\mathrm{r}}$ net count rate at the gamma line of the radionuclide r in a background spectrum, in s^{-1}.

The generalized expression to calculate the uncertainty of the net count rate is given in equation (3), with the coefficients μ_k to be determined according to equation (4):

$$u^2(R_{\mathrm{n,r}}) = \mu_0 \cdot R_{\mathrm{n,r}}^2 + \mu_1 \cdot R_{\mathrm{n,r}} + \mu_2 \tag{3}$$

$$\mu_0 = 0 \qquad \mu_1 = \frac{1}{t_\mathrm{m}} \qquad \mu_2 = \frac{R_{\mathrm{T,r}} + R_{\mathrm{0,r}}}{t_\mathrm{m}} + u^2(R_{\mathrm{T,r}}) + u^2(R_{\mathrm{0,r}}) \tag{4}$$

Using the trapezoidal method (assuming a linear background continuum) the coefficient μ_2 is given by equation (5):

$$\mu_2 = \frac{R_{\mathrm{T,r}}}{t_\mathrm{m}} \cdot \left(1 + \frac{b}{2 \cdot L}\right) + R_{\mathrm{0,r}} \cdot \left(\frac{1}{t_\mathrm{m}} + \frac{1}{t_0}\right) + \frac{R_{\mathrm{T,0,r}}}{t_0} \cdot \left(1 + \frac{b_0}{2 \cdot L_0}\right) \tag{5}$$

Herein are:

t_0 duration of the background measurement, in s;

b line widths of sample spectra at the respective peak baselines, in channels;

b_0 line widths of background spectra at the respective peak baselines, in channels;

L numbers of channels for the sample spectrum, respectively, over which the background continuum to the left and to the right of the peaks are estimated;

L_0 numbers of channels for the background spectrum, respectively, over which the background continuum to the left and to the right of the peaks are estimated;

$R_{\mathrm{T,0,r}}$ background continuum count rate at the line of the radionuclide r within the background spectrum, e. g. as a trapezoidal background count rate, in s^{-1}.

Equation (5) is a sufficient approximation for the background estimated by an empirical background step function.

The μ_k-coefficients only need to be inserted into equation (3) to receive the standard uncertainty of the net count rate $u(R_{\mathrm{n,r}})$ given by equation (6):

$$\begin{aligned} u^2(R_{\mathrm{n,r}}) &= \frac{R_{\mathrm{n,r}}}{t_m} + \mu_2 = \\ &= \frac{R_{\mathrm{n,r}}}{t_m} + \frac{R_{\mathrm{T,r}}}{t_\mathrm{m}} \cdot \left(1 + \frac{b}{2\,L}\right) + R_{\mathrm{0,r}} \cdot \left(\frac{1}{t_m} + \frac{1}{t_0}\right) + \frac{R_{\mathrm{T,0,r}}}{t_0} \cdot \left(1 + \frac{b_0}{2\,L_0}\right) \end{aligned} \tag{6}$$

When no count rate occurs at corresponding gamma ray energy of background spectrum equation (6) is reduced by the last two terms.

The combined standard uncertainty of the specific activity $u(a_\mathrm{r})$ using equation (1) is calculated as:

$$u(a_\mathrm{r}) = a_\mathrm{r} \cdot \sqrt{u_{\mathrm{rel}}^2(\varphi) + u_{\mathrm{rel}}^2(R_{\mathrm{n,r}})} \tag{7}$$

The relative standard uncertainty of the procedural calibration factor $u_{\mathrm{rel}}(\varphi)$ is determined according to equation (8), where the uncertainty of the decay correction may be neglected:

$$u_{\mathrm{rel}}(\varphi) = \sqrt{u_{\mathrm{rel}}^2(f_1) + u_{\mathrm{rel}}^2(f_2) + u_{\mathrm{rel}}^2(\varepsilon) + u_{\mathrm{rel}}^2(p_\gamma) + u_{\mathrm{rel}}^2(m_\mathrm{F})} \quad (8)$$

5.2 Worked example

The following example is used to calculate the specific I-131 activity in 1 kg fresh fish flesh (FM) using only the intensity of the gamma-ray energy at 364,5 keV. The following values are used:

$R_{\mathrm{n,I-131}}$ = 0,5115 $\mathrm{s^{-1}}$;
m_F = 1,00 kg;
p_γ = 0,812;
ε = 0,01775 $\mathrm{Bq^{-1} \cdot s^{-1}}$
f_1 = 1,000;
f_2 = 1,0;
$b/(2 \cdot L)$ = 0,523.

$R_{\mathrm{T,I-131}}$ = 0,00196 $\mathrm{s^{-1}}$;
$u_{\mathrm{rel}}(m_\mathrm{F})$ = 0,004;
$u_{\mathrm{rel}}(p_\gamma)$ = 0,00985;
$u_{\mathrm{rel}}(\varepsilon)$ = 0,029;
$u_{\mathrm{rel}}(f_1)$ = 0;
$u_{\mathrm{rel}}(f_2)$ = 0;

The standard uncertainties of the following input quantities are negligible:

t_A = 57600 s;
t_m = 1800 s.

$\lambda_{\mathrm{I-131}}$ = 9,999·10^{-7} $\mathrm{s^{-1}}$;

This leads to the correction factor f_3 for the decay during the duration of the measurement:

$$f_3 = \frac{9{,}999 \cdot 10^{-7}\ \mathrm{s^{-1}} \cdot 1800\ \mathrm{s}}{1 - \mathrm{e}^{-9{,}999 \cdot 10^{-7} \mathrm{s^{-1}} \cdot 1800\ \mathrm{s}}} = 1{,}0009$$

The detection efficiency in ash ε_A is calculated according to equation (4):

$$\varepsilon_\mathrm{A} = \frac{0{,}03056}{0{,}976}\ \mathrm{Bq^{-1} \cdot s^{-1}} = 0{,}03131\ \mathrm{Bq^{-1} \cdot s^{-1}}$$

The specific activity in the fresh fish flesh (FM) results from equation (1):

$$a_{\mathrm{I-131}} = \frac{1{,}0 \cdot 1{,}0 \cdot 1{,}0009 \cdot \mathrm{e}^{9{,}999 \cdot 10^{-7} \mathrm{s^{-1}} \cdot 57600\ \mathrm{s}}}{0{,}01775\ \mathrm{Bq^{-1} \cdot s^{-1}} \cdot 0{,}812 \cdot 1{,}0\ \mathrm{kg}} \cdot 0{,}5115\ \mathrm{s^{-1}} =$$

$$= 73{,}5613\ \mathrm{Bq^{-1} \cdot s^{-1} \cdot kg} \cdot 0{,}5115\ \mathrm{s^{-1}} = 37{,}6266\ \mathrm{Bq \cdot kg^{-1}}\ (\mathrm{FM})$$

The relative standard uncertainty of the procedural calibration factor is calculated by equation (8):

$$u_{\mathrm{rel}}\,(\varphi) = \sqrt{0^2 + 0^2 + 0{,}029^2 + 0{,}00985^2 + 0{,}004^2} = 0{,}030887$$

The standard uncertainty of the net count rate is obtained by equation (6) with neglecting the last two terms:

$$u\left(R_{\mathrm{n,I-131}}\right) = \sqrt{\frac{0{,}5115\ \mathrm{s}^{-1}}{1800\ \mathrm{s}} + \frac{0{,}00196\ \mathrm{s}^{-1}}{1800\ \mathrm{s}} \cdot (1 + 0{,}523)} = 1{,}6906 \cdot 10^{-2}\ \mathrm{s}^{-1}$$

The combined standard uncertainty of the specific activity $u(a_{\mathrm{I-131}})$ is calculated according to equation (7):

$$u(a_{\mathrm{I-131}}) = 37{,}6266 \cdot \sqrt{0{,}030887^2 + \left(\frac{1{,}6906 \cdot 10^{-2}}{0{,}5115}\right)^2}\ \mathrm{Bq} \cdot \mathrm{kg}^{-1} =$$

$$= 37{,}6266\ \mathrm{Bq} \cdot \mathrm{kg}^{-1} \cdot 0{,}04524 = 1{,}7021\ \ \mathrm{Bq} \cdot \mathrm{kg}^{-1}\ (\mathrm{FM})$$

Finally, the specific I-131 activity is obtained as:

$$a_{\mathrm{I-131}} \ = \ (37{,}6 \ \pm \ 1{,}7)\ \mathrm{Bq} \cdot \mathrm{kg}^{-1}\ (\mathrm{FM})$$

5.3 Consideration of uncertainties

The combined standard uncertainties of the specific activity amount to be 20 % or less except that the activities are so small that the relative uncertainties of the net counting rate already clearly exceed 20 %. The standard uncertainty of the self-attenuation correction factor does not contribute anything to this.

For multi-line radionuclides such as Cs-134, the uncertainty contribution of the coincidence summing correction factors (see basic chapters γ–SPEKT/GRUNDL and γ-SPEKT/SUMESC of these measuring instructions) has to be taken into account, which may lead to additional few percent in case of significant corrections.

6 Characteristic limits of the procedure

The calculation of the characteristic limits follows the standard ISO 11929 (2, 3, 4).

An Excel spreadsheet (see section 7.3.1) as well as a project file for the software UncertRadio (see section 7.3.2) are available on the website of this procedures manual.

Further considerations concerning the characteristic limits are to be found in the general chapters ERK/NACHWEISGR-ISO-01 and ERK/NACHWEISGR-ISO-02 of these procedures manuals.

6.1 Equations

6.1.1 Decision threshold

For the calculation of the decision threshold a_r^* of the specific activity of the radionuclide r it is referred to section 6.1 of the procedure G-γ-SPEKT-FISCH-01.

6.1.2 Detection limit

For the calculation of the detection limit $a_\mathrm{r}^\#$ of the specific activity of the radionuclide r it is referred to section 6.1 of the procedure G-γ-SPEKT-FISCH-01.

6.1.3 Limits of the coverage interval

The calculation of the limits of the coverage interval is not required in this case.

6.2 Worked example

Using the values of the input quantities from section 5.2 and the quantiles of the normal distribution, $k_{1-\alpha}$ = 3,0 and $k_{1-\beta}$ = 1,645, the coefficient μ_2 is calculated first. In this case, only the first term of equation (5) is used, because no corresponding line was observed in the background effect spectrum.

$$\mu_2 = \frac{0{,}00196}{1800} \cdot (1 + 0{,}523)\ \mathrm{s}^{-2} = 1{,}6584 \cdot 10^{-6}\ \mathrm{s}^{-2}$$

Using this value, the decision threshold of the specific activity $a_{\mathrm{I-131}}^*$ is calculated according to equation (22) of the procedure G-γ-SPEKT-FISCH-01 considering the procedural calibration factor φ:

$$a_{\mathrm{I-131}}^* = 73{,}5613\ \mathrm{Bq}^{-1} \cdot \mathrm{s}^{-1} \cdot \mathrm{kg} \cdot 3{,}0 \cdot \sqrt{1{,}6584 \cdot 10^{-6}\ \mathrm{s}^{-2}} = 0{,}2842\ \mathrm{Bq} \cdot \mathrm{kg}^{-1}\ (\mathrm{FM})$$

According to equation (23) of the procedure G-γ-SPEKT-FISCH-01 and with the values of the auxiliary quantities

$$\theta = 1 - 1{,}645^2 \cdot 0{,}030887^2 = 0{,}9974$$

$$\psi = 1 + \frac{1{,}645^2}{2 \cdot 0{,}2842} \cdot \frac{73{,}5613}{1800} = 1{,}1946$$

the detection limit of the specific activity $a_{\mathrm{I-131}}^\#$ is:

$$a_{\mathrm{I-131}}^\# = 0{,}2842\ \mathrm{Bq} \cdot \mathrm{kg}^{-1} \cdot \frac{1{,}1946}{0{,}9974} \cdot \left[1 + \sqrt{1 - \frac{0{,}9974}{1{,}1946^2} \cdot \left(1 - \frac{1{,}645^2}{3{,}0^2}\right)}\right] =$$

$$= 0{,}3404\ \mathrm{Bq} \cdot \mathrm{kg}^{-1} \cdot 1{,}715 = 0{,}5838\ \mathrm{Bq} \cdot \mathrm{kg}^{-1}\ (\mathrm{FM})$$

7 Catalogue of chemicals and equipment

7.1 Chemicals

The chemicals used should be of analytically pure quality.

— Cleaning agent: e. g. RBS-50-Super-Flüssigkonzentrat® 2 %.

— Preserving agent: Sodium azide, NaN_3
required for longer sample storage or in case of long (overnight) duration of measurement.

7.2 Equipment

Ordinary equipment of a radiochemical laboratory.

7.2.1 Sampling

— ice container / cooling boxes;

— plastic bags;

— deep freezer (ca. -18 °C), if the samples have to be stored.

7.2.2 Sample preparation

— filleting board made of plastic;

— sharpened filleting knifes;

— cut-resistant gloves.

7.2.3 Calibration and measurement

— 1-liter-Marinelli-beaker (reentrant beaker);

— Plastic foil or plastic bags, as splash guard for detector and interior room of the lead shielding.

7.3 Software supported calculation

7.3.1 Example of an Excel spreadsheet

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G-γ-SPEKT-FISCH-02 Version November 2015 / verified March 2020

Procedures manual for monitoring of radioactive substances in the environment and of external radiation (ISSN 1865-8725)

SAMPLE IDENTIFICATION: I-131 (Evaluation as single line radionuclide by its 364,5 keV-energy)

#Number of parameters p	13
k_alpha	3
k_beta	1,645
gamma	0,05

Create Excel variables!

User-Input:	Input of values
	Definition Excel variables
	Input of Excel formulae
Excel-VBA:	**#Keywords**
	Values from Vbasic

Data input: variable names: Uncertainty budget:

	#Values of parameters p	Unit	Excel variable	Input values	StdDev	partial derivatives	uncertainty budget:	budget in %
p 1	#Number of gross counts Ng		Ng	924,23	30,4011513	0,04086729	1,24241279	53,27511713
p 2	trapezoidal BG count rate	1/s	RT	1,9600E-03	7,5464E-04	-73,56113	0,05551253	0,106359094
p 3	b/2L		b2L	5,2300E-01	0,0000E+00	0	0	0
p 4	detection efficiency		eps	1,7750E-02	5,1475E-04	-2119,80151	1,09116783	41,09374246
p 5	emission probability, 364,5 keV		p_gamm	8,1200E-01	8,0000E-03	-46,3381301	0,37070504	4,7429612
p 6	fresh mass of the sample	kg	mF	1,0000E+00	4,0000E-03	-37,6265616	0,15050625	0,781810752
p 7	time period Sampling-->StartMeasum	s	tA	5,7600E+04	0,0000E+00	3,7623E-05	0	0
p 8	half-live of I-131	s	thalf	6,9321E+05	1,6400E+02	-3,175E-06	0,0005207	9,35754E-06
p 9	factor for coincidence summing correction		_f1	1,0000E+00	0,0000E+00	37,6265993	0	0
p 10	self-attenuation correction factor		_f2	1,0000E+00	0,0000E+00	37,6265993	0	0
p 11	duration of measurement	s	tm	1,8000E+03	0,0000E+00	-0,02096494	0	0
p 12	net count rate of the BG peak	1/s	RnBG	0,0000E+00	0,0000E+00		0	0
p 13	duration of BG measurement	s	tBG	7,2000E+04	0,0000E+00	0	0	0
	(List can be continued here)							

	Model section		**c = phix * Rn**	
	Auxiliary equations h			(Formulae)
h 1	#Gross count rate Rg	1/s	Rg	5,1346E-01
h 2	decay correction counting duration		_f3	9,9910E-01
h 3	decay correction Sampling-->StartMes		_f4	1,0593E+00
	(List can be continued here)			
	#Net count rate Rn	1/s	Rn	5,1150E-01
	#Calibration factor, proc.dep.	Bq*s/kg	phix	7,3561E+01
	#Value output quantity	Bq/kg	Result	3,7627E+01 — 0,58371675 <-- output value modifiable by VBA
	#Combined standard uncertainty	Bq/kg	uResult	1,7022E+00
	#Decision threshold	Bq/kg		0,284191691
	#Detection limit	Bq/kg		0,583716677

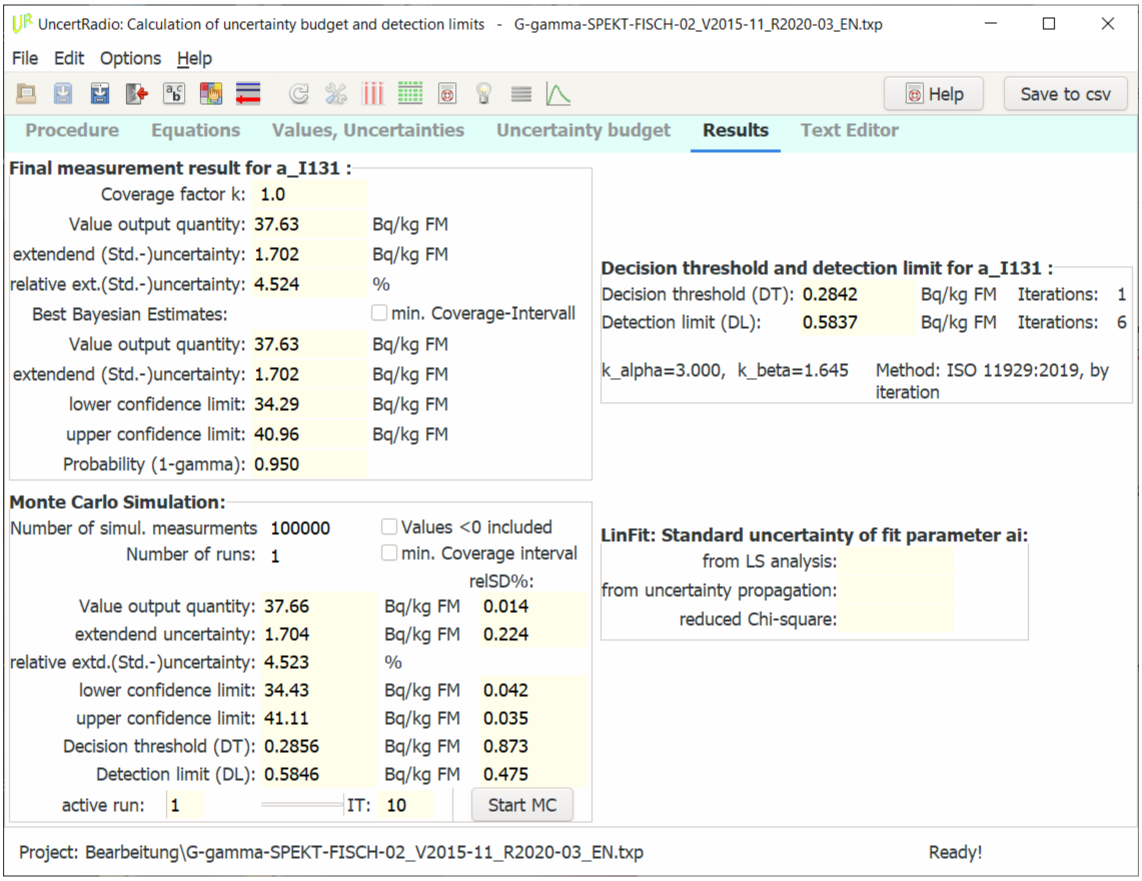
Calculate!

further derived values

Auxiliary quantity Omega		Omega	1
Best estimate	Bq/kg	BestEst	3,7627E+01
Uncertainty best estimate	Bq/kg		1,7022E+00
Lower confidence limit	Bq/kg		3,4290E+01
Upper confidence limit	Bq/kg		4,0963E+01

The corresponding Excel spreadsheet is available on the website of this procedures manual.

7.3.2 Example of an UncertRadio project



The corresponding UncertRadio project file is available on the website of this procedures manual.

References

(1) *Guidelines for fish, crustaceans, molluscs and products thereof. Includes guidelines for frozen fish, crustaceans, molluscs and products thereof* (in German). GMBl Nr. 23-25 S. 451 ff from 19.06.2008. 51 pages.

(2) ISO 11929-1:2019, *Determination of the characteristic limits (decision threshold, detection limit and limits of the coverage interval) for measurements of ionizing radiation — Fundamentals and application — Part 1: Elementary applications*.

(3) ISO 11929-2:2019, *Determination of the characteristic limits (decision threshold, detection limit and limits of the coverage interval) for measurements of ionizing radiation — Fundamentals and application — Part 2: Advanced applications*.

(4) ISO 11929-3:2019, *Determination of the characteristic limits (decision threshold, detection limit and limits of the coverage interval) for measurements of ionizing radiation — Fundamentals and application — Part 3: Applications to unfolding methods*.