TECHNICAL APPENDICES

This section contains detailed information about the traceability of measurement results, the calculation of uncertainties and surface contamination monitoring. An overview of quality control requirements for sealed radioactive sources is given. A table of nuclear decay scheme data is given at the end of this section.

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9.1 Traceability

Traceability is the property of a result of a measurement whereby it can be related to appropriate standards, generally international or national standards, through an unbroken chain of comparisons.

Reference sources and standardized solutions supplied by Eckert & Ziegler Nuclitec GmbH are traceable to standards held by National Laboratories such as: the Physikalisch-Technische Bundesanstalt (PTB), Germany; the National Physical Laboratory (NPL), UK; the Laboratoire Primaire de Rayonnements Ionisants (LPRI), France; and the National Institute of Standards and Technology (NIST), USA.

The National Laboratories participate in validation and intercomparison exercises organised under the auspices of the International Bureau for Weights and Measures (BIPM) in France. Traceability to one National Laboratory can often be accepted as attributing traceability to other laboratories.

The administrative system to confirm traceability depends on the country to which traceability is sought. In particular, there are differences between the systems for Europe and the USA.

Traceability in Europe - Accreditation

Eckert & Ziegler Nuclitec GmbH operates an accredited measurement laboratory in Germany.

Accreditation is a system of assessment of laboratories by independent experts to the European standard EN ISO/IEC 17025. The assessments are carried out by experts representing the national accreditation body. The accreditation body in the UK is the United Kingdom Accreditation Service (UKAS), and in Germany the body is the Deutscher Kalibrierdienst (DKD).

The assessors check that the laboratories are meeting essential conditions, such as:
- technical competence
- impartiality
- valid calibration methods
- traceability to national standards
- effective quality system

If the laboratory passes the assessment and the surveillance visits, the laboratory is permitted to issue certificates of calibration marked with the symbol issued by the accreditation body (UKAS uses the UKAS logo under license from the UK government, DKD uses the DKD logo under license from the PTB).

The advantages of UKAS or DKD certificates are:
- Assurance that work has been carried out to the required standard
- Assurance that agreed methods have been followed
- Assurance that measurements are traceable to national standards

In turn, accreditation bodies such as UKAS and DKD are evaluated by a team of assessors from the European Co-operation for Accreditation of Laboratories (EA). The EA has set up mutual recognition agreements, so a UKAS or DKD certificate has one further advantage:
- Accepted in many countries world-wide

For example, a UKAS or DKD certificate of calibration has the same status in France as a COFRAC certificate (the accreditation body in France).

Traceability in the USA - NIST

The requirements for traceability to the National Institute of Standards and Technology are set out in the American National Standards Institute standard ANSI N42.22-1995 'American National Standard - Traceability of Radioactive Sources to the National Institute of Standards and Technology (NIST) and Associated Instrument Quality Control'.
The standard requires that source manufacturers meet certain criteria. The criteria fall under four main headings:
- Quality assurance management system
- Facilities and equipment
- Participation in NIST measurement assurance program
- Certificates of calibration

9.1 Traceability

Eckert & Ziegler Nuclitec GmbH's reference sources and standardized solutions satisfy the criteria for traceability as:

- Eckert & Ziegler Nuclitec GmbH's measurement laboratory and production facilities meet the requirements of international standards (ISO 9001), but for the sake of completeness have also been audited against the specific requirements of ANSI N42.22 and found to be in full compliance.
- Facilities and equipment are audited by independent experts from UKAS and DKD
- Eckert & Ziegler Nuclitec GmbH is a charter member of the Steering Group of the Nuclear Energy Institute (NEI)/NIST Measurement Assurance Program. Eckert & Ziegler Nuclitec GmbH's measurement laboratory carries out intercomparison exercises with NIST, and ensure that the results meet the acceptance criteria required by ANSI N42.22.
- The certificates of calibration provide the information required by ANSI N42.22.

9.2 Calculation of uncertainties

Every measurement is subject to an error, where the error is defined to be the measured result minus the (unknown) true value. The uncertainty is the range about zero in which the error is thought to lie, with a certain level of confidence.

For all of the standards described in this catalogue, the uncertainties in the measurements have been calculated following the 'Guide to the Expression of Uncertainty in Measurement', published by the International Organisation for Standardization, Geneva, in 1993. The guide was written by the BIPM, IEC, ISO and OIML, under the auspices of the Comité International des Poids et Mesures. The method described in the guide is recommended by national standards laboratories and accreditation bodies (see for example, NIST Technical Note 1297 (1994), UKAS document NIS3003 (1995)).

In brief, the uncertainties are calculated in the following way:

I. The overall uncertainty is composed of many different components (eg, counting statistics, instrumental drifts, uncertainties in standards).

II. Each component of the uncertainty is classified as either a Type A or a Type B uncertainty:
Type A: uncertainty estimated by a statistical method
Type B: uncertainty estimated by another method (eg, theoretical calculation)

III. Each component is then characterised by a standard deviation (u_i), taking into account the probability distribution of the error (eg, Gaussian, rectangular, U-shaped etc.).

IV. The estimated standard deviations are then summed in quadrature to give the overall standard deviation: $u_c=(\Sigma u_i^2)$

V. This figure is multiplied by a coverage factor (k) to obtain the expanded uncertainty (U): $U=ku_c$. For the standards in this catalogue, the coverage factor chosen is 2.0, which is approximately equivalent to a level of confidence of 95%.

Formerly, uncertainties were calculated following ICRU Report 12 ('Certification of Standardized Radioactive Sources') published by the International Commision on Radiation Units and Measurement in 1968. The main differences with the new approach are:

- The terms random and systematic uncertainties are no longer used. The reason is that a random uncertainty at one stage in a measurement can become a systematic uncertainty at the next (for example, the uncertainty in a calibration standard).
- Under the new scheme, components of the uncertainty are combined in quadrature rather than linearly as in ICRU Report 12. The disadvantages of combining uncertainties linearly are that the uncertainty can be unrealistically large, and the probability that a result is near the edge of the overall uncertainty quoted is extremely low.

The new method of calculating uncertainties therefore allows a more meaningful comparison of measurements.

9.3 Quality control

ISO classification

The International Organization for Standarization (ISO) has proposed a system of classification of sealed radioactive sources based on the safety requirements for typical uses (see ISO2919:1999). This system provides a manufacturer of sealed radioactive sources with a set of tests to evaluate the safety of his products. It also assists a user of such sealed sources to select types which suit the application in mind.
The tests to which specimen sources are subjected are listed in the following table.
Each test can be applied in several degrees of severity. Test results are expressed as a five figure code to indicate the severity of the tests.
These figures are preceded by the letter C or E to show whether the source activity is less than or greater than certain limits. These limits depend upon the toxicity, solubility and reactivity of the active component of the source.
C indicates that the activity level of the source does not exceed the prescribed limit and **E** that the limit is exceeded.

Classification of sealed radioactive source performance standards according to ISO 2919

Test	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
Temperature	No test	-40°C (20min) +80°C (1h)	-40°C (20min) +180°C (1h)	-40°C (20min) +400°C (1h) and thermal shock 400°C to 20°C	-40°C (20min) +600°C (1h) and thermal shock 600°C to 20°C	-40°C (20min) +800°C (1h) and thermal shock 800°C to 20°C
External pressure	No test	25kPa absolute to atmospheric	25kPa absolute to 2MPa absolute	25kPa absolute to 7MPa absolute	25kPa absolute to 70MPa absolute	25kPa absolute to 170MPa absolute
Impact	No test	50g from 1m	200g from 1m	2kg from 1m	5kg from 1m	20kg from 1m
Vibration	No test	3 x 10min 25kHz to 500Hz at 5g acceleration max. amplitude	3 x 10min 25Hz to 50Hz at 5g acceleration max. amplitude and 50Hz to 90Hz at 0.635mm amplitude peak to peak and 90Hz to 500Hz at 10g acceleration max. amplitude	3 x 30min 25Hz to 80Hz at 1.5mm amplitude peak to peak and 80Hz to 2000Hz at 20g acceleration max. amplitude		
Puncture	No test	1g from 1m	10g from 1m	50g from 1m	300g from 1m	1kg from 1m

9.3 Quality control

IAEA special form

'Special Form' is a test specification for sealed sources given in the IAEA transport regulations (IAEA Safety Standards Series No. ST-1, 1996). It is used in determining the maximum acceptable activities for various types of transport containers.

Leakage and contamination tests

Stringent tests for leakage are an essential feature of radioactive sources production. They are based on ISO9978. Some standard methods used for testing radiation sources are listed below.

Wipe test I (A)	Immersion test II (L)	Bubble test III (D)	Emanation test IV
The source is wiped with a swab or tissue, moistened with ethanol or water; the activity removed is measured.	The source is immersed in a suitable liquid at 50°C for 4 hours and the activity removed is measured.	The source is immersed in water or a suitable liquid and the pressure in the vessel reduced to 25-15 kPa. No bubbles must be observed. (This test conforms to ISO9978 exept that for sources, the 100mm³ free volume requirement is not met).	The source is placed in a gas tight enclosure with a suitable absorber and is left there for at least 3h. The source is considered leak tight when not more than 200Bq Radon related to a collection time of 12h can be measured afterwards.
Limit 200Bq	Limit 200Bq		

9.4 Surface contamination monitoring

In this appendix, the difference between class 2 and working sources will be explained in the context of measuring surface contamination. Measuring surfaces in the workplace for radioactive contamination is an important part of ensuring that the radiation doses workers receive are kept as low as reasonable practicable. Two written standards have been published by ISO (International Organization for Standardization) to advise on the measurement of radioactive contamination on surfaces:

ISO8769:1988 part 1 'Reference sources for the calibration of surface contamination monitors - Beta emitters (maximum beta energy greater than 0.15MeV) and alpha emitters'.
This document describes how calibration standards should be constructed and measured for beta and alpha emitting radionuclides.

ISO8769:1996 part 2 'Reference sources for the calibration of surface contamination monitors - Electrons of energy less than 0.15MeV and photons of energy less than 1.5MeV'.
The second part extends the standard to include photon emitting radionuclides (eg, Ga-67, Tc-99m, In-111).

ISO7503:1988 part 1 'Evaluation of surface contamination - Part 1: Beta emitters (maximum beta energy greater than 0.15MeV) and alpha emitters'.
This document then describes how the calibrated instrument is used to assay beta- and alpha-emitting contamination on surfaces.

ISO7503:1988 part 2 'Evaluation of surface contamination - Tritium surface contamination'.

ISO7503:1996 part 3 'Evaluation of surface contamination - Isomeric transition and electron capture emitters, low energy beta emitters (maximum beta energy less than 0.15MeV)'.

These documents extend part 1 to cover tritium and photon emitting radionuclides.

9.4 Surface contamination monitoring

Alpha-and beta-surface emitting radionuclides - ISO8769

This document defines a hierarchy of calibration standards. There are 3 levels:

Class 1 standards
- The sources must be as close as possible to an ideal, infinitely thin, source.
- The surface emission rate must be measured at a National Standards Laboratory with an uncertainty which shall not exceed 3%.

Class 2 standards
- The sources must be as close as possible to an ideal, infinitely thin, source.
- The particle emission rate must be measured against a class 1 standard with an uncertainty which shall not exceed 6%.

Working sources
- A robust source construction can be used; the source does not have to be as close as possible to an ideal, infinitely thin, source.
- The surface emission rate must be measured against either a class 1 source or a class 2 source. The stated uncertainty is normally ±10% or less.

In general, class 1 sources are used by source manufacturers to calibrate transfer instruments used to produce class 2 and working sources. The class 2 sources are used by instrument calibration facilities or users to calibrate contamination monitors for the statutory annual test (depending on the country's regulations). Working sources are used more frequently (monthly, or daily) to check calibrations in the field.

Eckert & Ziegler Nuclitec GmbH has implemented ISO8769 in the following way, taking account of the different applications of the sources:
- Class 1, class 2 and working sources are all constructed using the same manufacturing method, which results in a robust but thin active layer
- Class 1 sources are calibrated at a National Laboratory (available on request).
- Class 2 sources are issued with an DKD certificate of calibration, due to the requirement for proof of traceability to national standards for statutory tests.
- Working sources are issued with an Eckert & Ziegler Nuclitec GmbH certificate of calibration to provide cost-effective sources for regular use.

Strictly, the terms class 1, class 2 and working sources only apply to sources greater than 100cm^2 in area. The classification has been retained for smaller sources to help identify the best source for different applications.

Photon emitting wide area reference sources - ISO8769 part 2

Many radionuclides (for example, Tc-99m used in nuclear medicine) decay by emitting photons only. The set of sources described in ISO8769 part 2 can be used to calibrate surface contamination monitors for such radionuclides.

Each of the seven sources (see page 28) in the set has been constructed to emit monoenergetic photons covering a range of energies from 6keV to 1200keV. The active area of each source is 10x10cm^2 on a 3mm thick backing plate 15x15cm^2 in area. Where applicable, the source is covered with an inactive foil to absorb particles that could interfere with the measurements.

The certificate of calibration for each source states the mean photon energy and the photon emission rate (for the sources listed on page 28, these quantities are directly traceable to UK primary standards). To use the source set, the monitor response is determined at each photon energy. A calibration curve is then plotted and the response of the instrument to any photon-emitting radionuclide can then be estimated.

The advantages of using this set of sources are:

- Comply with international standard for calibrating monitors for photon emitting radionuclides
- Calibration factors can be derived for any photon emitting radionuclide
- Consistent, defined, method for comparing suitability of different types of monitor

The nuclear decay scheme data shown on the following pages are intended as a guide for selecting the radionuclides for your application[1] and show the major radiations only. The decay scheme data are taken from the JEF-2.2 Radioactive Decay Data library. The JEF (Joint Evaluated File) project started in 1981 with the aim of setting up a comprehensive database for fission reactor applications, for OECD member countries. The latest version (JEF-2.2) contains the decay schemes of 2344 radionuclides and includes the energies and intensities of 69835 gamma rays.

9.5 Nuclear decay scheme data

Key to symbols

α	alpha decay
ß⁻	beta decay [2]
ß+	positron decay
ec	electron capture
it	isomeric transition
ic	internal conversion
y	years
d	days
h	hours
m	minutes
s	seconds

For further details on the JEF-2.2 library contact:

OECD countries:
NEA Databank
Le Seine St-Germain
12, Boulevard des Îles
92130 Issy-les-Moulineaux
France
e-mail: NEA@FRNEAAB51

USA and Canada:
National Nuclear Data Center
Brookhaven National Laboratory
Upton
NY 11973-5000
USA

Non-OECD countries:
IAEA Nuclear Data Section
PO Box 100
A-1400 Vienna
Austria

Radio-nuclide	half life	Decay mode	Alpha Energy [MeV]	Alpha Intensity [%]	Beta Energy [MeV]	Beta Intensity [%]	Photon Energy [MeV]	Photon Intensity [%]
H-3	12.33y	ß⁻			0.019	100.0		
Be-7	53.3d	ec				100.0	0.478	10.3
C-14	5730y	ß⁻			0.157	100.0		
Na-22	2.60y	ß+			0.546 1.820	90.5 0.06	0.511 1.275	from ß+ 99.94
		ec				9.5		
Na-24	14.98h	ß⁻			0.277 1.390	0.1 99.9	1.369 2.754	100.0 99.9
P-32	14.3d	ß⁻			1.710	100.0		
S-35	87.5d	ß⁻			0.168	100.0		
Cl-36	3.02x10^{5}y	ß⁻ ec			0.710	98.1 1.9		
K-42	12.4h	ß⁻			1.684 1.997 3.521	0.35 18.4 81.1	0.313 1.525	0.35 18.9
Ca-45	163d	ß⁻			0.256	100.0		
Sc-46	83.8d	ß⁻			0.357 1.478	100.0 0.004	0.889 1.121	100.0 100.0
Ca-47	4.54d	ß⁻			0.691 1.221 1.988	82.0 0.1 18.0	0.489 0.530 0.767 0.808 1.297	6.7 0.1 0.2 6.9 74.9
via Sc-47	3.40d	ß⁻			0.441 0.600	70.0 30.0	0.159	70.0
Cr-51	27.7d	ec				100.0	0.320 0.005	9.8 22% X-rays
Mn-54	312.5d	ec				100.0	0.835	99.98
Fe-55	2.7y	ec				100.0	0.006	28% X-rays

[1] The decay scheme data relevant to a particular source are given on the certificate of calibration or measurement report. These data may not be exactly the same as the data listed here, as regulations may require that specific data are used.
[2] The energy given in the table is the end-point energy.

9.5 Nuclear decay scheme data

Radio-nuclide	half life	Decay mode	Alpha Energy [MeV]	Alpha Intensity [%]	Beta Energy [MeV]	Beta Intensity [%]	Photon Energy [MeV]	Photon Intensity [%]
Co-56	78.8d	ß+			0.423	1.1	0.511	from ß+
					1.461	18.6	0.847	99.9
		ec				80.3	0.977	1.4
							1.038	14.1
							1.175	2.3
							1.238	67.0
							1.360	4.3
							1.771	15.5
							2.015	3.0
							2.035	7.8
							2.599	16.7
							3.010	1.0
							3.202	3.0
							3.254	7.4
							3.273	1.7
							3.451	0.9
Co-57	271.4d	ec				100.0	0.014	9.6
							0.122	85.5
							0.136	10.7
							0.692	0.2
Co-58	70.8d	ß+			0.473	15.0	0.511	from ß+
		ec				85.0	0.811	99.5
							0.864	0.7
							1.675	0.5
Fe-59	45.1d	ß-			0.085	0.1	0.143	1.0
					0.132	1.3	0.192	3.1
					0.275	45.3	0.335	0.3
					0.467	53.1	0.382	0.02
					1.566	0.2	1.099	56.5
							1.292	43.2
							1.482	0.1
Co-60	5.27y	ß-			0.318	99.9	1.173	99.9
					1.491	0.1	1.333	99.98
Ni-63	100.0y	ß-			0.066	100.0		
Zn-65	244.3d	ß+			0.329	1.5	1.116	50.7
		ec				98.5		
Ga-67	3.26d	ec				100.0	0.091	3.0
							0.093	37.0
							0.185	20.4
							0.209	2.3
							0.300	16.6
							0.394	4.6
							0.494	0.1
							0.794	0.1
							0.888	0.1

9.5 Nuclear decay scheme data

Radio-nuclide	half life	Decay mode	Alpha Energy [MeV]	Alpha Intensity [%]	Beta Energy [MeV]	Beta Intensity [%]	Photon Energy [MeV]	Photon Intensity [%]
Se-75	119.8d	ec				100.0	0.066	1.1
							0.097	3.5
							0.121	17.3
							0.136	59.0
							0.199	1.5
							0.265	59.1
							0.280	25.2
							0.304	1.3
							0.401	11.6
via As-75m	17ms	it					0.304	0.9
Br-82	1.47d	ß$^-$			0.258	1.4	0.221	2.3
					0.439	98.6	0.554	70.6
							0.606	1.2
							0.619	43.1
							0.698	27.9
							0.776	83.4
							0.828	24.2
							1.008	1.3
							1.044	27.4
							1.317	26.9
							1.475	16.6
							1.650	0.8
Kr-85	10.72y	ß$^-$			0.173	0.4	0.514	0.4
					0.687	99.6		
Sr-85	64.84d	ec				100.0	0.514	98.3
							0.014	60% X-rays
Rb-86	18.7d	ß$^-$			0.698	8.8	1.077	8.8
					1.775	91.2		
Y-88	106.6d	ß$^+$			0.761	0.2	0.511	from ß$^+$
		ec				99.8	0.898	94.0
							1.836	99.4
							2.734	0.6
Sr-89	50.5d	ß$^-$			0.583	0.01		
					1.492	99.99		
via Y-89m	16.06s	it					0.909	0.01
in equilibrium								
Sr-90	29.12y	ß$^-$			0.546	100.0		
via Y-90	2.67d	ß$^-$			0.523	0.016	1.761	
0.02ic								
					2.284	99.98		
Y-90	2.67d	ß$^-$			0.523	0.016	1.761	
0.02ic								
					2.284	99.98		
Y-91	58.5d	ß$^-$			0.338	0.3	1.205	0.3
					1.543	99.7		

9.5 Nuclear decay scheme data

Radio-nuclide	half life	Decay mode	Alpha Energy [MeV]	Alpha Intensity [%]	Beta Energy [MeV]	Beta Intensity [%]	Photon Energy [MeV]	Photon Intensity [%]
Nb-93m	16.4y	it				100.0	0.017	11% X-rays
Nb-95	35.2d	ß⁻			0.160	100.0	0.766	100.0
Zr-95	63.98d	ß⁻			0.365	55.0	0.724	44.4
					0.398	44.6	0.757	54.9
					0.887	0.7		
via Nb-95m in equilibrium	3.61d						0.235	0.3
via Nb-95	35.2d	ß⁻			0.160	100.0	0.766	100.0
Mo-99	2.75d	ß⁻			0.436	16.6	0.041	1.1
					0.848	1.2	0.140	4.9
					1.214	82.0	0.181	6.1
							0.366	1.2
							0.740	12.2
							0.778	4.3
via Tc-99m in equilibrium	6.02h	it				100.0	0.140	89.0
Tc-99	2.13×10^5y	ß⁻			0.294	100.0		
Tc-99m	6.02h	it					0.140	89.00
Ru-103	39.4d	ß⁻			0.112	6.5	0.053	0.37
					0.225	90.0	0.295	0.25
					0.723	3.5	0.444	0.32
							0.497	88.9
							0.557	0.83
							0.610	5.6
via Rh-103m	56.1m	it					0.040	0.1
							0.021	8% X-rays
Ru-106	1.01y	ß⁻			0.039	100.0		
via Rh-106	29.8s	ß⁻			1.979	1.7	0.512	20.7
					2.407	9.8	0.622	9.8
					3.029	8.4	0.874	0.4
					3.541	78.6	1.050	1.5
							1.128	0.4
							1.562	0.2
Cd-109	1.27y	ec				100.0	0.023	68% X-rays
via Ag-109m in equilibrium	39.6s	it					0.088	3.7
							0.023	35% X-rays

9.5 Nuclear decay scheme data

Radio-nuclide	half life	Decay mode	Alpha Energy [MeV]	Alpha Intensity [%]	Beta Energy [MeV]	Beta Intensity [%]	Photon Energy [MeV]	Photon Intensity [%]
Ag-110m	249.9d	ß-			0.084	67.5	0.447	3.7
					0.531	30.6	0.620	2.8
							0.658	94.7
							0.678	10.7
							0.687	6.5
							0.707	16.7
							0.744	4.7
							0.764	22.4
							0.818	7.3
							0.885	72.9
							0.937	34.3
							1.384	24.4
							1.476	4.0
							1.505	13.1
							1.562	1.2
via Ag-110	24.6s	ß-			2.235	4.4	0.658	4.5
					2.893	95.2		
In-111	2.83d	ec				100.0	0.171	90.2
							0.245	94.0
Sn-113	115.1d	ec				100.0	0.255	1.8
via In113m	1.66h	it				100.0	0.392	64.9
I-123	13.2h	ec				100.0	0.159	83.3
							0.529	1.4
Sb-124	60.2d	ß-			0.212	8.8	0.603	97.9
					0.612	52.0	0.646	7.2
					0.867	3.6	0.709	1.4
					0.948	2.0	0.714	2.4
					1.580	5.4	0.723	11.3
					1.657	2.5	0.791	0.7
					2.303	22.6	0.968	1.8
							1.045	1.8
							1.326	1.4
							1.355	0.9
							1.368	2.4
							1.437	1.0
							1.691	48.8
							2.091	5.6
I-125	60.1d	ec				100.0	0.035	6.7
							0.028	140%X-rays

9.5 Nuclear decay scheme data

Radio-nuclide	half life	Decay mode	Alpha Energy [MeV]	Alpha Intensity [%]	Beta Energy [MeV]	Beta Intensity [%]	Photon Energy [MeV]	Photon Intensity [%]
Sb-125	2.73y	β^-			0.095	13.6	0.036	4.3
					0.125	5.8	0.176	6.8
					0.131	18.1	0.321	0.4
					0.242	1.6	0.380	1.5
					0.303	40.2	0.428	29.4
					0.323	0.1	0.463	10.5
					0.446	7.1	0.601	17.8
					0.622	13.5	0.607	5.0
							0.636	11.3
							0.671	1.8
via Te-125m	58.0d	it				100.0	0.035	6.7
not necessarily in equilibrium							0.109	0.3
I-129	1.57×10^7y	β^-			0.150	100.0	0.040	7.5
							0.030	65% X-rays
I-131	8.04d	β^-			0.248	2.1	0.080	2.6
					0.304	0.6	0.284	6.1
					0.334	7.4	0.364	81.2
					0.606	89.4	0.637	7.3
					0.807	0.4	0.723	1.8
via Xe-131m	11.9d	it				100.0	0.164	2.0
Ba-133	10.52y	ec				100.0	0.053	2.2
							0.080	2.6
							0.081	34.1
							0.161	0.6
							0.223	0.4
							0.276	7.2
							0.303	18.3
							0.356	62.1
							0.384	8.9
Xe-133	5.25d	β^-			0.266	0.7	0.080	0.2
					0.346	99.3	0.081	37.1
							0.161	0.1
Cs-134	2.06y	β^-			0.089	27.1	0.475	1.5
					0.415	2.5	0.563	8.4
					0.658	70.3	0.569	15.0
							0.605	97.5
							0.796	85.1
							0.802	8.8
							1.038	1.0
							1.168	1.9
							1.365	3.2

9.5 Nuclear decay scheme data

Radio-nuclide	half life	Decay mode	Alpha Energy [MeV]	Alpha Intensity [%]	Beta Energy [MeV]	Beta Intensity [%]	Photon Energy [MeV]	Photon Intensity [%]
Cs-137	30.00y	β^-			0.512	94.6		
					1.173	5.4		
via Ba-137m in equilibrium	2.55m	it					0.662	85.1
							0.033	7% X-rays
Ce-139	137.6d	ec				100.0	0.166	79.9
							0.034	80% X-rays
Ba-140	12.74d	β^-			0.454	24.7	0.014	1.2
					0.567	9.9	0.030	13.7
					0.872	3.8	0.163	6.2
					0.991	39.0	0.305	4.3
					1.005	23.0	0.424	3.1
							0.438	1.9
							0.537	24.4
La-140	1.68d	β^-			1.213	0.6	0.329	20.7
					1.239	11.1	0.432	3.0
					1.244	5.7	0.487	45.9
					1.279	1.1	0.752	4.4
					1.296	5.6	0.816	23.6
					1.348	43.7	0.867	5.6
					1.412	5.1	0.920	2.7
					1.677	21.6	0.925	7.0
					2.164	5.0	1.596	95.4
							2.521	3.4
Ce-141	32.5d	β^-			0.436	70.5	0.145	48.4
					0.580	29.5	0.036	17% X-rays
Ce-144	284.9d	β^-			0.185	19.6	0.034	0.2
					0.238	3.9	0.041	0.3
					0.318	76.5	0.053	0.1
							0.080	1.4
							0.134	11.1
via Pr-144m	7.2m	β^-			0.109	0.03	0.059	0.1
					0.473	0.01		
					1.544	0.01		
		it				99.95		
via Pr-144	17.3m	β^-			0.810	1.1	0.697	1.3
					2.299	1.0		
					2.996	97.9		
Pm-147	2.62y	β^-			0.225	100.0		

9.5 Nuclear decay scheme data

Radio-nuclide	half life	Decay mode	Alpha Energy [MeV]	Alpha Intensity [%]	Beta Energy [MeV]	Beta Intensity [%]	Photon Energy [MeV]	Photon Intensity [%]
Eu-152	13.3y	ß$^-$			0.176	1.8	0.122	28.4
					0.385	2.4	0.245	7.5
					0.696	13.8	0.344	26.6
					1.475	8.2	0.411	2.2
		ß$^+$			0.733	0.02	0.444	2.8
		ec				71.8	0.779	13.0
							0.867	4.2
							0.964	14.5
							1.086	9.9
							1.112	13.6
							1.213	1.4
							1.299	1.6
							1.408	20.9
Gd-153	242.0d	ec				100.0	0.070	2.4
							0.075	0.1
							0.083	0.2
							0.089	0.1
							0.097	29.5
							0.103	21.1
Tb-160	72.3d	ß$^-$			0.438	4.5	0.087	13.2
					0.479	10.0	0.197	5.1
					0.551	3.4	0.216	3.9
					0.573	47.0	0.299	26.9
					0.788	6.5	0.765	2.0
					0.871	26.8	0.879	29.5
							0.962	9.8
							0.966	25.0
							1.178	15.2
							1.200	2.3
							1.272	7.5
							1.312	2.9
Tm-170	128.6d	ß$^-$			0.884	24.0	0.084	3.3
					0.968	75.9		
W-185	75.1d	ß$^-$			0.307	0.1	0.125	0.02

9.5 Nuclear decay scheme data

Radio-nuclide	half life	Decay mode	Alpha Energy [MeV]	Alpha Intensity [%]	Beta Energy [MeV]	Beta Intensity [%]	Photon Energy [MeV]	Photon Intensity [%]
					0.432	99.9		
Ir-192	73.8d	ß$^-$			0.079	0.1	0.201	0.5
					0.256	5.6	0.206	3.2
					0.536	41.6	0.283	0.2
					0.672	48.1	0.296	28.7
		ec				4.7	0.309	29.8
							0.317	83.0
							0.374	0.7
							0.416	0.7
							0.468	47.7
							0.485	3.1
							0.489	0.4
							0.589	4.5
							0.604	8.1
							0.613	5.3
							0.885	0.3
							1.061	0.1
Au-198	2.70d	ß$^-$			0.290	1.3	0.412	95.5
					0.962	98.7	0.676	1.1
							1.088	0.2
Au-199	3.14d	ß$^-$			0.245	18.9	0.050	0.3
					0.295	66.4	0.158	36.9
					0.453	14.7	0.208	8.4
Tl-201	3.04d	ec				100.0	0.031	0.3
							0.032	0.3
							0.135	2.8
							0.166	0.2
							0.167	10.6
Hg-203	46.6d	ß$^-$			0.212	100.0	0.279	81.4
Tl-204	3.78y	ß$^-$			0.763	97.4	0.068-0.080	1.5% X-rays
		ec				2.6		
Po-208	2.90y	α	5.115	100.0				
Po-209	102y	α	4.625	0.5			0.261	0.2
			4.880	79.4			0.263	0.1
			4.883	19.9			0.896	0.3
Pb-210	22.3y	ß$^-$			0.017	82.0	0.047	4.5
					0.063	18.0		
via Bi-210	5.01d	ß$^-$			1.162	100.0		
via Po-210	138.4d	α	5.305	100.0				

9.5 Nuclear decay scheme data

Radio-nuclide	half life	Decay mode	Alpha Energy [MeV]	Alpha Intensity [%]	Beta Energy [MeV]	Beta Intensity [%]	Photon Energy [MeV]	Photon Intensity [%]
Po-210	138.4d	α	5.305	100.0				
Ra-226	1600y	α	4.602	5.6			0.186	3.3
			4.785	94.5				
daughters								
Rn-222	3.83d	α	4.988	0.07				
			5.489	99.93				
Po-218	3.05m	α	6.003	99.98				
		ß⁻			0.256	0.02		
Pb-214	26.8m	ß⁻			0.191	2.2	0.053	1.1
					0.496	1.0	0.242	7.5
					0.678	48.2	0.295	19.2
					0.735	43.0	0.352	36.9
					1.030	5.6		
Bi-214	19.9m	α	5.448	0.01			0.274	0.2
		ß⁻			0.822	2.9	0.609	46.9
					1.066	5.9	0.665	1.6
					1.151	4.3	0.768	5.0
					1.253	2.7	1.120	15.5
					1.423	8.5	1.378	4.1
					1.505	18.0	1.765	16.2
					1.540	18.2	2.204	5.3
					1.727	3.2		
					1.892	7.6		
					3.270	16.1		
Po-214	165µs	α	7.687	100.0				
Pb-210 and daughters not necessarily in equilibrium								
Ac-227	21.77y	α, ß⁻	4.938	0.6	0.021	9.9	0.009	0.03
			4.951	0.6	0.036	34.5	0.084	0.02
					0.045	54.2	0.087	0.02
							0.100	0.04
Th-228	1.91y	α	5.138	0.04			0.084	1.2
			5.177	0.2			0.132	0.1
			5.211	0.4			0.166	0.1
			5.340	27.6			0.216	0.3

9.5 Nuclear decay scheme data

Radio-nuclide	half life	Decay mode	Alpha Energy [MeV]	Alpha Intensity [%]	Beta Energy [MeV]	Beta Intensity [%]	Photon Energy [MeV]	Photon Intensity [%]
			5.423	71.7				
daughters of Th-228								
Ra-224	3.62d	α	5.449	5.1			0.241	4.0
			5.686	94.9				
Rn-220	55.6s	α	5.749	0.1			0.550	0.1
			6.288	99.9				
Po-216	145ms	α	5.989	0.002			0.805	0.002
			6.779	100.0				
Pb-212	10.6h	β^-			0.158	5.1	0.115	0.6
					0.334	82.6	0.239	43.4
					0.573	12.3	0.300	3.2
Bi-212	1.01h	α	5.607	0.4			0.040	1.0
			5.769	0.6			0.288	0.3
			6.051	25.2			0.328	0.1
			6.090	9.7			0.453	0.3
							0.727	6.8
		β^-			0.625	1.9	0.785	1.1
					0.733	1.4	0.893	0.4
					1.519	4.5	0.952	0.1
					2.246	55.2	1.079	0.6
							1.513	0.3
							1.621	1.5
							1.679	0.1
							1.806	0.1
Po-212	300ns	α	8.785	100.0				
Th-229	7340y	α	4.798	1.3			0.031	2.5
			4.815	9.3			0.086	3.4
			4.837	4.8			0.125	1.1
			4.845	56.2			0.137	1.2
			4.901	10.2			0.148	1.1
			4.968	6.0			0.156	1.2
			4.979	3.2			0.194	4.4
			5.050	5.2			0.211	3.2
			5.052	1.6				
Th-230	75400y	α	4.621	23.4			0.068	0.4
			4.687	76.3				
Pa-231	32760y	α	4.734	8.5			0.027	11.1
			4.951	22.9			0.284	1.7
			5.014	25.4			0.300	2.4
			5.030	20.0			0.303	2.5
			5.059	11.0			0.330	1.4
U-232	69.80y	α	5.137	0.3			0.058	0.2
			5.264	30.9			0.129	0.1
			5.320	68.8				

9.5 Nuclear decay scheme data

Radio-nuclide	half life	Decay mode	Alpha Energy [MeV]	Alpha Intensity [%]	Beta Energy [MeV]	Beta Intensity [%]	Photon Energy [MeV]	Photon Intensity [%]
U-233	159250y	α	4.729	1.9				
			4.784	14.9				
			4.824	82.7				
U-234	245710y	α	4.723	28.4			0.053	0.1
			4.775	71.4				
U-235	7.04x10^{8}y	α	4.325	4.8			0.109	1.5
			4.364	1.8			0.144	11.0
			4.368	15.8			0.163	5.1
			4.396	58.0			0.186	57.2
			4.415	5.8			0.202	1.1
			4.506	1.6			0.205	5.0
			4.556	2.4				
			4.598	2.3				
Pu-236	2.90y	α	5.614	0.2			0.048	0.07
			5.721	30.7			0.109	0.02
			5.768	69.1				
U-236	2.34x10^{7}y	α	4.335	0.2			0.049	0.1
			4.445	22.4				
			4.496	77.5				
Np-237	2.14x10^{6}y	α	4.640	5.9			0.029	15.2
			4.665	2.8			0.087	12.3
			4.766	8.0			0.118	0.17
			4.771	25.0			0.143	0.43
			4.788	48.0			0.151	0.23
			4.804	1.5			0.195	0.19
			4.817	2.5				
			4.874	4.3				
via Pa-233	27.0d	ß$^{-}$			0.157	25.1	0.075	1.3
					0.174	16.4	0.087	2.0
					0.232	48.5	0.104	0.9
					0.274	5.5	0.271	0.3
					0.572	4.5	0.300	6.6
							0.312	38.6
							0.341	4.5
							0.375	0.7
							0.399	1.4
							0.416	1.7
Pu-238	87.7y	α	5.358	0.1			0.043	0.04
			5.457	28.8			0.011	13% X-rays
			5.499	71.0			to 0.022	

9.5 Nuclear decay scheme data

Radio-nuclide	half life	Decay mode	Alpha Energy [MeV]	Alpha Intensity [%]	Beta Energy [MeV]	Beta Intensity [%]	Photon Energy [MeV]	Photon Intensity [%]
U-238	$4.47x10^9$y	α	4.150	23.0			0.050	0.1
			4.199	77.0				
daughters in equilibrium								
Th-234	24.1d	ß⁻			0.086	2.8	0.063	4.0
					0.106	6.2	0.092	2.7
					0.106	18.0	0.093	2.7
					0.199	72.5	0.113	0.3
Pa-234m	1.17m	ß⁻			2.282	98.2	0.074	0.01
							0.766	0.2
							1.001	0.6
U-234	245710y	α	4.604	0.2			0.053	0.1
			4.723	28.4				
			4.775	71.4				
Pu-239	24110y	α	5.106	11.5			0.039	0.01
			5.144	15.1			0.052	0.03
			5.156	73.3				
Pu-240	6560y	α	5.022	0.01			0.045	0.04
			5.124	27.0				
			5.168	72.9				
Am-241	433y	α	5.388	1.4			0.026	2.4
			5.443	12.8			0.033	0.1
			5.486	85.2			0.043	0.1
			5.512	0.2			0.060	35.9
			5.544	0.3			0.070	0.6
Pu-241	14.4y	ß⁻			0.021	100.0		
Pu-242	$3.74x10^5$y	α	4.856	23.5			0.045	0.04
			4.901	76.5				
Am-243	7360y	α	5.178	1.1			0.044	5.9
			5.233	10.6			0.075	67.4
			5.276	88.0				
			5.319	0.1				
			5.349	0.2				
Cm-244	18.1y	α	5.763	23.0			0.043	0.020
			5.805	77.0			0.099	0.001
							0.153	0.001
Cf-252	2.65y	α	6.076	15.2			0.043	0.02
			6.118	81.6			0.100	0.01