
**Nuclear energy — Nuclear fuel
technology — Scaling factor method to
determine the radioactivity of low- and
intermediate-level radioactive waste
packages generated at nuclear power
plants**

*Énergie nucléaire — Technologie du combustible nucléaire — Méthode
des ratios pour déterminer la radioactivité des colis de déchets de faible
et moyenne activité produits par les centrales nucléaires*



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Foreword

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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Introduction

Burial disposal of low- and intermediate-level radioactive waste has been practiced in several countries. Before disposal, the radioactivity of specific nuclides in waste packages have to be declared in accordance with limits and criteria derived from safety assessment of the disposal facility. Some of these nuclides are difficult to measure from the outside of the waste packages, because they are beta or alpha emitting nuclides.

There are a number of activity determination methods. The scaling-factor method is widely applied in order to evaluate these difficult-to-measure nuclides. The scaling-factor method is based on a correlation between easily measurable gamma emitting nuclides and difficult-to-measure nuclides. This International Standard presents guidelines on the empirical scaling-factor method for evaluating the radioactivity of nuclear power plant's low and intermediate level waste.

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Nuclear energy — Nuclear fuel technology — Scaling factor method to determine the radioactivity of low- and intermediate-level radioactive waste packages generated at nuclear power plants

1 Scope

This International Standard gives guidelines for the common basic methodology of empirically determining scaling factors to evaluate the radioactivity of difficult-to-measure nuclides in low- and intermediate-level radioactive waste packages.

This International Standard gives common guidelines for the scaling factors used in the characterization of contaminated wastes produced in nuclear power plants with water-cooled reactor. This International Standard is also relevant to other reactor types, such as gas-cooled reactors. Methodologies for determining scaling factors based on theoretical considerations (i.e. not based on experimental measurement) are not covered by this International Standard.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1

difficult-to-measure nuclide

nuclide whose radioactivity is difficult to measure directly from the outside of the waste packages by non-destructive assay means

EXAMPLE Alpha emitting nuclides, beta emitting nuclides, and characteristic X-ray emitting nuclides.

2.2

key nuclide

gamma emitting nuclide whose radioactivity is correlated with that of difficult-to-measure nuclides and can be readily measured directly by non-destructive assay means

NOTE Also called “easy-to-measure nuclide” or “marker nuclide”.

EXAMPLE ^{60}Co and/or ^{137}Cs .

2.3

scaling factor

factor or parameter derived from mathematical relationship used in calculating the radioactivity of difficult-to-measure nuclide from that of key nuclide determined from sampling and analysis data

2.4

waste package

product of conditioning that includes the waste form and any container(s) and internal barriers (e.g. absorbing materials and liner), as prepared for handling, transportation, storage and/or disposal

NOTE Adapted from IAEA *Radioactive Waste Management Glossary*. 2003 Edition^[1].

2.5
representative sample

sample taken from a process of the material in that process or that quantity of material which is considered to possess the average characteristics of the material

NOTE 1 Adapted from ISO 921:1997^[2].

NOTE 2 Samples of waste are used to determine the scaling-factor parameters for the target waste stream. A representative sample is meant to closely resemble the characteristic nuclide content and activity proportions of the target waste stream.

2.6
composite sample

mixture of samples from different containers such that the mass ratio of the samples is equal to the ratio of the material masses contained in the containers

NOTE Adapted from ISO 921:1997^[2].

EXAMPLE Series of samples taken over a given period of time and weighted by collection rate; or a combined sample consisting of a series of discrete samples taken over a given period of time and mixed according to a specified weighting factor, such as stream flow or collection rate.

2.7
corrosion product nuclide

nuclide produced by activation of corrosion products temporarily deposited on in-core surfaces

EXAMPLE ⁶⁰Co, ⁶³Ni.

2.8
fission product nuclide

nuclide produced either by fission or by the subsequent radioactive decay of nuclides thus formed

NOTE Adapted from ISO 921:1997^[2].

EXAMPLE ¹³⁷Cs, ⁹⁰Sr.

2.9
alpha emitting nuclide

nuclide emitting an alpha particle when it decays

EXAMPLE Most actinides and transuranic nuclides.

2.10
transuranic nuclide

nuclide with atomic numbers above 92

2.11
dry active waste

solid waste generated in various waste streams in a nuclear power plant, including protective clothing, replaced equipment, parts, plastics, polyvinyl chloride sheets, and high efficiency particulate air filters removed during plant operation and maintenance

2.12
homogeneous waste

radioactive waste that shows an essentially uniform distribution of activity and physical contents

EXAMPLE Flowable wastes such as concentrates, solidified liquids and spent resins, in which the radioactivity may reasonably be assumed to be uniformly distributed over the volume or flowable wastes uniformly mixed with a solid matrix.

2.13
heterogeneous waste

radioactive waste that does not meet the definition of homogeneous waste, including solid components and mixtures of solid components, such as dry active waste and cartridge filters

3 Principle

The empirical scaling-factor method is a method for evaluating the radioactivity of defined difficult-to-measure nuclides from the radioactivity of key nuclides, based on the correlations between difficult-to-measure nuclides and key nuclides. To achieve this, it is important to understand the nuclide production mechanisms, the physico-chemical behavior of nuclides and observe radiochemical analysis data. Statistical calculation is a supplemental technique used for the quantitative evaluation of scaling-factor parameters from groupings of radiochemical data.

The difficult-to-measure nuclides of primary interest are those with very long half-lives that persist in a disposal site long after the period of institutional control. Their declarations are often important for the assessment of the health and safety of the disposal site. Some national programs for low-level radioactive-waste disposal establish specific limits on the concentrations of these nuclides in individual waste packages as well as on their total content in the disposal site. These are specific acceptance criteria which are set by the national regulatory system or waste management programs and are derived from the safety assessment of disposal facilities. The information about the activity concentration and total activity are also required for the transport of radioactive material.

Scaling factors provide a mechanism for estimating the quantities of difficult-to-measure nuclides in individual waste packages based on limited radiochemical analysis of samples from the bulk waste stream. This is achieved by observing the consistent and reproducible relationships between individual nuclides in samples from a stream, which, with reasonable confidence, can be assumed to represent the entire stream.

4 Sampling

4.1 General

Scaling factors in the context of this International Standard are based on a database of samples. Therefore, it is quite important to conduct appropriate sampling and create a database of analytical results. Described in 4.2.1 and 4.2.2 are two basic concepts employed for the collection of radioactivity data that serve as the basis for the scaling-factor method.

4.2 Representative sampling

Two common approaches to ensuring representative samples are

- homogenized sampling,
- accumulated sampling.

4.2.1 Homogenized sampling

This sampling applies to waste that can be considered as homogeneous. In order to ensure that the activity contained in the sample is uniformly distributed, the waste is sufficiently mixed before sampling or within the sample process. Satisfactory accuracy can be ensured even for scaling factors obtained from a small number of samples.

- a) Waste is uniformly stirred and sampled from storage tanks.
- b) Composite samples can be prepared by proportionally mixing waste.

4.2.2 Accumulated sampling

In this approach, waste samples are collected in suitable number or manner to represent the characteristic features of a population of waste samples. This is applicable to both homogeneous waste streams and heterogeneous waste streams.

4.2.3 Activity concentration range of waste samples

When sampling a defined waste stream in the case of accumulated sampling, it is important to obtain radioactive waste samples having a wide range of activity concentrations in order to ensure effective correlations between difficult-to-measure nuclides and key nuclides for waste from that stream.

4.3 Rejection of outliers

If an outlier is found within analysis results, the cause should be identified and the outlier can be corrected or abandoned based on the study of distribution of data and origin of data. If the cause of such an outlier is not identified, statistical methods can be applied optionally for rejection of outliers.

4.4 Records of samples

The following information should be recorded together with the measurement data of individual samples:

- sample identification number;
- plant name;
- reactor identification and building identification;
- reactor type (e.g. boiling water reactor, pressurized water reactor, heavy water reactor, etc.);
- waste stream identification;
- type of waste (e.g. spent resin, concentrates, metal, smear, etc.);
- date of waste sampling;
- date of waste analysis;
- organization that conducted analysis;
- radioactivity and detection limits of each nuclide (the activity concentration of each nuclide should be corrected for decay to the generation date of waste);
- moisture content of the waste (to be measured if necessary for ^3H evaluation).

5 Evaluation methodology for scaling factor

5.1 Applicability of scaling-factor method

The scaling-factor method relies on correlations or predictable relationships between nuclides. The crucial step is deciding whether a correlation exists, i.e. whether the scaling-factor method is applicable.

The applicability of the scaling-factor method for a given difficult-to-measure nuclide and a key nuclide pair can be checked by either or both of the following ways:

- consider their production mechanism, physicochemical behavior and observation of their correlation diagrams;
- use statistical methods to check for existence of a correlation.

5.2 Evaluation by linear relationship

The radioactivity of the difficult-to-measure nuclide is predicted by multiplying its scaling factor by the concentration of the key nuclide. The scaling factor is determined as the geometric mean of analyzed values.

$$a_d = f_{SF} \times a_k \quad (1)$$

where

a_d is the activity concentration of the difficult-to-measure nuclide in either activity per mass or activity per volume, e.g. expressed in Bq/kg or in Bq/m³;

f_{SF} is the scaling factor, see Equation (2);

a_k is the activity concentration of the key nuclide in either activity per mass or activity per volume, e.g. expressed in Bq/kg or in Bq/m³.

The geometric mean can be used to calculate scaling factors for the evaluation of activity concentrations in the following manner:

$$f_{SF} = \sqrt[n]{(a_{d,1}/a_{k,1} \times \dots \times a_{d,i}/a_{k,i} \times \dots \times a_{d,n}/a_{k,n})} \quad (2)$$

where

$a_{k,i}$ is the activity concentration of the key nuclide in sample i ($i = 1 \dots n$), e.g. expressed in Bq/kg if the activity is expressed per mass;

$a_{d,i}$ is the activity concentration of the difficult-to-measure nuclide in sample i ($i = 1 \dots n$), e.g. expressed in Bq/kg if the activity is expressed per mass;

n is the number of samples.

5.3 Evaluation by nonlinear relationship

The following method using linear regression of logarithms of measurement data can be applied for the evaluation of difficult-to-measure nuclides where there is a nonlinear relationship between the difficult-to-measure nuclide and key nuclide. For example, when the nuclide ratio shows a dependence on concentration, there can be a nonlinear relationship.

$$a_d = \alpha \times \alpha_k^\beta \quad (3)$$

This corresponds to

$$\ln(a_d) = \alpha' + \beta \times \ln(a_k) \quad (4)$$

where

a_d is the activity concentration of the difficult-to-measure nuclide to be determined, e.g. expressed in Bq/kg if the activity is expressed per mass;

a_k is the activity concentration of the key nuclide, e.g. expressed in Bq/kg if the activity is expressed per mass;

α, α' are constants ($\alpha' = \ln \alpha$);

β is the regression coefficient.

5.4 Selection of key nuclides

The key nuclides used in evaluating the activity concentrations of difficult-to-measure nuclides are selected based on the following factors. Gamma-emitting nuclides shall meet the basic characteristics and it is recommended that they meet at least one of the additional characteristics.

a) Basic characteristics:

- can be measured by non-destructive means when present in waste packages,
- having activity levels above the detection limit,
- having a correlation with required difficult-to-measure nuclides,
- having a relatively long half-life (e.g. years rather than days).

b) Additional characteristics:

- having a nuclide production mechanism similar to that of difficult-to-measure nuclides, and/or
- having physical properties (particularly solubility) similar to those of difficult-to-measure nuclides.

Specifically, ^{60}Co is normally used as a key nuclide for corrosion-product nuclides and activation-product nuclides from reactor coolant and ^{60}Co and/or ^{137}Cs as key nuclides for fission product nuclides and alpha-emitting nuclides.

5.5 Integration and classification methodology for scaling factor

Data collected from various waste streams can be combined for the determination of particular Scaling Factors providing that it can be demonstrated that the data are all part of the same general population of data. That is, based on a comparison of means and variance, it can be established that the data populations are not different.

Data can be integrated over extended waste streams given that no significant trends or no significant changes in operating status are occurring.

5.5.1 Integration and classification of corrosion product nuclides

5.5.1.1 Consideration by type and design of nuclear power plant

The correlation of difficult-to-measure nuclides such as corrosion product nuclides to key nuclides strongly depends on the composition of the materials involved.

Therefore, if the compositions of materials are not significantly different among several plants, the associated radiochemical analysis data can be merged to establish a single scaling factor. Different reactor types (e.g. boiling water reactor, pressurized water reactor) generally produce different scaling factor parameters for the same combination of nuclides from similar waste streams because of differences in the compositions of some in-core materials and water chemistry.

5.5.1.2 Consideration by waste stream

Many corrosion product nuclides show a common production mechanism and transport behavior in the plant. Thus, classification by waste stream might not be necessary for those corrosion product nuclides in a given plant design.

5.5.2 Integration and classification of fission product nuclides and alpha emitting nuclides

5.5.2.1 Consideration by nuclear power plant history

The correlation between fission-product nuclides, alpha-emitting nuclides and key nuclides can change depending on the history of fuel failure (i.e. the inventory of fission-product nuclides and alpha-emitting nuclides).

Therefore, if the inventory (e.g. of the reactor cooling water) of fission-product nuclides and alpha-emitting nuclides is not significantly different among several similar plants, the associated radiochemical analysis data can be merged to establish a single scaling factor.

5.5.2.2 Consideration by waste stream

Since the solubility of fission products and alpha-emitting nuclides can differ from that of the key nuclides, it can be necessary to group waste streams based on combinations of difficult-to-measure nuclides and key nuclides. This accounts for the differences in the individual nuclides transport behavior in given plant systems.

5.6 Scaling-factor accuracy

Scaling-factor accuracy is influenced by several factors, including representative sampling and laboratory analysis. This accuracy is the primary parameter under the control of the waste generator.

One of the following two approaches should be applied to ensure the accuracy of the scaling factors used to determine the radioactive concentrations of waste packages.

- Accuracy is ensured by applying homogenized sampling.

NOTE Detail for homogenized sampling is given in 4.2.1.

- When accumulated sampling is applied, one of the following three methods is sufficient to ensure the accuracy. Confidence in individual scaling factors can be achieved by considering the uncertainty or by applying averaging methods to multiple sample records.

NOTE Details for accumulated sampling is given in 4.2.2.

- a) Consider the parameters affecting uncertainty of the scaling factors.
- b) Obtain a suitable number of analyzed data.
- c) Consider appropriate manner of sampling.

The scaling-factor uncertainty can be evaluated taking into account the following sample data:

- number of data;
- standard deviation.

Annex A (informative)

Practices and examples of application of scaling-factor method

This annex provides explanatory notes on the stipulations in the main text and matters relating to them. This annex gives examples and practices to assist the understanding or use of the standard document.

A.1 Application

A.1.1 General

The scaling-factor (SF) method is an evaluation technique to determine the activity concentrations of difficult-to-measure (DTM) nuclides. Such nuclides include those emitting low energy photons, pure beta emitters and alpha emitting nuclides that are important to long-term disposal safety.

Using the SF method, the activity concentrations of DTM nuclides in waste packages are estimated by using a correlation between their activity concentrations and those of key nuclides such as ^{60}Co .

One approach to the application of the SF method is to perform an empirical evaluation, in which the combined effects of various factors (e.g. variations in the amounts of nuclides produced by nuclear reactions, transportation behavior, and properties of those nuclides) are accounted for by the use of representative mean values. These are derived by combining data from analysis (e.g. radiochemical) of actual wastes. It is important to understand this fundamental approach to apply the SF method.

Figure A.1 shows a basic flow for application of the SF method. The evaluation and application typically proceed through the following steps.

A.1.2 Step 1

For proper use of SF approach, where data from multiple power plants are combined, it is important to evaluate and investigate the characteristic differences between plants and the properties (e.g. homogeneity, etc.) of the waste subject to sampling. Some plant characteristics important to this process are listed below:

- reactor type;
- reactor component materials;
- fuel performance history;
- mechanism through which nuclides are produced;
- variations in waste treatment;
- plant operational condition.

In this step, plant characteristics and other factors, such as waste streams that affect the composition ratios between DTM nuclides and key nuclides (i.e. SF), are studied and SF classifications based on SF variability due to these factors are assessed. In addition, a sampling plan is developed covering the grouping of plants, waste streams and range of activity concentration of wastes.

NOTE The basic concept of representative sampling is specified in Clause 4.

A.1.3 Step 2

Appropriate sampling is carried out in accordance with the studies shown in Step 1. The selected wastes are sampled, and nuclide analysis data are collected through analysis of the samples.

NOTE 1 Requirements for sampling are specified in Clause 4. Records are managed accordingly.

NOTE 2 The practices of selecting key nuclides are shown in A.2.

A.1.4 Step 3

Using the nuclide analysis data, the correlation between DTM nuclides and the key nuclides is observed through the use of scatter diagrams. SF groupings are studied considering the influencing factors that were examined in Step 1.

The applicability of the SF method for a particular grouping is determined based on whether there is an observable correlation between the concentrations of DTM nuclides and selected key nuclides.

If applicability of SF method cannot be confirmed, another evaluation method for determining the DTM nuclide may be employed, such as “Mean activity” method. The so called “Mean activity” is based on calculating the mean value from a set of measurements on representative samples and applying this value to other packages. Alternatively, the upper bound value from measurement or by theoretical calculation can be used instead of the mean value to produce a conservative estimate.

The possibility of integration or classification of waste streams and plants is determined based on, for example, observation of scatter diagrams.

NOTE 1 The basic concept of selecting key nuclides is given in 5.4.

NOTE 2 For determining the applicability of the SF method, refer to 5.1.

NOTE 3 The basic concept in integrating waste streams for SF evaluation is shown in 5.5.

NOTE 4 Practices about SF differences among various plant types and waste streams are discussed in Clauses A.3 and A.4.

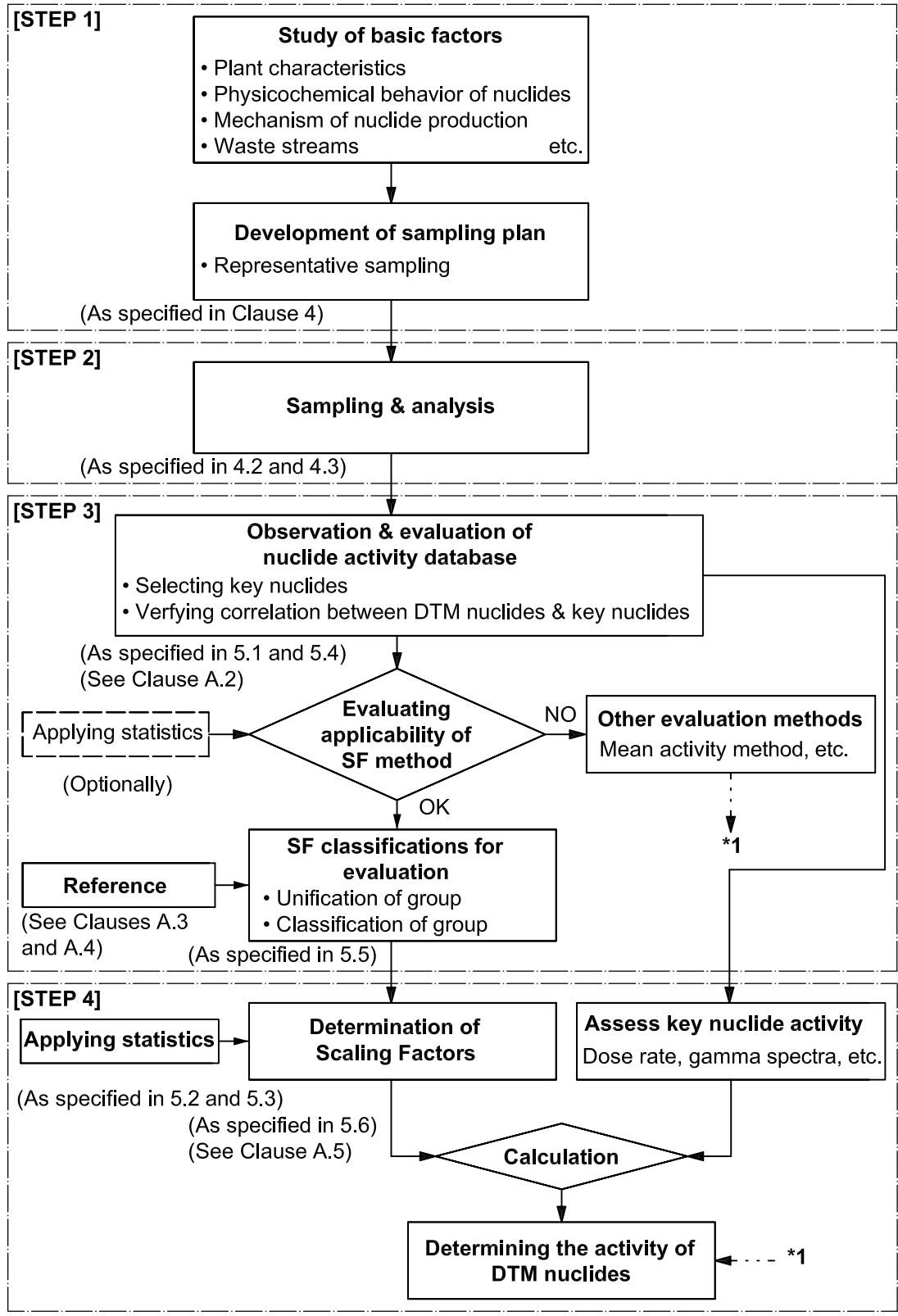
A.1.5 Step 4

The activity concentrations or total activity of key nuclides in each waste package to be assayed are determined by measuring the surface dose rate of the waste package and calculating a key nuclide activity using a “dose-rate-to-activity” conversion calculation, or by gamma spectroscopy or other means. The activity concentrations of DTM nuclides are calculated based on the nuclide specific SFs and the appropriate key nuclides activity for each waste package.

NOTE 1 Appropriate calculation methods for determining SF values from collected nuclide analysis data, see 5.2 and 5.3.

NOTE 2 The ways to keep accuracy of applicable SFs are given in 5.6.

NOTE 3 An example method to maintain SF accuracy is given in Clause A.5.



NOTE SF is Scaling Factor, DTM nuclide is difficult-to-measure nuclide.

Figure A.1 — Basic flow of application for Scaling Factor (SF) method

A.2 Key nuclide selection

A.2.1 Basic approach

This International Standard requires in 5.4 the following four basic characteristics for a gamma-emitting key nuclide:

- nuclide that can be measured by non-destructive means when present in waste packages;
- having activity levels above the detection limit;
- having a correlation with required difficult-to-measure (DTM) nuclides;
- having a relatively long half-life.

Since ^{60}Co and ^{137}Cs in most cases satisfy the above basic characteristics, they are widely used as key nuclides. ^{137}Cs is usually preferred for use as a key nuclide for fission products. However, it is not often found in sufficient concentration to be consistently determined by external non-destructive measurement. Note that ^{60}Co can be used as key nuclide for fission-product nuclides, alpha-emitting and transuranic nuclides (hereinafter alpha-emitting nuclides) in addition to the key nuclide for corrosion product nuclides. Various examinations of scaling factors have demonstrated that ^{60}Co provides comparable correlations for fission-product nuclides and alpha-emitting nuclides.

A.2.2 United States practice

A number of examinations of scaling-factor data have been undertaken by the Electric Power Research Institute (EPRI) on behalf of the United States nuclear power industry. In these studies, analysis data were collected from member utilities covering a range of plant conditions and operating histories. Separate tabulations were made for boiling water reactor (BWR) and pressurized water reactor (PWR) plant types.

As demonstrated in Tables A.1 and A.2, both ^{60}Co and ^{137}Cs are comparably applicable as key nuclides for ^{239}Pu .

Table A.1 — 10CFR61 Scaling factors for full database^[3]

Radionuclides	PWR			BWR		
	Data points	Ratio	LMD ^a	Data points	Ratio	LMD ^a
$^{239}\text{Pu}/^{137}\text{Cs}$	303	4×10^{-4}	50	192	3×10^{-4}	28
$^{239}\text{Pu}/^{60}\text{Co}$	383	1×10^{-4}	27	235	5×10^{-5}	18

^a LMD is log mean dispersion.

Table A.2 — Scaling factors (new database)^[4]

Radionuclides	PWR			BWR		
	Data points	LMA ^a	LMD ^b	Data points	LMA ^a	LMD ^b
$^{239}\text{Pu}/^{137}\text{Cs}$	288	$2,0 \times 10^{-4}$	36	91	$1,5 \times 10^{-4}$	11
$^{239}\text{Pu}/^{60}\text{Co}$	382	$9,0 \times 10^{-4}$	21	113	$2,0 \times 10^{-5}$	7

^a LMA is log mean average.
^b LMD is log mean dispersion.

A.2.3 European practice

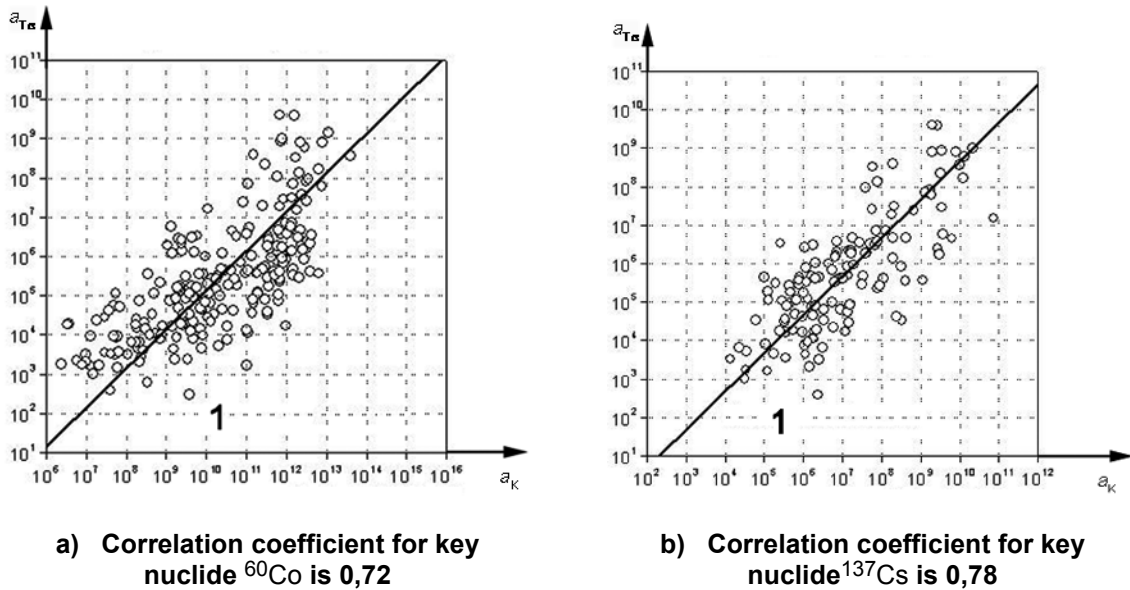
In a collaborative study of scaling factors among European countries, amongst others, correlations between key nuclides (^{60}Co , ^{137}Cs) and fission-product nuclides and alpha-emitting nuclides were calculated. Comparable correlations were demonstrated in the study. Results are listed in Table A.3.

Table A.3 — Applicable correlations for European waste ^[5]

Radionuclides	PWR		BWR	
	Number of data points	Correlation coefficient	Number of data points	Correlation coefficient
$^{241}\text{Am}/^{60}\text{Co}$	73	0,82	35	0,67
$^{241}\text{Am}/^{137}\text{Cs}$	67	0,84	34	0,63
$^{244}\text{Cm}/^{60}\text{Co}$	99	0,84	44	0,67
$^{244}\text{Cm}/^{137}\text{Cs}$	—	—	42	0,62
$^{238}\text{Pu}/^{60}\text{Co}$	88	0,85	35	0,63
$^{238}\text{Pu}/^{137}\text{Cs}$	—	—	34	0,62
$^{90}\text{Sr}/^{60}\text{Co}$	110	0,78	29	0,74
$^{90}\text{Sr}/^{137}\text{Cs}$	108	0,77	17	0,76

A.2.4 Japanese practice

Figure A.2 shows scatter diagrams plotting the correlation between total alpha emitting nuclides activity and ^{60}Co and total alpha emitting nuclides activity and ^{137}Cs . These data are obtained by analysis of dry active waste generated at PWR plants. In the both cases, a correlation exists between total alpha emitting nuclides and the key nuclide, and it is seen that not only ^{137}Cs but also ^{60}Co can be selected as a key nuclide for total alpha emitting nuclides.

**Key**

a_k activity of the key nuclide, Bq/t

$a_{T\alpha}$ total alpha activity, Bq/t

1 Geometric mean.

Figure A.2 — Correlation coefficient as a function of key nuclide concentration for total alpha activity in dry active waste generated at PWR plants^[6]

A.3 Grouping by nuclear power plant type

A.3.1 Basic approach

From the nuclide-analysis data collected up to the present and the accumulated knowledge from scaling-factor evaluations, the following are determined as likely factors causing scaling-factor variation:

- differences in reactor component materials (due to differences in reactor type, adoption of low-cobalt materials, etc.);
- differences in fuel stability history (due to differences in fuel type, fuel damage history, etc.);
- differences in the physical or chemical behavior of the nuclides (due to differences in volatility, solubility, etc.).

NOTE An example of differences in the physical or chemical behavior is shown in Clause A.4.

While these factors may be considered in developing the initial grouping of waste streams, the primary affecting factor is based on an observable correlation within each group. Optionally, statistical methods may be used to support these evaluations.

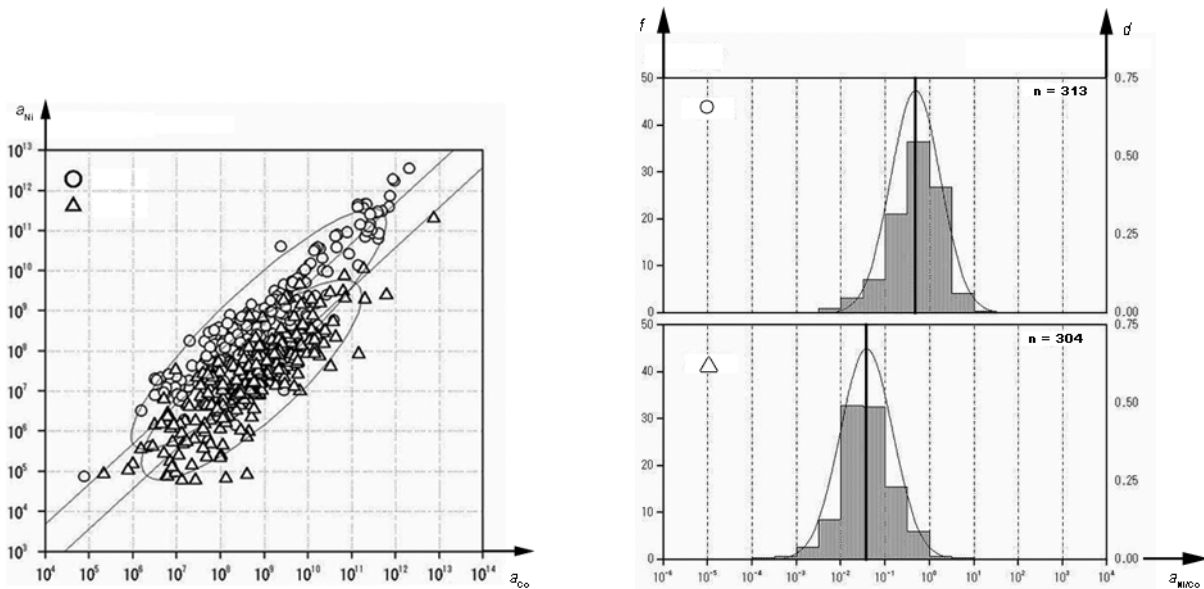
A.3.2 Examples of plant type differences

A.3.2.1 Corrosion product nuclides

Corrosion product compositions change depending on the reactor type. For example, the major source of corrosion-product nuclides from a pressurized water reactor (PWR) are nickel alloy and stainless steel, with

little use of carbon steel. On the other hand, those of a boiling water reactor (BWR) are carbon steel and stainless steel.

The nickel and niobium concentrations relative to cobalt in a PWR are higher than those in a BWR. Thus, when the radioactivity of corrosion-product nuclides is evaluated, it is necessary that waste be classified by reactor type because of the varying reactor component materials. This difference is illustrated in Figure A.3 and Table A.4.



a) Scatter diagram of the $^{63}\text{Ni}/^{60}\text{Co}$ ratio

b) Distribution diagram of the $^{63}\text{Ni}/^{60}\text{Co}$ ratio

Key

- a_{Co} activity of ^{60}Co , Bq/t
- a_{Ni} activity of ^{63}Ni , Bq/t
- $a_{\text{Ni}/\text{Co}}$ activity of ^{63}Ni /activity of ^{60}Co ratio
- f ratio, %
- d probability density
- pressurized water reactor (PWR)
- △ boiling water reactor (BWR)

Figure A.3 — Scaling factors for corrosion-product nuclides as a function of reactor type from French, German, Japanese and United States practices^[7]

Table A.4 — Scaling factors for corrosion-product nuclides from United States practice^[7]

Radionuclides	Scaling factor	
	All BWR	All PWR
$^{63}\text{Ni}/^{60}\text{Co}$	$5,70 \times 10^{-2}$	$3,27 \times 10^{-1}$

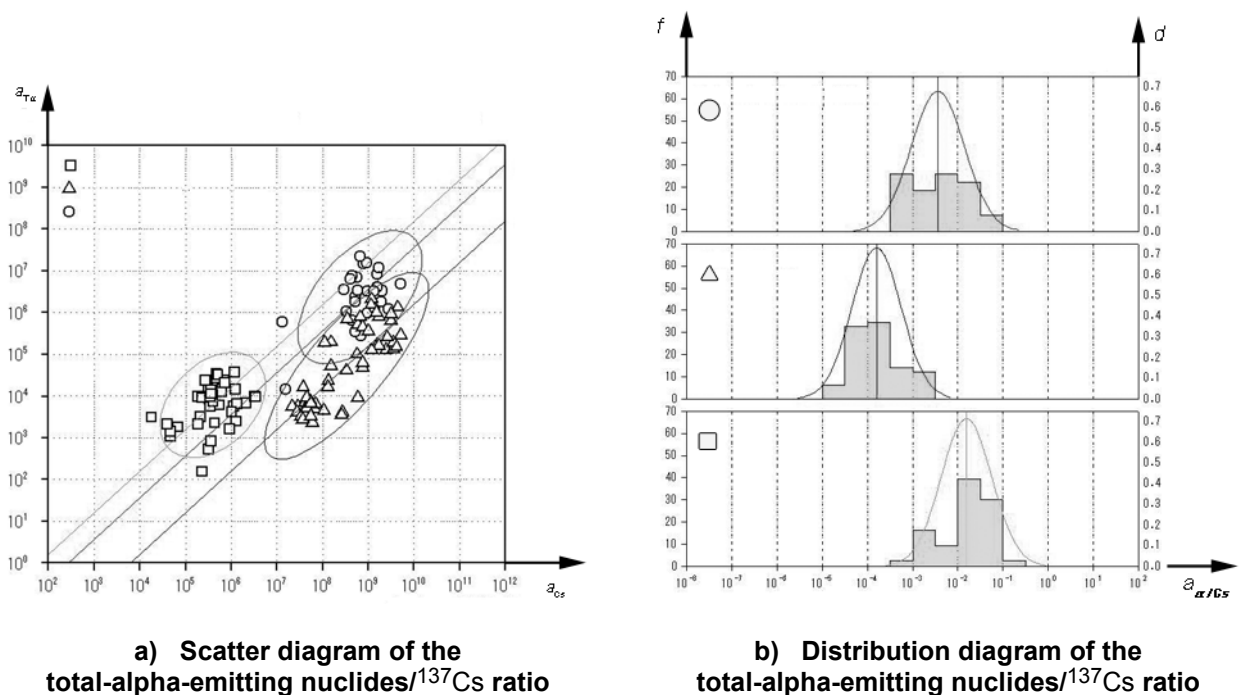
A.3.2.2 Fission product nuclides and alpha emitting nuclides

The contents of fission-product nuclides and alpha emitting nuclides in wastes vary with the integrity of the fuel, specifically the level of fission-product nuclides concentration.

Waste-stream grouping between various plants takes into account one of the following three levels of fuel failure:

- a) plant having no fuel failure: all fission products and alpha emitting nuclides release is due to the fuel rod surface contamination;
- b) plant that has experienced light fuel failure: fission-product release is retarded by diffusion through small openings in fuel clad, relatively volatile nuclides are released through this process;
- c) plant that has experienced relatively serious fuel failure: openings are sufficiently large to allow direct coolant contact with fuel surface.

Figure A.4 illustrates as an example of the variations caused by differing levels of fuel integrities on the ratio between alpha emitting nuclides and ¹³⁷Cs.



Key

- | | | | |
|-----------------|--|-----|---------------------------------|
| $a_{T\alpha}$ | total alpha activity, Bq/t | d | probability density |
| a_{Cs} | activity of ¹³⁷ Cs, Bq/t | □ | no fuel failure |
| $a_{\alpha/Cs}$ | total alpha activity/activity of ¹³⁷ Cs ratio | Δ | light fuel failure |
| f | ratio, % | ○ | relatively serious fuel failure |

Figure A.4 — Different scaling factors for fission-product nuclides as a function of the integrity of fuel in Japanese practice^[9]

A.4 Grouping by waste stream type

A.4.1 Basic approach

The ratios of difficult-to-measure nuclides and key nuclides observed within each system of a nuclear power plant will show little variation during steady state plant operation.

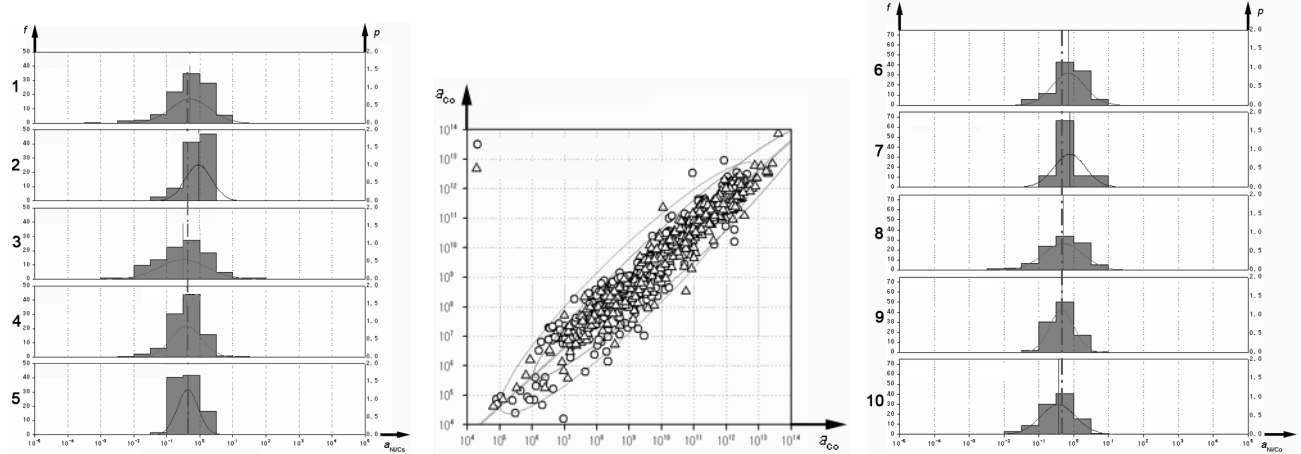
In particular, corrosion-product nuclides are similar in physicochemical behavior and their relative proportions within a stream are not readily altered through plant processes or changing plant conditions. Thus, common scaling factors for corrosion-product nuclides generally can be determined for all waste streams within particular plants.

Fission-product nuclides and alpha-emitting nuclides can show differences in solubility between the DTM nuclides and selected key nuclides. Therefore, it can be appropriate to consider the determination of a particular scaling factor for each stream.

A.4.2 Examples of waste stream differences

A.4.2.1 Appropriate waste stream grouping for corrosion product nuclides

Corrosion-product nuclides show only small differences in transport behavior. As a result, the differences in the nuclide composition ratios of the key nuclide to DTM nuclides among waste streams are small. Therefore, it can be possible to develop a unified scaling factor for an entire plant. Figure A.5 compares the $^{63}\text{Ni}/^{60}\text{Co}$ ratio for various sample streams typically found in pressurized water reactors (PWRs). The data base includes a compilation of data from French, German and Japanese PWRs. Figure A.5 shows that the mean ratios are relatively constant across various waste streams and over a broad range of concentrations.



- 1 Japan — Homogeneous waste
- 2 France — Homogeneous waste
- 3 Germany — Homogeneous waste
- 4 Japan — Heterogeneous waste
- 5 France — Heterogeneous waste

- 6 reactor coolant
- 7 spent resin
- 8 concentrates
- 9 cartridge filter
- 10 dry active waste

a) International comparison:
DTM nuclide/key nuclide ratio

b) International comparison:
homogeneous and
heterogeneous waste (correlation)

c) Detailed comparison among
waste streams:
DTM nuclide/key nuclide ratio

Key

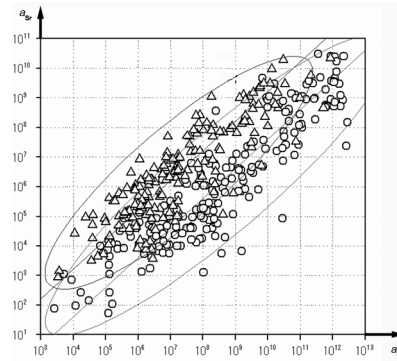
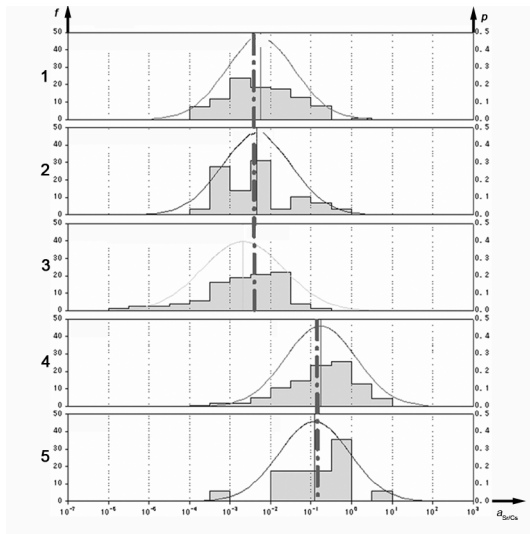
$a_{Ni/Co}$	activity of ^{63}Ni /activity of ^{60}Co ratio	p	probability
a_{Co}	activity of ^{60}Co , Bq/t	\circ	homogeneous waste (Japan, France, Germany)
a_{Ni}	activity of ^{63}Ni , Bq/t	Δ	heterogeneous waste (Japan, France, Germany)
f	ratio, %		

Figure A.5 — Ratios for a single corrosion-product nuclide for different waste streams — Example: French, German and Japanese practices for the $^{63}Ni / ^{60}Co$ ratio for PWRs^[10]

A.4.2.2 Appropriate waste-stream grouping for fission-product nuclides

In practice, fission-product nuclides are most often correlated either to ^{137}Cs or ^{60}Co . In particular, because ^{137}Cs is relatively soluble, ^{137}Cs does not collect on the surface of heterogeneous wastes in proportion with the non-soluble fission-product nuclides. Figure A.6 compares the $^{90}Sr/^{137}Cs$ ratios in homogeneous and heterogeneous wastes, and the variability between homogeneous waste and each heterogeneous waste for French, German and Japanese PWRs. As a result, it is appropriate to consider the influence of the solubility of nuclides on homogeneous and heterogeneous wastes.

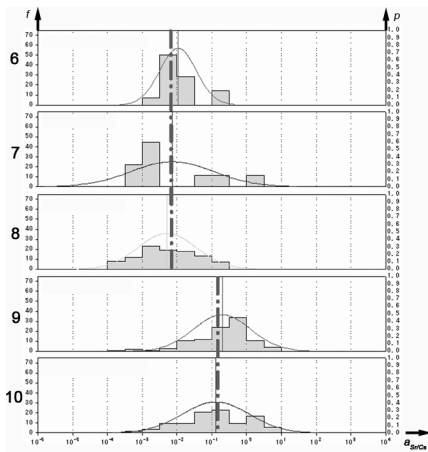
In the alternative case where ^{60}Co is used as the key nuclide, as illustrated in Figure A.7, there is a similarity in the variability of values and a general expectation of constancy in similar fuel integrity plant group. Since ^{60}Co is produced through a mechanism different from that for ^{90}Sr , the $^{90}Sr/^{60}Co$ scaling factors show constancy in accordance with the fuel integrity in a particular nuclear power plant.



- 1 Japan — Homogeneous waste
- 2 France — Homogeneous waste
- 3 Germany — Homogeneous waste
- 4 Japan — Heterogeneous waste
- 5 France — Heterogeneous waste

a) International comparison: DTM nuclide/key nuclide ratio

b) International comparison: homogeneous and heterogeneous waste (correlation)



- 6 reactor coolant
- 7 spent resin
- 8 concentrates
- 9 cartridge filter
- 10 dry active waste

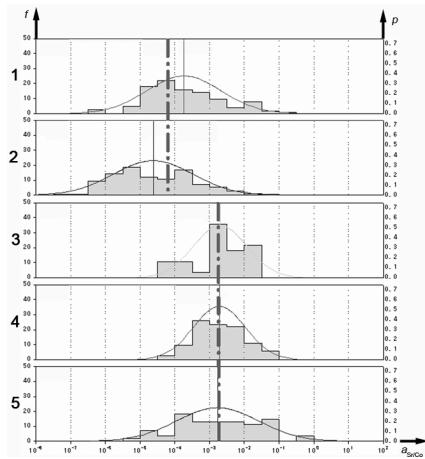
c) Detailed comparison among waste streams: DTM nuclide/key nuclide ratio

Key

- $a_{Sr/Cs}$ activity of ^{90}Sr /activity of ^{137}Cs ratio
- a_{Cs} activity of ^{137}Cs , Bq/t
- a_{Sr} activity of ^{90}Sr , Bq/t
- f ratio, %

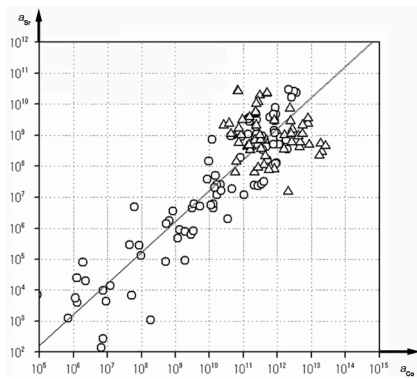
- p probability
- homogeneous waste (Japan, France, Germany)
- △ heterogeneous waste (Japan, France, Germany)

Figure A.6 — Ratios for a single fission-product nuclide for different waste streams — Example: French, German and Japanese practices for the $^{90}Sr/^{137}Cs$ ratio for PWRs^[10]

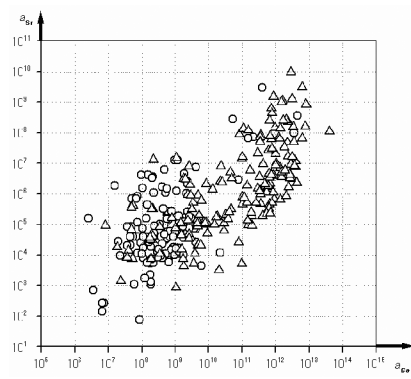


- 1 Japan — Homogeneous waste
- 2 Japan — Heterogeneous waste
- 3 France — Homogeneous waste
- 4 Allemagne — Homogeneous waste
- 5 France — Heterogeneous waste

a) International comparison: DTM nuclide/key nuclide ratio



b) Comparison of homogeneous and heterogeneous waste: correlation for plants that have experienced a relatively serious fuel failure — French and German nuclear power plants



c) Comparison of homogeneous and heterogeneous waste: correlation for plants that have experienced no or light fuel failure — Japanese nuclear power plants

Key

- $a_{Sr/Co}$ activity of ^{90}Sr /activity of ^{60}Co ratio
- a_{Co} activity of ^{60}Co , Bq/t
- a_{Sr} activity of ^{90}Sr , Bq/t
- f ratio, %

- p probability
- homogeneous waste
- △ heterogeneous waste

NOTE The two groups, Japan and France/Germany, represent plants that have different fuel integrity.

Figure A.7 — Ratio of a single fission-product nuclide for different fuel integrities and waste streams — Example: French, German and Japanese practices for $^{90}Sr/^{60}Co$ for PWRs^[10]

A.5 Scaling-factor accuracy

A.5.1 Basic approach

The scaling-factor method targeted by this International Standard is an activity concentration evaluation technique for waste packages, which is applied to determine the total activity of difficult-to-measure (DTM) nuclides when they are subjected to disposal.

The accuracy of the scaling factors specified in this International Standard does not include errors in individual analysis (e.g. radiochemical analysis). Such errors in this kind of analysis should be covered by a standard for the particular method of analysis.

The approaches to the recommended accuracy are discussed by indicating how to treat conditions affecting a scaling factor, such as variations in the behavior of nuclides and any uncertainty of scaling-factor values (e.g. the number of samples, range of samples).

Therefore, accuracy in determining the mean activity concentration for all of the waste packages intended for joint disposal in the repository is significant.

Scaling-factor accuracy can be ensured by applying either homogenized sampling or accumulated sampling as specified in 5.6.

An example of three approaches to ensure the accuracy for “accumulated sampling” is shown in A.5.2.

A.5.2 Examples of scaling-factor accuracy

A.5.2.1 Considering the parameters affecting uncertainty of the scaling factors

A.5.2.1.1 General

An extremely conservative treatment of uncertainty for nuclide declarations overestimates the actual activity. Treatment of uncertainty should be established in accordance with the requirements for safe disposal.

One of following three methods can be used to treat the uncertainty that is closely tied to the ultimate characterization. The following three methods can be applied to both linear and non-linear relationships.

- a) Limits of application based on concentration.
- b) Limits of application based on relationship.
- c) Consideration of the effect of uncertainty on the scaling-factor value.

A.5.2.1.2 Limits on the application as a function of concentration

When uncertainty is not incorporated into the scaling-factor value, it is appropriate to limit the application of the scaling factor. For example, the application of scaling-factor method is restricted to be used within a definite range of activity concentrations (e.g. screening level derived from maximum activity concentration of disposal facility).

NOTE In this case, it is not necessary to take the uncertainty into consideration for the calculation of the scaling-factor value.

A.5.2.1.3 Limits of application based on relationship

In cases, when a nonlinear relationship between the DTM and the key nuclide is expected or has been observed in the graphical representation of the correlated data, the evaluation may be performed in accordance with the method outlined in 5.3. An example of the practical implementation of such a method is given below.

The parameters α (the proportionality constant) and β (the regression coefficient) are determined.

From these parameters, a correlation line can be constructed in a log-log-diagram. A second line that is parallel to the correlation line and covers 95 % of the evaluated data points (e.g. 95 % of the data points are below this line) is plotted as an upper bound for the activity determination. Thus, the correlation line and the second line have the same slope β and an offset from the origin of α' and α'_{\max} , respectively.

A first prerequisite for acceptable accuracy in nonlinear conditions is a limitation on the ratio of α_{\max}/α (e.g. $\alpha_{\max}/\alpha < 100$ can be used). This criterion has been derived empirically and implicitly meets practical concerns regarding the required degree of conservativeness considering the high scatter of data. Therefore, an acceptable accuracy implies that α_{\max}/α has met the criterion.

A.5.2.1.4 Considering effects of uncertainty on scaling-factor value

When scaling-factor values are evaluated based on a relationship between DTM nuclides and key nuclides using accumulated sample data, the database contains uncertainty due to the dispersion in the ratios of nuclides. For example, when the number of accumulated data is very small, evaluating scaling-factor values with such uncertainty is an appropriate approach.

NOTE 1 For large databases, there is reasonable confidence that the data-set bounds the range of values included in the average. For small data bases, it can be appropriate to add a factor to cover the uncertainty.

One approach to bounding the range of scaling-factor values is to adopt the upper confidence limit of scaling-factor for ensuring uncertainty due to uncertainty in the database. An example of this approach is given in Equation (A.1):

$$\ln(f_{\text{SF,C}}) = \ln(f_{\text{SF}}) \pm t_{0,95} \frac{s}{\sqrt{n}} \quad (\text{A.1})$$

where

- $f_{\text{SF,C}}$ is the confidence limit of the scaling factor;
- f_{SF} is the scaling factor for DTM nuclides;
- s is the variance (s^2) of the sample for a lognormal distribution;
- n is the number of samples;
- $t_{0,95}$ is the t -distribution factor for level of confidence (95 % in this example).

NOTE 2 By applying this interval-estimation method, the log of scaling-factor values whose 95 % upper and lower confidence limit can be calculated.

A.5.2.2 Obtaining a suitable number of analyzed data

The suitable number of data for determining scaling factor is defined here by applying the following basic qualitative approach.

The number of data points is sufficient when investment in additional sampling and measurement produces no appreciable improvement in the statistical uncertainty.

Quantitative application of this approach (the stability of statistics of data; e.g. correlation coefficient) is based on each country's condition of disposal and/or allowance of activity inventory. Statistical variation should not be required to be extremely small (e.g. a reasonable value should be accepted for standard deviation or dispersion, based on the safety requirements of the facility, rather than artificially requiring a very small value). Optimization and minimization of sampling should be considered.

A.5.2.3 Considering appropriate manner of sampling

When the database includes only a small number of power plants, waste characterization is conducted on an individual stream basis using appropriate sampling manners. Accuracy can be secured by appropriate sampling manners that are shown in below:

- sampling based on the distribution of activity concentration;
- sampling based on the grouping of waste-stream properties;
- sampling by uniformly dividing and mixing.

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