Note:
This is a translation of the ESK statement entitled
"Zuverlässigkeitsverbessernde Maßnahmen bei der Nuklidvektorzuordnung im Freigabeverfahren"
In case of discrepancies between the English translation and the German original, the original shall prevail.

STATEMENT of the Nuclear Waste Management Commission

Reliability-enhancing measures for nuclide vector assignment in the clearance procedure

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1 Advisory request to the Nuclear Waste Management Commission

During dismantling and management of residues in shut down nuclear installations, large quantities of materials and objects are produced that must undergo clearance due to legal requirements (§ 2(5) of the Waste Management Transfer Act (EntsorgÜG)). Background information on the clearance of radioactive material can be found, for example, in the ESK information paper of 1 September 2022[1]. Residues to be cleared generally contain a mixture of several radionuclides that differ in their permissible mass- or surface-related activity (clearance level). For assessing the permissibility of clearance by measurements, so-called nuclide vectors are defined, which represent the share of the total activity by the individual radionuclides.

First, a radiological characterisation is carried out by means of preliminary examinations, usually in the form of sampling. Based on the operating history, samples are taken at representative locations for the plant, plant section or system, which are used to determine the radionuclide mixture and the spatial activity distribution. If necessary, all relevant radionuclides (alpha, beta and gamma emitters) are determined by means of an analysis of so-called difficult-to-measure nuclides, which are taken into account in the calculations if they cannot be measured directly by the measurement method used in the clearance procedure. It is important that, for clearance, the nuclide vectors derived in this way each contain at least one easy-to-measure radionuclide (key nuclide) that can be measured directly by the measurement method used. Radionuclides that are not directly measurable in the clearance procedure can be taken into account by measuring these key nuclides and using previously defined correlation parameters. The nuclide vector must cover the substances and objects to which it is to be applied, or the uncertainties associated with the nuclide vector must be taken into account (DIN 25457 1:2024 05, sections 6.2 and 7.2).

According to the Radiation Protection Ordinance (StrlSchV), Annex 8, Part A, No. 1(e), the prerequisite for clearance is that the sum of the ratios C_i/R_i (sum formula) of the specific activity (C_i) to be cleared and the respective clearance levels (R_i) of the individual radionuclides (i) does not exceed the value of 1. According to the StrlSchV, radionuclides need not be taken into account when calculating the sum if the proportion of unconsidered nuclides in the sum of all ratios C_i/R does not exceed 10 percent (10% rule).

By measuring the specific activity of the key nuclides in the clearance process, the specific activities of the relevant non-measurable radionuclides[2] are also taken into account. The prerequisite for this is that, in the case of a (possible) occurrence of several nuclide vectors, the substance or object to be cleared is correctly assigned to the respective nuclide vector. The use of an incorrect nuclide vector can lead to overestimation or underestimation of specific activities. If a specific activity is underestimated, this can lead to an incorrect clearance decision in individual cases. An underestimation of the specific activity is not necessarily associated with an underestimation of the exposure and therefore does not necessarily represent a violation of the dose criterion for clearance.

Due to nuclide vector mix-ups that have occurred in German facilities, the BMUV requested the ESK, with the involvement of the SSK, to comment on the following questions:

[1] ESK information paper on the clearance of radioactive material and removal of non-radioactive material from the dismantling of nuclear power plants (“Freigabe radioaktiver Stoffe und Herausgabe nicht radioaktiver Stoffe aus dem Abbau von Kernkraftwerken” of 1 September 2022 (https://www.entsorgungskommission.de/de/beratungsergebnisse)

[2] For the purpose of this Statement, radionuclides that cannot be measured within the scope of the decision measurement are referred to as non-measurable.

Question 1: "Which most probable and which most unfavourable incorrect nuclide vector assignments can be identified based on experience, what are the possible causes and which deviations can be expected as examples in the determination of activity in clearance monitors?"

Question 2: "Which possible or already implemented measures for a reliable assignment of nuclide vectors to substances and objects to be cleared are known to the ESK, for example a combination of total gamma clearance monitors with in-situ gamma spectrometry?"

Question 3: "How can the measures for a reliable assignment of nuclide vectors as well as measures for reviewing the assignment be assessed with regard to their effectiveness and suitability for practical use, in particular taking into account high material throughput, and which measures does the ESK consider suitable?"

Question 4: "What other clearance measurement methods or procedures are known compared to clearance monitors and how does the ESK assess them with regard to the reliability of compliance with clearance levels, especially with regard to nuclide vector assignment? Furthermore, what measures can be recommended to increase reliability in addition to these methods and procedures?"

In order to meet the BMUV's advisory request, on 25 January 2024, the ESK Committee on DECOMMISSIONING (ST), set up the ad hoc working group on nuclide vectors (Ad-hoc-Arbeitsgruppe NUKLIDVEKTOREN – AG NV) at its 93rd meeting, which included members of the ESK and the ESK Committee ST as well as members of the SSK Committee on Applied Radiation Protection and Radiological Protection in Nuclear Installations (Angewandter Strahlenschutz und Strahlenschutz bei Anlagen – A7). The ad hoc working group prepared a draft statement in eight meetings from July 2024 to February 2025 and presented it to the ST Committee at its 99th meeting on 5 February 2025 and at its 100th meeting on 19 March 2025. Furthermore, the status of consultations was presented and discussed at the 103rd of the A7 on 21 November 2024. At its 122nd meeting on 3 and 4 April 2025, the ESK discussed the consultation results and adopted this statement.

2 Terms and definitions

Nuclide distribution:

A nuclide distribution represents actual activity ratios for various radionuclides of an analysed sample or substance.

Nuclide vector:

The nuclide vector gives the activity percentages for each nuclide in the total activity.

A nuclide vector is an abstractly selected construct of different radionuclides which serves to ensure that nuclide distributions belonging to its scope are conservatively covered when using, for example, a total gamma measurement method with regard to the respective clearance levels according to Annex 4, Table 1 StrlSchV and taking into account the sum formula.

The construct may or may not correspond to a real nuclide distribution. In general, the selection of the radionuclides within the framework of the derivation/definition of a nuclide vector is based on radionuclides that are to be expected at the corresponding nuclear installation and that are relevant for clearance. Nuclide vectors are subject to a decay correction.

3 Incorrect assignment of nuclide vectors, causes and effects

Question 1: Which most probable and which most unfavourable incorrect nuclide vector assignments can be identified based on experience, what are the possible causes and which deviations can be expected as examples in the determination of activity in clearance monitors?

In the majority of decommissioned German nuclear power plants, the nuclide distribution during decommissioning is dominated by the activation products Fe-55, Co-60 and Ni-63. In the first few years after shutdown, other activation products such as Mn-54, Co-58, Zn-65, Nb-95, Zr-95, Ag-110m or Sb-125 also contribute to the nuclide distribution.

On the side of the fission products, the isotopes Sr-90 and in particular Cs-137 play a role in the contamination of radiation-controlled areas during the dismantling of the plant.

Due to their volatility, the radionuclides H-3 and C-14, which dominate the discharge of radioactive substances during normal operation of a nuclear power plant, only occur in high concentrations in a few contaminated substances.

In the case of activated concrete structures, the radionuclides H-3, Ca-41, Co-60, Ba-133 and various europium isotopes may occur in significant proportions.

In individual nuclear power plants, particularly older ones, nuclear fuel has entered the primary coolant due to fuel rod damage. Spent nuclear fuel contains a large number of long-lived alpha emitters (e.g. various plutonium and curium isotopes) including the alpha- and gamma-emitting radionuclide Am-241. In clearance, alpha emitters only play such a significant role in a few older plants that they account for several percent of the total activity of the contamination. In reprocessing plants, significantly higher proportions of alpha emitters are to be expected in some areas.

When clearing radioactive material, the clearance level of a radionuclide is determined by various factors such as physical and biological half-life (remaining in the body in the event of incorporation), the energy released during radioactive decay, the type of radiation, exposure pathways and their modelling. In the case of decommissioned nuclear power plants, the number of potentially dose-relevant radionuclides can be narrowed down considerably for clearance purposes. These are typically Co-60, Sr-90, Cs-137 and alpha emitters (in particular Am-241) and, in rare cases, C-14 and isotopes of europium.

For other nuclear installations (e.g. high-temperature and research reactors), the relevant nuclides generally correspond to those mentioned above, even if different activity ratios, in particular increased Sr-90 activities in high-temperature reactors, may occur in certain areas. Uranium isotopes and their daughter nuclides

dominate in uranium enrichment and fuel fabrication facilities. This is taken into account when determining clearance measurement strategies.

The consideration of dose-relevant radionuclides also directly results in the most unfavourable incorrect assignments of nuclide vectors:

Owing to the dominance of the two nuclides, the most likely incorrect assignment lies in an incorrect ratio of Co-60 to Cs-137 in the plant contamination. Due to the very different formation and transport processes of these two radionuclides, both Co-60 and Cs-137 can occur in nuclide mixtures (after application of the so-called 10% rule, which allows radionuclides that are not dose-relevant to be disregarded) in proportions of 0% to 100% and they are not correlated with each other.

Both nuclides have a clearance level for unrestricted clearance of 0.1 Bq/g, but the detector response (pulses/second per Becquerel) in a classical clearance monitor with large-area scintillation detectors differs by a factor of about 3 with regard to the two nuclides. In measurement geometries with strong self-shielding of the material to be measured (e.g. in the case of an inhomogeneous activity distribution in the material), this difference in response may well amount to a factor of 5. Co-60 is easier to measure here than Cs-137 due to the emission of two photons per decay, the high emission probabilities and the high gamma energies. The result is that calibrations of a clearance monitor that assume a high proportion of Co-60 in the contamination are susceptible to underestimating the sum formula exhaustion in the material to be measured when there is actually a Cs-137-dominated contamination.

In the case of clearance according to Annex 4, Table 1, Column 6 StrlSchV (building rubble > 1,000 Mg/a) and Column 10 (disposal on a landfill up to 1,000 Mg/a), the above-mentioned factor of 3 in response would be covered by the higher clearance level of Cs-137 if Co-60 contamination is assumed when Cs-137 contamination is actually present.

In the event of incorrect assignment, it is not relevant whether the specific total activity of the measured material is underestimated as a result, but whether the degree of sum formula exhaustion – in relation to the respective nuclide vector – will not exceed 100%. The StrlSchV requires that the sum formula assumes a value of < 1 on the scale of the permissible averaging mass (generally a maximum of 300 kg). With regard to the question of compliance with the de minimis concept of clearance, however, the following point should not be disregarded: The clearance levels for unrestricted clearance of the IAEA Safety Guide RS-G-1.7 [1], on which the levels in the StrlSchV are based, are derived in IAEA Safety Report Series No. 44 [2]. The dose per Bq/g calculated in [2] is lower for Cs-137 than for Co-60 by a factor of 3.85. Only rounding to whole powers of ten when converting to the clearance levels results in the identity of the clearance level of Co-60 and Cs-137. Without rounding, the clearance level of Cs-137 would be 3.85 times higher. The rounding carried out in [2] is justified there by the fact that the accuracy of the radiological models would not justify a higher precision of the results. A confusion of Co-60 and Cs-137 (i.e. Co-60 assumed, Cs-137 present) would therefore mathematically lead to an incorrect determination of the sum formula exhaustion in the sense of the StrlSchV and thus, in the case of unnoticed exceedance of the value of 1 for the sum formula, would violate the conditions of the granted clearance. However, a violation of the dose criterion of the clearance cannot necessarily be derived from this.

There is no violation of the clearance dose criterion either if Co-60 is incorrectly assumed instead of Cs-137 in the clearance according to Annex 4, Table 1, Column 8 (for disposal on a landfill less than 100 Mg/a) and Column 9 (for incineration less than 100 Mg/a). Here, the clearance level for Cs-137 is only 1.67 times higher (Column 8) or 1.43 times higher (Column 9) than the clearance level for Co-60, which is not due to the exposure determination but to a limitation of the clearance levels for Cs-137 by the exemption level of 10 Bq/g valid at the time of their derivation. Determining the exposure, however, resulted in arithmetically permissible specific Cs-137 activities of 27.07 Bq/g (Column 8) and 28.42 Bq/g (Column 9), i.e. ratios of the clearance levels of Cs-137 to Co-60 of 4.3 (Column 8) and 4.0 (Column 9), respectively [3, p. 29ff], which is practically identical to the ratio of the responses of the radionuclides Co-60 and Cs-137 in the clearance monitor. The ratio of the surface contamination limits and the clearance levels for Cs-137 to Co 60 resulting from the exposure determination without further rounding is shown in Table 1 for the relevant clearance options of the StrlSchV.

Table 1: Surface contamination limits and clearance levels for Co-60 und Cs-137 and their ratio according to the StrlSchV and according to the dose determination from derivation

Column in Annex 4, Table 1 StrlSchV	**Unit**	**Clearance level**		**Ratio of the clearance levels Cs-137/Co-60**	
		Co-60	**Cs-137**	**acc. to StrlSchV**	**from dose determination**
Column 3: unrestricted clearance	Bq/g	0.1	0.1	1	3.85*
Column 5: surface contamination	Bq/cm²	1	1	1	4*
Column 6: building rubble > 1,000 Mg/a	Bq/g	0.09	0.4	4.44	4.49*
Column 8: disposal on a landfill < 100 Mg/a	Bq/g	6	10	1.67	4.32**
Column 9: incineration < 100 Mg/a	Bq/g	7	10	1.43	4.00**

Column 10: disposal on a landfill < 1,000 Mg/a	Bq/g	2	8	4	4.32*
Column 11: incineration < 1,000 Mg/a	Bq/g	2	3	1.5	1.51*
Column 14: scrap metal for recycling	Bq/g	0.6	0.6	1	1*
* without rounding of the clearance level ** without capping the clearance level of Cs-137 at the then exemption level of 10 Bq/g and without rounding the clearance level					

Only in the cases of Column 11 and Column 14 (Table 1) could a significant incorrect assignment of the Co 60/Cs 137 ratio lead to a violation of the dose criterion for clearance.

The radionuclides C-14 and Sr-90 are relevant in light water reactors only in very limited plant areas, for example in parts of the exhaust system and in BWR turbine condensers. Europium isotopes represent a significant proportion of the total activity only in activated mineral structures (biological shield). In high-temperature reactors, however, C-14 and Sr-90 can play a more significant role regarding the sum formula exhaustion than in light water reactors.

The non-consideration of C-14 and Sr-90 in nuclide vectors of light water reactors is in most cases unproblematic since they only occur in high proportions in very limited plant areas (see above). However, it is essential that appropriate radiological experience is available and that particular attention is paid to corresponding analyses of difficult-to-measure nuclides for the radiological characterisation of these potentially C-14- and Sr-90-contaminated systems. However, clearance-relevant surface contamination with these two pure beta emitters can be identified, for example, by preliminary analyses and orientation measurements since surface contamination monitors frequently used here can detect pure beta emitters. If the measurement is carried out in a qualified manner, parts contaminated with pure beta emitters can therefore be sorted out prior to the decision measurement.

The non-consideration of alpha emitters in the nuclide vector usually only leads to minor errors in the clearance measurement. It can only be a problem in those plants that have alpha proportions in the nuclide vector of at least a few percent. However, specific processes have been established in these plants to prevent underestimation of alpha proportions.

The following are examples of reasons for incorrect assignment:

1 Inadequate analysis scope in the context of radiological characterisation, e.g. non-performance of special nuclide analyses for residual material that may have significant proportions of pure alpha or beta emitters. Instead, application of standard correlations to systems for which these standard correlations are not suitable.

2 Use of nuclide vectors formed from averaged nuclide fractions without adequate consideration of DIN 25457-1:2024-05, sections 6.2 and 7.2 (see Appendix) on the scale of the permissible averaging quantities (“either using a conservative nuclide vector or performing a type B uncertainty analysis”). This may concern both the gamma-spectrometrically measurable key nuclides and the difficult-to-measure nuclides.

3 Inadvertent mix-up of the nuclide vector assignment or unintentional change of the nuclide distribution of packages due to human error, possibly in connection with unclear processes for nuclide vector determination, for the collection and treatment of residual material and for package labelling.

In view of errors 2 and 3 in the above list, the following recommendation is given:

The ESK recommends that control samples be taken and subjected to gamma spectrometric analysis if the nuclide vector had not been conservatively defined to cover all nuclide distributions occurring throughout the plant with regard to the various gamma emitters and if an activity threshold to be defined is exceeded during the decision measurement. The activity threshold should be based on the conservatism of the nuclide vector ("How large could the realistically possible underestimation of the sum formula exhaustion or the dose determination be if the nuclide vector is incorrectly assigned?"). If such a control measurement reveals a significant deviation in the distribution of gamma emitters from the nuclide vector, it is to be clarified whether the sum formula is still complied with given the activity contained. If this is not the case, the remaining packages of the batch are also to be assessed and the procedure is to be agreed upon with the nuclear supervisory authority.

Control sample evaluations by means of difficult-to-measure nuclide analyses would prevent the occurrence of error 1, but it is not expedient to eliminate fundamental weaknesses in radiological characterisation when performing clearance measurements. Here, it is of great importance to establish a robust procedure for radiological characterisation in the operational rules and regulations and to have it approved by the competent nuclear supervisory authority. In the view of the ESK, the implementation of a step-by-step radiological characterisation, the level of detail of which is highest in the clearance process, has meanwhile become 'good practice' in Germany.

4 Measures for reliable nuclide vector assignment

Question 2: Which possible or already implemented measures for a reliable assignment of nuclide vectors to substances and objects to be cleared are known to the ESK, for example. a combination of total gamma clearance monitors with in-situ gamma spectrometry?

In nuclear installations, various measures are implemented along the entire clearance process to ensure that the corresponding nuclide vector is reliably assigned to the material or object to be cleared.

These different measures relate to the following main steps of the clearance process:

a) sampling for nuclide vector determination,
b) measurement in the operator's own laboratory,
c) measurement in external laboratories,
d) determination of the nuclide vector,
e) dismantling of the components,
f) processing,
g) clearance measurement, and
h) storage of samples and packages until clearance or other decision on the waste management path.

a) Sampling for nuclide vector determination

- consideration of the system characteristics and operating history in order to select suitable sampling points, procedures and analysis methods,
- determination of the nuclide vector using sampling programmes agreed with authorised experts,
- clear labelling of the samples and allocation to dismantling areas (sampling points):
  - adhesive labels, and
  - photo protocol,
- sample database including measurement results,
- validation of calculations/simulations of activity build-up in systems by sampling and measurement, if these are used for the determination and assignment of a clearance nuclide vector, and
- archiving of exemplary samples until clearance is completed.

The basis for determining the nuclide distribution is a representative sampling of the materials and system areas as well as a sufficiently sensitive analysis of the samples.

The sampling points are selected taking into account the system characteristics (different temperature, pressure and flow areas, upstream/downstream filters, areas with different water chemistry, etc.) and are agreed with the supervisory authority or the independent authorised expert consulted by it.

Samples and sampling points are clearly labelled to prevent samples from being mixed up and to ensure traceable assignment. Both adhesive labels and photo protocols are used for this purpose.

Attention is paid to a sufficient number of samples and an appropriate selection of sampling and analysis methods to be able to detect or exclude difficult-to-measure nuclides.

Furthermore, the sample information and analysis results are managed in databases and, where appropriate, exemplary reference samples are stored until clearance is completed. If the assignment of a nuclide vector is to be based on calculations and simulations of the activity build-up (e.g. activation calculation based on the neutron flux), these calculations are verified by sampling and measurements where necessary.

b) Measurement in the operator's own laboratory

- qualified measuring equipment,
- trained staff,
- geometries/calibrations confirmed by authorised experts,
- evaluation with quality assurance (e.g. four-eyes principle), and
- plausibility check based on reference samples and the operating history.

When analysing the samples to determine the nuclide distribution, only qualified measurement methods are used in the operators' own laboratories. The measuring equipment and methods comply with the applicable recognised codes and standards and have been inspected and reviewed by the supervisory authority or the independent expert consulted by it. This also applies, in particular, to the various calibrations depending on the type and geometry of the material to be measured.

The measurements are carried out and analysed by trained staff and are described in the internal regulations, including the measures for quality assurance (e.g. analysis manual).

c) Measurement in external laboratories (e.g. analysis of difficult-to-measure nuclides)

- selection of the analysis methods when being commissioned,
- consideration of difficult-to-measure nuclides in the analysis in order to check/exclude their occurrence,
- use of accredited laboratories, and
- quality assurance of the measurement results (plausibility check by the client).

External laboratories are also used to determine the nuclide distribution, in particular for the analysis of difficult-to-measure nuclides. Only laboratories accredited by the competent nuclear supervisory authority are commissioned for this purpose and the results are checked for plausibility by the operators commissioning the nuclear analysis (e.g. on the basis of comparable measurements and the operating history).

d) Determination of the nuclide vector

- use of standardised calculation routines,
- determination of the nuclide vector with the involvement of the authorised expert,
- internal review / quality assurance (e.g. four-eyes principle), and
- use of a residue tracking program for traceable documentation.

The nuclide vector is determined on the basis of the respective nuclide distribution obtained from the analysis, taking into account the requirements of the StrlSchV and the relevant DIN standards with standardised calculation routines. These are checked by the supervisory authority or by independent authorised experts consulted by it, respectively.

The operators have the nuclide vector determination checked by a second person (four-eyes principle) and document the result in a residue flow tracking system. Only certain persons are authorised to enter or change nuclide vectors, which is documented.

e) Dismantling of the components

- clear labelling,
- training of staff (acting professionally),
- work preparation meetings taking into account the radiological specifications for sorting; issues to be given special attention, etc.,
- sorting of the dismantled material into batches with the same nuclide vector (at the dismantling location),
- covering of the boxes/transport containers (to avoid cross-contamination and uncontrolled material entry).

The materials and system areas intended for clearance must be clearly and visibly labelled in the dismantling area so that sorting into batches with the same nuclide vector can already take place during dismantling. Other measures to ensure correct nuclide vector assignment are, for example, the planning of a dismantling sequence according to identical nuclide vectors or the covering of loaded transport containers to avoid cross-contamination or the uncontrolled entry of material. Staff are sensitised for the topic of radiology through appropriate training prior to the activities and in the framework of work preparation meetings immediately before the start of the dismantling work (e.g. training in professional behaviour, human performance optimisation).

f) Processing

- processing according to identical nuclide vectors (further cutting, decontamination),
- intermediate cleaning of processing equipment when changing material (different nuclide vectors),
- checking correct nuclide vector transfer (parent/daughter packages), i.e. when dividing material between several containers, and
- measurement/control of emptied packages.

During further disassembly and decontamination of the materials, care is taken to ensure that materials with different nuclide vectors are not mixed. Only material with the same nuclide vector is handled in each processing facility and the machines are to be cleaned before changing materials to prevent cross-contamination.

Since labels on the material, including those identifying the nuclide vector, must necessarily be removed during decontamination and further cutting and the material is repackaged into other transport containers, care is taken to ensure that the associated nuclide vector information remains correctly assigned and preserved. To this end, the labels on the packages are checked before and after processing (“parent-daughter relationship”) and compared with the information in the residue flow tracking system.

When qualifying decontamination procedures, it is generally considered whether there is an unfavourable change in the nuclide vector that may need to be taken into account.

Regular contamination control and, if necessary, decontamination of empty containers before reuse also prevent cross-contamination.

g) Clearance measurement

- automatic import of the nuclide vector into the clearance monitor wherever possible
- interlocking wherever possible: “no measurement without a verified nuclide vector!”,
- quality assurance of clearance measurement records and clearance documentation,
- random in-situ gamma spectrometry of packages (or representative material samples from the packages) as a separate measurement in addition to the clearance monitor to verify the nuclide vector,
- selection criteria, e.g. degree of exhaustion of clearance levels, special nuclide distributions, clearance path, etc., and
- control of clearance measurement and documentation by the supervisory authority or its authorised experts, also by independent measurements.

Since clearance measurements, for example in a total gamma clearance monitor, are a key element in the clearance decision process, the correct assignment of the nuclide vector is of great importance alongside the validated measurement procedure and the application of the correct calibration that is dependent on both the material being measured and its geometry. Ideally, the assigned nuclide vector is read into the clearance monitor automatically or semi-automatically. This is done, for example, by means of a bar code or QR code on the transport containers in combination with a database (or a residue flow tracking system). An additional check of all the above points by trained operating personnel and a description of the measurement process with corresponding inspection steps in the internal regulations is mandatory.

Independent control of the nuclide vector can be carried out by randomly determining the nuclide ratio in individual packages of a clearance batch by means of sampling and laboratory gamma spectrometry or in-situ gamma spectrometry. Due to the time required for gamma spectrometry, these control measurements are usually carried out after the total gamma measurement but before the clearance decision is made by the radiation protection executive, who is the holder of the clearance. Selection criteria for this control measurement include, for example, the degree of exhaustion of the clearance level or special assigned nuclide vectors. If such a control measurement reveals a significant deviation in the distribution of gamma emitters from the nuclide vector, it is to be clarified whether the sum formula is still complied with given the activity contained. If this is not the case, the remaining packages of the batch are also to be assessed and the procedure is to be agreed upon with the nuclear supervisory authority (see recommendation).

Before the radiation protection executive or the radiation protection officer appointed by the radiation protection executive determines whether clearance is possible, the documentation is reviewed, including the correct assignment and transfer of the nuclide vector, based on the available information (system assignment, photo protocols, measurement records, etc.).

Furthermore, the supervisory authority has the option of verifying the clearance decision by conducting its own measurements, accompanying the operator's clearance process and controlling the clearance documentation.

h) Storage of samples and packages until decision on the waste management path/clearance

- secure storage of samples to prevent access by third parties and prevent the addition of material, and
- securing the packages (containers etc.) with a seal.

To prevent samples and packages from being mixed up or cross-contamination after the decision measurement, they are stored in such a way that they are protected from access by third parties. Covers and/or seals on storage containers ensure that no material is removed or added.

In the opinion of the ESK, the measures described in this chapter for reliable nuclide vector assignment are proven practice in nuclear installations.

The combination of total gamma radiation measurement facilities with in-situ gamma spectrometry is addressed in more detail in Chapter 5.

5 Measures for reviewing the nuclide vector assignment

Question 3: How can the measures for a reliable assignment of nuclide vectors as well as measures for reviewing the assignment be assessed with regard to their effectiveness and suitability for practical use, in particular taking into account high material throughput, and which measures does the ESK consider suitable?

To ensure that radioactive waste is cleared in compliance with legal requirements, the radiation protection executive, who is holder of the clearance, has to establish a clearance process that includes appropriate quality assurance steps that are adequate within the overall process. A suitable selection can be made from the list provided under Question 2. The process is agreed upon with the competent supervisory authority.

The reliability of the technical implementation of the clearance process can be increased by minimising manually operated interfaces in order to prevent the incorrect assignment of a nuclide vector and other measurement parameters relevant for the clearance measurement to the material to be cleared. For example, data assigned to the material (nuclide vector, calibrations, geometries) can automatically be imported from a database into the measuring equipment used for the decision measurement. Likewise, a plausibility check is performed with regard to the measurement parameters assigned to the material to be cleared, including the nuclide vector, using the four-eyes principle, for example during the review of the clearance documentation.

An additional quality assurance measure may be the performance of random gamma spectrometric measurements, which can be used to verify the use of an appropriate nuclide vector in the decision measurement. Independent measurements by third parties (authorised experts, supervisory authorities) serve

exclusively for regulatory supervision. The clearance procedure to be established by the operator must, independently of this, enable reliable statements to be made on whether the material can be cleared.

The report by GRS [4] can be used to assess the practicality of combining a clearance monitor with a high-purity germanium (HPGe) detector. When dismantling nuclear installations, high throughput is also relevant with regard to the clearance of batches. In its report [4], prepared on behalf of the ESK, GRS estimates the measurement times for clearance measurements using an HPGe detector, as used in in-situ gamma spectrometry. In tables 3-1 and 3-2, simulated measurement times for an HPGe detector for the nuclides Co-60 and Cs-137 are specified, which are associated with the most likely incorrect assignments and occur in significant quantities in virtually all nuclear power plants (see Question 1).

When performing a total gamma measurement using a clearance monitor, a measurement time of 20 s to 100 s is usually sufficient to demonstrate that the values are below those specified in Annex 4, Table 1, Column 3 StrlSchV. In [4], GRS concludes that for a 50/50 mixture of Co-60 and Cs-137 with a batch mass of 100 kg and the clearance target of unrestricted clearance, the measurement time would be in the order of 45 minutes until both peaks become visible in the spectrum. These measurement times are unfavourable in view of the high material throughput during the decommissioning of nuclear installations. For shorter measurement times, only limited and hardly quantifiable statements can be made regarding the Co-60/Cs-137 ratio, especially for masses significantly below 300 kg.

For some clearance paths – especially in the case of unrestricted clearance – the decision measurement using clearance monitors demonstrates not only that the mass-specific clearance levels are below the applicable limits, but also that the limits for surface contamination specified in Annex 4, Table 1, Column 5 StrlSchV are not exceeded. This proof would also lead to significantly increased measurement times when using gamma spectrometric detectors in the clearance monitor. This applies not only when using the averaging area of 1,000 cm² in accordance with the StrlSchV, but also when using increased averaging areas of, for example, 1 m². However, if no proof of compliance with surface contamination limits is required as part of the decision measurement and in cases where the permissible specific activity for clearance is above 0.5 Bq/g, the measurement time of a gamma spectrometric detector installed in the clearance monitor is reduced to values that are no longer significantly above the typical measurement times of clearance monitors.

Practical experience from combining a clearance monitor with a gamma spectrometric measurement from VKTA – Radiation Protection, Analytics & Disposal (VKTA) is already available from [5]. It indicates that optimal boundary conditions were postulated for the simulation results in [4]. If a gamma spectrum is to be recorded during the measurement, longer measurement times are required. The longer the measurement time, the more reliable the spectrum and the more gamma emitters can be identified. It is therefore evident that, in the case of spectrometry accompanying the total-gamma measurement, an optimum must be found between the spectrometric information obtained and the measurement time available within the assessment process for large material quantities. The measurement time may need to be adjusted during the decommissioning process, depending on which nuclides are expected to be present in the packages. According to [5], at the VKTA it offers an added value to use a recorded gamma spectrum to reduce the degree of conservatism for the declared nuclide vector to the extent that information can be obtained from the accompanying gamma spectrum, especially when nuclide vectors with larger uncertainties are present. It can therefore be stated that, for facilities where the nuclide ratios are less uniform and standardisable, such as research facilities, a combination of total gamma clearance monitors and simultaneous in-situ gamma spectrometry can be an

appropriate approach. For small quantities of materials to be decommissioned, the measurement time of the decision measurement is a less decisive factor with regard to the throughput of the overall process. Therefore, an additional in-situ gamma spectrometry can increase the reliability and plausibility of the nuclide vectors used. This likewise requires that the personnel evaluating the gamma spectra possess not only technical but also scientific expertise since such measurements cannot be fully standardised, which runs counter to industrial application with high material throughput during the dismantling of power reactors.

In a presentation by GRS [6] at the 99th meeting of the ESK Committee ST on 5 February 2025, the case study of the FRM-03 was presented, which is used as a pure gamma spectrometry clearance facility at the Chernobyl nuclear power plant for the clearance of scrap metal and is currently in trial operation. The facility can be used for batches of several thousand kilograms, with activity determination taking place in several sectors, each weighing no more than 1,000 kg. For Cs-137 activities of several MBq in the measured material, a quantitative determination of the activity was possible exemplarily, with a measurement time of 80 seconds. Small batch masses in the range of 100 kg or the examination of surface contamination of the material on averaging areas of 1 m² were not required in the case study. The ESK draws no conclusions from the GRS report [6] that differ from those presented by the VKTA presentation and from the GRS simulation results [4] with regard to the scalability and throughput for the unrestricted clearance of smaller batch masses or for the required demonstration of compliance with surface contamination limits.

The ESK considers a combination of total gamma clearance monitors with simultaneous in-situ gamma spectrometry or accompanying random gamma spectrometric measurements generally not an appropriate approach from a practical point of view, among other things due to the increased measurement time and other metrological constraints of gamma spectrometry with regard to the throughput capability of the clearance process. However, such measurement systems may be appropriate in justified individual cases, for example, when no conservative nuclide vector can be assigned to the packages or in facilities that only need to achieve low material throughput in the clearance process (e.g. research facilities). The application of the combination can be determined individually and on a facility-specific basis in each case.

6 Other clearance measurement methods

Question 4: What other clearance measurement methods or procedures are known compared to clearance monitors and how does the ESK assess them with regard to the reliability of compliance with clearance levels, especially with regard to nuclide vector assignment? Furthermore, what measures can be recommended to increase reliability in addition to these methods and procedures?

Other clearance measurement methods are:

a) gamma spectrometric analysis of representative samples (e.g. for measured materials that can be homogenised),
b) direct measurement of surface contamination,
c) in-situ gamma spectrometry,
d) mass spectrometry (e.g. fuel fabrication), and
e) conveyor-belt measurement systems.

a) Gamma spectrometric analysis of representative samples

When evaluating representative samples, gamma spectrometry is generally used as the measurement method, which enables quantitative nuclide-specific statements to be made with regard to gamma-emitting radionuclides. Provided that the materials to be measured can be homogenised well (e.g. liquids), this method can be considered reliable in terms of nuclide vector assignment and thus also for assessing compliance with clearance levels. In addition, gamma spectrometry of samples is suitable in cases where control samples are taken from clearance measurement batches that have been measured in a clearance monitor (see recommendation). These control samples are used exclusively to verify the nuclide vector and not to verify compliance with clearance levels. The reason for this is that, although clearance batches generally have a uniform nuclide distribution since the materials originate from the same location or system, the activity distribution within the clearance batch is not always homogeneous in the case of solids. The evaluation of the control samples therefore provides proof that the calibration of the clearance monitor ensures that the sum formula exhaustion had not been underestimated in the decision measurement.

b) Direct measurement of surface contamination

Direct surface contamination measurements are usually performed using instruments that are sensitive to beta radiation (e.g. gas-filled counter tubes or scintillation detectors equipped with suitably thin foils that allow beta radiation to enter the sensitive volume or the detector). Direct surface contamination measurement is mainly used for preliminary or orientation measurements in order to identify and sort out contaminated material prior to the decision measurement. When combined with a decision measurement using a clearance monitor, this measurement method has the advantage that radionuclides such as Sr-90 and Cs-137 – which have a poorer response at the clearance monitor compared to Co-60 (the response of Sr-90 is extremely low) – can be detected in the initial measurements. If a decision measurement is carried out exclusively by means of direct surface contamination measurements, the following is to be taken into account: Here, too, the selection of the calibration nuclide is decisive for the conservativeness of the decision measurement. For this reason, Co-60 calibration is often applied since Co-60 has a poorer response to beta radiation when using beta-sensitive contamination monitors than Sr-90 and Cs-137 due to its lower beta energies. However, since beta radiation is not able to penetrate the material being measured, it is necessary here that the surface of the measured material will be covered as completely as possible by the measuring device. When making clearance decisions based on direct contamination measurements, it must also be noted that, in addition to compliance with the permissible limits for surface contamination, it also has to be demonstrated that the mass-specific clearance levels are not exceeded. This results in requirements for the minimum required material thickness. For very thin materials to be measured, such as thin metal sheets, direct surface contamination measurement can generally not be used as the sole measurement method for clearance decisions. In

practice, this measurement method is therefore used, for example, for the clearance measurement of large metallic components.

c) In-situ gamma spectrometry

In-situ gamma spectrometry is a method used in the nuclear sector to measure building surfaces and land areas or also in radiological characterisation of operational waste. The possibility of combining in-situ gamma spectrometry with a clearance monitor was already discussed in chapters 4 and 5. At this point, the ESK therefore addresses the independent use of in-situ gamma spectrometry for decision measurements in the clearance procedure. In-situ gamma spectrometry has very good energy resolution, which is capable of distinguishing all typical gamma emitters occurring during decommissioning. However, the large number of measuring channels and the generally rather small detector volumes (compared to large-area scintillation detectors) result in a relatively low number of net pulses per measuring channel and thus in increased counting-statistical uncertainties. This has consequences for the measurement times of in-situ gamma spectrometric measurements, which often range from five minutes to one hour. The use of in-situ gamma spectrometry for clearance measurements of building surfaces has the advantage that even contamination that has penetrated to a depth of a few millimetres to a few centimetres can still be detected with good response. The priority given to clearance measurement on the standing structure is laid down in the StrlSchV. It is based on the requirement to identify and remove easily measurable contamination on building surfaces before demolition-related homogenisation mixes contaminated material with uncontaminated material from the interior of the walls. This would considerably complicate the subsequent removal of activity accumulations.

d) Mass spectrometry

For uranium isotopes and other long-lived nuclides that are not easily detected by gamma spectrometry, the mass spectrometric analysis of samples can be used as a measurement method for the clearance of materials. This applies to materials from which representative samples can be taken (e.g. bulk materials or liquids). In Sweden, for example, both solid and liquid waste from fuel fabrication is cleared using inductively coupled plasma mass spectrometry (ICP-MS) for analyses. This measurement method allows conclusions to be drawn about individual nuclides and has very low detection limits for specific activity in the case of very long-lived radionuclides (e.g. various uranium isotopes). However, the measurement method is costly and time-consuming and is unsuitable for common reactor nuclides such as Co-60, Sr-90 or Cs-137. It should therefore primarily be regarded as a supplementary method for the clearance measurement of waste from fuel fabrication.

e) Conveyor-belt measurement systems

Conveyor-belt measurement systems, such as referred to in [7], do not in themselves represent an additional measuring method since the detectors used here are also used in other measurement systems. These may be gamma spectrometric measurement systems or the detectors already mentioned for determining surface contamination (e.g. beta-sensitive scintillation detectors). Differences to other measurement systems – in particular to ‘classic’ clearance monitors – lie in the lower shielding of the measurement system against ambient radiation, the nuclide-specific resolution through gamma

spectrometry and the associated relatively low detector volumes. Although these factors enable the differentiation of various gamma emitters and the parallel detection of pure beta emitters, there are various factors that can lead to longer measurement times and additional type B measurement uncertainties:

Measurements on the conveyor belt require bulk material that can be easily homogenised, such as soil. Even broken building rubble exhibits greater inhomogeneities and quantitative direct beta measurements are generally not possible in this case.

7 Conclusions

With regard to the possible exceedance of clearance levels, it should be noted that the question of which nuclide vector assignment is to be regarded as conservative depends on whether compliance with mass-specific clearance levels or compliance with surface contamination limits is verified. Since both beta-sensitive detectors (direct surface measurement) and gamma-sensitive detectors (e.g. clearance monitor) are used here, it is often not possible to define a single 'enveloping' nuclide vector. In some nuclear installations, a simple and conservative approach has therefore been adopted, using two nuclide vectors for the evaluation of the decision measurement. For decision measurements using direct surface contamination measurement, nuclide vectors are used that tend to overestimate the Co-60 content in the measured material, while for measurements with the clearance monitor, nuclide vectors are used that tend to overestimate the Cs-137 content in the measured material. This applies, in particular, in the case of unrestricted clearance.

With regard to an incorrectly assumed Co-60/Cs-137 ratio, this may lead to an incorrect determination of the sum formula exhaustion, but this does not generally result in a violation of the dose criterion for clearance (see Chapter 3 of this statement). Exceptions to this may occur in the case of clearance of material for disposal by incineration < 1,000 Mg/a or in the case of clearance of scrap metal for recycling. This is to be taken into account when determining the activity thresholds for control samples (see recommendation).

In particular, when nuclide vectors are used that have not been defined conservatively in the above sense and activity thresholds are exceeded, it is necessary to verify the suitability of the nuclide vector used to prove that the sum formula value is below 1.

Regardless of the method used for decision measurements, it is common practice to overestimate all non-measurable nuclides, such as alpha emitters or Sr-90, in the nuclide vector.

Additional detectors that could detect non-gamma-emitting radionuclides do not offer any relevant safety benefits during the dismantling of nuclear power plants with light water reactors. The detection of gamma radiation emitted from the measured material is significantly more robust against inhomogeneous local activity distributions. The ESK considers the recommended control samples to be sufficiently effective and suitable. They do not interfere with high material throughput in the clearance process.

To minimise the proportion of suspected clearance level exceedances for measured materials that are actually qualified for clearance, a re-evaluation of measured batches that have only slightly exceeded the alarm setpoints during the decision measurement can be carried out. For this purpose, a realistic nuclide vector may

be applied, provided its applicability to the specific package is demonstrated through appropriate sample analysis or in-situ gamma spectrometry.

In summary, the ESK concludes that the clearance procedures established in German nuclear installations provide for reliable compliance with the requirements of the StrlSchV. It generally does not consider additional nuclide-specific measurement systems in clearance monitors to be necessary, particularly with regard to decommissioned nuclear power plants (see recommendation). However, such measurement systems may be appropriate in justified individual cases, for example, when no conservative nuclide vector can be assigned to the packages or in facilities that only need to achieve low material throughput in the clearance process (e.g. research facilities).

Other alternative clearance monitors – such as conveyor-belt measurement systems – may be used in special cases for measuring material that can be homogenised, such as soil.

8 Recommendation

The ESK recommends that control samples be taken and subjected to gamma spectrometric analysis if the nuclide vector had not been conservatively defined to cover all nuclide distributions of gamma-emitters occurring throughout the plant and if an activity threshold to be defined is exceeded during the decision measurement. The activity threshold should be based on the conservatism of the nuclide (“How large could the realistically possible underestimation of the sum formula exhaustion or the dose determination be if the nuclide vector is incorrectly assigned?”). If such a control measurement reveals a significant deviation in the distribution of gamma emitters from the nuclide vector, it is to be clarified whether the sum formula is still complied with given the activity contained. If this is not the case, the remaining packages of the batch are also to be assessed and the procedure is to be agreed upon with the nuclear supervisory authority.

9 References

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Appendix: Requirements of the statutory and substatutory regulations

StrlSchV, Annex 8, Part A, No 1b:
The proof of compliance with the clearance levels shall be provided using measurements. Additionally, where a solid surface is available on which a contamination measurement can be carried out, compliance with the limits for surface contamination shall be proved if a solid surface is present on which a contamination measurement is possible; this proof too shall be provided on the basis of measurements.

ESK recommendation "Guidelines for the decommissioning of nuclear installations" of 5 November 2020, Section 5:
Administrative regulations have to ensure that the radiological characterisation serves to define definite nuclide vectors and enveloping measuring geometries for clearance.

ESK recommendation "Guidelines for the decommissioning of nuclear installations" of 5 November 2020, Section 7.3:
The clearance procedure must allow the review of basic data (nuclide vector, suitability and calibration of measuring equipment, origin of the material and, where appropriate, activity distribution) as well as random control measurements.

Guide to the decommissioning, the safe enclosure and the dismantling of facilities or parts thereof as defined in § 7 of the Atomic Energy Act of 16 September 2021, Section 6.4:
The clearance measurement is performed in accordance with the provisions laid down in the clearance notice. […] The clearance measurement is to be performed such that the specific activity or contamination of the material cannot be underestimated (conservatism of the measurement).

DIN 25457-1: Activity measurement methods for the clearance of radioactive substances and nuclear facility components – Part 1: Fundamentals; Section 6.2
The desired conservatism for the clearance decision is given for enveloping nuclide vectors by their calculation. For other nuclide vector calculation methods, it can be ensured by applying threshold values. The threshold values indicate the percentage up to which the clearance levels may be exhausted. The threshold values can be based, among other things, on the variability of the measurement effect in the derived clearance level of the nuclide mixtures of the related sample collection used to calculate the nuclide vector. The threshold value depends on the respective clearance option and the nuclide-specific response of the measuring device used.
[...]
If the selected nuclide vector and the threshold values are sufficiently conservative, the type B uncertainty of the nuclide vector according to Section 7.2 can be disregarded.
(Note: Section 7.2 of DIN 25457-1 regulates the boundary conditions for the decision measurements, taking into account the requirements of DIN ISO 11929).

DIN 25457-1: Activity measurement methods for the clearance of radioactive substances and nuclear facility components – Part 1: Fundamentals; Section 7.2:
The primary measurement result must be compared with the detection limit. If the primary measurement result is greater than the detection limit, there is at least a 95% probability that artificial radioactive substances are present in the measured material and the upper limit of the confidence level must be determined.

The upper limit of the confidence interval must be used for the comparison with reference levels. The one-sided significance level of 5% must be used to determine the confidence interval.