22NRM07 GuideRadPROS

# D1 Summary report on developing a harmonised approach to X-ray spectrometry in accordance with the ISO 4037 standard series. This includes evaluating the discrepancies between measured and calculated half-value layer (HVL) of X-ray spectra

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# 1 Introduction

The standard series ISO 4037:2019 (1) (2) (3) (4) (hereinafter ISO 4037) describes the requirements and procedures for establishing photon reference fields for radiation protection dosimetry and thus ensures that standard instruments and dosemeters are calibrated and tested under well-defined conditions.

The four parts of the standard were updated in 2019, and numerous changes were introduced. The new requirements for reference fields place high demands on calibration and testing laboratories. These include requirements for tube potential, and thickness of additional filtration.

According to ISO 4037, reference radiation fields can be realized in two ways: as matched fields and as characterized fields. When establishing matched reference radiation fields, the tabulated conversion coefficients listed for each radiation quality in ISO 4037-3:2019 (3) must be used. The use of the conversion coefficient must be validated separately for each radiation quality. ISO 4037-1 offers three methods: Dosimetry, measurement of half-value layer (HVL), and spectrometry. This ensures that the spectral fluence of the X-ray field is sufficiently close to that used to calculate the tabulated conversion coefficients for the radiation qualities. No validation is necessary for characterized radiation fields. Instead, the conversion coefficients are calculated either from spectrometry or dosimetry.

A harmonized approach in X-ray spectrometry is defined as one that enables all National Metrology Institutes (NMIs) to obtain spectra that are metrologically equivalent. To achieve this, equivalence is assessed through consistent beam quality parameters, in particular comparable half-value layer (HVL) values, filtration thicknesses and tube voltage (kV). Ensuring agreement in these parameters allows the realization of equivalent x-ray radiation qualities for radiation protection applications in the framework of ISO 4037.

The need for a harmonized approach to spectrometry is underscored by surveys and workshops conducted by the GuideRadPROS consortium, which revealed that current standards offer only limited direction for performing spectrometric measurements. In addition, there is a notable lack of published data on such measurements, including their comparability across laboratories, their agreement with theoretical simulations, and the level of precision that can realistically be achieved.

This deliverable summarises the results of calculations, dosimetry measurements, and spectrometric measurements by different laboratories, which is, among other outcomes, used for evaluation of discrepancies between measured and calculated HVL values and confirmation of adoption of the harmonised approach to X-ray spectrometry by the participating laboratories.

# 2 Harmonised approach to X-ray spectrometry: study of the requirements on tube potential and filter thickness

## 2.1 Background

A harmonised approach to x-ray spectrometry is required to ensure that spectra realised by different laboratories are metrologically equivalent. In this context, the main influence parameters governing the spectral shape (the tube potential, the filtration thickness and the half-value layer, HVL) must be systematically assessed. While HVL remains a key beam quality indicator, variations in tube voltage and filtration characteristics can lead to significant spectral differences even for similar HVL values. Therefore, metrological equivalence of spectra can only be achieved if these parameters remain within defined limits.

In general, the requirements for the matched field are stricter than those for characterized fields, so that tabulated conversion coefficients may be used for matched fields. However, the requirements for tube potential and filter thickness are identical in both cases, and they are based on variations in the associated conversion coefficients of no more than 2 %.

As far as the tube potential is concerned, the maximum permissible deviations specified in ISO 4037-1 for mean energies of 12 keV or more and for angles between 0° and 90° are taken from (5). For lower energies, they are estimated from (4) (5) (6). For the filter thickness, the permissible deviations are taken from (6). The values in (5) are based on spectral models and real spectra, while the values in (6) are derived from simplified spectra. This needs to be checked, as the former is based only on the spectra of one facility, and the latter on a simplification of the spectra.

## 2.2 Participants

Six laboratories have been participating in the test of field parameters:

- Centre for Energy, Environmental and Technological Research (CIEMAT), Spain
- Czech Metrology Institute (CMI), Czech Republic
- Ruđer Bošković Institute (IRB), Croatia
- Central Office of Measures (GUM), Poland
- Physikalisch-Technische Bundesanstalt (PTB), Germany
- Radiation and Nuclear Safety Authority (STUK), Finland

The laboratories generated both reference or non-reference fields by varying filter and tube potential parameters and investigated these with different methods to determine maximum allowed deviations in tube potential, filter thickness and half-value layer, as described in Sections 0 and 3. A summary of the methods each institute has employed is given in **Error! Reference source not found.**.

*Table 1 List of the parameters which were varied and the methods which were employed by each participating institute in the test of the field parameters, i.e. half-value layer, filter thickness and tube potential (HPGe = high-purity germanium detector; CdTe = cadmium telluride semiconductor detector; Si-PIN = Silicon PIN diode).*

| Laboratory | Variation of | | Determination of half-value layer by | | | | | |
|---|---|---|---|---|---|---|---|---|
| | filter thickness | tube potential | Ionization chamber | Spectrometry | | | SpekPy | Monte Carlo |
| | | | | HPGe | CdTe | Si-PIN | | |
| **CIEMAT** | Yes | Yes | Yes | Yes | No | No | Yes | No |
| **CMI** | Yes | Yes | No | No | Yes | No | No | Yes |
| **IRB** | Yes | Yes | No | Yes | No | No | Yes | No |
| **GUM** | Yes | No | No | No | Yes | Yes | No | No |
| **PTB** | Yes | Yes | Yes | Yes | No | No | No | No |
| **STUK** | Yes | Yes | No | Yes | No | No | Yes | No |

## 2.3 Method

The aim – to investigate the limits for the tube potential and filter thickness – is achieved by varying these parameters and observing the changes in the spectral conversion coefficients. The conversion coefficients are calculated from the fluence spectra, which are multiplied bin-by-bin to the monoenergetic conversion coefficients specified in ISO 4037-3 and summed up. The spectra were measured or generated using three methods: X-ray spectrometry, Monte-Carlo calculations, or semi-empirical model calculations using SpekPy (7):

- X-ray spectrometry was performed using HPGe and CdTe detectors. **Error! Reference source not found.** lists the detector types employed by each institute.

- Monte-Carlo calculations were performed using a general-purpose Monte-Carlo code MCNP® version 6.2 (refMC1) with electron-photon relaxation library EPRDATA14 (8) (9). Geometrical model for simulation of full transport and interactions of ionizing radiation with matter was developed for an X-ray tube at CMI with an anode angle of 21° and an inherent filtration of 1 mm Be.

- Spectral model calculations were performed using SpekPy v2, an open-source software toolkit using Python programming language that allows modelling reflection geometry X-ray tubes with thick target anodes consisting of the elements W (20–300 kV), Mo or Rh (20–50 kV). The most important keywords that can be specified in a SpekPy model are tube potential, anode angle, target material and filtration material and thickness. For this evaluation we used a W anode with 20° angle and mass energy photon coefficients from PENELOPE database (10). CIEMAT used their own open source developed software called USpekPy which is built on SpekPy (https://pypi.org/project/uspekpy/).

Four radiation qualities were chosen for the measurements and MCNP simulations: N-30, N-40, N-60 and H-60 according to ISO 4037-1. These qualities have relatively strict requirements for the thickness of the filtration, and they are realized with filters made of one material, which makes it easier to change the entire filter by a fixed ratio. As the method is very time-consuming, especially the preparation of the filters, the results are used as validation for the use of SpekPy models, for which quick calculations are possible and hence were done for all radiation qualities.

## 2.4 Results

### 2.4.1 Fits of the collected data for each laboratory and radiation quality

Plots of the relationship between ΔHV and $\Delta h^*_K(10)$ for variations in tube potential are shown in Figure 1 and between $\Delta d_{\text{filter}}$ and $\Delta h^*_K(10)$ for variations in filter thickness are shown in Figure 2, both for N-60. The variations of ΔHV, $\Delta d_{\text{filter}}$ and $\Delta h^*_K(10)$ are given relative to the nominal values for the radiation quality.

The plots allow the following conclusions to be drawn:

- The data is well described by linear fits. Therefore, the data are suitable for identifying relationships between changes in HV and changes in operational quantities, and to test the limits.
- The slopes of the fits are very similar for different laboratories. Therefore, the results can be generalized.
- The slopes of the fits are very similar for different methods, and the methods can be used interchangeably to set new limits for all radiation qualities.
- All the above points apply to both HV and filter thickness variations, again proving that results can be generalized.

In the figures, the existing limits for tube potential, filter thickness, operational quantities and HVL are shown as dashed lines. Ideally, the fits reach the limits at their crossing points.

The results for the other qualities allow the same conclusions to be drawn and are not shown here for reasons of clarity.

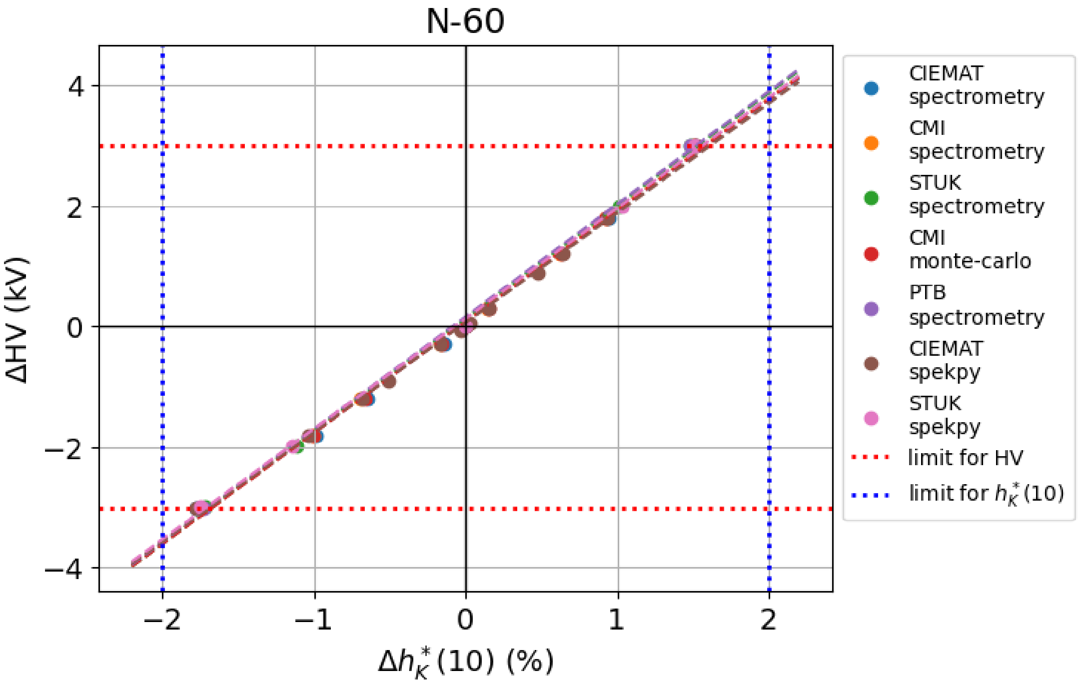

*Figure 1 Data and fits for the variations of tube potential, ΔHV, with respect to changes in $h^*_K(10)$ for N-60 across different laboratories and calculation methods. The maximum allowable deviation in tube potential and $h^*_K(10)$ according to ISO 4037 are given as red and blue dashed lines, respectively.*

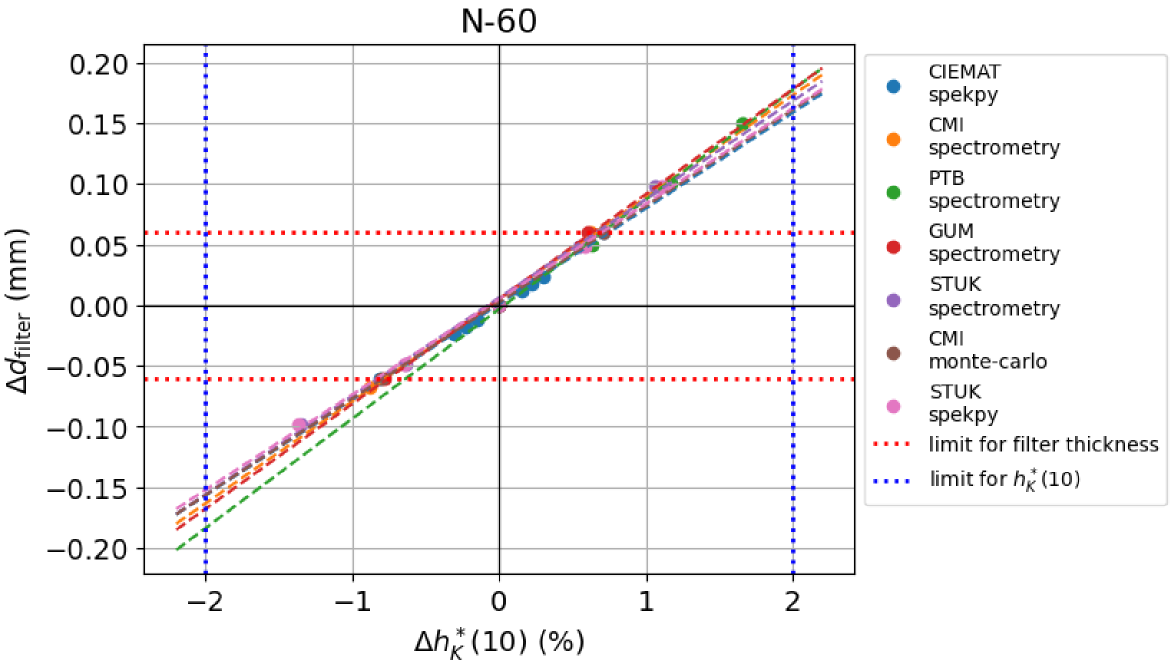

*Figure 2 Data and fits for the variations of filter thickness, $\Delta d_{\mathrm{filter}}$, with respect to changes in $h^*_K(10)$ for N-60 across different laboratories and calculation methods. The maximum allowable deviation in filter thickness and $h^*_K(10)$ according to ISO 4037 are given as red and blue dashed lines, respectively.*

### 2.4.2 Update of requirements for X-ray fields: derivation of new maximum allowed deviations for tube potential and filter thickness

Based on the available data, new limit values for the maximum permissible deviation of the tube potential and the filter thickness can be calculated. For this purpose, a correlation between the variation of these parameters and a variation of the conversion coefficient ($\Delta h^*_K(10)$, $\Delta h_{pK}(0{,}07)_{\mathrm{rod}}$, $\Delta h_{pK}(0{,}07)_{\mathrm{slab}}$) is established by a linear fit of the data as described in section 2.4.1, and the value for the parameter, at which the conversion coefficient changes by 2% is determined. The results for $\Delta h^*_K(10)$, the tube potential and the filter thickness are shown and compared to the limits in ISO 4037 in Figure 3 and Figure 4.

The diagrams allow for following conclusions to be drawn:

- The calculated limits for spectrometry, SpekPy, and Monte-Carlo calculations agree well with each other, and can be used interchangeably.
- In some cases, the nominal value from ISO 4037 agrees very well with the calculated and measured ones. This applies in particular to $\Delta h^*_K(10)$ for N-30, and for the limit values for the filter thickness with respect to $\Delta h^*_K(10)$ for N-40. In these cases, the limits have been confirmed by the data.
- On the other hand, there are cases with very large shifts compared to the nominal values, for example in the limit values for tube potential with respect to $\Delta h^*_K(10)$ for H-60 (change from 0.9 kV (ISO 4037) to 3.2 keV (average of methods), i.e. an increase by 360 %), or for the limit values for the filter thickness with respect to $\Delta h^*_K(10)$ for N-30 (change from 0,16 mm (ISO 4037) to 0.40 mm (average of methods), i.e. an increase by 250 %).

The results for the other quantities investigated allow the same conclusions to be drawn and are not shown here for reasons of clarity.

To summarise, a re-assessment of the limits appears to be necessary, as many show a shift between the data of ISO 4037, and the newly obtained data.

SpekPy calculations give similar results as spectrometry and are less tedious and time consuming. Therefore, they seem to be the appropriate method to perform the calculations for all radiation qualities of ISO 4037.

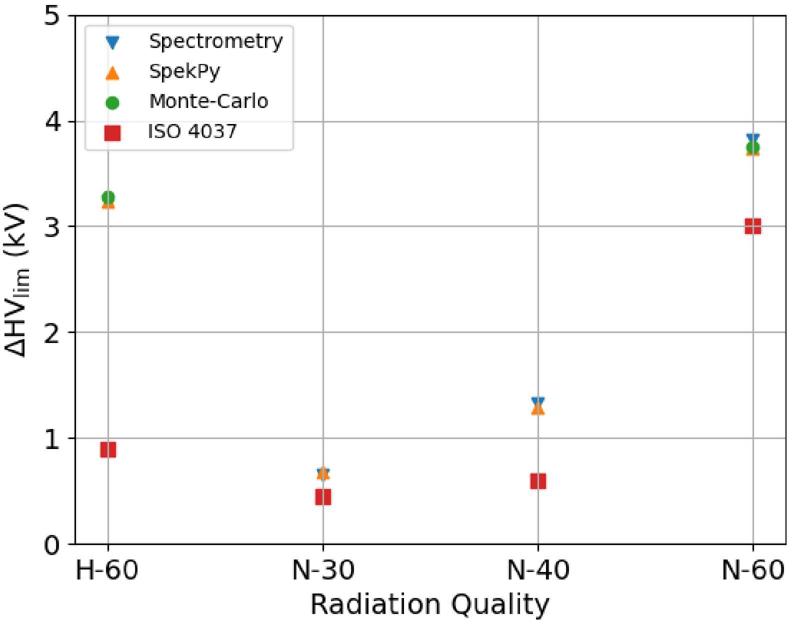

*Figure 3 Newly calculated maximum deviation of high voltage, $\Delta HV_{lim}$, based on the 2-%-limit of $h^*_K(10)$ compared to the present limits by ISO 4037-1 for the four investigated radiation qualities.*

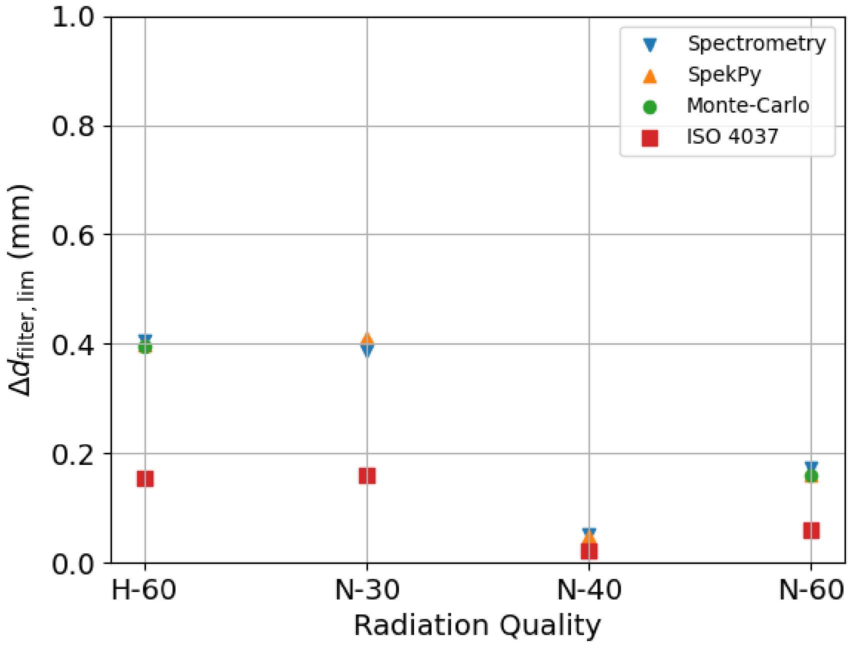

*Figure 4 Newly calculated maximum deviation of filter thickness, $\Delta d_{\mathrm{filter,lim}}$, based on the 2-%-limit of $h^*_K(10)$ with compared to the present limits by ISO 4037-1 for the four investigated radiation qualities.*

# 3 Measured and calculated HVL to test the validation of reference radiation fields

## 3.1 Background

The conformity of matched reference radiation field with the requirements of ISO 4037-1 can be validated by dosimetry, spectrometry, or measurement of the half-value layer (HVL). The latter is energy-dependent, i.e. it depends on the spectral fluence and can be used as a parameter to describe the radiation field. The procedure for determining the HVL is described in ISO 4037-1 and is carried out in accordance with ICRU report 10b (11). Discrepancies between measured and calculated HVLs were analysed to identify potential inconsistencies. For validation, the HVL must not deviate from the nominal values by more than the limit values specified in ISO 4037. These were calculated by correlation with the change in conversion coefficients, with a change of 2 % being permissible. These limits are based on a paper that has never been published and are therefore in need of a validation.

## 3.2 Method

### *3.2.1 Calculated HVL*

The goal – to investigate the limits of the HVL in relation to the range of the conversion coefficient bounds - is achieved by determining these parameters for variations in tube potential and filter thickness. HVL and conversion coefficients can be calculated from the spectra:

- The conversion coefficients were calculated from the fluence spectra by performing a kerma weighted average of the monoenergetic conversion coefficients given in ISO 4037-3.
- The HVL is determined in an iterative process, by calculation of the air kerma of the unattenuated radiation field $K_0$ for a known fluence spectrum, then computationally attenuating the fluence spectrum bin-by-bin using tabulated mass-attenuation coefficients of the attenuating material, namely aluminum

($\rho$ = 2.70 g·cm$^{-3}$) or copper ($\rho$ = 8.96 g·cm$^{-3}$), calculating the air kerma of the attenuated radiation field $K_{att}$, and changing the material thickness until $K_{att}$ = 0.5 $K_0$. Unrenormalized values of the mass-energy absorption coefficients of air and the monoenergetic mass-attenuation coefficient of attenuating materials were taken from the XCOM database (12) The tabulated monoenergetic values were fitted using a 4-point double logarithmic (interpolation on a log-log scale) Lagrange interpolation.

The spectra were measured or generated using three methods, spectrometry, Monte-Carlo calculations, or spectral model calculations using SpekPy (7), as described in Section 2.3.

The same four radiation qualities as in Section 0 were chosen for the test, N-30, N-40, N-60 and H-60 according to ISO 4037-1, as they have strict requirements on filter thicknesses and filters made of one material (see Section 2.3).

### *3.2.2 Measured HVL*

In addition, the HVL were also determined directly by measurement of air kerma with ionization chambers (here denoted by “dosimetry”) and plotted against tube potential and filter thickness variation to validate the results calculated from spectra.

## 3.3 Results

### *3.3.1 Fits of the collected data for each laboratory and radiation quality*

The plots of the relationship between ΔHVL and ΔHV or $\Delta d_{filter}$ for N-60 are shown in Figure 5 and Figure 6. The diagrams of the relationship between ΔHVL and $\Delta h^*_K(10)$ for variations of tube potential and filter thickness for the same radiation quality are shown in Figure 7 and Figure 8. All are given relative to the nominal values for the radiation qualities.

The graphs allow the following conclusions to be drawn:

- The data are well described by linear fits. For example, the uncertainty of the slopes in the fits of the data on N-60 in Figure 5 are all below 2 %. Thus, the data are suitable for establishing a relationship between the variations in HVL and ΔHV, $\Delta d_{filter}$, $\Delta h^*_K(10)$, $\Delta h_{pK}(0{,}07)_{rod}$ or $\Delta h_{pK}(0{,}07)_{slab}$, and for testing the limits.
- The slopes of the fits are in most cases very similar for different laboratories. For example, in Figure 5, the mean value of the slopes of the fits has a standard uncertainty of 1,7 %. Therefore, the results can be generalized.
- With regard to HVLs derived from measured spectra and those estimated dosimetrically, the slopes of the fits are in most cases very similar for the different methods, therefore the methods can be used interchangeably for setting new limits for all radiation qualities. The observed agreement further suggests that potential additional sources of discrepancy arising from the simplified assumptions commonly adopted in the HVL calculation (particularly the assumption that the spectrum is dominated by primary photons as we add successive filter thicknesses and that attenuation follows a simple exponential law) do not have a significant influence under the investigated conditions.
- The relation of HVL and the conversion coefficients is independent of changing filter thickness or tube potential (see Figure 7 and Figure 8).

In the figures, the existing limit values for the tube potential, the filter thickness, the conversion coefficients and the HVL are shown as dashed lines. Ideally, the fits reach the limits at their crossing points.

The results for the other quantities investigated allow the same conclusions to be drawn and are not shown here for reasons of clarity.

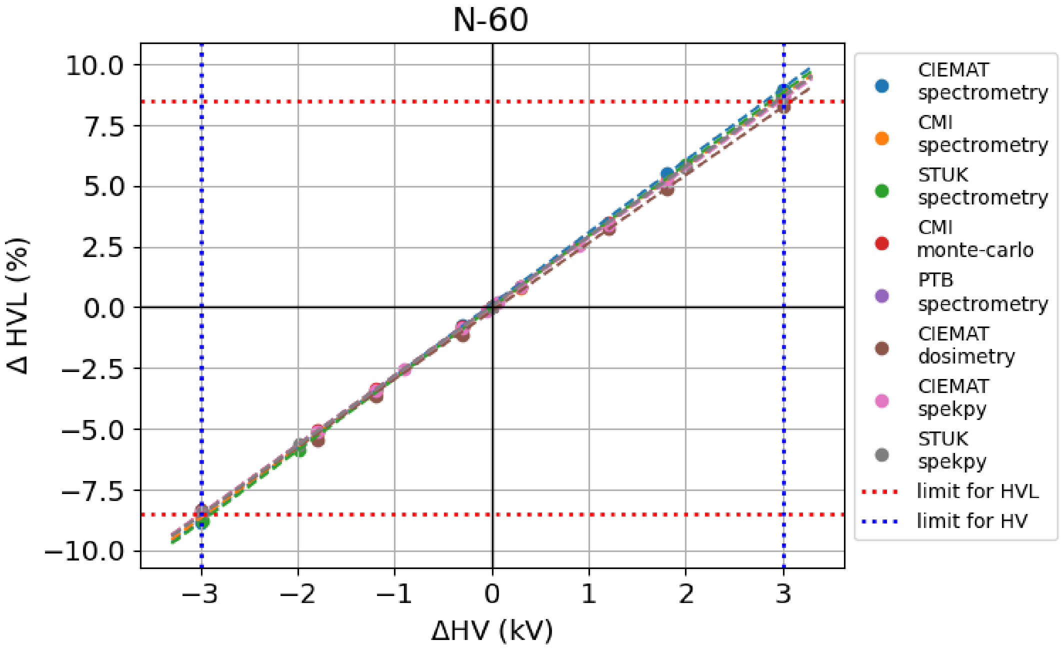

*Figure 5 Data and fits showing HVL variation, ΔHVL, with respect to variation in tube potential, ΔHV, for N-60 across different laboratories and calculation methods. In red and blue, the maximum allowable deviation in tube potential and HVL according to ISO 4037 are given, respectively.*

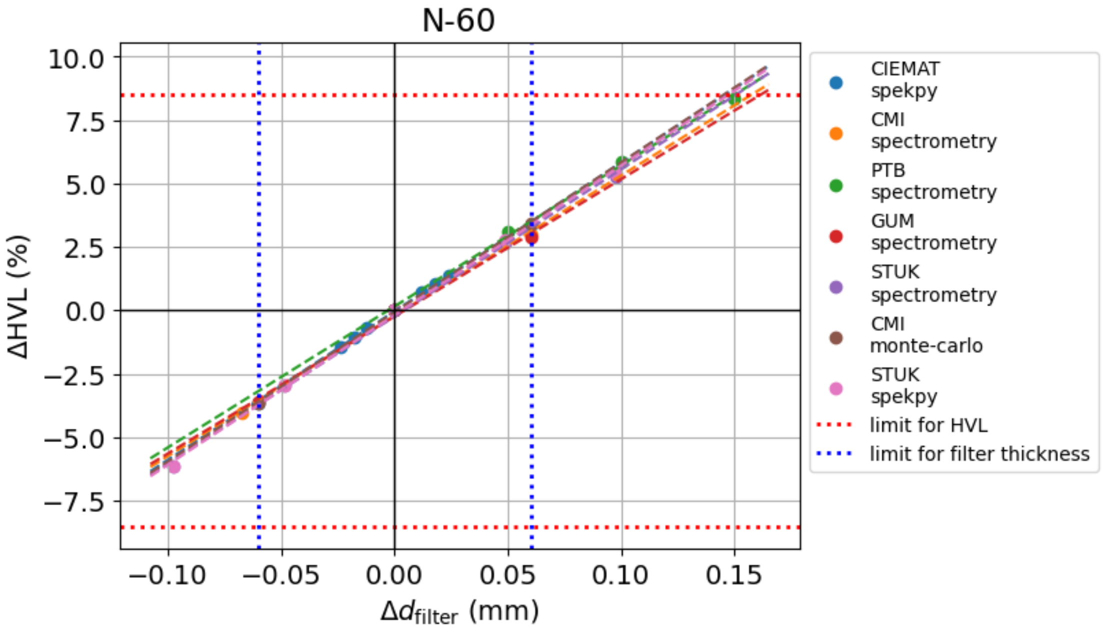

*Figure 6 Data and fits showing HVL variation, ΔHVL, with respect to variation in filter thickness, $\Delta d_{\mathrm{filter}}$ for N-60 across different laboratories and calculation methods. In red and blue, the maximum allowable deviation on filter thickness and HVL according to ISO 4037 are given, respectively*

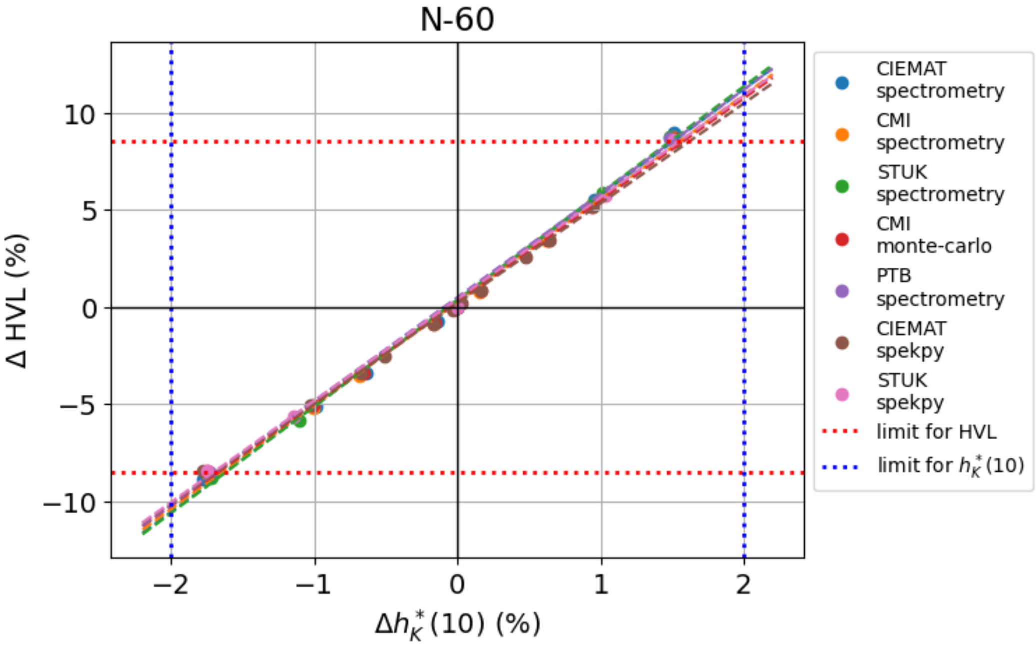

*Figure 7 Data and fits showing HVL variation, ΔHVL, with respect to relative change in the conversion coefficient, Δh*$_K$ (10), for variation in tube potential. Given for N-60 across different laboratories and calculation methods. In red and blue, the maximum allowable deviation in the conversion coefficient and HVL according to ISO 4037 are given, respectively.*

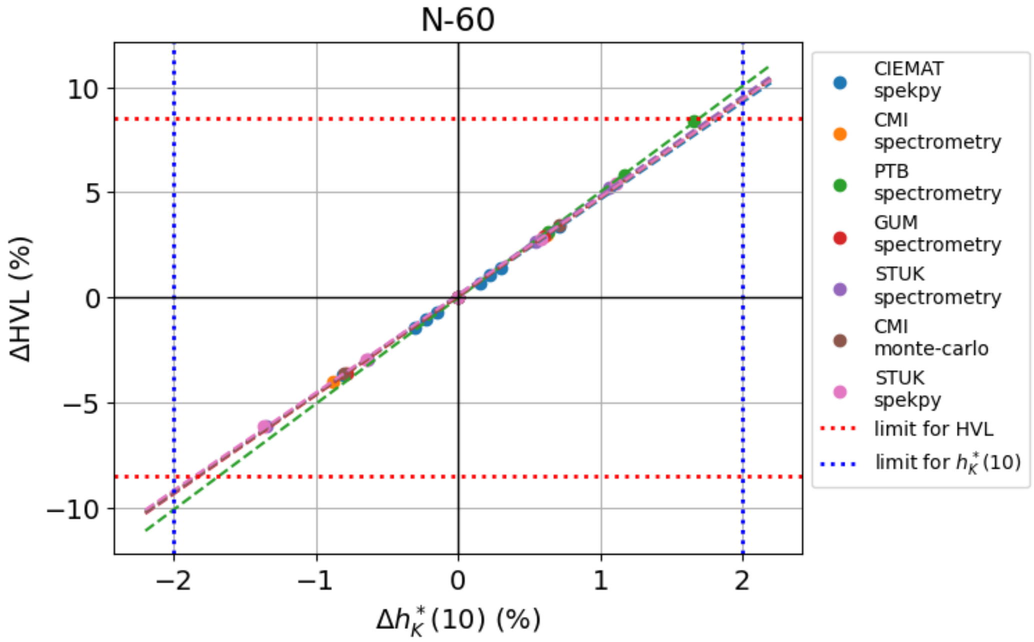

*Figure 8 Data and fits showing HVL variation, ΔHVL, with respect to relative change in the conversion coefficient, Δh*$_K$(10), for variation in filter thickness. Given for N-60 across different laboratories and calculation methods. The maximum allowable deviation in the conversion coefficient and HVL according to ISO 4037 are given as red and blue dashed lines, respectively.*

### 3.3.2 Update of requirements: Derivation of new maximum allowed deviations for the half-value layer

New limit values for the permissible deviation of HVL can be determined on the basis of the available data. For this purpose, a relationship between HVL and Δ$h^*_K$(10) (or any other conversion coefficient) is established by a linear fit of the data. The new limit is the value of the parameter, for which the operational quantity changes by 2 %. The results with respect to $\Delta h^*_K(10)$ for spectrometry, SpekPy and Monte-Carlo calculations are shown in Figure 9 (for HV variation) and Figure 10 (for filter thickness variation), where they are compared to the limits given in ISO 4037.

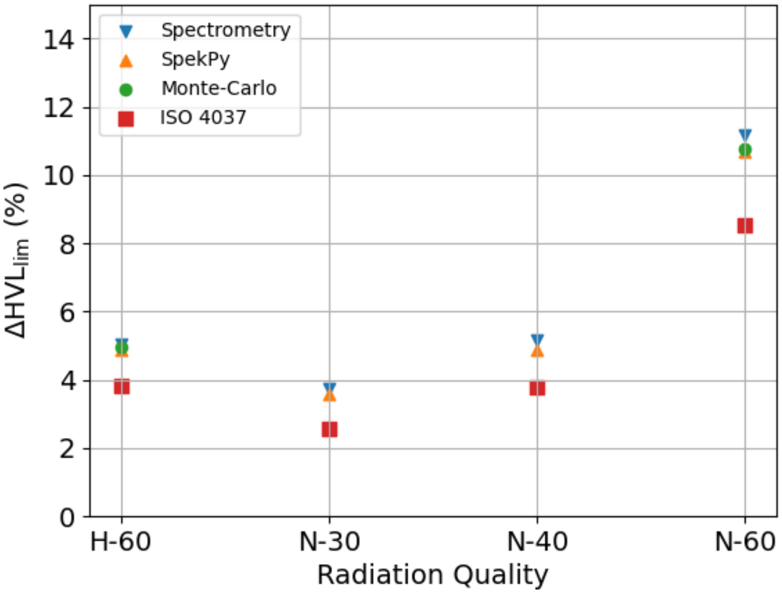

*Figure 9 New calculations of the maximum allowed deviation of HVL, $\Delta HVL_{lim}$, for the four radiation qualities, based on a 2-% change in $h^*_K(10)$ for variation in tube potential, and compared to the limits in ISO 4037.*

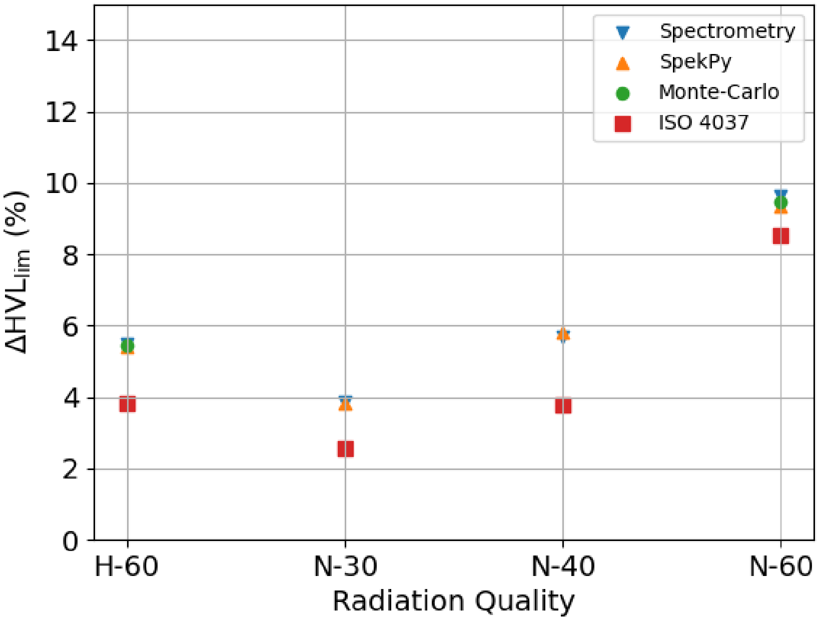

*Figure 10 New calculations of the maximum allowed deviation of HVL, $\Delta HVL_{lim}$, for the four radiation qualities, based on a 2-% change in $h^*_K(10)$ for variation in filter thickness, and compared to the limits in ISO 4037.*

The plots allow following conclusions to be drawn:

- The calculated limits for spectrometry, SpekPy, and Monte-Carlo calculations agree well with each other, and can be used interchangeably.
- The calculated HVL limits agree well, when the filter thickness and tube voltage are varied. As these are independent results, they support the validity of the new calculations.
- The nominal value from ISO 4037 agrees well with the calculated and measured ones for $\Delta h^*_K(10)$ except for a small deviation.

The results for the other quantities investigated allow the same conclusions to be drawn and are not shown here for reasons of clarity.

To summarise, a re-evaluation of the limits seems necessary, as many results show a shift between the data of ISO 4037 and the newly obtained data. As spectrometry is complex and time-consuming, SpekPy calculations seem to be the appropriate method for doing the calculations for all radiation qualities of ISO 4037.

# 4 Test of the validation of reference radiation fields by secondary standard chamber measurement by varying the field parameters

## 4.1 Background

The conformity of the reference radiation field with the requirements of ISO 4037-1 can be validated by directly measuring the conversion coefficients. This is done by measuring the air kerma $K_a$ using a standard chamber calibrated in units of $K_a$ and estimating the operational quantity of interest using a standard chamber calibrated in this quantity, for each radiation quality which shall be validated. The reference conversion coefficient from ISO 4037-3 shall then be within the 95-% confidence interval of the measured conversion coefficient.

## 4.2 Participants

Following four laboratories have been participating in the investigation of the validation method by dosimetry as described in Sections 4 and 5:

- Centre for Energy, Environmental and Technological Research (CIEMAT), Spain
- Czech Metrology Institute (CMI), Czech Republic
- Physikalisch-Technische Bundesanstalt (PTB), Germany
- Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Italy

## 4.3 Method

To test the validation method, reference radiation fields are generated whose conversion coefficients are determined spectrometrically by the laboratories. These radiation qualities were changed by varying the tube voltage and the filter thickness of the additional filters so that the conversion coefficient changes by a few per cent. Both the reference radiation quality and the modified radiation fields were then measured using standard chambers for air kerma and for the operational quantities in order to determine the conversion coefficients.

The change in the measured conversion coefficients is compared to the change in calculated conversion coefficients using SpekPy simulations and X-ray spectrometry for a selected number of cases (for details on SpekPy and spectrometry see Section 0).

The measurements have been performed using secondary standard chambers, a chamber of type PTW TM32002 for air kerma measurements, a chamber of type PTW TM32045 for measurements of $H^*(10)$, and a chamber of type PTW T34035 for measurements of $H_p(10,0°)$. These have a small energy dependency over a wide range but have a non-negligible energy dependency at low energies. The calibration coefficients with respect to the mean energies of the N-series are shown in **Error! Reference source not found.**.

*Table 2 Calibration coefficients of the standard chambers used to measure the conversion coefficients for the test of the dosimetric validation method.*

| ***Radiation quality*** | **$E_{mean}$ (keV)** | **$N_K$ (TM32002) normalised to N-250** | **$N_{H^*(10)}$ (TM32045) normalised to N-250** | **$N_{Hp(10)}$ (TM34035) normalised to N-250** |
|---|---|---|---|---|
| **N-30** | **24.6** | 1.24 | 0.79 | 1.00 |
| **N-40** | **33.3** | 1.06 | 0.93 | 1.06 |
| **H-60** | **38.0** | 1.07 | 0.94 | 1.06 |
| **N-60** | **47.9** | 0.98 | 1.05 | 1.07 |
| **N-250** | **207** | 1.00 | 1.00 | 1.00 |

Following parameters have been chosen for the tests:

- The radiation qualities N-30, N-40, N-60, H-60 and N-250 according to ISO 4037-1. The first four are in a region, where the conversion coefficients change by a large amount, and in which ionisation chambers often show larger energy dependency. N-250 is chosen additionally to cover also a higher-energy quality for comparison.
- The operational quantities $H^*(10)$ and $H_p(10,0°)$.
- Changes in tube potential and filter thickness to generate a variation in conversion coefficients.

- X-ray spectrometry for N-30 and N-40.
- Simulation with SpekPy.

## 4.4 Results

### *4.4.1 Measurement results of the relative change in conversion coefficients*

The results are shown in Figure 11 to Figure 15 for relative changes in $h^*_K(10)$ and tube potential variations. To guide the eye, linear fits of the data points are included in the graph. Several observations can be made:

- The measurement results between the different laboratories agree well with each other.
- The calculations from spectrometry and from SpekPy agree well with each other.
- The dosimetry measurements and the calculations with SpekPy and spectrometry have different slopes. Generally, the slope of the latter is steeper than that for the measured results.
- With increasing mean energy, the slopes of the dosimetry measurements and of the calculations using SpekPy approach each other.
- With increasing mean energy, the slope of the SpekPy results decreases. This correlates to less variability of the conversion coefficients for higher energies, as is also apparent from tabulated literature values as the ones published in Table 14 of ISO 4037-3.
- For N-250, the range of conversion coefficients is small, therefore, the fit of the experimental data has larger uncertainty, and differences between measurement and calculation are less significant than for lower energies.

The data looks similar for other combinations of $h_{pK}(10)$, $h^*_K(10)$, filter thickness variation and tube potential variation, though less pronounced and with higher uncertainty due to the smaller range in conversion coefficients covered.

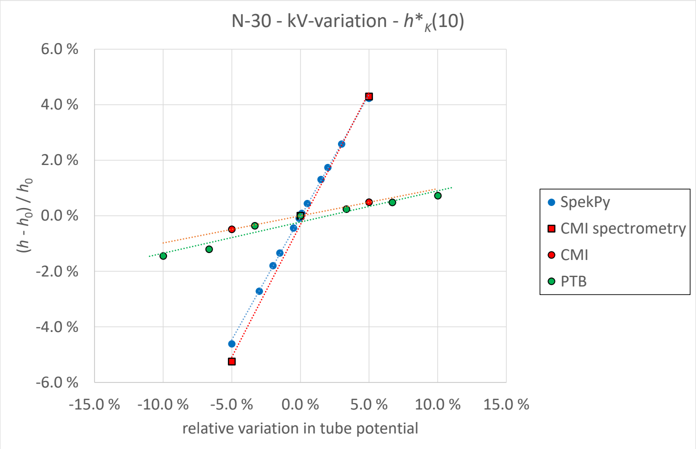

*Figure 11 Relative variation of conversion coefficients $h^*_K(10)$ versus variation in tube potential for N-30. The variations are given relative to their value at 30 kV. For CMI and PTB, $h^*_K(10)$ was measured using standard chambers, and compared to SpekPy calculations and spectrometxy measurements.*

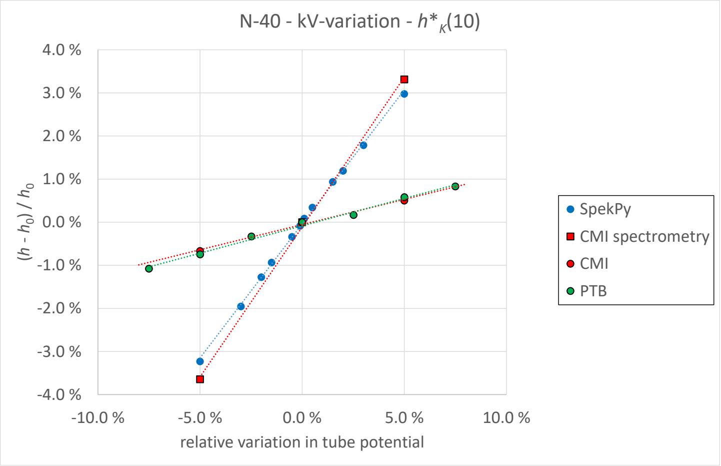

*Figure 12 Relative variation of conversion coefficients $h^*_K(10)$ versus variation in tube potential for N-40. The variations are given relative to their value at 40 kV. For CMI and PTB, $h^*_K(10)$ was measured using standard chambers, and compared to SpekPy calculations and spectrometry measurements.*

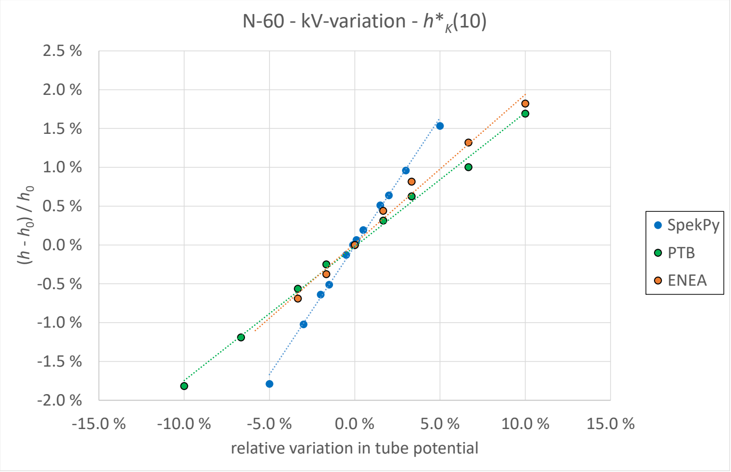

*Figure 13 Relative variation of conversion coefficients $h^*_K(10)$ versus variation in tube potential for N-60. The variations are given relative to their value at 60 kV. $h^*_K(10)$ was measured using standard chambers and compared to SpekPy calculations.*

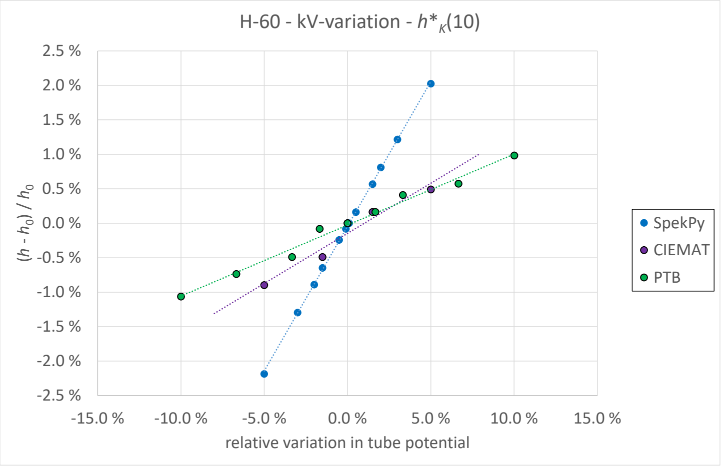

*Figure 14 Relative variation of conversion coefficients $h^*_K(10)$ versus variation in tube potential for H-60. The variations are given relative to their value at 60 kV. $h^*_K(10)$ was measured using standard chambers and compared to SpekPy calculations.*

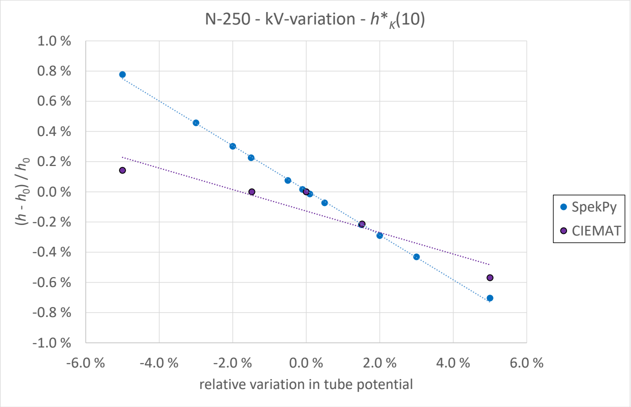

*Figure 15 Relative variation of conversion coefficients h*$_K$(10) versus variation in tube potential for N-250. The variations are given relative to their value at 250 kV. h*$_K$(10) was measured using standard chambers and compared to SpekPy calculations.*

### *4.4.2 Conclusions for the dosimetric validation method*

In this study, the SpekPy results can be taken as reference. SpekPy is expected to give results which agree within uncertainties to results from spectrometry, as is evident from the results in Section 0 and 3. The excellent agreement between spectrometry and SpekPy in Figure 11 and Figure 12 supports this assessment.

The uncertainty for the chamber measurements is estimated in Section 5 to be approximately 6.4 % ($k$ = 2). However, the measurements are highly correlated, as only the tube potential or filter thickness is varied within one measurement series. Therefore, the uncertainty of the calibration and of the calculation of the conversion coefficients do not contribute, and the remaining uncertainty can be estimated to be 1,5 %. Taking this into account, the differences in the linear slopes of the calculated and experimental data are significant.

The most likely reason for the difference is the energy dependence of the chambers. **Error! Reference source not found.** lists the calibration coefficients of the standard chambers used in this investigation, normalised to N-250. At N-30, the coefficients change substantially to 1.24 and 0.79 for $K_a$, $H^*(10)$, while it stays at 1.00 for $H_p(10,0°)$. Also, the change from N-40 to N-30 is in all cases larger than the change from H-60 to N-40, or from N-60 to H-60. Thus, the calibration coefficients show a steeper change for lower energies. Therefore, already small changes in the measured fields have a large effect on the measured conversion coefficients, as is evident in the results.

The results for the measurements with respect to $H_p(10,0°)$ show less pronounced differences, as the calibration coefficients have less energy dependent. The results for filter thickness variation show a less pronounced change in conversion coefficients, possibly as the spectra do not change that much in the investigated range.

# 5 Test of the validation of reference radiation fields by secondary standard chamber measurement in a comparison study of several laboratories

## 5.1 Participants

Following laboratories have been participating in the investigation of the validation method by dosimetry as described in Sections 4 and 5:

- Centre for Energy, Environmental and Technological Research (CIEMAT), Spain
- Czech Metrology Institute (CMI), Czech Republic
- Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Italy

Calibrated secondary standard chambers for air kerma, $H_\mathrm{p}(10)$ and $H^*(10)$ were provided by the Physikalisch-Technische Bundesanstalt (PTB), Germany.

## 5.2 Method

The conformity of the reference radiation field with the requirements of ISO 4037-1:2019 can be validated by directly measuring the conversion coefficients. This is done by measuring the air kerma $K_\mathrm{a}$ using a standard chamber calibrated in units of $K_\mathrm{a}$ and estimate the operational quantity of interest using a standard chamber calibrated in this quantity, for each radiation quality which shall be validated. The reference conversion coefficient from ISO 4037-3:2019 shall then be within the 95-% confidence interval of the measured conversion coefficient.

A measurement comparison is made with four partners to test the validity of this approach. The chambers are calibrated at the first laboratory and then sent to three other laboratories with spectrometry capabilities. There, the measured conversion coefficients are compared to conversion coefficients, which the laboratories retrieve by their own spectrometry.

## 5.3 Results

The relative difference of the conversion coefficients from chamber measurements, to the ones from spectrometry, are shown in Figure 16 and Figure 17 for $h^*_K(10)$ and $h_{\mathrm{p}K}(10,0°)$, respectively. Additionally, a first estimate of the uncertainty is given, taken only into account the uncertainty of the calibration coefficients (3.0 % for $K_\mathrm{a}$ and 4.0 % for the operational quantities, all for $k = 2$). As an estimate of the uncertainty for the conversion coefficients determined by spectrometry, the uncertainty of the tabulated conversion coefficients is taken, which are given in ISO 4037-3 (4.0 % ($k = 2$)). This gives an overall estimate for the uncertainty of 6.4 % ($k = 2$)

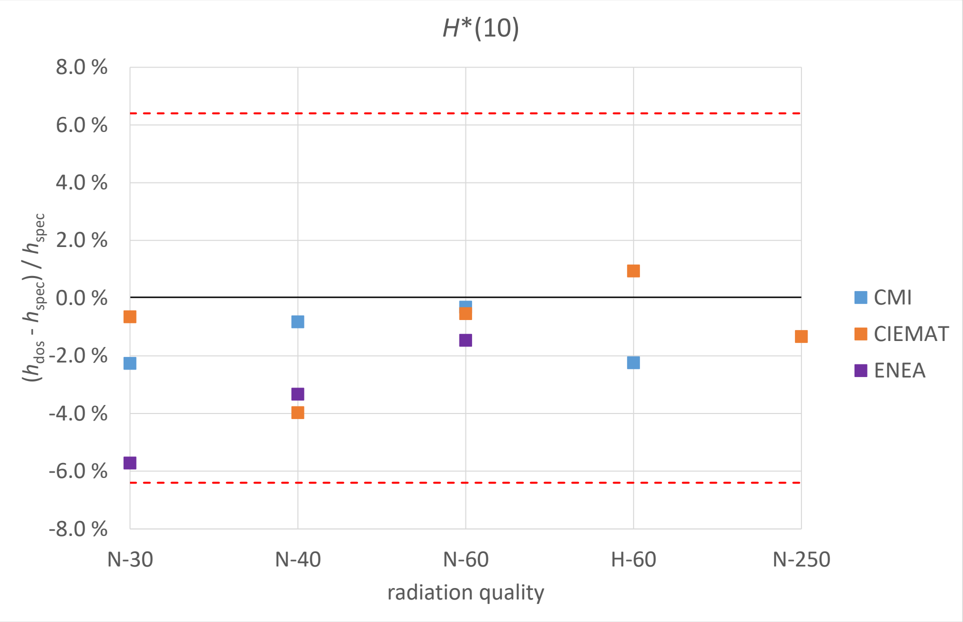

*Figure 16 Relative difference of the conversion coefficients $h^*_K(10)$ determined using secondary standard measurements, to the ones determined using spectrometry.*

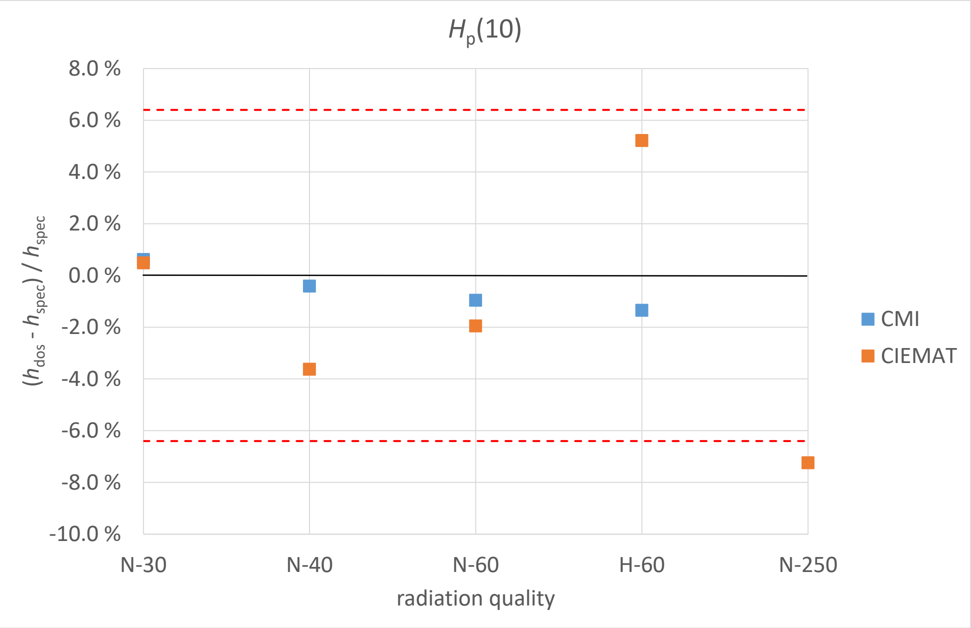

*Figure 17 Relative difference of the conversion coefficients $h_{pK}(10,0°)$ determined using secondary standard measurements, to the ones determined using spectrometry.*

For $H^*(10)$, the differences between the conversion coefficients determined by spectrometry and dosimetry for CMI, CIEMAT and ENEA are well within the uncertainty. The differences are close to zero in most cases, and within 4.0 % for all but N-30 for ENEA.

For $H_p(10,0°)$, the difference between the conversion coefficients is within the uncertainties for all radiation qualities for both laboratories except for N-250 at CIEMAT, where the difference is close to the limits. Note that the uncertainty is only a first estimate and might be larger when calculated more thoroughly.

In both cases, no bias towards positive or negative values is apparent, which would hint to an error in the calibration at the pilot laboratory.

In conclusion, the comparison seems to support the validation method by dosimetry, as the conversion coefficients determined by spectrometry in each laboratory agree in most cases very well with the ones determined by chamber measurements.

# 6 Implications on the requirements on reference fields and validation methods

Following conclusions can be drawn from the investigation of the requirements on reference radiation fields according to ISO 4037, and from the investigation of the validation methods required by the standard:

- Development of a harmonised approach to X-ray spectrometry in accordance with the ISO 4037 standard series: This deliverable summarises the results of calculations, dosimetric measurements, and spectrometric measurements by different laboratories. Very good agreement of outcomes of spectrometric measurements between each other as well as in comparison to calculations in computations codes obtained in the study of the requirements on tube potential, filter thickness and filter purity (chapter 2) is a confirmation of adoption of the harmonised approach to X-ray spectrometry by the participating laboratories. The procedure has been written down in the good-practice guide on spectrometry of reference fields presented as a separate document, in the deliverable D2 of this project.
- Evaluation of discrepancies between measured and calculated HVL values: The results of HVL measurements by the different laboratories and their comparison is presented in chapter 3.

- New requirements on HVL, filter thickness and tube potential can be proposed from the results of this study, based on a collaborative effort from different laboratories with different methods, i.e. dosimetric measurements, spectrometry, spectral model calculations, and Monte-Carlo simulations.
- The results show, that in many cases, calculated new limits disagree with present ones. Therefore, a complete re-calculation of all requirements in tube potential, filter thickness and HVL is proposed for all radiation qualities in ISO 4037. As this is a very extensive work experimentally, and as SpekPy results agree very well to results by spectrometry, it is proposed to use SpekPy calculations to update ISO 4037 in the future (out of the scope of this project).
- Validation of matched reference fields by dosimetry measurements employing chambers calibrated in $K_a$ and the operational quantities might not be sensitive enough to changes in the spectrum caused by tube potential or filter thickness variations, especially for low energies. This is caused by a non-negligible energy dependency of the chambers especially for low energies. The general procedure of the dosimetric validation should be carefully revised, for example, the requirements on the energy dependency of the chamber response might need an update.
- Nevertheless, the comparison between spectrometric and dosimetric determination of conversion coefficients agree well, showing that in most cases, the method works well.

# 7 References

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