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Characteristics of the reference X-ray narrow-spectrum series at SSDL of Institute for Nuclear Science and Technology

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Abstract: This paper presents the characteristics of the reference X-ray narrow-spectrum series used in the Secondary Standard Dosimetry Laboratory (SSDL) at Institute for Nuclear Science and Technology (INST) with X-ray beam irradiator. In order to perform calibration works, it is highly important to verify the characteristics and qualities of reference X-ray beam recommended by the International Standardization Organization (ISO) 4037:2019. The characteristics of the X-ray beams in terms of the half-value layer, homogeneity coefficient and the air kerma rate are determined for the narrow-spectrum series in the 40 and 150 keV range. The related dosimetric quantities such as the ambient dose equivalent and personal dose equivalent also determined. The experimental values are well consistent with the recommended values of the ISO 4037 criteria. It implies that the reference X-ray narrow-spectrum series (N-series) can be applied in calibration works of X-ray measuring devices used in radiation safety assessment.

Keywords: *X-ray, narrow-spectrum series, calibration, ISO 4037, air kerma.*

I. INTRODUCTION

Atomic energy has been widely applied for the purposes of peace and services of the people. In fact, occupational exposure to ionizing radiation can occur in industry, medical institutions, research establishments, universities and nuclear fuel cycle facilities. Adequate radiation protection for workers is an essential requirement for the safe and acceptable use of radiation, radioactive materials and nuclear energy. According to the recommendations of International Atomic Energy Agency (IAEA), each individual instrument should be calibrated before its first use and then should be recalibrated periodically, usually every 12 to 14 months [1].

The INST is a member of the Vietnam Atomic Energy Institute (VINATOM), possesses a unique secondary standard dosimetry laboratory (SSDL) in the country on ionizing radiation dosimetry and calibration. The task of this laboratory is to calibrate the ionization radiation measuring instruments. Recently, the photon calibration facility equipped with a new X-ray system for research and calibration purposes. To put the calibration facility into operation, the characterization of the X-ray reference field according to international criteria is needed to ensure the reliability of the radiation measurements and safety assessment. The International Standard Organization (ISO) is published ISO-4037 [2-5] which related to photon radiation (gamma and X-ray) for calibration of photon measuring devices in practical works.

In this paper, the characterization of a X-ray reference field at the INST in terms of

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half value layer (HVL), homogeneity coefficient (h) and the air kerma rate ($\dot{K}_{air}$)) for the narrow-spectrum series (N-40, N-60, N-80, N-100, N-120, N-150) based on the ISO-4037 recommendations. The experimental values of quantities obtained are compared with the published data of the ISO-4037 criteria. In addition, the dosimetric quantities as photon ambient dose equivalent rates ($\dot{H}^{*}(10)$) and photon personal dose equivalent (($\dot{H}_{p}(10)$) were also determined by using the coefficient factors from $\dot{K}_{air}$ to $\dot{H}^{*}(10)$ and $\dot{H}_{p}(10)$.

II. MATERIALS AND METHODS

A. X-ray system and instruments

The Hopewell Design Inc. (USA, manufactured in 2020) X-ray system installed at the INST was used for establishing the ISO-4037 X-ray reference fields (N-series) in this work. The X-ray system consists of an X-ray tube with a filter of 0.8 ± 0.1mm Be and a tungsten target at an angle of 20º to the direction of incident electron beam line. The X-ray system is operated in such following technical specifications: high voltage from 0.1 to 160 kV, current from 0.1 to 45 mA, and long enough irradiation time for calibration process. The X-ray tube is put in a shield with the lead thickness of 10 mm which is placed between two metal shells. The instrument table and rail system are used to move the calibrated devices following three axis (X,Y,Z) with the dimension 400 x 100 x 30 cm and has the ability to rotate 360º. Fig.1 and Fig.2 show the X-ray calibration room and X-ray system at the INST, respectively.

A control wheel system for the additional filters accompanying X-ray system (see Fig.3) is used to create the narrow spectrum X-ray beam qualities according to ISO-4037 (N-40, N-60, N-80, N-100, N-120, N-150) [2]. The speed sensors will find out the selected additional filters and stop the motor rotation. In this study, aluminum and copper absorbers are also used to determine the half value layers. The additional filters and absorbers include tin (Sn), copper (Cu) and aluminum (Al) with 99% purity and 0.01 to 5 mm thickness.

Measurements were performed with a measuring instrument system consisting of an ion chamber and an electrometer. The ion chamber is the Exradin A4, with an active volume of 30 cm^3 and the electrometer is SuperMax, with two independent measurement channels (measuring range: 0.001 pC to 999.9 nC). The ion chamber and the electrometer are manufactured by the Standard Imaging Corporation and are calibrated in term of $\dot{K}_{air}$ at VSL (Dutch Metrology Institute).

B. Determination of inherent filtration

The quality of X-ray beams depends on the total filtration used during X-ray irradiation. The total filtration comprises the inherent filtration and the additional filtration. Following ISO-4037 standard, the first step to be performed when producing X-ray qualities is to determine the inherent filtration of the X-ray tube. For the radiation qualities N-40 to N-150, the inherent filtration consists of the fixed filtration of the tube plus the aluminum filters, which are added to obtain a total inherent filtration equivalent to that of 4 mm Al [1]. Using the measuring instruments (ion chamber and electrometer) described above, the inherent filtration shall be adjusted at a high voltage of 60 kV at the distance of 100 cm from the tube using calculating the first half-value layer (HVL_1) and converting the HVL_1 to inherent filtration based on the ISO-4037 standard.

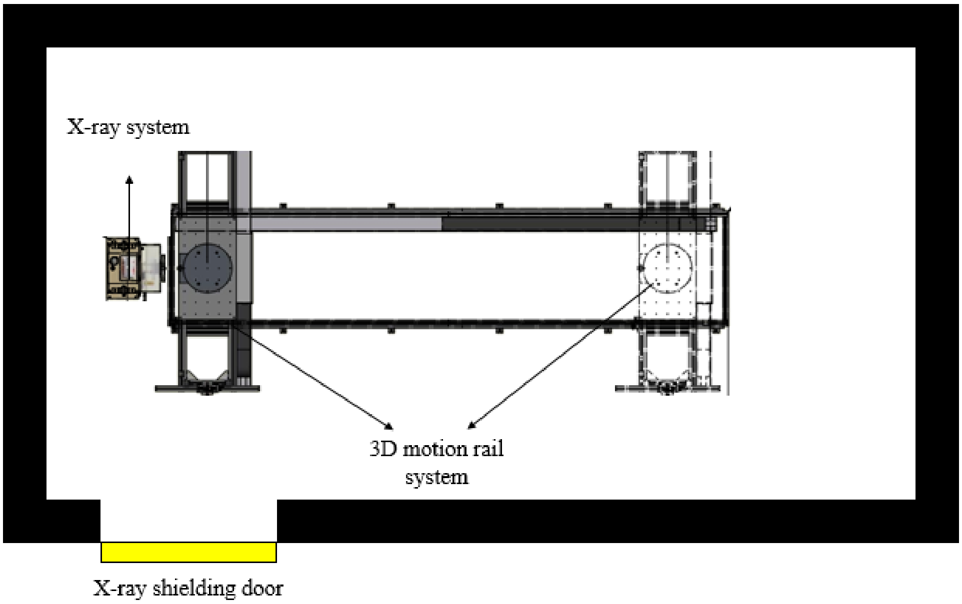

Fig. 1. X-ray calibration room

Fig. 2. X-ray system

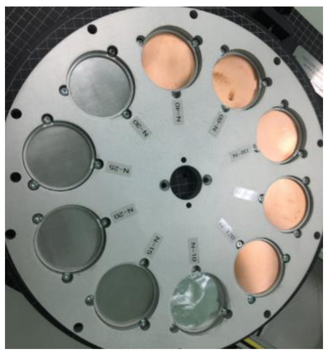

Fig. 3. The additional filters for N-series

Fig. 4. Ion chamber and electrometer

C. Determination of the first and the second half-value layer (HVL_1 and HVL_2) and calculation of beam quality homogeneity coefficient (h)

For an X-ray parallel beam, the relationship between a beam without (R_0) and with (R_d) shielding material (thickness of d) is expressed as equation (1):

$$R_d = R_0 \times e^{-\mu d} \quad (1)$$

The first half value layer (HVL_1) expresses the thickness of absorbing material needed for reduction of the incident photon radiation intensity by a factor of two. The fourth value layer (FVL_1) expresses the thickness of absorbing material needed for reduction of the incident radiation intensity by a factor of four. Then, the second half value layer (HVL_2) shall be calculated by subtracting HVL_1 to FVL_1 as (2):

$$HVL_2 = FVL_1 - HVL_1 \quad (2)$$

For experimental measuring the HVL_1 and HVL_2 for the X-ray beam qualities (N-40 to N-150), the measuring instruments (ion chamber and electrometer) was used to determine the electric charges created by the X-ray beam without (R_0) and with (R_d) the different filter thicknesses of a specific material at the distance of 100 cm from the X-ray focal spot. The measuring time was chosen so that the uncertainties of the obtained electric charges less than 1%. The electric charges were then corrected for the influence of temperature and pressure and normalized to the same duration time. The corrected electric charges obtained were fitted according to equation (1). Based on the fitting curve, the half-value layer HVL_1 and HVL_2 can be determined. The measurements were repeated with the specific X-ray beam qualities (N-40 to N-150). The values of HVL_1 and HVL_2 were then compared with the recommended values of the ISO-4037 standard.

Since the values of HVL_1 and HVL_2 are obtained, the X-ray beam quality homogeneity coefficient *(h)* can be deduced as equation (3):

$$h = \frac{HVL_1}{HVL_2} \quad (3)$$

D. Measurement of air kerma rate ($\dot{K}_{air}$) and dosimetric quantities

Based on the measured values of R_0 in a time unit (nC/h), the $\dot{K}_{air}$ of X-ray beam qualities can be determined by the following equation (4):

$$\dot{K}_{air} = R_0 \times N_K \times k_{T,P} \quad (4)$$

Where, N_K is the calibration factor of the instruments at a specific X-ray beam quality (taken from the calibration certificate of VSL); $k_{T,P}$ is the correction factor for the influence of temperature and pressure [1].

From the $\dot{K}_{air}$ obtained above, the photon ambient dose equivalent rates ($\dot{H}^*(10)$) and photon personal dose equivalent (($\dot{H}_p(10)$) can be calculated as follows equation (5-6):

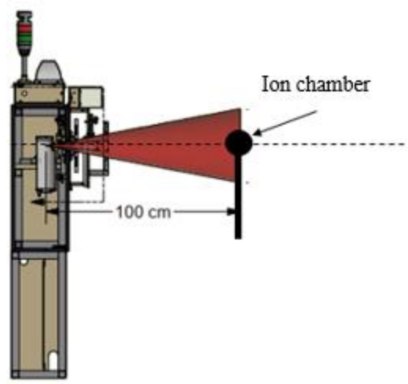

Fig. 5. The set-up used for the measurement of air kerma rate ($\dot{K}_{air}$) at the distance of 100 cm from the X-ray focal spot

$$\dot{H}^*(10) = \dot{K}_{air} \times C^*(10) \quad \left(\frac{Sv}{h}\right) \quad (5)$$

$$\dot{H}_p(10) = \dot{K}_{air} \times C_p(10) \quad \left(\frac{Sv}{h}\right) \quad (6)$$

Where, $C^*(10)$ and $C_p(10)$ are resspectively the conversion coefficients from $\dot{K}_{air}$ to $\dot{H}^*(10)$ and $\dot{H}_p(10)$. These coefficients, which depend on the mean energy of X-ray beam, are taken from the International Commission on Radiological Protection (ICRP) [6,7].

III. RESULTS AND DISCUSSIONS

A. Inherent filtration

Using the measuring instruments and Al absorbers with different thickness, the first half value layer (HVL_1) is approximately 0.15 mm Al. This value is lower than the lowest values in ISO-4037-1 [1]. Therefore, the inherent filtration of the X-ray tube can be estimated by extrapolation. The extrapolated value is equivalent to the thickness of 0.1 mm Al. Therefore, to reproduce the ISO-4037 narrow spectrum series, a thickness of 3.9 mm Al filter has to be added to achieve a total inherent filtration equivalent to that of 4 mm Al. The 3.9 mm Al filter shall be placed behind the additional filters.

B. Half value layer of the beam and beam quality homogeneity coefficient

The half value layers are determined for the X-ray beam qualities of the N-series, going from 40 to 150 kV at the distance of 100 cm from the X-ray focal spot and the results are expressed in Table I. The comparison among the experimental values and the published values of the ISO-4037 standard is in good agreement for each specific X-ray beam quality.

The beam quality homogeneity coefficients of X-ray beam qualities are determined through equation (3) and show in Table I. The beam quality homogeneity coefficients are within 0.88 to 0.96, satisfied the ISO 4037 recommendation [2].

Table I. Results of HVL_1 và HVL_2 for N-series (N-40 to N-150) at the distance of 100 cm from the X-ray focal spot

Radiation quality	High voltage (kV)	HVL_1 INST (mm)	HVL_1 ISO (mm)	Deviation (μm)	HVL_2 INST (mm)	HVL_2 ISO (mm)	Deviation (μm)	Recommended deviation (μm)	h INST	h ISO
N-40 (Al*)	40	2.699	2.630	*69*	2.831	2.830	*1*	100	0.95	0.93
N-60 (Cu)	60	0.240	0.234	*6*	0.258	0.263	*5*	20	0.93	0.89
N-80 (Cu)	80	0.576	0.578	*2*	0.655	0.622	*33*	100	0.88	0.93
N-100 (Cu)	100	1.105	1.090	*15*	1.171	1.150	*21*	200	0.94	0.95
N-120 (Cu)	120	1.741	1.670	*71*	1.805	1.730	*75*	200	0.96	0.97
N-150 (Cu)	150	2.409	2.300	*109*	2.543	2.410	*133*	200	0.95	0.95

*: The metal absorber using to determine HVL is Al.

Table II. Air kerma rate ($\dot{K}_{air}$), ambient dose equivalent rates ($\dot{H}^*(10)$) and personal dose equivalent (($\dot{H}_p(10)$) of X-ray beam quality

Radiation quality	High voltage (kV)	Mean energy (keV)	Total filtration (mm)			$\dot{K}_{air}$ $(\frac{mGy}{h.mA})$	$\dot{H}^*(10)$ $(\frac{mSv}{h.mA})$	$\dot{H}_p(10)$ $(\frac{mSv}{h.mA})$
			Al	Sn	Cu			
N-40	40	33.3	4		0.21	4.60	5.43	5.38
N-60	60	47.9	4		0.6	6.92	11.00	11.42
N-80	80	65.2	4		2.0	3.64	6.30	6.84
N-100	100	83.3	4		5.0	1.80	3.08	3.38
N-120	120	100.0	4	1.0	5.0	1.94	3.18	3.51
N-150	150	118.0	4	2.5		14.08	22.25	24.36

C. Air kerma rate ($\dot{K}_{air}$) and dosimetric characteristics of X-ray beam quality

From the R_0 (nC/h) values obtained, the $\dot{K}_{air}$ of each X-ray beam quality at the distance of 100 cm from the X-ray focal spot can be calculated from equation (4). Table II shows the values of $\dot{K}_{air}$ for N-series (N-40 to N-150). The highest value is 14,08 $\frac{mGy}{h.mA}$ for N-150 beam quality and the lowest value is 1,80 $\frac{mGy}{h.mA}$ for N-100 beam quality.

The dosimetric quantities in terms of ($\dot{H}^*(10)$) and (($\dot{H}_p(10)$) were also determined by using the $C^*(10)$ and $C_p(10)$ according to equation (5-6). The results are also given in Table II. These obtained values can be applied in the practical calibration purposes.

IV. CONCLUSIONS

The characterization of narrow-spectrum X-ray reference field at the Institute for Nuclear Science and Technology (N-40, N-60, N-80, N-100, N-120, N-150) including: half value layer (HVL), homogeneity coefficient (h), the air kerma rate ($\dot{K}_{air}$)), photon ambient dose equivalent rates ($\dot{H}^*(10)$) and photon personal dose equivalent (($\dot{H}_p(10)$) was determined based on ISO-4037 standard. The obtained results show a good agreement with published recommendations of the International Standard Organization. This means the narrow-spectrum X-ray reference field at the Institute for Nuclear Science and Technology can be well applied in the practical calibration of X-ray measuring devices.

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