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Establishment of ISO 4037-1 Narrow-Spectrum Series X-rays for an Eye Dosimeter Performance Test in KHNP CRI

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Abstract The International Commission on Radiological Protection (ICRP) recommended lowering occupational dose limit for the eyes from 150 mSv in a year to average 20 mSv over five years (or 50 mSv maximum in a year). The revised eye dose limit is same with the effective dose limit of workers. Assessment of eye dose could be conducted by wearing an eye dosimeter near the eyes. To obtain the reliability of the eye dose assessment result evaluated by eye dosimeters, the dosimeters must meet the performance criteria. In this study, we established five X-rays according to the International Organization for Standardization to conduct performance tests of eye dosimeters. The half value layer (HVL) measurement method was applied to verify the equivalent filtration effect of the established radiation fields. Although the measured HVLs of the five X-rays had deviations, from 0.004 to 0.11 mm, with reference X-rays but satisfied the criteria.

Key words: Nuclear power plant worker, Eye dose limit, Eye dosimeter, ISO 4037-1

1. INTRODUCTION

The International Commission on Radiological Protection recommended lowering occupational dose limit for the eyes from 150 mSv in a year to an average of 20 mSv over five years and 50 mSv maximum in a year through Publication 118 in 2012 [1]. In Korea, the eye dose limit for workers is 150 mSv in a year according to ICRP Publication 60. In addition, the effective dose limit for workers in Korea is an average of 20 mSv over five years and 50 mSv maximum in a year [2].

Since the current eye dose limit in Korea is 3 to 7.5 times higher than the effective dose limit, it is very unlikely that the eye dose would exceed the limit if the effective dose for workers is controlled at below the limit [3]. However, if the latest recommendation of ICRP Publication 118 on the eye dose limit is applied in Korea, controlling the eye dose will be important because the eye dose limit is the same level as the effective dose limit.

Assessment of eye dose for workers could be conducted in two ways. One way is evaluating the eye dose using the eye dose assessment algorithm included in the whole-body dosimeter system. The other one is evaluating the eye dose directly by wearing an eye dosimeter near the eyes. However, when there is a non-uniform radiation field, the evaluated values of eye dose using the whole-body dosimeter algorithm would be inaccurate due to differences in the amount of actual exposure dose between the eyes and the whole-body dosimeter position. Thus, an eye dosimeter should be worn near the eyes to obtain acceptable eye dose assessment results in non-uniform radiation fields. Although it is not a regulatory requirement, in prepa-

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ration for the lowering the eye dose limit, KHNP is considering adoption of eye dosimeters for the safety of workers.

In addition, in order to improve the reliability of the eye dose assessment result evaluated by eye dosimeters, the dosimeters must meet the internationally accepted performance criteria. The International Electrotechnical Commission (IEC) recommended performance test methods and criteria for various operational quantities related to dosimeters in publication 62387. According to IEC 62387, the performance tests for a dosimeter should be conducted using the International Organization for Standardization (ISO) reference radiation fields [4]. For the operational quantity $H_p(3)$ related to eye dosimeters, the radiation fields are recommended in IEC 62387 for narrow spectrum (NS) series X-rays or gamma sources suggested in ISO 4037-1 and beta sources suggested in ISO 6908.

In the Korea Hydro & Nuclear Power Co., LTD Central Research Institute (KHNP CRI), the gamma-ray generator and beta-ray generator, sealed with ^{137}Cs and $^{90}Sr/^{90}Y$, respectively, are already established and used for whole-body dosimeters calibration and performance test [5]. In addition, X-rays (namely, M30, M60) according to the National Institute of Standards and Technology are established in the KHNP CRI. However, the NS X-rays of ISO 4037-1 are not established yet. The purpose of this study is establishment of NS X-rays according to ISO 4037-1 for performance tests of eye dosimeters to enhance the reliability of the assessment results.

2. MATERIALS AND METHODS

2.1. Comparison of requirements of ISO and the status of the X-ray irradiation equipment in KHNP CRI

16 NS X-rays were suggested by ISO 4037-1, but only five NS X-rays (namely, NS 40, NS 60, NS 80, NS 100, and NS 150) are planned to be established in this study. The numbers after the 'NS' indicate the maximum voltage potential of the X-rays [6].

The five NS X-rays are established using the X-ray generator installed in the KHNP CRI. In order to use the five NS X-rays for eye dosimeter performance tests, the conditions of the X-ray irradiation equipment in the KHNP CRI must meet the requirements given in ISO 4037-1. This section reviews the requirements of ISO 4037-1 for NS X-rays and compares them to the status of the X-ray facility in the KHNP CRI. Table 1 represents the summary of the comparison results between ISO requirements and the KHNP CRI X-ray irradiation equipment status.

2.1.1. Conditions of the high voltage generator

A high voltage generator was used to generate potential differences between the cathode and anode in the X-ray tube. Since the potential difference affects the X-rays spectrum, the potential difference must be constant to obtain a stable spectrum. Thus, the ISO 4037-1 requires a certain range of ripples as a requirement for the high voltage generator. In particular, the required ripple range for five NS X-rays is 1% to 6%. The high

Table 1. Summary of ISO requirements and KHNP CRI X-ray facility status for NS X-rays

Category	ISO requirements	KHNP CRI status	Note
High voltage generator Ripple	1~6%	<1%	
Target material	Tungsten	Tungsten	X-ray tube Y.TU 320-D03 is installed in KHNP CRI
Angle of target material	15°~40°	20°	
Inherent filtration	4 mm Al	3 mm Be + 4 mm Al	
Purities of additional filtration	95~99%	>99.9	Aluminum, copper and tin
Field uniformity	±5%	±5%	Range from center: Upper (12 cm), Lower (13 cm), Left (11 cm), Right (12 cm)

voltage generator installed in the X-ray facility of the KHNP CRI is the MGG 43 model of YXLON. According to the manufacturer, the MGG 43 has less than 1% ripple, which meets the ISO requirements [7].

2.1.2. Characteristics of the X-ray tube anode

The ISO 4037-1 requires tungsten as the material of an X-ray tube anode and a specific angle of the anode depending on the generating potentials. A range of the anode angle between 15° and 30° is required for generating potentials above 30 kV. The five NS X-rays for this study required a tube potential of more than 40 kV. The X-ray tube installed in the KHNP CRI facility is Y.TU 320-D03 model of YXLON. According to the manufacturer, the X-ray tube Y.TU 320-D03 has a tungsten anode with an angle of 20° [8].

2.1.3. Inherent filtration condition

The ISO recommends 4 mm aluminum as the inherent filter for reference radiation fields such as the NS 40, 60, 80, 100 and 150. If the 4 mm aluminum is not available as an inherent filter, it is recommended that equivalent filters should be used to establish reference radiation fields. The X-ray generator of the KHNP CRI has a combined inherent filter of 3 mm beryllium and 4 mm of aluminum. Thus, we determined that the inherent filter of KHNP CRI's X-ray generator has an effect equivalent to the inherent filter presented by ISO. In this study, we demonstrated the filtration effect of the inherent filter using Monte Carlo simulation.

Fig. 1 presents the X-ray spectrum under two types of filter conditions for the same X-ray energy. One is only a 4 mm aluminum filter attached to the X-ray tube and the other one is a 3 mm beryllium filter added to the 4 mm aluminum filter. The shapes of the spectrums are similar and the mean energy of the spectrums is 37.65 keV and 37.71 keV, respectively. These results confirm that the two types of filter conditions have an equivalent effect.

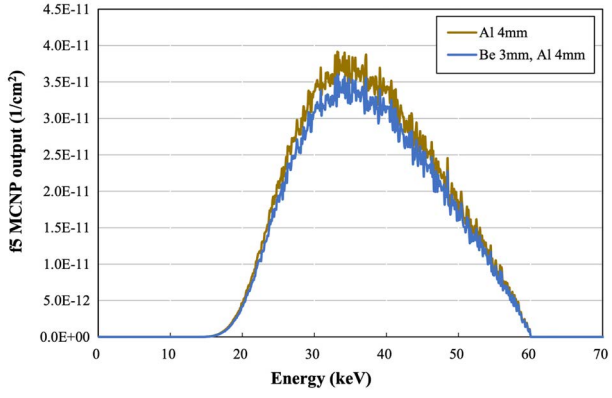

Fig. 1. Monte Carlo simulation results of inherent filter's effect.

2.1.4. Additional filtration conditions

The ISO requires criteria for impurities of additional filters and the criteria are different for filter material and surface density. The impurity criteria of aluminum and copper or tin are 0.3~1%, 1~5%, respectively. The impurities of the additional filter held by the KHNP CRI are under 0.1%, which meet ISO requirements [5].

2.1.5. Field uniformity

The performance test of dosimeters must be conducted under uniform radiation fields. The ISO requires radiation field uniformity for a performance test under ±5% in the air KERMA rate from the center of the phantom. A cylindrical phantom was used for the field uniformity test as required by ISO.

In this study, we used the ion chamber A3 of Standard Imaging to evaluate the field uniformity of the five X-ray fields. The ion chamber is a spherical gas detector with a radius of 9.7 mm and consists of air equivalents material C552 [9]. The field uniformity is measured by moving the ion chamber 1 cm in the upper, lower, left and right directions at a distance of 1 m from center of the source. The results met the ISO requirements within a range of 12 cm (upper), 13 cm (lower), 11 cm (left) and 12 cm (right) for the four directions as shown in Fig. 2. These results mean that the eye dosimeters need to be attached within this area on the phantom for the performance test.

2.2. Characteristics of narrow series X-ray to be deployed

Table 2 presents the characteristics of the five NS X-rays. All five X-rays is required 4 mm aluminum as the inherent filter. The NS 150 used tin as an additional filter and the other four X-rays use copper as an additional filter to build reference X-rays of the ISO 4037-1.

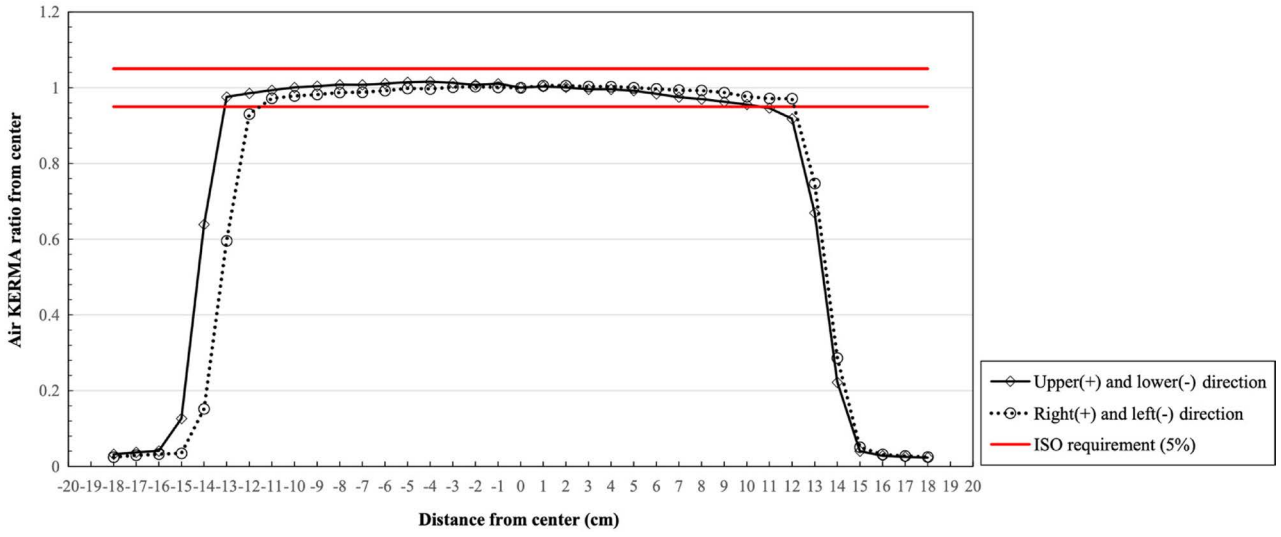

Fig. 2. Field uniformity test results for four directions.

Table 2. Characteristics of five NS X-rays

X-rays	Tube potential [kV]	Inherent filtration	Additional filtration	Half Value Layer (HVL) of ISO 4037-1 (at a distance of 1 m)	
				1st HVL	2nd HVL
NS 40	40	4 mm Al	0.21 mm Cu	2.63 mm Al	2.83 mm Al
NS 60	60		0.6 mm Cu	0.234 mm Cu	0.263 mm Cu
NS 80	80		2.0 mm Cu	0.578 mm Cu	0.622 mm Cu
NS 100	100		5.0 mm Cu	1.09 mm Cu	1.15 mm Cu
NS 150	150		2.5 mm Sn	2.30 mm Cu	2.41 mm Cu

2.3. Characteristics of the X-ray generator

As described above, in this study, the X-ray generator, installed in KHNP CRI facility, was used to establish the ISO reference radiation field. The X-ray generator has X-ray tube of YXLON's model Y.TU 320-D03. Table 3 shows the main specifications of the X-ray generator used in this study.

Table 3. Specifications of the X-ray generator in KHNP CRI facility

Category	Specification
X-ray tube model	Y.TU 320-D03
Target material	Tungsten
Angle of target material	20°
Tube potential	15 kV~320 kV
Accuracy of tube current	±1%
Maximum tube current	13 mA
Inherent filtration	Be 3 mm + Al 4 mm
Maximum power	4,500 W
High Voltage ripple	10 V mA^{-1} (1% below at maximum tube current)

2.4. Methods of establishment and verifying reference X-rays

The ISO 4037-1 presents three methods, the Half Value Layer (HVL) measurement, spectrum analysis and dose assessment, to verify that radiation fields in irradiation facilities produce equivalent effects to the reference radiation fields of the ISO. In this study, we used the HVL measurement method using an ion chamber to verify the five NS X-rays.

The ISO presents first and second HVLs of the reference radiations as shown in Table 2. In addition, ISO requires the maximum deviation criteria of the HVLs compared to the measured HVLs of the established

radiation fields and HVLs of the ISO's. The criteria for the maximum deviation criteria of the HVLs for the five NS X-rays are represented in Table 4.

2.5. Procedures for measuring half value layers

The ion chamber, signal cable, current measuring device and PC need to be connected to collect the current generated from the ion chamber. Because the ion chamber is filled with gases, the generating current is affected by the ambient temperature and pressure of the installed area. Therefore, a thermometer and a barometer need to be installed near the ion chamber to consider those effects.

When the installation of equipment such as the ion chamber and thermometer is completed, we align the center of ion chamber parallel to the center of X-ray generation point and move the ion chamber so that the distance between the ion chamber and the X-ray generation point is 1 m, and we fix it in place. When the ion chamber is fixed in place, we measure the amount of background current under conditions that do not generate X-rays. The measurements are repeated 10 times and we use the average value as the background current. Then we generate X-rays and measure the current under the additional filters and tube potential conditions for the NS X-rays required by ISO. The measurements are repeated 10 times and we use the average value as the reference current for the NS X-rays.

When the measurement of the background and the reference current are completed, we use various filters consisting of the materials required by ISO to find the filter thickness in which 50% and 25% of the current compared to the reference current is measured (so called the 1st and 2nd HVL, respectively). If the exact HVLs of the NS X-rays are not found due to the limitations of the given filter's thickness, the three points of the filter thickness, where the current is measured approximately 50% or 25% of the reference current, are linearly interpolated to calculate the 1st and 2nd HVLs. After calculating the 1st and 2nd HVLs of the NS X-rays, the HVLs are compared with the maximum deviation

Table 4. Maximum deviation criteria for five NS X-rays

X-rays	Maximum deviation criteria (only applicable to $H_p(3)$) [Absolute value, mm]
NS 40	0.2
NS 60	0.02
NS 80	0.2
NS 100	0.2
NS 150	0.2

Table 5. Characteristics of the five NS X-rays established in KHNP CRI

X-rays	Tube potential [kV]	Inherent filtration	Additional filtration	1st HVL	2nd HVL
NS 40	40	3 mm Be + 4 mm Al	0.179 mm Cu	2.669 mm Al	2.863 mm Al
NS 60	60		0.6 mm Cu	0.238 mm Cu	0.270 mm Cu
NS 80	80		2.0 mm Cu	0.601 mm Cu	0.644 mm Cu
NS 100	100		5.01 mm Cu	1.151 mm Cu	1.162 mm Cu
NS 150	150		2.012 mm Sn	2.362 mm Cu	2.516 mm Cu

Table 6. Verification results of the five NS X-rays established in KHNP CRI

X-rays	HVLs of KHNP CRI (mm)		HVLs of ISO (mm)		Deviations in absolute value (mm)		Deviation criteria (mm)
	1st	2nd	1st	2nd	1st	2nd	
NS 40	2.67	2.86	2.63	2.83	0.04	0.03	0.2
NS 60	0.238	0.270	0.234	0.263	0.004	0.007	0.02
NS 80	0.601	0.644	0.578	0.622	0.043	0.022	0.2
NS 100	1.15	1.16	1.09	1.15	0.06	0.01	0.2
NS 150	2.36	2.52	2.30	2.41	0.06	0.11	0.2

criteria of the ISO (see Table 4). If the HVL deviation of the NS X-ray meet the criteria, the X-ray is considered as the reference radiation field.

3. RESULTS

Table 5 presents the characteristics of the five NS X-rays established in this study. Among the X-ray generation conditions, tube potential was the same as recommended by ISO, but the thickness of inherent filter and additional filters were slightly different. The difference of the inherent filter was due to design characteristic in X-ray generators held by the KHNP CRI. However, as described earlier, the equivalent effect of the inherent filter was demonstrated through computer simulation. The reason for the difference in additional filter thickness was that the nominal thickness of the filter in possession of the KHNP CRI slightly differs from that of the ISO.

Furthermore, as shown in Table 6, the five NS X-rays established in this study had slightly different HVLs compared with the ISO requirements. The second HVL of the NS 150 had the biggest deviation at about 0.11 mm. However, it can be seen that the ISO's HVL criteria were satisfied when the absolute value of the deviation of the HVL was calculated for the NS X-rays.

4. CONCLUSION

This study established five NS X-rays among the ISO reference radiation fields for the performance test of eye dosimeters. First of all, the ISO requirements for the X-ray generation conditions and the status of the KHNP CRI were reviewed to confirm that the X-ray generation conditions of the KHNP CRI meet the ISO requirements. Then, the HVL measurement method was applied among the three methods suggested by the ISO to verify that the radiation fields had an equivalent effect with the ISO reference radiation fields.

Compared with the represented filter thickness of the ISO, the five NS X-rays established in this study had different thicknesses of the inherent filter and additional filters. In addition, two kinds of HVLs of the NS X-rays had deviations from 0.004 to 0.11 mm. However, the deviations satisfied the ISO criteria. Thus, the five NS X-rays established in this study were verified to have an equivalent effect with ISO reference NS X-rays. Finally, these five NS X-rays will be used as reference radiation for performance tests on eye dosimeters according to IEC 62387. Also these five NS X-rays will be calibrated periodically and will be re-established when the KHNP CRI X-ray facility condition changes, such as replacing inherent filtration.

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