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Original Article

A preliminary evaluation of the implementation of a radiation protection program for the lens of the eye in Korean nuclear power plants

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ABSTRACT

Epidemiological research has revealed that radiation exposure can cause cataracts. The Korean nuclear regulatory body has proposed the reduction of the occupational dose limit for the lens of the eye from 150 mSv/y to 100 mSv/5y, with an additional limitation of not exceeding 50 mSv/y for a specific year, taking into account the recommendations of the International Commission on Radiological Protection, and the International Atomic Energy Agency. This means that radiation workers should receive the same level of radiation safety for the lens of the eye as for whole-body protection. Korean nuclear power plants (NPPs) are conducting research to establish the radiation protection program for the lens of the eye. In terms of the preliminary results of the implementation of the radiation protection program for the lens of the eye dedicated to Korean NPPs, this review article summarizes the current state of understanding of the regulations, technical guidance, eye lens dosimeters, and radiation field conditions resulting in lens dose.

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1. Introduction

The lens of the eye is located in the front part of the eye and is a colorless transparent structure with a convex lens on both sides, which serves to collect light. Mainly, the lens allows the focus of distant and nearby objects to accurately focus on the retina. The lens is transparent and flexible, but as, due to aging or trauma, the lens becomes cloudy, the elasticity may deteriorate. A cataract is a symptom in which the lens becomes cloudy, and the light does not reach the retina. Radiation exposure can also cause cataracts [1–3].

The International Commission on Radiological Protection (ICRP) has established the equivalent dose of the lens, the average absorbed dose received by the lens, as the protection quantity, and provides an annual dose limit to protect the lens of the radiation worker [4]. Since the protection quantity is a conceptual value based on the amount of radiation energy absorbed by an organ or tissue of the human body, it is not an actual measurable amount. Thus, the radiation dose received by the radiation worker is measured and evaluated using an operational quantity. The operational quantity is the amount used for practical regulation. The International Commission on Radiation Units and Measurements (ICRU) recommends using the personal dose equivalent, $H_p(3)$, at a depth of 3 mm in the tissue, as the operational quantity, to measure the radiation dose to the lens [5,6].

In the ICRP 1990 recommendations (ICRP Publication 60), the difference between the effective dose limit (average 20 mSv/y) and the lens equivalent dose limit (150 mSv/y) of radiation workers was remarkable. Hence, the possibility that the lens dose of nuclear power plant (NPP) workers would exceed its dose limit was very low [4,7,8]. Thus, in many countries eye lens dose assessment has not been a legal requirement and has not been included in regulatory reporting requirements. Inevitably, when a dose assessment of the lens was required, the personal dose equivalent, $H_p(0.07)$, at a depth of 0.07 mm in the tissue, which is the measurement point for skin exposure, was measured instead, and conservatively evaluated.

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The ICRP 2007 recommendations (ICRP Publication 103) indicated that the annual dose limit to the lens for radiation workers needed to be lowered. The ICRP Publication 118 issued in 2012 recommended that the dose limit for occupational exposure to the lens of the eye be reduced to the same value as the effective dose limit [4,9]. The International Atomic Energy Agency (IAEA) accepted the ICRP's recommendations, and revised the basic safety standards for radiation protection [10]. The Nuclear Safety and Security Commission (NSSC), the Korean nuclear regulatory body, also researched the implementation of ICRP Publication 103 to Korean nuclear regulation, which reduces the dose limit to the lens of the eye for radiation workers [11]. If the lens dose limit is reduced to an average of 20 mSv/y, this is approximately 25 times lower than the skin dose limit of occupational exposure, of 500 mSv/y. Thus, if the lens dose is conservatively evaluated with the skin dose, the possibility of exceeding the lens dose limit increases.

Korean NPPs have not yet established a radiation protection program to evaluate the radiation dose to the lens of the eye for radiation workers. The Korea Hydro & Nuclear Power (KHNP), a Korean utility company, is currently researching the establishment of the radiation protection program for the lens of the eye. Korean NPPs will soon use the research results to prepare for the change in the lens dose limit. This paper introduces the preliminary results of the implementation of the radiation protection program for the lens of the eye dedicated to Korean NPPs, including regulations, technical guidance, eye lens dosimeters, and radiation field conditions resulting in lens dose.

2. Regulations and technical guidance

2.1. Change of dose limits

In addition to the effective dose limit, the ICRP recommends the use of dose limits for the lens of the eye and skin because radiation doses to the lens or local area of the human body cannot always be protected by the effective dose limit only [4,7]. These doses are classified as equivalent doses and are defined as doses that apply a radiation weighting factor to the average absorbed dose of a tissue or organ. ICRP Publication 103 maintained that the dose limit for the lens of the eye was temporarily the same as that of the previous ICRP recommendations, ICRP Publication 60; however, it indicated that the ICRP was considering the revision of the dose limit in accordance with the results of epidemiological research on the lens since 1999 [4]. The ICRP issued ICRP Publication 118 in 2012 and lowered the threshold dose and dose limit for the lens. Table 1 shows the before and after values of the change of threshold doses and equivalent dose limits for the lens of the eye [4,7,9]. In contrast to the occupational dose limit to the lens of the eye, the ICRP recommended that the dose limit to the lens for the general public remain at the existing dose limit of 15 mSv/y. The ICRP estimated that even though the threshold dose for the lens was lowered, the public would not be exposed to radiation exposure exceeding the absorbed dose of 0.5 Gy, the threshold dose, under the conditions of the effective dose limit for the general public, of 1 mSv/y [9].

The IAEA revised the existing basic safety standards for radiation protection to General Safety Requirements (GSR) Part 3 issued in 2014, in accordance with ICRP Publication 103 [10,12]. The IAEA requires each member country to use these safety standards, and IAEA member countries adopt these requirements into their domestic regulations. According to the IAEA GSR Part 3, the occupational dose limit for the lens of the eye has been lowered as recommended in ICRP Publications 103 and 118. Adult workers over the age of 18 can receive radiation dose up to 50 mSv in any single year, within a range not exceeding 100 mSv for 5 years for planned exposure situations, which are the general radiological work situation [10]. The dose limit for the lens is the same value as the effective dose limit for radiation workers, which means that radiation safety for the lens of the eye should be provided at the same level as whole-body protection. However, it was decided to maintain the existing lens dose limit of 15 mSv/y for the general public.

The European Union revised the basic safety standards for radiation protection, taking into account ICRP Publication 103 and IAEA GSR Part 3, and announced the revised standards as Council Directive 2013/59/EURATOM in 2013 [13]. Council Directive 2013/59/EURATOM also lowered the equivalent dose limit for occupational exposure to the lens of the eye to 20 mSv/y, similar to the lens dose limit provided by the IAEA, and to 100 mSv over 5 years within the range of not exceeding 50 mSv/y for a specific year under the laws of any particular country [13]. In particular, the IAEA GSR Part 3 applies an average of 20 mSv for 5 years as the equivalent dose limit for the lens, while Council Directive 2013/59/EURATOM does not apply the average concept, and stipulates the occupational lens dose limit of 20 mSv in any single year. Furthermore, the lens dose limit for trainees between the ages of 16 and 18 has been adjusted to 15 mSv/y, which is the same value as the dose limit for the public.

The National Council on Radiation Protection and Measurements (NCRP) was requested by the US Nuclear Regulatory Commission (NRC) to assess the risk of radiation-induced cataract, and to provide guidance on whether or not the existing lens dose limit should be reduced in the United States. The NCRP issued NCRP Commentary No. 26 at the end of 2016 and announced that it is prudent to reduce the occupational lens dose limit from an equivalent dose of 150 mSv/y to an absorbed dose of 50 mGy/y, the same value as the occupational effective dose limit of 50 mSv/y in the United States [1]. In addition, when addressing specific tissue reactions, the NCRP takes the position of using the absorbed dose. However, in December 2016, the NRC decided to discontinue the rulemaking activities associated with the revision of the existing radiation protection regulations and guidance with respect to ICRP Publication 103 and also withdrew the reduction of the equivalent dose limit for the lens of the eye [14–16].

The NSSC, the Korean nuclear regulatory body, conducted the research to revise the radiation protection regulations, taking into

Table 1
Reduction of the threshold doses and dose limits for the lens of the eye in the adult human.

		Before (ICRP Publications 60 & 103)	After (ICRP Publication 118)
Threshold doses[a]	Opacity	Acute exposure: 0.5–2 Gy Chronic exposure: 5 Gy	Acute and chronic exposure: 0.5 Gy (or 0.5 Sv)[b]
	Cataract	Acute exposure: 5 Gy Chronic exposure: 8 Gy	
Occupational dose limits	Lens	150 mSv/y	100 mSv/5y (50 mSv/y)[c]

[a] The smallest dose of radiation that will produce a specified effect in the tissue or organ.
[b] Gy, Unit of absorbed dose; Sv, Unit of equivalent dose (1 Gy ≈ 1 Sv in soft tissue).
[c] 100 mSv per five years, and not exceeding 50 mSv for a specific year.

account both ICRP Publication 103 and IAEA GSR Part 3 [11]. As a result, the draft of radiation protection regulations shows that radiation workers are classified into two groups: group A and group B. Group A involves occupational exposure where the effective dose may exceed 2 mSv/y, whereas group B includes all workers except group A workers, such as frequent visitors. The reason for applying 2 mSv as the criteria for the classification of groups A and B is that the annual average dose limit of radiation workers is 20 mSv and its value applying 10% is 2 mSv [11]. According to the draft of occupational dose limits, the lens dose limit for workers in group A is determined as 100 mSv over 5 years (an average of 20 mSv/y) within the range of not exceeding 50 mSv/y for a specific year [11]. In group B, workers can receive radiation dose up to 15 mSv/y, which is the same value as the lens dose limit for the public. This indicates that lens dose monitoring in the workplace will be an upcoming issue in terms of radiation protection at nuclear and radiation industries in Korea.

2.2. Technical guidance

In general, monitoring of external radiation exposure to workers is carried out using a personal dosimeter worn on the body. Thus, the true value of the operational quantity depends on the radiation exposure situation in the vicinity of where the dosimeter is worn. The ICRU recommends using personal dose equivalents, H_p(d), as operational quantities, to monitor external radiation exposure [5,6]. The personal dose equivalent is defined as the dose equivalent in the ICRU soft tissue at an appropriate depth, *d*, below a specified point on the human body. The specified point generally refers to the location where a personal dosimeter is worn. It is recommended to use a depth $d = 10$ mm to evaluate the effective dose and a depth $d = 0.07$ mm depth to evaluate the equivalent dose of the skin or extremities (hands and feet) [5,6]. In particular, a depth $d = 3$ mm is suggested as being suitable when monitoring the lens dose [4–7].

The International Organization for Standardization (ISO) published the standard, ISO 15382:2015, to provide radiation monitoring guidelines for the lens, skin, and extremities (hands and feet) of radiation workers [17]. This standard states that under non-uniform exposure conditions, whole-body monitoring may not adequately assess the radiation dose to the lens of the eye. ISO 15382:2015 also emphasizes the need to monitor radiation exposure to the lens under non-uniform exposure conditions, because the radiation dose due to low energy gamma rays or beta is not negligible [17]. Thus, in workplaces where radiation sources are located around the eyes of workers, or where high energy beta sources are present, radiation monitoring for the lens is essential.

It is important to analyze the characteristics of the radiation field to determine whether or not radiation monitoring is necessary for the workplace. Gamma radiation fields of all energy levels cause radiation exposure to the lens, skin, and extremities of the worker. In the case of beta having an energy of 60 keV or higher, it can cause radiation exposure to the skin, since it can penetrate up to a depth of 0.07 mm in the body. Beta over 700 keV can penetrate to a depth of 3 mm in the body, affecting the dose to the lens [17]. In NPPs, low-energy betas are to be expected around unsealed radioactive materials. High-energy betas of 700 keV or higher are to be expected for used fuel handling and at nuclear fuel leakage areas; hence, radiation monitoring for the lens is recommended. As the monitoring levels that require monitoring of radiation exposure to the lens, the ISO proposed 15 mSv for any single year, or 6 mSv for consecutive years, which is one-third of the lens dose limit [17].

In terms of the new dose limit for the lens of the eye, the IAEA issued TECDOC No.1731 to guide lens protection in the workplace. This technical report states that when the equivalent dose to the lens is likely to exceed 5 mSv/y, radiation monitoring is necessary [18]. The method of radiation monitoring for the lens mainly depends on the type of radiation incident. It is affected by three factors: the energy and angle of incident radiation, the geometry of the radiation field, and the use of personal protective equipment. Figs. 1 and 2 demonstrate the guidance on monitoring the dose to the lens depending on the three factors for gamma and beta radiation [18].

The International Radiation Protection Association (IRPA) has provided practical guidance on the implementation of lens dose monitoring and the eye protection of radiation workers, with regard to the reduction of the ICRP's lens dose limit [19]. According to the guidance, the occupational workers who are expected to be exposed to the lens of the eye may be classified into three types: workers receiving uniform radiation exposure to the whole body, which applies to most radiation workplaces, workers with high lens dose due to high-energy betas of 700 keV or higher in non-uniform radiation fields but low effective dose, and medical workers with high lens dose but low effective dose, due to the shielding of a part of the body by using personal protective equipment, such as a lead apron. For workers exposed to uniform radiation fields, an adequate assessment of the dose to the lens can be made by using a whole-body dosimeter worn on the chest [19]. Thus, it is not necessary to wear a separate lens dosimeter, and no additional monitoring procedures are required. On the other hand, workers in the second and third categories are required to monitor the dose to the lens of the eye. In these cases, to establish appropriate protection procedures, it is necessary to analyze the radiation field and to investigate the maximum energy of beta. If the radiation field of the workplace is well known, the lens dose, $H_p(3)$, can be estimated through the measurement of other operational quantities, $H_p(0.07)$ or $H_p(10)$ [19]. To use other operational quantities instead of $H_p(3)$, the application of correction factors may be needed, to take into account differences between the wearing and calibration conditions of dosimeters. The IRPA proposed 6 mSv/y as a dose level that requires the regular monitoring of radiation exposure to the lens [19]. The dose level, 6 mSv/y, is the same value as the dose criterion proposed by the ISO for monitoring the lens [17].

3. Eye lens dosimeter

3.1. Performance requirements

The International Electrotechnical Commission (IEC) and the ISO provide standards for a personal dosimeter whose performance should meet the technical specifications requirements shown in Table 2 [17,20]. Table 2 shows that there is currently no technical specification for an active dosimeter for the personal dose equivalent, $H_p(3)$, used in the evaluation of lens dose [17]. Furthermore, when the incident radiation is neutron, there is no technical standard for either active or passive dosimeters for $H_p(3)$ [17]. Therefore, the lens dose measurement in the current situation can be performed reliably in gamma and beta radiation fields using a passive dosimeter.

In 2020, the IEC updated the previous technical specifications for passive dosimetry systems for individual, workplace, and environmental monitoring of gamma and beta radiation [20]. In particular, this standard provides requirements for passive dosimeters that measure $H_p(3)$ in gamma and beta radiation fields. Table 3 shows the dose and energy ranges required by the IEC for an $H_p(3)$ dosimeter in gamma and beta radiation fields [20]. In addition to dose and energy ranges, it is required that the variation of the relative response due to a change of the radiation energy and angle of incidence within the rated ranges shall not exceed the criteria given in the IEC performance requirements. The relative response, *r*, is defined as the quotient of the response, *R*, and the reference response, R_o. The relative response variation must be

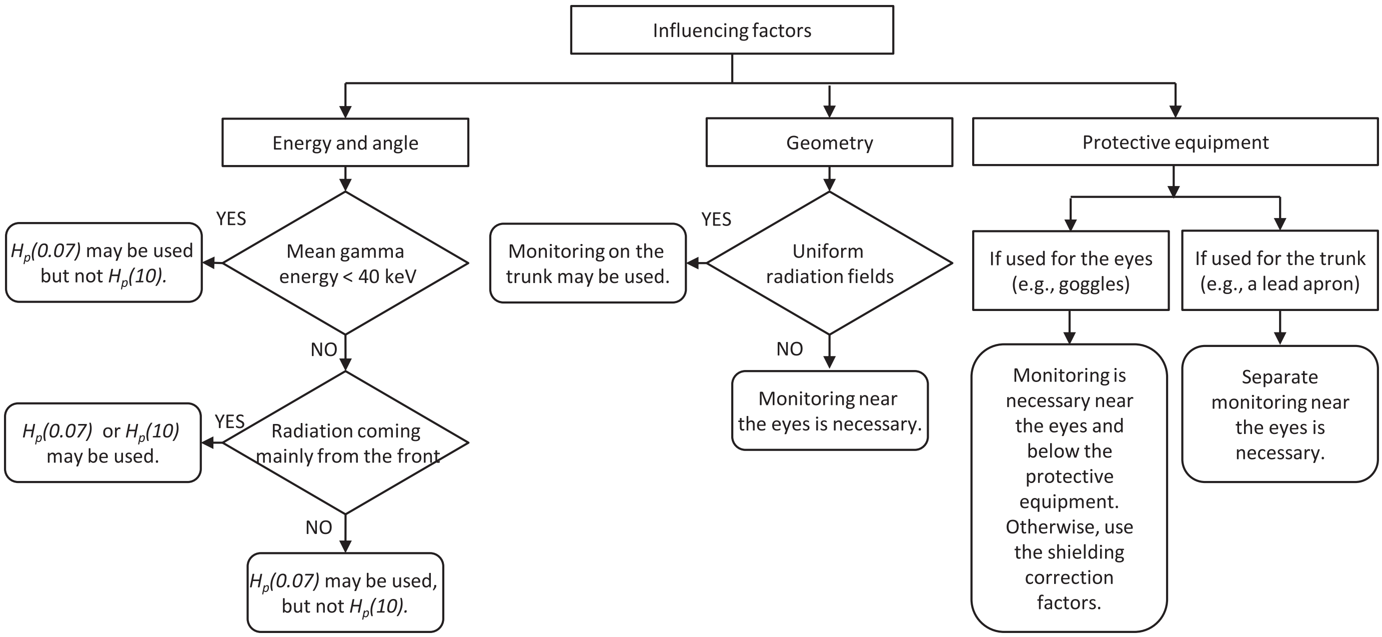

Fig. 1. IAEA guidance on monitoring the dose to the lens of the eye for exposure to gamma radiation.

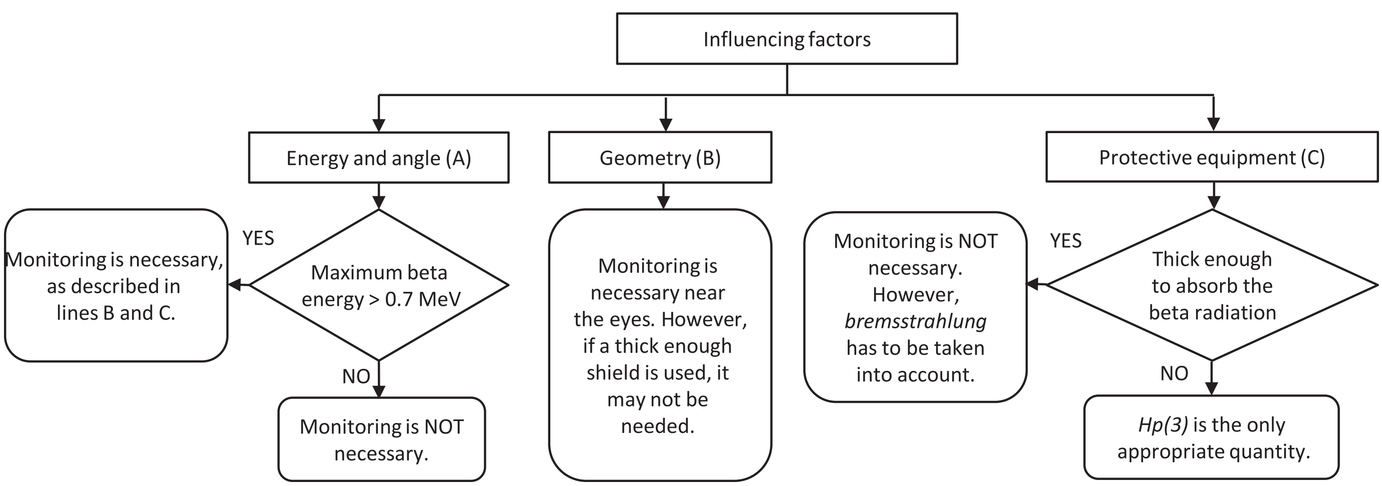

Fig. 2. IAEA guidance on monitoring the dose to the lens of the eye for exposure to beta radiation.

Table 2
International standards for individual dosimeters.

Radiation		Active dosimeters	Passive dosimeters
Gamma and beta radiation	Standard	IEC 61526	IEC 62387
	Operational quantities	$H_p(0.07)$ and $H_p(10)$	$H_p(0.07)$, $H_p(3)$, and $H_p(10)$
Neutron	Standard	None	ISO 21909-1
	Operational quantities		$H_p(10)$

Table 3
IEC guidance on the mandatory and maximum energy ranges for an $H_p(3)$ dosimeter.

Measuring quantity	Mandatory mean energy range for gamma radiation	Maximum mean energy range for testing gamma radiation	Mandatory mean energy range for beta radiation	Maximum mean energy range for testing beta radiation
$H_p(3)$	30–250 keV	8 keV to 7 MeV	0.8 MeV[a]	0.7[a] to 1.2 MeV

[a] For beta radiation, the energy of 0.7 MeV is required to reach the radiation-sensitive layers of the eye lens at a depth of about 3 mm (approximately 3 mm of ICRU tissue).

between 0.71 and 1.67 for both gamma radiation with average energies from 30 keV to 1.25 MeV and angles of incidence from 0° to 60° and beta radiation with average energy of 0.8 MeV and angles of incidence from 0° to 60° [20]. The radiation beam codes for the irradiation of dosimeters are specified in ISO 4037:2019 for gamma radiation [21–24]. The three lowest energies, which can be offered from a laboratory, among reference beam codes, which are N-10, N-15, N-20, N-30, N-40, N-60, N-80, N-100, N-150, N-200, N-300, S–Cs (^{137}Cs), S–Co (^{60}Co), R–C (4.4 MeV), and R–F (6.7 MeV), should be used for gamma irradiation. For beta radiation, ^{90}Sr/^{90}Y (mean energy ≈ 0.8 MeV) or ^{106}Ru/^{106}Rh (mean energy ≈ 1.2 MeV) is recommended as a reference radiation for irradiation according to ISO 6980 [25,26]. As stated above, beta over 700 keV can penetrate to a depth of 3 mm in the body, affecting the dose to the lens; however, some low-energy betas of less than 700 keV might contribute to $H_p(3)$, which reduce the performance of a $H_p(3)$ dosimeter. Thus, the IEC requires an additional performance standard, which is that the indicated value of the $H_p(3)$ dosimeter due to low-energy betas with energies up to the energy equivalent of ^{85}Kr (mean energy ≈ 0.24 MeV) shall be less than 10% of $H_p(0.07)$ [20].

3.2. Manufacturing characteristics

The four main characteristics that eye lens dosimeters should have for monitoring the radiation exposure to the lens of radiation workers are as follows: appropriate measurement capability for the operational quantity, $H_p(3)$, suitable response to various energies and incident angles of radiation, comfortable fit, and wearability around the eyes. Currently, several manufacturers worldwide supply eye lens dosimeters to radiation and nuclear facilities. Despite the different manufacturers, most eye lens dosimeters have the following common characteristics; thermoluminescent dosimeter (TLD) is used as a lens dosimeter, and a dosimeter holder is provided to be worn as close to the eye as possible [27]. Eye lens dosimeters available worldwide are passive dosimeters (TLDs), while active dosimeters have not yet been manufactured for the lens dose measurement. The reasons for not using the active dosimeters as eye lens dosimeters are that active dosimeters, such as electronic dosimeters, are more expensive than passive dosimeters and are too large and heavy for radiation workers to wear around the eyes [27]. In addition, there are currently no performance requirements for $H_p(3)$ active dosimeters [17].

The most common phosphor materials used in personal TLDs are lithium fluoride (LiF) and lithium borate ($Li_2B_4O_7$). However, most dosimeter manufacturers use LiF as a thermoluminescent material of eye lens dosimeters. The lithium fluoride is a representative material used in Harshaw TLD™. It is used as LiF: Mg, Ti doped with impurities: magnesium and titanium or LiF: Mg, Cu, P doped with magnesium, copper, and phosphorus [28]. Although eye lens dosimeters are manufactured in different shapes from several manufacturers, the TLD material is the same as lithium fluoride. On the other hand, lithium borate is a representative material used in Panasonic TLD™. Although it is used in whole-body and extremity dosimeters, it is not commercially used in dosimeters for $H_p(3)$ measurement.

The eye lens dosimeter was developed in earnest by the ORAMED project, which was set up to optimize the working procedures in medical fields concerning radiation protection [27,29]. As a result of the research project, the first eye lens dosimeter EYE-D™ was developed using LiF: Mg, Cu, P as a TLD material. The EYE-D dosimeter showed satisfactory performance by presenting the response within approximately 20% as a result of both experimental measurements of energy and incident angle of gamma rays (Cesium-137) and Monte Carlo calculations [30]. Public Health England (PHE) has also developed an eye lens dosimeter using the same TLD material (LiF: Mg, Cu, P) as the EYE-D dosimeter [31]. The PHE dosimeter uses a 1.5 mm polytetrafluoroethylene (PTFE) filter, and the total filtration thickness is 3.3 mm, similar to the depth of 3 mm in the soft tissue of ICRU [27,31]. In particular, the PHE dosimeter is a modification of the existing extremity (finger) dosimeter, Harshaw EXTRAD™, which meets the relevant requirements of both ISO and ORAMED [27]. On the other hand, the DOSIRIS™ dosimeter, an eye lens dosimeter using LiF: Mg, Ti as a TLD material, was developed by IRSN, the French radiation protection research institute [32]. In addition, the VISION® lens dosimeter, using LiF: Mg, Ti, was developed by LANDAUER, an American optically stimulated luminescent (OSL) dosimeter manufacturer [33]. This means that to date, technical reliability has not yet been fully validated to carry out lens dose evaluation using OSL technology. Both the DOSIRIS™ and VISION® dosimeters comply with the requirements of IEC 62387–1:2012, the performance standard for passive dosimeters [32–34]. Some nuclear facilities in Canada use modified extremity dosimeters for $H_p(3)$ measurement, although it is not commercially available. They modified $H_p(0.07)$ dosimeters to allow the measurement of $H_p(3)$, using an additional filter of 300 mg cm^{-2}, which provides the acceptable performance for eye lens monitoring [35]. Table 4 summarizes the characteristics of eye lens dosimeters available in the commercial market [30–33].

4. Radiation field conditions resulting in lens dose

4.1. Non-uniform radiation and high-energy beta fields

In general, most radiation fields in NPPs are characterized as aligned and expanded radiation fields where radiation workers are homogeneously exposed from one direction, and the difference of the radiation dose between the chest and other specific areas of the body is not large [36]. In uniform radiation fields at NPPs, it is considered that the equivalent dose of the lens, skin, and extremities of the body will be similar to the effective dose, which is the whole-body dose [37]. Therefore, radiation exposure to workers in NPPs is comprehensively controlled by monitoring the effective dose using a whole-body dosimeter on the chest. In particular, since most radiation workers in NPPs receive effective dose of around 1 mSv/y, the individual dose is considered to be insignificant, compared with the effective dose limit of 20 mSv/y, and the equivalent dose limits of 150 mSv/y for the lens, and 500 mSv/y for the skin and extremities; thus, even if there are some differences in the radiation dose between the chest and other specific areas of the body, the dose is unlikely to exceed the equivalent dose limits [38,39,42].

Unlike uniform radiation fields, workers in non-uniform radiation fields at NPPs may receive relatively more radiation exposure to certain parts of the body, such as the extremities and head, including the lens, than to the chest, where a whole-body dosimeter is normally worn. That is, in non-uniform radiation fields, wearing only one whole-body dosimeter on the chest of the body may make it difficult to adequately measure the radiation dose received during work. In this regard, several multi-dosimeter algorithms have been developed worldwide to properly evaluate the effective dose of radiation workers in non-uniform radiation fields, and after various field tests, Korean NPPs selected the optimized two-dosemeter algorithm [36]. This two-dosimeter algorithm is applied to the radiation safety procedures in Korean NPPs. Two dosimeters are provided for the radiation work where the difference in the expected dose between the chest and specific parts of the body in the high-radiation controlled area, in which the radiation dose rate exceeds 1 mSv/h, is expected to be more than 30%, and a dose of more than 2 mSv is expected in a single task [36,40].

Table 4
Summary of the characteristics of eye lens dosimeters.

Dosimeter model	EYE-D™	PHE	DOSIRIS™
Figure			
Detector	Single element TLD (^{7}LiF: Mg, Cu, P)	Single element TLD (^{7}LiF: Mg, Cu, P)	Single element TLD (^{7}LiF: Mg, Ti)
TLD type	Pellet (4.5 mm dia., 0.9 mm thick)	Powder (3.1 mm dia.)	Powder (3.6 mm dia.)
Calibration phantom	Cylindrical 20 cm × 20 cm, PMMA wall, Water-filled		
Pre-heat temperature	75 °C for 20 min	165 °C for 10 s	50 °C for 0 s
Acquisition maximum temperature	260 °C for 16 s	255 °C for 13.3 s	300 °C for 16.6 s
Localization	Head	Head	Side of the eye
Dose range	0.01 mSv–10 Sv	0.15 mSv–10 SV	0.1 mSv–50 Sv
Energy range	Photon: 30 keV–1.3 MeV	Photon: 16–662 keV Beta: 1.7–3.5 MeV	Photon: 20 keV–1.3 MeV Beta:>700 keV

In particular, when working in a steam generator water chamber, the radiation worker may be relatively more exposed to radiation to the head than to the chest, due to non-uniform radiation fields, which results in high lens dose, compared to the effective dose measured at the chest. Since two-dosimeter algorithms were developed for the accurate measurement of effective dose, they are not suitable for estimating the equivalent dose to the lens of the eye. Korean NPPs have not yet established a dosimetry program to estimate the radiation dose to the lens of the eye for radiation workers. Currently, the difference between the effective dose limit of 20 mSv/y and the eye lens equivalent dose limit of 150 mSv/y for radiation workers is remarkable in Korea, so it is very unlikely that a radiation worker in Korean NPPs will exceed the dose limit to the lens of the eye. However, when the lens equivalent dose limit is reduced to the value that is the same as the effective dose limit, the probability that a worker's lens equivalent dose exceeds the dose limit will increase in a non-uniform radiation field at NPPs [8].

In addition to the radiation field geometry, it is important to analyze the radiation field's characteristics to determine the need for monitoring the eye lens dose of radiation workers. Gamma radiation of all energy levels causes radiation exposure to the lens, skin, and extremities of the worker. Beta with an energy of 60 keV or higher can affect the equivalent dose of the skin because it can penetrate the body to 0.07 mm depth. A beta of 700 keV or higher can penetrate the body to 3 mm depth, affecting the lens's equivalent dose [17]. Most workplaces in NPPs are characterized as uniform radiation fields, and the individual dose is controlled by monitoring the effective dose using a whole-body dosimeter worn on the chest for gamma rays, so it is necessary to pay attention to high-energy betas that do not affect the effective dose of workers, but do affect the equivalent dose of the lens. To carry out the monitoring of radiation workers' lenses in NPPs, it is necessary to investigate the radiation field and relevant work in which a high-energy beta of 700 keV or higher is expected.

The Electric Power Research Institute (EPRI) published guidance on lens radiation protection for NPP workers [8]. According to this guidance, the radiation field where the lens dose of a radiation worker is likely to exceed the effective dose is determined by the following three conditions: a function of the radionuclide mix, the geometry of the source, and the positioning of the worker in the radiation field. First, high-energy beta or electrons can reach the lens, although they do not affect the effective dose. Second, a higher dose gradient from above, where the head is close to the source, can cause a higher radiation dose to the lens of the eye, than to most of the body. Last, partial shielding of part of the body, except the lens, can cause a relatively higher lens dose than the effective dose. In general, it is very unlikely to receive relatively high radiation exposure to the lens only, compared to the whole body of the worker, because most workplaces in NPPs are uniform radiation fields. Thus, the EPRI conducted a questionnaire survey on some US NPPs to identify the workplaces with high-energy beta sources that could give high radiation exposure to the lens of the worker, even in a uniform radiation field. As a result, some NPPs responded that high-energy beta might be present in the primary system, steam generator primary sidewalks, fuel pool, reactor cavity, fuel transfer canal, and during instrument calibration and checks with a strontium/yttrium-90 source [8]. In addition, the EPRI provides the guidance on the use of non-leaded protective eyewear, with a protection factor between 6 and 14 for polymethyl methacrylate thicknesses between 2.0 mm and 2.6 mm, for the substantial reduction of the lens dose from the high-energy beta particle [41].

4.2. Radiation fields at Korean NPPs

In order to identify the radiation work and workplaces that can expose radiation to the lens of the worker in Korean NPPs, interviews were conducted with the managers of radiation protection in NPPs. As a result, responses were collected that at Korean pressurized water reactors (PWRs), during normal radiation work, workers are unlikely to receive radiation exposure to the lens of the eye. However, the radiation fields under non-uniform exposure conditions, which are considered to provide higher radiation exposure to the head than the chest, or high-energy beta exposure conditions can be classified as the workplaces that may result in radiation exposure to the lens. Furthermore, the radiation work mainly conducted in these places could be regarded as work that potentially induces lens exposure.

Similar to the above literature review, the steam generator water chamber is identified as a typical workplace in a non-uniform radiation field at Korean PWRs. The space inside the steam generator water chamber is very narrow, and a large number of high-energy gamma sources are distributed on the surface of the chamber inside, so it is difficult to build a uniform radiation field [36,37]. Fig. 3 shows the source geometry of a typical steam generator at Korean PWRs [36]. As shown in Fig. 3, the working space inside the steam generator water chamber is limited and has a low ceiling, so the head of the worker, including the lens, is closer to the radiation source than the chest. Thus, it is anticipated that

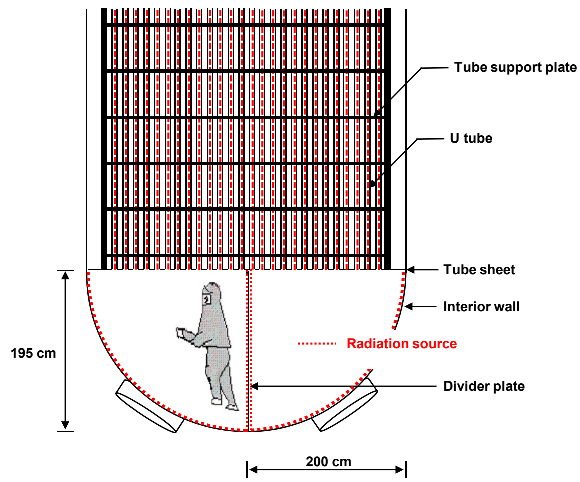

Fig. 3. The geometry of the steam generator in Korean pressurized water reactors.

the lens might receive relatively high radiation exposure, compared to the whole body.

In addition to the steam generator water chamber, the U-tube support plates were also identified as a place with a non-uniform radiation field. In Fig. 3, there are tube support plates to prevent the U-tubes from shaking, and radioactive corrosion products (CRUD) are mainly produced from the support plate at the upper side of the U-tubes. These radioactive corrosion products generate non-uniform exposure conditions for workers who conduct radiation work adjacent to the tube support plate. On the other hand, even if the workplace is a non-uniform radiation field, the exposure situation can change, depending on the positioning of the worker. For example, when conducting work in the steam generator water chamber, some radiation workers do maintenance by bending at the waist, which has shown that radiation exposure to the chest or back is higher than to the head [36].

From the perspective of radiation tasks, maintenance in the steam generator and at its surroundings is classified as work that may give radiation exposure to the lens of the eye. It was found that the installation and removal of the steam generator nozzle dam was typical work in a non-uniform radiation field in Korean PWRs. Eddy current testing (ECT) and foreign object search and retrieval (FOSAR) inspection in the steam generator are also conducted under non-uniform exposure conditions. In particular, installation and removal of the FOSAR inspection tools are usually conducted by the worker inserting his or her head into the steam generator, in which position, radiation exposure to the lens is relatively higher than to the whole body. Meanwhile, work to disassemble the reactor drain valve was suggested as radiation work that could be exposed to high-energy beta sources. This was attributed to the likelihood of high-energy betas among radiation sources on the valve surface when disassembling the drain valve.

In addition to PWRs, interviews were conducted with the managers of radiation protection in Korean pressurized heavy water reactors (PHWRs), to find the radiation work and workplaces where the eye lens could be exposed to radiation. Similar to the results from PWRs, it was confirmed that it is unusual for workers to receive radiation dose to the lens during normal radiation work at Korean PHWRs. However, some radiation work and workplaces in the radiation fields were found that were under non-uniform or high-energy beta exposure conditions. Table 5 shows the radiation work and workplaces that may induce radiation exposure to the lens of the eye at both Korean PWRs and PHWRs.

The steam generator water chamber, similar to the results from PWRs, has been identified as a typical workplace where non-uniform radiation fields are formed in Korean PHWRs. Space is limited at the steam generator water chamber, and the inside surface is covered with many high-energy gamma sources. In terms of radiation work, the ECT, lancing, and manway opening are classified as typical work under non-uniform exposure conditions. Furthermore, the inspection of delayed neutron tubes is considered as radiation work that could be exposed to high-energy beta sources in Korean PHWRs, because high-energy beta sources can be present among the radiation sources on the surface of the tubes, due to leakage.

5. Summary and conclusion

After several epidemiological investigations, it was found that radiation exposure can cause cataracts. The ICRP and IAEA have lowered the occupational dose limit to the eye lens from 150 mSv/y to 100 mSv (annual average of 20 mSv) for 5 years. The NSSC, the Korean regulatory body, also proposed that the occupational lens dose limit be reduced to the same level as from the ICRP and IAEA. The equivalent dose limit of 20 mSv/y to the eye lens is the same value as the occupational effective dose limit. This indicates that radiation safety for the lens of the eye should be provided at the same level of whole-body protection. The Korean NPPs are currently conducting research to establish a radiation protection program for the lens of the eye in a timely manner. This article introduces the regulation and technical standards for the dose assessment of the lens, the performance criteria and design characteristics of the lens dosimeters, and the radiation field and work conditions resulting in lens dose to provide the technical basis for establishing the lens protection program in NPPs.

The ICRU recommends the use of a personal dose equivalent, $H_p(3)$, at a depth of 3 mm in body tissue, to measure the radiation dose to the lens. The ISO has revealed that under non-uniform radiation field conditions, radiation monitoring of the whole body of a worker may not adequately assess the dose to the lens. In particular, it is highlighted that where high-energy betas of 700 keV or higher are present in workplaces, lens dose monitoring is required. As the dose levels that require monitoring of radiation exposure to the lens, the ISO and IRPA proposed 6 mSv/y, which is one-third of the lens dose limit, while the IAEA suggested 5 mSv/y. Meanwhile, the IRPA states that for workers exposed to uniform radiation fields, an appropriate assessment of the dose to the lens can be made by using a whole-body dosimeter worn on the chest.

The eye lens dosimeter is designed and manufactured to measure personal dose equivalent, $H_p(3)$, by being worn around the eyes of a radiation worker. The IEC provides technical specifications for passive dosimeters measuring $H_p(3)$ in gamma and beta radiation fields. Most dosimeter manufacturers use lithium fluoride (LiF) as a thermoluminescent material for the eye lens dosimeter. Lithium fluoride is a representative material used in Harshaw's thermoluminescent dosimeter (TLD). Although several suppliers sell the eye lens dosimeter, a single manufacturer provides the raw material for the thermoluminescent element.

As a result of the literature review on radiation fields in NPPs, it was confirmed that most workplaces are under uniform exposure conditions, and it is unlikely for the lens only to receive relatively high radiation exposure, compared to the whole body of a worker. Interviews with the managers of radiation protection in Korean NPPs also reveal that during normal radiation work at Korean PWRs and PHWRs, workers are unlikely to receive radiation exposure to the lens of the eye. However, under non-uniform exposure conditions, the radiation fields that can cause higher radiation exposure to the head than the chest, or high-energy beta exposure

Table 5
Radiation work and workplaces in Korean NPPs that may give radiation exposure to the lens of the eye.

Category	Type of reactor[a]	Radiation work or workplaces	Radiation field
Workplace	PWR & PHWR	Steam generator water chamber	Non-uniform
	PWR	U-tube support plates of steam generator	Non-uniform
Work	PWR	Disassembling of the reactor drain valve	High-energy beta radiation
	PWR	Installation and removal of thesteam generator nozzle dam	Non-uniform
	PWR & PHWR	Eddy current test at the steam generator	Non-uniform
	PWR	FOSAR inspection in the steam generator[b]	Non-uniform
	PHWR	Lancing at the steam generator	Non-uniform
	PHWR	Opening manway of the steam generator	Non-uniform
	PHWR	Inspection of delayed neutron tube	High-energy beta radiation

[a] PWR, pressurized water reactor; PHWR, pressurized heavy water reactor.
[b] FOSAR, foreign object search and retrieval.

conditions, can be classified as workplaces that may give radiation exposure to the lens. The steam generator water chamber is identified as a typical workplace where non-uniform exposure conditions are made in both Korean PWRs and PHWRs. In terms of radiation tasks, disassembling of the reactor drain valve in PWRs and the inspection of delayed neutron tubes in PHWRs are considered as radiation work that could be exposed to high-energy beta sources in Korean NPPs.

Korean NPPs are currently carrying out research to establish a radiation protection program for the lens of the eye. This preliminary evaluation provides results on regulations, technical guidance, eye lens dosimeters, and radiation field conditions resulting in lens dose. Korean NPPs will use the research results not only to prepare for the change in the lens dose limit, but also to implement a radiation protection program for the lens of the eye.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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