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Original Article

Derivation of a new dose constraint applicable to radioactive discharges from Korean nuclear power plants through retrospective dose assessment

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ABSTRACT

A new methodology to derive a dose constraint for radioactive effluent from a unit of nuclear power plant (NPP) through retrospective assessment was developed to reflect operational flexibility in line with international standards. The new dose constraint can retain the safety margin between the offsite dose and the past dose constraints. As case studies, the new approach was applied to 24 Korean NPPs to address the limitations of the existing seven dose constraints that do not fully comply with current international radiation protection standards. Therefore, an effective dose constraint for Korean NPPs was proposed as no less than 0.15 mSv/y, which is comparable to the international practices and previous studies (0.05–0.3 mSv/y). Although the lower bound of the equivalent dose constraint was calculated as 0.17 mSv/y, it is not proposed in this study since the compliance with the derived effective dose constraint can prevent accompanied equivalent doses to any organs from exceeding equivalent dose limits. The new framework and the case studies are expected to contribute toward and support the revision of existing dose constraints for radioactive effluent from NPPs, ensuring better compliance with the current international safety standards as well as reflect the operational flexibility in practice.

1. Introduction

The International Atomic Energy Agency (IAEA) states that the general objective of discharge control of radioactive effluent released from NPPs is to minimize the radiological impacts on the public and the environment under the principles of justification and optimization [1]. Accordingly, radioactive effluent discharged from nuclear power plants (NPPs) should be regulated in terms of radioactivity discharged annually (Bq/y), activity concentration (Bq/m^3), or annual radiation dose (mSv/y) [1]. In addition, the IAEA Safety Guide specifies that the dose constraint for a single source should be expressed in terms of annual effective dose, which should be greater than 10 μSv/y but less than 1 mSv/y. In addition, 0.3 mSv/y was presented as the maximum value of a general dose constraint for radioactive effluent discharged from NPPs, and the Guide further recommends that operational flexibility should be considered when setting the discharge limit to allow for an appropriate margin for anticipated fluctuations in performance that may occur during operation and thereby preventing frequent violations of regulatory standards [1]. Furthermore, previous experience (e.g. historical discharge data) of a target facility can provide useful information regarding the allowance for flexibility that should be permitted [2].

Some countries specify a single effective dose constraint for a unit NPP or site (see Table 1), whereas others have established dose constraints in multiple terms of radiation doses, as in the cases of Korea and the United States (see Table 2).

Table 1
Dose constraints for radioactive effluent adopted in selected countries.

Organization/country	Effective dose constraint (mSv/y)	Target facility/Site
IAEA [1]	0.3	Nuclear fuel cycle facilities
China [3]	0.25	Nuclear fuel cycle facilities (site)
Finland [4]	0.1	A unit of NPP
Germany [5]	0.3	Nuclear fuel cycle facilities (site)
Japan [6]	0.05	A unit of NPP
Spain [7]	0.1	Nuclear fuel cycle facilities (site)
United Kingdom [8]	0.3	A unit of NPP
	0.5	Nuclear fuel cycle facilities (site)

Note: In Japan, the effective dose equivalent rather than effective dose is applied.

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Table 2
Multiple terms of radiation dose constraints adopted in Korea and the United States.

Target		ID	Dose term		Dose constraint
			Korea [9]	United States [10]	
A unit of NPP	Gas	G1	Gamma absorbed dose	Gamma dose in air	0.1 mGy/y
		G2	Beta absorbed dose	Beta dose in air	0.2 mGy/y
		G3	Effective dose of External exposure	Dose to total body of external exposure	0.05 mSv/y
		G4	Skin equivalent dose of External exposure	Dose to skin of external exposure	0.15 mSv/y
		G5	Equivalent dose of radioactive iodine, ^{3}H, ^{14}C, and particulates	Dose to organ from radioactive iodine and particulates	0.15 mSv/y
	Liquid	L1	Effective dose	Dose to total body	0.03 mSv/y
		L2	Equivalent dose	Dose to any organ	0.1 mSv/y
Site			Effective dose	Dose equivalent to whole body	0.25 mSv/y
			Thyroid equivalent dose	Dose equivalent to thyroid dose	0.75 mSv/y
			–	Dose equivalent to any organ	0.25 mSv/y

Note: ID represents the abbreviation of each dose constraint term.

The United States Nuclear Regulatory Commission (USNRC) explained that the dose constraints presented in the US federal regulations 10 CFR 50 Appendix I shown in Table 2 were established considering the "operating data" of US light-water reactors (LWRs) in 1970s and knowledge about the state-of-technology of radioactive waste systems at the time in its regulatory statement [11]. These values are small fractions of the dose limit according to the International Commission on Radiological Protection (ICRP) recommendations that were in effect then. The "operating data" mentioned in the statement can be interpreted as the historical discharge data from LWRs as presented in the Annex of the same document [11]. The USNRC addressed the need to revise the regulatory standards not conforming to the latest ICRP recommendations in 2014, and proposed a few options for the revision of 10 CFR 50 Appendix I including the following [12]:

- Option 1. Assess whether to omit reporting requirements of Appendix I for organ doses (e.g., skin and thyroid);
- Option 2. Assess whether the gamma and beta air dose constraints should remain in Appendix I;
- Option 3. Change the "dose to total body" constraints for liquid and gaseous effluent into the "effective dose".

However, discussion on the revision was discontinued in 2016, and the old standards continue to be applied to date because the USNRC concluded that estimated implementation costs would impose a significant burden on the industry that would not be justified by the improvements in public and occupational protection [13]. No subsequent studies have been reported in relation to this issue.

In Korea, the dose constraints for radioactive effluent were first established in 1996 based on US federal regulations 10 CFR 50 Appendix I [14]. The Korean government superficially changed the dose terms (i.e. "total body dose" to "effective dose" and "organ dose" to "equivalent dose") in 1998 and has applied them ever since, without any further careful consideration for compliance with the recommendations of the ICRP 60 and the potential need for updating the numerical values (see Table 2) [15,16], which is comparable to Option 3 considered by the USNRC as above. Therefore, the following limitations have been noted regarding the compliance with currently effective ICRP recommendations.

- As the dose constraints for liquid and gaseous effluents are specified separately, it is difficult to represent the integrated radiological impact;
- The "Gamma absorbed dose" and "Beta absorbed dose" for gaseous effluent in Table 2 are not directly related to the current radiological protection recommendations in Korea;
- As the "Effective dose of external exposure" for gaseous effluent in Table 2 includes only external exposure from noble gases, no direct limits on the actual effective dose from both internal and external exposures are specified [17].

Recently, two existing studies have proposed new effective dose constraints for liquid and gaseous radioactive effluent from a unit of Korean NPP. Kong et al. (2015) derived a new dose constraint of 0.2 mSv/y per reactor from the present constraints in Table 2 by assuming that the "effective dose" for a unit reactor is the sum of the effective doses from liquid effluent and direct exposure to gaseous effluent, and introduced an adjustment factor of 2.5 (i.e. $(0.03 + 0.05)$ mSv/y $\times$ 2.5 = 0.2 mSv/y) [18]. On the other hand, Lee (2021) suggested 0.1 mSv/y as a new dose constraint for a unit of NPP taking into consideration the unconsented exposure to the public, and compared the value with the sum of the effective doses from liquid effluent and direct exposure to gaseous effluent (0.08 mSv/y) [19]. These studies have inherent limitations in that the assumed "effective dose" excluding internal exposure from gaseous discharge is not based on actual effective dose, and the operational flexibility of operating NPPs has not been reflected at all.

Therefore, this study aims to identify new dose constraints for radioactive effluent for a single NPP in Korea, which complies with the current system of radiological protection and may ensure the same level of historical safety margin by considering operational flexibility. To this end, a general model to derive dose constraints with operational flexibility through retrospective offsite dose calculations using actual liquid and gaseous radioactive effluent data is developed and applied to Korean NPPs in operation. Furthermore, dominant radionuclides contributing to the newly proposed dose constraints and additional radiological characteristics of effluents from Korean NPPs will be analyzed.

2. Materials and method

Fig. 1 shows the stepwise procedure developed in this study to derive new dose constraints by reflecting the operational flexibility of a target facility through retrospective assessment. Each step in Fig. 1 will be explained in following sections.

2.1. Offsite dose calculation model for existing and new dose constraints (Step 1 in Fig. 1)

To assess radiation dose from radioactive discharges from NPPs, the Offsite Dose Calculation Manual (ODCM) provided by the Korea Institute of Nuclear Safety (KINS) Regulatory Guideline 2.2, Rev.2 is adopted in this study [20]. The ODCM assumed the USNRC Regulatory Guide 1.109, Rev.1 exposure pathways which are shown in Fig. 2 and considered in this study [20,21].

The equation to calculate the offsite radiation dose can be represented by the following equation [21]:

$$R_{a,p,i,j} = C_{m,i} \times U_{a,p} \times DCF_{a,p,i,j} \;, \tag{1}$$

where $R_{a,p,i,j}$ is the radiation dose for age group a, a pathway p, radionuclide i, and an organ j (mSv/y), $C_{m,i}$ is the activity concentration corresponding to each media in Fig. 2 (Bq/kg, Bq/m^3, or Bq/m^2), $U_{a,p}$ is the habitual data (kg/y, l/y, or h/y), and $DCF_{a,p,i,j}$ is the dose conversion factor (DCF) (Sv/Bq, Sv/y per Bq/m^3 or Sv/y per Bq/m^2).

The radioactivity concentration $C_{m,i}$ in Eq. (1) should be calculated for an environmental media (e.g. water, air, and foodstuff, etc.). Firstly, $C_{air,i}$, the radioactivity concentration of radionuclide i in the air (Bq/m^3), is calculated as below [21]:

$$C_{air,i} = \left(3.17 \times 10^{-8}\right) \times (\chi / Q) \times \dot{Q}_i \;, \tag{2}$$

where $\dot{Q}_i$ is the release rate of radionuclide i in the effluent (Bq/y), (χ / Q) is the atmospheric dispersion factor (s/m^3), and (3.17×10^{-8}) is the factor to convert (Bq/y) into (Bq/s).

The concentration of radionuclide i in the receiving water body (e.g. seawater), $C_{water,i}$ (Bq/m^3), can be calculated by applying Eq. (3) [21]. It is noted that no freshwater effluent pathways exist for Korean NPPs which are all located at coastal regions and discharge liquid effluent into the sea [20]:

$$C_{water,i} = \frac{\dot{Q}_i}{F+f} \times \frac{1}{DF} \times \exp(-\lambda_i t_b) \approx \frac{\dot{Q}_i}{F} \times \frac{1}{DF} \times \exp(-\lambda_i t_b) \;, \tag{3}$$

where F is the dilution flow rate of liquid effluent (m^3/s), f is the volume discharge rate of the liquid radioactive waste (m^3/s), DF is the dimensionless dilution factor for the receiving water body, and t_b is the average transit time for the radionuclide to reach the point of exposure (s). $(F+f)$ can be approximated by F due to the much smaller value of f than F.

The activity concentration of foodstuffs, such as livestock, fish, and grain, can be calculated using a transfer factor or bioaccumulation factor and the activity concentration in the environmental media. For instance, the activity concentration in fish is derived by multiplying the bioaccumulation factor by $C_{water,i}$.

2.2. Input data for dose calculation (Step 2 in Fig. 1)

The historical discharge data of radioactive effluent from operating NPPs has to be collected prior to calculating the radiation dose. Firstly, the annual discharge data of each radionuclide in terms of radioactivity, $\dot{Q}_i$ in Eqs. (2) and (3), can be obtained from reports by the NPP operators [22,23]. Secondly, the environmental data to determine the activity concentration of the media (e.g. (χ / Q) in Eq. (2), and F and DF in Eq. (3)) can also be obtained from the NPP operational reports or from the licensing documents of the respective NPP. Lastly, the habitual data, $U_{a,p}$ in Eq. (1), is an assumed parameter for each exposure pathway (e.g. ingestion, inhalation, or external exposure), and can be found in the ODCM guideline of the regulatory institutions or the licensing documents [20,21,24].

2.3. General approach to derive new dose constraint reflecting operational flexibility through retrospective assessment (Steps 3 to 6 in Fig. 1)

The radiation dose term k of an NPP n in a year t ($D_{k,n}(t)$) for existing dose constraint ($DC_{exi,k}$) is calculated by applying the historical input data (see Section 2.2) to the offsite dose calculation model (see Section 2.1) in Step 3 in Fig. 1. Subsequently, the safety factor is assessed to maintain a margin between the radiation dose caused by the effluent discharged in the past and the existing dose constraints. Thus, the safety factor of each reactor n for each year ($SF_n(t)$) is defined as below (see Step 4 in Fig. 1):

$$SF_n(t) = \begin{cases} \dfrac{D_n(t)}{DC_{exi}}, & \textit{for a single dose term} \\ max\left\{\dfrac{D_{k,n}(t)}{DC_{exi,k}} : k \in K\right\}, & \textit{for multiple dose terms} \end{cases} \tag{4}$$

where $D_n(t)$ and DC_{exi} are the radiation dose and the existing dose constraint for a single dose term, respectively, and K is the set of dose terms for existing dose constraints.

After this, a new dose term in a year t for the NPP n for a new dose constraint, $ND_n(t)$, is retrospectively assessed by applying the input data from Section 2.2 to the dose calculation model in Section 2.1 (See Step 5 in Fig. 1), which can be given by the maximum of the sums of radiation doses from gaseous and liquid effluents for each age group and target organ.

$$ND_n(t) = max\left[\sum_i \left\{ND_{a,gas,i,j,n}(t) + ND_{a,liq,i,j,n}(t)\right\} : a \in A, j \in J\right] \;, \tag{5}$$

where A and J are the sets of age groups and organs, respectively.

To ensure operational flexibility, the new dose constraint for the NPP n ($DC_{new,n}$) should be no less than the maximum of $DC_{new,n}(t)$

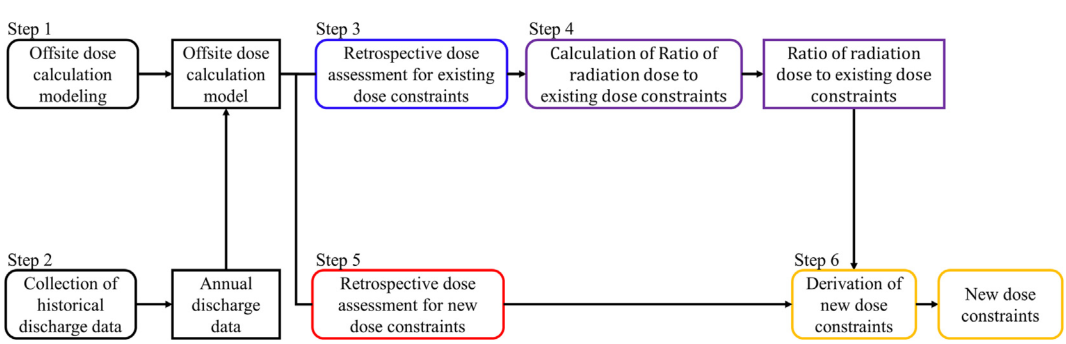

Fig. 1. General approach to estimate the dose constraint proposed in this study.

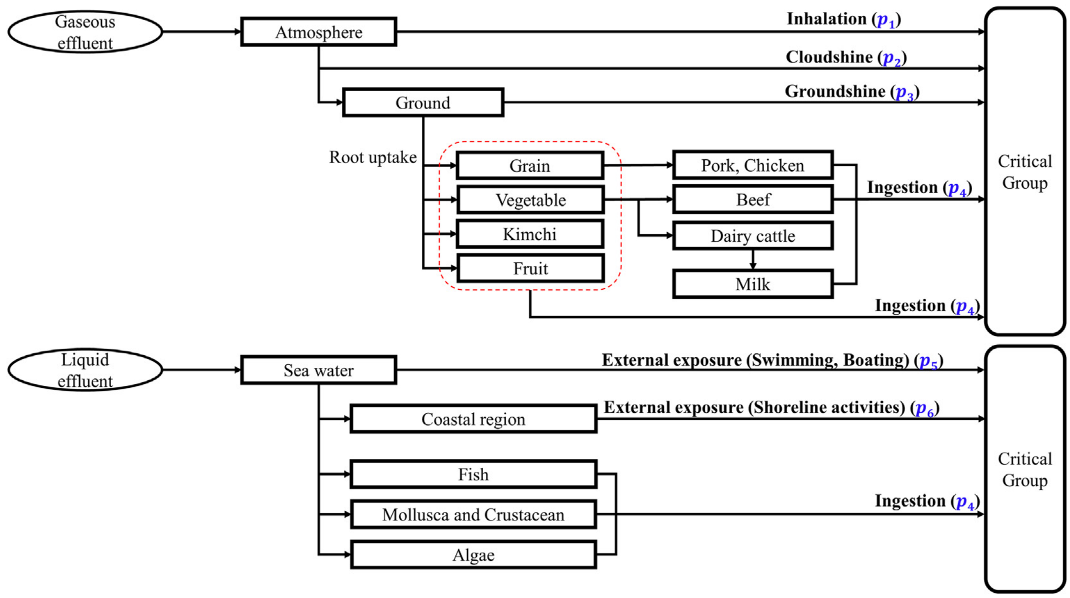

Fig. 2. Transport pathways and exposure pathways for gaseous and liquid radioactive effluent for the offsite dose calculation model in this study. Each rectangle represents an environmental media or food stuff in which discharged radionuclides migrate and are present. The symbol ‘p’ stands for exposure pathway and each subscript indicates a specific pathway number.

for the assessment period as described below (see Step 6 in Fig. 1):

$$DC_{\mathrm{new},n} \geq max\left\{ND_n(t) \times \frac{1}{SF_n(t)} : t = t_1 \cdots t_x\right\} = max\{DC_{\mathrm{new},n}(t) : t = t_1 \cdots t_x\} , \quad (6)$$

where t_1 is the first and t_x is the last year of the assessment period. In other words, $DC_{new,n}$ derived in Eq. (6) is the lower bound of the new dose constraint to retain the minimum margin of the radiation dose against past regulatory standards.

By expanding Eq. (6), the new dose constraint for a group of multiple facilities in a country or at the same site can be derived as given by Eq. (7).

$$DC_{new} \geq max\{DC_{new,n} : n \in N\} , \quad (7)$$

where N is the set of facilities in the group considered.

2.4. Specific approach to derive new dose constraint for Korean NPPs

In this study, a specific framework has been established to derive new dose constraints for Korean NPPs based on the general approach shown in Fig. 1. Both discharge data and environmental data was collected from Korean NPPs operators, while reference habitual data for Korean NPPs in KINS Guideline 2.2, Rev.2 being directly adopted for specific assessment [20,23]. In order to apply the general approach to Korean cases, the offsite dose calculation model addressed in Section 2.1 was further specified and tailored for Korean regulations.

Firstly, a set of dose terms $D_{k,n}(t)$ and target organs for retrospective assessment for existing dose constraints (see Step 3 in Fig. 1) with applicable exposure pathways, DCFs, and radionuclides of concern are provided in Table 3.

Secondly, two types of new dose terms, effective dose $E_n(t)$ and maximum equivalent dose $H_n(t)$, were specifically assumed since the same dose constraint terms have been applied to liquid effluent from Korean NPPs (see Table 2). This set of dose terms together with target organs assumed for retrospective assessment for new dose constraints (see Step 5 in Fig. 1) with applicable exposure pathways, DCFs, and radionuclides of concern are provided in Table 4. As such, the two terms of new dose constraints can be derived in terms of effective dose ($DC_{new,eff,n}$) and the equivalent dose ($DC_{new,eq,n}$).

Fig. 3 shows a schematic of the proposed stepwise approach to derive new dose constraints for Korean NPPs.

Table 3
Radiation dose terms and respective dose conversion factors (DCF) assumed to conduct retrospective assessment for the existing dose constraints [20,21,25–28].

Radiation dose	Organ	Pathway	Reference of DCF	Radionuclide
$D_{G1,n}(t)$	N/A	p_2	USNRC RG 1.109 Rev.1	Noble gas
$D_{G2,n}(t)$	N/A			
$D_{G3,n}(t)$	Effective		FGR 12	
$D_{G4,n}(t)$	Skin			
$D_{G5,n}(t)$	23 organs	p_1	ICRP 71	Except noble gas
		p_3	FGR 12	
		p_4	ICRP 72	
$D_{L1,n}(t)$	Effective	p_4	ICRP 72	All radionuclides
		p_5, p_6	FGR 12	
$D_{L2,n}(t)$	23 organs	p_4	ICRP 72	
		p_5, p_6	FGR 12	

Note: N/A means not applicable.

Table 4
Proposed radiation dose terms and respective dose conversion factors (DCF) assumed to conduct retrospective assessment for the new dose constraints [20,25–28].

Radiation dose	Organ	Pathway	Reference of DCF	Radionuclide
$E_n(t)$	Effective	p_2, p_3, p_5, p_6	FGR 12	All radionuclides
		p_1	ICRP 71	
		p_4	ICRP 72	
$H_n(t)$	23 organs	p_2, p_3, p_5, p_6	FGR 12	
		p_1	ICRP 71	
		p_4	ICRP 72	

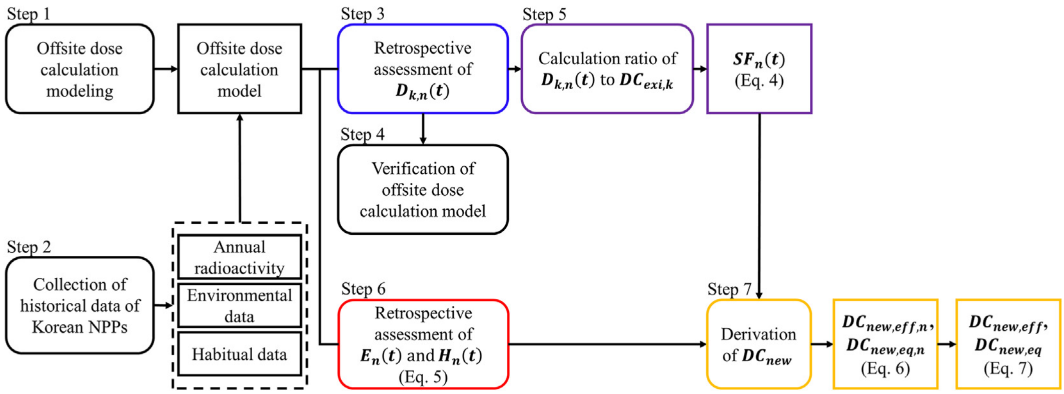

Fig. 3. Specific approach to derive new dose constraints for Korean NPPs adopted in this study.

3. Results and discussion

3.1. Offsite dose modeling and collection of discharge data for Korean NPPs

The offsite dose calculation model for Korean NPPs was established in accordance with Section 2.1 and materialized in a MS Excel® spreadsheet for repeated calculations (see Step 1 in Fig. 3). The annual discharge data and the environmental data was taken from official reports prepared by Korea Hydro and Nuclear Power Co. Ltd (KHNP) from 2009 to 2019 for 24 units of Korean NPPs, and the habitual data was sourced from KINS Guideline 2.2, Rev.2 [20,23]. The reason for using the data from 2009 is that the KHNP reports have been publicly available from the 2009 edition [29]. To analyze the data for NPPs in operational phase, the data for Kori Unit 1 and Wolsong Unit 1 permanently shut down in 2017 and 2019, respectively, was included up to the year preceding the year of permanent shutdown. In addition, Shin Kori Units 1 and 2 and Shin Wolsong Units 1 and 2 started commercial operations between 2009 and 2019, therefore discharge data was included for the years after commercial operations. Table 5 summarizes the basic information for the NPPs and the time span of the discharge data used in this study [30].

3.2. Verification of offsite dose calculation model adopted in this study

As explained in Section 2.4, $D_{k,n}(t)$ was calculated with the discharge data of each Korean NPP (see Step 3 in Fig. 3). To verify the dose calculation model in this study, calculated values of $D_{k,n}(t)$ were compared with the radiation doses officially reported from the 2012 to 2019 editions of the regulatory evaluation reports published by the KINS (see Step 4 in Fig. 3). The reason for using the reports since 2012 is that the radiation dose to the public from each unit reactor has been publicly available since 2012 in the KINS annual volumes [31]. All the publicly available input data presented in the KINS reports was also used in this study for verification purposes. Table 6 presents the statistics of the yearly averaged relative errors of $D_{k,n}(t)$ and the radiation doses from the KINS reports (See Case 1 in Table 6) and the yearly averaged relative

Table 5
Basic information on Korean NPPs and their respective data compiled in this study.

Site	Reactor	ID	Type	Design capacity (MWe)	Commercial operation date (Month/Day/Year)	Period of data used
Kori	Kori 1	K1	PWR	587	04/29/1978	2009 to 2016
	Kori 2	K2	PWR	650	07/25/1983	2009 to 2019
	Kori 3	K3	PWR	950	09/30/1985	
	Kori 4	K4	PWR	950	04/29/1986	
	Shin Kori 1	SK1	PWR	1000	02/28/2011	2012 to 2019
	Shin Kori 2	SK2	PWR	1000	07/20/2012	2013 to 2019
Wolsong	Wolsong 1	W1	PHWR	679	04/22/1983	2009 to 2018
	Wolsong 2	W2	PHWR	700	07/01/1997	2009 to 2019
	Wolsong 3	W3	PHWR	700	07/01/1998	
	Wolsong 4	W4	PHWR	700	10/01/1999	
Shin Wolsong	Shin Wolsong 1	SW1	PWR	1000	07/31/2012	2013 to 2019
	Shin Wolsong 2	SW2	PWR	1000	07/24/2015	2016 to 2019
Hanbit	Hanbit 1	H1	PWR	950	08/25/1986	2009 to 2019
	Hanbit 2	H2	PWR	950	06/10/1987	
	Hanbit 3	H3	PWR	1000	03/31/1995	
	Hanbit 4	H4	PWR	1000	01/01/1996	
	Hanbit 5	H5	PWR	1000	05/21/2002	
	Hanbit 6	H6	PWR	1000	12/24/2002	
Hanul	Hanul 1	U1	PWR	950	09/10/1988	
	Hanul 2	U2	PWR	950	09/30/1989	
	Hanul 3	U3	PWR	1000	08/11/1998	
	Hanul 4	U4	PWR	1000	12/31/1999	
	Hanul 5	U5	PWR	1000	07/29/2004	
	Hanul 6	U6	PWR	1000	04/22/2005	

Note: PWR and PHWR represent pressurized water reactor and pressurized heavy water reactor, respectively.

Table 6
Statistics (mean ± standard deviation) of the relative error for each dose term. Case 1 is for the relative error of the radiation doses calculated in this study and evaluated by the KINS, and Case 2 is for those reported by KHNP and evaluated by the KINS.

Dose term		D_{G1}	D_{G2}	D_{G3}	D_{G4}	D_{G5}	D_{L1}	D_{L2}
Relative error	Case 1	33% ± 73%	43% ± 168%	32% ± 60%	42% ± 87%	29% ± 40%	33% ± 48%	38% ± 60%
	Case 2	84% ± 515%	92% ± 523%	30% ± 65%	41% ± 71%	103% ± 667%	126% ± 312%	198% ± 1327%

errors of doses officially reported by the KHNP and evaluated by the KINS (See Case 2 in Table 6) for the 24 NPPs from 2012 to 2019 [23,31].

As shown in Table 6, the relative errors of $D_{k,n}(t)$ and the radiation doses from the KINS reports ranged from 29% to 43%. These errors can be attributed to the alternative input parameter values and conditions assumed in this study, which are not explicitly presented in the KINS reports (e.g. classification of age groups and habitual data, dilution factor of liquid effluent in the sea, critical organs and critical age groups, etc.). Furthermore, the different computational tools used by the KINS (i.e. an in-house computer code and an Integrated Dose Assessment Code package (INDAC), which is not publicly available) and this study (i.e. separately coded MS Excel® spreadsheets) may induce additional relative errors. To be more specific, different default input data for each version may occur relative errors since the used version of INDAC has not been specified in the KINS reports from 2015 to 2019 editions. Since the relative errors and the standard deviations of the radiation doses calculated in this study turned out to be much smaller than those reported by the KHNP with respect to the radiation doses evaluated by the KINS, it can be concluded that the dose calculation model in this study is reliable and can be used for retrospective assessment of $E_n(t)$ and $H_n(t)$.

3.3. Calculation of safety factor

Fig. 4 shows the distribution of safety factors $SF_n(t)$ for each NPP calculated for every year from 2009 to 2019 using Eq. (4) (see Step 5 in Fig. 3). $SF_n(t)$ was determined by the dose term G5 (i.e. an equivalent dose of radioactive iodine, ^{3}H, ^{14}C, and particulates) in 243 out of 246 reactor-year cases, since the ratios of $D_{G5,n}(t)$ to $DC_{exi,G5}$ ranging from 3.73×10^{-4} to 0.57 (or 0.048 ± 0.066) was approximately 50 times larger than the ratio of other dose terms ranging from 1.98×10^{-7} to 0.26 (or $9.08 \times 10^{-4} \pm 0.0083$). This indicates that the margin between the radiation dose $D_{G5,n}(t)$ and the corresponding dose constraint $DC_{exi,G5}$ is relatively small compared to those of the other dose terms. Furthermore, as shown in Fig. 4, the general increase in $SF_n(t)$ from 2012 implies that the assessed offsite radiation dose from Korean NPPs has increased as well. This can be ascribed to the reporting of ^{14}C from PWRs which commenced in 2012 [32]. However, it might not be the increase of actual radiation doses as ^{14}C was already being discharged but not reported before 2012. More details are discussed in Sections 3.4 and 3.5.

In the remaining 3 reactor-year cases (Wolsong Unit 1 in 2010, 2011, and 2013), $SF_n(t)$ was determined by the ratio of $D_{L1,n}(t)$ to $DC_{exi,L1}$. It is deduced by the relative increase of annual ^{60}Co radioactivity in liquid effluent in 2010 and 2011 compared to other years (approximately 3.5–3.9 times larger than the average annual ^{60}Co discharge from Wolsong Unit 1 from 2009 to 2019). The temporal increase of ^{60}Co can be ascribed to the replacement of pressure tubes of Wolsong Unit 1 between April 2009 and July 2011 [33].

3.4. Retrospective assessment to derive new dose constraint

The historical effluent data compiled in Section 3.1 was applied to the retrospective calculation of $E_n(t)$ and $H_n(t)$ for each Korean NPP using Eq. (5). The resulting $E_n(t)$ was calculated to be 0.0062 ± 0.0085 mSv/y (or 5.95×10^{-5} to 0.074 mSv/y), and $H_n(t)$ was to be 0.0074 ± 0.0099 mSv/y (or 6.17×10^{-5} to 0.086 mSv/y). The candlestick charts of $E_n(t)$ and $H_n(t)$ with statistical values for each NPP are provided in Figs. 5 and 6.

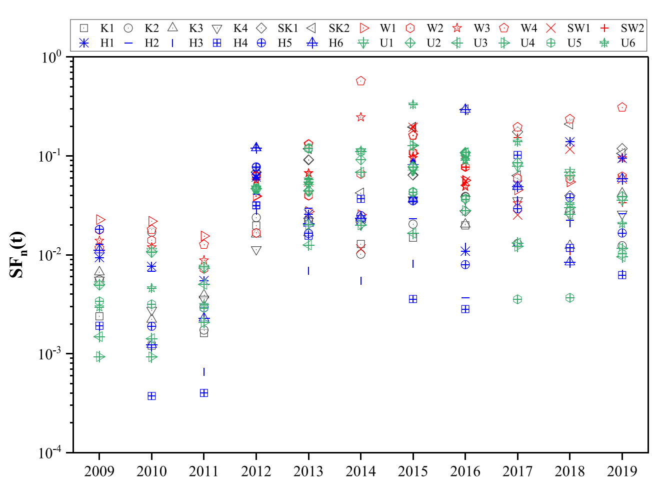

Fig. 4. Distribution of $SF_n(t)$ for each Korean NPP annually calculated from 2009 to 2019.

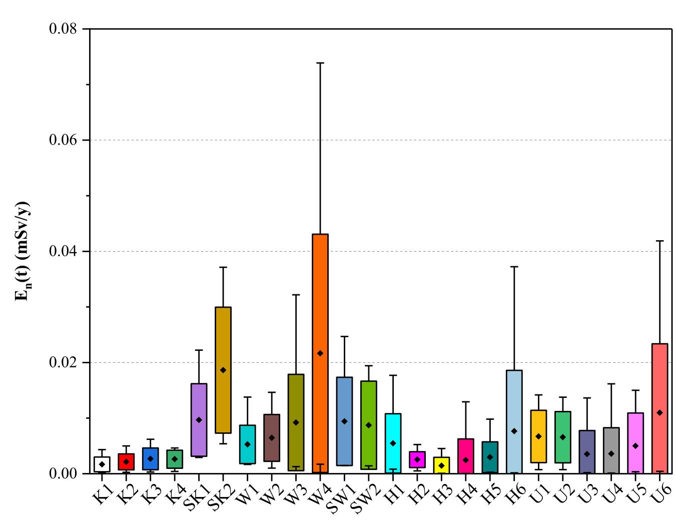

Fig. 5. Statistics of $E_n(t)$ retrospectively calculated for each unit of Korean NPP. The real body (i.e. bar) shows mean ± standard deviation, the lower shadow to the upper shadow (I) represents the range from minimum to maximum, and the diamond symbol (◆) indicates the mean.

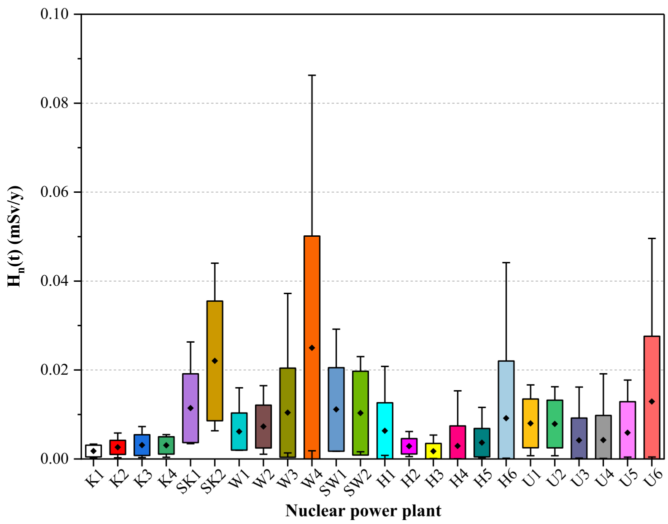

Fig. 6. Statistics of $H_n(t)$ retrospectively calculated for each unit of Korean NPP. The real body (i.e. bar) shows mean ± standard deviation, the lower shadow to the upper shadow (I) represents the range from minimum to maximum, and the diamond symbol (◆) indicates the mean.

It is evident that $E_n(t)$ and $H_n(t)$ of each NPP show different statistical distributions and no specific trends or similarities can be found for the reactors at the same site or of the same type. However, the statistical trend of $E_n(t)$ for each NPP are similar to those of $H_n(t)$, and the order of the mean values in both figures are the same. This implies that the organ receiving the highest equivalent dose and thus determining $H_n(t)$ in Fig. 6 mostly contributes to $E_n(t)$ in Fig. 5. For all Korean NPPs, $H_n(t)$ was determined by the 1-year-old age group, and the stomach was the critical organ with the most significant contribution, followed by the bone surface and lower large intestine.

The $E_n(t)$ and $H_n(t)$ calculated for 4 pressurized heavy water reactors (PHWRs) were about 2.7 times larger than those of 20 pressurized water reactors (PWRs) on average. The PHWRs obtained the maximum $E_n(t)$ and $H_n(t)$ among all NPPs for 8 out of 11 years. The results were deduced to 16.1 times and 2.8 times larger radioactivity of ^{3}H and ^{14}C, respectively, in gaseous effluent discharged annually from PHWRs compared to the average of them from PWRs. The larger discharge of ^{3}H from PHWRs is because heavy water (D_2O) is used as the coolant and moderator, leading to more $^{2}H(n,\gamma)^{3}H$ reaction than in PWRs. Additionally, the larger ^{14}C discharge from PHWRs is due to a greater contribution of $^{17}O(n,\alpha)^{14}C$ reaction because of the higher isotopic abundance of ^{17}O in heavy water than in ordinary water [34].

Fig. 7 shows the ratio of the radiation doses from gaseous effluent to total radiation doses in terms of $E_n(t)$ and $H_n(t)$; the radiation dose from gaseous effluent accounted for approximately 99% of $E_n(t)$ and $H_n(t)$ for most NPPs. It is presumed that the exclusion of drinking water from exposure pathways of Korean NPPs resulted in a relatively small radiation dose from liquid effluent. In fact, the total body dose and the maximum organ dose from liquid effluent in the APR 1400 Design Control Document, which explicitly includes the drinking water pathway, are about 11 times and 1.4 times higher than the effective dose and the maximum equivalent dose of the first APR 1400 NPPs (i.e. Shin Kori Units 3&4) in operation at a coastal region where the drinking water pathway is screened out [24,35].

The contributions of liquid effluent from PHWRs to the total radiation dose were generally larger than that from PWRs, which can be attributed to 1.6 to 4.5 times larger discharge of fission and activation products in liquid effluent from PHWRs than PWRs as observed in the discharge data compiled in Section 3.1. As in Fig. 7(b), the ratio of the radiation dose from liquid effluent to the total radiation dose was greater than 10% in 5 out of 246 cases. For instance, the radiation dose from liquid effluent accounted for 19% of $H_n(t)$ due to the increase of ^{60}Co discharge in liquid effluent from Wolsong Unit 1 in 2010 as described in Section 3.3. In the case of Hanbit Unit 3 in 2014, the maximum equivalent dose from liquid effluent accounted for 11% of $H_n(t)$, which can be ascribed to the largest annual discharge of ^{131}I in liquid effluent among all NPPs caused by the leakage of steam generator tubes at Hanbit Unit 3 reported in 2014 [36].

The dominant radionuclides contributing to the radiation dose from gaseous effluent from 2009 to 2019 were ^{14}C (68.2% in $E_n(t)$ and 68.8% in $H_n(t)$), ^{3}H (30.5% in $E_n(t)$ and 30.0% in $H_n(t)$), and ^{41}Ar (0.5% for both $E_n(t)$ and $H_n(t)$). Whereas ^{3}H (63.4% in $E_n(t)$ and 66.1% in $H_n(t)$), ^{95}Nb (10.4% in $E_n(t)$ and 8.8% in $H_n(t)$), and ^{60}Co (7.5% in $E_n(t)$ and 7.7% in $H_n(t)$) mainly contributed to the radiation dose from liquid effluent. From 2009 to 2019, ^{3}H accounted for 88.0% ± 17.3% (an average of 2.39 TBq/y) and 92.1% ± 11.3% (an average of 38.68 TBq/y) in the radioactivity of gaseous effluent annually discharged from PWRs and PHWRs, respectively. On the

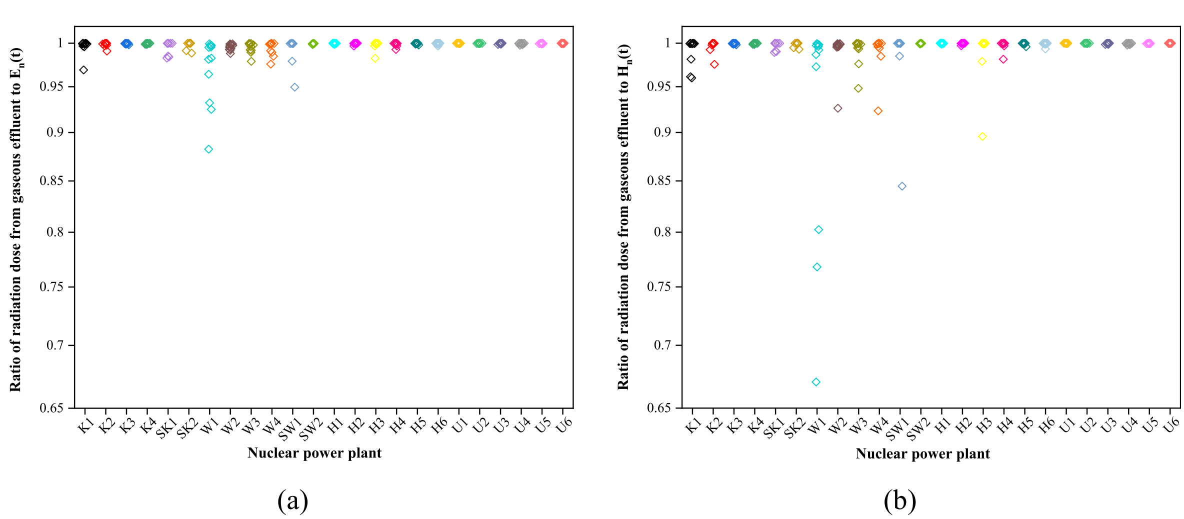

Fig. 7. Ratio of radiation dose from gaseous effluent to total radiation dose for each Korean NPP: (a) is for the effective dose and (b) is for the maximum equivalent dose. The diamond symbol (◇) represents the ratio of the radiation dose from gaseous effluent to the total radiation dose for each NPP in each year.

other hand, ^{14}C accounted for 4.8% ± 0.6% (an average of 0.08 TBq/y) and 5.5% ± 0.5% (an average of 0.19 TBq/y) in total gaseous radioactivity from PWRs and PHWRs, respectively. Although the radioactivity of ^{14}C was less than ^{3}H in gaseous effluent, ^{14}C contributed more than ^{3}H to the total radiation dose due to its higher dose conversion factors. That is, the effective dose conversion factor for ^{14}C ingestion (1.6×10^{-9} Sv/Bq) is about 33 times larger than that for ^{3}H (4.8×10^{-11} Sv/Bq) for the 1-year-old age group [27].

3.5. Derivation of new dose constraints

3.5.1. $DC_{new,eff,n}$ and $DC_{new,eq,n}$ for each NPP

3.5.1.1. $DC_{new,eff,n}$ and $DC_{new,eq,n}$ from 2009 to 2019 discharge data. Based on the results from Sections 3.3 and 3.4, $DC_{new,eff,n}$ and $DC_{new,eq,n}$ were derived using Eq. (6) (see Step 7 in Fig. 3). Figs. 8 and 9 present the candlestick charts of calculated $DC_{new,eff,n}(t)$ and $DC_{new,eq,n}(t)$.

$DC_{new,eff,n}(t)$ and $DC_{new,eq,n}(t)$ were calculated to be 0.13 ± 0.017 mSv/y (or 0.035–0.16 mSv/y) and 0.15 ± 0.0074 mSv/y (or 0.081–0.21 mSv/y), respectively. According to Eq. (6), $DC_{new,eff,n}$ and $DC_{new,eq,n}$ of each NPP from 2009 to 2019 are the maximum values of $DC_{new,eff,n}(t)$ and $DC_{new,eq,n}(t)$ for each NPP in Figs. 8 and 9; were 0.15 ± 0.0091 mSv/y (or 0.13–0.16 mSv/y) and 0.16 ± 0.015 mSv/y (or 0.15–0.21 mSv/y), respectively. Since $SF_n(t)$ was mostly determined by the dose term G5 as explained in Section 3.3 and $DC_{exi,G5}$ is constant (0.15 mSv/y), the ratios of $E_n(t)$ to $D_{G5,n}(t)$ and that of $H_n(t)$ to $D_{G5,n}(t)$ are the controlling factors to determine the new dose constraints $DC_{new,eff,n}$ and $DC_{new,eq,n}$ in Eq. (6).

The highest ratios of $E_n(t)$ to $D_{G5,n}(t)$ and $H_n(t)$ to $D_{G5,n}(t)$ for each NPP are close to the unity ("1"), that is, 0.99 ± 0.06 (or 0.85 to 1.07) and 1.07 ± 0.09 (or 1.00 to 1.42), respectively. The highest ratios close to the unity can be interpreted by the ratios of the effective dose conversion factor to the equivalent dose conversion factor for a critical organ of ^{14}C and ^{3}H in gaseous effluent; calculated to be 0.84 and 1, respectively. Moreover, the ratio of $H_n(t)$ to $D_{G5,n}(t)$ for gaseous ^{14}C and that of ^{3}H are exactly unity because the DCFs for $H_n(t)$ and $D_{G5,n}(t)$ are the same for those radionuclides. Additionally, the radiation dose from liquid effluent and that from noble gases in gaseous effluent increase the ratios further because the additional liquid effluent and the noble gases contribute to increase $E_n(t)$ and $H_n(t)$ values, while $D_{G5,n}(t)$ is not affected by them.

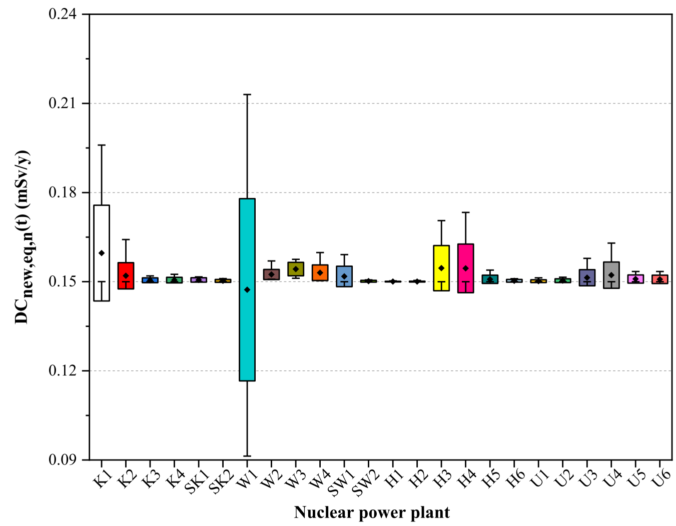

Fig. 9. Statistics of $DC_{new,eq,n}(t)$ derived for 2009 to 2019. The real body (i.e. bar) is mean ± standard deviation, the lower shadow to the upper shadow (I) represents the range from minimum to maximum, and the diamond symbol (◆) indicates the mean.

3.5.1.2. $DC_{new,eff,n}$ and $DC_{new,eq,n}$ from 2012 to 2019 discharge data. As of 2012, gaseous discharge of ^{14}C from PWRs has been included in the annual discharge report (see Section 3.3), therefore, $DC_{new,eff,n}$ and $DC_{new,eq,n}$ were additionally derived using the data from 2012 to 2019. Figs. 10 and 11 show the statistical values of calculated $DC_{new,eff,n}(t)$ and $DC_{new,eq,n}(t)$ for each NPP derived as such.

$DC_{new,eff,n}$ and $DC_{new,eq,n}$ for 2012 to 2019 are the maximum values of $DC_{new,eff,n}(t)$ and $DC_{new,eq,n}(t)$ for each NPP in Figs. 10 and 11 $DC_{new,eff,n}$ and $DC_{new,eq,n}$ were derived to be 0.13 ± 0.0058 mSv/y (or 0.13–0.15 mSv/y) and 0.15 ± 0.0041 mSv/y (or 0.15–0.17 mSv/y), respectively. The results are 12.4% and 5.0% less than those of the period 2009 to 2019 derived in Section 3.5.1.1.

The ratios of $E_n(t)$ to $D_{G5,n}(t)$ and that of $H_n(t)$ to $D_{G5,n}(t)$ decreased because the discharge data from 2009 to 2011 that did not include gaseous discharge of ^{14}C from PWRs was excluded. From 2009 to 2011, the $E_n(t)$ to $D_{G5,n}(t)$ ratio of each PWR was

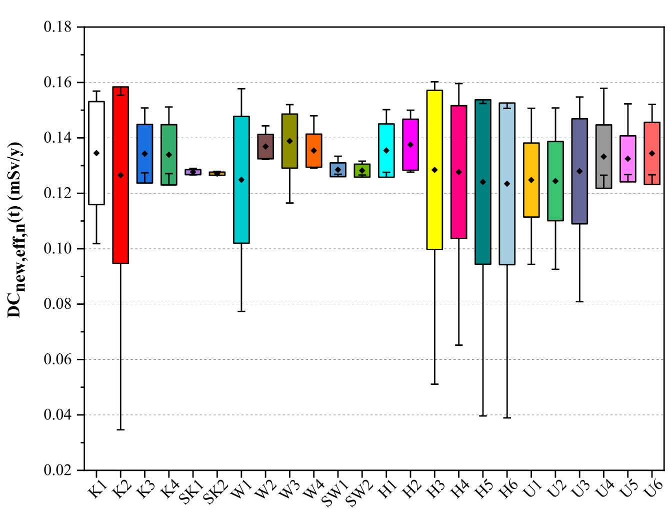

Fig. 8. Statistics of $DC_{new,eff,n}(t)$ derived for 2009 to 2019. The real body (i.e. bar) is mean ± standard deviation, the lower shadow to the upper shadow (I) represents the range from minimum to maximum, and the diamond symbol (◆) indicates the mean.

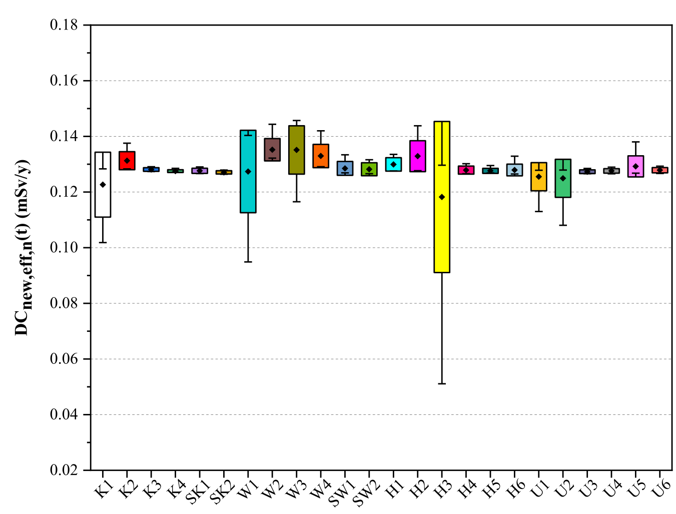

Fig. 10. Statistics of $DC_{new,eff,n}(t)$ derived for 2012 to 2019. The real body (i.e. bar) is mean ± standard deviation, the lower shadow to the upper shadow (I) represents the range from minimum to maximum, and the diamond symbol (◆) indicates the mean.

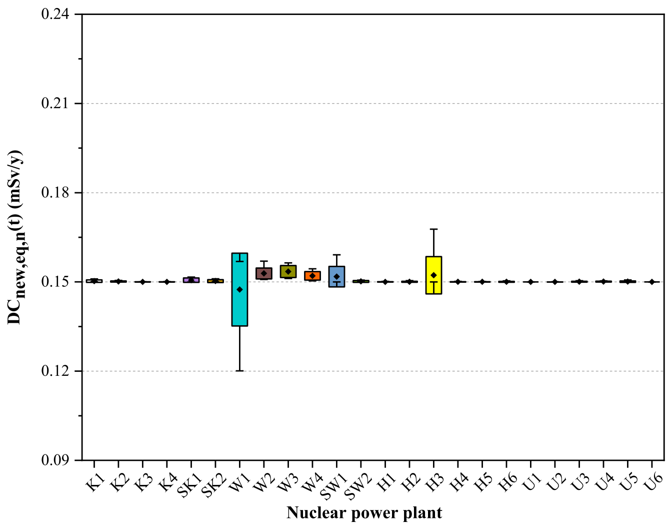

Fig. 11. Statistics of $DC_{new,eq,n}(t)$ derived for 2012 to 2019. The real body (i.e. bar) is mean ± standard deviation, the lower shadow to the upper shadow (I) represents the range from minimum to maximum, and the diamond symbol (◆) indicates the mean.

0.91 ± 0.22, which is similar to the ratios of their respective DCFs for ^{3}H (1 as discussed in Section 3.5.1.1). However, it decreased to 0.85 ± 0.05 which is similar to the ratio of their respective DCFs for ^{14}C (0.84) due to the exclusion of the gaseous discharge of ^{14}C from PWRs for the 2009 to 2011 period and the dominant contribution of ^{14}C to the radiation dose from 2012 to 2019. Similarly, the ratio of $H_n(t)$ to $D_{G5,n}(t)$ for PWRs from 2012 to 2019 (1.00 ± 0.01) decreased by 3.4% compared to the ratio for 2009 to 2011 (1.04 ± 0.05). It can be ascribed to the reduced relative contribution of noble gases and increased relative contribution of ^{14}C since 2012. Accordingly, the 2012 to 2019 derived values of $DC_{new,eff,n}$ and $DC_{new,eq,n}$ are generally less than those of 2009–2019.

Moreover, standard deviations for 2012 to 2019 of $DC_{new,eff,n}(t)$ and $DC_{new,eq,n}(t)$ (0.0078 and 0.0029, respectively), shown in Figs. 10 and 11, are 54% and 60.5% less than those for 2009 to 2019 (0.017 and 0.0075, respectively) in Figs. 8 and 9. This can be ascribed to the higher heterogeneity of the 2009 to 2019 discharge data in which gaseous ^{14}C discharge from PWRs was not included for the first three years.

Consequently, the discharge data of ^{14}C in gaseous effluent from PWRs is expected to have a major impact on the determination of the dose constraints of radioactive effluent from Korean NPPs. Thus, to ensure consistency in discharge data, it is proposed that the new dose constraints for Korean NPPs are derived by applying the discharge data for the period 2012 to 2019 when the discharge of gaseous ^{14}C from PWRs was fully reported.

3.5.2. *Dominant radionuclides affecting new dose constraints*

For more specific analysis, Fig. 12 shows the annual average contribution of each dominant radionuclide to the effective dose caused by gaseous effluent from each site for the 2009 to 2011 and 2012 to 2019 periods. Fig. 13 depicts similar data but for the maximum equivalent dose.

As illustrated in Fig. 12, the three most dominant radionuclides contributing to the effective dose from gaseous effluent from PWRs for 2009 to 2011 were ^{3}H (95.7%), ^{131}I (1.4%), and ^{41}Ar (1.2%). From 2012 onwards, ^{14}C (90.7%) took the lead and was followed by ^{3}H (9.1%) and ^{131}I (0.1%). The maximum equivalent dose from gaseous effluent in Fig. 13 shows a similar trend for the effective dose observed in Fig. 12. Additionally, the critical organ for $H_n(t)$ was skin, lower large intestine, and bone surface from 2009 to 2011, but mostly the stomach from 2012 onwards.

For PHWRs in Korea, ^{14}C discharge has been reported since 1998 [37]. The effective and maximum equivalent doses in terms of the major radionuclides from PHWRs were ^{3}H (55.2%), ^{14}C (43%), and ^{41}Ar (1.6%) from 2009 to 2011, and ^{14}C (71.8%), ^{3}H (26.6%), and ^{41}Ar (1.5%) for 2012 to 2019. This change can be ascribed to the reduced release of ^{3}H owing to the operation of a Tritium Removal Facility installed at the Wolsong Site for PHWRs in 2007 and increasing tendency of gaseous ^{14}C discharge from the PHWRs during 2010–2019 [38].

3.5.3. ***$DC_{new,eff}$*** *and* ***$DC_{new,eq}$*** *for each site, each reactor type, and for all Korean NPPs*

Through this process, the lower bounds of the new dose constraint, $DC_{new,eff}$ and $DC_{new,eq}$, were derived using the 2012 to

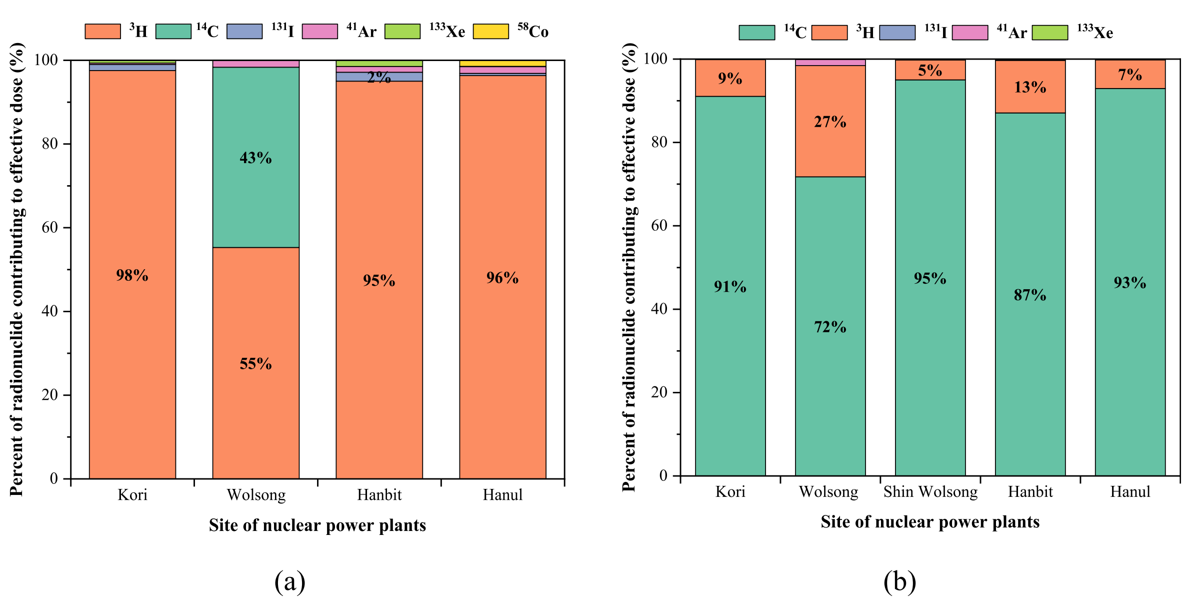

Fig. 12. Average percentage of each radionuclide contributing to the effective dose caused by gaseous effluent from each Korean nuclear power plant site: (a) from 2009 to 2011 and (b) from 2012 to 2019.

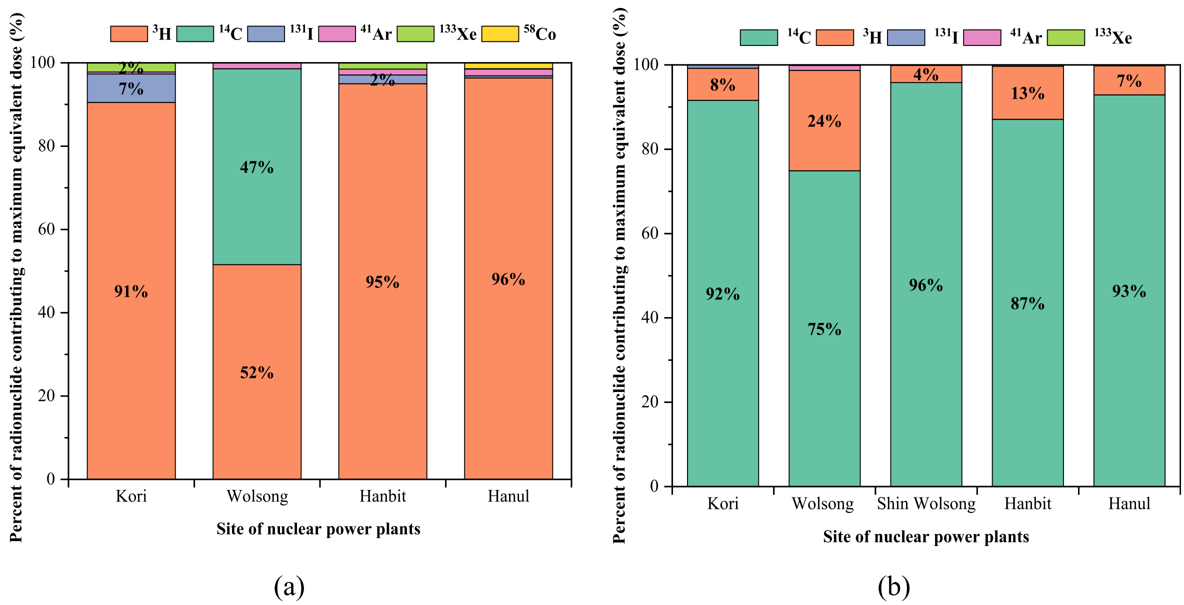

Fig. 13. Average percentage of each radionuclide contributing to the maximum equivalent dose caused by gaseous effluent from each Korean nuclear power plant site: (a) from 2009 to 2011 and (b) from 2012 to 2019.

2019 discharge data for each site, each reactor type, and all NPPs in Korea (see Table 7).

Because the maximum values of all derived dose constraints from all units at a site $DC_{new,n}$ were selected as the dose constraints DC_{new} using Eq. (7), it can be said that the new dose constraints for each site are determined by discharge characteristics of each NPP rather than site-specific features. This also applies to the dose constraints for each reactor type and for all NPPs in Korea. $DC_{new,eff}$ of 0.15 mSv/y derived for all Korean NPPs was determined by the $DC_{new,eff,n}(t)$ of Wolsong Unit 3 in 2012 in which the largest contribution of gaseous ^{41}Ar (4.34%) to $E_n(t)$ and the relatively less contribution of ^{14}C (41.4%) compared to the average of all NPPs (87.6%) were observed. Furthermore, $DC_{new,eq}$ of 0.17 mSv/y for all Korean NPPs was determined by the $DC_{new,eq,n}(t)$ of Hanbit Unit 3 in 2014 in which the largest annual discharge of ^{131}I in liquid effluent (see Section 3.4) resulted in the highest ratio of $H_n(t)$ to $D_{G5,n}(t)$.

The derived value of $DC_{new,eff}$ for all Korean NPPs (0.15 mSv/y) is reasonably acceptable compared to the IAEA recommended generic dose constraint, and the practical dose constraints used by other countries in Table 1, 0.05 to 0.3 mSv/y. Moreover, it is the middle of the range of previously proposed effective dose constraints per reactor in investigations by Lee (0.1 mSv/y) and Kong et al. (0.2 mSv/y).

On the other hand, this study concludes that the equivalent dose constraint may not be established in line with the international standard which recommends set the dose constraint for radioactive discharge control in terms of 'annual effective dose', and additionally states that the equivalent dose limits to specific organs (e.g. lens of the eye, skin, etc.) are not relevant for radioactive discharges during normal operation because of the conditions in which such exposure would typically occur [1]. Furthermore, the compliance with the derived effective dose constraint can prevent the equivalent dose from exceeding the equivalent dose limits. That is, when the effective dose is assessed to be its constraint derived in this study (i.e. 0.15 mSv/y), the maximum equivalent dose will be 15 mSv/y for the skin or the bone surface which has the smallest tissue weighting factor (0.01) among various organs, which means that the existing equivalent dose limit such as 50 mSv/y to the skin will not be exceeded [16]. In Germany, the existing equivalent dose constraints for radioactive discharges were removed because separate calculations for the equivalent doses would not be necessary due to the reason above [39].

Additionally, based on the lower bound of the new effective dose constraint derived in this study, an optimization process might be necessary to revise the existing dose constraints in Korean regulations (see Table 2).

Table 7
$DC_{new,eff}$ and $DC_{new,eq}$ for each site, each reactor type, and all NPPs in Korea (mSv/y).

Target		$DC_{new,eff}$	$DC_{new,eq}$
Site	Kori	0.14	0.15
	Wolsong	0.15	0.16
	Shin Wolsong	0.13	0.16
	Hanbit	0.14	0.17
	Hanul	0.14	0.15
Reactor type	PWR	0.14	0.17
	PHWR	0.15	0.16
All Korean NPPs		0.15	0.17

4. Conclusion

A general model to derive a new dose constraint for radioactive effluent from a single unit of NPP with operational flexibility through retrospective assessment using historical discharge data was developed in this study. The dose constraint for each NPP, each site, each reactor type, or all NPPs in a country can be derived using the proposed model. As a test case, this study developed a specific model to propose new dose constraints for Korean NPPs using actual discharge data from 2012 to 2019. The derived lower bound of the effective dose constraint is 0.15 mSv/y for all Korean NPPs and it turned out to be comparable to the recommended values in the international standards, the international practices (0.05–0.3 mSv/y), and the results of previous studies (0.1 and 0.2 mSv/y). Although the lower bound of the maximum equivalent dose constraint was also derived to be 0.17 mSv/y for Korean NPPs, this study suggests establishing a single dose constraint in terms of effective dose since it is in line with the international standards and since the compliance with the derived effective dose constraint can also prevent accompanied equivalent doses from exceeding existing equivalent dose limits. Furthermore, an optimization process might be necessary to determine a single value of dose constraint based on the lower bound of new effective dose constraint derived in this study. As the basic equation of the proposed model, the following controlling factors were identified to derive the new dose constraint: the safety factor to retain the margin between calculated radiation dose and the existing dose constraints, and the larger ratio of the newly assessed radiation dose for the new dose constraint to radiation dose for the existing dose constraint.

In the process of deriving new dose constraints for Korean NPPs, the ratios of the radiation dose to the existing dose constraint of the maximum equivalent dose of radioactive iodine, ^{3}H, ^{14}C, and particulates in gaseous effluent were selected for most cases and used to reflect operational flexibility. In addition, the dominant radionuclides contributing to derivation of new dose constraints turned out to be ^{14}C, ^{3}H, and ^{41}Ar in gaseous effluent which account for about 99% of the effective dose and the maximum equivalent dose from liquid and gaseous effluent. In addition, the temporal increase in discharge of specific radionuclides (e.g., ^{131}I, ^{60}Co, etc.) in liquid effluent contributed to determining the dose constraints. Particularly, the dose constraints derived using the data from 2012 to 2019 were smaller than those derived using the data from 2009 to 2019. It can be attributed to the fact that the gaseous discharge of ^{14}C from PWRs has only been reported since 2012. Thus, it is proposed that the new dose constraints for Korean NPPs should be derived by applying discharge data for the period 2012 to 2019 for consistency in discharge data. It is additionally recommended to check the consistency of discharge data when applying the general model of this study, since the above analysis implies that the inconsistent discharge data may cause misleading results.

The generalized model and retrospective assessment framework developed in this study are expected to be used to derive new dose constraints for radioactive discharges from a single unit of NPP or a group of NPPs in a country by reflecting operational flexibility based on historical discharge data.

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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