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Technical Note

Administrative dose control for occupationally-exposed workers in Korean nuclear power plants

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ABSTRACT

Korean nuclear power plants (NPPs) have various radiation protection programs to attain radiation exposure as low as reasonably achievable (ALARA). In terms of ALARA, this paper provides a comprehensive overview of administrative dose control for occupationally-exposed workers in Korean NPPs. In addition to dose limits, administrative dose constraints are implemented to resolve an inequity of radiation exposure in which some individuals in NPPs receive relatively higher doses than others. Occupational dose constraints in Korean NPPs are presented in this paper with the background of how those values were determined. For pressurized water reactors, 80% and 90% of the annual average limit for an effective dose, 20 mSv/y, are set as the primary and secondary dose constraints, respectively. Pressurized heavy water reactors (PHWRs) have also established the primary and secondary dose constraints corresponding to 70% and 80% of the effective dose limit, and additional constraints for tritium concentration are provided to control internal exposure in PHWRs. Follow-up measures for exceeding these administrative dose constraints are also introduced compared to exceeding the dose limits. Finally, analysis results of dose distributions show how the implementation of administrative dose constraints impacted the occupational dose distributions in Korean NPPs during the years 2009–2018.

1. Introduction

Occupational workers in nuclear power plants (NPPs) are likely to receive radiation exposure during maintenance activities. Although there is a regulatory dose limit for occupational workers to protect them from excessive exposure, Korean NPPs provide a more aggressive radiation protection program not only to attain radiation exposure as low as reasonably achievable (ALARA), taking into account societal and economic factors but also to resolve the inequity in the occupational dose distribution. Implementation of administrative dose constraints is one of the most significant ALARA measures in Korean NPPs, preventing radiation workers from exceeding a particular dose level below the limit [1].

ALARA and dose constraints usually have the same goal to reduce the radiation doses as low as reasonably achievable; however, it should be clear that ALARA is a goal or objective of radiation protection, and dose constraints are one of the operational tools to achieve ALARA. Specifically, under the principle of ALARA, the minimization of all radiation doses has been pursued to ensure an adequate level of radiation protection. On the other hand, dose constraints are aimed at minimizing inequitable radiation doses that are relatively higher than the average using the analysis of dose distribution. It should also be noted that the application of ALARA and dose constraints involves highly subjective value judgments, which may include economic and other societal factors.

Korean NPPs have established administrative dose constraints by optimization process to achieve goals of both keeping radiation exposure at low levels and not providing an excessive economic burden to NPP operation. The constraints are applied to all Korean NPPs with the same conditions since all Korean NPPs belong to Korea Hydro & Nuclear Power (KHNP), the state-run NPP operator in Korea. This paper not only introduces the occupational dose control system, focusing on dose constraints dedicated to Korean NPP operation but also shows how administrative dose constraints are implemented in practice.

2. Concept of dose constraints

The International Committee on Radiological Protection (ICRP)

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introduced the dose constraint to reduce the substantial inequity of radiation exposure between individuals [2,3]. According to ICRP Publication 103, a dose constraint is defined as a prospective and source-related restriction on the individual dose from a radiation source in a planned exposure situation [2]. That is, a dose constraint is established to control potential radiation exposure from a single source during normal operation. However, there are multiple radiation sources in an NPP, and this situation could be complicated for setting dose constraints for all sources in the field. Thus, the dose constraint is generally established for a dominant source in an NPP, which is also recommended by the ICRP [2].

In order to provide more effective protection measures depending on the target to be controlled, two approaches, individual-related and source-related, are introduced by the ICRP. The individual-related approach focuses on controlling the radiation exposure of an individual from multiple sources, while the source-related approach focuses on controlling the single source, which is able to give radiation exposure to individuals, as illustrated in Fig. 1 [2]. For example, dose limits are applicable to an individual-related approach, while dose constraints or reference levels are applicable to a source-related approach. A reference level is similar to a dose constraint; however, its suitable exposure situation is different from that for a dose constraint. A reference level is used in emergency or existing exposure situations [2]. Table 1 shows the different types of restrictions on individual doses depending on exposure situations and categories of exposure [2].

The source of radiation exposure is used as the target for implementing a dose constraint. If some individuals receive much more radiation exposure than others, radiation protection options can be carried out to reduce the radiation doses, such as installing additional shielding materials, improving water chemistry to prevent from occurring radioactive corrosion products, etc. Options resulting in radiation doses greater in extent than dose constraints should be excluded at the planning stage. Occupational dose constraints are set voluntarily by a nuclear licensee to lower the individual doses, which are relatively higher than the average [4]. Thus, dose constraints should not be used as a prescriptive regulatory limit [2]. Dose constraints focus on narrowing the distribution of individual doses toward low levels to resolve inequities of radiation exposure among individual workers. Fig. 2 shows the distribution of individual doses before and after the implementation of dose constraints [2]; individual doses levels beyond a dose constraint can be allowed, but if additional measures are taken, the dose levels can decrease.

3. Dose limits in Korean NPPs

Dose limits are regulatory requirements applied to both occupational and public exposure in planned exposure situations. Thus, exceeding a dose limit is a violation of Korean regulation. According to Korean nuclear safety regulations, the dose limit is defined as the upper limit of the total amount of external and internal radiation exposure dose [5]. The values of dose limits are based on ICRP Publication 60 and the International Basic Safety Standards, which were issued by the International Atomic Energy Agency (IAEA) [3,6]. Both the ICRP and IAEA have the same dose limits. Table 2 demonstrates individual dose limits for effective dose and equivalent dose from all regulated sources in planned exposure situations [5]. In Table 2, a radiation worker is defined as an individual who is routinely exposed to radiation while working. On the other hand, a person with frequent access means an individual who frequently accesses a radiation controlled area (RCA) on duty, such as housekeeping, other than radiation workers. A transport worker is defined as an individual who is involved in the transport of radioactive materials in non-RCAs.

4. Administrative dose constraints in Korean NPPs

The Korean regulatory body does not currently require NPP licensees to set occupational dose constraints; however, Korean NPPs are familiar with the concept of dose constraint because they have already established ALARA planning values, such as self-imposed dose constraints, in their radiation protection programs. Since these administrative dose constraints are set and implemented voluntarily by nuclear licensees, exceeding an administrative dose constraint is not a violation of Korean regulations. If an

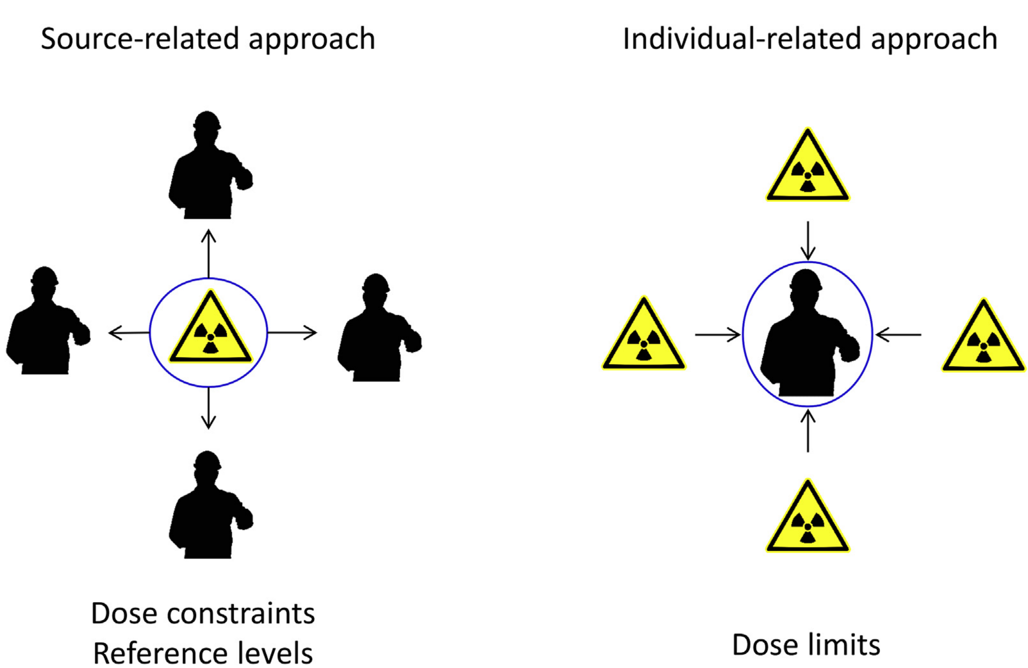

Fig. 1. Differences between source-related and individual-related approaches.

Table 1
Different types of restrictions on individual doses depending on exposure situations and categories of exposure.

Exposure situations	Occupational exposure	Public exposure	Medical exposure
Planned	Dose limit Dose constraint	Dose limit Dose constraint	Diagnostic reference level[a] (Dose constraint[b])
Emergency	Reference level[c]	Reference level	Not applicable
Existing	Not applicable[d]	Reference level	Not applicable

[a] Patients.
[b] Caregivers, comforters, and volunteers in research only.
[c] Long-term recovery operations belong to planned occupational exposure.
[d] Exposures resulting from long-term remediation operations or from extended work in contaminated areas should be treated as part of planned occupational exposure, although the source of radiation is 'existing.'

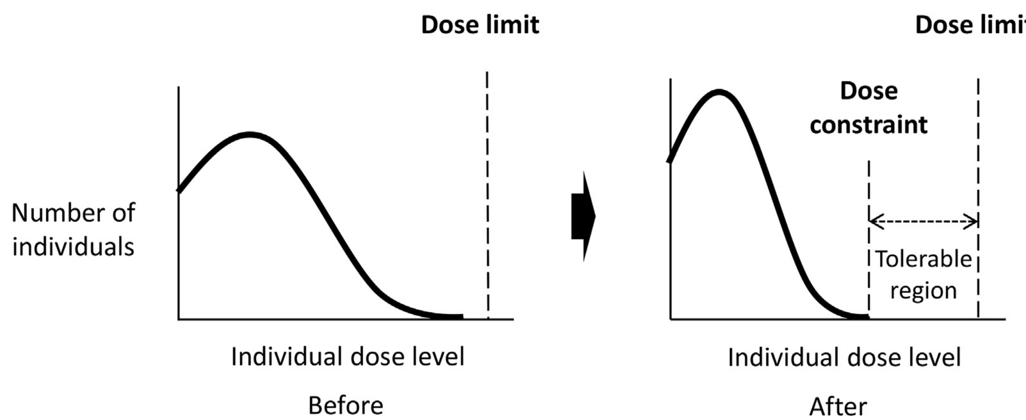

Fig. 2. Distribution of individual doses as a result of the use of dose constraints.

Table 2
Dose limits in Korean nuclear safety regulations.

Classification		Radiation worker	Persons with frequent access or engaging in transport	Public
Effective dose		100 mSv/5y or 50 mSv/y[a]	6 mSv/y	1 mSv/y
Equivalent dose	Lens of the eye	150 mSv/y	15 mSv/y	15 mSv/y
Equivalent dose	Hands, feet, and skin	500 mSv/y	50 mSv/y	50 mSv/y

[a] Occupational dose limit of 100 mSv over five years with no more than 50 mSv in a single year.

administrative dose constraint is exceeded, an NPP is required to take measures to check whether the protection was optimized and whether additional steps to reduce doses to acceptable levels would be proper.

The total number of operating nuclear power reactors in Korea is 25, including 21 pressurized water reactors (PWRs) and four pressurized heavy water reactors (PHWRs) [7]. All nuclear power reactors belong to the sole nuclear licensee, Korea Hydro & Nuclear Power (KHNP), and apply the same administrative dose constraints to their radiation protection programs, depending on the type of nuclear power reactor, PWR or PHWR. To establish administrative dose constraints, Korean NPPs select a two-unit power plant as a single source since radiation workers commonly carry out maintenance jobs at two units [1,4]. Administrative dose constraints for occupationally-exposed workers in Korean NPPs are summarized in Table 3 [1]. Particularly, Table 3 provides the upper administrative limits of tritium concentration in the human body, taking into account internal radiation exposure due to tritium at PHWRs. For PWRs, 80% and 90% of the annual average limit for an effective dose, 20 mSv/y, are determined as the primary and secondary administrative dose constraints, respectively. Since a radiation worker is likely to be exposed by tritium in PHWRs, 70% and 80% of the effective dose limit are set as the primary and secondary administrative dose constraints, respectively, and additional constraints for tritium concentration are provided to restrict internal radiation exposure in PHWRs. According to the KHNP radiation protection program, 1,850 Bq/cm^3 and 3,700 Bq/cm^3 in the urine sample, as shown in Table 3, are evaluated as effective doses of 0.75 mSv and 1.50 mSv, respectively [8]. If the tritium concentration decreases below 740 Bq/cm^3, corresponding to an effective dose of 0.3 mSv, the radiation work restrictions at PHWRs are lifted. In terms of equivalent dose, 80% of the equivalent dose limit is determined as administrative dose constraint.

5. Follow-up measures for exceeding administrative dose constraints and dose limits in Korean NPPs

If an individual needs to conduct radiation work exceeding the primary administrative dose constraints, the worker should submit an exception request to the radiation safety manager prior to work being scheduled. The radiation safety manager determines whether the work is approved or not after reviewing the request, including an interview with the applicant, if necessary. If an exception request is approved, all records of the radiation exposure history, including the date of work completed, dosimeter numbers, etc., are maintained in the radiation exposure database. In cases of exceeding the secondary dose constraints, the supervisor of the maintenance job instead of the worker should submit an exception request to the radiation safety manager before the work is planned. Unlike the previous case of exceeding the primary dose constraints,

Table 3
Administrative dose constraints for occupationally-exposed workers in Korean nuclear power plants.

Classification		Radiation worker		Persons with frequent access or engaging in transport	
		PWR[a]	PHWR[b]	PWR	PHWR
Effective dose	Primary	16 mSv/y	14 mSv/y	4 mSv/y	3 mSv/y
	Secondary	18 mSv/y	16 mSv/y	5 mSv/y	4 mSv/y
Equivalent dose	Lens of the eye	120 mSv/y		12 mSv/y	
	Hands, feet, and skin	400 mSv/y		40 mSv/y	
Tritium concentration in the human body[c]	Limitation on work	1,850 Bq/cm^3		1,850 Bq/cm^3	
	Prohibition of work	3,700 Bq/cm^3		3,700 Bq/cm^3	

[a] 80% and 90% of the annual average limit for an effective dose, 20 mSv/y, are determined as the primary and secondary administrative dose constraints for PWRs, respectively.
[b] 70% and 80% of the effective dose limit are set as the primary and secondary administrative dose constraints, respectively, and additional constraints for tritium concentration are provided to restrict internal radiation exposure in PHWRs.
[c] Applicable to PHWRs only.

the plant manager determines whether the work is allowed or not after reviewing the request. If necessary, the radiation safety manager has an interview with the applicants, the supervisor of the maintenance job, and the worker. If an exception request is accepted, similar to the previous case of exceeding the primary dose constraints, all records of the radiation exposure history are kept in the radiation exposure database. If the primary or secondary administrative dose constraints are exceeded without prior permission, according to the KHNP radiation protection program, the worker is required to report the radiation dose to the plant manager and to take a whole-body counting to check possible internal radiation exposure [8].

If a dose limit is exceeded by a radiation worker in a Korean NPP, he or she is required to take a whole-body counting and medical examination immediately, and access to the RCA is prohibited by the radiation protection program. The NPP at which the exceeding of dose limits occurred should report instantly the personal information and dose records of the worker who exceeded the dose limits to the regulatory body. In addition, the NPP licensee is required to submit a written report that includes details of the occurrence, estimated dose, results of medical examination, corrective measures, etc., to the regulatory body within 20 days of the incident [9].

In Korean PHWRs, if the tritium concentration of an individual exceeds 1,850 Bq/cm^3 or 3,700 Bq/cm^3, his or her radiation work is limited or forbidden by the radiation protection program, so as to keep the internal radiation exposure as low as reasonably achievable [1]. The radiation safety manager determines whether the individual can return to work or not when the tritium concentration is reduced below 740 Bq/cm^3.

6. Occupational dose distribution in Korean NPPs

To identify trends in the number of individuals in certain dose ranges, annual dose distributions in Korean NPPs from 2009 to 2018 were studied using data from the KHNP annual reports for occupational exposure [10–19]. The dose distributions were acquired by calculating the number of individuals in certain dose ranges. The total number of occupationally-exposed workers in Korean NPPs increased by approximately 35% over ten years, from 11,723 in 2009 to 15,877 in 2018, due to the increase in the number of reactors. These total number of monitored individuals do not include office workers and visitors since they are not involved in radiation work in the field, and their radiation exposure is not required to be measured. The numbers of individuals whose doses were less than 1 mSv/y, compared to the total number of individuals, increased gradually from 75% in 2009 to 85% in 2018. Fig. 3 illustrates the probability distribution and cumulative probability distribution of occupational exposure in Korean NPPs during the years 2009–2018 [10–19]. The analysis data finds that the dose distributions for occupationally-exposed workers in Korean NPPs were lognormal and significantly skewed to very low doses; that is, the tail on the right side is longer than that on the left side.

No individual received a dose more than the annual dose limit of 50 mSv. Particularly, numbers of individuals whose doses exceeded 20 mSv/y, compared to the total number of individuals, were approximately 0.01%, and this was mainly due to pressure tube replacement at PHWRs from 2009 to 2010. Furthermore, no individual has received a dose of more than 20 mSv/y since 2013. The occupational dose distributions in Korean NPPs during the years 2009–2018 are shown in Table 4, and it can be seen that the average individual dose during the years 2009–2018 was 0.5–1.4 mSv/y for all Korean NPPs. This means that the average dose in Korean NPPs accounted for only 1.0–2.8% of the annual occupational dose limit. For the maximum individual dose, the dose range was distributed between 13.7 and 29.8 mSv/y. Due to the strengthening of the ALARA program, including the implementation of administrative dose constraints, the dose distributions have shifted to low levels, and the maximum individual dose at Korean NPPs has decreased gradually from 29.8 mSv/y in 2009 to 13.7 mSv/y in 2018.

In addition to the average individual dose, the collective dose is also used to estimate the total dose to the individuals in Korean NPPs. The collective dose is calculated as the sum of all individual doses during the NPP operation. This dose quantity is useful to check whether or not the average individual dose is reduced due to an increase in the number of workers. As shown in Table 4, the total collective dose in Korean NPPs decreased continuously from 16,320 person-mSv in 2009 to 9,026 person-mSv in 2018 despite the increase in the number of reactors from 20 in 2009 to 25 in 2018. This finding indicates that the decrease in the average individual dose in Korean NPPs is due to not increasing the number of individuals but implementing an aggressive radiation protection program to achieve ALARA goals.

To evaluate the ALARA performance in Korean NPPs, the occupational dose distributions in Korean NPPs were also compared with those in the US NPPs using the previous research results in the US [4]. There are a few things to be aware of before comparing data. The US research used a different period of occupational dose records during the years 2003–2012 to analyze the dose distributions in the US NPPs. Furthermore, the annual occupational dose limit in the US is 50 mSv/y, while an average of 20 mSv/y over a five-year period is generally used in Korea, although the dose limit for a single year is still 50 mSv. In the comparison of annual occupational doses over 10 years, the average individual doses were 0.5–1.4 mSv/y for Korean NPPs and 1.4–2.1 mSv/y for the US NPPs taking into account transient individuals who worked at more than one nuclear facility during the year and 1.0–1.6 mSv/y for the US NPPs

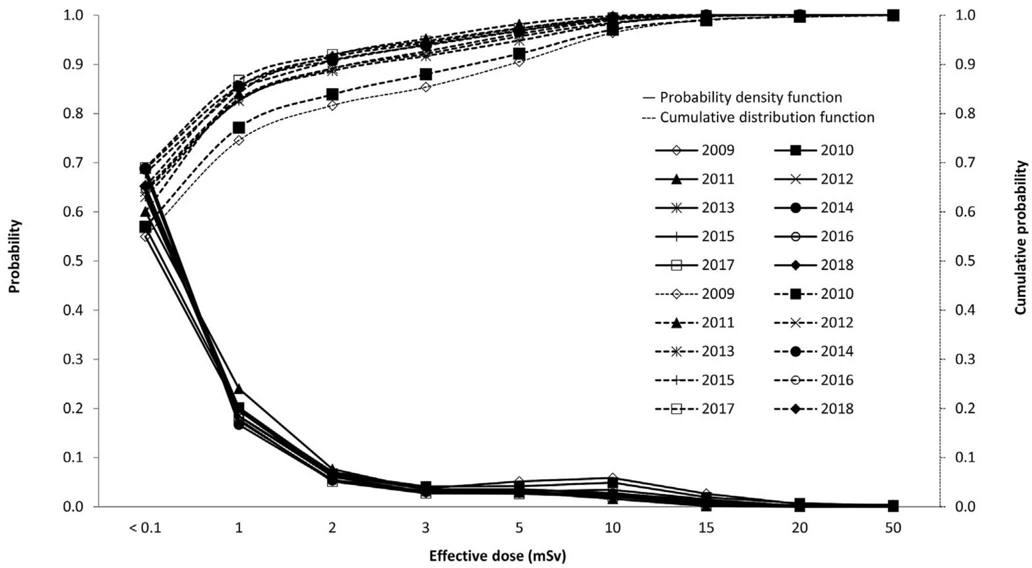

Fig. 3. Probability distribution and cumulative probability distribution of occupational exposure in Korean NPPs during years 2009–2018.

Table 4
Occupational dose distributions in Korean NPPs during years 2009–2018.

Year	Number of reactors	Total number of monitored individuals	Number of individuals in dose ranges (mSv/y)									Maximum individual dose (mSv/y)	Average individual dose (mSv/y)	Total collective dose (person-mSv)	Collective dose per reactor (person-mSv)
			<0.1	[0.1–1]	[1–2]	[2–3]	[3–5]	[5–10]	[10–15]	[15–20]	[20–50]				
2009	20	11,723	6,446	2,292	834	437	605	691	309	62	47	29.8	1.4	16,320	816
2010	20	13,236	7,538	2,674	892	545	553	649	254	92	39	27.5	1.2	15,884	793
2011	21	20,918	12,561	5,029	1,607	725	619	342	34	1	0	15.4	0.5	11,174	532
2012	23	14,715	9,436	2,715	965	519	524	412	131	12	1	26.6	0.7	10,471	455
2013	23	14,786	9,321	2,892	901	449	465	510	224	24	0	18.2	0.8	12,122	527
2014	23	14,260	9,811	2,382	765	430	415	375	77	5	0	16.5	0.6	8,325	360
2015	25	14,926	10,129	2,615	815	476	433	355	95	8	0	16.3	0.6	8,862	355
2016	25	14,396	9,300	2,644	894	431	510	398	184	35	0	18.1	0.8	11,008	440
2017	25	14,501	10,008	2,584	751	397	382	305	66	8	0	17.6	0.5	7,528	301
2018	25	15,877	10,356	3,198	969	462	466	328	89	9	0	13.7	0.6	9,026	361

without considering transient workers [4]. In addition to the average individual dose, the fractions of the number of individuals whose annual doses were less than 1 mSv to the total number of individuals were 75–85% for Korean NPPs and 58–70% for the US NPPs with regards to transient individuals and 52–64% for the US NPPs without considering transient workers [4]. This indicates that the annual occupational doses in both Korean and US NPPs realistically have been kept at very low levels by their radiation protection programs. There was no individual in NPPs who received the occupational dose more than the annual dose limit for both countries.

7. Conclusion

In addition to dose limits, Korean NPPs implement administrative dose constraints to achieve occupational radiation exposure as low as reasonably achievable. These occupational dose constraints are set voluntarily by KHNP, the sole licensee of nuclear power generation in Korea, to reduce individual doses, which are relatively higher than average. In contrast to dose limits, which are regulatory requirements, exceeding administrative dose constraints do not represent a violation of Korean regulations. According to the KHNP radiation protection program, 80% and 90% of the annual average limit for an effective dose, 20 mSv/y, are determined as the primary and secondary administrative dose constraints, respectively, for PWRs. For PHWRs, 70% and 80% of the effective dose limit are set as the primary and secondary administrative dose constraints, respectively, because it is likely for workers to be exposed to tritium in PHWRs. In addition to dose constraints, additional constraints for tritium concentration are provided to restrict internal radiation exposure in PHWRs.

In Korean NPPs, an individual who needs to carry out radiation work exceeding the administrative dose constraints is required to submit an exception request to the radiation safety manager prior to work being scheduled. Only a worker whose exception request is approved can conduct radiation work over the administrative dose constraints. In the case of exceeding the dose constraints without prior approval, the worker should report the radiation dose to the plant manager and take a whole-body counting to scan for possible internal radiation exposure.

Administrative dose constraints basically focus on narrowing the distribution of individual doses to low levels to resolve an inequity in which some individuals at NPPs receive relatively higher annual doses than others. The annual dose distributions in Korean NPPs during the years 2009–2018 indicate that the dose distributions for occupationally-exposed workers were significantly skewed to very low doses. This means that approximately 75–85% of the total number of individuals received annual doses less than 1 mSv. It was also found that the dose distributions have shifted to low levels of individual doses.

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.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.net.2020.06.023.

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