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Technical Note

Radioactive effluents released from Korean nuclear power plants and the resulting radiation doses to members of the public

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ABSTRACT

Korean nuclear power plants (NPPs) periodically evaluate the radioactive gaseous and liquid effluents released from power reactors to protect the public from radiation exposure. This paper provides a comprehensive overview of the release of radioactive effluents from Korean NPPs and the effects on the annual radiation doses to the public. The amounts of radioactive effluents released to the environment and the resulting radiation doses to members of the public living around NPPs were analyzed for the years 2011–2015 using the Korea Hydro & Nuclear Power Co., Ltd's annual summary reports of the assessment of radiological impact on the environment. The results show that tritium was the primary contributor to the activity in both gaseous and liquid effluents. The averages of effective doses to the public were approximately on the order of 10^{-3} mSv or 10^{-2} mSv. Therefore, even though Korean NPPs discharged some radioactive materials into the environment, all effluents were within the regulatory safety limits and the resulting doses were much less than the dose limits.

1. Introduction

In Korea, 24 nuclear power plants (NPPs) are currently in operation, 20 pressurized water reactors (PWRs) and four pressurized heavy water reactors (PHWRs). With an additional five PWRs under construction and another four PWRs planned to be constructed in the near future, the number of NPPs in Korea is continuously increasing. In addition, owing to the increase in the number of operating NPPs, concerns from the public and the regulatory body for radioactive materials released from NPPs to the environment have increased rapidly. In particular, periodic monitoring and safety management for radioactive materials are conducted thoroughly to achieve radiation protection for members of the public living around NPPs, taking into account the operation of multiple reactors in a single site.

In general, radioactive materials created by the operation of NPPs are categorized into two types: gaseous and liquid materials. All these materials are controlled as radioactive wastes, which are defined by the Korean regulation of radiation protection, regardless of their concentration of radioactivity [1]. Gaseous and liquid wastes are discharged to the environment under monitoring after appropriate processes of waste management [2,3]. Radioactive effluents are defined as gaseous and liquid wastes that are released to the environment. Furthermore, the management of radioactive effluents includes the whole process of monitoring and controlling radioactive materials in the effluents. This management of radioactive effluents is normally regarded as a very important factor not only to reduce the radiation risks to both the public and the environment but also to increase public acceptance of nuclear facilities.

The goal of this study was to understand the current status of the release of radioactive effluents from Korean NPPs and its characteristics. To achieve this goal, the amounts of radioactive effluents released to the environment and the resulting radiation doses to members of the public living around NPPs were analyzed for the years 2011–2015. The results of the analysis can be used to compare the changes of the release of radioactive effluents and the radiation dose to the public, because the monitoring of carbon-14 at PWRs has been conducted since 2012 and the number of operating NPPs in a single site has increased during the years 2011–2015.

2. Materials and methods

2.1. Radioactive effluents released from NPPs

The Korean regulation “Standards for Radiation Protection, etc.” requires the continuous monitoring of gaseous and liquid effluents

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released from NPPs to prevent radiological hazards to the environment [1]. Radioactive effluents are generally regulated by two criteria: the concentration of radioactivity and the dose to members of the public. First, the concentration of radioactivity in effluents should be less than the effluent control limits at the boundary of the unrestricted area. The values of the effluent control limits are equivalent to the radionuclide concentrations, which—if inhaled or ingested continuously over the course of a year—would produce the annual dose limit for the public, 1 mSv/y [1]. Second, the dose from radioactive effluents to members of the public living around NPPs should not exceed the annual dose standards, which are design objectives for equipment to keep levels of radioactive effluents to unrestricted areas as low as reasonably achievable (ALARA) during the normal operation of NPPs [1]. Theses annual dose standards are practically used as dose constraints for the public in Korea. Table 1 shows the numerical guidance on annual dose standards for members of the public as applied in the design of Korean NPPs [1]. In particular, dose standards are based on the design objectives of Appendix I to 10 Code of Federal Regulations (CFR) Part 50, part of the US Nuclear Regulatory Commission (USNRC) regulations pertaining to radioactive effluents, and 40 CFR 190 Subpart B, part of the US Environmental Protection Agency (USEPA) regulations pertaining to environmental standards [4,5]. These regulations are based on a common concept that dose estimation for members of the public originates from the release of radioactive effluents from NPPs. Therefore, in this study, we analyzed the amount of radionuclides discharged from NPPs to the environment in gaseous and liquid effluents to understand their effects on maximum annual doses to the public resulting from these effluent releases. The Korea Hydro & Nuclear Power Co., Ltd (KHNP) provides annual summary reports, “Survey of radiation environment and assessment of radiological impact on environment in vicinity of nuclear power facilities,” and the 2011, 2012, 2013, 2014, and 2015 summary reports are currently available [6–10]. Common radionuclides in radioactive effluents are identified through the analysis, and their contributions to the total activities of radioactive effluents are also evaluated.

2.2. Dose estimation for members of the public at NPPs

According to the Korean regulation “Survey and assessment of radiological impact to the environment around nuclear facilities,” NPPs must estimate the dose to members of the public living around NPPs and evaluate compliance with the annual dose limits [11]. Dose estimation for the public is calculated as the projected dose prior to the release of radioactive effluents from NPPs per reactor unit. The dose at the boundary of the unrestricted area is calculated as the sum of the doses for all reactor units in a single site. The KDOSE-60 program is currently used to conduct dose calculations for members of the public living around Korean NPPs. This program consists of the three following codes: GAS for dose calculations due to gaseous effluents, LIQ for dose calculations due to liquid effluents, and XQDQWQ for calculation of the atmospheric diffusion parameters [10]. KDOSE-60 calculates the most conservative estimate of the dose received by members of the public, where a hypothetical person receiving this dose is referred to as the maximally exposed individual (MEI). The MEI is defined as the single individual with the highest exposure in a given population [12]. The exposure pathways from gaseous and liquid effluents are based on USNRC Regulatory Guide 1.109 and comprise some site-specific considerations [13,14]. Other particular parameters including population information, meteorology, and effluent release activity around plants are taken from the annual reports on radioactive material released from the individual NPPs. Because KDOSE-60 operates under the conditions of routine NPP operation and the normal environment, it is not appropriate to use it for evaluating the dose due to short-term release of effluents and for assessing the accident dose. The simplified process of dose estimation for the public, including exposure pathways and computer codes, is shown in Fig. 1.

3. Results and discussion

3.1. Analysis of radioactive effluents released from NPPs

In general, NPP operation produces various radioactive materials. The amount of radioactive materials is expressed as activity with the unit Bq. Most of these radioactive sources originate from the fission of nuclear fuel and activated corrosion products. During the normal operation of NPPs, a small fraction of these radioactive sources is generally discharged to the environment through gaseous and liquid effluents. These radioactive effluents typically originate from several sources: (1) the fission of tramp uranium, which is dissolved from exposed fuel rods and plated out onto the structure of the coolant system; (2) leaks from failed fuel rods; (3) the diffusion of radioactive gases through intact fuel rods; (4) the activation of materials in the reactor cooling water; and (5) corrosion of activated materials from pipes, valves, pumps, and ancillary equipment [15]. According to a series of KHNP annual summary reports of radioactive effluents and public doses, some radionuclides are typically reported in effluent release from NPPs, and these are shown in Table 2 [6–10].

We analyzed the amount of radioactive effluents released from NPPs during the years 2011–2015, including both PWRs and PHWRs in Korea, using the data from the KHNP's annual summary reports. The total annual activities in radioactive effluents discharged from Korean NPPs were 4.87×10^{14} Bq, 4.87×10^{14} Bq, 3.80×10^{14} Bq, 3.96×10^{14} Bq, and 4.06×10^{14} Bq in 2011, 2012, 2013, 2014, and 2015, respectively [6–10]. The activities of radionuclides in gaseous and liquid effluents are displayed in Table 3 for each NPP site [6–10]. The activities in effluents released from Wolsong site, which includes four PHWRs and two PWRs, were approximately 2–5 times higher than those from other sites. The percentages of the activities in effluents released from Wolsong site

Table 1
Dose standards applied to the design of nuclear facilities (at the boundary of the unrestricted area).

Effluents	Category	Annual limits per unit	Annual limits per site
Gaseous	Air absorbed dose by gamma ray	0.1 mGy/y	Under the operation of multiple reactors at a single site
	Air absorbed dose by beta ray	0.2 mGy/y	- Effective dose: 0.25 mSv/y
	Effective dose by external radiation exposure	0.05 mSv/y	- Thyroid equivalent dose: 0.75 mSv/y
	Skin equivalent dose by external radiation exposure	0.15 mSv/y	
	Organ equivalent dose by particle radioactive substances, ^{3}H, ^{14}C, and radioiodine	0.15 mSv/y	
Liquid	Effective dose	0.03 mSv/y	
	Organ equivalent dose	0.1 mSv/y	

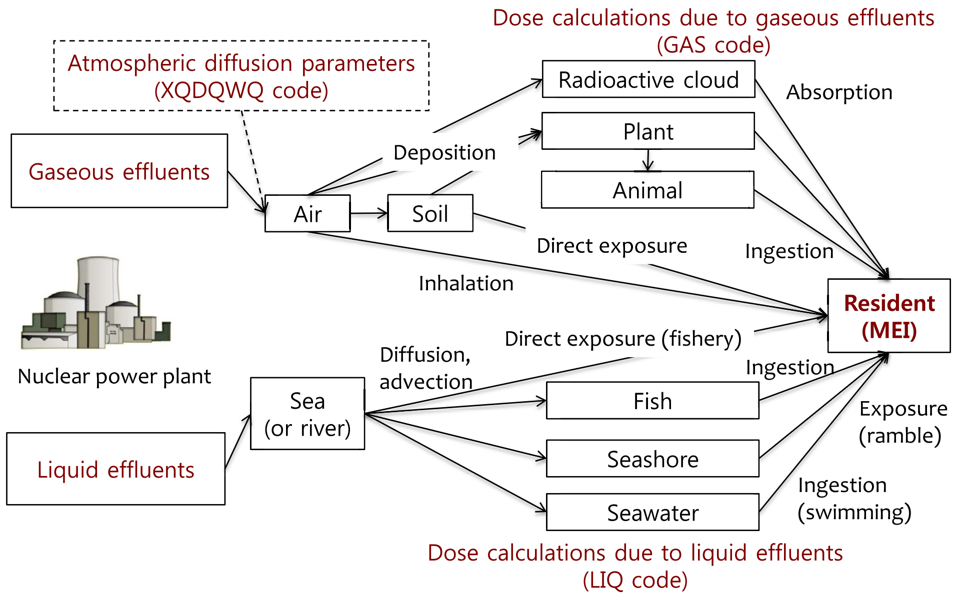

Fig. 1. Pathways of radioactive effluents. MEI, maximally exposed individual.

Table 2
Common radionuclides in radioactive effluents released from Korean NPPs.

Type	Category	Radionuclide
Gaseous	Tritium	Hydrogen (^{3}H)
	Carbon-14	Carbon (^{14}C)
	Noble gases	Argon (^{41}Ar)
		Krypton (^{85}Kr, ^{85m}Kr, ^{87}Kr, ^{88}Kr)
		Xenon (^{129m}Xe, ^{131}Xe, ^{131m}Xe, ^{133}Xe, ^{133m}Xe, ^{135}Xe)
	Particulates	Bromine (^{82}Br)
		Cobalt (^{58}Co, ^{60}Co)
		Chromium (^{51}Cr)
		Niobium (^{95}Nb)
		Strontium (^{89}Sr, ^{90}Sr)
	Iodine	Iodine (^{131}I, ^{132}I, ^{133}I)
Liquid	Tritium	Hydrogen (^{3}H)
	Carbon-14	Carbon (^{14}C)
	Dissolved noble gases	Xenon (^{133}Xe)
	Particulates	Antimony (^{122}Sb, ^{124}Sb, ^{125}Sb)
		Cesium (^{134}Cs, ^{137}Cs)
		Cobalt (^{56}Co, ^{57}Co, ^{58}Co, ^{60}Co)
		Iron (^{55}Fe)
		Manganese (^{54}Mn)
		Niobium (^{95}Nb, ^{97}Nb)
		Strontium (^{89}Sr, ^{90}Sr, ^{92}Sr)
		Zirconium (^{95}Zr)
	Iodine	Iodine (^{131}I, ^{133}I)

NPPs, nuclear power plants.

were approximately 47–59% of the total activities from all of the NPP sites. This phenomenon results from the higher production of tritium in PHWRs. In general, heavy water is used in both the PHWR moderator system and coolant system, and tritium is produced primarily from neutron capture by deuterium (^{2}H) in heavy water [16]. Table 3 also shows that the main radionuclide, which primarily contributed to the activity in both gaseous and liquid effluents, was tritium. The percentage of activity from tritium effluents of the total activity was approximately 95% for all NPP sites. In particular, the remarkable difference in effluent monitoring between 2011 and 2012–2015 was the carbon-14 monitoring in gaseous effluents. Korean NPPs have generally monitored the radionuclides that account for greater than about 1% of the total annual activities in radioactive effluents. As noble gases and particulates released to the environment have been decreasing continuously owing to the effluent reduction efforts of Korean NPPs, the contribution by carbon-14 to the effluent activities has relatively increased [17]. Thus, Korean PWRs have been monitoring carbon-14 in effluents since 2012. The percentage of activity from carbon-14 of the total activity in effluents was 0.43–0.72% after 2012.

3.2. Analysis of the radiation dose to members of the public living around NPPs

To ensure compliance with the requirements of the Nuclear Safety and Security Commission's (NSSC) annual dose standards and dose limits for the public, all NPPs regularly estimate the public dose from radioactive effluents released from NPPs [6–10]. This estimation is based on both measurements and theoretical models, including (1) real measurements of radioactive effluents to the environment; (2) models for the dispersion and dilution of radioactive materials in the environment; (3) models for the incorporation of radioactive materials into animals, plants, and soil; and (4) a biokinetic model for the human uptake and metabolism of radioactive materials [13]. These models were developed to estimate the dose to an MEI who may be exposed to the highest activities from effluents. Therefore, the estimated dose would be much higher than the actual dose to the residents living around NPPs. All NPPs established procedures for estimating the public dose according to the Regulatory Guide 02 of Korea Institute of Nuclear Safety and the USNRC Regulatory Guide 1.109, and they were combined into the offsite dose calculation manual [13,14,18].

The annual effective dose resulting from radioactive effluents released from NPPs was analyzed using the data from the KHNP's annual summary reports. During the years 2011–2015, the effective doses to members of the public due to radioactive effluents released from NPPs met both the NSSC's dose standard and the dose limit. The averages of effective doses to the public for 2011, 2012, 2013, 2014, and 2015 were 3.14×10^{-3} mSv, 1.46×10^{-2} mSv, 1.28×10^{-2} mSv, 3.55×10^{-2} mSv, and 2.02×10^{-2} mSv, respectively. These average values were much lower than the dose standard for a site, 0.25 mSv/y. In comparison with the dose limit, the effective doses to members of the public from 2011 to 2015 were

Table 3
Radioactive effluents released from Korean NPPs during the years 2011–2015.

Year	Effluents	Category	Site				Total (Bq)	Percent (%)
			Kori (Bq)	Hanbit (Bq)	Wolsong (Bq)	Hanul (Bq)		
2015	Gaseous	^{3}H	1.76×10^{13}	1.41×10^{13}	1.41×10^{14}	1.27×10^{13}	1.85×10^{14}	45.69
		^{14}C	7.79×10^{11}	2.88×10^{11}	9.50×10^{11}	7.74×10^{11}	2.79×10^{12}	0.69
		Noble gas	4.85×10^{12}	2.50×10^{10}	2.19×10^{13}	7.74×10^{10}	2.69×10^{13}	6.62
		Particulate	9.75×10^{5}	3.38×10^{3}	4.95×10^{4}	2.44×10^{4}	1.05×10^{6}	0.00
		Iodine	1.40×10^{7}	5.98×10^{4}	2.44×10^{7}	–	3.85×10^{7}	0.00
		Subtotal	2.32×10^{13}	1.44×10^{13}	1.64×10^{14}	1.36×10^{13}	2.15×10^{14}	53.00
	Liquid	^{3}H	6.88×10^{13}	4.52×10^{13}	2.58×10^{13}	5.09×10^{13}	1.91×10^{14}	47.00
		^{14}C	–	–	2.69×10^{8}	–	2.69×10^{8}	0.00
		Dissolved noble gases		–	2.89×10^{5}	–	2.89×10^{5}	0.00
		Particulate	4.13×10^{8}	2.82×10^{8}	4.77×10^{8}	8.29×10^{7}	1.25×10^{9}	0.00
		Iodine	–	–	2.27×10^{5}	–	2.27×10^{5}	0.00
		Subtotal	6.88×10^{13}	4.52×10^{13}	2.58×10^{13}	5.09×10^{13}	1.91×10^{14}	47.00
	Total		9.20×10^{13}	5.96×10^{13}	1.90×10^{14}	6.45×10^{13}	4.06×10^{14}	100.00
2014	Gaseous	^{3}H	1.54×10^{13}	1.72×10^{13}	1.37×10^{14}	1.21×10^{13}	1.82×10^{14}	45.89
		^{14}C	3.35×10^{11}	3.16×10^{11}	1.65×10^{12}	5.32×10^{11}	2.83×10^{12}	0.72
		Noble gas	5.09×10^{12}	1.11×10^{12}	2.61×10^{13}	5.26×10^{10}	3.24×10^{13}	8.17
		Particulate	7.46×10^{6}	–		8.53×10^{5}	8.31×10^{6}	0.00
		Iodine	2.70×10^{7}	2.52×10^{7}			5.22×10^{7}	0.00
		Subtotal	2.08×10^{13}	1.86×10^{13}	1.65×10^{14}	1.27×10^{13}	2.17×10^{14}	54.77
	Liquid	^{3}H	3.96×10^{13}	3.72×10^{13}	4.84×10^{13}	5.39×10^{13}	1.79×10^{14}	45.23
		^{14}C	–	–	2.89×10^{8}	–	2.89×10^{8}	0.00
		Dissolved noble gases	7.31×10^{4}	–	2.23×10^{5}	–	2.96×10^{5}	0.00
		Particulate	1.42×10^{8}	2.28×10^{9}	5.00×10^{8}	1.02×10^{8}	3.03×10^{9}	0.00
		Iodine	–	1.30×10^{8}	–	–	1.30×10^{8}	0.00
		Subtotal	3.96×10^{13}	3.72×10^{13}	4.84×10^{13}	5.39×10^{13}	1.79×10^{14}	45.23
	Total		6.04×10^{13}	5.58×10^{13}	2.13×10^{14}	6.66×10^{13}	3.96×10^{14}	100.00
2013	Gaseous	^{3}H	1.81×10^{13}	1.76×10^{13}	1.35×10^{14}	1.25×10^{13}	1.83×10^{14}	48.25
		^{14}C	4.91×10^{11}	3.32×10^{11}	6.71×10^{11}	4.47×10^{11}	1.94×10^{12}	0.51
		Noble gas	2.82×10^{12}	3.19×10^{10}	1.48×10^{13}	1.80×10^{11}	1.78×10^{13}	4.70
		Particulate	7.41×10^{4}	5.10×10^{5}	–	1.66×10^{6}	2.24×10^{6}	0.00
		Iodine	1.77×10^{6}	–	–	–	1.77×10^{6}	0.00
		Subtotal	2.14×10^{13}	1.80×10^{13}	1.50×10^{14}	1.31×10^{13}	2.03×10^{14}	53.46
	Liquid	^{3}H	3.87×10^{13}	3.47×10^{13}	6.92×10^{13}	3.41×10^{13}	1.77×10^{14}	46.54
		^{14}C	–	–	–	–	–	0.00
		Dissolved noble gases	–	–	1.37×10^{6}	–	1.37×10^{6}	0.00
		Particulate	4.83×10^{8}	3.46×10^{8}	9.84×10^{8}	4.69×10^{7}	1.86×10^{9}	0.00
		Iodine	–	–	1.63×10^{5}	–	1.63×10^{5}	0.00
		Subtotal	3.87×10^{13}	3.47×10^{13}	6.92×10^{13}	3.41×10^{13}	1.77×10^{14}	46.54
	Total		6.01×10^{13}	5.27×10^{13}	2.20×10^{14}	4.72×10^{13}	3.80×10^{14}	100.00
2012	Gaseous	^{3}H	1.50×10^{13}	1.00×10^{13}	1.55×10^{14}	1.15×10^{13}	1.92×10^{14}	39.34
		^{14}C	5.12×10^{11}	5.77×10^{11}	4.49×10^{11}	5.67×10^{11}	2.11×10^{12}	0.43
		Noble gas	1.88×10^{12}	2.11×10^{11}	1.34×10^{13}	7.03×10^{11}	1.62×10^{13}	3.33
		Particulate	2.04×10^{5}	3.75×10^{7}	8.53×10^{5}	1.07×10^{4}	3.86×10^{7}	0.00
		Iodine	9.08×10^{6}	9.52×10^{6}	2.23×10^{5}	8.15×10^{7}	1.00×10^{8}	0.00
		Subtotal	1.74×10^{13}	1.08×10^{13}	1.69×10^{14}	1.28×10^{13}	2.10×10^{14}	43.10
	Liquid	^{3}H	6.19×10^{13}	7.80×10^{13}	9.27×10^{13}	4.44×10^{13}	2.77×10^{14}	56.90
		^{14}C	–	–	–	–	–	0.00
		Dissolved noble gases	–	–	–	–	–	0.00
		Particulate	8.20×10^{8}	3.63×10^{8}	1.45×10^{9}	2.52×10^{7}	2.66×10^{9}	0.00
		Iodine	–	1.35×10^{6}	3.87×10^{7}	–	4.01×10^{7}	0.00
		Subtotal	6.19×10^{13}	7.80×10^{13}	9.27×10^{13}	4.44×10^{13}	2.77×10^{14}	56.90
	Total		7.93×10^{13}	8.88×10^{13}	2.62×10^{14}	5.72×10^{13}	4.87×10^{14}	100.00
2011	Gaseous	^{3}H	1.32×10^{13}	1.09×10^{13}	1.88×10^{14}	1.02×10^{13}	2.22×10^{14}	45.65
		^{14}C	NA	NA	4.06×10^{11}	NA	4.06×10^{11}	0.08
		Noble gas	1.67×10^{12}	1.73×10^{11}	4.61×10^{12}	8.14×10^{11}	7.27×10^{12}	1.49
		Particulate	5.47×10^{3}	–	1.03×10^{6}	3.14×10^{8}	3.15×10^{8}	0.00
		Iodine	3.99×10^{5}	–	–	8.07×10^{6}	8.47×10^{6}	0.00
		Subtotal	1.49×10^{13}	1.11×10^{13}	1.93×10^{14}	1.10×10^{13}	2.30×10^{14}	47.22
	Liquid	^{3}H	4.95×10^{13}	5.70×10^{13}	9.21×10^{13}	5.84×10^{13}	2.57×10^{14}	52.77
		^{14}C	–	–	–	–	–	0.00
		Dissolved noble gases	–	–	–	–	–	0.00
		Particulate	1.78×10^{8}	2.25×10^{8}	1.76×10^{9}	7.33×10^{7}	2.24×10^{9}	0.00
		Iodine	–	–	2.76×10^{6}	–	–	0.00
		Subtotal	4.95×10^{13}	5.70×10^{13}	9.21×10^{13}	5.84×10^{13}	2.57×10^{14}	52.78
	Total		6.44×10^{13}	6.81×10^{13}	2.85×10^{14}	6.94×10^{13}	4.87×10^{14}	100.00

NPPs, nuclear power plants.

only 0.31–3.55% of the annual dose limit for members of the public, 1 mSv/y. Because the average natural background radiation dose received by an individual in Korea is approximately 2.5 mSv/y, the effective doses to the public due to radioactive effluents from NPPs during the years 2011–2015 were only 0.13–1.42% of what the average person receives each year from natural background radiation [19]. The effective doses to members of the public living around NPPs from 2011 to 2015 are summarized in Table 4.

Table 4
Effective dose to members of the public living around Korean NPPs during the years 2011–2015.

Year	Effluents	Category	Site					Total (mSv)	Percent (%)
			Kori (mSv)	Hanbit (mSv)	Wolsong (mSv)	Hanul (mSv)	Average (mSv)		
2015	Gaseous	^{3}H	4.89×10^{-4}	6.68×10^{-4}	1.03×10^{-2}	1.08×10^{-3}	3.14×10^{-3}	1.26×10^{-2}	15.54
		^{14}C	6.18×10^{-3}	7.66×10^{-3}	3.35×10^{-2}	1.99×10^{-2}	1.68×10^{-2}	6.72×10^{-2}	83.27
		Noble gas	1.08×10^{-5}	4.41×10^{-6}	8.67×10^{-4}	1.80×10^{-5}	2.25×10^{-4}	9.00×10^{-4}	1.11
		Particulate	4.75×10^{-9}	4.49×10^{-10}	1.95×10^{-9}	6.29×10^{-9}	3.36×10^{-9}	1.34×10^{-8}	0.00
		Iodine	1.76×10^{-8}	1.21×10^{-8}	3.16×10^{-6}	–	1.06×10^{-6}	3.19×10^{-6}	0.00
		Subtotal	6.68×10^{-3}	8.33×10^{-3}	4.47×10^{-2}	2.10×10^{-2}	2.02×10^{-2}	1.01×10^{-1}	99.93
	Liquid	^{3}H	4.13×10^{-6}	1.41×10^{-5}	3.04×10^{-6}	1.61×10^{-6}	5.73×10^{-6}	2.29×10^{-5}	0.03
		^{14}C	–	–	1.92×10^{-6}		9.60×10^{-7}	1.92×10^{-6}	0.00
		Dissolved noble gas	–	–	–	–	–	–	0.00
		Particulate	2.37×10^{-6}	4.91×10^{-6}	2.44×10^{-5}	3.03×10^{-7}	7.99×10^{-6}	3.20×10^{-5}	0.04
		Iodine	–	–	9.43×10^{-8}	–	9.43×10^{-8}	9.43×10^{-8}	0.00
		Subtotal	6.50×10^{-6}	1.91×10^{-5}	2.94×10^{-5}	1.91×10^{-6}	1.42×10^{-5}	5.69×10^{-5}	0.07
	Total		6.68×10^{-3}	8.35×10^{-3}	4.47×10^{-2}	2.10×10^{-2}	2.02×10^{-2}	1.01×10^{-1}	100.00
2014	Gaseous	^{3}H	4.19×10^{-4}	8.18×10^{-4}	1.27×10^{-2}	1.61×10^{-3}	3.87×10^{-3}	1.55×10^{-2}	10.91
		^{14}C	2.14×10^{-3}	7.04×10^{-3}	9.16×10^{-2}	2.45×10^{-2}	3.13×10^{-2}	1.25×10^{-1}	88.18
		Noble gas	2.04×10^{-5}	1.25×10^{-5}	6.51×10^{-4}	1.44×10^{-5}	1.75×10^{-4}	6.98×10^{-4}	0.49
		Particulate	3.82×10^{-6}	6.02×10^{-10}	–	1.31×10^{-7}	1.32×10^{-6}	3.95×10^{-6}	0.00
		Iodine	2.44×10^{-6}	4.08×10^{-6}	–		3.26×10^{-6}	6.52×10^{-6}	0.00
		Subtotal	2.59×10^{-3}	7.87×10^{-3}	1.05×10^{-1}	2.61×10^{-2}	3.54×10^{-2}	1.41×10^{-1}	99.59
	Liquid	^{3}H	1.13×10^{-5}	8.86×10^{-6}	5.71×10^{-5}	1.72×10^{-6}	1.98×10^{-5}	7.90×10^{-5}	0.06
		^{14}C	–	–	1.29×10^{-5}	–	1.29×10^{-5}	1.29×10^{-5}	0.01
		Dissolved noble gas	–	–	–	–	–	–	0.00
		Particulate	8.03×10^{-5}	2.99×10^{-5}	2.77×10^{-4}	3.01×10^{-7}	9.69×10^{-5}	3.88×10^{-4}	0.27
		Iodine	–	1.00×10^{-4}	6.77×10^{-7}	–	5.05×10^{-5}	1.01×10^{-4}	0.07
		Subtotal	9.17×10^{-5}	1.39×10^{-4}	3.48×10^{-4}	2.02×10^{-6}	1.45×10^{-4}	5.81×10^{-4}	0.41
	Total		2.68×10^{-3}	8.01×10^{-3}	1.05×10^{-1}	2.61×10^{-2}	3.55×10^{-2}	1.42×10^{-1}	100.00
2013	Gaseous	^{3}H	4.97×10^{-4}	6.78×10^{-4}	8.37×10^{-3}	9.95×10^{-4}	2.63×10^{-3}	1.05×10^{-2}	20.65
		^{14}C	3.70×10^{-3}	5.14×10^{-3}	1.77×10^{-2}	1.11×10^{-2}	9.39×10^{-3}	3.75×10^{-2}	73.57
		Noble gas	1.28×10^{-5}	4.76×10^{-6}	6.23×10^{-4}	7.67×10^{-6}	1.62×10^{-4}	6.49×10^{-4}	1.27
		Particulate	2.48×10^{-10}	2.29×10^{-6}	–	8.34×10^{-10}	7.64×10^{-7}	2.29×10^{-6}	0.00
		Iodine	3.10×10^{-7}	–	–	–	3.10×10^{-7}	3.10×10^{-7}	0.00
		Subtotal	4.21×10^{-3}	5.82×10^{-3}	2.66×10^{-2}	1.21×10^{-2}	1.22×10^{-2}	4.87×10^{-2}	95.50
	Liquid	^{3}H	6.52×10^{-5}	9.34×10^{-6}	1.58×10^{-4}	7.21×10^{-6}	6.00×10^{-5}	2.40×10^{-4}	0.47
		^{14}C	–	–	–	–	–	–	0.00
		Dissolved noble gas	–	–	–	–	–	–	0.00
		Particulate	2.69×10^{-4}	3.94×10^{-6}	1.78×10^{-3}	1.21×10^{-6}	5.14×10^{-4}	2.06×10^{-3}	4.03
		Iodine	3.1×10^{-7}		9.41×10^{-8}	–	2.02×10^{-7}	4.04×10^{-7}	0.00
		Subtotal	3.35×10^{-4}	1.33×10^{-5}	1.94×10^{-3}	8.42×10^{-6}	5.74×10^{-4}	2.30×10^{-3}	4.50
	Total		4.55×10^{-3}	5.84×10^{-3}	2.86×10^{-2}	1.21×10^{-2}	1.28×10^{-2}	5.10×10^{-2}	100.00
2012	Gaseous	^{3}H	3.60×10^{-4}	6.26×10^{-4}	9.85×10^{-3}	8.52×10^{-4}	2.92×10^{-3}	1.17×10^{-2}	20.02
		^{14}C	3.51×10^{-3}	1.54×10^{-2}	1.15×10^{-2}	1.48×10^{-2}	1.13×10^{-2}	4.53×10^{-2}	77.59
		Noble gas	8.38×10^{-6}	5.55×10^{-6}	6.71×10^{-4}	8.25×10^{-6}	1.73×10^{-4}	6.93×10^{-4}	1.19
		Particulate	1.22×10^{-6}	9.37×10^{-6}	4.40×10^{-7}	4.94×10^{-10}	2.76×10^{-6}	1.10×10^{-5}	0.02
		Iodine	8.55×10^{-9}	4.10×10^{-7}	–	2.45×10^{-5}	8.32×10^{-6}	2.50×10^{-5}	0.04
		Subtotal	3.88×10^{-3}	1.61×10^{-2}	2.20×10^{-2}	1.57×10^{-2}	1.44×10^{-2}	5.77×10^{-2}	98.86
	Liquid	^{3}H	3.56×10^{-5}	2.33×10^{-5}	3.28×10^{-5}	1.23×10^{-5}	2.60×10^{-5}	1.04×10^{-4}	0.18
		^{14}C	–	–	–	–	–	–	0.00
		Dissolved noble gas	–	–	–	–	–	–	0.00
		Particulate	2.68×10^{-4}	6.00×10^{-6}	2.58×10^{-4}	5.99×10^{-7}	1.33×10^{-4}	5.33×10^{-4}	0.91
		Iodine	–	2.46×10^{-7}	2.61×10^{-5}	–	1.32×10^{-5}	2.64×10^{-5}	0.05
		Subtotal	3.04×10^{-4}	2.95×10^{-5}	3.17×10^{-4}	1.29×10^{-5}	1.66×10^{-4}	6.63×10^{-4}	1.14
	Total		4.18×10^{-3}	1.61×10^{-2}	2.24×10^{-2}	1.57×10^{-2}	1.46×10^{-2}	5.83×10^{-2}	100.00
2011	Gaseous	^{3}H	1.53×10^{-3}	2.69×10^{-3}	2.68×10^{-3}	2.98×10^{-3}	2.47×10^{-3}	9.88×10^{-3}	78.55
		^{14}C	NA	NA	1.38×10^{-3}	NA	1.38×10^{-3}	1.38×10^{-3}	10.97
		Noble gas	1.89×10^{-5}	1.58×10^{-5}	5.62×10^{-5}	3.39×10^{-5}	3.12×10^{-5}	1.25×10^{-4}	0.99
		Particulate	2.04×10^{-10}	–	–	2.34×10^{-4}	1.17×10^{-4}	2.34×10^{-4}	1.86
		Iodine	7.13×10^{-9}	1.44×10^{-6}	–	4.12×10^{-6}	1.86×10^{-6}	5.57×10^{-6}	0.04
		Subtotal	1.55×10^{-3}	2.71×10^{-3}	4.12×10^{-3}	3.25×10^{-3}	2.91×10^{-3}	1.16×10^{-2}	92.42
	Liquid	^{3}H	4.92×10^{-5}	3.42×10^{-6}	8.76×10^{-5}	3.83×10^{-5}	4.46×10^{-5}	1.79×10^{-4}	1.42
		^{14}C	–	–	–	–	–	–	0.00
		Dissolved noble gas	–	–	–	–	–	–	0.00
		Particulate	1.19×10^{-4}	7.55×10^{-7}	6.52×10^{-4}	2.77×10^{-6}	1.94×10^{-4}	7.75×10^{-4}	6.16
		Iodine	–	–	–	–			0.00
		Subtotal	1.68×10^{-4}	4.18×10^{-6}	7.40×10^{-4}	4.11×10^{-5}	2.38×10^{-4}	9.53×10^{-4}	7.58
	Total		1.72×10^{-3}	2.71×10^{-3}	4.86×10^{-3}	3.29×10^{-3}	3.14×10^{-3}	1.26×10^{-2}	100.00

NPPs, nuclear power plants.

Gaseous effluents contributed more to the total radiation doses than liquid effluents. More than 92% of total effective dose resulted from the gaseous effluents. Therefore, most of the effective dose in radioactive effluents released from NPPs during the years 2011–2015 resulted from gaseous effluents. The main radionuclide that primarily contributed to the effective dose to the public was carbon-14 in gaseous effluents. The percentages of dose from gaseous carbon-14 of the total effective dose for 2012, 2013, 2014, and 2015 were 67%, 88%, 74%, and 78%, respectively. Prior to 2012, the tritium in gaseous effluents was the main contributor to the public dose. Estimates of public radiation dose were higher approximately 4–10 times during the years 2011–2015 compared with the public dose in 2011 due to carbon-14 monitoring in gaseous effluents in PWRs. Although carbon-14 is a minor nuclide in the total effluent release, it is the main contributor to the effective dose around NPPs.

4. Conclusion

This analysis confirmed that there were no remarkable differences in the amount of radioactive effluents released from Korean NPPs during the years 2011–2015. Effluents released from Wolsong site including four PHWRs and two PWRs were relatively higher than those from other NPP sites, which have only PWRs. The primary contributor to the activity in both gaseous and liquid effluents was tritium, accounting for approximately 95%. Although carbon-14 monitoring in gaseous effluents in PWRs has been conducted since 2012, the contribution of carbon-14 in gaseous effluents to the total activity from both gaseous and liquid effluents was regarded as minor, accounting for approximately less than 1%.

During the years 2011–2015, the effective doses to members of the public due to radioactive effluents released from Korean NPPs met both the NSSC's dose standard and the dose limit. The averages of effective doses to the public from 2011 to 2015 were approximately on the order of 10^{-3} mSv or 10^{-2} mSv. This analysis indicated that although carbon-14 is a minor nuclide in effluent releases, it is the main contributor to the effective dose to members of the public living around NPPs. As public doses have realistically been kept at very low levels, the annual doses to the public from radioactive effluents released from NPPs under normal operating conditions are considered trivial when compared to the dose limit and even the natural background radiation dose.

Conflicts of interest

None.

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