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Technical Paper

Off-site Dose Assessment during the Operational States of APR1400

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Abstract - Normal operation and anticipated operational occurrences (AOOs) of nuclear power plants (NPPs) involves periodic or continuous release of solid, liquid, and gaseous radioactive effluents to the environment. In this study, gaseous and liquid effluents of Shin Kori unit 3, one of Advanced Power Reactor 1400 (APR1400) in Korea, were analyzed from 2016 to 2018 in order to ensure compliances with regulations of Nuclear Safety and Security Commission (NSSC) for radioactive effluents releases. Meteorological data from Ulsan city area was applied for gaseous effluents. Doses for 80 km radius from the site, exclusion area boundary (EAB) and low population zone (LPZ) were considered. Doses to age groups and 14 body organs were studied via various pathways for gaseous and liquid effluents. Three computer codes were used; XOQDOQ for atmospheric dispersion and deposition, GASPAR for gaseous effluent doses and LADTAP for liquid effluents doses. Wind stability classification showed 2016 to be calmer than 2017 and 2018 implying higher overall depositions and subsequent doses. Highest air beta and gamma absorbed doses at EAB were 0.04 $mGy \cdot yr^{-1}$ and 0.003 $mGy \cdot yr^{-1}$, respectively, which were sufficiently lower than NSSC limits of 0.2 $mGy \cdot yr^{-1}$ and 0.1 $mGy \cdot yr^{-1}$, respectively. Children doses were highest at EAB and LPZ. Child effective dose at EAB was 0.02 $mSv \cdot yr^{-1}$ and skin equivalent dose was 0.051 $mSv \cdot yr^{-1}$ which were below NSSC limits of 0.05 $mSv \cdot yr^{-1}$ and 0.15 $mSv \cdot yr^{-1}$, respectively. Effective dose from liquid effluents was highest to children at 0.01 $mSv \cdot yr^{-1}$ and equivalent doses to any internal organ was 0.08 $mSv \cdot yr^{-1}$ for gastrointestinal lower large intestine which were below NSSC limits of 0.03 $mSv \cdot yr^{-1}$ and 0.1 $mSv \cdot yr^{-1}$, respectively. Consumption of invertebrates and algae were found to contribute highest doses. This study showed regulatory compliances of gaseous and liquid effluents for Shin Kori unit 3 during its normal operations and anticipated operational occurrences.

Key words : APR1400, Operational States, Radioactive effluents, Off-site dose

INTRODUCTION

Normal operation of nuclear power plants (NPPs) involved production and release of radionuclides to the environment. Solid, liquid and gaseous effluents were discharged to the environment either periodically or continuously. Gaseous and liquid effluents were especially of interest since they were readily dispersed in waterways and the atmosphere (US NRC 1977). Atmospheric dispersion (X/Q) and deposition (D/Q) factors determined the dispersal and subsequent deposition of radionuclides in the atmosphere. X/Q and D/Q were determined from atmospheric parameters of wind speed, wind direction and environment temperature. These factors were also influenced by atmospheric stability, i.e., how the air was mixed in the atmosphere (Segendorf *et al*. 1982). Hydrological dispersion of radionuclide was determined from the concentration of aqueous solution released, the rate of release and dilution rate in the water body (Strenge *et al*. 1986a; Strenge *et al*. 1986b). Exposure to radionuclides occurred through many pathways including plume, ground deposition, inhalation, taking food and

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Table 1. Gaseous source term of APR1400 ($Bq \cdot yr^{-1}$)

Nuclide	Release rate	Nuclide	Release rate	Nuclide	Release rate
^{131}I	6.66×10^{7}	^{133}Xe	2.59×10^{12}	^{95}Zr	3.70×10^{5}
^{132}I	1.78×10^{9}	^{135m}Xe	2.96×10^{11}	^{95}Nb	1.55×10^{6}
^{133}I	8.51×10^{8}	^{135}Xe	1.89×10^{12}	^{103}Ru	6.29×10^{5}
^{134}I	2.92×10^{9}	^{137}Xe	1.11×10^{11}	^{106}Ru	2.89×10^{4}
^{135}I	1.70×10^{9}	^{138}Xe	1.11×10^{11}	^{125}Sb	2.26×10^{4}
^{85m}Kr	2.59×10^{11}	^{51}Cr	3.59×10^{6}	^{134}Cs	1.78×10^{6}
^{85}Kr	1.81×10^{14}	^{54}Mn	2.11×10^{6}	^{136}Cs	1.22×10^{6}
^{87}Kr	7.40×10^{10}	^{57}Co	3.03×10^{5}	^{137}Cs	3.33×10^{6}
^{88}Kr	1.85×10^{11}	^{58}Co	1.78×10^{7}	^{140}Ba	1.55×10^{5}
^{131m}Xe	8.14×10^{13}	^{60}Co	4.07×10^{6}	^{141}Ce	4.81×10^{5}
^{133m}Xe	4.81×10^{12}	^{59}Fe	1.04×10^{6}	^{3}H	5.92×10^{12}
^{41}Ar	1.26×10^{12}	^{89}Sr	5.92×10^{6}	^{14}C	2.70×10^{11}
^{90}Sr	2.33×10^{6}				

Table 2. Liquid source term of APR1400 ($Bq \cdot yr^{-1}$)

Nuclide	Release rate	Nuclide	Release rate	Nuclide	Release rate
^{24}Na	7.03×10^{7}	^{91}Sr	9.62×10^{5}	^{132}I	2.66×10^{7}
^{32}P	6.66×10^{6}	^{91m}Y	6.29×10^{5}	^{133}I	1.26×10^{8}
^{51}Cr	2.22×10^{8}	^{91}Y	3.33×10^{6}	^{134}I	9.25×10^{5}
^{54}Mn	1.81×10^{8}	^{93}Y	1.07×10^{6}	^{134}Cs	4.07×10^{8}
^{55}Fe	3.00×10^{8}	^{95}Zr	4.81×10^{7}	^{135}I	8.51×10^{7}
^{59}Fe	8.88×10^{7}	^{95}Nb	7.77×10^{7}	^{136}Cs	1.44×10^{8}
^{58}Co	4.07×10^{8}	^{99}Mo	2.81×10^{7}	^{137}Cs	5.92×10^{8}
^{60}Co	5.18×10^{8}	^{99m}Tc	2.07×10^{7}	^{137m}Ba	1.55×10^{7}
^{63}Ni	6.29×10^{7}	^{103}Ru	1.44×10^{8}	^{140}Ba	1.67×10^{8}
^{65}Zn	1.30×10^{7}	^{103m}Rh	1.37×10^{8}	^{140}La	1.81×10^{8}
^{187}W	5.18×10^{6}	^{106}Ru	2.63×10^{9}	^{141}Ce	1.11×10^{7}
^{239}Np	8.14×10^{6}	^{106}Rh	2.29×10^{9}	^{143}Ce	7.03×10^{6}
^{89}Sr	5.92×10^{6}	^{124}Sb	1.59×10^{7}	^{143}Pr	2.41×10^{6}
^{90}Sr	8.14×10^{5}	^{129m}Te	3.26×10^{6}	^{144}Ce	2.44×10^{8}
^{132}Te	7.40×10^{6}	^{129}Te	2.29×10^{6}	^{144}Pr	9.99×10^{7}
^{131}Te	6.66×10^{5}	^{131m}Te	3.66×10^{6}	^{3}H	5.40×10^{13}
^{131}I	9.99×10^{7}	^{110m}Ag	7.77×10^{7}		

water and performing activities in the environment. These contributed doses externally to the body, the gastro intestinal - lower large intestine (GI-LLI), bone, liver, kidneys, lungs, thyroid, skin, pancreas, spleen, gastro intestinal - upper large intestine (GI-ULI), airways, uterus, bone marrow and stomach. The effect of radiation was also influenced by the age of the person; adult, teenager, child or infant (Chesapeake Nuclear Services 2012). Exposure to radionuclides posed health risks. Risks would be reduced by setting limits to doses received by the public to normal operation of NPPs (NSSC 2016). Taking the gaseous and liquid source terms of NPP normal operation, the dose to public could be estimated to address compliance with set limits. Therefore, this study aimed at analyzing radiological dose resulting from the normal operation and anticipated operational occurrences (AOOs) of Shin Kori unit 3 in order to ensure compliances with Korean regulations of radioactive effluents releases.

MATERIALS AND METHODS

XOQDOQ has been used by the nuclear regulatory commission (NRC) staff in the independent meteorological evaluation of routine or anticipated, intermittent releases of radionuclides at commercial nuclear power stations. Relative atmospheric dispersion factors, X/Q values, and deposition factors, D/Q values, were computed for 22 specific distances out to 80 km from the site. X/Q and D/Q values were computed for user-inputted specific points of interest such as exclusion area boundary (EAB) and low population zone (LPZ) (Segendorf *et al*. 1982). Meteorological data of nearby Ulsan city from 2016~2018 were used (KMA 2019). The

Table 3. Input parameters of XOQDOQ

Parameter	Value	Note
Wind data source	Ulsan Metropolitan City, 2016, 2017, and 2018 data	Closest open source meteorological data
Joint frequency distribution table	3 tables	R Programing codes
Stability classes	7 (A, B, C, D, E, F, G)	Pasquill stability classes
Directions	16 directions	Compass directions divided into 16 sectors
Wind height	10 m	Meteorological site data
Distance	80 km	US NRC
EAB	560 m	APR1400 DCD
LPZ	3.5 km	APR1400 DCD
Depletion	0, 2.26, and 8 days	US NRC

Table 4. Input parameters of GASPAR

Parameter	Value	Note
Dispersion, Deposition	Meteorological data	XOQDOQ generated
Radionuclides	Table 1	APR1400 DCD
Number of release points	1	One NPP considered
Pathways	6	Plume, ground, inhalation, milk, vegetable, and meat
Organs	14	Gastrointestinal (lower and upper) large intestine, bone, liver, kidney, thyroid, lung, skin, pancreas, spleen, airways, uterus, marrow, stomach
Population	7 million	Free map tools, 2019
Vegetation	931 million kg	Lee and Chung 2008
Milk	288 million L	Chun and Larrabee 2018
Meat	35.4 million kg	Chung 2018
Fraction of consumption	1	US NRC

data was not readily usable in XOQDOQ. A joint frequency distribution (JFD) was created and passed to XOQDOQ including locations of interest, EAB of 560 m to south-south-west and LPZ of 3.5 km to south-west directions (Google Earth 2019) using Microsoft Excel and the R programming language (R Core Team 2019). The 'Openair' package was used to plot weather-related parameters in R including wind roses (Carslaw and Ropkins 2012). Pasquill stability classes (Pasquill 1961) was calculated using circular normal distribution statistics in R from the directional library (Michail *et al*. 2019). Created JFD tables and other relevant parameters in Table 3 were used as the inputs of XOQDOQ.

GASPAR code has been used for the analysis of doses to individuals and populations resulting from radioactive effluents discharged into the atmosphere from nuclear power plants. It estimated doses due to inhalation, ingestion and external exposure. GASPAR has been used by the United States Environmental Protection Agency (EPA) in provision of information to the National Environmental Policy Act (NEPA) which addressed regulatory compliances (Strenge *et al*. 1986a). Two main inputs were the source terms shown in Table 1 (KEPCO and KHNP 2014) and the outputs of XOQDOQ including population, meat, vegetable, and milk consumption as summarized in Table 4. The population within a radius of 80 km was determined to approximately 7 million people from geographic information system (GIS) (Free Map Tools 2019). Beef consumption data was derived from the fraction of imported beef and domestically produced beef adjusted for the population estimated to be 35.4 million kg (Chung 2018). Vegetable consumption was determined from statistics of vegetable population consumption patterns adjusted for the population estimated to be 931 million kg (Lee and Chung 2008). Milk consumption data was derived from the fraction of imported milk and domestically produced milk adjusted for the population estimated to be 288 million liters (Chun and Larrabee 2018).

LADTAP code has been used to analyze liquid radioactive waste releases to surface waters. It estimated doses to individuals (adults, teenagers and children) by considering internal exposures (water, fish, algae and invertebrates), and external exposures (shoreline, swimming and boating). LADTAP has been also used by the U.S. EPA in provision of information to the NEPA which addressed regulatory compliances (Strenge *et al*. 1986b). The main inputs to LADTAP code were the source terms and site-specific parameters as shown in Table 2 and Table 5, respectively.

Table 5. Input parameters of LADTAP

Parameter	Value	Note
Water type selection	Saltwater	Assumed that the liquid effluents are discharged to ocean
Liquid effluent discharge rate (L/min)	3.79×10^4	Based on APR1400DCD
Shore-width factor	0.2	Based on APR1400DCD
Reconcentration model index	0	Assumed that there is no reconcentration
Source terms	Table 2	Based on PWR-GALE code calculation
Dilution factor for aquatic food and boating	5	Conservative dilution factor of 5.0 is assumed for evaluating individual doses from liquid effluents.
Dilution factor for shoreline and swimming	5	〃
Dilution factor for drinking water	5	〃
Dilution factor for irrigation water usage location for the current food product	5	〃
Irrigation rate (L/month)	0	Assumed ocean water is not used for irrigation purposes
Fraction of animal feed not produced with contaminated irrigation water	1	Assumed no animal drinks ocean water
Fraction of animal drinking water not obtained from contaminated irrigation water	1	Assumed no animal drinks ocean water
Transit time for any exposure pathway	0	
Midpoint of plant life (years)	30	Half of the APR1400 design life of 60 years
Adults, Teenagers, and Children population fractions	0.79, 0.12, and 0.09	Population pyramid of Korea
Food Usage of Adult		
Fish	$28.3\ kg \cdot yr^{-1}$	
Invertebrate	$13.7\ kg \cdot yr^{-1}$	
Algae	$6\ kg \cdot yr^{-1}$	
Shoreline	$12\ hr \cdot yr^{-1}$	
Food Usage of Teenager		
Fish	$11.7\ kg \cdot yr^{-1}$	
Invertebrate	$11.2\ kg \cdot yr^{-1}$	
Algae	$3.2\ kg \cdot yr^{-1}$	
Shoreline	$67\ hr \cdot yr^{-1}$	
Food Usage of Children		
Fish	$10.4\ kg \cdot yr^{-1}$	
Invertebrate	$3.9\ kg \cdot yr^{-1}$	
Algae	$2.7\ kg \cdot yr^{-1}$	
Shoreline	$14\ hr \cdot yr^{-1}$	

RESULTS

Wind roses using the R programming language for the study period (2016~2018) were plotted as shown in Fig. 1. Dispersion and deposition factors were depicted in Fig. 2 and Fig. 3, respectively. Stability classes for the study period grouped percentage-wise were shown in Fig. 4. The maximum dispersion factors were 2.75×10^{-4}, 1.10×10^{-4} and 1.10×10^{-4} for the year 2016, 2017 and 2018, respectively, all blowing to the south. The maximum deposition factors were 4.20×10^{-7}, 4.10×10^{-7} and 4.40×10^{-7} to south-east for the year 2016, 2017 and 2018, respectively.

The maximum population dose was 65 person-mSv in 2016 as shown in Fig. 5. Plotted on a log scale in Fig. 6, the highest EAB air beta and gamma absorbed doses were $0.04\ mGy \cdot yr^{-1}$ and $0.003\ mGy \cdot yr^{-1}$ which were lower than NSSC limits of $0.2\ mGy \cdot yr^{-1}$ and $0.1\ mGy \cdot yr^{-1}$, respectively (NSSC 2016). Highest child effective dose at EAB was $0.02\ mSv \cdot yr^{-1}$. Highest doses by plume pathway was $0.002\ mSv \cdot yr^{-1}$ as shown in Fig. 7 and skin equivalent dose at $0.051\ mSv \cdot yr^{-1}$ which were below NSSC limits of $0.05\ mSv \cdot yr^{-1}$ and $0.15\ mSv \cdot yr^{-1}$, respectively (NSSC 2016). Effective dose from liquid effluents shown in Fig. 8 was highest to children at $0.01\ mSv \cdot yr^{-1}$ which was below NSSC limits of $0.03\ mSv \cdot yr^{-1}$. Equivalent dose to any internal organ shown in Fig. 9 was $0.08\ mSv \cdot yr^{-1}$ for gastrointestinal lower large intestine which was below NSSC limits of $0.1\ mSv \cdot yr^{-1}$.

DISCUSSION

Wind rose plots of this study showed predominant wind direction blowing south and similar wind flow patterns.

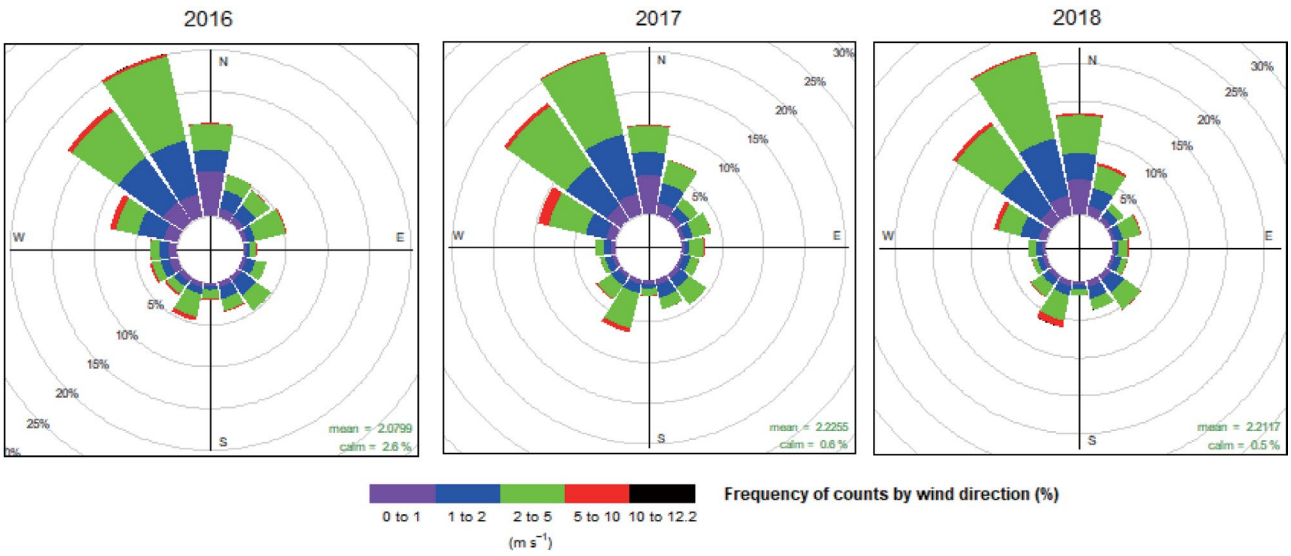

Fig. 1. Wind rose plots for the period of 2016~2018.

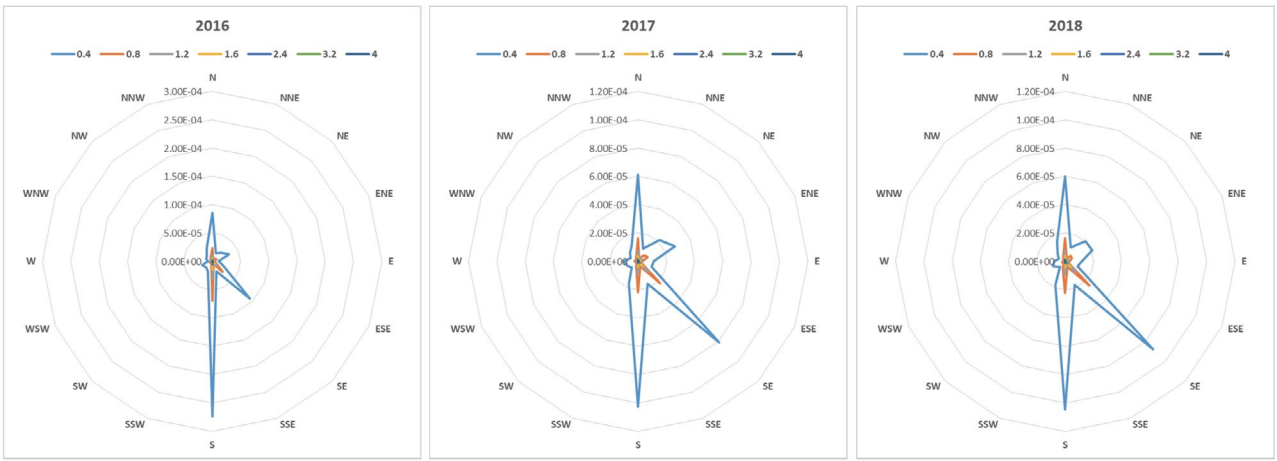

Fig. 2. Annual averaged atmospheric dispersion factors X/Q (sec · m^{-3}).

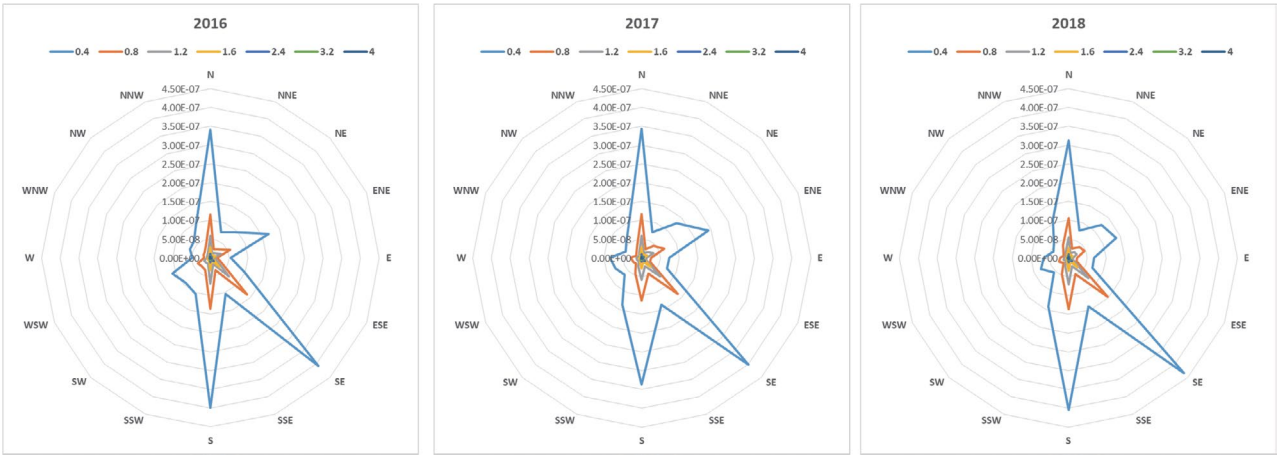

Fig. 3. Annual averaged ground deposition factors D/Q (sec · m^{-2}).

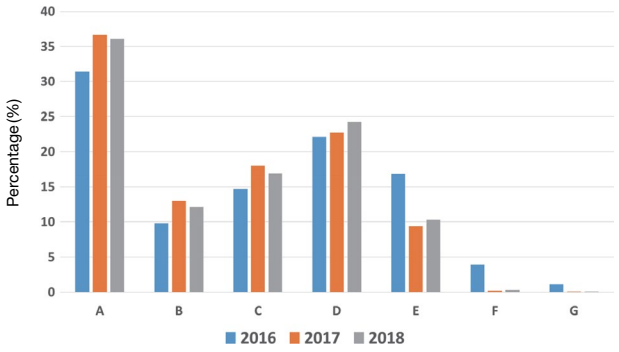

Fig. 4. Percentage of wind stability classes per year.

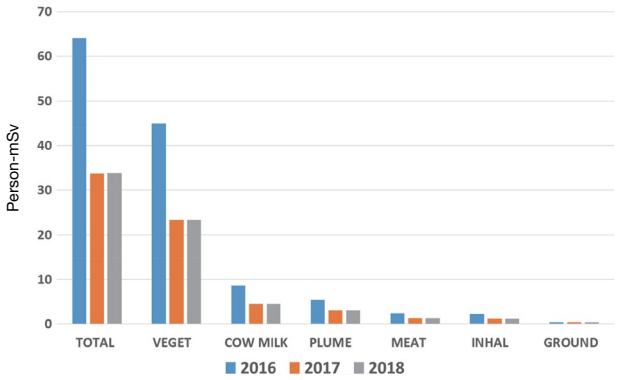

Fig. 5. Annual integrated population doses by pathway (Person-mSv).

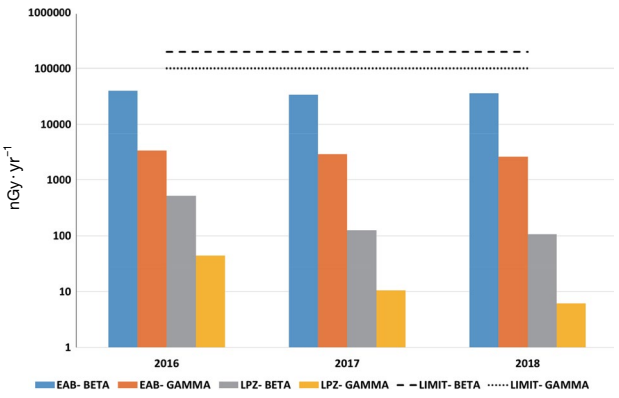

Fig. 6. Annual beta and gamma air doses at EAB and LPZ (nGy · yr^{-1}).

Plotting wind roses served as a first indicator to the nature of doses received according to wind direction. Stability classes showed the year of 2016 was calmer than those of 2017 and 2018. The calmest year of 2016 led to have higher overall doses in the EAB and LPZ. Stability was a second key indicator to the amount of doses received each year. Dispersion and deposition factors followed wind flow patterns as depicted in Fig. 2 and Fig. 3 respectively. Visualization of dispersion and deposition confirmed the accuracy of the wind roses and its effects on the analyses. Dispersion factor was a third indicator to the doses received compared to other years considering such pathway as plume. Deposition factors showed that uniform dose might be received across the years especially on deposition-based pathways like vegetation.

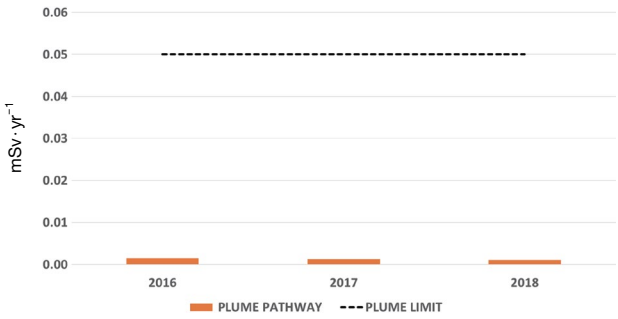

Fig. 7. Individual effective doses by plume pathway at EAB (mSv · yr^{-1}).

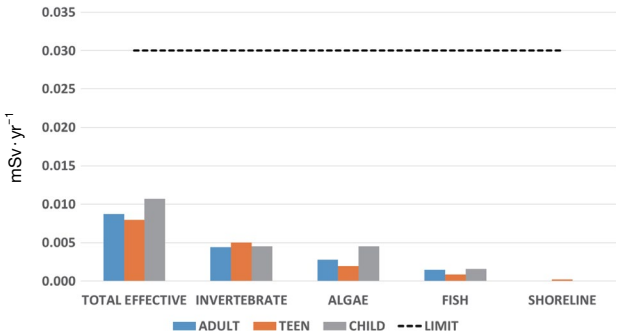

Fig. 8. Effective doses to age groups by pathway due to liquid effluents (mSv · yr^{-1}).

High population doses in 2016 followed from the calm conditions that were experienced during the year as shown in Fig. 5. The main contributor to population dose was vegetation followed by cow milk and the plume pathway, respectively. ^{14}C, ^{3}H, ^{85}Kr, ^{131}mXe and ^{41}Ar were shown to contribute the highest doses across the study period with the first three radionuclides showing consistent rank. Population doses in 2016 were almost double the other years because of higher deposition as shown in Table 6. The plume pathway was of interest in individual dose assessment since the EAB area considered was not agricultural. Child doses were higher than other age groups at both EAB and LPZ due to the related conversion factors. Skin doses were shown to be the highest across all age groups due to radionuclides being airborne. KEPCO and KHNP in their

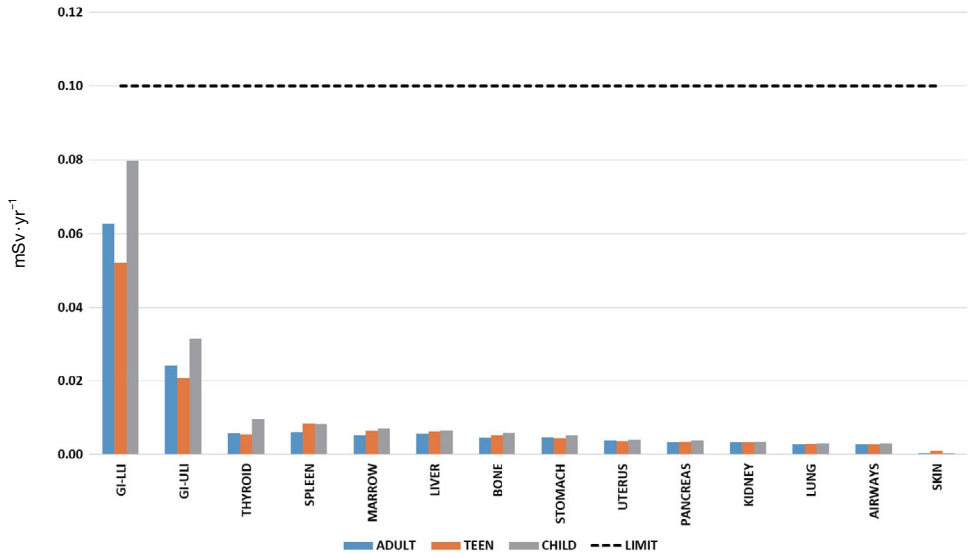

Fig. 9. Equivalent doses to organs of different age groups due to liquid effluents ($mSv \cdot yr^{-1}$).

Table 6. Top 5 radionuclides significantly contributing to population doses (person-mSv)

2016		2017		2018	
Nuclide	Dose	Nuclide	Dose	Nuclide	Dose
^{14}C	5.45×10^{1}	^{14}C	2.82×10^{1}	^{14}C	2.83×10^{1}
^{3}H	3.58×10^{0}	^{3}H	1.85×10^{0}	^{3}H	1.86×10^{0}
^{85}Kr	1.83×10^{0}	^{85}Kr	9.50×10^{-1}	^{85}Kr	9.52×10^{-1}
^{131m}Xe	1.16×10^{0}	^{41}Ar	6.78×10^{-1}	^{41}Ar	6.97×10^{-1}
^{41}Ar	1.10×10^{0}	^{131m}Xe	6.10×10^{-1}	^{131m}Xe	6.13×10^{-1}

application for Nuclear Regulatory Commission (NRC) licensing of APR1400 reported annual air beta and gamma absorbed doses at 0.08 $mGy \cdot yr^{-1}$ and 0.006 $mGy \cdot yr^{-1}$, respectively. They further reported dose by plume pathway at 0.003 $mSv \cdot yr^{-1}$ and skin equivalent dose at 0.056 $mSv \cdot yr^{-1}$ (KEPCO and KHNP 2014). Similarly, their study reported figures within the regulatory limit.

Effective child doses were highest due to sensitivity of dose conversion factors to age groups. Adults and teens were second and last most affected age groups. Consumption of invertebrates and algae were shown to contribute highest dose. Children were most affected by the consumption of algae and fish. Teenagers were most affected by consumption of invertebrates and relatively by spending more time on shoreline activities. This could be attributed to consumption patterns of teenagers and the tendency to have more physical activity. Adults and children were similarly affected by algae and fish consumption which could be attributed to parents and children spending time mostly together. Gastrointestinal upper large intestine was second most affected organ. This could be attributed to ingestion of marine foods. Thyroid was the third most affected organ which was attributable to algae (seaweed) consumption. KEPCO and KHNP in their Design Control Document (DCD) showed effective doses at 0.02 $mSv \cdot yr^{-1}$ to adult and internal organ dose at 0.02 $mSv \cdot yr^{-1}$ to the liver, and this was within the regulatory limits (KEPCO and KHNP 2014).

CONCLUSION

Several analyses were performed in this study to assess the offsite radiological impact of normal operation and anticipated operational occurrences of Shin Kori unit 3. XOQDOQ required other data preprocessing tools to be effective. Wind rose plots were pointers to dispersion and deposition characteristics of the atmosphere. Atmospheric stability though primarily determined from vertical temperature differences and their unavailability in many weather stations could be compensated by using horizontal standard devi-

ation of wind direction. GASPAR generated doses having received formatted data from XOQDOQ. Doses were found to be important especially to the directions within EAB and LPZ. The doses to the overall population should be considered as conservative estimates due to uneven distribution of population and agricultural production within the region considered in this study. Results of GASPAR showed good compliances to Korean regulations. LADTAP considered input parameters that represented population fractions, water-based foods and activities. Consumption of ocean food showed the significance of Korean traditional foods such as seaweeds and invertebrates in terms of contributing to overall doses. LADTAP results also showed good compliances with Korean regulations. XOQDOQ, GASPAR and LADTAP operated on plain texts of input and output data which required detailed analysis. In conclusion, the results of this study showed the good compliances of gaseous and liquid effluents for Shin Kori unit 3 during its normal operations and anticipated operational occurrences.

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