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A Study on Annual Release Objectives and Annual Release Limits of Gaseous Effluents During Decommissioning of Nuclear Power Plants

원전 해체 시 기체상 유출물의 연간 방출관리치 및 방출한도치에 관한 연구

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Decommissioning is a critical issue in Korea. Although compared with the operation of nuclear power plants the release of radioactive materials during decommissioning is not expected to be significant, residents should always be protected from radiation exposure. To manage this effectively, Annual Release Objectives (ARO) and Annual Release Limits (ARL) were derived from dose standards in the NSSC Notice and dose limit for the public. Based on meteorological data for the three years from 2008 to 2010 in the Shin Kori nuclear power plant site, atmospheric dispersion and ground deposition factors of gaseous effluent were evaluated using the XOQDOQ computer code. The exposure dose was evaluated using the ENDOS-G computer code.
Because of differences in radiological sensitivity according to age groups, the results of Annual Release Objectives (ARO) and Annual Release Limits (ARL) showed significant differences depending on the radionuclides. The evaluation methodology of this study will provide meaningful information for radioactive effluent management for decommissioning of nuclear power plants.

Keywords: Gaseous effluents, Decommissioning, Annual Release Objectives (ARO), Annual Release Limits (ARL)

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최근 한국에서 원전해체는 중요한 이슈이다. 원전의 운영 시와 비교해볼 때, 원전 해체 시에는 방사성물질의 방출이 크지 않을 것으로 예상되지만, 주민은 항상 방사선피폭으로부터 보호되어야 한다. 이에 대한 효과적인 관리를 위해, 연간 방출관리치와 방출한도치를 원자력안전위원회 고시 및 일반인 선량한도 기준으로부터 유도하였다.
기체상 유출물에 의한 대기 확산 및 침적 인자는 신고리 발전소 기상탑에서 2008년부터 2010년까지 3년간 수집 된 기상자료를 토대로 XOQDOQ 컴퓨터 코드를 이용해서 평가하였다. 선량평가는 ENDOS-G 컴퓨터 코드를 사용하였다. 이 컴퓨터 코드를 이용하여 기체상 유출물의 연간 방출관리치 및 방출한도치를 평가한 결과, 핵종별로 차이가 있었는데, 이는 연령에 따른 방사선민감도의 차이에 기인한다고 할 수 있다. 본 평가 방법 및 결과는 향후 원전 해체 시 방사성유출물 관리에 중요한 정보를 제공할 수 있을 것으로 판단된다.

중심단어: 기체상 유출물, 원전 해체, 연간 방출관리치, 연간 방출한도치

1. Introduction

Decommissioning is a critical issue in Korea. Korea's first nuclear power plant, Kori Unit 1, was permanently shut down in June 2017 with the approval of the Nuclear Safety and Security Commission (NSSC). Decommissioning refers to administrative and technical actions to release some or all of the regulatory restrictions of nuclear facilities. The types of decommissioning work include decontamination and dismantling of radioactive materials, waste, and radioactive contaminated equipment and structures. These actions are performed progressively and systematically to reduce radiation risks, and the public and environment need adequate protection from radiation hazards during the decommissioning process. Dose standards, which are set on the basis of the three principles for radiation protection, "Justification, Optimization, and Dose limit" are applied to protect the public and environment from radioactive effluents during the decommissioning process.

In the Enforcement Decree of the Nuclear Safety Act of Korea, the dose limit for the public is set at the effective dose of 1 mSv/yr. In accordance with the basic principles of radiation protection recommended by the International Commission on Radiological Protection (ICRP), dose standards for nuclear facilities and sites are stipulated in the NSSC Notice [1].

In the case of Korea, there is no clear provision for decommissioning work. However, in the case of the United States, in the U.S. NRC's Regulatory Guide 1.184, it states that numerical guides of the design objectives for operation of the nuclear power plants described in the Code of Federal Regulations (10CFR Part50) are applied equally to the decommissioning process [2]. Therefore, it would be appropriate to apply the standards for operation of domestic nuclear power plants equally to the decommissioning work and site.

Since various radionuclides are inevitably released during decommissioning of nuclear power plants, the radioactive effluents management and increasing the reliability for safety of the decommissioning are crucial task. During decommissioning, the dose assessment will be periodically conducted to verify the radiation safety. The study about Annual Release Objectives (ARO) and Annual Release Limits (ARL) is necessary because there are different types of radionuclides which have potential impact on the public resulting from environmental releases of radioactive effluents during the decommissioning process differently from the operation of nuclear power plants. They are measureable quantities based on dose standards in the NSSC Notice and dose limit for the public set at the effective dose of 1 mSv/yr, and can be a more effective way for the radioactive effluents management.

Table 1. Significant radionuclides during decommissioning

Radionuclides									
^{3}H	^{14}C	^{36}Cl	^{39}Ar	^{41}Ca	^{45}Ca	^{46}Sc	^{51}Cr	^{53}Mn	^{54}Mn
^{55}Fe	^{59}Fe	^{58}Co	^{60}Co	^{59}Ni	^{63}Ni	^{65}Zn	^{79}Se	^{81}Kr	^{85}Kr
^{90}Sr	^{93}Zr	^{95}Zr	^{92m}Nb	^{94}Nb	^{93}Mo	^{99}Tc	^{108m}Ag	^{121m}Sn	^{124}Sb
^{129}I	^{134}Cs	^{135}Cs	^{137}Cs	^{131}Ba	^{133}Ba	^{145}Pm	^{146}Sm	^{151}Sm	^{152}Eu
^{154}Eu	^{155}Eu	^{158}Tb	^{166m}Ho	^{178m}Hf	^{182}Ta	^{205}Pb	^{233}U	^{239}Pu	

Although the quantity of radioactive materials and kinds of radionuclides to be released during decommissioning is not expected to be significant compared with the operation of nuclear power plants, residents should always be protected from radiation exposure.

The objective of this study is to identify the representative radionuclides that can be released in the decommissioning process and to study the impact on Annual Release Objectives (ARO) and Annual Release Limits (ARL) for gaseous effluents to manage radioactive effluents effectively.

2. Material and Method

2.1 Selection of Radionuclides Released into the Environment

We reviewed the radionuclides, which can be released to the environment during decommissioning. Selection of radionuclides is an essential information to estimate exposure dose during decommissioning.

NUREG/CR-3474 ‘Long-Lived Activation Products in Reactor Materials’ provides information on long-lived radionuclides that may be activated in the reactor materials during decommissioning [3]. IAEA-SRS-95 ‘Methodologies for Assessing the Induced Activation Source Term for Use in Decommissioning Applications’ defines the source terms as the quantity of radionuclides that may be activated during decommissioning [4].

Table 1 lists the significant radionuclides primarily from NUREG/CR-3474 and IAEA-SRS-95 in addition to key fission products such as ^{90}Sr, ^{129}I, ^{137}Cs, etc.

2.2 Meteorological Data Analysis

Meteorological observations are carried out at the site of the decommissioning facility by operating a meteorological tower according to the NSSC Notice 2017-26. In the Notice, the collection rate of meteorological data should be at least 90%, and it is required to have an observation period for at least the last year for the permission of construction and at least the last two years for the permission of operation [5]. IAEA recommends at least three to five years of meteorological data collection for the assessment for the safety of decommissioning site [6].

During the normal operation of nuclear facilities, the meteorological data measured at the height that can represent the release height is applied to the evaluation of the atmospheric dispersion and ground deposition factors.

The Joint Frequency Distribution (JFD) is used by analyzing the meteorological data observed at the meteorological tower. It is a statistical data representing occurrence probability of wind speed classes and directions in accordance with atmospheric stability classes. In the U.S. NRC’s Regulatory Guide 1.23 [7], 16 directions, 7 atmospheric stability classes (A~G), and 11 wind speed classes (<0.5, 0.5~1.0, 1.1~1.5, 1.6~2.0, 2.1~3.0, 3.1~4.0, 4.1~5.0, 5.1~6.0, 6.1~8.0, 8.1~10.0, 10.0< m/sec) are given as an example of creating the JFD. The wind direction of calm, any wind speed below the starting threshold of the wind speed or direction sensor, whichever is greater, is distributed proportionally to the JFD of the first non-calm wind speed class.

2.3 Evaluation of the Atmospheric Dispersion and Ground Deposition

The gaseous effluent released into the atmosphere is dispersed under the influence of the surrounding meteorological conditions. The XOQDOQ computer code [8] has been developed to evaluate the atmospheric dispersion and ground deposition in a routine release of radioactive effluents in according with the methodology recommended in the U.S. NRC's Regulatory Guide 1.111 [9]. It is a straight-line Gaussian plume model using a joint frequency distribution data, observed at the meteorological tower. As the results, the annual averaged atmospheric dispersion factor (χ/Q, sec/m^3) and ground deposition factor (D/Q, 1/m^2), which represents capabilities of dispersion to the atmosphere and deposition to the ground of radioactive effluents released into the environment, are calculated respectively.

2.3.1 Atmospheric Dispersion Factor

The annual averaged atmospheric dispersion factor is evaluated differently for the ground release and elevated release. In case of no stack release, it is assumed as a ground release. The atmospheric dispersion factor is determined whichever is greater, as calculated by the following formula (1) and (2) [8]:

$$\frac{X}{Q}(x,k) = \frac{2.032}{x} RF(x,k)\, \Sigma_{ij} DP_{ij}(x,k)\, DC_i(x)\, f_{ij}(x,k)\, [u_i(\sigma_{zj}^2(x) + C\, D_z^2/\pi)^{1/2}]^{-1} \quad (1)$$

$$\frac{X}{Q}(x,k) = \frac{2.032}{x} RF(x,k)\, \Sigma_{ij} DP_{ij}(x,k)\, DC_i(x)\, f_{ij}(k)\, [\sqrt{3}\, u_i\, \sigma_{zj}(x)]^{-1} \quad (2)$$

Where,

X/Q: Atmospheric dispersion factor (sec/m^3)
x: Downwind distance (m)
i: ith wind speed class
j: jth atmospheric stability class
k: kth wind direction class
u_i: Mid-point value of the ith wind speed class (m/sec)
$\sigma_{zj}(x)$: Vertical plume spread for stability class j at distance x
$f_{ij}(k)$: Joint probability of occurrence of the ith wind speed class, jth atmospheric stability class, and kth wind direction sector
$RF(x,k)$: Correction factor for recirculation and stagnation at downwind distance x and kth wind direction class
$DP_{ij}(x,k)$: Reduction factor due to plum depletion at distance x for the ith wind speed class, jth atmospheric stability class, and kth wind direction class
DC_i(x): Reduction factor due to radioactive decay at distance x for the ith wind speed class
D_Z: Building height (m)
C: Building-wake constant (=0.5)

2.3.2 Ground Deposition Factor

For the annual averaged deposition factor, only the dry deposition is considered and calculated by the following formula (3) [8]:

$$\frac{D}{Q}(x,k) = \frac{RF(x,k)\, \Sigma_{ij}\, D_{ij}\, f_{ij}(k)}{(2\pi/n)x} \quad (3)$$

Where,

$D/Q(x,k)$: Average relative deposition per unit area at downwind distance x and direction k (1/m^2)
D_{ij}: The relative deposition rate for the ith wind speed class and jth atmospheric stability class (m)
$f_{ij}(k)$: Joint probability of the ith wind speed class, jth atmospheric stability class, and kth wind direction sector

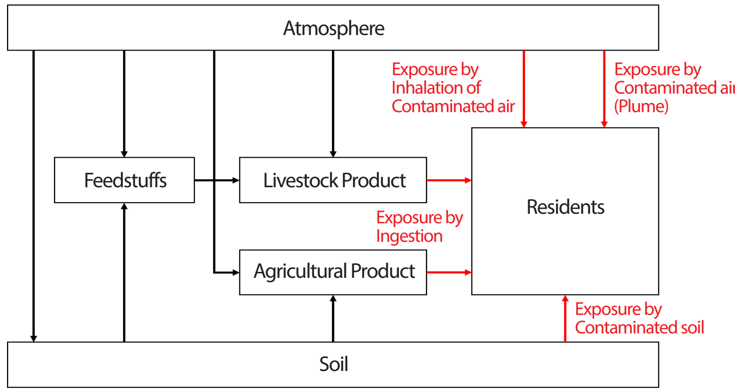

Fig. 1. Main exposure pathways from gaseous effluent.

x: Downwind distance (m)

$RF(x,k)$: Correction factor for air recirculation and stagnation at distance x and kth wind direction

n: Number of downwind direction (=16)

2.4 Off-site Radiological Dose Assessment

2.4.1 Exposure Pathways

The main exposure pathways for residents from gaseous effluent released into the environment during decommissioning are shown in Fig. 1.

As shown in Fig. 1, the following exposure pathways are considered for the dose assessment for residents from gaseous effluent.

- External exposure by contaminated air (plume)
- External exposure by contaminated soil
- Internal exposure by inhalation of contaminated air
- Internal exposure by ingestion of contaminated crops

The foods for evaluating the ingestion pathway is classified into cereals, fruits, kimchi, leafy vegetables, milk, beef, pork and chicken in consideration of the domestic agricultural environment.

2.4.2 Dose Calculation

The GASDOS [10] computer code was developed by the Korea Institute of Nuclear Safety (KINS) to include the characteristics of domestic sites, based on NRC's Regulatory Guide 1.109 [11]. After that, the Korea Atomic Energy Research Institute (KAERI) developed the ENDOS-G computer code, which modified the GASDOS by considering the dose coefficients recommended in the ICRP-60.

We have modified and supplemented the ENDOS-G computer code to accommodate the decommissioning of nuclear facilities in Korea such as the new database of dose coefficients for specific radionuclides for the decommissioning and the soil accumulating period.

The maximum exposed individual dose is defined as an individual who has a life-style that represents a reasonable deviation from the average exposure dose of the group, and applies to the exposure dose of residents who live at a specific location. The specific location means a location such as an Exclusion Area Boundary, the nearest resident area, etc.

Age groups should be classified to have homogeneous characteristics to take into account their lifestyles and radiological sensitivity. According to ICRP-60, the dose coefficient is given for six age groups [12]. The dose coefficient is a value for quantification of radiation sensitivity against tissues or organs of human body. It depends on particle size and chemical form for inhalation. IAEA recommends 1μm of Activity Median Aerodynamic Diameter (AMAD) for

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  27 60 4.18E-093.68E-08
7.40E-061.63E-051.26E-056.29E-068.88E-066.66E-064.44E-05     Ingestion
1.44E-053.15E-053.70E-051.41E-051.48E-051.92E-041.78E-05     Inhalation of Particle M
4.14E-082.92E-083.06E-083.00E-082.96E-083.02E-083.00E-08     External Dose Coefficients
  28 59 2.93E-130.00E+00
1.37E-071.37E-072.33E-071.37E-071.33E-071.37E-071.41E-06     Ingestion
2.89E-072.89E-074.81E-072.89E-072.89E-071.74E-065.92E-07     Inhalation of Particle M
0.00E+000.00E+000.00E+000.00E+000.00E+000.00E+000.00E+00     External Dose Coefficients
  28 63 2.29E-100.00E+00
3.22E-073.22E-075.55E-073.22E-073.22E-073.22E-073.40E-06     Ingestion
7.03E-077.03E-071.78E-067.03E-076.66E-079.25E-061.44E-06     Inhalation of Particle M
0.00E+000.00E+000.00E+000.00E+000.00E+000.00E+000.00E+00     External Dose Coefficients
  30 65 3.29E-088.68E-09
2.00E-051.33E-051.44E-051.30E-051.41E-051.18E-051.92E-05     Ingestion
5.18E-064.81E-065.92E-063.70E-063.70E-061.89E-054.81E-06     Inhalation of Particle M
9.84E-096.82E-097.21E-097.17E-096.90E-097.07E-097.01E-09     External Dose Coefficients
  34 79 3.38E-131.21E-12
3.55E-065.18E-051.07E-053.55E-061.18E-043.55E-068.51E-06     Ingestion
1.41E-062.04E-054.07E-061.41E-064.81E-051.44E-062.74E-06     Inhalation of Particle F
8.05E-131.33E-132.18E-132.16E-131.66E-131.53E-139.22E-14     External Dose Coefficients
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Fig. 2. New database of dose coefficients for specific radionuclides for the decommissioning.

the public, and provides recommended chemical forms if there is no information. Using the handbook of dose coefficients [13], we created the new database about information of dose coefficients for the each radionuclides mentioned in Section 2.1, as shown in Fig. 2.

2.5 Dose Limit and Regulation Standard

In the Enforcement Decree of the Nuclear Safety Act of Korea, the dose limit for public is set at the effective dose of 1 mSv/yr. In accordance with the general principles of radiation protection recommended by ICRP, the dose standards for sites where nuclear facilities and multiple facilities operate are specified in the NSSC Notice. Only the standards for operation are established, and there are no clear standards for the decommissioning process.

As mentioned in the introduction, in the case of United States, in the U.S. NRC's Regulatory Guide 1.184, it states that numerical guides of the design objectives for operation of the nuclear power plants described in the Code of Federal Regulations (10CFR Part50) are applied equally to the decommissioning process. Therefore, in this study, the dose standards applied in the design or operation of the domestic nuclear facilities are used for the decommissioning work and site, as shown in Table 2.

2.6 Methodology for the Derivation of Annual Release Objectives (ARO) and Annual Release Limits (ARL)

The Annual Release Objectives (ARO) can be evaluated by the following formula (4) based on Table 2 according to the NSSC Notice.

$$ARO_i = \frac{DS}{D_i} \tag{4}$$

Where,

DS: Dose Standards for off-site ($\frac{mGy}{yr}$ or $\frac{mSv}{yr}$)

D_i: Off-site dose for annual unit release of radionuclide i $\frac{\frac{mGy}{yr} \; or \; \frac{mSv}{yr}}{\left(\frac{Bq}{yr}\right)}$

The Annual Release Limits (ARL) are evaluated by the following formula (5) based on the dose limit for the public set at the effective dose of 1 mSv/yr.

$$ARL_i = \frac{DL}{E_i} \tag{5}$$

Where,

DL: Dose limit for the public (=1 mSv/yr)

Table 2. Dose standards based on annual dose at the EAB during the normal operation in the NSSC Notice [1]

Item	Dose Standards
Air absorption dose by gamma rays	0.1 mGy/yr
Air absorption dose by beta rays	0.2 mGy/yr
Effective dose by external exposure	0.05 mSv/yr
Skin equivalent dose	0.15 mSv/yr
Organ equivalent dose by particles, ^{3}H, ^{14}C, and iodine	0.15 mSv/yr

JOINT FREQUENCY DISTRIBUTION OF WIND SPEED AND DIRECTION IN FRACTIONS: ATMOSPHERIC STABILITY CLASS A

U (m/s)	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
Calm																	0.91
0.51~ 1.00	0.12	0.11	0.07	0.08	0.07	0.07	0.07	0.07	0.13	0.12	0.10	0.17	0.11	0.07	0.08	0.12	1.57
1.01~ 1.50	0.16	0.14	0.12	0.15	0.10	0.11	0.12	0.14	0.30	0.18	0.10	0.27	0.16	0.10	0.08	0.11	2.32
1.51~ 2.00	0.25	0.24	0.17	0.20	0.15	0.13	0.18	0.23	0.40	0.15	0.11	0.30	0.30	0.09	0.07	0.12	3.09
2.01~ 3.00	0.39	0.39	0.37	0.46	0.40	0.37	0.37	0.57	0.45	0.25	0.24	0.40	0.70	0.28	0.18	0.47	6.29
3.01~ 4.00	0.11	0.10	0.28	0.51	0.41	0.23	0.18	0.16	0.17	0.14	0.16	0.11	0.37	0.37	0.16	0.34	3.81
4.01~ 5.00	0.03	0.01	0.16	0.38	0.16	0.08	0.04	0.04	0.06	0.03	0.05	0.03	0.13	0.30	0.13	0.16	1.79
5.01~ 6.00	0.00	0.00	0.04	0.14	0.02	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.03	0.18	0.08	0.03	0.61
6.01~ 8.00	-	0.00	0.00	0.04	0.00	0.00	0.01	0.00	-	0.00	0.00	0.00	0.01	0.08	0.04	0.01	0.21
8.01~10.00	-	-	-	-	-	-	-	-	-	-	0.01	-	-	0.01	-	0.00	0.02
10.00<	-	-	-	-	-	-	-	-	-	-	-	-	-	0.00	-	-	0.00
Total	1.06	0.99	1.20	1.96	1.31	1.01	1.00	1.22	1.54	0.88	0.79	1.28	1.80	1.49	0.82	1.37	20.64

JOINT FREQUENCY DISTRIBUTION OF WIND SPEED AND DIRECTION IN FRACTIONS: ATMOSPHERIC STABILITY CLASS B

U (m/s)	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
Calm																	0.15
0.51~ 1.00	0.03	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.01	0.02	0.02	0.01	0.01	0.01	0.25
1.01~ 1.50	0.04	0.03	0.03	0.03	0.02	0.01	0.01	0.01	0.03	0.02	0.02	0.02	0.02	0.02	0.02	0.01	0.33
1.51~ 2.00	0.05	0.04	0.03	0.03	0.04	0.03	0.01	0.01	0.02	0.01	0.03	0.03	0.04	0.01	0.01	0.03	0.42
2.01~ 3.00	0.09	0.04	0.08	0.08	0.10	0.06	0.04	0.03	0.03	0.03	0.05	0.05	0.06	0.06	0.04	0.09	0.94
3.01~ 4.00	0.05	0.01	0.06	0.08	0.04	0.05	0.01	0.01	0.02	0.02	0.05	0.01	0.04	0.05	0.03	0.11	0.64
4.01~ 5.00	0.02	0.01	0.04	0.05	0.02	0.01	0.00	0.00	0.01	0.01	0.02	0.00	0.03	0.06	0.03	0.04	0.32
5.01~ 6.00	-	0.00	0.01	0.01	-	0.00	0.00	0.00	-	0.00	0.00	0.00	0.01	0.02	0.01	0.01	0.09
6.01~ 8.00	-	0.00	0.00	0.00	-	-	-	-	-	-	0.00	0.00	0.00	0.00	0.01	-	0.02
8.01~10.00	-	-	-	-	-	-	-	-	-	-	0.00	-	-	-	-	-	0.00
10.00<	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	0.27	0.16	0.26	0.30	0.24	0.17	0.08	0.07	0.12	0.12	0.18	0.14	0.21	0.24	0.16	0.30	3.18

Fig. 3. Joint Frequency Distribution Data at Shin Kori Site.

E_i: Effective dose for annual unit release of radionuclide i $\frac{\left(\frac{mSv}{yr}\right)}{\left(\frac{Bq}{yr}\right)}$

3. Results and Discussion

3.1 Results of the Atmospheric Dispersion and Ground Deposition Factor

The annual averaged atmospheric dispersion and ground deposition factor of the gaseous effluents are calculated using the XOQDOQ computer code. For this calculation, the meteorological data was obtained at a 10 meter height from a meteorological tower in Shin Kori nuclear power plant site for 3 years from 2008 to 2010, as shown in Fig. 3.

The meteorological data collection rate during this period is 97.35%. According to the frequency distribution of stability class measured at the site during this period, the stable state was 50.18% (Atmospheric stability grade E: 34.28%, F: 12.97%, G: 2.93%), the unstable state was 27.26% (Atmospheric stability grade A: 20.64%, B: 3.18%, C: 3.44%), and neutral (Atmospheric stability grade D) was 22.57%.

The evaluation locations are the Exclusion Area Boundary (EAB) of 16 overall directions. The EAB of Kori unit 1 is a 700 meter radius. The effect of recirculation and stagnation is considered and the effect of building wake was not considered.

If the maximum value of the evaluation results at the

Table 3. Results of the atmospheric dispersion and ground deposition factor at the EAB

Direction	(χ/Q) (sec/m^3)	(χ/Q)^D (sec/m^3)	(χ/Q)^{DD} (sec/m^3)	D/Q (1/m^2)
S	4.499×10^{-5}	4.480×10^{-5}	4.137×10^{-5}	1.016×10^{-7}
SSW	2.789×10^{-5}	2.774×10^{-5}	2.564×10^{-5}	5.338×10^{-8}
SW	2.190×10^{-5}	2.178×10^{-5}	2.013×10^{-5}	5.150×10^{-8}
WSW	1.722×10^{-5}	1.712×10^{-5}	1.583×10^{-5}	4.812×10^{-8}
W	1.941×10^{-5}	1.931×10^{-5}	1.784×10^{-5}	4.205×10^{-8}
WNW	1.903×10^{-5}	1.894×10^{-5}	1.750×10^{-5}	3.839×10^{-8}
NW	1.959×10^{-5}	1.947×10^{-5}	1.801×10^{-5}	2.940×10^{-8}
NNW	1.841×10^{-5}	1.830×10^{-5}	1.692×10^{-5}	2.950×10^{-8}
N	2.393×10^{-5}	2.379×10^{-5}	2.200×10^{-5}	4.121×10^{-8}
NNE	3.289×10^{-5}	3.275×10^{-5}	3.025×10^{-5}	5.623×10^{-8}
NE	3.793×10^{-5}	3.777×10^{-5}	3.488×10^{-5}	8.139×10^{-8}
ENE	4.563×10^{-5}	4.539×10^{-5}	4.195×10^{-5}	7.892×10^{-8}
E	3.325×10^{-5}	3.309×10^{-5}	3.057×10^{-5}	7.034×10^{-8}
ESE	2.641×10^{-5}	2.630×10^{-5}	2.429×10^{-5}	6.760×10^{-8}
SE	3.226×10^{-5}	3.213×10^{-5}	2.967×10^{-5}	6.793×10^{-8}
SSE	4.333×10^{-5}	4.318×10^{-5}	3.986×10^{-5}	1.223×10^{-7}

Note) χ/Q (sec/m^3): Atmospheric dispersion factor which is not considered decay and depletion
(χ/Q)^D (sec/m^3): Atmospheric dispersion factor which is only considered decay
(χ/Q)^{DD} (sec/m^3): Atmospheric dispersion factor which is considered decay and depletion
D/Q (1/m^2): Ground deposition factor

EAB meets the criteria, the residents at all other locations may be considered to be protected from radioactive effluents. Among results of the 16 overall directions, the maximum atmospheric dispersion factor was in the ENE direction as shown in Table 3.

3.2 Results of the Annual Release Objectives and Annual Release Limits

The maximum atmospheric dispersion factor is in the ENE direction, so the atmospheric dispersion and ground deposition factors in the ENE direction are used as input data for ENDOS-G. The soil accumulating period was applied for 40 years, which is a total operating period of Kori Unit 1.

Depending on the chemical form of the radionuclides, the dose coefficient, which affects the human body, is different. In ICRP-60, the lung absorption modes are shown as F (Fast), M (Moderate), and S (Slow) depending on the chemical form of the radionuclides. In this study, the lung absorption mode recommended by the IAEA was selected, when there were no information.

Among the radionuclides defined on the basis of NUREG/CR-3474, ^{39}Ar, ^{81}Kr, and ^{85}Kr are radionuclides corresponding to noble gases. ^{39}Ar and ^{81}Kr were excluded from the evaluation because the information was not found.

Table 4. Results of Annual Release Objectives (ARO)

	Lung Absorption Type	Critical Organ	Critical Age	Equivalent Dose $\left(\frac{mSv/yr}{Bq/yr}\right)$	ARO (Bq/yr)	Remark
^{3}H	Tritiated Water	Same	1 Year	1.12×10^{-15}	1.34×10^{14}	
^{14}C	Carbon dioxide	GI-Tract	1 Year	8.81×10^{-13}	1.70×10^{11}	
^{36}Cl	M	GI-Tract	3 Months	8.59×10^{-10}	1.75×10^{8}	
^{41}Ca	M	Bone	15 Years	6.05×10^{-12}	2.48×10^{10}	
^{45}Ca	M	Bone	3 Months	5.30×10^{-12}	2.83×10^{10}	
^{46}Sc	S	GI-Tract	1 Year	2.81×10^{-12}	5.34×10^{10}	
^{51}Cr	S	GI-Tract	1 Year	4.16×10^{-14}	3.60×10^{12}	
^{53}Mn	M	GI-Tract	1 Year	7.81×10^{-13}	1.92×10^{11}	
^{54}Mn	M	Bone	5 Years	2.54×10^{-12}	5.92×10^{10}	
^{55}Fe	M	Bone	3 Months	3.54×10^{-13}	4.24×10^{11}	
^{59}Fe	M	GI-Tract	1 Year	1.66×10^{-12}	9.04×10^{10}	
^{58}Co	M	GI-Tract	1 Year	1.02×10^{-12}	1.47×10^{11}	
^{60}Co	M	Bone	10 Years	4.19×10^{-11}	3.58×10^{9}	Same in 3 months, 1 year and 5 years
^{59}Ni	M	GI-Tract	3 Months	7.38×10^{-13}	2.03×10^{11}	
^{63}Ni	M	GI-Tract	3 Months	1.65×10^{-12}	9.07×10^{10}	
^{65}Zn	M	Bone	3 Months	6.73×10^{-12}	2.23×10^{10}	
^{79}Se	F	Kidney	3 Months	3.89×10^{-9}	3.85×10^{7}	
^{90}Sr	F	Bone	15 Years	3.86×10^{-9}	3.88×10^{7}	
^{93}Zr	M	Bone	Adult	1.06×10^{-11}	1.41×10^{10}	
^{95}Zr	M	GI-Tract	1 Year	1.79×10^{-12}	8.40×10^{10}	
^{94}Nb	M	Bone	10 Years	1.47×10^{-10}	1.02×10^{9}	Same in 3 months, 1 year and 5 years
^{93}Mo	M	Bone	Adult	1.71×10^{-10}	8.75×10^{8}	
^{99}Tc	M	GI-Tract	1 Year	5.62×10^{-10}	2.67×10^{8}	
^{108m}Ag	M	Bone	1 Year	1.46×10^{-10}	1.03×10^{9}	
^{121m}Sn	M	GI-Tract	1 Year	2.05×10^{-12}	7.30×10^{10}	
^{124}Sb	M	GI-Tract	1 Year	5.30×10^{-12}	2.83×10^{10}	
^{129}I	Elemental iodine vapor	Thyroid	10 Years	8.03×10^{-10}	1.87×10^{8}	
^{134}Cs	F	Bone	15 Years	1.49×10^{-11}	1.01×10^{10}	Same in Adult
^{135}Cs	F	GI-Tract	1 Year	1.57×10^{-12}	9.54×10^{10}	
^{137}Cs	F	GI-Tract	Adult	6.46×10^{-12}	2.32×10^{10}	

^{131}Ba	M	GI-Tract	1 Year	2.17×10^{-13}	6.91×10^{11}
^{133}Ba	M	Bone	15 Years	2.44×10^{-11}	6.14×10^{9}
^{145}Pm	M	Bone	5 Years	5.05×10^{-12}	2.97×10^{10}
^{146}Sm	M	Bone	5 Years	3.92×10^{-9}	3.83×10^{7}
^{151}Sm	M	Bone	5 Years	1.41×10^{-12}	1.07×10^{11}
^{152}Eu	M	Bone	5 Years	5.05×10^{-11}	2.97×10^{9}
^{154}Eu	M	Bone	5 Years	4.24×10^{-11}	3.54×10^{9}
^{155}Eu	M	Bone	5 Years	4.41×10^{-12}	3.40×10^{10}
^{158}Tb	M	Bone	5 Years	8.14×10^{-11}	1.84×10^{9}
^{166m}Ho	M	Bone	5 Years	1.85×10^{-10}	8.09×10^{8}
^{178m}Hf	F	Bone	5 Years	2.57×10^{-10}	5.84×10^{8}
^{182}Ta	S	GI-Tract	1 Year	2.15×10^{-11}	6.97×10^{9}
^{205}Pb	M	Bone	15 Years	5.24×10^{-12}	2.86×10^{10}
^{233}U	M	Lung	5 Years	5.14×10^{-10}	2.92×10^{8}
^{239}Pu	M	Bone	Adult	1.57×10^{-8}	9.57×10^{6}
^{85}Kr	Noble Gas			7.62×10^{-16} [1)]	2.62×10^{14}

[1)] Annual Beta Air Dose and unit is $\left(\frac{mGy/yr}{Bq/yr}\right)$

^{85}Kr was evaluated based on the annual beta air dose, the most severe condition. Since the internal exposure by the noble gas does not occur, the organ dose is not considered. In addition, ^{92m}Nb was also excluded from the evaluation because the information was not found. In the case of radionuclides without the information, it might have relatively little impact on the human body as compared with other radionuclides.

In order to meet regulatory standards for the organ equivalent, the highest dose was selected among the various organs and 6 age groups. Using this value, Annual Release Objectives (ARO) and Annual Release Limits (ARL) were evaluated.

At first, we evaluated the Annual Release Objectives (ARO) compared with dose standards as shown in Table 2. The results are summarized in Table 4. In the case of ^{60}Co, one of the representative radionuclides that can be released during decommissioning, the Annual Release Objectives (ARO) is 3.58×10^{9} Bq/yr, which corresponds to dose standards in the NSSC Notice. The critical organ is bone and the 10 years group is the critical age group.

In addition, we evaluated the Annual Release Limits (ARL) compared with dose limit for the public set at the effective dose of 1 mSv/yr. The results are summarized in Table 5. In the case of ^{60}Co, the Annual Release Limits (ARL) is 3.16×10^{10} Bq/yr, which corresponds to dose limit for the public set at the effective dose of 1 mSv/yr and 5 years group is the critical age group.

Except for the noble gases, all selected radionuclides corresponds to the organ equivalent dose of 0.15 mSv/yr for Annual Release Objectives (ARO). In the case of ^{60}Co, the Annual Release Objectives (ARO) is 3.58×10^{9} Bq/yr, which means if ^{60}Co releases 3.58×10^{9} Bq/yr during decommissioning, the organ equivalent dose will be 0.15

Table 5. Results of Annual Release Limits (ARL)

	Lung Absorption Type	Critical Age	Effective Dose $\left(\frac{mSv/yr}{Bq/yr}\right)$	ARL (Bq/yr)	Remark
^{3}H	Tritiated Water	1 Year	1.12×10^{-15}	8.94×10^{14}	
^{14}C	Carbon dioxide	1 Year	8.30×10^{-13}	1.21×10^{12}	
^{36}Cl	M	3 Months	7.03×10^{-10}	1.42×10^{9}	
^{41}Ca	M	15 Years	2.34×10^{-13}	4.28×10^{12}	
^{45}Ca	M	3 Months	4.32×10^{-13}	2.31×10^{12}	
^{46}Sc	S	5 Years	1.41×10^{-12}	7.09×10^{11}	
^{51}Cr	S	1 Year	1.03×10^{-14}	9.74×10^{13}	
^{53}Mn	M	1 Year	9.11×10^{-14}	1.10×10^{13}	
^{54}Mn	M	5 Years	1.86×10^{-12}	5.36×10^{11}	
^{55}Fe	M	3 Months	1.29×10^{-13}	7.76×10^{12}	
^{59}Fe	M	3 Months	7.84×10^{-13}	1.28×10^{12}	
^{58}Co	M	5 Years	6.08×10^{-13}	1.64×10^{12}	
^{60}Co	M	5 Years	3.16×10^{-11}	3.16×10^{10}	Same in 1 year
^{59}Ni	M	3 Months	1.16×10^{-13}	8.60×10^{12}	
^{63}Ni	M	3 Months	2.68×10^{-13}	3.73×10^{12}	
^{65}Zn	M	3 Months	4.73×10^{-12}	2.11×10^{11}	
^{79}Se	F	3 Months	6.95×10^{-10}	1.44×10^{9}	
^{90}Sr	F	15 Years	1.71×10^{-10}	5.84×10^{9}	
^{93}Zr	M	Adult	2.16×10^{-13}	4.62×10^{12}	
^{95}Zr	M	5 Years	5.27×10^{-13}	1.90×10^{12}	
^{94}Nb	M	10 Years	1.04×10^{-10}	9.61×10^{9}	Same in 1 year and 5 years
^{93}Mo	M	Adult	8.70×10^{-12}	1.15×10^{11}	
^{99}Tc	M	3 Months	1.48×10^{-10}	6.76×10^{9}	
^{108m}Ag	M	1 Year	1.03×10^{-10}	9.71×10^{9}	
^{121m}Sn	M	5 Years	4.05×10^{-13}	2.47×10^{12}	Same in 1 year
^{124}Sb	M	1 Year	1.26×10^{-12}	7.96×10^{11}	
^{129}I	Elemental iodine vapor	10 Years	4.05×10^{-11}	2.47×10^{10}	
^{134}Cs	F	15 Years	1.16×10^{-11}	8.64×10^{10}	
^{135}Cs	F	Adult	9.76×10^{-13}	1.02×10^{12}	
^{137}Cs	F	Adult	5.05×10^{-12}	1.98×10^{11}	
^{131}Ba	M	5 Years	6.92×10^{-14}	1.45×10^{13}	

^{133}Ba	M	15 Years	1.02×10^{-11}	9.84×10^{10}	
^{145}Pm	M	5 Years	1.00×10^{-12}	1.00×10^{12}	
^{146}Sm	M	5 Years	1.59×10^{-10}	6.29×10^{9}	
^{151}Sm	M	5 Years	8.30×10^{-14}	1.21×10^{13}	
^{152}Eu	M	10 Years	3.24×10^{-11}	3.08×10^{10}	Same in 5 years
^{154}Eu	M	5 Years	2.61×10^{-11}	3.83×10^{10}	
^{155}Eu	M	5 Years	8.51×10^{-13}	1.17×10^{12}	
^{158}Tb	M	15 Years	4.84×10^{-11}	2.07×10^{10}	Same in 5 years and 10 years
^{166m}Ho	M	5 Years	1.16×10^{-10}	8.64×10^{9}	
^{178m}Hf	F	5 Years	1.07×10^{-10}	9.34×10^{9}	
^{182}Ta	S	1 Year	3.11×10^{-12}	3.22×10^{11}	
^{205}Pb	M	15 Years	2.78×10^{-13}	3.59×10^{12}	
^{233}U	M	5 Years	7.14×10^{-11}	1.40×10^{10}	
^{239}Pu	M	5 Years	5.54×10^{-10}	1.80×10^{9}	
^{85}Kr	Noble Gas	Adult	7.68×10^{-18}	1.30×10^{17}	Same in all age groups

mSv/yr, under the dose standard in the NSSC Notice. Similarly, all selected radionuclides corresponds to the dose limit for the public set at the effective dose of 1 mSv/yr for Annual Release Limits (ARL). In the case of ^{60}Co, the Annual Release Limits (ARL) is 3.16×10^{10} Bq/yr, which means if ^{60}Co releases 3.16×10^{10} Bq/yr during decommissioning, the dose limit will be 1 mSv/yr.

The Annual Release Objectives (ARO) and the Annual Release Limits (ARL) evaluated from this study showed significant dependence on the radionuclides, because of the differences in radiological sensitivity in organ according to the age groups.

4. Conclusions

In this study, the Annual Release Objectives (ARO) and the Annual Release Limits (ARL) were evaluated from dose standards in the NSSC Notice and dose limit for the public set at the effective dose of 1 mSv/yr through the radiological dose assessment for the gaseous effluents during decommissioning of nuclear power plants.

For this purpose, we reviewed the radionuclides which can be released to the environment at the site during decommissioning and analyzed the meteorological data measured at the Shin Kori nuclear power plant site for 3 years. The atmospheric dispersion and ground deposition factors of the gaseous effluent were evaluated using the XOQDOQ computer code. The exposure dose for the gaseous effluent was evaluated using the ENDOS-G computer code. We modified and supplemented with this computer code to accommodate the decommissioning of nuclear facilities in Korea. This evaluation methodology would provide meaningful information to radioactive effluent management for the decommissioning of nuclear power plants.

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