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Derivation of site-specific derived concentration guideline levels at Korea Research Reactor-1&2 sites

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ABSTRACT

The objective of this study was to derive derived concentration guideline levels (DCGLs) reflecting the site-specific characteristics of KRR-1&2. A total of 7 nuclides (H-3, C-14, Co-60, Sr-90, Cs-137, Eu-152, and Eu-154) were selected for DCGLs derivation. Radiation dose at the sites was evaluated with RESRAD-ONSITE program. The dose contribution due to direct external exposure was the highest during the entire evaluation period. Ingestion had the second effect. The DCGLs of Co-60 was derived to be 0.051 Bq/g, and DCGLs of Cs-137 was 0.193 Bq/g. The DCGLs of H-3 showed the highest value of 129 Bq/g. The ratio of DCGLs derived by applying site-specific values and default values ranged from 0.27 to 19.6. For six nuclides excluding H-3, KRR-1&2 sites and the overseas NPP sites showed similar DCGLs. H-3 showed large differences in DCGLs from this study and overseas NPPs. The large difference resulted from input parameter values applied to the sites. In conclusion, it is critical to apply site-specific parameter values reflecting the site characteristics to derive DCGLs for decommissioned site clearance. The result of this study can be used as a reference for nuclide selection and DCGLs derivation reflecting the site characteristics when decommissioning nuclear facilities, including nuclear power plants in Korea.

1. Introduction

Korea Research Reactor Units 1&2 (KRR-1&2) are the first nuclear reactors in Korea, and were operated from 1962 to 1995 for training, research, and isotope production. With the operation of the High-Flux Advanced Neutron Application Reactor (HANARO), a multipurpose research reactor, the utility of KRR-1&2 gradually declined, and official decommissioning work began in 1997 [1]. The International Atomic Energy Agency (IAEA) has declared that decommissioned sites can be reused with restriction or without restriction depending on satisfaction of requirements, including derived concentration guideline levels (DCGLs) [2]. In Korea, the radiation dose criteria for reuse of the site and the remaining buildings is suggested as 0.1 mSv/y. To satisfy the dose criteria, the operator should derive DCGLs and use them as the standard for the investigation of residual radioactivity on the site or building after decommissioning [3]. To unrestrictedly use the KRR-1&2 sites, they should satisfy the dose criteria. To this end, it is essential to derive the DCGLs, which reflect the site-specific characteristics influencing radiation dose.

For the KRR-1&2 sites, Lee et al. previously estimated radiation doses due to five gamma-emitting nuclides (Co-60, Cs-134, Cs-137, Eu-152, and Eu-154) assuming final status of the decommissioning [4]. However, the selection of the target radionuclides for site release was not systematic. They were just selected among radionuclides detected during the KRR decommissioning. In addition, information of the site-specific characteristics was insufficient. The derivation of the preliminary DCGLs values were conducted in other nuclear facilities. Hong et al. derived DCGLs for site release of a uranium conversion plant following decommissioning [5]. Preliminary studies to derive DCGLs of commercial nuclear power plant (NPP) site were performed for the Kori Unit 1 in Korea [6,7]. Site-specific exposure scenarios were developed and site-specific characteristics were applied in the studies. In addition, a sensitivity study was performed to identify the parameters influencing radiation dose at the site and to reflect the site-specific characteristics in the parameters [8]. The DCGLs for building rather than site were derived at a nuclear fuel fabrication facility [9]. Kamboj et al. and Rima derived DCGLs for the clearance of experimental buildings [10,11]. Several studies associated with KRR-1&2 DCGLs derivation have been performed. Residual nuclide radioactivity around

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KRR-1&2 was measured with in-site measurement system [12,13]. Scaling factors for the dismantling of KRR Unit 2 were developed to assess radioactive inventory and non-detectable nuclide evaluation [14–16]. Studies using 3-D modeling were conducted to develop decommissioning scenarios [17–19].

Through recent analyses of the waste generated in KRR-1&2, differences were observed in nuclides applied in the previous KRR-1&2 DCGLs studies [4]. Recent DCGLs studies have been focused on commercial reactors. In the case of research reactors, since the reactor type or operation history is different from that of commercial reactors, it is unreasonable to apply the same approach for nuclide selection and DCGLs derivation considering the site characteristics. Therefore, the site release of KRR-1&2 requires revision of nuclide selection and DCGLs derivation considering the site-specific characteristics.

The objective of this study was to derive DCGLs reflecting the site-specific characteristics of KRR-1&2. To achieve the objective, the target nuclides for site release were selected through site history surveys of KRR-1&2. Total effective dose equivalent (TEDE) at the sites after decommissioning were evaluated and site-specific input values and sensitivities for the nuclide-specific applied parameters were confirmed. On this basis, the nuclide-specific DCGLs at KRR-1&2 sites were derived.

2. Materials and methods

2.1. Selection of target nuclides for site release

Deriving the DGCLs first requires the selection of potential nuclides believed to exist at the site. Fig. 1 shows the procedure for selecting the target nuclides for the release of the KRR-1&2 sites in this study. The procedure was developed based on NUREG-1757 [20]. To select the target nuclides for investigation, the potential target nuclides of KRR-1&2 should be selected considering the nuclide inventory of KRR-1&2, the nuclides handled in operation, the data from the analytical results of concrete and soil waste generated from decommissioning of KRR-1&2, and information from overseas research reactors.

Among the potentially selected nuclides for investigation, those not detected at the site were excluded. In addition, inert nuclides unlikely to remain at the site at the end of decommissioning were excluded from the final target nuclides. Finally, after excluding the undetected and inert nuclides, among those remaining, the nuclides with low dose contributions were excluded. The United States (US) Nuclear Regulatory Commission (NRC) regards radionuclides and exposure pathways that contribute no greater than 10% of the dose criteria to be insignificant contributors [20]. The 10% limit for insignificant contributors is an aggregate limitation only. That is to say, the sum of the dose contributions from all radionuclides and pathways considered insignificant should be no greater than 10% of the dose criteria. However, in decommissioning projects in the US, 0.1% was applied considering the uncertainty of the data [21]. This study also applied 0.1% for conservative estimation. In radiation dose evaluation, the nuclide-specific concentrations of radioactive waste from research reactors were applied for the nuclide concentrations. In addition, the maximum specific activity of each nuclide of KRR-1&2 waste was applied to perform a conservative evaluation considering the nuclide-specific pollutant fraction. According to the target nuclide selection procedure, the nuclides with total dose contribution less than 0.1% of the dose

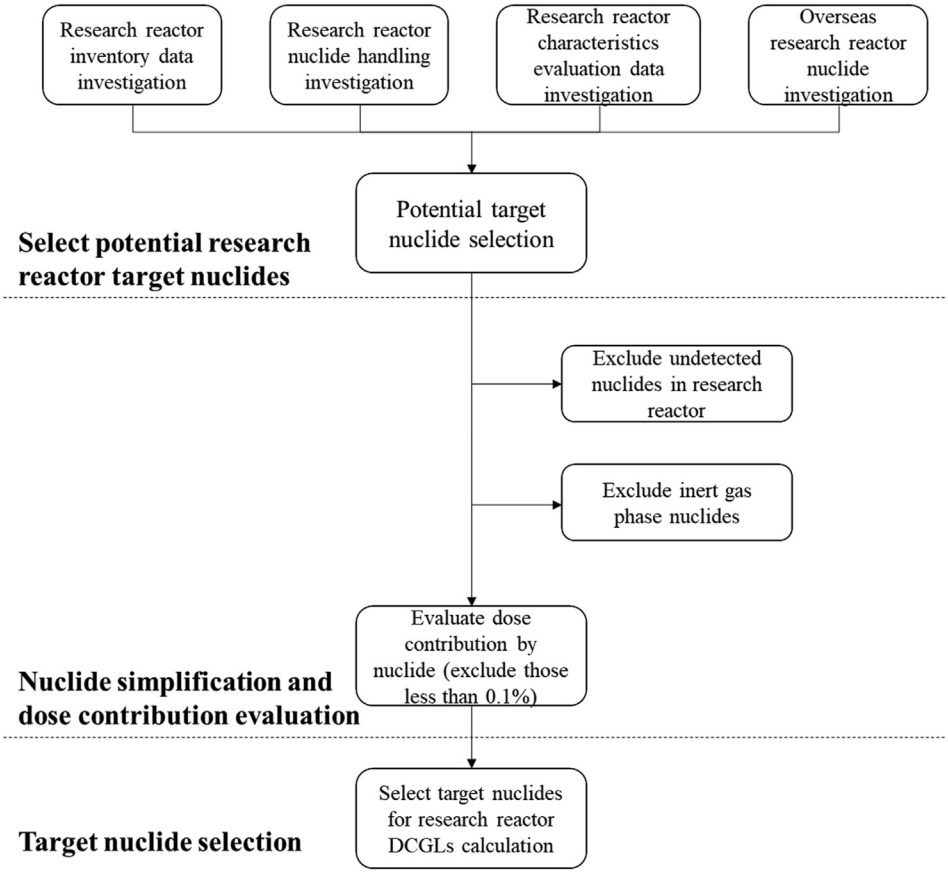

Fig. 1. Procedure for selecting target nuclides for the release of the KRR-1&2 site.

criteria were considered as insignificant and excluded. For site release without restriction, resident farmer scenario was used for dose evaluation. It is typically worst-case use scenario. This scenario includes all environmental pathways for on-site and is expected to result in the highest predicted lifetime dose. In this study, radiation dose from each nuclide was calculated and then the nuclides with total dose contribution less than 0.1% were excluded. Finally, reflecting the procedure to select target nuclides among the potential target nuclides of KRR-1&2, the nuclides to be investigated for the site release of KRR-1&2 were selected.

2.2. Evaluation of total effective dose equivalent (TEDE)

The radiation doses at the KRR-1&2 sites were evaluated for the target nuclides selected at the previous step. The radiation doses were calculated using RESRAD-Onsite (ver. 7.2), which was developed to assess the radiological effects on the residents of contaminated sites. The procedure of the radiation dose evaluation consisted of several steps, including development of exposure scenarios, selection of input parameters, and radiation dose calculation.

The building of KRR-1&2 has been decontaminated. Also, all the buildings are still standing. The site will be reused after all these buildings are demolished in the future. However, reuse plans for the KRR-1&2 sites have not been established yet. Therefore, resident farmer scenario was selected in this study for conservative evaluation. In the resident farmer scenario, a family is assumed to move to the released site, build a home, and raise crops and livestock for family consumption [28]. The family members may receive radiation dose through external and internal radiation exposures: direct radiation exposure from radionuclides in the soil, inhalation of resuspended dust from ground soil, and ingestion of water, soil, and food from crops, livestock, and fish from the release site.

Input parameters to be applied to the scenario were determined to calculate the radiation doses reflecting the exposure scenario. This study preferentially used domestic data, and when domestic data were not available, used default value of RESRAD. Table 1 shows the main domestic data applied in this study. Applied area was 47,417 m^2, which was the research reactor area. Surface soil thickness was 15 cm, which is the depth of contamination within the site in decommissioning considered in NUREG-1575 [22]. A maximum evaluation period of 1,000 years was used in accordance with Notice 2016–33 of the Nuclear Safety and Security Commission [3]. To derive the residual radioactivity targets for the individual nuclides from the evaluated radiation dose based on radioactivity per unit mass, the initial concentration for each nuclide was assumed to be 1 Bq/g.

To verify the degree of parameters affecting the total effective dose equivalent (TEDE), a sensitivity analysis of the target nuclides was performed to identify the major nuclide-specific influencing parameters among the parameters applied to the radiation dose evaluation. The objective of the analysis was to enable efficient evaluation by focusing on parameters with a relatively large influence on the total radiation dose when applying site-specific parameters for dose assessment [25]. This study applied the normalized dose difference (NDD) method for the sensitivity analysis of the nuclide-specific variables. The NDD method normalizes the difference between the maximum peak total dose and the minimum peak total dose to the maximum total dose obtained from the input variable set as the reference value [26]. This study used the difference between the maximum and minimum total doses calculated by designating the total dose using the RESRAD default value and default value to the site characteristic value as the upper and lower range. The NDD was derived with equation (1) where Total $Dose_{base}$ is the dose calculated by setting the parameters to their default values. Total $Dose_{max}$ and Total $Dose_{min}$ are the doses obtained by setting the parameters to their maximum and minimum values, respectively [27].:

$$\mathrm{NDD}(\%) = \left| \frac{Total\ Dose_{max} - Total\ Dose_{min}}{Total\ Dose_{base}} \right| \times 100 \quad (1)$$

Parameters with a value greater than 20% of the calculated NDD value were selected as highly sensitive parameters in this study [26].

2.3. Derivation of DCGLs at KRR site

Target nuclide-specific DCGLs at KRR-1&2 site were derived based on radiation dose evaluation results from the previous step.

Table 1
Input parameters available in domestic data.

Parameter	Site-Specific Value	Default Value	Note
Contaminated zone			
Area of contaminated zone (m^2)	47,417	10,000	Area of KRR site
Thickness of contaminated zone (m)	0.15	2	NUREG-1575 [22]
Length parallel to aquifer flow (m)	245.71	100	Diameter of release site
Hydrological data			
Irrigation mode (m)	0.4	0.2	Reference [23]
Well pump intake depth (m)	17	10	Reference [23]
Inhalation			
Inhalation rate (m^3/y)	7,400	8,400	Reference [24]
Mass loading for inhalation (m)	0.000006	0.0001	Reference [23]
Ingestion pathway: dietary data			
Fruit, vegetable, grain consumption (kg/y)	346.9	160	Reference [24]
Leafy vegetable consumption (kg/y)	100	14	Reference [24]
Milk consumption (L/y)	73.2	92	Reference [24]
Meat and poultry consumption (kg/y)	71.1	63	Reference [24]
Fish consumption (kg/y)	32.4	5.4	Reference [24]
Other seafood consumption (kg/y)	21.9	0.9	Reference [24]
Drinking water intake (L/y)	196.3	510	Reference [24]

Site release criteria of 0.1 mSv/y by the Nuclear Safety and Security Commission were applied to derive the DCGLs. The nuclide-specific DCGLs were derived with equation (2) [28]:

$$\text{Nuclide} - \text{specific DCGLs (Bq/g)} = \frac{\text{Nuclide} - \text{specific radioactivity concentrations (Bq/g)} \times \text{Dose reference value (mSv/y)}}{\text{Nuclide} - \text{specific effective dose (mSv/y)}} \quad (2)$$

The derived DCGLs with site characteristic parameters were compared with DCGLs derived by applying the RESRAD default values. In addition, the overseas cases related to nuclear power plant decommissioning were also compared.

3. Results and discussion

3.1. Selection of target nuclides for site release

Table 2 shows potential nuclides, excluded nuclides, and final target nuclides selected for KRR-1&2 site clearance. A total of 20 potential nuclides were selected based on the nuclide inventory evaluation data of KRR-1&2, operational history data, actual measurement data, and nuclide inventory evaluation data of overseas research reactors [29–31]. Among them 13 nuclides were selected for exclusion, consisting of those not detected on site, inert gas state nuclides, and those with total dose contribution less than 0.1% (Fe-55: 0.0045%, Ni-63: 0.0003%, and Cs-134: 0.0838%). Finally, these 13 nuclides were excluded from the 20 potential target nuclides due to their low importance for the site clearance. A total of 7 nuclides (H-3, C-14, Co-60, Sr-90, Cs-137, Eu-152 and Eu-154) were finally selected to derive the DCGLs at the KRR-1&2 sites. Compared with previous KRR-1&2 DCGLs derivation research [4], Cs-134, which was previously considered, was observed to have a low dose contribution and was therefore excluded. H-3, C-14, and Sr-90 were confirmed through the actual analytical results and thus were added to the nuclides for investigation.

3.2. Evaluation of total effective dose equivalent (TEDE)

Fig. 2 shows the changes in radiation dose over time after the site clearance of KRR-1&2. In addition, the pathway-specific contributions to radiation dose over time were identified. The maximum radiation dose at KRR-1&2 sites was 5.92 mSv/y after 0.92 year when the representative nuclide-specific concentration was assumed to be 1 Bq/g. Subsequently, the radiation dose continuously decreased, and after 100 years, it converged to almost zero. Based on the confirmation of pathway-specific contributions during the evaluation period, the dose contribution due to direct external exposure from radionuclides in the ground was the highest during the entire evaluation period. Ingestion of radioactive materials had the second effect and the radiation dose due to ingestion increased up to 3 years and then decreased over time. Radiation dose due to the inhalation of radioactive materials had the smallest effect.

Fig. 3 shows the changes in radiation dose by nuclide over time. Until the first 3 years after site release, the radiation dose of Co-60 was the most dominant, followed by Eu-152 and Eu-154. After about 10 years, Cs-137 was observed to be dominant. Despite continuous decrease of radiation dose due to Co-60 over time, the maximum radiation dose from all nuclides was observed after 0.92 year (Fig. 2). This is because the increase in radiation dose resulting from C-14 was greater than the dose resulting from Co-60, which decreased between 0 year and 0.92 year. For Co-60, the radiation dose decreased by 12% from 1.95 mSv/y at 0 year to 1.72 mSv/y at 0.92 year. For C-14, the radiation dose increased by 456% from 0.24 mSv/y at 0 year to 1.35 mSv/y at 0.92 year. The increase in the radiation dose of C-14 compared with the decrease in the radiation

Table 2
Potential nuclides and final target nuclides selected for KRR-1&2 site.

Radio nuclide	Potential Nuclides				Excluded Nuclides			Final Target Nuclide
	Nuclide Inventory	Research Reactor Handling	Charac -teristics Evaluation	Overseas Data	Undetected	Inert Gas Phase	Dose Below 0.1%	
H-3			○	○				○
C-14			○					○
Na-22	○				×			
Mn-54	○				×			
Fe-55	○		○	○			×	
Fe-59		○			×			
Ni-59	○				×			
Co-60	○	○	○	○				○
Ni-63			○				×	
Sr-90			○					○
Nb-94	○				×			
Tc-99 m		○			×			
I-131		○			×	×		
Ba-133				○	×			
Cs-134			○				×	
Cs-137		○	○					○
Eu-152	○		○	○				○
Eu-154	○		○	○				○
Ir-192		○			×			
Au-198		○			×			

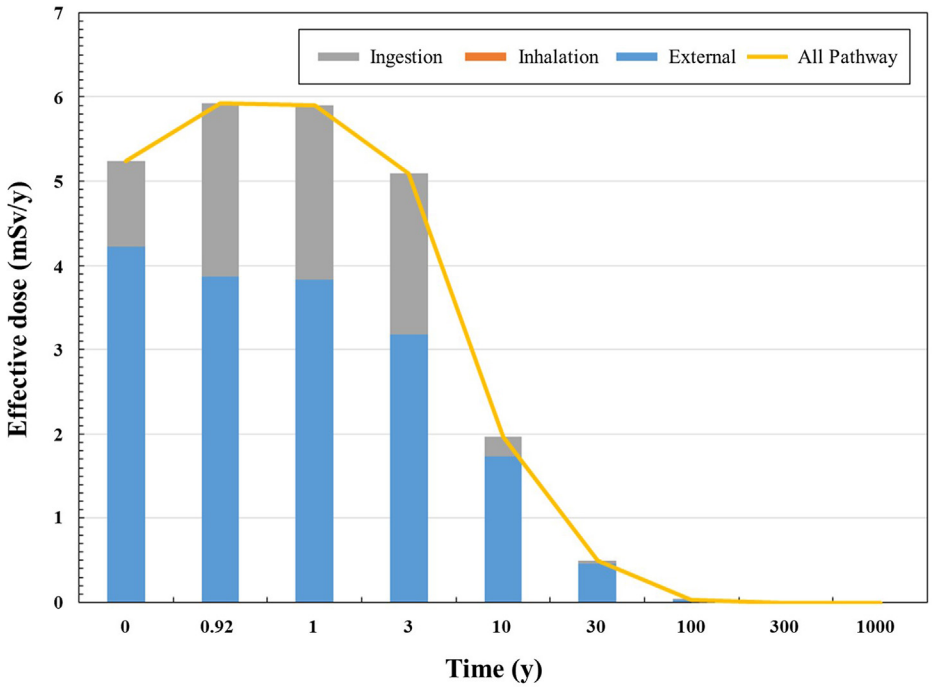

Fig. 2. Changes in radiation dose by pathway over time.

dose of Co-60 caused the increase in the overall radiation dose during initial years. Moreover, the radiation dose due to C-14 shows a high contribution to the overall radiation dose up to 3 years after site release. C-14 was identified to affect radiation dose by ingestion pathway up to about 3 years after site release because the main route through which C-14 enters the human body is through food ingestion [28]. In addition to the two radionuclides, Eu-152 and Eu-154 showed high contributions throughout the entire period. Thus, in the KRR-1&2 sites, the external exposure due to gamma-emitting nuclides (Co-60, Cs-137, Eu-152, and Eu-154) was observed to be the most dominant in the overall exposure.

Table 3 shows the results of the sensitivity analysis to identify the major influencing parameters for each nuclide among the parameters applying the site-specific values. Beta emitting nuclides

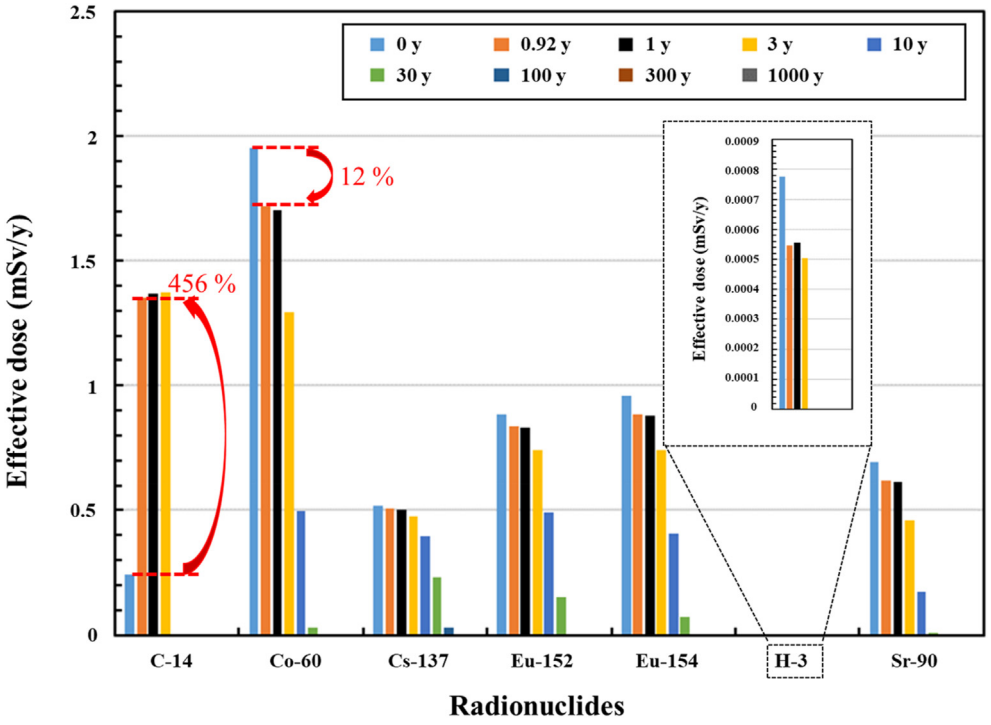

Fig. 3. Changes in radiation dose by nuclide over time.

Table 3
Sensitivity analysis results by target nuclide (Unit: %).

Parameter	Co-60	Cs-137	Eu-152	Eu-154	H-3	C-14	Sr-90
Area of contaminated zone	7.0	**21.7**	6.0	6.0	14.2	**330.4**	**36.9**
Thickness of contaminated zone	16.1	**20.3**	12.4	12.9	**494.4**	**853.3**	**85.5**
Precipitation	0.0	0.0	0.0	0.0	10.3	**48.3**	0.5
Irrigation mode	0.0	0.0	0.0	0.0	17.3	**38.8**	0.2
Well pump intake depth	0.0	0.0	0.0	0.0	**138.5**	**148.1**	0.0
Well Pumping rate	0.0	0.0	0.0	0.0	**52.5**	19.7	0.0
Inhalation rate	0.0	0.0	0.0	0.0	**899.8**	0.0	0.0
Fruit, vegetable, grain consumption	2.4	19.0	0.1	0.1	19.6	**23.8**	**194.3**
Leafy vegetable consumption	0.6	4.4	0.0	0.0	6.3	**41.7**	**41.7**
Fish consumption	0.0	0.0	0.0	0.0	0.0	**355.7**	0.0
Other seafood consumption	0.0	0.0	0.0	0.0	0.0	**46.2**	0.0
Drinking water intake	0.0	0.0	0.0	0.0	**125.9**	**34.6**	0.0

(H-3, C-14, and Sr-90) compared to gamma emitting nuclides (Co-60, Cs-137, Eu-152, and Eu-154) have higher sensitivity for each parameter. In addition, the beta emitting nuclides were found to be highly sensitive to parameters related to inhalation and ingestion.

C-14 had the greatest impact on ingestion. The parameter sensitivity analysis demonstrated that it had an effect through the most parameters. Most of these parameters were confirmed to be related to ingestion. Among the ingestion parameters of C-14, one that greatly influenced the radiation dose was identified as fish consumption, as the transfer factor of carbon was the highest applied for radiation dose evaluation [32]. The C-14 in the ocean is diluted by stable carbon isotopes in the ocean's sedimentary layers, and in the case of seaweed as well, the C-14 concentration may be diluted by photosynthesis. However, in the case of fish, dilution did not occur, and high concentrations were reported [33]. Consequently, due to the high bioaccumulation factor of fish, the transfer factor also increased, thus increasing the radiation dose due to ingestion [32]. Among the analyzed parameters, the thickness of the contaminated zone showed sensitivities more than at least 10% for all nuclides. For the gamma emitting nuclides, the pathway of direct external exposure showed high contribution to total radiation dose, and the parameter sensitivity analysis also confirmed that the parameters affecting the external exposure were the main parameters. However, the effect of parameters related to ingestion or inhalation was observed to be small. For the beta-emitting nuclides, numerous parameters were observed to influence the change in total radiation dose. In particular, the parameters causing internal exposure by ingestion or inhalation were confirmed as the main parameters.

Sensitivity parameters for H-3 and Sr-90 were also related to the characteristics of nuclides. H-3 forms chemical compounds identical to other isotopes, the most important compounds is water [34]. Using a well or drinking water was an action that directly affects the ingestion of H-3, so high sensitivity to water-related parameter (Well pump intake depth, Well pumping rate and Drinking water intake) was confirmed. Sr-90 has a property of a high rate of transfer from soil to plants [35]. For this reason, the high sensitivity to plant-related factors (Fruit, Vegetable, grain consumption and Leaf vegetable consumption) was confirmed.

3.3. Derivation of DCGLs at KRR site

Table 4 shows the nuclide-specific DCGLs of KRR-1&2 sites derived based on radiation doses evaluated in this study. The DCGLs of Co-60, which showed the highest dose contribution during the first 3 years after site release, was derived to be 0.051 Bq/g, and DCGLs of Cs-137, which showed the highest dose contribution after 10 years, was 0.193 Bq/g. The DCGLs of H-3 showed the highest value of 129 Bq/g. This study could additionally confirm the differences between the DCGLs derived with the site-specific values and the DCGLs applied with the RESRAD default values. The ratio of DCGLs derived by applying site-specific values and default values ranged from 0.27 to 19.6. As DCGLs are derived from the nuclide-specific radiation doses, the differences in DCGLs according to the applied parameters are also due to the differences in radiation doses evaluated according to the applied parameters. The DCGLs difference was relatively small for gamma-emitting nuclides (DCGLs ratio = 1.11–1.14) while it was large for beta-emitting radionuclides (DCGLs ratio = 0.27–19.6). As mentioned in section 3.2, there were differences in sensitivity for each factor depending on

Table 5
Comparison of derived DCGLs with oversea data.

Radionuclide	DCGLs (Bq/g)		
	KRR1&2	Connecticut Yankee [36]	Yankee Rowe [37]
Co-60	0.051	0.056	0.059
Cs-137	0.193	0.117	0.127
Eu-152	0.113	0.149	0.148
Eu-154	0.104	0.137	0.141
H-3	129	6.098	5.476
C-14	0.073	0.084	0.081
Sr-90	0.145	0.023	0.025

Table 4
Comparison of DCGLs by applied parameter.

Radionuclide	Application of Site-Specific Value		Application of Default Value		DCGLs Ratio
	Effective Dose (mSv/y)	DCGLs (Bq/g)	Effective Dose (mSv/y)	DCGLs (Bq/g)	
Co-60	1.952	0.051	2.237	0.045	1.14
Cs-137	0.517	0.193	0.577	0.173	1.11
Eu-152	0.884	0.113	0.986	0.101	1.11
Eu-154	0.957	0.104	1.068	0.094	1.11
H-3	7.76×10^{-4}	129	1.52×10^{-2}	6.596	19.6
C-14	1.379	0.073	0.366	0.273	0.27
Sr-90	0.692	0.145	1.004	0.100	1.46

the nuclide, and in particular, it was confirmed that there were many factors with higher sensitivity to beta-emitting nuclide than to gamma-emitting nuclide. For beta-emitting nuclides, major sensitive parameters for H-3 are mainly associated with water pathway, C-14 with fish pathway, and Sr-90 with plant pathway. In the study results, it was confirmed that the main exposure pathway for each nuclide was groundwater use for H-3, fish consumption for C-14, and fruit, vegetable, and grain consumption for Sr-90. High sensitivity means that it has a large influence on the change in dose depending on the applied factor value. In other words, due to the effect of these dose changes, the difference in DCGLs for beta-ray emitting nuclides was large according to the difference in factor application. The results confirmed that it is critical to apply site-specific parameter values reflecting the site characteristics for decommissioned site release.

Table 5 shows comparison of DCGLs derived in this study with the DCGLs of overseas commercial NPP sites. For six nuclides excluding H-3, KRR-1&2 sites and the overseas NPP sites showed similar DCGLs. Co-60, which had the highest dose contribution in all the cases, showed the most similar values in all comparison groups. DCGLs value is high when the radiation dose is low, and it is low when the radiation dose is high. For KRR-1&2 site, H-3 among the selected nuclides showed the lowest contribution of 0.19% to total radiation dose. It showed a dose of 5.45×10^{-4} mSv/y at 0.92 year, which is the maximum effective dose, with a contribution of 0.01%. This led to higher DCGLs than the other nuclides. Furthermore, H-3 showed large differences (more than 30 times) in DCGLs from this study and overseas NPPs. The large difference resulted from input parameter applied to the sites. Sensitivity study and comparison with overseas commercial reactors showed that main parameters resulting such difference were the thickness of the contaminated zone, well pump intake depth, well pumping rate, drinking water intake, and inhalation rate. The comparison demonstrated that the input parameter applied to the research reactor (KRR 1&2) sites were lower than those applied to compared NPP sites. Most parameters above affect H-3 ingestion; as the ingestion amount and radiation dose rise with the input value, KRR-1&2 sites, which applied relatively low values, showed low radiation doses. Consequently, the derived DCGLs were high. For confirmation, the DCGLs of H-3 was derived by applying the same input parameters from Yankee Rowe NPP. It was 6.935 Bq/g, a similar value with those at overseas NPP sites. This again demonstrates that it is required to site-specific parameter reflecting the site characteristics.

4. Conclusion

The DCGLs for KRR-1&2 site release after completing of decommission were derived by reflecting site-specific characteristics. To this end, the target nuclides were first selected and radiation dose at the sites were evaluated by considering site characteristics and site-specific input parameters. On this basis, the nuclide-specific DCGLs at KRR-1&2 sites were derived based on the dose criteria.

A total of 7 nuclides (H-3, C-14, Co-60, Sr-90, Cs-137, Eu-152 and Eu-154) among 20 potential nuclides were finally selected to derive the DCGLs at the KRR-1&2 sites based on the nuclide selection procedure developed in this study. H-3, C-14, and Sr-90 were confirmed through the actual analytical results and thus were added to the nuclides for investigation. From the aspect of radiation dose contribution, the nuclides can be divided into two groups, including gamma-emitting nuclides (Co-60, Cs-137, Eu-152, and Eu-154) and beta-emitting nuclides (H-3, C-14, and Sr-90).

Based on the confirmation of pathway-specific contributions according to the evaluation period, the dose contribution due to direct external exposure from radionuclides in the ground was the highest during the entire evaluation period. Ingestion had the second effect and inhalation had the smallest effect. Up until the first 3 years after site release, the radiation dose of Co-60 was the most dominant, followed by Eu-152 and Eu-154. After about 10 years, Cs-137 was observed to be dominant. C-14 among beta-emitting nuclides highly contributed to the overall radiation dose up to 3 years after site release.

The DCGLs of Co-60 was derived to be 0.051 Bq/g, and Cs-137 DCGLs was 0.193 Bq/g. The DCGLs of H-3 showed the highest value of 129 Bq/g. The ratio of DCGLs derived by applying site-specific values and default values ranged from 0.27 to 19.6. The DCGLs difference was relatively small for gamma-emitting nuclides (DCGLs ratio = 1.11–1.14) while it was large for beta-emitting radionuclides (DCGL ratio = 0.27–19.6). Such difference in DCGLs resulted from the differences in the applied input parameters. For six nuclides excluding H-3, KRR-1&2 sites and the overseas NPP sites showed similar DCGLs. H-3 showed large differences (more than 30 times) in DCGLs from this study and overseas NPPs. The large difference resulted from input parameter applied to the sites.

In conclusion, it is critical to apply site-specific parameter reflecting the site characteristics to derive DCGLs for decommissioned site release. This study results can be used as a reference for nuclide selection and DCGLs derivation reflecting the site characteristics when decommissioning nuclear facilities, including nuclear power plants in Korea.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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