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Original Article

Calculation of preliminary site-specific DCGLs for nuclear power plant decommissioning using hybrid scenarios

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ABSTRACT

Korea's first commercial nuclear power plant at Kori site was permanently shut down in 2017 and is currently in transition stage. Preparatory activities for decommissioning such as historical site assessment, characterization, and dismantling design are being actively carried out for successful D&D (Dismantling and Decontamination) at Kori site. The ultimate goal of decommissioning will be to ensure the safety of workers and residents that may arise during the decommissioning of nuclear facilities and, thereby finally returning the site to its original status in accordance with the release criteria. Upon completion of decommissioning, the resident's safety at a site released will be assessed from the evaluation of dose caused by radionuclides expected to be present or detected at the site. Although the U.S. commercial nuclear power plants with decommissioning experience use different site release criteria, most of them are 0.25 mSv/y. In Korea, both the unrestricted and restricted release criteria have been set to 0.1 mSv/y by the Nuclear Safety and Security Commission. However, since the dose is difficult to measure, measurable concentration guideline levels for residual radionuclides that result in dose equivalent to the site release criteria should be derived. For this derivation, site reuse scenario, selection of potential radionuclides, and systematic methodology should be developed in planning stage of Kori site decommissioning.

In this paper, for calculation of a preliminary site-specific Derived Concentration Guideline Levels (DCGLs) for the Nuclear Power Plant site, a novel approach has been developed which can fully reflect practical reuse plans of the Kori site by taking into account multiple site reuse scenarios sequentially, thereby striking a remarkable distinction with conventional approaches which considers only a single site scenario.

1. Introduction

The final goal of the decommissioning of nuclear facility is to remove related regulatory controls from the facility by safely disposing of the radioactive waste generated during the decommissioning and to reduce the residual radiation on the site at the level meeting the site release criteria. To do this, the Derived Concentration Guideline Levels (DCGLs) corresponding to the site reuse should be calculated in the decommissioning planning stage. The Korean regulator requires that, for Nuclear Power Plant (NPP) decommissioning, site-specific values of DCGLs should be included in its final decommissioning plan, which should be approved by the regulator before the dismantling and decontamination begin. The decommissioning site can be finally released or reused when it is demonstrated that the level of residual radioactivity in media such as soil satisfies the site release criteria.

International Atomic Energy Agency (IAEA) safety guideline (WS-G-5.1) recommends that the site release criteria be optimized within the range of 10–300 μSv/y [1]. So, the U.S. Nuclear Regulatory Commission (NRC) set the unrestricted site release criteria at 0.25 mSv/y, but the Korean regulator stipulates 0.1 mSv/y for both unrestricted and restricted site release in the Nuclear Safety and Security Commission Notice No. 2016-33 [2]. Since the dose is difficult to measure, it is necessary to apply measureable radionuclides concentration in accordance with the site release criteria such as DCGLs which are mostly used in U.S. So, for timely decommissioning of Kori which is scheduled in 2022, preliminary site-specific DCGLs should be calculated to prepare its final decommissioning plan.

The purpose of this study is to present what input factors are

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needed for DCGLs calculation and to propose preliminary DCGLs for radionuclides which are potentially present at the site. For this, RESRAD (Residual RADioactivity)-ONSITE (hereafter referred to as RESRAD), a computer code for assessing dose incurred from contaminated soils, was used and the required factors to be defined to derive DCGLs reflecting the site specific characteristics, such as radionuclides of interest, probabilistic parameters and appropriate site reuse scenarios were considered. Especially, in applying site reuse scenario, a novel approach has been developed which can fully reflect practical reuse plans of the Kori site by taking into account multiple site reuse scenarios sequentially.

2. Requirement analysis for DCGL calculation

The RESRAD, which was developed by the U.S. Argonne National Laboratory (ANL) under the support of Department of Energy (DOE) and the U.S. NRC, has been used as an exposure pathway modeling code to assess doses incurred from radioactively contaminated sites. RESRAD has been used to calculate the DCGLs at decommissioning sites, not only in U.S. but also in the non-U.S countries. Since RESRAD is used in various fields and also used for licensing purpose in Korea, it is very likely that the code will also be accepted for such a calculation in decommissioning projects.

As shown in Fig. 1, in order to use RESRAD code, we analyzed what input factors should be defined to calculate DCGLs. Consideration should be given to various factors, among which input parameters need to be defined basically. For accurate calculation, it is necessary to reflect the site specific characteristics of Kori, and applicable scenarios should also be considered. There are deterministic and probabilistic analysis in the dose assessment method, so one of these should be considered. In addition, a selection should be made for the radionuclide of interest that is expected to be present in the soil of the site.

Fig. 2 shows the sub-factors between the elements required for DCGL calculation. First, definition of the input parameters is a part that should be established to execute RESRAD. The input parameters can be largely divided into radionuclide of interest, deterministic and probabilistic parameters. It needs to decide whether to use deterministic or probabilistic. The former is assigned a single value and the latter is assigned a distribution to the input parameters. Before this, the radionuclides of interest that is expected to be present in the soil of the site had to be selected. Site reuse scenario is another part of required elements in calculating dose.

After investigating the factors required and the sub-factors among them, we established activities for DCGLs calculation as shown in Fig. 3. In the first phase, two site reuse scenarios for resident farmer and industrial worker are selected. For the resident farmer scenario, the assessment of dose incurred from the potential radionuclides selected can be performed using a deterministic mode. From this, potential radionuclides of interest can be established. An analysis using a probabilistic mode is performed for each

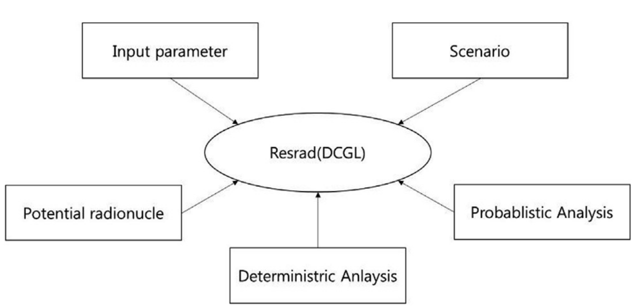

Fig. 1. Factors required for DCGL calculation.

of the both scenarios. In the following phase, the RESRAD is executed along with the selected radionuclides to identify sensitive parameters. A single deterministic value is applied to sensitive parameters identified and then, DCGLs are obtained again through the secondary RESRAD execution.

Work sequence necessary in each phase of the DCGLs calculation was also established taking into account the relationship among the factors, as shown in Fig. 4. It starts with identifying parameter type and priority, and performing the parameter selection process. Next, the scenarios to be applied, i.e. resident farmer and industrial worker, will be defined. To exclude some radionuclides, whose dose contributions are not significant, from a list of potential radionuclides, the parameters set as deterministic can be used with the resident farmer scenario. After obtaining the list of potential radionuclides, a value or distribution for each parameter can be assigned for the probabilistic analysis to execute the RESRAD for derivation of DCGLs.

3. Parameter selection process

Prior to determining the input value, a distinction must first be made between deterministic and probabilistic parameters. To do this, it is necessary to refer to the type and classification of each parameter. Based on this, the parameter selection process can be performed. These parameters may vary in value and distribution depending on the scenario to be applied.

3.1. Parameter categorization

RESRAD input parameters are classified into behavioral, metabolic, or physical according to their characteristics [3]. Behavioral parameters depend on the behavior of a receptor and the definition of a scenario. Thus, their values can vary as a different scenario applies for the same group of receptors. Metabolic parameters are independent of scenarios or site conditions, representing features of the receptor's metabolism, such as dose conversion factors, food intake rates, and inhalation rates. Physical parameters do not depend on the group of receptors and represent variables that are determined by the source and location and geological characteristics of the site.

3.2. Parameter priority

The priority of the RESRAD parameters is divided into three according to their importance in meeting the objective of the analysis [4]: priority 1 (high), priority 2 (medium), and priority 3 (low). The level of the parameter was divided based on the relevance of parameters in dose calculations, the dose variation according to the change of the parameter value, parameter type, and data availability. In addition, the level is a criteria for judging whether to treat the parameter probabilistically or deterministically. While the deterministic analysis gives in a single value of dose using a single value for each of input parameters, probabilistic analysis generates a range of doses using distribution for each of input parameters.

3.3. Input parameter selection

The input parameter selection process in calculating the site-specific DCGLs shown in Fig. 5 was established by referring the steps used in the decommissioning of the U.S. nuclear power plant [5]. The process can be performed in either deterministic mode or probabilistic mode based on the type and priority of a parameter of concern. Deterministic values are assigned to the parameters for behavioral and metabolic parameters. For the physical parameters,

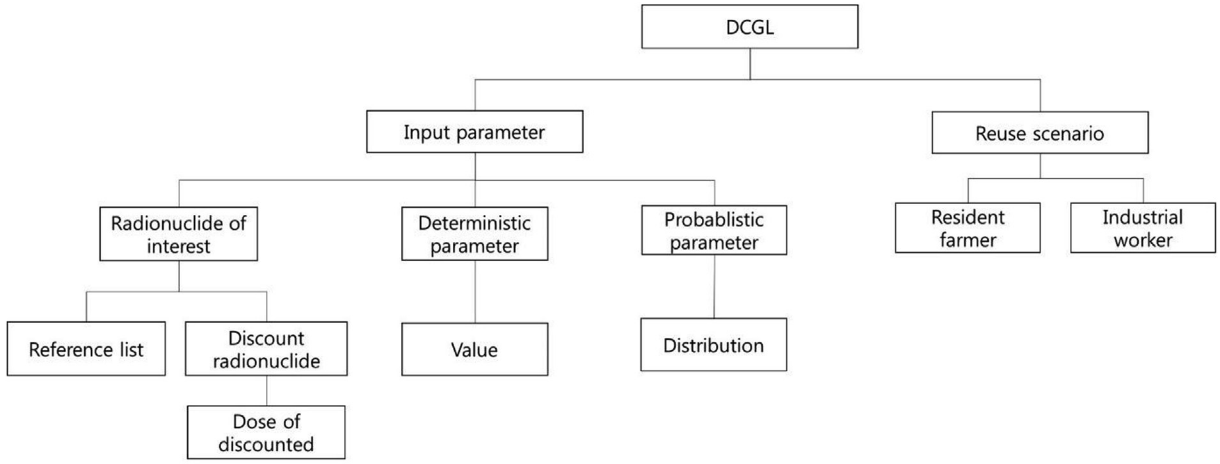

Fig. 2. Sub-factors required DCGL calculation.

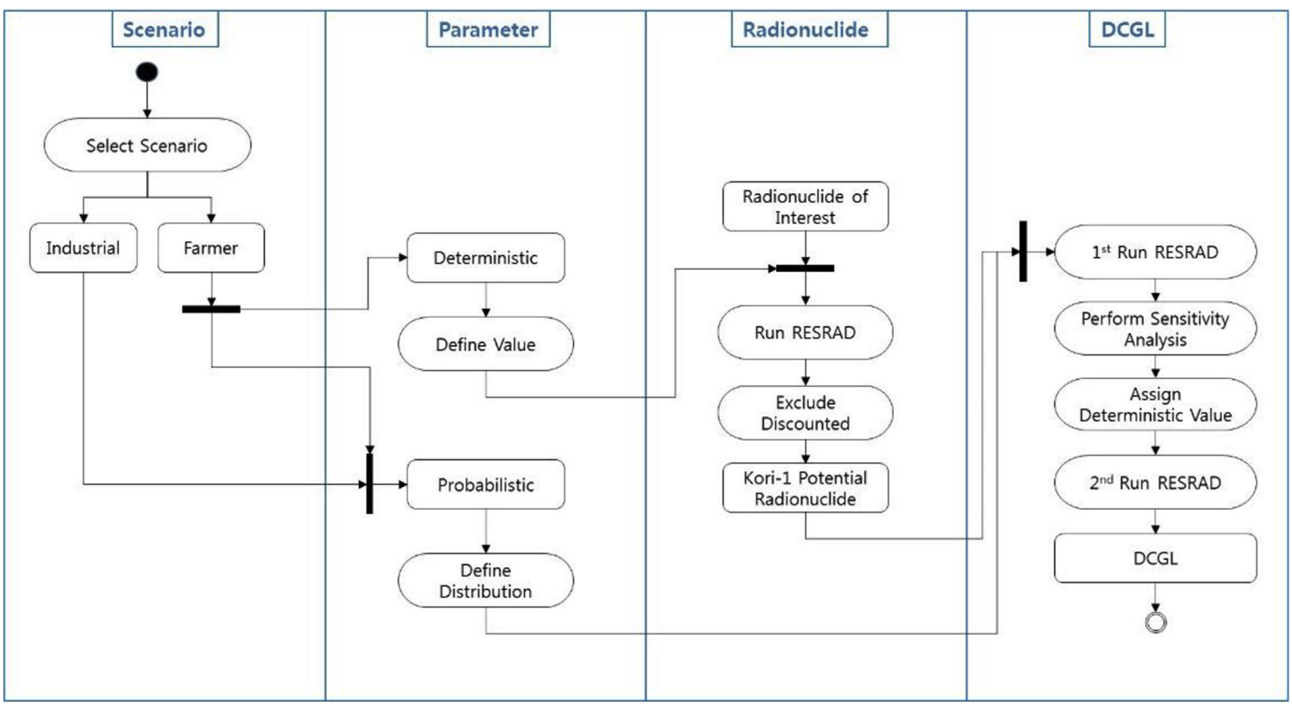

Fig. 3. Activities for DCGL calculation.

deterministic values are also assigned if site specific data is available, otherwise, a distribution or default value is assigned according to its priority. The parameters of priority 3 are set with deterministic values and the parameters of priority 1 and 2 are input with a distribution. Then, through the sensitivity analysis, the parameters of priority 1 and 2 are classified as sensitive or non-sensitive. If the absolute value of the Partial Rank Correlation Coefficient (PRCC) included in the RESRAD uncertainty report is 0.25 or more, it is classified as a sensitive parameter. For the sensitive parameters, the 75th percentile of their distribution if the sign of the PRCC value is positive or the 25th percentile value if the sign is negative, are input as a deterministic.

4. Site reuse scenario

There are several scenarios for a site reuse after the completion of the decommissioning. A residential farmer scenario is the most conservative, which takes into account all possible exposure pathways. However, an actual site reuse scenario for a specific site should be determined taking into account many related factors such as location, use, scope and physical characteristics of the site. Therefore, the characteristics of the site and realistic site reuse scenarios should be reflected in the DCGLs calculation.

There are 6 commercial nuclear power plants in Kori site, of which 5 are currently in operation with Kori-1 being permanently shut down. It is very likely that when the decommissioning of Kori Unit 1 will be completed which is expected to occur 15 years later (minimum 5 years of transition period, minimum 7–8 years of decommissioning and dismantling, and minimum 2 years of site restoration and release), the other units will still be in operation. Considering this, a more realistic site reuse scenario after the decommissioning is Industrial Worker Scenario (Brown Field)

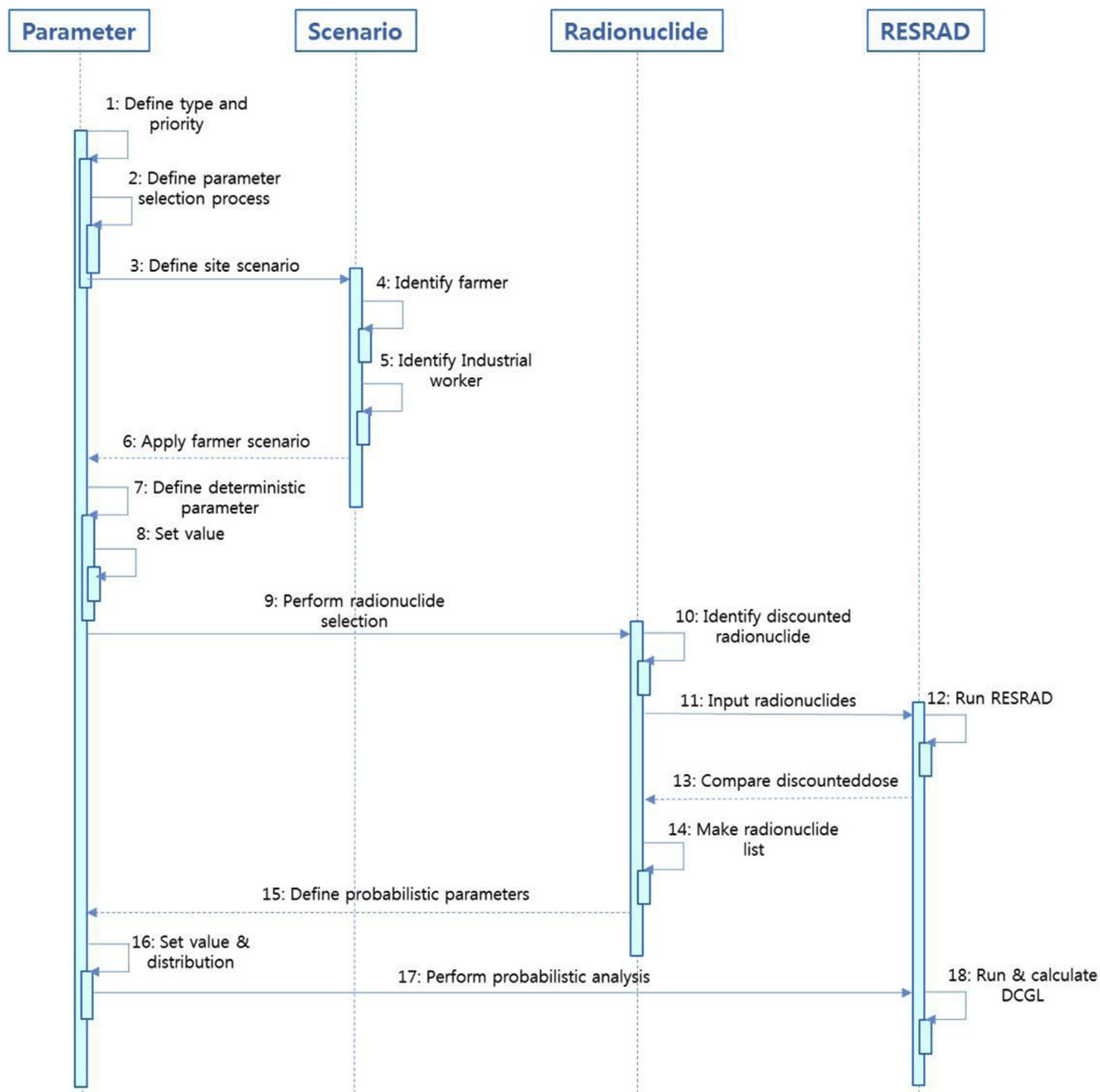

Fig. 4. Work sequence of DCGL calculation.

rather than Residential Farmer Scenario (Green Field). As a result, until the decommissioning of the other adjacent units will be completed, the site reuse scenario of Brown will be acceptable reasonably for the Kori site.

Six nuclear reactors which are located at the Kori site are shown in Table 1 [6]. Among them, those units which are close enough to Kori Unit 1 to be able to influence the site reuse scenario of Kori 1 are Kori Units 2 to 4 with the decommissioning of Kori Unit 4 being scheduled to be completed in 2040. Another point of view, it might be possible to take into account the expected period until the completion of the decommissioning of the most recently constructed plant of the Kori site, Shinkori-2, which will be completed at the latest. In this paper, we assumed that the period until the completion of Kori Unit 4 is considered to affect the site reuse scenarios of Kori Unit 1 for conservative approach. This part may be subject to change in the future use of the site by the licensee and the policy effect. However, it is possible to assume that the site of Kori Unit 1 can be reused as Industrial Worker Scenario at least until Kori Unit 4 will be decommissioned, after which, it can be reused as Resident Farmer Scenario.

This study employs two scenarios sequentially: industrial worker scenario from 2032 to 2040 and resident farmer scenario after 2040. While the resident farmer scenario which is the most conservative scenario will result in the lowest values for DCGLs, the industrial worker scenario which is a realistic scenario will provide reasonable values for DCGLs. The highest values of dose for each scenario were chosen during each period applying the resident and industrial worker scenarios. The final DCGLs are derived by taking the value of a conservative among the selected doses. Table 2 and Table 3 show the differences in the pathways and key parameters for each scenario.

In the resident farmer scenario, it is assumed that a family stays 24 h on contaminated soil layers, with growing crops, raising livestock, and consuming agricultural and livestock products produced thereby. Exposure pathways considered are direct external exposure by contaminated soil, internal exposure of inhalation and

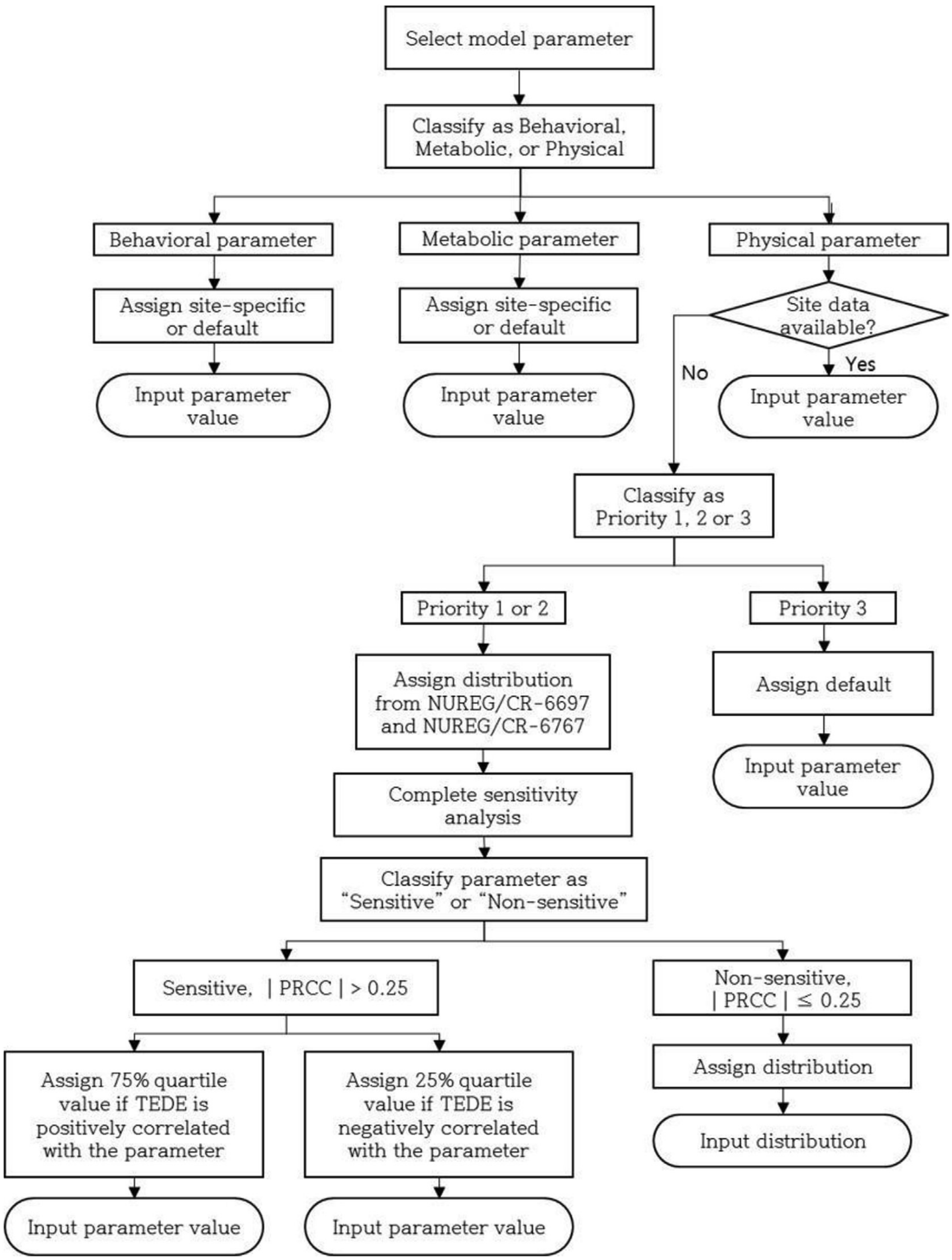

Fig. 5. Parameter selection process.

Table 1
Kori site reactors.

NPP	Commercial operation	Design life expiration	Expected completion of Decommissioning
Kori-1	1978–4	2017–6	2032
Kori-2	1983–7	2023–4	2038
Kori-3	1985–9	2024–9	2039
Kori-4	1986–4	2025–8	2040
Shinkori-1	2011–2	2050–5	2065
Shinkori-2	2012–7	2051–12	2066

ingestion. The ingestion pathway include plants, meats and milk cultivated in the contaminated soil, fish caught in the contaminated lake, contaminated ground water, lake water, and contaminated soil.

In the industrial worker scenario, it is assumed that an employee or contractor who is allowed access to the contaminated area for operational reasons will spend 50 weeks a year (2000 h per year) onsite [7]. Industrial workers are assumed to have 50% of total hours for indoor hours and outdoor hours. Several pathways such as plant, meat, milk, and aquatic routes that are unlikely to be allowed in industrial areas are excluded. For drinking water, the contamination fraction was assumed to be 1 and the usage rate to be 0.7.

5. Input parameter values

The main input parameters for executing the RESRAD computer code are radionuclides, site physical parameters, site environment parameters, external exposure related parameters, and ingestion related parameters in the decommissioning site. For an accurate dose evaluation, the values of the parameters reflecting the geological survey and environmental characteristics of the site should be used. For this purpose, the historical site assessment (HSA) and the evaluation data on the radioactive transport in groundwater were reflected. In addition, we referred to the data developed by the regulatory agency such as exposure dose evaluation for general public (INDAC) [8], development of regulatory requirements for radioactive waste [9], and development of technology in radiation safety regulations [10]. The RESRAD manual [11] and the RESRAD Data Collection Handbook [12] were also used to set parameter values.

For the dose assessment, the dose conversion factor library in the RESRAD code should be selected to match the domestic situation. The dose conversion factors based on the ICRP-60 were applied for external exposure, and the dose conversion factor based on the ICRP-72 were applied for the inhalation and the ingestion.

The contaminated zone related parameters were selected based on the results of the HSA performed. The contaminated zone area is set at 50,000 square meters and its thickness is set at 0.15 m. Length parallel to aquifer flow is equal to the diameter of the section when the contaminated area is cylindrical. Based on this, the contamination area is 50,000 square meters, so the length parallel to aquifer flow is assume to be 252 m.

In order to obtain a conservative evaluation result, the receptor was assumed to be exposed to the contaminated zone directly, that is, the thickness of the cover layer is set to 0 m. The parameter values such as total porosity, field capacity, hydraulic conductivity, and distribution coefficient of the contaminated zone are taken from the RESRAD Data Collection Handbook and the soil type in the contaminated layer is assumed to be silt in consideration of the geological characteristics of the Kori site. Wind speed and annual precipitation values are taken as given in the Final Safety Analysis Report (FSAR) of Kori Unit 1.

The thickness of the saturation zone and the unsaturated zone below the contaminated zone were set to 3.82 m using hydrological data. The unsaturated zone was assumed to consist of a single layer between the contaminated zone and the groundwater level. The physical data of the silt presented in the RESRAD Data Collection Handbook is applied to the unsaturated zone in consideration of the Kori site geological characteristics. The hydrologic parameters for the saturated zone are set assuming the zone is composed of a generic soil. The depth of the well pump intake is defined as the depth of the well in the underground water surface. Based on the Ministry of Construction and Transportation and regulatory reference [9], the well pump intake depth is set at 17 m and the pumped water volume is set at 4000 cubic meters per year.

Indoor time fraction means the ratio of time spent staying inside a building located above the decommissioning site during a year. In the industrial worker scenario, it is set at 0.114, which is 50% of total hours for indoor and outdoor, based on 50 weeks per year (2000 h per year). Inhalation rates were quoted for adults who could serve as workers [8]. The internal exposures of workers and general public in the decommissioning site are caused by dispersing the radioactive material contained in the site into the air in the form of dust and inhaling these dusts.

Table 2
Pathways for residential farmer and industrial worker.

Exposure Pathway	Residential Farmer	Industrial Worker
External gamma exposure	○	○
Inhalation of dust	○	○
Radon inhalation	○	○
Ingestion of foods	○	–
Ingestion of meat	○	–
Ingestion of milk	○	–
Ingestion of fish	○	–
Ingestion of soil	○	○
Ingestion of water	○	○

Table 3
Parameters for residential farmer and industrial worker.

Input Parameters	Unit	Residential Farmer	Industrial Worker
Exposure duration	yr	30	25
Inhalation rate	m^3/yr	7400	11,400
Mass loading for inhalation	g/m^3	6.0e-06	5.0e-04
Fraction of time indoors	–	0.5	0.114
Fraction of time outdoors	–	0.25	0.114
Contaminated fractions of food			
- Plant food	–	1	Not used
- Meat	–	1	Not used
- Milk	–	1	Not used
- Aquatic food	–	Distribution	Not used
Soil ingestion	g/yr	36.5	36.5
Drinking water intake	L/yr	196.3	196.3

Parameters that relate with the receptor's direct ingestion include fruits, vegetables and grains, leafy vegetables, milk, meat, fish, seafood, soils and drinking water. For each food intake rates, the values suggested in reference [8] were used. In this study, it is assumed that all the food consumed by the residents is contaminated for a conservative approach because the contaminated fraction of food in the pathway of exposure greatly affects the result of internal exposure. Other input parameters related to ingestion were compared with among the regulatory references [8–10] and set to conservative values.

6. Selection of radionuclides

A list of radionuclides is needed to ensure that doses have been evaluated using RESRAD in terms of possible radionuclides that may exist. The NRC documents [13] provide guidance on which radionuclides should be considered in developing the initial list of radionuclides for commercial light water reactor sites, and whether the resources and methodologies used are appropriate. The owner of a nuclear facility should ensure that the list of radionuclides is applicable and appropriate based on site characteristics and operational history.

There are three references for technical considerations and limitations: “Long-Lived Activation Products in Reactor Materials”, NUREG/CR-3474 [14]; “Residual Radionuclide Contamination Within and Around Commercial Nuclear Power Plants”, NUREG/CR-4289, which describes radionuclides with a half-life of more than two years among the actual radionuclide surveys conducted at seven nuclear power stations; “Technology, Safety and Cost of Decommissioning”, NUREG/CR-0130 [15]. The start to prepare the potential radionuclides will be possible based on these three references. However, the list of potential radionuclides based on these references cannot be directly used for DCGL calculations of certain facilities or sites, so additional technical reviews are needed.

The selection of the radionuclides to be considered at the site remediation stage should be based on the historical site assessment and characterization data that are basically conducted to reflect characteristics of a site. In addition, it would be beneficial to consider the distribution of radionuclides in the wastes produced during operation and to perform a modeling using computer codes such as ORIGEN to support radionuclide determinations. Other reference materials may include not only the 14 radionuclides specified in the NSSC Notice No. 2017-60, “Regulations for the Management of Low and Intermediate Level Radioactive Waste” [16], but also the data on the radioactivity measurement of spent fuel pool in FSAR.

Although the main methodology has been described in the previous for potential radionuclides, it is necessary to finally select the radionuclides detected in the characterization and site remediation stage. In case of overseas nuclear power plants such as the Rancho Seco site [17], Humbolt Bay Power Plant [18] and Zion Station [19], which have experience of decommissioning, the potential radionuclide selection reflects the characteristics of each site with the result being that radionuclides detected were considered. Therefore, in this paper, six radionuclides, C-14, Co-60, Ni-63, Sr-90, Cs-134, and Cs-137, were selected for the DCGLs calculation by referring to these examples of overseas cases and reflecting radionuclides that normally expected to have a high concentration ratio in the site of nuclear power plants. The aim of this paper is to mainly introduce a methodology to derive preliminary DCGLs using systems engineering approaches and to apply multiple scenarios considering the influence of nearby plants at the site, so the selection of site-specific potential radionuclides will be further detailed in future studies.

7. Settings for probabilistic analysis

The deterministic analysis sets a single value for input parameters and assigns all the parameters with values rather than distributions to calculate the effect on the dose. On the other hand, probabilistic analysis assigns a distribution to the input parameters, and performs multiple calculations at the same time with the dose result having a distribution rather than a single value. The parameter selection for probabilistic analysis is performed for each of the resident framer and industrial worker scenarios according to the parameter selection process as shown in Fig. 5. The initial radionuclide concentration is set to 1 Bq/g. For the physical parameters such as hydrological and geological, deterministic values were set according to their priorities when site characteristics data were available, and the other remaining parameters were set with distributions referring to Rancho Seco probabilistic DCGLs calculation [5]. The RESRAD settings for probabilistic analysis are Latin Hypercube Sampling as a sampling technique, random speed: 1,000, number of observations: 300, number of repetitions: 3, and group of observations: correlated or uncorrelated.

8. DCGL calculation

8.1. Results of sensitivity analysis

The site reuse scenarios and input parameters have been selected for RESRAD dose calculation. For each scenario, the parameters with deterministic values and/or probabilistic distributions, were input and RESRAD was executed for each of the six potential radionuclides. The output files showed that PRCC values of input parameters listed for 3 repetitions can be set as a deterministic. If the absolute value of the PRCC exceeds 0.25 in two out of three repetitions, it is assumed to be a sensitive parameter, and a

Table 4
Sensitive parameters of resident farmer scenario.

Parameter	Radionuclide					
	C-14	Co-60	Ni-63	Sr-90	Cs-134	Cs-137
Density of contaminated zone (g/cm^3)	1.47 (+)	1.47 (+)			1.47 (+)	1.47 (+)
Kd of contaminated zone (cm^3/g)	94.83 (+)	1284.19 (+)		129.91 (+)	2115.84 (+)	2138.22 (+)
External gamma shielding factor		0.4 (+)			0.4 (+)	0.4 (+)
Depth of root (m)			1.22 (−)	1.22 (−)	1.22 (−)	1.22 (−)
Depth of soil mixing layer (m)			0.15 (−)			
Plant transfer factor			0.0918 (+)	0.587 (+)	0.0779 (+)	0.0776 (+)
Meat transfer factor			0.00925 (+)		0.0654 (+)	0.0654 (+)
Milk transfer factor			0.032 (+)			

Table 5
Sensitivity parameters of industrial worker scenario.

Parameter	Radionuclide					
	C-14	Co-60	Ni-63	Sr-90	Cs-134	Cs-137
Density of contaminated zone (g/cm3)	1.47 (+)	1.47 (+)		1.47 (+)	1.47 (+)	1.47 (+)
Kd of contaminated zone (cm^3/g)	95.64 (+)	1283.0 (+)	1129.2 (+)	130.58 (+)	2127.71 (+)	2127.71 (+)
Kd of saturated zone (cm^3/g)	1.25 (+)					
External gamma shielding factor		0.4 (+)		0.4 (+)	0.4 (+)	0.4 (+)
Depth of soil mixing layer (m)			0.15 (−)	0.15 (−)		
Mass loading for inhalation			2.87e-5 (+)			

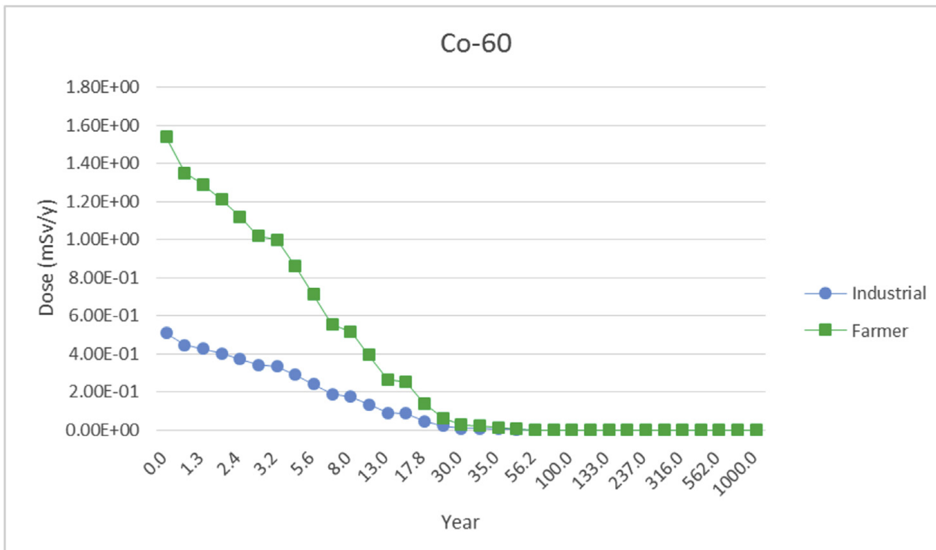

Fig. 6. Dose trend for Residential Farmer and Industrial Worker Scenarios.

deterministic value can be obtained. Table 4 and Table 5 show the parameters classified as sensitive and their deterministic values from a result of the first run of RESRAD for the resident farmer and industrial worker scenarios, respectively. It can be seen that the sensitivity parameters vary depending on the radionuclides of interest. The negative and positive sign next to the selected deterministic values indicate whether the dose increases or decreases as the value of the parameter increases.

8.2. Dose calculation

From the sensitivity analysis, the deterministic value was applied to the sensitive parameter and the dose was calculated by applying the distribution previously used to the remaining parameters. Secondary evaluation was performed and the dose was calculated for the resident farmer and the industrial worker scenario, respectively.

In the output file of RESRAD, the peak of mean dose for the 3 repetitions is obtained, which is usually used for DCGLs calculation. The mean values are calculated considering the evaluation period of 1000 years and doses are presented in the corresponding time frames set in the RESRAD "calculation times". Since the peak of mean dose in each evaluation years is changed and DCGLs should be derived considering the entire period, the highest dose among them is selected and compared with the dose limit (0.1 mSv/y) for DCGLs derivation. With a peak of mean dose, RESRAD also provides median doses, 90%, 95%, 97.5%, and 99% doses of each percentile at the times from a probabilistic analysis.

In general, it was found that the 90th and 95th percentile of the dose were more conservative than the peak of mean dose. The choice of the mean, median, or each percentile doses provided by the RESRAD in conducting probabilistic analysis will determine whether DCGLs will be derived, either by reflecting the cases of other decommissioned plant in overseas, by conservative approach or by consultation with the regulatory body. In accordance with the U.S. regulatory document NUREG-1757 [13], it is usually possible to select a peak of mean dose. On the other hand, in statistical probabilities, a 95th percentile range which is generally acceptable in all areas can be selected. Therefore, in this study, a dose equivalent to 95th percentile was selected for a more conservative assessment of the DCGLs.

For example, in the case of the representative radionuclides (Co-60), the 95th percentile doses calculated from RESRAD is shown graphically in Fig. 6 at the times for each of residential farmer and industrial worker scenarios. In both residential worker and industrial worker scenarios, the initial dose of 0 years is the maximum dose, and this is because the direct exposure is the critical in exposure pathways as Co-60 is a gamma-emitting radionuclide. Therefore, if each scenario is chosen for the adequate applicable scenario for site reuse, a dose of 0 years would be selected and DCGLs are derived, accordingly.

8.3. Preliminary DCGLs

In order to obtain DCGLs, it needs to apply scenarios suitable for site reuse with probabilistic analysis results. As described in section 4, the influence of the operation of adjacent units at the Kori site should be taken into account. The period from the completion of

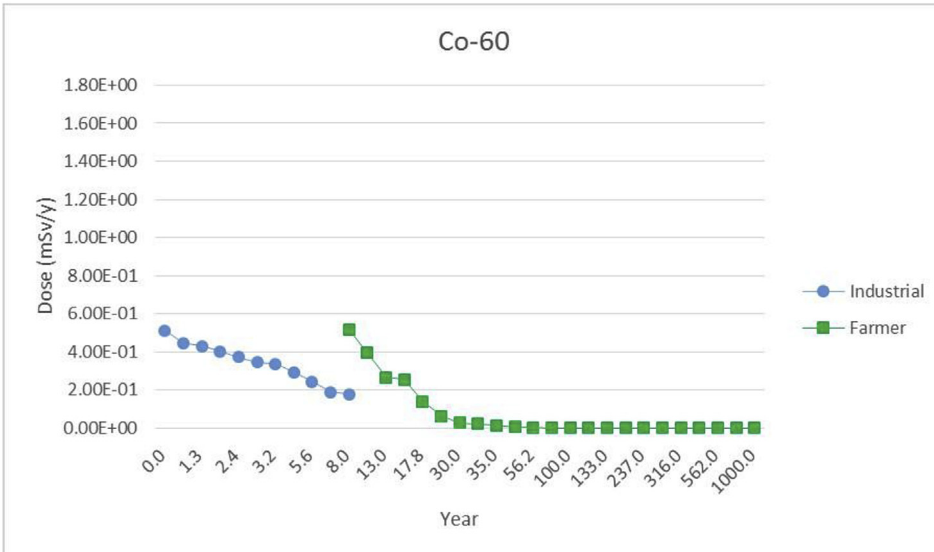

Fig. 7. Dose trend for hybrid scenario.

Kori Unit 1 decommissioning to the completion of adjacent unit decommissioning is assumed to be 8 years, and the peak dose from the industrial worker scenario until 8 years after decommissioning of Kori Unit 1 was taken. In the 8th years, we compared the dose of the industrial worker with that of the resident farmer scenario. For the period up to the next 1000 years, the peak dose of the resident farmer scenario was taken. Finally, the most conservative dose among the selected doses of each stages was taken to calculate DCGLs. The DCGLs can be derived as follows in Eq. (1).

$$DCGL_i = Dose_i / DSR_i \tag{1}$$

where

$DCGL_i$ = derived concentration guideline level of radionuclide i (Bq/g)
$Dose_i$ = allowable dose of radionuclide i (mSv/yr).
DSR_i = dose to source ratio (mSv/yr per Bq/g)

As in the case of Co-60 in Fig. 6, if hybrid scenarios are employed as in this paper, the industrial worker scenario before 2040 (8th in the evaluation period) and the residential worker scenario after 2040, dose trend to be considered during the 1000 years is plotted as shown in Fig. 7. Therefore, in order to select the peak dose in this case, consideration should be given to each assessment period: peak dose during the period from 0 to 8 years in industrial worker scenario, and peak does from 8 to 1000 years in residential farmer scenario should be taken into account. In addition, at 8 years, doses for each of two scenarios should be compared. As an example of Co-60 in Fig. 7, doses in 2 points where at 0 and 8 years are high level and the dose at 8 years of residential farmer scenario is the highest, so the dose at 8 years where the residential farmer scenario starts becomes the peak dose for the entire period, which is used to calculate DCGLs.

For six radionuclides considered in this paper, doses represented by industrial worker scenario and residential farmer scenario divided by the year of 2040, the hybrid scenario, for the assessment period of 1000 years, are shown in Fig. 8. In the initial period when industrial worker scenario is applied, the dose is lower than when residential farmer scenario of the same period is applied. Therefore, it can be seen that the peak dose for the entire period mainly comes from the year of 2040 when the residential farmer scenario starts than the initial 0 year of industrial worker scenario. Particularly, C-14 shows a gradual increase in dose after 2040, so the peak dose is selected as the dose after 2040. This depends on the scenario, plus the nature of the radionuclides also determine the peak dose over a period of 1000 years.

For the hybrid scenario where industrial worker scenario and residential farmer scenario are applied sequentially, the maximum of the dose peaks among the two scenarios are used to compute the DCGLs for the six radionuclides. The dose for each period, maximum dose obtained, and the DCGLs calculated for the six radionuclides are shown in Table 6. For Co-60, Cs-137, Ni-63, and Sr-90 nuclides, the maximum doses occur in the year of 2040 when the residential farmer scenario starts. This means that the doses of these radionuclides under the residential farmer scenario would have been higher than those under the industrial worker scenario over the initial 8-year period. On the other hand, the maximum dose of C-14 occurs after 2040 and the maximum dose of Cs-134 occurs when the industrial worker scenario just starts in the 0 year.

9. Conclusions

Since one of the NPPs at Kori site has been permanently shut down, preparations for its decommissioning, such as preparation of a decommissioning plan, are now being actively carried out. Especially, residual radioactivity evaluation should be conducted at the preparatory stage of decommissioning in order to prepare a final decommissioning report which includes a description on how to finally release the site after the completion of decommissioning. Based on the case of overseas decommissioning nuclear power plants, DCGLs reflecting the site characteristics were calculated.

In this study, we identified what factors are needed to calculate DCGLs and established the activities and sequences based on the understanding of the relationship between the factors identified. The primary factors are input parameters and site reuse scenarios, and the input parameters are divided into deterministic, probabilistic, and a list of potential radionuclides. After reviewing the factors and their relationships, we constructed the activities and sequences for calculating DCGLs.

After the parameters were selected and two reasonable scenarios (resident farmer and industrial worker) were applied in

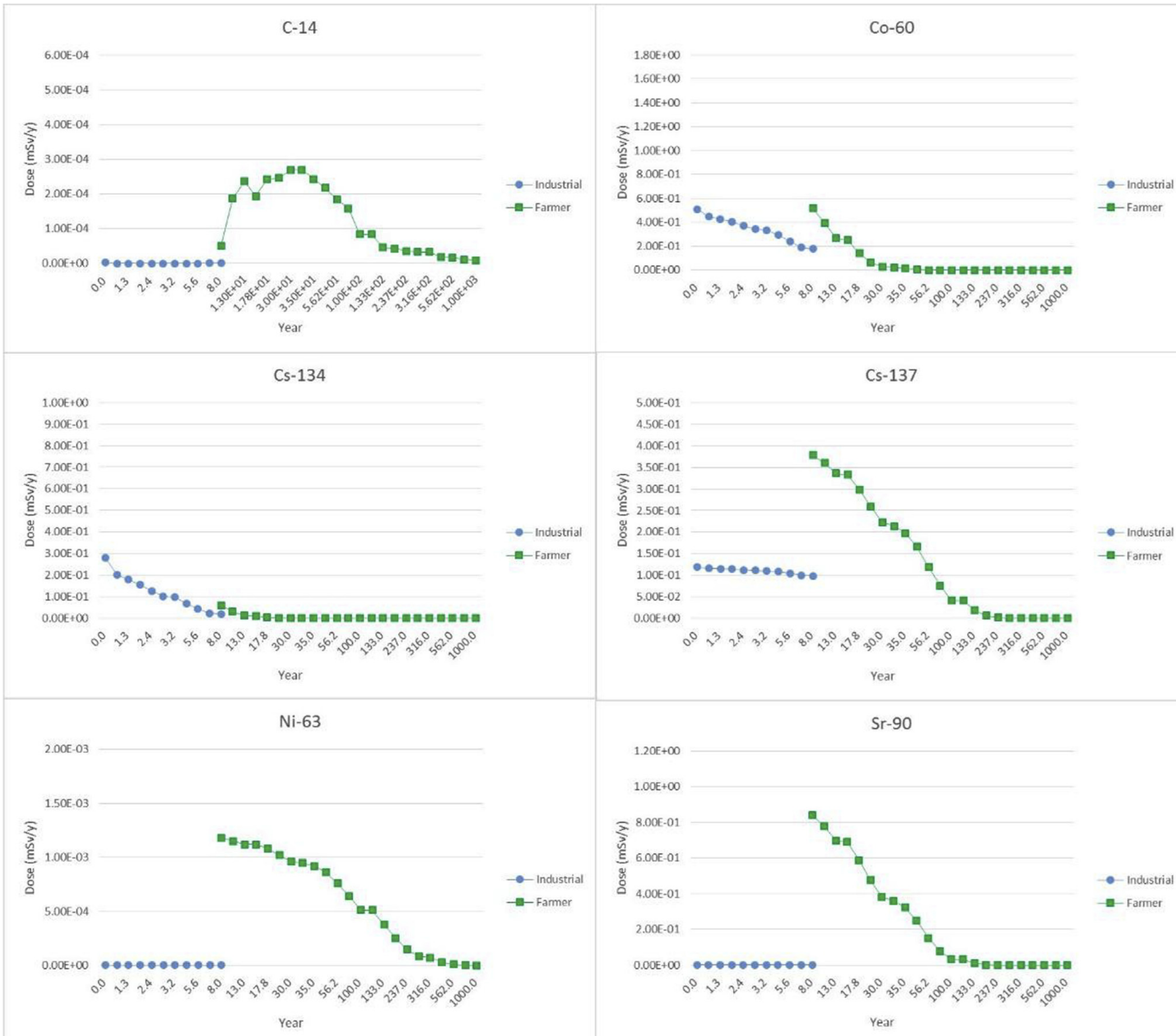

Fig. 8. Dose trends for radionuclides in hybrid scenario.

Table 6
Preliminary DCGLs.

Radionuclide	Dose of Industrial Worker (mSy/y)/(Bq/g)		Dose of Residential Farmer (mSy/y)/(Bq/g)		Max. Dose (mSy/y)/(Bq/g)	DCGL (Bq/g)
	0–8 years	At 8 years	At 8 years	8–1000 years		
C-14	2.80E-06	2.19E-06	1.97E-04	4.20E-04	4.20E-04	2.38E+02
Co-60	5.10E-01	1.77E-01	5.17E-01	5.17E-01	5.17E-01	1.93E-01
Ni-63	1.27E-06	1.18E-06	1.18E-03	1.18E-03	1.18E-03	8.47E+01
Cs-134	2.81E-01	1.90E-02	5.82E-02	5.82E-02	2.81E-01	3.56E-01
Cs-137	1.19E-01	9.83E-02	3.79E-01	3.79E-01	3.79E-01	2.64E-01
Sr-90	1.91E-03	1.47E-03	8.46E-01	8.46E-01	8.46E-01	1.18E-01

sequence, the primary evaluation was performed using the RESRAD. As a result, sensitivity analysis resulted in six radionuclides. It was possible to identify the sensitive parameters of radionuclides for both resident farmer and industrial worker scenarios. Then, a deterministic value was assigned for the sensitive parameters. Secondary evaluation was carried out resulting in the peak dose for each period of site reuse scenarios, and preliminary DCGLs were calculated., A more realistic and reasonable DCGLs have been calculated by applying resident farmer and industrial worker scenarios in sequence with due consideration of the characteristics of Kori site, rather than applying just one scenario. Therefore, this novel approach is very beneficial in calculating DCGLs which reflect the characteristics and future reuse plans of a site more effectively and reasonably than do conventional approaches. Based on this preliminary evaluation, in the future study, DCGLs should be finalized reflecting the measurement data of radionuclides present at the time of decommissioning and site release.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2019.01.018.

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