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Original Article

Derivation of preliminary derived concentration guideline levels for surface soil at Kori Unit 1 by RESRAD probabilistic analysis

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ABSTRACT

Preliminary surface soil Derived Concentration Guideline Levels (DCGLs) were derived conforming to the Multi-Agency Radiation Site Survey and Investigation Manual (MARSSIM) procedure for the site release and reuse of Kori Unit 1 in Korea. Based on the decommissioning experiences of the U.S. nuclear power plants, a suite of residual radionuclides was determined, and uncertainties contributed to the resultant dose by the input parameters were quantified via the sensitivity analysis of parameters. The peak of the mean dose was obtained via the probabilistic analysis of the RESRAD (RESidual RADioactivity)-ONSITE code. Consequently, $DCGL_W$ of Kori Unit 1 in accordance with two scenarios, industrial worker and residential farmer scenario, were derived and the results were compared respectively with other NPPs. It could be used as a basic guideline for establishing regulatory standards for reuse planning, designing the site characterization surveys and implementing final status survey (FSS).

1. Introduction

In accordance with the suspension of operation of Kori Unit 1, which is the first commercial nuclear power plant (NPP) of Korea, procedures and regulatory guidelines related to site release and reuse after decommissioning are under preparation. In this study, referring to the procedures of Multi-Agency Radiation Site Survey and Investigation Manual (MARSSIM) and license termination plans (LTP) of the U.S. NPPs, Derived Concentration Guideline Levels ($DCGL_W$) of surface soil at the site of Kori Unit 1 considering related radionuclides and suitable scenarios were derived via the probabilistic analysis of RESRAD-ONSITE code. Based on the screening methodology of radionuclides applied to the dismantlement case of the U.S. pressurized water reactors (PWRs, e.g. Rancho Seco, Zion NPP), a suite of site-specific radionuclides of Kori Unit 1 was virtually selected. Then, surface soil $DCGL_W$ of Kori Unit 1 was derived by applying two scenarios, the industrial worker scenario, which is expected to be close to practical reuse scenario and the residential farmer scenario, which is generally applied for the most conservative evaluation. After the uncertainty was quantified using sensitivity analysis, the $DCGL_W$ for surface soil exposure was derived from the probabilistic dose. In order to demonstrate whether the residual radioactivity level in each survey unit satisfies the release criteria in the FSS, the derivation of $DCGL_W$ via probabilistic analysis is essential to follow the general guidelines of the MARSSIM procedures.

2. Materials and methods

Currently, the decommissioning and decontamination planning for Kori Unit 1 are underway mainly based on MARSSIM methodology. The objective of the DCGLs derivation is to establish specific concentration limits of the radionuclides corresponding to the residual radioactivity to be considered for reuse after site release. It is considered essential to perform a scoping survey, to complement the historical site assessment (HSA), to identify contamination areas, and check for missing areas. Referring on the precedent decommissioning case in the U.S., the derivation of DCGLs used in this study includes the following steps: (A) establishment of a suite of site-specific radionuclides based on the screening methodology used in Rancho Seco and Zion NPPs in the U.S., and description of applied scenarios; (B) definition and description of the probabilistic analysis of the RESRAD-ONSITE code; (C) sensitivity analysis of probabilistic parameters using the site-specific parameters of the site; (D) derivation of preliminary $DCGL_W$ for the site 1 using the probability dose.

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2.1. Development of site-specific radionuclides and scenario

NUREG-1757, Vol. 2 recommends NUREG/CR-3474, NUREG/CR-4289, and NUREG/CR-0130 as theoretical radionuclides supplementary guidance documents [1]. NUREG/CR-3474 provides a list of theoretical radioactive materials for PWRs and boiling water reactors (BWRs) based on reactor construction materials. NUREG/CR-4289 provides the results of analysis of samples contaminated with actual fission and activation from the seven reference nuclear reactors (PWRs and BWRs) operating at that time [2,3]. NUREG/CR-0130, Vol. 1 provides the results of an investigation of radionuclides in the system during operation [4]. Rancho Seco NPP added radionuclides with half-lives of two or more years, by cross-referring to all the above documents. Additional radionuclides were added using the ORIGEN code developed at the Oak Ridge National Laboratory in the U.S. to simulate the buildup, decay, and processing of radioactive materials. Based on the HSA and referring to NCRP Report No. 58 [5], radionuclides capable of being detected in the nuclear fuel was added. The final suite of theoretical radionuclides for Rancho Seco NPP was completed by adding site specific radionuclides, ^{22}Na and ^{40}K with a half-life of more than 2 years [6]. Zion NPP added radionuclides with a half-life greater than 2 years with reference to WINCO-1191 instead of NUREG/CR-0130, Vol. 1 [7]. The final suite of theoretical radionuclides was completed by adding radionuclides with a relative fraction of at least 0.01% of the detected radionuclides in the sample analysis including the analysis of the waste/process streams collected at the Zion NPP site. The detailed procedures of developing a theoretical suite of radionuclides used at two representative U.S. NPPs decommissioning cases are summarized in Table 1.

Subsequently, the radionuclides that are not expected to be present in the FSS or that have a low dose contribution were excluded to produce a realistic list of potential radionuclides. For Rancho Seco NPP, radionuclides accounting for less than 0.1% of the total dose contribution based on the consideration of the aforementioned radioactive materials (NUREG radionuclides) and spent nuclear fuel (ORIGEN radionuclides) were excluded using the calculation of DandD code which is a code for simple screening analysis developed by NRC. Potential dose contribution of remaining radionuclides not supported by DandD code was also considered. Totals of weighted inhalation and ingestion exposure-to-dose conversion factors (DCFs) for each discounted radionuclides were compared with the sum of weighted DCFs for the most abundant radionuclides, ^{60}Co and ^{63}Ni. ^{242}Pu was added by waste stream analysis according to 10 CFR Part 61 to the samples of characterization survey and inert gases and naturally occurring radionuclides were excluded. As a result, a suite of site-specific radionuclides was derived [6]. The Zion NPP compared the calculated radioactivity of the theoretical neutron activation product with the radioactivity concentrations of ^{60}Co and ^{63}Ni, which were the major radionuclides identified in the actual samples collected at the site. Radionuclides exhibiting radioactivity concentrations below 0.01% were excluded and additionally added via characterization sample. Finally, 26 site-specific radionuclides were determined for both NPPs [8]. (Common radionuclides: ^{108m}Ag, ^{14}C, ^{60}Co, ^{134}Cs, ^{137}Cs, ^{152}Eu, ^{154}Eu, ^{155}Eu, ^{55}Fe, ^{3}H, ^{59}Nb, ^{59}Ni, ^{63}Ni, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{90}Sr, ^{99}Tc, ^{241}Am, ^{244}Cm, ^{237}Np, ^{125}Sb, ^{147}Pm,; Radionuclides specific to Rancho Seco NPP: ^{22}Na, ^{242}Pu,; Radionuclides specific to Zion NPP: ^{243}Am, ^{243}Cm).

Concerned radionuclides to be applied to soil were selected from the site-specific radionuclide list. Based on the analysis of sample characterization survey, for Rancho Seco NPP, the concerned radionuclides were selected with positively detected radionuclides from the most contaminated spent pool cooler pad soil sample on the site with a high purity germanium (HPGe) detector. Subsequently, the samples were submitted to General Engineering Laboratories (GEL) for laboratory analysis and hard-to-detect (HTD) radionuclide analysis was performed. Based on this, nuclide fraction (*nf*) and fraction contribution of radionuclide have established. *nf* is a value obtained by dividing the concentration of each nuclide by the total concentration, determined from the total radionuclide mixture by normalizing the remaining radionuclide fraction. Using the *nf* of calculated radionuclides including other samples, it was confirmed that the contribution dose to the excluded radionuclide was less than 10% of the site release criterion [9]. For Zion NPP, dose factors were used to select radionuclides for soil. Dose factor is the factor by multiplying concentration factor and exposure factor from groundwater. Concentration factor is derived from the water concentration of basement calculated with DUST-MS code, and exposure factor is calculated by dividing the maximum dose derived from RESRAD-ONSITE v.7.0 by the well water concentration at $t = 0$. Subsequently, the percentage of radionuclides in the total source term through the maximum concentration of basement determined using the DUST-MS code. This can be normalized by 1 Ci and multiplied by the dose factor to estimate the relative contribution of the radionuclides. As a result, radionuclides applied to soil were selected which accounted for more than 99.5% of the total dose in the auxiliary building [10]. The concerned radionuclides selected for the two NPPs were the same, with the exception of ^{14}C for Rancho Seco NPP. Since the characterization survey of Kori Unit 1 has just started, there is not enough information about radionuclides that can be directly applied to soil of the site. Referring to methodologies for selecting concerned radionuclides in soil of two U.S. NPPs cases, the remaining radionuclides were assumed to be same as Rancho Seco NPP. The concerned radionuclides of Kori Unit 1 were preliminarily selected as listed in Table 2.

In this study, both industrial worker scenarios and residential farmer scenarios were evaluated. Compared to residential farmer scenario, which considers all of the pathways of exposure in the code to scenarios in which receptors migrate after the release of the site for unrestricted reuse to build a home and cultivate crops and livestock for consumption, industrial worker scenario of this study excludes ingestion pathways that are unlikely to be allowed in industrial areas. However, drinking water pathway was included to be more conservative. The average members of the critical group in the industrial worker scenarios for surface soil exposure can potentially be exposed owing to the direct exposure of contaminated soil, inhalation of contaminated soil that becomes airborne, ingestion of contaminated soil, drinking water, and buried piping. The average members are employees and contractors who are allowed access to the occupational area of impact, assuming 50 working hours per week (2000 h per year) and 50% occupation of the site [6]. The average members of the critical group in the residential farmer scenario were assumed to spend 24 h days per year on indoor, outdoor, and gardening, based on the assumption that 50% of a receptor's time is spent indoors, and 25% is spent outdoors [11].

2.2. Probabilistic analysis of RESRAD-ONSITE

RESRAD-ONSITE codes have been developed by Argonne National Laboratory (ANL) under the auspices of Department of Energy (DOE) and Nuclear Regulatory Commission (NRC) in the U.S. in order to develop cleanup criteria for radioactively contaminated sites and to assess dose and risk of receptors located at the site. The code has been used by the EPA (Environmental Protection Agency) to compile legislation related to site releases and has been approved for use by the NRC and widely being used for decommissioning of the NPPs.

Compared with deterministic analysis, which uses single

Table 1
Procedures for developing a theoretical suite of radionuclides.

NPP	Rancho Seco (PWR, Babcocks & Wilcox)	Zion 1,2 (PWR, Westinghouse)
Document	NUREG/CR-3474 [2]	
Table	• Table 5.6. Activation of PWR Bioshield (Ci/gm), Average Rebar, 30 EFPY at Core Axial Midplane • Table 5.13. Activity Inventory of PWR Internals at Shutdown • Table 5.15. Inventories of PWR and BWR Vessel Walls at Shut down	• Table 5.1. Activation of PWR Internals (Ci/gm), Type 305L Stainless Steel, 30 EFPY at Core Axial Midplane • Table 5.3. Activation of Pressure Vessel Walls (Ci/gm), 30 EFPY at Core Axial Midplane • Table 5.4. Activation of PWR Bioshield (Ci/gm), Average Concrete, 30 EFPY at Core Axial Midplane
Common	^{108m}Ag, ^{39}Ar, ^{133}Ba, ^{14}C, ^{41}Ca, ^{36}Cl, ^{60}Co, ^{134}Cs, ^{137}Cs, ^{152}Eu, ^{154}Eu, ^{155}Eu, ^{55}Fe, ^{3}H, ^{178m}Hf, ^{166m}Ho, ^{129}I, ^{81}Kr, ^{85}Kr, ^{53}Mn, ^{93}Mo, ^{94}Nb, ^{59}Ni, ^{63}Ni, ^{205}Pb, ^{145}Pm, ^{239}Pu, ^{79}Se, ^{146}Sm, ^{151}Sm, ^{121m}Sn, ^{90}Sr, ^{158}Tb, ^{99}Tc, ^{233}U, ^{93}Zr (+36)	
Difference	^{135}Cs, ^{93m}Nb (+2)	^{240}Pu, ^{92m}Nb (+2)
Total	38	38
Document	NUREG/CR-4289 [3]	
Table	• Table 3.1. Residual Radionuclide Compositions in Total Plant Inventories at Seven Nuclear Generating Stations • Table 3.2. Concentration Ranges of Radionuclides in Corrosion Films on Piping Exposed to Primary Reactor Coolant • Table 3.3. Concentration Ranges of Radionuclides in Corrosion Films Internally Deposited in Piping and Hardware Exposed to Liquid Radwastes and Secondary Coolant • Table 3.4. Concentration Ranges of Radionuclides Associated with Concrete from Highly Contaminated Areas Within Selected Nuclear Generating Stations	
Common	^{238}Pu, ^{241}Am, ^{244}Cm, ^{125}Sb, ^{237}Np (+5)	
Difference	^{240}Pu (+1)	^{243}Am (+1)
Document	NUREG/CR-0130, Vol. 1 [4]	WINCO-1191 [7]
Table	• Table 7.3–9. Reactor Coolant Radionuclide Concentrations (12) in an Operating PWR • Table 7.3–10. Radioactive Surface Contamination in the Reference PWR Resulting from Accumulated Coolant Leakage in an Ion Exchanger Vault (Fractional Activity Normalized at Reactor Shutdown) • Table 7.3–11. Isotopic Composition of Accumulated Radioactive Surface Contamination in the Reference PWR (Renormalized for Each Decay Time)	• Table 1 – Radionuclides Found in Nuclear Power Reactors (Limited to half-lives longer than 50 days)
Difference	–	^{147}Pm, ^{241}Pu(+2)
Total	44	46
	ORIGEN Code	19 Representative samples [7]
	^{147}Pm, ^{241}Pu, ^{243}Am, ^{243}Cm (+4)	^{243}Cm (+1)
	NCRP Report No.58 [5]	
	^{234}U, ^{235}U, ^{236}U, ^{238}U (+4)	
Theoretical suite of radionuclides		
Common	^{108m}Ag, ^{39}Ar, ^{133}Ba, ^{14}C, ^{41}Ca, ^{36}Cl, ^{60}Co, ^{134}Cs, ^{137}Cs, ^{152}Eu, ^{154}Eu, ^{155}Eu, ^{55}Fe, ^{3}H, ^{178m}Hf, ^{166m}Ho, ^{129}I, ^{81}Kr, ^{85}Kr, ^{53}Mn, ^{93}Mo, ^{94}Nb, ^{59}Ni, ^{63}Ni, ^{205}Pb, ^{145}Pm, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{79}Se, ^{146}Sm, ^{151}Sm, ^{121m}Sn, ^{90}Sr, ^{158}Tb, ^{99}Tc, ^{233}U, ^{93}Zr, ^{241}Am, ^{243}Am, ^{243}Cm, ^{244}Cm, ^{125}Sb, ^{147}Pm, ^{241}Pu, ^{237}Np (46)	
Difference	^{135}Cs, ^{93m}Nb, ^{234}U, ^{235}U, ^{236}U, ^{238}U, ^{22}Na, ^{40}K (8)	^{92m}Nb (1)
Total	54	47

parameter values for all variables in the code so that is not suitable for assessing the effect of simultaneous changes in parameters on the dose output results, as shown in Fig. 1, probabilistic analysis performs numerous simulations that vary simultaneously based on the distribution function to which the values of selected sets of input parameters are assigned. Latin hypercube sampling (LHS) technique has been used to divide the distribution of each input parameter into non-overlapping regions of the same probability, and it derives a random sample value from each region based on the probability density function (PDF) for that region. Subsequently, the cumulative density function (CDF) of the sensitivity parameter can be used to obtain quantitative results for the distribution percentile, and the variability of the dose estimate owing to the variability of the input parameters using the distribution is also identifiable. In the resulting distributed value of dose output, based on NUREG/CR-1757, Vol. 2, “Peak of the mean dose” was derived [1].

Table 2
A preliminary suite of concerned radionuclides for soil at Kori Unit 1 reuse scenario.

Radionuclide	Half-life (years)
^{14}C	5.73×10^{3}
^{60}Co	5.27×10^{0}
^{134}Cs	2.06×10^{0}
^{137}Cs	3.02×10^{1}
^{90}Sr	2.86×10^{1}
^{63}Ni	1.00×10^{2}

NUREG/CR-6676 emphasizes performing a probabilistic analysis of site characterization using parameter distributions developed for RESRAD codes and NUREG/CR-6692. The requirements, design, and operation of the RESRAD probabilistic module are documented to establish and validate the features and functions of the probabilistic module. In addition, nonparametric statistical analysis, which is a statistical method from the probabilistic viewpoint for environmental data evaluation, is recommended [1,11,12]. Referring to these technical reports, RESRAD parameters are classified into behavior, metabolism, and physical parameters, and ranked in order of Priority 1, Priority 2, and Priority 3. NUREG/CR-6697 has developed a statistical parameter distribution for physical parameters determined by the source and site-specificity, categorized as Priority 1, and 2 respectively [14].

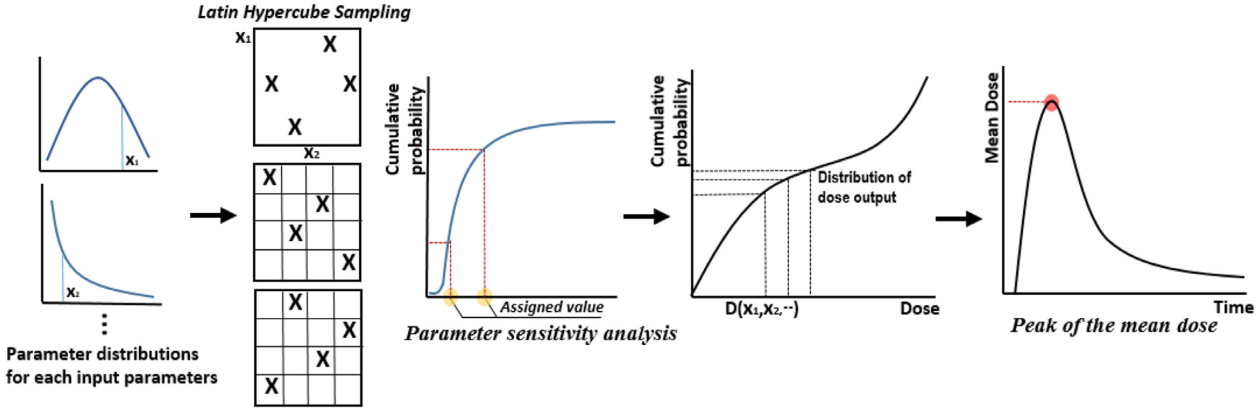

Fig. 1. Conceptual figure of RESRAD-ONSITE probabilistic analysis.

2.3. Input parameters for Kori Unit 1 for RESRAD-ONSITE

The initial concentration of concerned radionuclides for the sensitivity analysis is 0.037 Bq/g (= 1 pCi/g). This is to indicate a DCGL for a radionuclide in pCi/g units when the value of "Peak of the mean dose" in Section 2.4, which is expressed as the dose per unit concentration, is divided by the primary dose limit. After the development of RESRAD-ONSITE v7.0, recent dosimetric data from ICRP Publication 107 are included to use the "DCFPAK 3.02" internal exposure dose conversion factor of the in-code dose factor library which includes external exposure dose conversion factor based on the dosimeter described in ICRP 107 and FGR 12 (EPA 1993). For the conservative evaluation, the cover layer was not considered, and the hydrogeological model of Kori Unit 1 was simplified as shown in Fig. 2, assuming that the unsaturated zone could be divided into four layers [15].

As shown in Table 3 and Table 4, based on the hydrogeological information, density, total porosity, effective porosity, field capacity, hydraulic conductivity, and *b* parameters of each layer were assigned with reference to NUREG/CR-6767, 6697 and for stone and sand below the layers, the arithmetic mean and upper boundary values of RESRAD data collection handbook were used [13,15,16].

Sampling inputs are set by 1000 random seeds, 300 observations, and 1 repetition of Latin Hypercube Sampling. Random seed determines the order of the generated random numbers. Observations are used to set the number of sample values generated for each iteration and input variables, and repetition is used to set the number of times the analysis is repeated. The distribution coefficients (K_d) of each radionuclide were determined by using the distribution of NUREG/CR-6697. Area of contaminated zone was entered as 10,000 m^2, which is the default value of the RESRAD-ONSITE code and the lower boundary value of Class 2 land area suggested by MARSSIM [18]. Table 5 displays the annual mean values of Korea meteorological administration resources for Ulsan, which is the closest observation point to Kori Unit 1 site, were used for the wind speed and precipitation parameters [19].

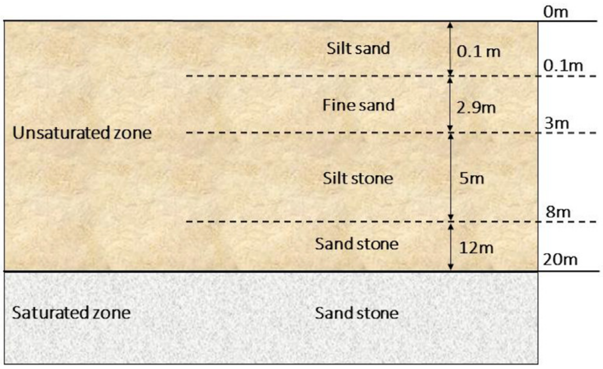

Fig. 2. Simplified hydrological model of Kori Unit 1.

In addition, parameters entered in the residential farmer scenario are shown in Table 6. This is not a default value embedded in RESRAD-ONSITE code but is a dedicated screening value for the residential farmer scenario according to NUREG/CR-5512, Vol. 3. Screening group presented here is site-independent population suitable for use on all sites and are expected to receive the maximum exposure according to the scenario definition [11]. Many previously decommissioned and under decommissioning NPPs applied the residential farmer scenario based on these values so using this value is suitable for the Kori Unit 1 until the domestic parameter values are ready.

2.4. Parameter sensitivity analysis

MARSSIM recommends statistically estimating the probability of not exceeding the release criteria quantitatively [18]. Therefore, partial rank correlation coefficient (PRCC), which estimates the nonlinear distinct relationship which provides a unique contribution of the input parameters to the resulting dose, was used [12]. If the absolute value of PRCC is greater than 0.25, then the parameter value at either the 75% quartile or the 25% quartile is selected based on total effective dose equivalent (TEDE) correlation with parameter. As shown in Table 7, whether the PRCC was positively or negatively correlated with dose, the 75% or 25% quantile value of the distribution was used, respectively instead of initial input distribution [6].

In industrial worker scenario, the external gamma shielding factor, density of the contaminated zone, and distribution coefficient of ^{60}Co in the contaminated zone were identified as the sensitive parameters in order of magnitude. The external gamma shielding factor indicates the ratio of the external gamma radiation level to the site indoor radiation level outside the site. Distribution coefficient of ^{60}Co in the contaminated zone indicates the distribution ratio of ^{60}Co between the groundwater and soil of contaminated zone. Otherwise, in residential farmer scenario, depth of roots, plant transfer factor for Sr were further identified as most sensitive parameters. Additionally, depth of roots represents the average root depth of various plants grown in contaminated areas. Plant transfer factor is defined as the ratio of the radionuclide concentration of the plant to the radionuclide concentration of the soil through root absorption [17].

Table 3
Site-specific hydrogeological parameters.

Parameter	Value				
Unsaturated Zone number	1	2	3	4	Saturated Zone
Thickness (m)	0.1	2.9	5	12	
Density (g/cm^3)	Normal distribution [16]	Normal distribution [16]	Normal distribution [16]	Normal distribution [16]	Normal distribution [16]
Total Porosity	Truncated normal distribution [14]	Truncated normal distribution [14]	0.35 [17]	0.34 [17]	0.34 [17]
Effective Porosity	Truncated normal distribution [16]	Truncated normal distribution [16]	0.12 [17]	0.27 [17]	0.27 [17]
Field Capacity	Truncated normal distribution [16]	Truncated normal distribution [16]	0.23 [17]	0.07 [17]	0.07 [17]
Hydraulic Conductivity (m/yr)	Bounded lognormal-n [14]	Bounded lognormal-n [14]	Bounded lognormal-n [14]	Bounded lognormal-n [14]	10 [17]
b parameter	Bounded lognormal-n [14]	Bounded lognormal-n [14]	Bounded lognormal-n [14]	Bounded lognormal-n [14]	Bounded lognormal-n [14]

Table 4
Site-specific hydrogeological distribution's statistical parameters.

Parameter	Distribution	Distribution's statistical parameters			
		1	2	3	4
Unsaturated zone 1, Unsaturated zone 3 density	Normal	1.330	0.202		
Unsaturated zone 1, Unsaturated zone 3 hydraulic conductivity	Bounded lognormal-n	2.66	0.475	3.302	62.2
Unsaturated zone 1, Unsaturated zone 3 b parameter	Bounded lognormal-n	1.16	0.140	2.06	4.89
Unsaturated zone 1 total porosity	Truncated normal	0.46	0.11	0.1161	0.7959
Unsaturated zone 1 effective porosity	Truncated normal	0.425	0.110	0.0839	0.766
Unsaturated zone 1 field capacity	Truncated normal	0.236	0.0578	0.0575	0.415
Unsaturated zone 2 total porosity	Truncated normal	0.43	0.06	0.2446	0.6154
Unsaturated zone 2 effective porosity	Truncated normal	0.383	0.0610	0.195	0.572
Unsaturated zone 2 field capacity	Truncated normal	0.0607	0.0150	0.0280	0.124
Unsaturated zone 2, Unsaturated zone 4 density	Normal	1.578	0.158		
Unsaturated zone 2, Unsaturated zone 4 hydraulic conductivity	Bounded lognormal-n	1.398	1.842	110	5870
Unsaturated zone 2, Unsaturated zone 4 b parameter	Bounded lognormal-n	−0.0253	0.216	0.501	1.90
Saturated zone density	Normal	1.578	0.158		
Saturated zone *b* parameter	Bounded lognormal-n	−0.0253	0.216	0.501	1.90

Normal: 1 = mean, 2 = standard deviation, Bounded lognormal-n: 1 = mean of underlying normal, 2 = standard deviation of underlying normal, 3 = lower limit, 4 = upper limit, Truncated normal: 1 = mean, 2 = standard deviation, 3 = lower quantile, 4 = upper quantile.

Table 5
Site-specific meteorological parameters.

Parameter	Value [19]
Wind speed (m/s)	2.1
Precipitation (m/yr)	1.28

2.5. Surface soil DCGL$_W$

DCGL$_W$ is the residual radioactivity concentrations that can be distinguished from the natural radioactivity level, assuming that the sources are uniformly distributed in the survey unit. It is radionuclide-specific concentration limits when the average member of the critical group received TEDE of 0.25 mSv (0.1 mSv in Korea), the maximum annual dose.

DCGL$_W$ is derived as follows [6]:

$$\mathrm{DCGLw} = \frac{\text{Regulatory dose limit} - \text{Potential dose}}{\text{Peak of the mean dose}} \tag{1}$$

For Rancho Seco NPP, potential dose percentage (2.29%) was considered based on the decay corrected minimum detectable activity (MDA) values for the HTD radionuclides analyzed in the soil

Table 6
Additional parameters for residential farmer scenario.

Parameter	Value [11]	Parameter	Value [11]
Indoor time fraction	0.6571	Outdoor time fraction	0.1181
Fruit, vegetables, grain consumption (kg/yr)	112	Leafy vegetable consumption (kg/yr)	21.4
Milk consumption (L/yr)	233	Meat and poultry consumption (kg/yr)	65.1
Fish consumption (kg/yr)	20.6	Other seafood consumption (kg/yr)	0.9
Soil ingestion rate (g/yr)	18.26	Drinking water intake (L/yr)	478.5
Livestock fodder intake for meat (kg/day)	28.3	Livestock fodder intake for milk (kg/day)	65.2
Livestock water intake for meat (L/day)	50.6	Livestock water intake for milk (L/day)	60
Mass loading for foliar deposition (g/m^3)	0.0004	Wet weight crop yield for leafy (kg/m^2)	2.89
Wet weight crop yield for fodder (kg/m^2)	1.91	Growing season for non-leafy (yr)	0.25
Growing season for leafy (yr)	0.12	Growing season for fodder (yr)	0.082
Wet foliar interception fraction for non-leafy, fodder			0.35
Dry foliar interception fraction for leafy, fodder			0.35

Table 7
Results of RESRAD-ONSITE sensitivity analysis.

Scenario	Parameter	PRCC	Quartile (%)	Assigned value
Industrial worker	External gamma shielding factor	0.90	75	0.396
	Contaminated zone density (g/cm^3)	0.61	75	1.466
	K_d of ^{60}Co in contaminated zone (cm^3/g)	0.43	75	1277.94
Residential farmer	External gamma shielding factor	0.97	75	0.396
	Depth of roots (m)	−0.54	25	1.22
	Plant transfer factor for Sr (pCi/g plant per pCi/g soil)	0.51	75	0.5840
	Contaminated zone density (g/cm^3)	0.50	75	1.466
	K_d of ^{60}Co in contaminated zone (cm^3/g)	0.31	75	1275.9

samples from the spent fuel cooler pad soil. Zion NPP corrected the $DCGL_W$ value using the insignificant contributor dose percentage (0.171%) [6,10]. The potential dose of the excluded radionuclides for Kori Unit 1 was not considered since there is no current study on the concentration of radionuclides at Kori Unit 1, this is assumed to be insignificant and excluded. The probabilistic dose modeling specifies the use of "peak of the mean dose" corresponding to the maximum time of the average dose based on the characteristics of the optimal estimate of the average dose determined at each discrete time. The "peak of the mean dose" for each radionuclide was derived by assigning the deterministic value of sensitive parameters instead of the probability distribution. This was calculated with RESRAD-ONSITE code by converting the initial input of unit radionuclide concentration to the annual dose at the maximum dose point. The $DCGL_W$ of Kori Unit 1 were both derived based on the release criteria in accordance with 10 CFR Part 20, Subpart E (0.25 mSv/yr), and the restricted and unlimited site release criteria currently proposed in Korea (0.1 mSv/yr) [20]. The results of "peak of the mean dose" and $DCGL_W$ according to each scenario are listed in Table 8.

3. Discussion

In this study, the preliminary $DCGL_W$ of surface soil exposure was derived under both industrial worker scenario and residential farmer scenario using RESRAD-ONSITE code. According to MARSSIM, which recommends quantitatively estimating the probability that the site will not exceed the release criteria using statistical methods, the correlation coefficient, i.e., PRCC, and percentile CDF for each parameter were used to quantify the uncertainty to determine which input parameters resulted in uncertainty of the results. The "peak of the mean dose" in probabilistic dose modeling was derived using the deterministic parameter values and probability distributions reflecting the characteristics of the Kori Unit 1 site, based on the maximum average dose specified in NUREG-1757, Vol. 2. Table 9 and Table 10 show the preliminary $DCGL_W$ derived for Kori Unit 1 compared with the values of other US NPPs.

In order to compare $DCGL_W$ of Kori Unit 1 and Rancho Seco NPP, the same water transport model was applied to Rancho Seco NPP and Kori Unit 1 and two DCFs were applied to Kori Unit 1 calculation. Recalculated $DCGL_W$ of Rancho Seco NPP does not consider the contribution of discounted radionuclides same as in that of Kori Unit 1, and all other conditions are applied in the same way as in Rancho Seco NPP's LTP. The $DCGL_W$ of Rancho Seco NPP uses mass balance model as four wells are available on the site. However, when the contaminated area exceeds 1000 m^2, non-dispersion model is recommended and for Kori Unit 1 non-dispersion model was applied [21]. In mass balance model, estimates are conservative assuming that all available radionuclides released from contaminated areas are withdrawn through wells. In non-dispersion model, it is assumed that the dispersivity is null, unsaturated zone is composed of one or more horizontal homogeneous strata, and saturated zone is treated as a single homogeneous layer, leading to a pattern of flow lines that can estimate the dilution factor by geometric considerations.

As a result of comparing $DCGL_W$ with the same water transport model and DCF (e.g. 3rd and 4th columns of Table 9), most radionuclides showed a slight difference but ^{14}C was identified as a radionuclide showing up to 30% difference. Since Kori Unit 1 and Rancho Seco NPP have difference in thickness of unsaturated and saturated zone but have the same geological structure, $DCGL_W$ of ^{14}C for Kori Unit 1 did slightly changed when parameters related to hydrological geologic characteristics and groundwater such as unsaturated thickness, water table drop rate, and well pump intake were adjusted. However, when the parameter 'wind speed' was

Table 8
Single radionuclide $DCGL_W$ for Kori Unit 1 NPP by release criteria.

Scenario	Radionuclide	Peak of the mean dose (mSv/yr per 0.037 Bq/g)	Dose criteria (mSv/yr)	
			0.25	0.1
			Kori Unit 1 NPP $DCGL_W$ (Bq/g)	
Industrial worker	^{14}C	0.0000000402	229,900	91,900
	^{60}Co	0.01826	0.51	0.20
	^{134}Cs	0.00998	0.93	0.37
	^{137}Cs	0.00419	2.21	0.88
	^{90}Sr	0.0000567	163.14	65.26
	^{63}Ni	0.0000000161	574,500	229,800
Residential farmer	^{14}C	0.001108	8.35	3.34
	^{60}Co	0.04372	0.21	0.08
	^{134}Cs	0.0253	0.37	0.15
	^{137}Cs	0.01125	0.82	0.33
	^{90}Sr	0.005841	1.58	0.63
	^{63}Ni	0.00002051	451	180

Table 9
Comparison of surface soil DCGLs for industrial worker scenario based on the dose criterion 0.25 mSv/yr.

NPP	Rancho Seco		Kori Unit 1	
	[6]	*Recalculated*		
Version used	v6.22	v7.2	v7.2	
DCF (Internal/External)	FGR11/FGR12	FGR11/FGR12	FGR11/FGR12	DCFPAK 3.02
Radionuclide transformations	ICRP 38	ICRP 38	ICRP 38	ICRP 107
Model for water transport parameter	Mass balance	Non-dispersion	Non-dispersion	Non-dispersion
Radionuclides of concern	$DCGL_W$ (Bq/g)			
^{14}C	308,200	*317,100*	226,100	229,900
^{60}Co	0.47	*0.47*	0.47	0.51
^{134}Cs	0.83	*0.85*	0.86	0.93
^{137}Cs	1.95	*2.02*	2.04	2.21
^{90}Sr	240	*246*	256	163
^{63}Ni	562,000	*570,000*	572,000	574,500

Table 10
Comparison of surface soil DCGLs for residential farmer scenario based on the dose criterion 0.25 mSv/yr.

NPP	Connecticut Yankee [22]	Yankee Rowe		Zion [24]	Kori Unit 1	
		[23]	*Recalculated*			
Version used	v6.21	v6.21	v7.2	v7.0	v7.2	
DCF (Internal/External)	FGR11/FGR12	FGR11/FGR12	DCFPAK 3.02	FGR11/FGR12	DCFPAK 3.02	
Number of unsaturated zone	1	1	1	1	1	4
Soil type	sand	sand	sand	sand	silt	Fig. 2
Radionuclides of concern	$DCGL_W$ (Bq/g)					
^{14}C	0.21	0.19	*0.41*	N/S	8.24	8.35
^{60}Co	0.14	0.15	*0.17*	0.17	0.21	0.21
^{134}Cs	0.17	0.19	*0.25*	0.28	0.36	0.37
^{137}Cs	0.29	0.32	*0.46*	0.58	0.82	0.82
^{90}Sr	0.06	0.06	*0.16*	0.53	1.75	1.58
^{63}Ni	27	30	*60*	148	547	451

NS: Not Significant.

adjusted, the $DCGL_W$ of ^{14}C was derived to be 323,100 Bq/g, similar to Rancho Seco NPP with a difference of about 2%. This is due to a code mechanism that converts most types of soil carbon to carbon dioxide (CO_2) through inorganic and organic reactions. The concentration of ^{14}C in the atmosphere above the contaminated area depends on the evasion rate of carbon from the soil, the size and location of the source area, and meteorological dispersion conditions, thus affecting the dose [21]. In addition, after the release of RESRAD-ONSITE v7.0, recent dosimetric data from ICRP Publication 107 are included to use the "DCFPAK 3.02" which is internal

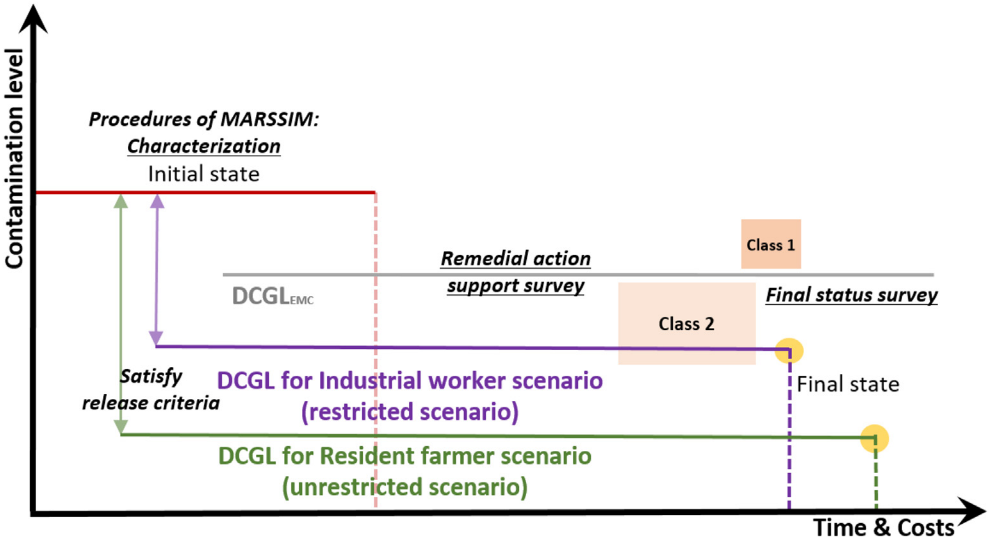

Fig. 3. Conceptual figure of decommissioning and decontamination phases based on DCGLs.

exposure dose conversion factor and the external exposure dose conversion factor based on the dosimeter described in ICRP 107 and FGR 12 (EPA 1993) library. Rancho Seco LTP is based on RESRAD-ONSITE v6.22 which uses ICRP 38 so for comparison, DCFPAK 3.02 library based on ICRP 107 was used to adjust results. It may be appropriate to use the $DCGL_W$ of ^{90}Sr value using the latest DCF library.

Rancho Seco LTP evaluated dose effects from varying contamination layer thicknesses and discrete pockets of contamination at depth using industrial worker scenario for surface soil exposure. As dose decreases with increasing depth, it is reasonable to apply conservative surface soil $DCGL_W$ values to subsurface soil contamination. Through a dose assessment using resident farmer scenario, it is estimated that within 30 years from the time when the final status survey is expected to be completed, the radiation standard of 10 CFR Part 20, Subpart E, 0.25 mSv/yr will be satisfied. However, in case of Kori Unit 1, as the characterization is undergoing, it is still in the stage to evaluate the dose effect of the radionuclide sample. Thus, $DCGL_W$ of the resident farmer scenario was derived like the other NPPs such as Connecticut Yankee, Yankee Rowe, and Zion NPP.

Same water transport model, non-dispersion model is used for comparison in Table 10. Unlike Rancho Seco NPP, which uses mass balance model with four unsaturated zones, Connecticut Yankee, Yankee Rowe, and Zion NPP use a single unsaturated zone. Thus, $DCGL_W$ for Kori Unit 1 under residential farmer scenario was derived by applying both single and 4 layers of unsaturated zones. One unsaturated zone is assumed to be 20 m in thickness based on Fig. 2. For Kori Unit 1, all values were derived to be higher than those of other NPPs with single unsaturated zone. The results from DCFPAK 3.02 and the latest RESRAD-ONSITE v7.2 (e.g. 4th column in Table 10) for Yankee Rowe NPP was also derived in conservative values compared to Kori Unit 1. The reason for this difference can be explained by soil type first, then the difference in thickness of contaminated zone. Kori Unit 1 assumes a 0.15 m thickness of contamination zone as in Zion and Rancho Seco NPP, instead, Connecticut Yankee and Yankee Rowe NPP were using a uniform distribution considering up to 3.8 m of contaminated zone thickness without any distinction between surface and subsurface soil [23]. On the other hand, Zion NPP assumes the same thickness assumption of contaminated zone, but there is a limit to direct comparisons due to differences in soil type and thickness of site-specific unsaturated zones, and use of different DCF library. However, $DCGL_W$ via probabilistic analysis used for all of the NPPs but only different version of code and DCF library. It would be desirable to use the most current version of RESRAD-ONSITE and DCF libraries for further updates on DCGLs for Kori Unit 1.

4. Conclusion

DCGL derivation is inevitable because decommissioning procedure of Kori Unit 1 is based on MARSSIM approach. DCGL provides goals for all phases of design, implementation and evaluation of FSS, and its development is an iterative process that can be continuously updated in subsequent surveys.

Time, expense, and release criterion satisfaction in the decommissioning and decontamination phases according to $DCGL_W$ for each scenario based on MARSSIM is summarized in Fig. 3. As can be seen in this study, in all NPPs, including Kori Unit 1, the $DCGL_W$ values by residential farmer scenarios are more conservative than those of the industrial worker scenario. In addition to $DCGL_W$, $DCGL_{EMC}$ can be considered, which is the concentration applied when there is elevated residual activity in a small area, that is, the concentration corresponding to Class 1 above $DCGL_W$ in MARSSIM. After the survey units are classified based on the DCGL values, the remedial action support survey will be able to determine the level of survey effort including radiological investigations through site soil scan and analysis. As the preliminary survey of Kori Unit 1 progresses, if $DCGL_W$ is derived by adding site-specific parameters that are not currently considered then, survey designs that provide more accurate scope of investigation can be developed by selecting the appropriate surveying equipments, techniques, and combinations of all. The site-specific suite of residual radionuclides and the methodology of $DCGL_W$ estimation obtained in this study can be used as basic guidelines to establish standards for the reuse plan and configuring of site evaluation scenarios according to the purpose of reuse and site characteristics.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.net.2018.07.018.

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