Nuclear Engineering and Technology 51 (2019) 1951–1956

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

A study on DCGL determination and the classification of contaminated areas for preliminary decommission planning of KEPCO-NF nuclear fuel fabrication facility

Seo-Yeon Cho [a], Yong-Soo Kim [a, *], Da-Won Park [b], Chan-Jun Park [b]

[a] Department of Nuclear Engineering, Hanyang University, 222, Wangsimni-ro, Seongdong-gu, Seoul, 04763, Republic of Korea
[b] KEPCO Nuclear Fuel, Daeduk-Daero 989-242, Yuseung-gu, Daejeon, 34057, Republic of Korea

ARTICLE INFO

Article history:
Received 27 February 2019
Received in revised form
20 May 2019
Accepted 8 June 2019
Available online 12 June 2019

Keywords:
DCGL
Decommissioning
Nuclear fuel fabrication facility
RESRAD-BUILD
MARSSIM

ABSTRACT

As a part of the preliminary decommissioning plan of KEPCO-NF fuel fabrication facility, DCGLs of three target radionuclides, ^{234}U, ^{235}U, and ^{238}U, were derived using RESRAD-BUILD code and contaminated areas of the facility were classified based on contamination levels from the derived DCGLs.

From code simulations, one-room modeling results showed that the grinding room in building #2 was the most restrictive ($DCGL_{gross}$ = 10493.01 Bq/m^2). The $DCGL_{gross}$ results in contaminated areas from one-room modeling were slightly more conservative than three-room modeling. Prior to the code simulation, field survey and measurements conducted by each survey unit. For a conservative approach, the most restrictive $DCGL_{gross}$ in each survey unit was taken as a reference to classify the contaminated areas of the facility. Accordingly, seven rooms and 37 rooms in the nuclear-fuel buildings were classified as Class 1 and Class 2, respectively. As expected, fuel material handling and processing rooms such as the grinding room, sintering room, compressing room, and powder collecting room were included in the Class 1 area.

1. Introduction

The first commercial nuclear power plant in South Korea, Kori unit #1, is in transition period to decommissioning after permanently shut down in June 2017 [1,2]. In addition, eleven nuclear power plants are expected to be shut down for decommissioning by the end of 2030. Considerable attention has thus been paid with regard to the preparation of nuclear facilities decommissioning by the Korean government and public. Recently, preliminary decommission plans for all operating nuclear facilities must be submitted to regulatory body according to nuclear safety law and enforcement ordinance.

Even for preliminary planning, radiological impact assessments are required to predict potential radiation exposure to workers, the public, and the environment during and after decommissioning [3]. For the assessment, contamination sources must be identified and contaminated areas must be classified as the first step. During this initial stage, the determination of the Derived Concentration Guideline Level (DCGL) is essential to set up target residual radioactivity levels of the decommissioned facility in compliance with site release criteria of 0.1 mSv per year [4].

In actuality, the DCGL is the maximum allowable limit of radionuclides resulting from radiation exposure pathway analysis in accordance with national regulation criteria for site release. For reference, Multi Agency Radiation Site Survey and Investigation Manual (MARSSIM) instructs users how to determine the average contamination level as $DCGL_w$ on the assumption that the residual radioactivity is evenly distributed throughout the survey unit [5]. When multiple radionuclides are present, individual DCGLs must be adjusted to $DCGL_{gross}$ for the gross activity evaluation [4].

Once DCGL is derived, contaminated areas can be classified into three categories by comparing their radioactivity with the $DCGL_w$. Class 1 areas are highly contaminated areas with an activity greater than $DCGL_w$, whereas Class 3 areas are not expected to contain any residual radioactivity or cover very small fractions of the $DCGL_w$, including buffer zones around Class 1 and Class 2 [5].

In this study, the $DCGL_{gross}$ of target radionuclides was derived for an operating Korea Electric Power Corporation Nuclear Fuel Company (KEPCO-NF) fuel fabrication facility using RESRAD-BUILD code (3.8 Beta version) and all contaminated areas in the facility were classified based on the derived DCGLs.

* Corresponding author.
E-mail address: yongskim@hanyang.ac.kr (Y.-S. Kim).

https://doi.org/10.1016/j.net.2019.06.012

2. Facility description and concepts of output in RESRAD-BUILD

2.1. Facility description

The main KEPCO-NF fabrication facility is composed of two buildings, building #1 and building #2. Slightly enriched UF_6 is converted to UO_2 powder and the fuel powder is compressed and sintered to fuel pellets in building #2. The sintered pellets are transported to building #1 for the fuel assembly manufacturing process: fuel pellets are loaded into cladding tubes, both end plugs are welded to the tubes, and the fuel rod assembly skeleton is assembled. In this facility, only low enriched ^{235}U between the range of 3–5% is processed without a fission reaction [6]. Therefore, only alpha emitting nuclides such as ^{234}U, ^{235}U and, ^{238}U along with their immediate progeny were considered as target radionuclides for the facility decommissioning in this study. A detailed description of the facility can be found elsewhere [7].

2.2. Concepts of output in RESRAD-BUILD code

The facility is currently operating and a detailed decommission plan has not yet been set up. In addition, considering that the facility is part of a national nuclear research complex, brown field site remediation was assumed without demolishing the decommissioned buildings. Hence, DCGLs were derived with RESRAD-BUILD developed by the Argonne National Laboratory and approved by the Nuclear Regulatory Commission, USA [8]. RESRAD-BUILD is a computer code designed for analyzing radiation exposure resulting from the occupation of a building contaminated with radioactive materials or housing contaminated equipment as well as remediating contamination.

Building-occupancy scenario was selected for assuming the receptor as an industrial worker who works 8 h per day for 260 days in a year. Source term was based upon surficial radioactive contamination by air exchange. Airborne particulates can be released into the indoor air or among compartments by diffusion and removal mechanisms. External exposure due to radioactive materials deposited on the floor, inhalation of airborne radioactive particulates and ingestion were the main pathways considered in the RESRAD-BUILD code. Contaminated portion of the room was set uniformly distributed at the entire floor and all four walls. After running simulations from input data applying surface activity, the code can yield Total Effective Dose Equivalent (TEDE) or Total Effective Dose (TED) as the output. The TEDE is the sum of the effective dose equivalent from external exposures and the committed effective dose equivalent from internal exposures [9]. In this study, TED was produced as the effective dose of a receptor resulting from a potential exposure followed the domestic recommendation of ICRP-60 [10].

3. Materials and methods

3.1. Field surveys

First, residual radioactivity surveys and measurements were performed on the surfaces of the two buildings following MARSSIM. All contaminated areas were divided into survey units of individual rooms. Field survey was performed in three phases: direct scanning measurement, smear testing, and sampling analysis. Scan surveys and smear tests were performed according to MARSSIM instructions to detect surface contamination on the floor and walls of each room.

A RadEye AB100 survey meter (Thermo Scientific, USA) was used for scanning; the maximum distance between the surface and detector probe was maintained to be less than 0.5 cm. Surficial radioactivity was calculated using the following equation [4]:

$$\text{surface activity}\left(Bq/m^2\right) = R_f(\text{cps}) \times \frac{1}{A_f(m^2)} \times \frac{100}{\varepsilon_f(\%)},$$

where R_f is the count rate after background elimination from the gross count rate, A_f is the probe area of the detector, and ε_f is the detector efficiency in counts per disintegration.

Hot spots were smeared over a 100 cm^2 area with circular smear paper for verification. The smeared papers were counted using a Ludlum model 3030 alpha-beta sample counter (Ludlum measurements, USA & CANADA) after 24 h. If the count rate exceeded the background, the surface activity was calculated using the following equation [11]:

$$\text{surface activity}\left(Bq/m^2\right) = R_S(\text{dps}) \times \frac{1}{A_S(m^2)} \times \frac{1}{\varepsilon_S(\%)},$$

where R_S is the count rate after background elimination from the gross count rate, A_S is the smear area, and ε_S is the smear efficiency (set to 50% according to regulations).

Measurement samples were collected from hot spots and high surface activity areas in the fuel powder processing rooms in which uranium contamination may have accumulated. The samples were analyzed using alpha spectrometry to identify the isotopic uranium fractions of the target radionuclides, ^{234}U, ^{235}U, and ^{238}U. ^{232}Th was also analyzed as an additional radionuclide to consider additional radioactivity.

3.2. Dose modeling

Based on the field survey data, dose modeling was performed using RESRAD-BUILD code to evaluate potential exposure doses of a receptor in each survey unit. As can be seen in Fig. 1 [8], the location of the receptor and sources were defined in the x, y, and z coordinate system. Up to 10 distinct sources and receptors were specified in this code. During one-room modeling, radiation-controlled areas were confined to each room as a survey unit. Six sources were specified as the floor, ceiling, and four walls of each room in accordance with the geometric size. Scanning data of field survey were used for surficial activity concentrations of the target radionuclides with their fraction.

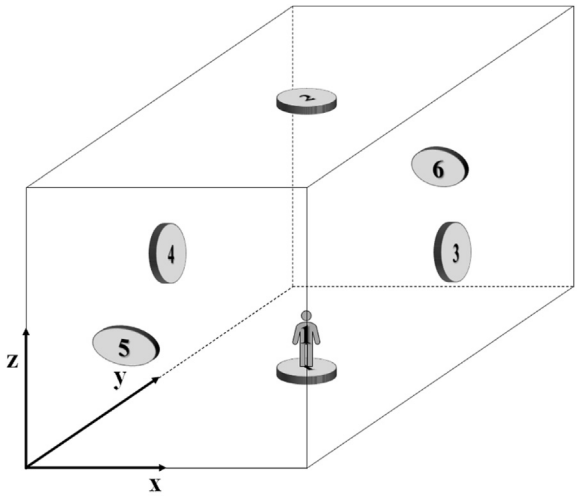

Fig. 1. Coordinate system of the receptor and sources in the RESRAD-BUILD code simulation.

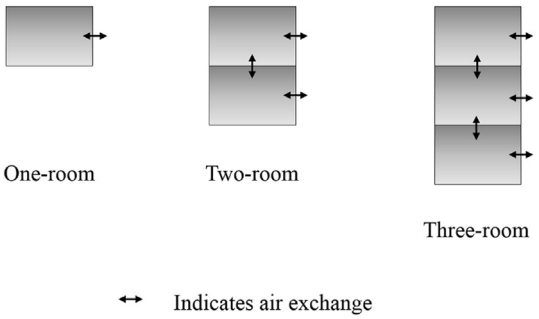

Fig. 2. Geometric room-modeling diagrams in the RESRAD-BUILD code simulation.

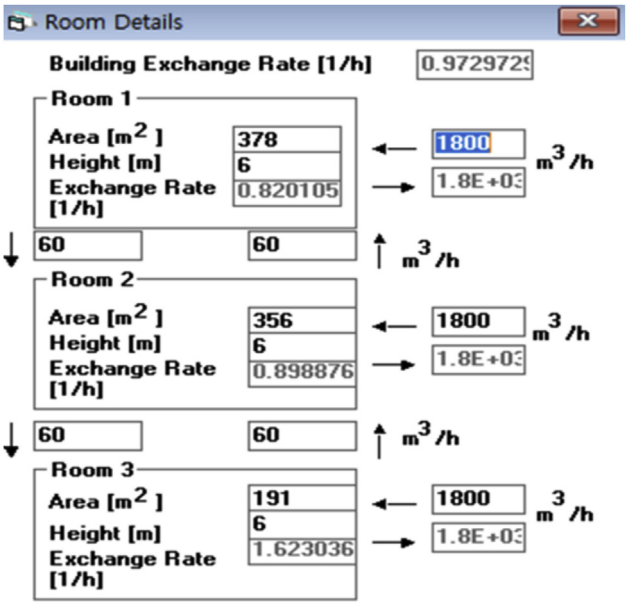

Fig. 3. Room details for three-room modeling in RESRAD-BUILD code.

Table 1
Alpha spectrometry and uranium isotopic fraction results.

Radionuclide	Sample result (Bq)	Fraction of radioactivity
^{238}U	114±11.6	0.214
^{235}U	17.4±1.8	0.033
^{234}U	401±40.9	0.753

Room-differentiated analysis up to three-room modeling was possible with the RESRAD-BUILD code, as seen in Fig. 2 [8]. In the multi-room modeling, the contamination of structural materials by air transport and inflow systems must be considered in detail for the preparation of input parameters. In this study, one-room modeling was initially performed; three-room modeling of the three most contaminated adjacent rooms connected side by side were simulated for comparison as can be seen in Fig. 3.

3.3. Key input parameters for simulating RESRAD-BUILD code

Dose coefficients were selected from ICRP-72 (Adult), which was suggested in ICRP-60 to follow domestic adoption. For a conservative approach, floor source activity data from the scanning survey, which was the highest surface activity among the six sources, was used for input data in the one-room modeling, instead of all the other five sources. The uranium isotopes considered for the simulation of this code were selected based on the fact that the facility used uranium compounds for uranium oxide fuel fabrication. The uranium isotopic fraction of radioactivity among three target radionuclides using alpha spectrometry confirmed by laboratory analysis are listed in Table 1. Isotopic fraction of radioactivity was applied to the floor source activity obtained from scanning as initial concentration of each radionuclide.

Shielding parameters were set to zero because decontamination has not yet begun in this area. The evaluation time was set to a year from the initial time *(t = 0)*, which was expected to result in a high exposure. With regard to three-room modeling, the building air exchange rate was 0.973 [1/h] for outdoor inflow consistency among the three rooms. Other major input parameters were the same as those used in one-room modeling, as presented in Table 2.

4. Results and discussion

4.1. Determination of DCGL

In the RESRAD-BUILD code simulation, surficial contamination DCGL of each radionuclide was calculated based on TED and the following equation [4]:

$$\mathrm{DCGL}\left(\mathrm{Bq}/\mathrm{m}^2\right) = \frac{\text{Dose limit}\left(mSv/y\right)}{\text{TED per unit area}\left(\mathrm{mSv}\times \mathrm{y}^{-1}/\mathrm{Bq}\times \mathrm{m}^{-2}\right)}$$

TED results can be obtained by the code simulation results upon each radionuclide. However, DCGL is not directly derived from the

Table 2
Major input parameters used in RESRAD-BUILD code simulation.

Parameters	Value	Note	
Time	Exposure duration [days]	365	
Building	Indoor fraction	0.237	8 h/day; 260 day/year
	Height [m]/Floor area [m^2]	Differ from each room; In accordance with each room model for one-room modeling	
	Building air exchange rate [1/h]	0.8	Deterministic Analysis Default Value, building air exchange rate for one-room model
	Resuspension rate [1/s]	5.0×10^{-7}	RESRAD dynamic resuspension model of uranium storage at uranium fuel fabrication plant
	Deposition velocity [m/s]	0.01	Deterministic Analysis Default Value, NUREG/CR-5512
	Air release fraction	0.357	RESRAD-BUILD Ver. 3.0 manual, Appendix J table 3.1, NUREG/CR-5512
Source	Source area [m^2]	Differ from each room; In accordance with each room model for one-room modeling	
	Type/Direction	Area/Floor and ceiling (Z), Four walls (X, Y)	
	Source location [m,m,m]	Center of each source	
	Types of Radionuclides	^{234}U,^{235}U,^{238}U	Unit concentration was applied with isotopic fractions.
	Air release fraction	0.357	Appendix J table 3.1(NUREG/CR-5512)
	Direct ingestion rate [g/h]	3.06×10^{-6}	Default value of building occupancy scenario
	Source removable fraction	0.1	Default value of building occupancy scenario
Receptor	Receptor location [m,m,m]	Assume the receptor standing on the center of each room with 1 m height from floor.	
	Breathing rate [m^3/day]	29.04	ICRP-66 Adult man breathing rate
	Ingestion rate [m^2/h]	0.0001	Deterministic analysis default value
	Time fraction	0.237	Same value as indoor fraction

RESRAD-BUILD code results so unit concentration should be considered for calculating DCGL values.

Based on the lab analysis in alpha spectrometry, only three alpha emitting uranium isotopes were chosen as target nuclides in this study: ^{234}U, ^{235}U, and ^{238}U. As expected, ^{235}U enrichment was in the range of 3–5% [12]. Additional analysis of the ^{232}Th radionuclide was performed; however, ^{232}Th represented only a very small fraction of the total inventory of present radionuclides thus it was considered as background radiation from the air inflow carried by workers [4]. Scanning data had less derivation and fluctuation compared to the smear test data to determine the level or quantity of radioactivity on a surface. Therefore, scanning results were substituted in the coded factor instead of smear results that can encounter less accuracy due to carryover contamination.

Since target radionuclides were composed of multiple radionuclides, surface DCGLs of the three radionuclides were integrated to $DCGL_{gross}$ such that the total surface activity due to residual contamination should not exceed the gross activity of DCGL. The gross DCGL for surfaces was calculated using the following equation [5]:

$$DCGL_{gross} = \frac{1}{\left(\frac{f_1}{DCGL_1} + \frac{f_2}{DCGL_2} + \cdots \frac{f_n}{DCGL_n}\right)},$$

where f_i is the fraction of activity contributed by each radionuclide.

Consequentially, $DCGL_{gross}$ became smaller while the areas of sources increased. This could be inferred from the following equation [6]:

$$\text{DSR (Dose to Source Ratio)} = \frac{\text{Dose limit}\left(mSv/y\right)}{\text{Radioactivity concentration}\ (Bq/m^2)}.$$

In fact, DSR is the dose to source ratio for the unit concentration of radioactivity in the media.

Hence, one-room modeling was respectively performed to determine the $DCGL_{gross}$ for each of the five most contaminated rooms according to the scanning survey data. Results for the five $DCGL_{gross}$ are listed for comparison in Table 3. As seen in the table, the grinding room, sintering room, and powder collecting room in building #2 were the most restrictive and their $DCGL_{gross}$ was around 1.05E+4 Bq/m^2. Isotopic surface DCGL results of the grinding room were ^{238}U (10543.85 Bq/m^2), ^{235}U (10680.62 Bq/m^2), and ^{234}U (10470.60 Bq/m^2). All the rooms were used for the handling or processing of fuel material powder, which could be spread and accumulated easily on the floor or in corners. The magnitude of $DCGL_{gross}$ appeared to be quite large but it was reminded that the major contaminants in the uranium fuel fabrication facility are only three alpha emitting uranium isotopes, ^{238}U, ^{235}U, and ^{234}U.

The determination of $DCGL_{gross}$ may depend on the geometric factors of sources and their distribution through air exchange within the facility. In addition, three-room modeling was performed to determine the $DCGL_{gross}$ for comparison with the one-room modeling results. For this model, the following three adjacent rooms connected side by side: the compressing, sintering, and grinding rooms in building #2 were chosen (Fig. 4). The results listed in Table 4 demonstrated that the three-room model yielded slightly higher DCGL results compared to the one-room model (Fig. 5), implying that the one-room model was more conservative than multi-room models. This difference may be due to variables of internal air flow between rooms in the three-room model, which were not considered in the enclosed one-room model. It needs to remarked that the one-room model results between Tables 3 and 4 were different because different input data were used due to the number limitation of contamination sources in the RESRAD-BUILD code. In actuality, maximum allowable number is ten, which limited the degrees of freedom to depict sources in conservative ways in the three-room model. Therefore, $DCGL_{gross}$ listed in Table 3 was a real conservative result; those in Table 4 were only for comparing the one-room and three-room modeling.

In the field measurements, it was found that alpha surface contamination may not be evenly distributed because of rough surfaces [13]. In addition, since alpha-radionuclides mainly caused internal exposure via ingestion and breathing, the results showed certain sensitivity to internal dose conversion factors. Previous works with regard to sensitivity analyses of the RESRAD-BUILD simulation also showed that the size of the contamination source may have an inverse relationship with DCGL due to incremental exposure doses [1,2,4,13].

4.2. Classification of contaminated areas

As mentioned in the previous section, contaminated areas of the nuclear facility could be classified into three categories: Class 1, 2, and 3, by comparing $DCGL_{gross}$ derived from dose modeling with the surface activity measured during field surveys. Following the MARSSIM instructions, contaminated areas in excess of the $DCGL_{gross}$ were classified as Class 1. Class 2 was assigned to the area where the areal contamination was higher than 25% of $DCGL_{gross}$, while Class 3 was defined as an area whose activity was lower than 25% of $DCGL_{gross}$ [5].

The simulation results in Table 3 showed that the grinding room in building #2 was the most restrictive ($DCGL_{gross}$ = 10493.01 Bq/m^2), which seemed to be due to the fact that grinding typically generates finely powdered fuel materials. For a conservative approach, the lowest DCGL was taken as a reference to classify the contaminated areas of the KEPCO-NF facility. Accordingly, 7 rooms and 37 rooms were classified as Class 1 and as Class 2, respectively, in both nuclear-fuel buildings. As expected, fuel powder handling or processing rooms such as the grinding room, sintering room, compressing room, and powder collecting room were included in the Class 1 area.

Table 3
DCGL results for five rooms in a Class 1 area.

Information		Survey area				
		Grinding room	Sintering room	Powder collecting room	Compressing room	Decontamination room
Floor area [m^2]		378	356	240	191	87
Surface activity [Bq/m^2]		3.75E+04	2.48E+04	3.76E+04	3.58E+04	3.59E+04
TED [mSv/y]		3.58E-01	2.28E-01	3.43E-01	2.28E-01	1.33E-01
Surface DCGL [Bq/m^2]	^{238}U	1.05E+04	1.09E+04	1.10E+04	1.58E+04	2.72E+04
	^{235}U	1.07E+04	1.11E+04	1.11E+04	1.59E+04	2.71E+04
	^{234}U	1.05E+04	1.09E+04	1.09E+04	1.57E+04	2.70E+04
$DCGL_{gross}$ [Bq/m^2]	Total U	1.05E+04	1.09E+04	1.10E+04	1.57E+04	2.71E+04

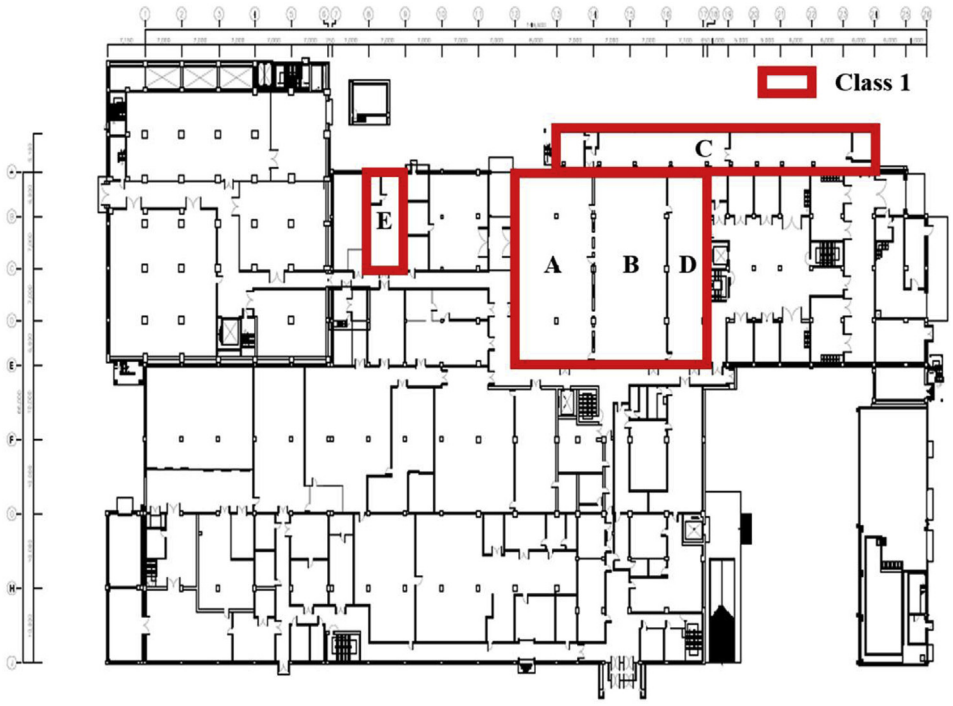

Fig. 4. Floor layout of rooms on the first floor in nuclear-fuel building #2. (A: grinding room, B: sintering room, C: powder collecting room, D: compressing room, and E: Decontamination room).

Table 4
$DCGL_{gross}$ comparison for three rooms in a Class 1 area: one-room *vs.* three-room modeling.

Survey area	DCGLgross [Bq/m^2]	
	One-room modeling	Three-room modeling
Grinding room	34221.13	34255.47
Sintering room	36266.81	36755.67
Compressing room	67419.51	67712.75

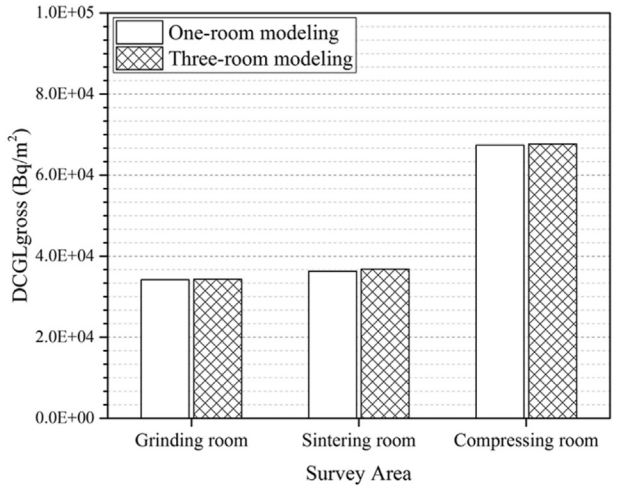

Fig. 5. $DCGL_{gross}$ comparison of three rooms in the Class 1 area: one-room *vs.* three-room modeling.

The layout of the rooms where fuel powder materials are processed in nuclear-fuel building #2 is seen in Fig. 4. As highlighted in the figure, three Class 1 rooms are connected side by side thus influenced between the rooms through the air transport and air inflow during fuel powder handling and processing, leading to continuous accumulation on the floor since the initial operation of the facility.

5. Conclusions

According to nuclear safety law and its enforcement ordinance, a preliminary decommission planning report of KEPCO-NF fuel fabrication facility was submitted to Korean regulation body on the basis of the brown field assumption of site end-state. As part of a preliminary environmental impact analysis, DCGLs of the facility were derived using RESRAD-BUILD code and contaminated areas were classified from the derived DCGLs.

In this study, prior to the code simulation, field surveys and measurements were performed and the data were used to simulate the code and categorize contaminated areas. From the characteristics of the facility without fission reactions, three uranium isotopes were regarded as target nuclides of surficial contamination sources: ^{234}U, ^{235}U, and ^{238}U.

One-room modeling results showed that the grinding room in building #2 was the most restrictive ($DCGL_{gross}$ = 10493.01 Bq/m^2) and the isotopic surface DCGL results in the room were ^{238}U (10543.85 Bq/m^2), ^{235}U (10680.62 Bq/m^2), and ^{234}U (10470.60 Bq/m^2).

For a conservative approach, the $DCGL_{gross}$ of the room was used as a reference to classify the contaminated areas of the facility. Accordingly, 7 rooms and 37 rooms were classified as Class 1 and as Class 2, respectively, in nuclear-fuel buildings #1 and #2. As expected, fuel material handling or processing rooms such as the grinding room, sintering room, compressing room, and powder collecting room were included in the Class 1 area.

Furthermore, the $DCGL_{gross}$ results from the one-room model were compared with that from the three-room model, which showed that the three-room model yielded slightly higher DCGLs

than the one-room model. This confirmed that one-room modeling is generally more conservative than three-room modeling.

Acknowledgements

This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP: Ministry of Science, ICT, and Future Planning) (No. NRF-2017M2B2B1072888) and by the Human Resources Program in Energy Technology of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resources from the Ministry of Trade, Industry, & Energy, Republic of Korea (No. 20184030201970).

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.net.2019.06.012.

References

[1] S. Hong, B. Brook, A nuclear- to-gas transition in South Korea: is it environmentally friendly or economically viable? Energy Policy 112 (2018) 67–73.
[2] J.S. Min, K.W. Lee, H.R. Kim, C.W. Lee, Radiological assessment of the decontaminated and decommissioned Korea Research Reactor-1 building, Nucl. Eng. Des. 322 (2017) 492–496.
[3] M. Laraia, Nuclear Decommissioning: Planning, Execution and International Experience, Elsevier Science, 2012.
[4] E.W. Abelquist, Decommissioning Health Physics: A Handbook for MARSSIM Users, second ed., CRC Press, 2013.
[5] U.S.NRC, Multi-Agency Radiation Survey and Site Investigation Manual (MARSSIM), 2000.
[6] J.M. Peterson, J.P. Englert, Estimation of residual radioactivity within a shutdown fuel reprocessing plant, in: Proceedings of the American Nuclear Society International Topical Meeting, Niagara Falls, NY, USA, 1986.
[7] KEPCO-NF. https://www.knfc.co.kr/eps, 2018.
[8] C. Yu, D. Lepoire, J.-J. Cheng, E. Gnanapragasam, J. Arnish, B.M. Biwer, A.J. Zielen, W.A. Williams, A. Wallo, P.H.T. Jr, User's Manual for RESRAD-BUILD Version 3, Argonne National Laboratory, 2019.
[9] W.E. Kennedy Jr., R.A. Peloquin, Residual Radioactive Contamination from Decommissioning: Technical Basis for Translating Contamination Levels to Annual Dose, 1990, p. 313. United States.
[10] 1990 recommendations of the international commission on radiological protection, Ann. ICRP 21 (1–3) (1991) 1–201.
[11] P.W. Frame, E.W. Abelquist, Use of smears for assessing removable contamination, Health Phys. 76 (1999) S57–S66.
[12] Westinghouse, Hematite Decommissioning Plan, License SNM-33, Docket No. 70-36, DO-04-004, 2005.
[13] N. Nassar, M.H.E. Monged, Evaluation of doses to an individual from a contaminated area with radioactive material, Arab J. Nucl. Sci. Appl. 50 (2) (2017) 250–257.