Nuclear Engineering and Technology 54 (2022) 1136–1144

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

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

Technical Note

Preliminary ALARA residual radioactivity levels for Kori-1 decommissioning and analysis of results and effects of remediation area

Hyung-Woo Seo*, Ji-Hwan Yu, Gi-Lim Kim, Jin-Won Son

Korea Hydro & Nuclear Power (KHNP) Central Research Institute, 70, 1312-gil, Yuseong-daero, Yuseong-gu, Daejeon, 34101, South Korea

A R T I C L E I N F O

Article history:
Received 27 July 2021
Received in revised form
16 September 2021
Accepted 22 September 2021
Available online 30 September 2021

Keywords:
Decommissioning
ALARA evaluation
DCGL
Cost-benefit analysis

A B S T R A C T

The effects of nearby residents and the public by the residual contamination from the decommissioning of nuclear facilities should comply with the dose criteria, and whether additional remediation action is necessary from the ALARA perspective must be determined. Therefore, we analyzed the requirements of ALARA action levels and performed preliminary ALARA evaluation. The ratio of residual contamination concentration to DCGL was calculated for the basement fill and the building occupancy mode. The results showed that the additional remediation actions below DCGL are not justified. In addition, we analyzed the effect of remediation area. It was noted that the increase of the remediation area showed a positive correlation with the Conc/DCGL value in the basement fill mode. On the other hand, in the building occupancy mode, since the floor area of the building is the target of remediation and has the effect of increasing the same as the evaluation area of the building occupants, but due to the difference in the amount of increase, the Conc/DCGL showed a negative correlation. We expect the approach and method of ALARA evaluation can be utilized for concrete cost-benefit calculation during the decommissioning or at the time of remediation.

1. Introduction

During the decommissioning process, the Systems, Structures and Components (SSCs) that are subjected to the decommissioning will be removed from each building area and/or on the site through various activities (i.e. cutting, decontamination and dismantlement). For subsequent termination of the license, a licensee should demonstrate that the residual radioactivity levels of the media (i.e. soil and structures) expected to remain that could affect the receptors have met the dose criteria. In general, the regulatory agencies present the criteria as a dose (Korea's dose criterion included in Nuclear Safety and Security Commission (NSSC) Notice No. 2021-21, "Criteria for reuse of site and remaining buildings after completion of decommissioning of nuclear power facilities") [1], and in practical terms, the licensees will utilize the Derived Concentration Guideline Levels (DCGLs) calculated from the dose criterion for each media.

By the time decontamination and dismantlement activities are completed, it should be ensured that the level of radioactivity concentration in the soil or structures that are expected to remain on the site or be reused is below the DCGL. In accordance with DCGLs, remediation activities to lower the level of contaminated media will be necessarily accompanied: if the level of contamination is higher than the DCGL, remediation should be carried out to meet the dose criteria. Here, it can be noted that the main exposed people affected by residual radioactivity after the completion of decommissioning of nuclear facilities are the general public. In this regard, DCGL derived from legal standards must be met, as well as the As Low As Reasonably Achievable (ALARA) requirement that was applied during operational phase, which can be seen in the experience of the U.S. decommissioning experiences. Because ALARA is represented as an optimization technique below the dose criteria [2], to justify this, an analysis of benefits (desired beneficial effects) and costs (undesired effects) for activities (i.e. actions) should be performed.

Therefore, the purpose of this study is to investigate the ALARA evaluation of remediation activities under consideration after the completion of decommissioning from the preceding

* Corresponding author.
E-mail address: sehywo1727@khnp.co.kr (H.-W. Seo).

https://doi.org/10.1016/j.net.2021.09.022

decommissioned nuclear power plants, and to present the methodology and results for the evaluation of the ALARA action level of Kori-1 decommissioning. By analyzing the data used for costs and benefits analysis presented in licensing documents for decommissioning cases of U.S., remediation actions, rates and basis for the costs and the benefits applicable to Kori-1 were identified. Based on this, an initial ALARA evaluation of Kori-1, which is currently in transition, was performed to evaluate whether additional clean-up below DCGL would be required for each remediation action. In addition, the results of each remediation action were compared with overseas cases, and sensitivity analysis was performed on parameters that had a large influence on costs and benefits to analyze the difference in results according to their changes. Although it is an early result, this study, which established the methodology of ALARA evaluation to be prepared for the first decommissioning project in Korea and presented the evaluation results, will be useful as a work performed in the stage of decommissioning preparation in the sense that it should be prepared as early as possible. The results of this study are expected to serve as a basis for continuous revision and supplementation during Kori-1 decommissioning process or the Final Status Survey (FSS) for future studies.

2. Methodology

In order to perform ALARA evaluation for the activities that may require remediation in the whole process of decommissioning, as an explicit method, quantitative results through cost-benefit analyses should be accompanied. To do this, a requirement analysis of what is necessary to calculate costs and benefits should be identified, and the subsequent determination of parameter values is required. The requirements include remediation actions, dose model (scenario), remediation cost basis, radionuclide fractions and source terms, and a methodology for quantitatively presenting them should be prepared. In this study, some set of data that need to be reflected site-specifically in domestic ALARA evaluation were recognized, and these were defined by referring to analyzes of overseas experiences.

2.1. Overseas experiences of ALARA evaluation

When decontamination and dismantlement activities are completed, a licensee will usually need to determine at what level of residual radioactivity concentration would require to meet ALARA requirement. In the U.S. experience, cost-benefit analyses were performed to meet the ALARA requirement, and this method has been utilized as a planning tool for remediation [2]. Costs and benefits analyzes are described in NUREG-1757 appendix N (ALARA Analyses), using dollars for comparable unit of measure. If the desired beneficial effects from the remediation action outweigh the costs, the remediation is cost-effective and should be performed. Conversely, if the undesirable costs outweigh the benefits, this indicate that, from ALARA's point of view, no further remediation actions would not require. As items that can be estimated as benefits form the remediation action, the collective averted dose of future site occupants, regulatory costs avoided, changes in land values, and esthetics/reduction in public oppositions can be considered, among which the collective averted dose is relatively easy to quantify and can be primarily considered. The total costs that can be balanced against the benefits are made up of several components: remedial action cost, transport and disposal of the waste, non-radiological risks, transportation risks, worker dose estimates, loss of economic use of property, environmental impacts, and others. When the costs accompanying the remediation action and the present worth of the collective dose averted from future occupants are set to equal, the residual radioactivity level that is ALARA is expressed as a concentration, Conc, and the ratio of the concentration to the DCGL can be determined in the following equation.

$$\frac{Conc}{DCGL} = \frac{Cost_T}{\$2000 \times P_D \times 0.025 \times F \times A} \times \frac{r+\lambda}{1-e^{-(r+\lambda)N}} \tag{1}$$

Where:

$\frac{Conc}{DCGL}$ = fraction of DCGL that is ALARA;
$Cost_T$ = total monetary cost of remediation action in dollars;
\$2000 = the dollar value of a person-rem averted (\$/p-rem);
P_D = population density for the critical group scenario (p/m^2);
0.025 = annual dose to an average member of the critical group from residual radioactivity at the DCGL concentration (rem/yr);
F = fraction of the residual radioactivity removed by remediation action;
A = area used to calculate the population density (m^2);
r = monetary discount rate (yr^{-1});
λ = radiological decay constant for the radionuclide (yr^{-1}); and
N = number of years over which collective averted dose is calculated (yr).

If multiple radionuclides exist, to address them, eq. (1) needs to be transformed: the present worth term on the right of eq. (1) is shown below.

$$\frac{Conc}{DCGL} = \frac{Cost_T}{\$2000 \times P_D \times 0.025 \times F \times A \times \frac{1-e^{-(r+\lambda)N}}{r+\lambda}} \tag{2}$$

For multiple radionuclides, the dose fractions in the denominator should be summed over all radionuclides as shown below [3].

$$\frac{Conc}{DCGL} = \frac{Cost_T}{\sum_i^n \$2000 \times P_D \times 0.025 \times Df_i \times F \times A \times \frac{1-e^{-(r+\lambda)N}}{r+\lambda}} \tag{3}$$

Where for the unitized dose factor:

$$\mathrm{Df_i} = Dose\ Fraction_{basement\ fil} = \frac{(nf_i)(United\ Dose\ Factor_i)}{\sum_i^n (nf_i)(United\ Dose\ Factor_i)} \tag{4}$$

Where for the screening value:

$$\mathrm{Df_i} = Dose\ Fraction_{building\ occupancy} = \frac{\frac{nf_i}{Screening\ Value_i}}{\sum_i^n \frac{nf_i}{Screening\ Value_i}} \tag{5}$$

And, nf_i = Nuclide fraction of the mixture radionuclides;
Unitized Dose Factor$_{i\ (basement\ fill)}$ = nuclide specific mrem/yr per dpm/100 cm^2; and
Screening Value$_{i\ (building\ occupancy)}$ = nuclide specific from NUREG-1727 Table C2.2.

The residual radioactivity concentration over DCGL that is ALARA can be calculated using eqs. (3)–(5). Therefore, if the Conc/DCGL value is calculated as greater than 1, the required residual radioactivity concentration, Conc, for the corresponding remediation action is the same as DCGL, indicating that additional clean-up below DCGL would not necessary. Conversely, if the Conc/DCGL result is less than 1, which means that the benefit calculated from the ALARA evaluation is greater than the costs, and the additional remediation action below the DCGL is justified. For literature review, in this study, we investigated the License Termination Plan

(LTP) of five decommissioned nuclear facilities in the U.S. to analyze how the cost-benefit evaluation was performed. The ALARA residual radioactivity level evaluation requires the determination of several types of remediation actions at the site, the applicable foreseeable scenarios, and the unit values taken into account to calculate costs and benefits. A summary of the cases evaluated for these can be shown in Table 1.

As seen in overseas cases, remediation actions for contaminated media differ from site to site. As a scenario for evaluating the dose to be received by the critical group due to the removal of the contaminated media, it is usually the basement fill scenario and a reuse scenario for a building. This is because the source of impacts critical group will receive from contamination remaining on the site according to each NPP's licensing termination plan can be soil, underground structures or components, and standing buildings. Therefore, scenarios that may be considered with respect to target media where radiation exposure to the critical group can be reduced by applying the ALARA concept in the decommissioning of nuclear facilities will largely be the basement fill and building occupancy. For remediation actions, MY and RSNGS were evaluated similarly with pressure washing, washing/wiping, scabbling, grit blasting, and soil excavation. As a difference, MY evaluated both the basement fill and building occupancy scenarios, whereas RSNGS evaluated the single building occupancy scenario. Materials that may be subjected to remediation include basement surfaces 3-feet below grade and soil. Therefore, basement fill mode assumes the cost-benefit from remediation of basement surfaces 3-feet below and soil considering the resident farmer scenario, whereas building occupancy mode assumes the event plans that standing building will remain and ALARA cost analyses are based on assumption that only the 100 m^2 floor area requires remediation. In case of Zion plant, ALARA evaluation was performed on two representative remediation actions: soil excavation and scabbling/washing for concrete structures. On the other hand, no specific remediation actions could be found in the LTP of CY and YR plants. As shown in Table 1, it can be seen that the results of Conc/DCGL were all calculated to be greater than 1 for all remediation methods, which indicates that addition remediation below the NRC 0.25 mSv/yr dose limit (i.e. DCGL) is not justified.

2.2. Remediation actions

The final goal of decommissioning nuclear facilities is to remove SSCs contaminated with radioactive materials and release reusable sites and remaining buildings to meet regulatory criteria. The remediation actions that are performed throughout the decommissioning process will have the purpose of minimizing the generation of radioactive waste, increasing the ease of activities in terms of reducing worker exposure doses, and reflecting lessons learned from each nuclear plant. For the ALARA action levels, from a view of the final decommissioning goal, the remediation actions considered will determine whether additional clean-up would be required in relation to the DCGL that meets the NRC dose criteria of 0.25 mSv/yr (for the U.S.). The activities to determine whether additional clean-up is justified under the regulatory criteria can be considered as remediation actions which is dependent on the material contaminated. Therefore, in case of overseas cases, the typical adopted materials that can be subjected to remediation are soils and structure basements 3-feet below grade.

Among the principle materials divided into two main categories (i.e. soils and structure surfaces), the contaminated soil of the site should be considered inevitably as a remediation action. This is because soil is an essential material that should be returned to the environment after the decommissioning and is a subject to prove contamination levels that comply with the annual dose criteria. Some actions involved in the decommissioning process on the structure surfaces can be typically listed as scabbling and shaving, needle guns, chipping, sponge and abrasive blasting, pressure washing, washing and wiping, grit blasting, and removal of activated/contaminated concrete [3,4]. The technology that may be taken for decontamination of the structure surfaces will depend on the development of decontamination technology and its adoption in the decommissioning/decontamination planning, but the remediation actions that may be considered in general for the transition phase of the decommissioning can be described as below. In addition, these activities have already been used in the general

Table 1
ALARA evaluation Conc/DCGL results.

Nuclear Facility	Remediation Action	Scenario	
		Basement Fill	Building Occupancy
Maine Yankee (MY) [3]	Pressure Washing	99.40	1.90
	Washing/Wiping	312.60	6.00
	Scabbling (Upper Bound)[a]	143.90	2.76
	Scabbling (Lower Bound)[b]	123.90	2.38
	Grit Blasting (Upper Bound)[c]	153.30	2.94
	Grit Blasting (Lower Bound)[d]	118.90	2.28
	Grit Blasting (Embedded Piping)	91.60	–
	Soil Excavation	733.90	–
Rancho Seco (RSNGS) [4]	Pressure Washing	–	1.31
	Washing/Wiping	–	6.31
	Scabbling (Upper Bound)[a]	–	5.75
	Scabbling (Lower Bound)[b]	–	5.72
	Grit Blasting (Upper Bound)[c]	–	2.19
	Grit Blasting (Lower Bound)[d]	–	1.82
	Grit Blasting (Embedded Piping)	42.77	–
	Soil Excavation	1142.00	–
Zion [5]	Soil Excavation	1001.03	–
	Scabbling and Washing	97.21	–
Connecticut Yankee (CY) [6]	ALARA evaluation results are not presented	–	–
Yankee Rowe (YR) [7]	ALARA evaluation results are not presented	–	–

[a] Upper Bound: bounding condition 0.635 cm surfaces.
[b] Lower Bound: bounding condition 0.32 cm surfaces.
[c] Upper Bound: bounding condition 1.25 contingency.
[d] Lower Bound: bounding condition no contingency.

industry and are expected to be useable in Kori-1 decommissioning. Therefore, in this study, the following actions were selected and used to evaluate ALARA action levels.

- Pressure water washing and vacuuming
- Washing and wiping remediation action
- Scabbling remediation action (bounding condition 0.635 cm concrete)
- Scabbling remediation action (bounding condition 0.32 cm concrete)
- Grit blasting (surfaces) remediation action (bounding condition 1.25 contingency)
- Grit blasting (surfaces) remediation action (bounding condition no contingency)
- Grit blasting (embedded/buried piping) remediation action
- Soil excavation remediation action

2.3. Methods for ALARA evaluation and dose models (scenarios)

In relation to decommissioning, the input factors for the possible costs and benefits should be distinguished and identified so that they can be calculated as quantitative values. Possible benefits from remediation actions can be composed of (1) collective dose averted, (2) regulatory costs avoided, (3) changes in land values, (4) esthetics, and (5) reduction in public opposition [2]. Among these factors, other than the collective dose averted, the qualitatively evaluated aspect may be preferred and it may be difficult to quantify. The collective dose averted benefit can be considered in terms of quantitative calculation, and it can be estimated from a reduction in the level of residual radioactivity as a monetary value to the future occupants of the site. The present worth of the collective dose averted in the future can be quantitatively calculated from the following equation (NUREG-1757, N-1 & N-2).

$$B_{AD} = \$2000 \times P_D \times 0.025 \times F \times A \times \frac{Conc}{DCGL} \times \frac{1 - e^{-(r+\lambda)N}}{r+\lambda} \tag{6}$$

Where:

B_{AD} = benefit from an averted dose for a remediation action, in the U.S. dollars; and

Other parameters are same as eq. (1).

In order to evaluate the possible costs for the selected remediation actions, as a fairly simple calculation, the costs generally can include (1) monetary cost of remediation action, (2) monetary cost for transport and disposal of waste, (3) monetary cost of worker accidents, (4) monetary cost of traffic fatalities, (5) monetary cost of dose received by workers, (6) monetary cost of the dose to the public, and (7) other costs as appropriate for the particular situation [2]. Therefore, the total costs for the remediation actions can be expressed as the sum of several components (NUREG-1757, N-3).

$$Cost_T = Cost_R + Cost_{WD} + Cost_{ACC} + Cost_{TF} + Cost_{WDose} + Cost_{PDose} + Cost_{Other} \tag{7}$$

Where

$Cost_R$ = cost of the remediation action (can include mobilization cost);
$Cost_{WD}$ = cost for transport and disposal of the waste generated;
$Cost_{ACC}$ = cost of worker accidents;
$Cost_{TF}$ = cost of traffic fatalities during transporting of the waste;
$Cost_{WDose}$ = cost of dose received by workers during remediation and transportation of waste;
$Cost_{PDose}$ = cost of the dose to the public during excavation, transport, and disposal of waste; and
$Cost_{Other}$ = other costs as possible situation.

When the costs and benefit equations presented in eqs. (6) and (7) are set to equal, the ratio of concentration, Conc, to DCGL is shifted to the left side of the equation and expressed again as in eq. (2). In this study, we used the U.S. dollar as a measurable unit, and one quantifiable collective dose averted was taken for the benefits (see eq. (6)), and five components were mainly evaluated such as $Cost_R$, $Cost_{WD}$, $Cost_{ACC}$, $Cost_{TF}$, and $Cost_{WDose}$ for the total costs. The remediation cost is an item that may increases according to the remediation size (i.e. area or volume) and consists of laborer cost, mobilization cost, and equipment cost. Regarding the cost of transporting and disposing of waste, it can be calculated as the amount of waste generated from remediation action and the unit cost of disposal using below equation.

$$Cost_{WD} = V_A \times Cost_V \tag{8}$$

Where

V_A = volume of waste in units of m^3; and
$Cost_V$ = cost of waste disposal and transport per unit volume, in units of $\$/m^3$.

The cost of non-radiological accidents is calculated from the conversion factor of monetary value, workplace fatality rate, and working hours as shown in eq. (9). We used 4.2×10^{-8}/hr as a workplace fatality rate, which is based on NUREG-1757.

$$Cost_{ACC} = \$3,000,000 \times F_W \times T_A \tag{9}$$

Where

\$3,000,000 = monetary value of a fatality equivalent to \$2000/p-rem (NUREG-1530);
F_W = workplace fatality rate in fatalities per hours; and
T_A = work hours.

The monetary cost for the risk of accidents due to waste transport is calculated as a monetary value of a fatality equivalent, the volume of waste generated, the volume of transport per truck, and the distance of transport. We used 13.6 m^3/shipment and 3.8×10^{-8}/km respectively based on NUREG-1757 as a volume of a truck shipment and a fatality rate in transport kilometers. The truck travel distance was assumed to be 170 km round trip based on the location of nuclear facility and the low and intermediate level radioactive waste repository.

$$Cost_{TF} = \$3,000,000 \times \frac{V_A}{V_{SHIP}} \times F_T \times D_T \tag{10}$$

Where

\$3,000,000 = monetary value of a fatality equivalent to \$2000/p-rem (NUREG-1530);
F_{SHIP} = volume of a truck shipment in m^3;
F_T = fatality rate in transport kilometers in units of fatalities/km; and
D_T = distance traveled in km.

The cost of worker dose estimates from remediation actions is calculated using the cost conversion factor per collective dose, dose per hours for required actions, and working hours, as shown in eq. (11).

$$Cost_{WDose} = \$2000 \times D_R \times T \tag{11}$$

Where

$2000 = monetary value in dollars of a person-rem (NUREG/BR-0058);
D_R = total effective dose equivalent (TEDE) rate in unit of rems/hr; and
T = work hours in units of person-hour.

In the remediation actions carried out in the process of decommissioning a nuclear power plant, the dose assessment scenario can be largely divided into two types: basement fill (resident farmer) and building occupancy scenarios. In basement fill mode, buildings and structures on the site are removed to a certain depth (3-feet) basement, and the effect of critical group according to the contamination of the remaining structures is considered. In general, the critical group is a resident farmer, and this condition was basically assumed in this study. In the building occupancy mode, it is assumed that the standing building remains on the site after the decommissioning is completed, and a situation with a floor area of 100 m^2 is assumed from a conservative approach. Common to both scenarios, groundwater drinking, irrigation water use, and direct exposure can be regarded as exposure pathways, and DCGL can be evaluated taking into account the effects of these pathways [3]. Therefore, the ALARA evaluation is calculated by applying parameters such as population density, evaluation time, monetary discount rate and area along with the corresponding scenario. Table 2 shows the parameters for each scenario used in this study.

2.4. Remediation cost basis

As shown in eq. (7), in order to quantitatively evaluate the cost components of remediation actions in monetary value of dollars, an appropriate unit cost values must be determined. To do this, first of all, it is necessary to determine the area, volume, or length, which are the working scale of the structure surfaces, soil, or buried piping as the remediation actions. For surface areas (i.e. volume or LF), a specific remediation plan can be established by reflecting the results of characterization survey before starting the remediation actions. In case of Kori-1, since it is currently in transition phase, it is difficult to specify the detailed size of the remediation surfaces. Therefore, in this study, the decision was made based on the experience of MY. In addition, for crew size, the component of manpower required in NUREG/CR-5884 [8] was referred to, and hourly cost and cleaning rate were determined in parallel with reference to LTP of overseas cases. The waste disposal cost, worker accident cost, transportation accident cost, and worker dose cost were calculated by applying the equations presented in eqs. (8)–(11), and the required unit values such as waste generated per area (in units of m^3/m^2), cost of waste disposal (in units of $/$m^3$), and the hourly dose rate for workers (in units of rem/crew-hr) were determined by referring to MY and RSNGS experiences as well. Overall, the basis for calculating the unit cost values for the remediation actions is summarized in Table 3, and the values applied to the preliminary ALARA evaluation of Kori-1 in this study are presented in Table 4.

2.5. Dose fractions and source term

In evaluating ALARA action levels, equation (3) can be used to decide whether additional clean-up compared to DCGL would be required. At this situation, the composition of radionuclides on the surface of the soil or structure is expected to be multiple rather than single radionuclide. To address multiple radionuclides, information on the radionuclides of interest, radioactivity concentrations and their dose contribution rate (unitized dose factor) are required. The radionuclide information is an important factor influencing ALARA evaluation and should be reflected based on the characterization survey of each site. However, as explained in the previous section, detailed information on site characterization surveys is still insufficient. Therefore, we used three types of radionuclides information for ALARA action level calculations with reference to overseas cases. Information on nuclides of overseas NPPs is the experience data of previous decommissioned NPPs, and since the reactor type is the same pressurized water reactor as that of Kori-1, it will be possible to use it as a preliminary ALARA evaluation. In this respect, the results of the residual action levels calculated in this study should reflect the site status more clearly by using the data of the site investigation survey in the future. The unitized dose fractions and radionuclide fractions used for the evaluation of ALARA action levels presented in the LTP of 3 nuclear facilities (MY, RSNGS and Zion) were investigated, and we applied these information as the Case 1, Case 2, and Case 3. The following Case 1 is the radionuclides information of MY, and since both basement fill mode and building occupancy mode were used, this study also applied this information for two scenarios.

Case 2 shows information on radionuclides used in RSNGS. In this case, RSNGS initially considered 26 radionuclides, but only 6 radionuclides were identified during the characterization surveys [4]. For ALARA evaluations, 2 major radionuclides, Co-60 and Cs-137, were considered. We identified their fractions and DCGL values by referring to the reference (DTBD-5-15) as shown in Table 5. In RSNGS, ALARA evaluation was performed for the industrial worker and building occupancy scenarios. Therefore, we used RSNGS radionuclide information for both basement fill and building occupancy scenarios.

In Case 3, information on radionuclides used in the ALARA evaluation of Zion plant is presented, and it shows the basement inventory level for the auxiliary building. In this case of Zion, two remediation activities (soil and scabbling) were evaluated by applying the basement fill mode. Therefore, in this study, the same as in the previous two cases, Zion's radionuclide information was used to evaluate two scenarios and remediation actions of Kori-1

Table 2
The parameters used in each scenario.

Parameter	Unit	Scenario			
		Basement Fill	Reference	Building Occupancy	Reference
Population density	Person/m^2	0.004	NUREG-1757	0.09	NUREG-1757
Area being evaluated	m^2	10,000	[3–5]	100	[3–5]
Monetary discount rate	/yr	0.02	NUREG-1757	0.07	NUREG-1757
Number of years	yr	1000	NUREG-1757	70	NUREG-1757

Table 3
Basis of unit cost values.

Parameter	Unit	Reference	Comments
Area	m^2, m^3 or m	MY and RSNGS experience	Units: surfaces (m^2), soil (m^3), grit blasting of embedded piping
Crew size	person	NUREG/CR-5884, V.2, Appendix C	Laborers, Crafts, HP and Crew leader
Hourly cost	$/hr	NUREG/CR-5884, V.2, Appendix C	The sum of unit price multiplied by number of member
Cleaning rate	m^2/hr, m^3/hr or m/hr	NUREG/CR-5884, V.2, Appendix C	Reference from MY and RSNPS LTP
Hours	hr	NUREG/CR-5884, V.2, Appendix C	Increased by real work time over 8 h and 1.25 contingency
Mobilization cost	$	MY & RSNPS experience	Reference from MY and RSNPS LTP
Labor cost	$	(Hourly cost)(Hours)	–
Equipment cost	$	NUREG/CR-5884, V.2, Appendix C	Reference from MY and RSNPS LTP
Grit/Consumables	$	MY & RSNPS experience	Based on industry experience
Liquid processing cost	$	NUREG-1757 (App. N), MY & RSNPS experience	(1$/g)(1.35 g/m2)(Area)(1.25 liquid contingency)
Waste disposal cost	$	NUREG-1757 (App. N), MY & RSNPS experience	(Waste generation in units of m^3/m^2)(unit disposal cost at $2500/$m^3$
Worker accident cost	$	NUREG-1757 (App. N), MY & RSNPS experience	($3,000,000)(worker fatality rate at 4.2E-8/h)(Hours)
Transportation accident cost	$	NUREG-1757 (App. N), MY & RSNPS experience	($3,000,000)(Waste/13.6)(fatality rate at 3.8E-8/h)(distance at 170 km)
Worker dose	$	NUREG-1757 (App. N), MY & RSNPS experience	Dose rate of 0.002 or 0.003 rem/crew-hr

Table 4
Unit cost value of remediation actions.

Parameter	Unit	Remediation actions*							
		Action 1	Action 2	Action 3	Action 4	Action 5	Action 6	Action 7	Action 8
Area	m^2, m^3 or m	4,182	4,182	4,182	4,182	4,182	4,182	1,632	1500
Crew size	person	4	3	3.5	3.5	3.5	3.5	4	4.5
Hourly cost	$/hr	148.27	98.57	102.03	102.03	102.03	102.03	148.27	175.06
Cleaning rate	m^2/hr, m^3/hr or m/hr	44.59	2.80	12.08	12.08	2.79	2.79	18.29	3.06
Hours	hr	234.45	2,053.66	1,298.50	649.25	1,873.66	1,498.92	111.54	980.39
Mobilization cost	$	600	600	7,100	7,100	15,293.53	15,292.03	4,000.00	700.00
Labor cost	$	34,762.11	202,429.34	132,479.48	66,239.74	191,169.11	152,920.30	16,538.28	171,627.45
Equipment cost	$	3480	21,571	95,102.15	38,059.04	51,315.00	37,320.00	6,538.57	71,228
Grit/Consumables	$	–	–	–	–	17,984.00	17,984.00	–	–
Liquid processing cost	$	7057.13	–	–	–	–	–	–	–
Waste disposal cost	$	20,910	35,442.45	66,389.25	33,246.90	40,290.00	40,290.00	2,623.46	3,750,000
Worker accident cost	$	29.54	258,76	163.51	81.81	236.08	188.86	14.05	123.53
Transportation accident cost	$	11.92	20.20	37.84	18.95	22.97	22.97	1.50	2137.50
Worker dose	$	234.45	2,738.21	2,226	1,113	3,211.98	2,569.59	111.54	871.46

*Action 1: Pressure Washing, Action 2: Washing and Wiping.
Action 3: Scabbling (bounding condition 0.635 cm surfaces), Action 4: Scabbling (bounding condition 0.32 cm surfaces).
Action 5: Grit Blasting (bounding condition 1.25 contingency), Action 6: Grit Blasting (bounding condition no contingency).
Action 7: Grit Blasting (embedded/buried piping), Action 8: Soil Excavation.

Table 5
Case 2: specific information of radionuclides from RSNGS.

Radionuclide	Half-life (yrs)	Λ (yrs^{-1})	Nuclide fraction [9]	DCGL [9]
Co-60	5.27E+00	1.31E-01	1.10E-01	1.47E+04
Cs-137	3.02E+01	2.30E-02	8.90E-01	4.55E+04

decommissioning.

3. Results of ALARA residual radioactivity level

The ALARA residual radioactivity level is calculated by substituting the values related costs and benefits as in eq. (3) to obtain "Conc", the remediation target concentration compared to the DCGL, from calculated Conc/DCGL. For Kori-1, the release criteria should be applied at 0.1 mSv/yr (0.25 mSv/yr in the U.S.), thus 0.025 in the denominator of eq. (3) should be changed to 0.01, and it can be expressed as eq. (12).

$$\frac{Conc}{DCGL} = \frac{Cost_T}{\sum_i^n \$2000 \times P_D \times 0.01 \times Df_i \times F \times A \times \frac{1-e^{-(r+\lambda)N}}{r+\lambda}} \quad (12)$$

The total costs, $Cost_T$, can be calculated by adding up each cost components for remediation actions as shown in Table 4. The population density (P_D), area being evaluated (A), monetary discount rate (r), and number of evaluation period (N) are divided by each scenario presented in Table 2 and substituted into eq. (12). In case of multiple radionuclides, the dose fraction (Df_i) that should be considered was calculated by dividing into Case 1, Case 2, and Case 3, and the values of the radionuclide fractions and dose or DCGL factions were substituted into eq. (4) or (5) based on each applicable scenario.

As a result, the first ALARA evaluation of basement fill mode, the total cost was calculated for each remediation action, and Conc/DCGL value was calculated by substituting the input variables required in eq. (12), which shown in Fig. 1. In the ALARA evaluation process of basement fill mode, the total cost can be derived for each remediation action as a unit cost per area. Therefore, the total cost in the building occupancy mode was calculated by multiplying the assumed floor area of 100 m^2 by the total cost per area value derived from the basement fill mode. Fig. 2 shows the results of Conc/DCGL ALARA evaluation for the building occupancy scenario.

As remediation actions that was considered in this study in the basement fill mode, a total of 8 actions, from pressure washing to soil excavation, were assumed, and their Conc/DCGL values were all calculated to be greater than 1. The action showing the relatively low Conc/DCGL was grit blasting (embedded or buried piping), while the highest value was the action of soil excavation. This means that the cost of soil excavation action (more than other actions) is high per area compared to the benefits, which indicates that the additional clean-up below DCGL is not justified in terms of ALARA concept. The results of classification of cases 1 to 3 based on the radionuclides information showed that there was no significant difference between 3 cases, but the Conc/DCGL were calculated to be large in the order of Case 2, Case 1, and Case 3. In summary, for the case of basement fill mode, the preliminary Conc/DCGL values of Kori-1 were all calculated to be greater than 1 for the foreseeable remediation actions, so additional remediation below the 0.1 mSv/yr dose criteria is not justified.

In the case of the building occupancy mode, the remediation actions selected in this study, a total of 6 actions, consisted of pressure washing to grit blasting as show in Fig. 2. As a result, the Conc/DCGL values were all calculated to be greater than 1 similarly as the basement fill mode results. However, in terms of magnitude, the Conc/DCGL values of building occupancy mode were lower than those of basement fill mode. The difference of Conc/DCGL between the two modes for each remediation action was 54 times on average. The main reason for this is that the cost of remediation action in the building occupancy mode was calculated and used in proportion to the area assumed in the building occupancy mode from the unit cost per area derived in the basement fill mode. Accordingly, since all cost items were linearly and uniformly reduced as the area decreased, the cost was calculated to be relatively low, and this was also evaluated in the light of conservatism. In summary, it can be seen that additional clean-up below the 0.1 mSv/yr dose criteria is not justified because the Conc/DCGL values were all calculated above 1 for the 6 remediation actions assumed in the building occupancy mode.

4. Discussions

4.1. Analysis of the Conc/DCGL values in basement fill scenario

The different results of Conc/DCGL values for each case in the evaluation of ALARA action levels are because the criteria and basis for the cost items of each case differ depending on the site. In this study, we determined the evaluation methodology and factors for calculating costs and benefits by referring to available references from 5 overseas cases (not all of them did a detailed cost-benefit analyses). The values for the items constituting the total cost are shown in Table 4. Therefore, it will be important to analyze the

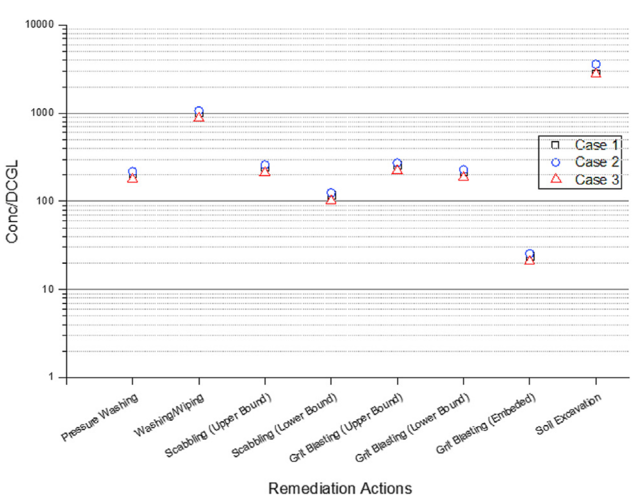

Fig. 1. Conc/DCGL results of Basement Fill scenario.

results of each remediation actions in overseas cases and the results derived from this study. For this purpose, the same dose criteria needs to be applied because the regulatory limits are different for overseas cases and Kori-1. Fig. 3 shows the Conc/DCGL values for each case of remediation actions under the same 0.25 mSv/yr of NRC dose criteria. Although the distribution of various values for each action at the different site appears, they all present results that cannot be justified for the need for additional remediation actions that are ALARA.

Basically, for the three NPPs MY, RSNGS, and Zion, different input values were used for remediation area and radionuclides information. In addition, in the basement fill mode, MY considered 8 actions, but RSNGS considered 2 actions of grit blasting (embedded/buried piping) and soil excavation, and Zion considered 2 actions of soil excavation and scabbling and washing. In this study, we performed the ALARA evaluation with reference to the remediation areas of MY, but due to changes in crew size, hourly cost, cleaning rate, and transportation accident cost of truck volume and transport distance, it was found that deviations occurred. As the value of some remediation areas, 4182 m^2, 20,312 m^2, and 2543 m^2 for MY, RSNGS, and Zion plants were used, respectively. As the basis, they used the values form the actual area, containment vessel area, and reference data. For crew size, MY considered 6, 7, 6, 6, 7, 7, 7, and 8 people for action 1 to 8. RSNGS considered 4, 3, 3.5, 3.5, 3.5, 3.5, 4, and 4.5 people and Zion considered 3.5 people. For hourly cost, values in the range of 75.12–157.12 for MY, 98.57 to 175.06 for RSNGS, and 236.74 for Zion were used. For cleaning rate, values in the range of 1–9.29 for MY, 2.8 to 22.3 for RSNGS, and 12.07 for Zion were used. Therefore, we determined input values for the cost and benefit calculation of Kori-1 based on overseas experience and the basis and the values are summarized in Tables 3 and 4. Because the results of Kori-1 were calculated from the values based on the experience data of the 3 NPPs, the Conc/DCGL values form a distribution as shown in Fig. 3, which was evaluated at a level similar to the results of overseas cases. Overall, although there are some differences, the results derived from this study indicate that a conservative evaluation was performed except for washing/wiping and soil excavation actions.

4.2. Analysis of the Conc/DCGL values in building occupancy scenario

Even in the building occupancy scenario, the Conc/DCGL values calculated using case-by-case radionuclide data and the results performed by MY and RSNGS pants are compared as shown in Fig. 4. The results of Case 1 to 3 are calculated by applying 0.25 mSv/yr for comparison with overseas cases instead of the domestic dose criteria of 0.1 mSv/yr. Among the results of evaluation of 6 remediation actions, Conc/DCGL values were greater than 1 for all other actions except for scabbling (Lower Bound). Among the input variables of eq. (12), the pressure washing action was calculated to have smallest cost per area, and the scabbling action showed the second smallest value of cost per area. In addition, the fraction of activity removed value was 0.25 for pressure washing action and 0.95 for scabbling, thus the ALARA Conc/DCGL value was calculated as the lowest and below 1 in scabbling (Lower Bound). However, because the 0.25 mSv/yr dose criteria was used for comparison with other cases, the result was calculated to be low, and the result of using the domestic criteria 0.1 mSv/yr was calculated to be greater than 1 as shown in Fig. 2. Since the Conc/DCGL value may be less than 1 depending on the dose criteria, from this evaluation result, the selection of input values such as the remediation area, crew size, hourly cost, cleaning rate, removal fraction and nuclides information should be based on the site specific condition at the time of remediation or site status survey. In summary, for the building

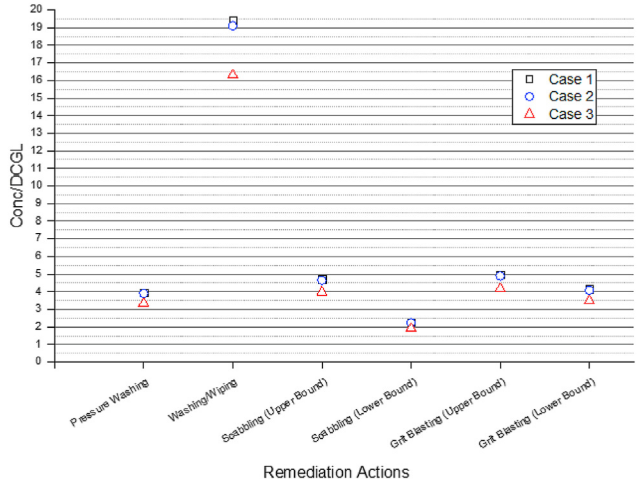

Fig. 2. Conc/DCGL results of Building Occupancy scenario.

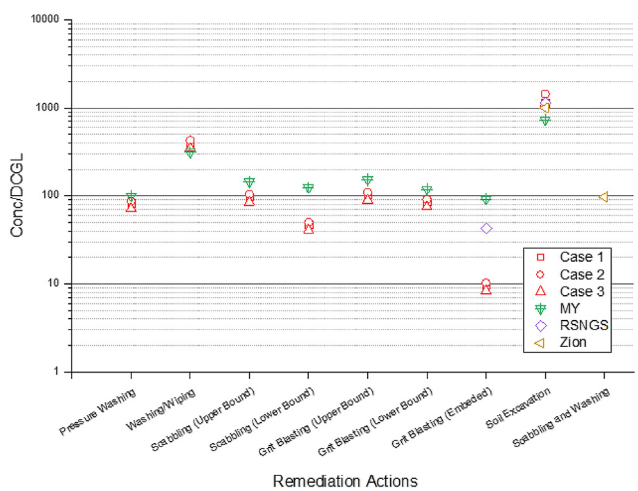

Fig. 3. Conc/DCGL results (0.25 mSv/yr) in the Basement Fill scenario.

occupancy scenario, except for washing/wiping action, the results

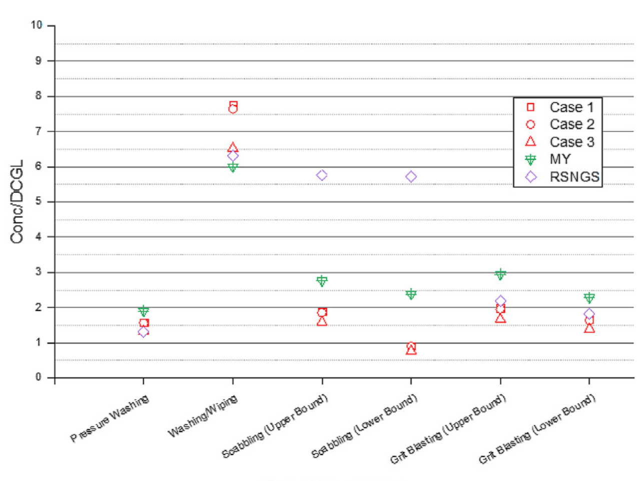

Fig. 4. Conc/DCGL results (0.25 mSv/yr) in the Building Occupancy scenario.

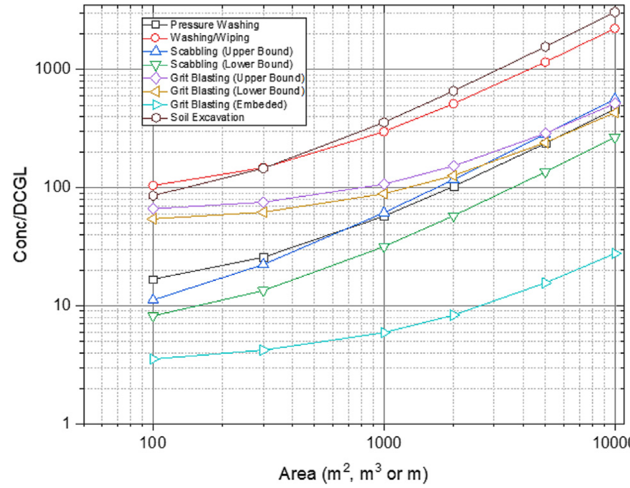

Fig. 5. Area effect on Conc/DCGL in Basement Fill scenario.

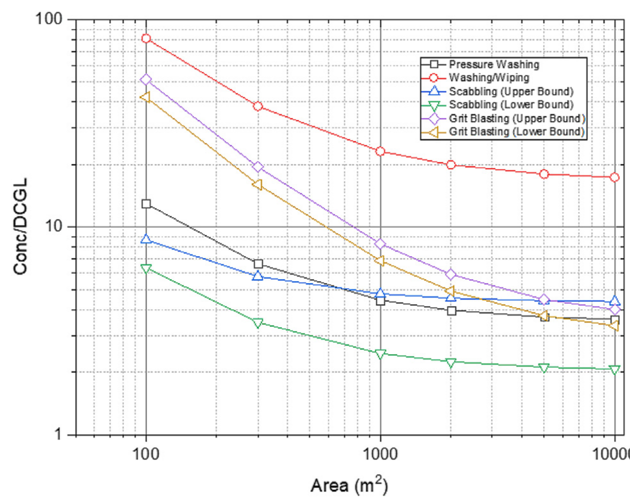

Fig. 6. Area effect on Conc/DCGL in Building Occupancy scenario.

of Case 1 to 3 of Kori-1 were conservative compared to overseas cases. It can be noted that the scabbling may be an action that may require additional clean-up depending on changes in input variables such as cost components including the remediation area, crew size, hourly cost, cleaning rate, radionuclide information and removal fraction.

4.3. The effect of remediation area on Conc/DCGL values

In this study, the costs and benefits of remediation actions were calculated and through their comparison, it was possible to determine what Conc, the remediation target concentration that is ALARA, should be compared to DCGL. For the calculation of benefits, we used an area value of 10,000 m^2 for the basement fill mode and 100 m^2 for the building occupancy mode as an area being evaluated in each scenario (see Table 2). On the other hand, the costs occur differently depending on the remediation actions, and among the major factors contributing to the costs, it was found that the remediation area functioned as a base for several cost items. In addition, depending on the area of remediation, the hours of remediation action, worker's labor, waste disposal cost, and waste transport accidents occur accordingly. In line with this, it is necessary to analyze how the area effect of increasing variables on the remediation ALARA results, and it may be possible to show implication in preparation for a situation in which the area is changeable.

First of all, the area used in this study for each remediation action in the basement fill mode among the two assumed scenarios was 4182 m^2 as shown in Table 4. We calculated each cost item while gradually increasing the area from 100 m^2 to 10,000 m^2, and calculated Conc/DCGL value accordingly, as shown in Fig. 5. As the remediation area increases, the cost is expected to naturally increase accordingly, so there are variations depending on the actions, but as shown in the graph, the Conc/DCGL value increases, indicating that additional clean-up would not require. In addition, as a result, under the cost calculation system of this study, remediation actions to the level of Conc below DCGL is not justified when the remediation area of the basement fill mode is 100 m^2 or more. We expect that the Conc/DCGL value will converge horizontally without significantly lowering even for an area of 100 m^2 less.

We initially assumed 100 m^2 as the remediation area and area being evaluated for the building occupancy scenario. In the basement fill mode, even if the area of remediation on structure surfaces increased, the area being evaluated was fixed at 10,000 m^2, so the remediation area and the Conc/DCGL value had a positive correlation. However, in the building occupancy mode, it is assumed that the residual radioactive contamination remains on the floor, and as the remediation area increases, the area being evaluated also increases accordingly to calculate Conc/DCGL. Therefore, Fig. 6 shows the effect of Conc/DCGL values for each remediation action on the change of the remediation area. As the floor area of a building increases, the cost and benefit tend to increase, but as the graph shows, the increase in benefits is greater than the increase in costs, so the Conc/DCGL value tends to decrease. In summary, in the building occupancy mode, if the remediation area for each action is small, additional clean-up is not required, and it is expected that the Conc/DCGL value will not fall below 1 even if the area reaches 10,000 m^2 or more.

5. Conclusions

The licensee needs to set a reasonable decontamination levels in terms of ALARA for the relevant building surfaces or materials in D&D activities that are one of the main tasks in the decommissioning of NPPs. To do this, we investigated various information such as the remediation actions, ALARA evaluation method, applicable scenario, cost calculation and basis, and dose contribution factor of residual radioactivity concentration on materials. Based on this, the Conc/DCGL value was calculated, from which it can be determined whether additional clean-up is required compared to DCGL for each remediation action.

In the basement fill mode, the results of 8 remediation actions were calculated using radionuclide information for 3 cases, and it showed that additional clean-up was not justified. Although the distribution of Conc/DCGL values was different for each remediation action, in particular, the value of soil excavation was calculated to be relatively high compared to other actions, indicating that the soil excavation is an action in which the cost is relatively greater than other actions compared to the benefit. In addition, because the results of Kori-1 were calculated from the values based on the experience data of the 3 NPPs, the Conc/DCGL values form a distribution at a level similar to the results of overseas cases. Although there are some differences, the results derived from this study indicate that a conservative evaluation was performed except for washing/wiping and soil excavation actions.

In the case of building occupancy mode, as a result of evaluating 6 actions, the Conc/DCGL value was calculated to be greater than 1. It was possible to analyze the differences between remediation actions by comparison with overseas cases, and it was noted that this was due to the factors such as the applied dose criteria, radioactivity removed, and the unit cost per area. Among the results of evaluation of 6 remediation actions, Conc/DCGL values were greater than 1 for all other actions except for scabbling (Lower Bound). This is because the results were calculated by applying 0.25 mSv/yr for comparison with overseas cases instead of the domestic dose criteria of 0.1 mSv/yr. Since the Conc/DCGL value may be less than 1 depending on the dose criteria, the selection of input values such as the remediation area, crew size, hourly cost, cleaning rate, removal fraction and nuclides information should be based on the site specific condition at the time of remediation or site status survey.

In addition, we analyzed the effect of remediation area, which is an important factor in calculation of the total cost, by remediation action and application scenario. In the case of basement fill mode, the Conc/DCGL value increased because the remediation area was considered to be 10,000 m^2 as the area being evaluated due to the characteristics of the scenario while the remediation area was increased from 100 m^2 to 10,000 m^2. As a result, it was noted that the increase of the remediation area showed a positive correlation with the Conc/DCGL value. On the other hand, in the building occupancy mode, since the floor area of the building is the target of remediation and has the effect of increasing the same as the evaluation area of the building occupants, the cost and benefit increased accordingly, but due to the difference in the amount of increase, the Conc/DCGL showed a negative correlation. Nevertheless, in both scenarios, the cost of remediation actions was relatively greater, so additional remediation activities are not justified for the benefit of ALARA.

Declaration of competing interest

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

References

[1] NSSC, Criteria for Reuse of Site and Builings after Completion of Decommissioning of Nuclear Facilities, Notice No. 2021-15, Nuclear Safety and Security Commission, 2021 (In Korean).
[2] NRC, Rev. 1, Consolidated Decommissioning Guidance, vol. 2, U.S. Nuclear Regulatory Commission, 2006. NUREG-1757.
[3] MYAPC, Maine Yankee's License Termination Plan, Maine Yankee Atomic Power Company, 2009. Rev. 5.
[4] SMUD, Rancho Seco License Amendment Request and License Termination Plan, Sacramento Municipal Uatility District, 2006. Rev. 0.
[5] ZIONSOLUTIONS, "Zion station restoration project license termination plan," (Chapter 4) Remediation Plan, Rev. 0.
[6] CYAPC, Connecticut Yankee Atomic Power Company, Haddam Neck Plant License Termination Plan, 2006. Rev. 4.
[7] YNPS, Yankee Nuclear Plant Station License Termination Plan, Rev. 1, Yankee Nuclear Power Station, 2004.
[8] NRC, Revised Analyses of Decommissioning for the Reference Pressurized Water Reactor Power Station, vol. 1, 1995. NUREG/CR-5884, PNL-8742.
[9] RSNGS, Rancho Seco Nuclear Generating Station Decommissioning Technical Basis Document, 2006. DTBD-05-015, Rev. 0.