Nuclear Engineering and Technology 55 (2023) 52–62

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

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

Original Article

A multi-criteria decision-making process for selecting decontamination methods for radioactively contaminated metal components

Inhye Hahm [a, c], Daehyun Kim [b], Ho jin Ryu [c, **], Sungyeol Choi [d, *]

[a] *Decommissioning Technology Research Division, Korea Atomic Energy Research Institute, 111, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, 34057, Republic of Korea*
[b] *Department of Decommissioning Regulation, Korea Institute of Nuclear Safety, 62 Gwahak-Ro, Yuseong-Gu, Daejeon, 34142, Republic of Korea*
[c] *Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Yuseong-gu, Daejeon, 34141, Republic of Korea*
[d] *Department of Nuclear Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul, 08826, Republic of Korea*

ARTICLE INFO

Article history:
Received 3 March 2022
Received in revised form
1 September 2022
Accepted 9 September 2022
Available online 16 September 2022

Keywords:
Steam generator
AHP
TOPSIS
PROMETHEE
Decommissioning

ABSTRACT

Various decontamination technologies have been developed for removing contaminated areas in industries. Although it is important to consider parameters such as safety, cost, and time when selecting the decontamination technology, till date their comparative study is missing. Furthermore, different decontamination technologies influence the decontamination effects in different ways. Therefore, this study compares different decontamination techniques for the steam generator using a multicriteria decision-making method. A steam generator is a large device comprising both low- and very low-level waste (LLW, VLLW) and reflects the difference in weights of the standards according to the classification of the waste. For LLW and VLLW decontaminations, chemical oxidizing reduction decontamination (CORD) and decontamination grit blasting were used as the preferred techniques, respectively, considering the purpose of decontamination differs based on the initial state of waste. An expert survey revealed that safety in LLW and waste minimization in VLLW exhibited high preference. This evaluation method can be applied not only to the comparison between each process, but also to the creation of process scenarios. Therefore, determining the decontamination approach using logical decision-making methods may improve the safety and economic feasibility of each step in the decommissioning process and ensure a public acceptance.

© 2022 Korean Nuclear Society, Published by Elsevier Korea LLC. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

The safe and environment friendly decommissioning of nuclear facilities is necessary to sustain nuclear energy. Furthermore, optimization of decontamination methods for radioactively contaminated metal components can provide great benefits, such as less waste, lower costs, faster completion, and lower radiological risk. However, this could lead to an unexpected delay of projects owing to the radiation dose of workers or the generation of secondary radioactive waste, which significantly increases total costs. Considering waste treatment accounts for approximately 50% of the total costs, the costs of projects may vary over tenfold depending on the decontamination techniques used [1]. In addition, it is necessary to develop a reasonable and systematic approach for the selection of decontamination techniques to engage stakeholders, including the public.

Multicriteria decision-making (MCDM) has been widely used in diverse energy sectors and other industries [2], [3], [4]. Some of them combine MCDM with large-scale data processing [5]. MCDM methods have been used in several different nuclear energy projects, such as assessing nuclear safety culture [6], selecting nuclear facility locations [7], and comparing different nuclear fuel cycle options [8]. Until now, MCDM methods have not been considered for selecting an optimized decontamination technique. Previous studies followed a systematic approach for the selection process by comparing decontamination techniques based on expert surveys

* Corresponding author.
** Corresponding author.
E-mail address: choisys7@snu.ac.kr (S. Choi).

https://doi.org/10.1016/j.net.2022.09.012
1738-5733/© 2022 Korean Nuclear Society, Published by Elsevier Korea LLC. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

[9], unit cost [1], logistic approach [10], decision-making technique [11], or risk assessment [12]. The selection of decontamination techniques is a complicated task and should consider parameters such as type, scale, the geometry of contaminated surfaces, primary and secondary waste management, technology effectiveness, and costs [9]. More importantly, the complexity also comes from the necessity to consider the classification of radioactive waste due to different regulatory guidelines and public perceptions. More informed decisions can be made by explicitly considering complex problems with multiple criteria.

In this study, we apply MCDM methods to compare decontamination techniques for steam generators (SGs). SGs cover a surface area of approximately 70% in the primary circuit system of a pressurized water reactor (PWR). Based on expert surveys, we evaluated several criteria such as safety, efficiency, cost-effectiveness, and waste minimization to determine their weight factors. Particularly, the different classifications of radioactive waste are considered. We combined the technique for order of preference by similarity to ideal solution (TOPSIS) and preference ranking organization method for enrichment evaluation (PROMETHEE) with the analytic hierarchy process (AHP) for the systematic evaluation of decontamination options. In addition, we compared decontamination scenarios using the evaluation results by reflecting the decommissioning sites of nuclear power plants, which is usually composed of multiple stages.

This allows a quantitative comparison between decontamination techniques. For decontamination techniques, standardized evaluation data are not available. Usually project managers have relied on empirical data or consider only one factor, such as cost or efficiency to identify the most proper option. However, due to the uniqueness of each decommissioning project, relying on experience may not result in desired performance. As new decontamination techniques are continuously developed, a methodology that can compare these techniques according to each situation is important.

2. Methods

TOPSIS and PROMETHEE were used to derive priorities among the final evaluation subjects based on the weights calculated by the AHP. Although AHP is simple to apply, it is frequently combined with other approaches because the decision-maker's subjective intervention is significant [13]. Furthermore, TOPSIS provides a mathematical basis for ranking while simultaneously considering both the optimal and worst options. PROMETHEE is conceptual and easy to maintain even when there are multiple evaluation items.

2.1. AHP

When using AHP to model a problem, a hierarchic or network structure is required to represent the problem and conduct pairwise comparisons to establish relations within the structure [14]. The idea of comparative judgment is used to create pairwise comparisons of relative importance, which can result in the type of matrix A. The i^{th} row and j^{th} column a_{ij} of A_{nxn} are the relative scores of the i^{th} and j^{th} elements for the n criteria, respectively.

$$A=\begin{bmatrix} 1 & & \cdots & s_1/s_n \\ s_2/s_1 & \ddots & & s_2/s_n \\ \vdots & & \ddots & \vdots \\ s_n/s_1 & \cdots & & 1 \end{bmatrix}$$

Furthermore, it uses the eigenvector method, which considers the eigenvector elements essential for the maximum eigenvalue. By multiplying matrix A with the importance vector $w=(w_1,w_2,\ \cdots,w_n)$, we obtained the following:

$$Aw=\lambda w$$

$$w_i=\frac{1}{n}\sum_{j=1}^{n}\frac{a_{ij}}{\sum_{k=1}^{n}a_{kj}}$$

where λ is the eigenvalue and w the eigenvector corresponding to λ.

The consistency ratio (C.R.), an index that checks whether pairwise comparisons are consistent, was obtained by comparing the consistency index (CI) with the appropriate set of numbers, each of which is an average random consistency index (RI) as shown in Table 1.

$$C.I.=\frac{\lambda_{max}\ -\ n}{n-1},\ \lambda_{max}\ \geq\ n,$$

$$C.R.=\frac{C.I.}{R.I.},$$

where n is the size of the pairwise comparison matrix. If the results are perfectly consistent, CI will be zero considering the eigenvalue is equal to n. According to Saaty, the C.R. of 0.1 or less be considered consistent and it should be definitely below 0.2 [14].

2.2. TOPSIS

TOPSIS is based on the concept that the best alternative solution has the shortest and longest distances from the positive and negative ideal solutions, respectively [15].

TOPSIS creates an evaluation matrix $(x_{ij})_{mxn}$ comprising m alternatives and n criteria. The matrix $(x_{ij})_{mxn}$ is normalized to form a matrix as:

$$r_{ij}=\frac{x_{ij}}{\sqrt{\sum_{i=1}^{m}x_{ij}^2}},$$

where m is the number of evaluation targets and x_{ij} is the performance score for the j_{th} evaluation item of the i_{th} target. The weighted normalized decision matrix is expressed as:

$$t_{ij}=r_{ij}\cdot w_j,$$

where, r_{ij} is the weight of the j_{th} evaluation item.

We determined the negative (A_w) and positive (A_b) ideal solutions as:

$$A_W=\{[max(t_{ij}=1,2,\ldots,m)|j\in J_-],\ [min(t_{ij}=1,2\ldots m)|j\in J_+]\times\}\equiv\{t_{wj}|j=1,2\ldots n\},$$

$$A_b=\{[min(t_{ij}=1,2,\ldots,m)|j\in J_-],\ [max(t_{ij}=1,2\ldots m)|j\in J_+]\times\}\equiv\left\{t_{bj}\middle|j=1,2\ldots n\right\},$$

where $J_+=\{j=1,2,\ldots n|j\}$ and $J_-=\{j=1,2,\ldots n|j\}$ are associated with the criteria having positive and negative impacts, respectively.

Then, we calculated the distance between the target alternative as:

$$d_{iw} = \sqrt{\sum_{j=1}^{n} \left(t_{ij} - t_{wj}\right)^2}$$

$$d_{ib} = \sqrt{\sum_{j=1}^{n} \left(t_{ij} - t_{wj}\right)^2}$$

Next, we calculated the similarity (s) to the worst condition and rank the alternatives according to s, given as:

$$s = \frac{d_{ib}}{d_{iw} + d_{ib}}$$

TOPSIS allowed for trade-offs between criteria, where a poor result in one criterion might be offset by a good result in the other.

2.3. PROMETHEE

PROMETHEE is a representative outranking method, where outranking means that if an alternative A is judged to be less inferior to alternative B, A can be selected depending on the subjective preference of the decision maker, even if there is no mathematical dominance between A and B [16]. The outranking method is capable of dealing with the trade-off problem between evaluation criteria of different scales by replacing the performance differences of alternatives with preference and can be used to resolve the theoretical limitations of the AHP [17].

Furthermore, PROMETHEE utilizes the concepts of leaving flow (ϕ^+) and entering flow (ϕ^-). PROMETHEE I determines the priority of alternatives using leaving and entering flows, whereas PROMETHEE II determines the ranking using the net flow.

The preference index for calculating the leaving flow and entering flow preferences is calculated as:

$$\pi(a, b) = \sum_{j=1}^{k} p_j(a,\ b) w_j$$

where p_j is a preference function value of the j^{th} criterion and wj is the weight of the j^{th} criterion. To calculate the preference index, it was necessary to determine the preference function.

Brans and Vincke suggested six types of preference functions, as summarized in Table 2 [18]. The decision maker selects a function suitable among these preference functions, calculates the value of the preference function for pair comparison, and multiples the preference function by the weight.

Leaving flow and entering flow can be expressed as:

$$\phi^+(a) = \frac{1}{n-1} \sum_{b \in A} \pi(a, b)$$

$$\phi^-(a) = \frac{1}{n-1} \sum_{b \in A} \pi(b, a)$$

For alternative A, the leaving flow refers to the average of the preference indices of alternative A and the remaining pair of alternatives, whereas the entering flow refers to the average of the preference indices of the pair of alternatives, where alternative A is compared to other alternatives. In PROMETHEE I, priority is judged by the leaving and entering flows, that is, the larger the leaving flow and smaller the entering flow, the better is the alternative. If they contradict each other, the comparison is said to be impossible. PROMETHEE II judges the superiority relationship based on the net flow, that is, the larger the net flow, the higher the priority.

Table 1
Random index according to the number of evaluation items.

n	1	2	3	4	5	6	7	8	9
R.I.	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

2.4. Decontamination techniques

The trend in nuclear decontamination technologies has shifted from decontamination during maintenance to decontamination during decommissioning. Currently, there is very little data on each technology. Although the partial radioactive level after decontamination is usually reduced to the clearance level, it is necessary to develop a decontamination technique that satisfies the perfect condition [19]. Table 3 summarizes the techniques used for general SG treatment by reviewing the literature on cases of decommissioning power plants or replacing SG.

SGs constitute a discrete waste stream of huge, complex items that can be handled, treated, recycled, and disposed of different ways. In most cases, SG has very low levels of contamination, with the exception of water chambers and tubes. The main purpose of SG treatment is to minimize the collective dose and disposal volume of waste.

2.4.1. Grit blasting

Abrasive blasting is a technology used to remove of fix surface contaminants by spraying abrasive materials such as silicon, sand, or grit using a spray nozzle. Abrasive blasting systems are commercially available in various configurations and sizes [27]. Steel grit is known to be highly effective in removing thin layers of concrete. Grit velocity and treatment time can be used to vary the depth of the attack. Although the amount of secondary waste produced strongly depends on the lifetime of the abrasive, the potential for injury increases as the abrasive hardness increases [28].

2.4.2. Electropolishing

Electropolishing is a polishing technique that uses an electrochemical reaction to smooth the metal surface. The material to be decontaminated and the electrode of the tank are considered the anode and cathode, respectively. Electropolishing has a high corrosion rate and is suitable for the decontamination of large areas; however, it is less suitable for industrial decontamination of complex geometries owing to inadequate treatment of the inner parts of the tubes or hidden elements. Secondary liquid waste is produced in the same manner as in chemical processes [29].

2.4.3. CORD

The chemical oxidizing reduction decontamination (CORD) process is commonly used for full-system decontamination (FSD) based on permanganic acid. Some CORD family processes such as HP CORD, CORD D UV, and CORD CS UV are slightly modified depending on the material and type [24]. The HP/CORD UV process is most commonly applied to PWR stainless steels as a multi-cycle process depending on the decontamination targets. The HP/CORD UV process is as follows [30]:

1 Pre-oxidation for dissolution of oxides containing Cr by oxidizing Cr^{3+} to Cr^{6+} using permanganic acid ($HMnO_4$)
2 Reduction of permanganic acid (manganese is reduced from Mn^{7+} to Mn^{2+}) using oxalic acid
3 Decontamination using oxalic acid

Table 2
Types of preference function.

Preference function	Definition	Parameter	Preference function	Definition	Parameter
Usual criterion	$p(d) = \begin{cases} 0 & d \le 0 \\ 1 & d > 0 \end{cases}$	-	Level criterion	$p(d) = \begin{cases} 0 & d \le q \\ 0.5 & q < d \le p \\ 1 & d > q \end{cases}$	p,q
U-shape Criterion	$p(d) = \begin{cases} 0 & d \le q \\ 1 & d > q \end{cases}$	q	V-shape with indifference criterion	$p(d) = \begin{cases} 0 & d \le q \\ \frac{d-q}{p-q} & < d \le p \\ 1 & d > q \end{cases}$	p,q
V-shape Criterion	$p(d) = \begin{cases} 0 & d \le q \\ 1 & d > q \end{cases}$	p	Gaussian criterion	$p(d) = \begin{cases} 0 & d \le 0 \\ 1 - exp\left(-\frac{d^2}{2\sigma^2}\right) & d > 0 \end{cases}$	s

Table 3
Steam generator treatment method for each decommissioning case [11], [20], [21], [22], [23], [24], [25], [26].

Case	Main process
KKS	Grit blasting
Ringhals	Grit blasting
Stade	CORD/Grit blasting
Chooz-A	CORD
Trino	CORD
BR-3	CORD/MEDOC
Jose Cabrera	DFD
KRB A	Electropolishing

4 Decomposition of decontamination chemicals to water and CO_2 using ultraviolet light and H_2O_2
Although HP/CORD UV exhibits a high decontamination factor (DF) and high material compatibility, local corrosion was observed in some materials and there was a risk of oxalate formation during the decontamination step.

2.4.4. MEDOC

Metal decontamination by oxidation with cerium (MEDOC) is a single-step process that uses cerium IV as a strong oxidant in sulfuric acid, with regeneration using ozone. Unlike CORD and DFD, which are closed systems, MEDOC is an open system. The concept of the MEDOC process is as follows [29]:

1 Decontamination of the contaminated metal using Ce^{4+}
2 Regeneration of Ce^{4+} solution using oxidation reduction potential

The steam generator in a BR-3 power plant in Belgium was decontaminated using the MEDOC process after performing FSD using CORD. MEDOC has a high efficiency and can reduce secondary waste generation by adding sulfuric acid. However, disadvantages such as the durability problems of electrolysis modules and hydrogen persist [31].

2.4.5. DFD

The DFD process involves circulating dilute fluoroboric acid and potassium permanganate through a system or component that requires decontamination to achieve conditions wherein the base metals slowly and uniformly dissolve while the dissolved radioactivity and metal are eliminated from the ion-exchange resin [32]. The DFD process is as follows:

1. Oxidation process between HBF_4, $KMNO_4$, and the metal surface
2. Reduction process between $C_2H_2O_4$ and the dissolved metal ion.
3. Purification process with ion exchange resin

The DFD process is effective in dissolving Cr-based oxides. In addition, because the final waste form was an ion-exchange resin, only a small amount of secondary waste was generated. However, a highly toxic solvent is necessary for a higher DF [31].

3. Results and discussion

3.1. Evaluation criteria

When selecting decommissioning strategies for nuclear facilities, parameters such as collective dose, radiological hazard, conventional safety, public acceptability, cost, efficiency, and waste generation should be addressed. Among these, four of the generally considered criteria were selected for evaluation. Fig. 1 summarizes the technology evaluation cases that were assessed and grouped into four categories: safety, efficiency, cost, and waste minimization [1]. [10] [33] [34] [35] [36].

Safety not only considers radiological risk but also conventional safety, such as chemical risk owing to external and internal exposure. Although chemical risks are caused by the toxicity of the decontamination solution, the solution is not highly toxic. In addition, considering most planned chemical decontamination works use liquid circulators, the chemical risk is low as workers do not directly handle chemicals [37]. However, explosive gases may be generated in the process of using highly corrosive solutions, and you may be exposed to physical hazards due to the blasting material. In the case of radiological risk, the collective dose of workers was considered. The lower the worker's exposure dose in the process of work, the more radiologically safe the process will be.

The efficiency of a decontamination technique can be evaluated based on its effectiveness in removing radioactive contamination from a target. Efficiency is also affected by the experience of workers with the technology. In this study, the efficiency was calculated using the decontamination factor (DF), which represents the degree of contamination removal. It also reflects whether the process can be applied according to the shape and material of the object, and whether it can be applied to the actual field by being sufficiently applied to various cases.

The cost included worker wages, process costs, and equipment costs. Uncertainty is very high in the case of decommissioning cost estimations. For similar types of nuclear power plants, the estimated costs are sometimes reported differently considering the database related to the decommissioning of nuclear facilities is highly uncertain, and the methods used for cost estimation, established economic and technical assumptions, and regulatory standards are different [38]. The purpose of this study is not to estimate the exact cost, but to obtain a relative value for selecting an alternative.

Waste minimization means that the technique should not produce large quantities of secondary waste, the treatment and disposal

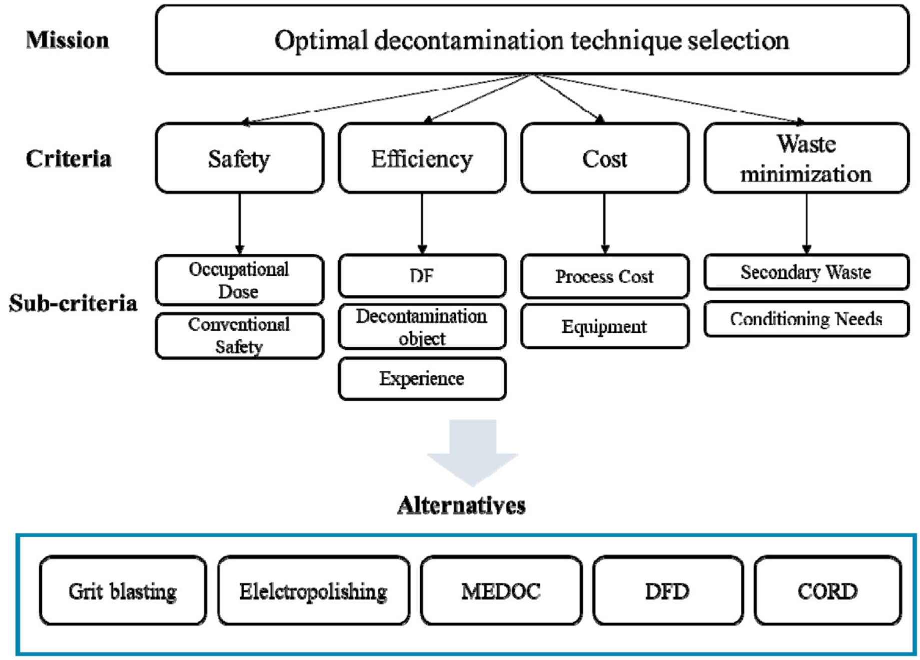

Fig. 1. Hierarchical structures of the evaluation criteria.

of which would result in excessive requirements. It should also be checked that, after the end of the process, no further treatment is required for the dismantled object as a result of the process.

3.1.1. *Weighting factors derived by AHP*

In order to see the difference according to the radioactive waste initial state, the case where the waste level was LLW and VLLW were divided. Pairwise comparisons were performed respectively. When conducting the survey, it was explained that the purpose of decontamination was to reduce the level of radioactivity for safe work and minimize radioactive waste through clearance, considering the target was SG.

The expert group consisted of 23 experts from academia, industry and regulatory bodies with previous work experience in the decommissioning of nuclear utility facilities. 18 experts from this group responded to our survey. They answered that they had experience in measuring radioactivity, cutting, decontamination, waste treatment, site restoration, safety assessment, cost assessment, and planning for the decommissioning of nuclear facilities. According to Saaty, the C.R. of 0.1 or less be considered consistent and it should be definitely below 0.2 [14]. In this study, it was decided to use only responses with a C.R. less than 0.1, and 13 responses passed this criteria. A summary of the respondents is given in Table 4. These respondents were 4 from regulators, 4 from academia and 5 from industry. There were 3 people with more than 10 years of experience, 6 people with more than 5 years and less than 10 years, and 4 people with less than 5 years of experience. The C.R. was 0.039 in the LLW case and 0.042 in the VLLW case.

Table 4
Experts profile summary.

Affiliation	
Academia	30.8%
Industry	38.4%
Regulatory	30.8%
Experience in decommissioning.	
~5 years	30.8%
5 ~ 10 years	46.1%
Over 10 years	23.1%

The survey results were processed anonymously in accordance with Article 33 (Protection of Confidentiality) of the Korea Statistics Act. Therefore, through the results of the study, the characteristics to which a specific individual did not respond were not exposed. Also it was not used for any purpose other than the research purpose in accordance with Article 31 (Usage of Statistical Data) of the Statistics Act.

The results are summarized in Table 5. It was confirmed that the weight considered by the decision-maker differed depending on the initial state of the waste.

As shown in Fig. 2, safety is the most important factor in LLW, whereas waste minimization is the most important factor in VLLW. Once the survey was completed, we received feedback from the experts on the results, which appeared to have been influenced by Korea's radioactive waste management policies. Korea has only one LILW disposal facility, an underground silo with a capacity of 100,000 drums, and an under-construction surface disposal facility with a capacity of 125,000 drums [39]. Currently, the amount already stored in the silo is approximately 24,000 drums, and this capacity should be used with caution owing to the planned decommissioning of nuclear facilities and the difficulty of selecting a disposal site. Therefore, in case of LLW, the preference for disposal at surface facilities through the highest possible efficiency while securing worker safety is reflected. In Korea, waste management costs are high. The cost of disposal of radioactive waste in 200 L drums is approximately $13,000, and there is no difference in the cost of disposal between VLLW and LLW [40]. Therefore, the preference for waste minimization is higher than that for performance, as VLLW can reach clearance levels even with low DF considering it is economical to reduce the overall waste management costs by reducing the amount of secondary waste generated.

3.2. *Performance indicators of decontamination techniques for evaluation criteria*

The quantitative and qualitative evaluation results are summarized in Table 7. Results that are difficult to quantify were compared qualitatively through expert advice.

Table 5
Determined final weights.

	Criteria	Weights	Subcriteria	Subweights	Final Weights
LLW	**Safety**	0.45	Occupational Dose	0.5	0.225
			Conventional Safety	0.5	0.225
	Efficiency	0.14	Decontamination Factor	0.333	0.04662
			Decontamination Object	0.333	0.04662
			Experience	0.333	0.04662
	Cost	0.13	Process Cost	0.5	0.065
			Equipment	0.5	0.065
	Waste minimization	0.28	Secondary waste	0.5	0.14
			Conditioning Needs	0.5	0.14
VLLW	**Safety**	0.19	Occupational Dose	0.5	0.095
			Conventional Safety	0.5	0.095
	Efficiency	0.23	Decontamination Factor	0.333	0.07659
			Decontamination Object	0.333	0.07659
			Experience	0.333	0.07659
	Cost	0.2	Process Cost	0.5	0.025
			Equipment	0.5	0.025
	Waste minimization	0.37	Secondary waste	0.5	0.185
			Conditioning Needs	0.5	0.185

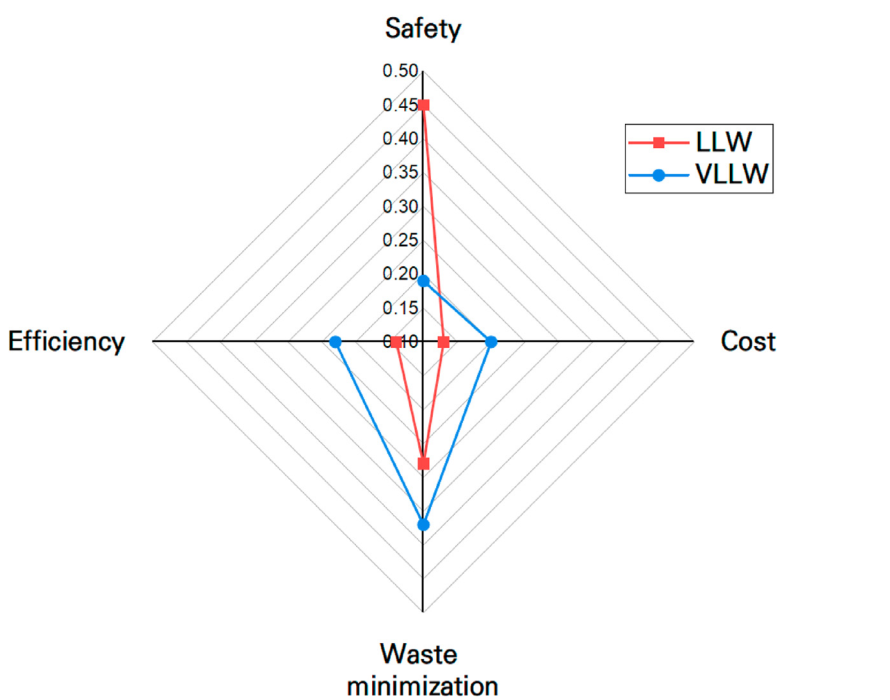

Fig. 2. Comparison of weights for the evaluation factor.

3.2.1. Safety

The safety was evaluated considering the fact that the application of decontamination techniques should not increase radiological and non-radiological risks. In case of radiological risk, we considered the collective dose of workers during decontamination. In the case of abrasive blasting, the occupational dose is low because remote operation is possible. Even in the experience of applying the grit blasting of Ringhals NPP, the collective dose of workers was about 70man-mSv, which was quite low [41]. However, there may be a physical risk from the abrasive material [42]. In the case of electropolishing, it is reported that the occupational dose is significantly higher, ranging from 100 to 1000 man-mSv compared to other processes [43]. Handling of components may lead to additional exposure to workers. Furthermore, electropolishing requires additional component handling owing to batch size limitations, resulting in additional exposure of workers. In the case of full-system decontamination such as CORD, workers are not exposed during decontamination process, so the collective dose is relatively low. In processes such as CORD, most exposures occur in the installation and dismantlement of equipment. MEDOC uses a relatively strong acid compared to CORD, while DFD can generate explosive gases using a high corrosive solution in the contaminated removal process. Therefore, the non-radiological risk is considered to be high [44]. Table 6 summarizes the usual occupational dose for each decontamination process and the occupational dose reported in actual cases.

3.2.2. Efficiency

The total radiation of the steam generator is approximately 5 and 95% in the water chamber and tubes, respectively. Therefore, it is important to decontaminate these two parts [20]. There are also processes in which it is difficult to remove contamination with complex shapes, and in this case, it is not effective in reducing radioactive contamination because the contamination inside the tube cannot be removed. Therefore, in evaluating Efficiency, not only DF, but also whether it is applicable to specific materials and shapes, and whether it is a level of technology that can be applied to the actual field is reviewed. Grit blasting exhibits high performance considering it is suitable for the decontamination of fine tubes. For the decontamination of Ringhals NPP steam generator tubes, results showed that over 85% of the activity from the tube bundle was eliminated [22]. Considering chemical decontamination shows high performance in the decontamination of steam generators, a high score was given in terms of efficiency. In particular, MEDOC is a single-step process using a relatively strong acid and shows high performance with hundreds of DFs in BR3 steam generator tubes [46]. In BR3, CORD was used for system decontamination in the initial stage, and the DF for the SG was 16 [47]. Additionally, while DFD can effectively dissolve oxides, is not PWR rich in Cr. Electropolishing is useful for decontamination of flats, corners, concave structures and many other places. However, due to the limitation of the size of the electrolytic cell, it is difficult to decontaminate large materials, and the contaminated area inside parts of tubes or hidden parts cannot be decontaminated completely.

3.2.3. Cost

Although the cost of the decontamination process depends on the type of abrasive material, the unit cost of abrasive blasting is known to be approximately twice the cost of chemical decontamination [36]. In chemical decontamination, there may be differences in cost depending on the type of acid, the number of repetitions, and recycling; however, the same score was given to the cost considering there was no significant difference. . In actual situations, decontamination cycles are determined according to the degree of contamination of the target, and the required time may vary accordingly. Differences in time required lead to differences in cost. For example, in BR3, 2 h of decontamination and 4 h of regeneration of cerium Ⅳ were repeated 30 times in total, which took 1700 man-hours. More than half of this was spent preparing. Considering electropolishing is widely used in the general industry, it is commercially available and inexpensive [48]. The cost of the main equipment is low, and the volume of solution used for decontamination is relatively small.

3.2.4. Waste minimization

In grit blasting, blasting material and oxides are generated considered secondary waste, and the amount is less compared to general chemical decontamination. In the case of Ringhals NPP, 3 m^3 of secondary waste was generated due to the blasting material and oxides used in the blasting process at a throughput of 400m3 [41]. Although electropolishing generates secondary liquid waste-like other chemical processes, the generation volume is relatively small. Secondary liquid waste generated from chemical decontamination requires treatment processes such as ion exchange, precipitation, filtration, and evaporation, and additional waste is generated in this process. CORD shows less secondary waste generation among chemical decontamination with lower concentrations with no K^+ or additives. CORD applied to the four steam generators, pressurizer, and loop piping of Chooz A NPP together generated 27 m^3 of the oxide layer and secondary waste [45].

3.3. Multi-criteria evaluation

3.3.1. Technique for order of preference by similarity to an ideal solution

As shown in Table 8, the first stage in TOPSIS is creating a weighted decision matrix. Based on this matrix, positive and negative ideal solutions are defined. Furthermore, as shown in Table 9, we calculated the Euclidean distance, which represents the relative closeness to the ideal solutions for each alternative.

According to Table 10, in the case of LLW and VLLW as the target, CORD and grit blasting, respectively, were found to be the most optimal option in terms of relative closeness to the ideal solution. Fig. 3 shows the relative closeness between the positive ideal solution of the 1st option and the 5th option.

3.3.2. Preference ranking organization method for enrichment evaluation

This type of preference function is defined as the first step in PROMETHEEE. In this study, there was no particular reason to consider the discontinuity of preference, and a linear function was assumed to minimize the assumption of the shape of the preference function.

Table 10 summarizes the leaving flow, which indicates how much an alternative dominates the others, and the negative preference entering flow, which indicates how much an alternative is dominated by the others.

3.4. Comparison between TOPSIS and PROMETHEE

The decontamination processes were compared by combining TOPSIS and PROMETHEE with the AHP. Table 11 summarizes the evaluation results for each method. The preferred process for each analysis for LLW and VLLW was CORD and grit blasting, respectively. The LLW evaluation showed is a small difference between the 4th and 5th positions owing to the mathematical background of each evaluation method. Despite the different evaluation methods, the results obtained from the MCDM method were similar and showed that the initial level of waste gave a different preference for each process, considering the weights derived through expert advice differed depending on the target waste. For LLW, safety and efficiency were the preferred factors, whereas for VLLWs, cost and waste minimization were the most important factors in

Table 6
Occupational dose estimates for decontamination of a steam generator (man-mSv) [22] [43] [45].

Technique	Occupational Dose	Comments
Abrasive Blasting	50–200	Remote operation
	70	Grit blasting in Ringhals NPP case
CORD	50	CORD in Chooz A NPP case
Electropolishing	100–1000	
Water Chemistry Modification	100–600	
Spray Application of Agent	200–500	Mostly from installation of spray equipment in channel head
Water Jet	50–200	Remote operation
Steam Jet	100–300	Remote operation

Table 7
Evaluation value of each criterion.

		Grit blasting	Electro polishing	MEDOC	DFD	CORD
Safety.	Worker exposure (man-mSv)	100	500	50	50	50
	Conventional Safety	Medium	Low	Medium	Low	High
Efficiency.	DF	10–25	100	100–1000	5–150	20–100
	Decontamination object	High	Low	Low	Medium	Medium
	Experience	High	Medium	Medium	Medium	High
Cost.	Process cost ($\$\bullet m^{-2}$)	52	10	21	21	21
	Equipment cost	Medium	Low	Medium	Medium	Medium
Waste minimization.	Secondary waste	Low	Low	Medium	High	Medium
	Conditioning needs	Low	Medium	Medium	High	Medium

Table 8
Weights decision matrix.

Initial state	Alternatives	Grit blasting	Electro polishing	MEDOC	DFD	CORD
LLW	Worker exposure	0.038	0.019	0.056	0.056	0.056
	Conventional safety	0.050	0.025	0.050	0.025	0.075
	DF	0.008	0.012	0.012	0.008	0.008
	Decontamination object	0.014	0.005	0.005	0.009	0.009
	Experience	0.012	0.008	0.008	0.008	0.012
	Process cost	0.007	0.020	0.013	0.013	0.013
	Equipment cost	0.012	0.018	0.012	0.012	0.012
	Secondary waste	0.038	0.038	0.025	0.013	0.025
	Conditioning needs	0.042	0.028	0.028	0.014	0.028
VLLW	Worker exposure	0.016	0.008	0.024	0.024	0.024
	Conventional safety	0.021	0.011	0.021	0.011	0.032
	DF	0.013	0.019	0.019	0.013	0.013
	Decontamination object	0.023	0.008	0.009	0.015	0.015
	Experience	0.019	0.013	0.013	0.013	0.019
	Process cost	0.003	0.008	0.005	0.005	0.005
	Equipment cost	0.005	0.007	0.005	0.005	0.005
	Secondary waste	0.050	0.050	0.034	0.017	0.034
	Conditioning needs	0.056	0.037	0.037	0.019	0.037

Table 9
Rating of alternatives in terms of relative closeness to ideal solution.

Initial state	Alternatives	d_{ib}	d_{iw}	CC_i	Ranking
LLW	Grit blasting	0.0346	0.0503	0.5927	2
	Electropolishing	0.0650	0.0326	0.3340	5
	MEDOC	0.0344	0.0495	0.5899	3
	DFD	0.0638	0.0384	0.3759	4
	CORD	0.0218	0.0659	0.7512	1
VLLW	Grit blasting	0.0157	0.0548	0.7779	1
	Electropolishing	0.0370	0.0393	0.5151	3
	MEDOC	0.0328	0.0322	0.4948	4
	DFD	0.0558	0.0181	0.2455	5
	CORD	0.0274	0.0380	0.5810	2

decontamination. The high preference for efficiency in LLW can be attributed to the purpose of disposal in the surface facility by lowering the classification level of the waste, given the limited underground silo capacity and difficulty of selecting a disposal facility. VLLW can achieve clearance levels even with a low DF, which indicates that the demand for waste minimization is greater than that for performance. This indicates that it is essential to consider the characteristics of the components or structures when selecting a decontamination process.

Table 10
Leaving and entering flow of alternatives and PROMETHEE II ranking.

Initial state	Alternatives	ϕ^+	ϕ^-	ϕ	Ranking
LLW	Grit blasting	0.051	0.025	0.026	2
	Electropolishing	0.030	0.066	-0.035	4
	MEDOC	0.035	0.023	0.011	3
	DFD	0.012	0.063	-0.052	5
	CORD	0.063	0.014	0.063	1
VLLW	Grit blasting	0.020	0.039	0.039	1
	Electropolishing	0.036	0.043	0.007	3
	MEDOC	0.027	0.023	-0.005	4
	DFD	0.067	0.008	-0.060	5
	CORD	0.021	0.060	0.038	2

3.5. Decontamination scenario

The various decontamination techniques have their own advantages and disadvantages in many respects [49]. Therefore, it is impossible to choose the best approach by merely comparing one component. Even under the same conditions, a more suitable process may exist depending on the situation. Also, combining two or more techniques may yield better results than using one technique. To deal with this quantitatively, a scenario of decontamination of a hypothetical SG was evaluated.

Target selected the Kori Unit 1 steam generator, which was permanently shut down in 2017 and is in the preparatory stage for decommissioning. The Kori Unit 1 steam generator is 21 m in height, 4.5 m in diameter, and weighs about 326 tons, and consists

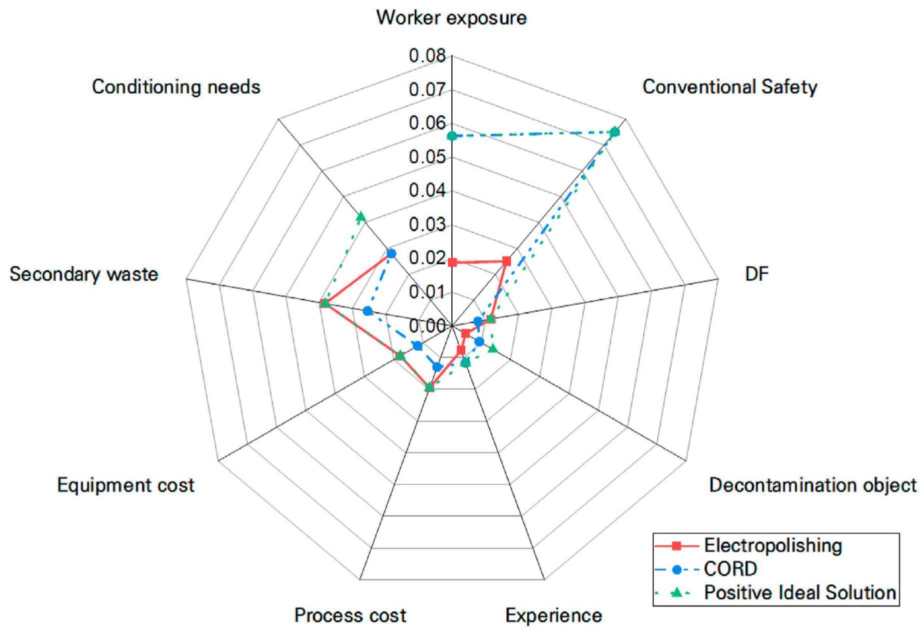

Fig. 3. Relative closeness to the positive ideal solution of each criterion.

Table 11
Results of TOPSIS and PROMETHEE.

Alternatives	LLW		VLLW	
	TOPSIS ranking	PROMETHEE Ranking	TOPSIS ranking	PROMETHEE Ranking
Grit blasting	2	2	1	1
Electropolishing	5	4	3	3
MEDOC	3	3	4	4
DFD	4	5	5	5
CORD	1	1	2	2

Table 12
Initial inventory of SG after 9 years [40] [50].

Radionuclide	Chamber($Bg{\bullet}g^{-1}$)	U-tube($Bg{\bullet}g^{-1}$)	Allowable concentration for clearance ($Bg{\bullet}g^{-1}$)
^{54}Mn	-	0.53	0.1
^{60}Co	15.9	4309	0.1
^{65}Zn	-	0.04	0.1
^{106}Ru	0.03	8.47	0.1
^{144}Ce	-	0.28	10
Total	15.93	4.32E+3	

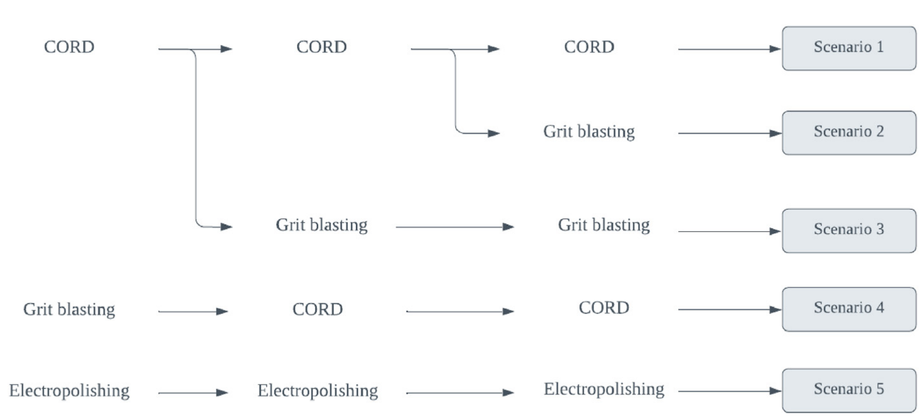

Fig. 4. Decontamination scenarios for evaluation.

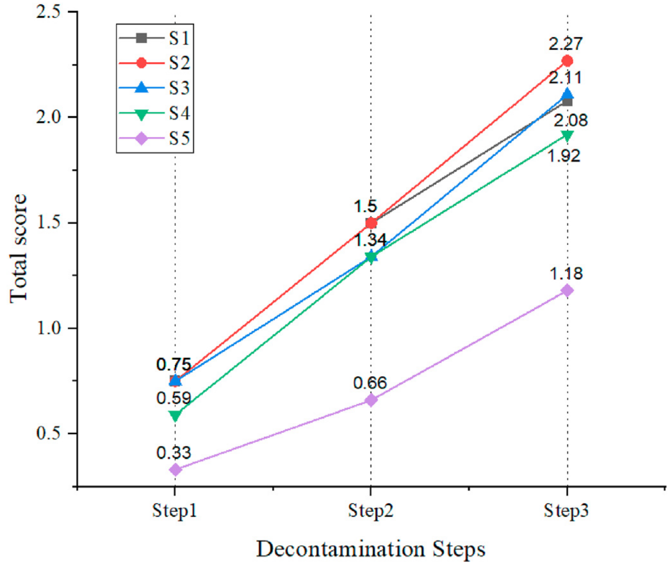

Fig. 5. Score for each stage of the scenario.

of 55 tons of water chamber and 45 tons of customs. The total radioactivity of the steam generator is 3.33 TBq, about 5% in the water chamber and 95% in the tubes. The completion of the waste treatment facility in the turbine building is in 2026, nine years after the permanent shutdown. Therefore, among the 16 nuclides, except for ^{54}Mn, ^{60}Co, ^{65}Zn, ^{106}Ru, and ^{144}Ce, which have long half-lives, the effect of radioactivity is expected to be very insignificant [50]. The decontamination may also be affected by other work plans, such as cutting and waste treatment, but this comparison is not taken into account as it is intended to evaluate decontamination scenarios. SG inventory calculated through previous studies and allowable concentration of each nuclide are summarized in Table 12. In Korea, based on 100 times the clearance level, high concentrations are classified as LLW and low concentrations as VLLW. For self-disposal of waste, the sum of fractions by nuclide must be less than 1 [40].

At least 40,000 DF is required for clearance. The Scenario was composed of CORD and Grit blasting, which had the highest score in the previous evaluation. For comparison, electropolishing, which had a relatively low score, was also added. This is summarized in Fig. 4.

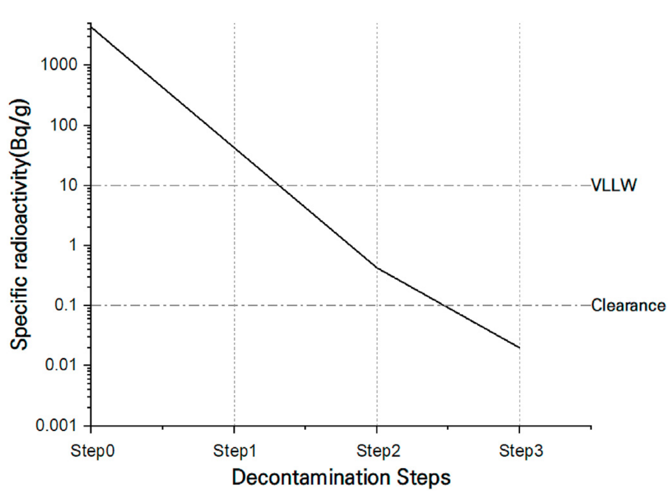

Fig. 6. Specific radioactivity changes in Scenario 2.

Fig. 5 shows the results. Scenario 2 shows the highest score. Scenarios 1 to 3 all started with the CORD, which had the highest score in LLW. This is because it consisted of a process that had a good rating in VLLW when LLW was lowered to VLLW through subsequent decontamination. Fig. 6 shows the change in radioactivity according to the steps.

4. Conclusion

In this study, we performed MCDM analysis on SG to improve the selection of decontamination techniques and evaluated the ranking of alternatives. Because evaluation using only one method can lead to biased results, PROMETHEE and TOPSIS were combined with AHP for the evaluation.

CORD and grit blasting were ranked first as the decontamination methods for LLW and VLLW, respectively, owing to the difference in the initial state of the waste. Furthermore, the expert survey showed that safety and efficiency were important factors in LLW, whereas cost and waste minimization were important factors in VLLW. As the results show, different options can be derived depending on the state of the radioactive waste.

Comparing a single technique is limited considering the evaluation data may vary depending on the circumstances in which the process was applied. It is necessary to evaluate decontamination scenarios in future studies. For example, performing grit blasting after CORD on an LLW target is considered a reasonable scenario. Comparisons between scenarios can reflect the changing state of the waste as the process is applied.

Additionally, one of the important parts of the evaluation method using MCDM is securing appropriate data. Each decontamination process can show very different performances, even for the same process, depending on the contamination state of the object, surface area, shape, and whether the contamination is fixed. Therefore, a standardized data format is necessary as an alternative.

The integrated approach of this study can benefit decision-makers and stakeholders. Furthermore, this approach can be extended to adequately respond to the management of radioactive waste during decommissioning when generating large volumes of waste in a short period.

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.

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) Grant funded by the Ministry of Science and ICT (NRF-2020M2C9A1068162).

References

[1] G. Barariu, R. Georgescu, F. Sociu, C. Bilbie, C. Bucur, The optimization of decontamination methods selected for contaminated areas used in decommissioning of CANDUn6 NPP, J. Energy Power Eng. 4 (2010).
[2] Ö. Kaya, K.D. Alemdar, M.Y. Çodur, A novel two stage approach for electric taxis charging station site selection, Sustain. Cities Soc. 62 (2020), 102396, https://doi.org/10.1016/j.scs.2020.102396.
[3] C. Achillas, C. Vlachokostas, N. Moussiopoulos, G. Perkoulidis, G. Banias, M. Mastropavlos, Electronic waste management cost: a scenario-based analysis for Greece, Waste Manag. Res. 29 (2011) 963–972, https://doi.org/10.1177/0734242X10389104.
[4] M. Bertolini, M. Braglia, G. Carmignani, Application of the AHP methodology in making a proposal for a public work contract, Int. J. Proj. Manag. 24 (2006) 422–430, https://doi.org/10.1016/j.ijproman.2006.01.005.
[5] K.D. Alemdar, Ö. Kaya, M.Y. Çodur, A GIS and microsimulation-based MCDA

approach for evaluation of pedestrian crossings, Accid. Anal. Prev. 148 (2020), https://doi.org/10.1016/j.aap.2020.105771.
[6] Y.J. Zhang, Z.R. Huang, F.Y. Zhao, Y. Wang, Mathematical modeling and evaluation of the safety culture for the operating nuclear power plants in China: critical review and multi-criteria decision analysis, Ann. Nucl. Energy 168 (2022), 108871, https://doi.org/10.1016/J.ANUCENE.2021.108871.
[7] I. Erol, S. Sencer, A. Özmen, C. Searcy, Fuzzy MCDM framework for locating a nuclear power plant in Turkey, Energy Policy 67 (2014) 186–197, https://doi.org/10.1016/J.ENPOL.2013.11.056.
[8] R. Gao, H.O. Nam, W. Il Ko, H. Jang, National options for a sustainable nuclear energy system: MCDM evaluation using an improved integrated weighting approach, Energies 10 (2017), https://doi.org/10.3390/en10122017.
[9] M.A. Ebadian, J.F. Boudreaux, S. Chinta, S.H. Zanakis, Decision Analysis System for Selection of Appropriate Decontamination Technologies, Federal Energy Technology Center Morgantown (FETC-MGN), Morgantown, WV, 1998.
[10] G. Dottavio, M.F. Andrade, F. Renard, V. Cheutet, A.-L. Ladier, S. Vercraene, P. Hoang, S. Briet, R. Dachicourt, Logistical optimization of nuclear waste flows during decommissioning, 8th Int. Conf. Energy Manag. 10 (2016) 968–973.
[11] J.S. Song, S.S. Shin, S.H. Lee, A study on the application of EXPERT-CHOICE technique for selection of optimal decontamination technology for nuclear power plant of decommissioning, J. Nucl. Fuel Cycle Waste Technol. 15 (2017) 231–237, https://doi.org/10.7733/jnfcwt.2017.15.3.231.
[12] K.S. Jeong, S.K. Park, I.H. Hahm, J.H. Ha, S.J. Min, S.B. Hong, B.K. Seo, B. Lee, D.H. Kim, J.H. Kim, S.Y. Jeong, S.M. Ahn, J.J. Lee, B.S. Lee, Approach to optimization of risk assessment based on an evaluation matrix for decommissioning processes of a nuclear facility, Ann. Nucl. Energy 128 (2019) 53–62, https://doi.org/10.1016/J.ANUCENE.2018.12.049.
[13] S.J. K, S. ha B, Sang Don Park, The enhancement strategy on national cyber capability using hybrid methodology of AHP and TOPSIS, Korea converg, Secur. Assoc. 15 (2015) 43–55.
[14] T.L. Saaty, A scaling method for priorities in hierarchical structures, J. Math. Psychol. 15 (1977) 234–281, https://doi.org/10.1016/0022-2496(77)90033-5.
[15] C.-L. Hwang, K. Yoon, Methods for multiple attribute decision making, in: Mult. Attrib. Decis. Mak. Methods Appl. A State-Of-The-Art Surv., Springer Berlin Heidelberg, Berlin, Heidelberg, 1981, pp. 58–191, https://doi.org/10.1007/978-3-642-48318-9_3.
[16] J.-P. Brans, Y. De Smet, PROMETHEE methods, in: S. Greco, M. Ehrgott, J.R. Figueira (Eds.), Mult. Criteria Decis. Anal. State Art Surv., Springer, New York, New York, NY, 2016, pp. 187–219, https://doi.org/10.1007/978-1-4939-3094-4_6.
[17] A. Guitouni, J.M. Martel, Tentative guidelines to help choosing an appropriate MCDA method, Eur. J. Oper. Res. 109 (1998) 501–521, https://doi.org/10.1016/S0377-2217(98)00073-3.
[18] J.P. Brans, P. Vincke, A preference ranking organisation method: (the PROMETHEE method for multiple criteria decision-making), Manage. Sci. 31 (1985) 647–656. http://www.jstor.org/stable/2631441.
[19] J.S. Song, M.Y. Jung, S. Lee, A study on the applicability for primary system decontamination through analysis on NPP decommission technology and international experience, J. Nucl. Fuel Cycle Waste Technol. 14 (2016) 45–55.
[20] M. Walberg, J. Viermann, M. Beverungen, L. Kemp, A. Lindström, G.N.S. Gesellschaft, K.S. Gmbh, B. Chaussee, Disposal of steam generators from decommissioning of PWR nuclear power plants, IYNC (2008), No.158, 2008.
[21] H.D. Mathieu Ponnet, Michel Klein, Vincent Massaut, B.N. SCK•CEN, Thorough Chemical Decontamination with the MEDOC Process: Batch Treatment of Dismantled Pieces or Loop Treatment of Large Components Such as the BR3 Steam Generator and Pressurizer Thorough Chemical Decontamination with the MEDOC Process: Batch Treatment, 2003, pp. 1–9.
[22] A. Lindström, B. Wirendal, M. Lindberg, NEW TREATMENT CONCEPT FOR STEAM GENERATORS- TECHNICAL ASPECTS, Waset Manag., 2007.
[23] C. Topf, Full system decontamination (FSD) with the CORD ® family prior to decommissioning-experiences at the German NPP obrigheim 2007, Iync (2008) 20–26.
[24] L.S. Belda, Decontamination in preparation for dismantlement - AREVA's chemical decontamination technologies, projects performed and results obtained in the period 2011-2016, in: Curr. Emerg. Methods Optimising Saf. Effic. Nucl. Decommissioning, 2017.
[25] IAEA, Decommissioning of Nuclear Facilities: Decontamination, Disassembly and Waste Management, 1983, p. 94. http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/15/018/15018658.pdf.
[26] B. Krause G. Amcoff, J. Robinson, Options for Steam Generator Decommissioning, vol. 10, 2016, pp. 103–106.
[27] G.N. Kim, M.W. Lee, H.M. Park, W.K. Choi, K.W. Lee, Abrasive blasting technology for decontamination of the inner surface of steam generator tubes, Nucl. Eng. Technol. 43 (2011) 469–476, https://doi.org/10.5516/net.2011.43.5.469.
[28] OECD/NEA, Decontamination and Dismantling of Radioactive Concrete Structures A Report of the NEA Co-operative Programme on Decommissioning (CPD) Decontamination and Dismantling of Radioactive Concrete Structures, 2011.
[29] M. Ponnet, Metal decontamination techniques used in decommissioning activities, in: Eur. Nucl. Decommissioning Train, Facil., 2002.
[30] Petri Kinnunen, ANTIOXI-decontamination Techniques for Activity Removal in Nuclear Environments, 2008, p. 58. https://www.vtt.fi/inf/julkaisut/muut/2008/VTT-R-00299-08.pdf.
[31] T. Yoon, S. Kim, J. Kim, J. Kim, S. Lee, Analysis on the Current Status of Chemical Decontamination Technology of Steam Generators in the Oversea Nuclear Power Plants, NPPs), 2015, pp. 29–31.
[32] EPRI, Decontamination of Reactor Systems and Contaminated Components for Disposal or Refurbishment Developments and Experience with the EPRI DFD Chemical Decontaminati O N Process, 2001.
[33] EPRI, Review of Plant Decontamination Methods: 1988 Update, 1989.
[34] E. Babilas, B. Brendebach, Selection and evaluation of decontamination and dismantling techniques for decommissioning of large NPPs components, Prog. Nucl. Energy 84 (2015) 108–115, https://doi.org/10.1016/J.PNUCENE.2014.09.005.
[35] IAEA, Selection of Decommissioning Strategies: Issues and Factors. Report by an Expert Group, 2005. IAEA-TECDOC-1478.
[36] EPA, Technology Reference Guide for Radiologically Contaminated Surfaces, 2006.
[37] ACS Committee on Chemical Safety, Identifying and Evaluating Hazards in Research Laboratories, 2015. https://www.acs.org/content/dam/acsorg/about/governance/committees/chemicalsafety/publications/identifying-and-evaluating-hazards-in-research-laboratories.pdf.
[38] KAERI, Study on the State-Of-The Arts Approaches and Methodologies for the Decommissioning Cost Estimation of Nuclear Facilities, 2004.
[39] Y.S. Hwang, C.H. Kang, S.G. Kim, H.S. Park, Progress of radioactive waste management in Korea, Prog. Nucl. Energy 42 (2003) 159–177, https://doi.org/10.1016/S0149-1970(03)80007-0.
[40] MOTIE, RADIOACTIVE WASTE MANAGEMENT ACT, 2017.
[41] A. Lindström, B. Wirendal, M. Lindberg, New treatment concept for steam generators technical aspects, in: Waste Manag. Symp. Conf. Sess., 2007, pp. 3–24.
[42] M.G. Carmichael, S. Aldini, R. Khonasty, A. Tran, C. Reeks, D. Liu, K.J. Waldron, G. Dissanayake, The ANBOT: an intelligent robotic Co-worker for industrial abrasive blasting, in: 2019 IEEE/RSJ Int. Conf. Intell. Robot. Syst., 2019, pp. 8026–8033, https://doi.org/10.1109/IROS40897.2019.8967993.
[43] G.R. Hoenes, M.A. Mueller, W.D. Mccormack, Radiological Assessment of Steam Generator Removal and Replacement : Update and Revision National Technical Informati on Service, 1980. https://digital.library.unt.edu/ark:/67531/metadc835289/.
[44] J. Moon, S. Kim, C. Wangkyu, B. Choi, D. Chung, B. Seo, The status and prospect of decommissioning technology development at KAERI, J. Nucl. Fuel Cycle Waste Technol. 17 (2019) 139–165, https://doi.org/10.7733/jnfcwt.2019.17.2.139.
[45] L. AITAMMAR, Chooz-A steam generators characterization, in: PREDEC 2016 Chooz-A Steam Gener. Charact., n.d.
[46] SCK•CEN, THE DECOMMISSIONING OF THE BR3 STEAM GENERATOR, 2005.
[47] M. Klein, M. Rahier, R. Mandoki, Ponnet, Comparison of Thorough Decontamination Techniques on Dismantled Pieces of a PWR Reactor, A, IAEA, 1998.
[48] OECD/NEA, Decontamination Techniques Used in Decommissioning Activities, 1999.
[49] S. Liu, Y. He, H. Xie, Y. Ge, Y. Lin, Z. Yao, M. Jin, J. Liu, X. Chen, Y. Sun, B. Wang, A state-of-the-art review of radioactive decontamination technologies: facing the upcoming wave of s. https://doi.org/10.3390/su14074021, 2022, 14.
[50] Y.J. Son, S.J. Park, J. Byon, S. Ahn, The assessment and reduction plan of radiation exposure during decommissioning of the steam generator in Kori unit 1, J. Nucl. Fuel Cycle Waste Technol. 16 (2018) 377–387, https://doi.org/10.7733/jnfcwt.2018.16.3.377.