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Options Manageing for Radioactive Metallic Waste From the Decommissioning of Kori Unit 1

고리1호기 해체시 발생할 방사성금속폐기물 관리 옵션 연구

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The purpose of this paper is to evaluate several leading options for the management of radioactive metallic waste against a set of general criteria including safety, cost effectiveness, radiological dose to workers and volume reduction. Several options for managing metallic waste generated from decommissioning are evaluated in this paper. These options include free release, controlled reuse, and direct disposal of radioactive metallic waste. Each of these options may involve treatment of the metal waste for volume reduction by physical cutting or melting. A multi-criteria decision analysis was performed using the Analytic Hierarchy Process (AHP) to rank the options. Melting radioactive metallic waste to produce metal ingots with controlled reuse or free release is found to be the most effective option.

Keywords: Decommissioning, Decontamination, Radioactive scrap metal, Melting technology VLLW, LLW, Volume reduction

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방사성금속폐기물의 관리 옵션들을 안전성, 경제성, 작업자 피폭, 부피 감용 등의 선별 기준을 적용하여 비교 평가하였다. 원전 해체로부터 발생하는 금속폐기물의 관리 옵션에는 무구속 방출, 제한적 재사용, 그리고 직접 처분이 있다. 고려된 각각의 옵션들은 금속폐기물의 절단과 용융에 의한 부피감용을 수반한다. AHP기법을 적용하여 각 옵션들의 순위를 부여하였다. 방사성금속폐기물을 용융하여 금속 잉곳을 제조한 후 제한적 재이용 또는 무구속 방출하는 방안이 가장 효율적인 옵션으로 도출되었다.

중심단어: 원전 해체, 제염, 방사성 금속스크랩, 용융, 극저준위폐기물, 저준위폐기물, 감용

1. Introduction

Korea's first commercial nuclear power plant (NPP), Kori Unit 1, will be permanently shut down and decommissioned in 2017. Kori Unit 1 will be the first commercial reactor to be closed after an additional 10 years of extended operation. A large amount of waste will be generated during the nuclear decommissioning process, which will be divided into radioactive waste as well as non-radioactive waste, and a considerable amount of slightly contaminated waste will be generated. In particular, most of the nuclear components, such as reactor pressure vessel (RPV), steam generator (SG), pumps, and pipes are metallic waste. In many cases, these components include valuable materials that can be recycled, such as stainless steel and Inconel [1], thus a reuse option should be considered.

The purpose of this paper is to evaluate several leading options for managing this waste using the most important criteria including safety, cost effectiveness, radiological dose to workers, and volume reduction. These criteria are used to rank order the leading options. Some of the metallic waste will be classified as intermediate level waste which presents different challenges for treatment and disposal and will be considered separately. Therefore, the scope of this paper is limited to LLW and VLLW.

Several options for managing the metallic wastes from decommissioning are evaluated in this paper. Each of these options may involve treatment of the metal waste by physical volume reduction or melting and may be suitable for land disposal, free release or controlled reuse in the Korean nuclear industry.

In order to develop a set of options and criteria to rank the options, the objectives for radioactive metallic waste management are first defined. The objectives are based on IAEA Policies and Strategies for the Decommissioning of Nuclear and Radiological Facilities [2] and are shown in Fig. 1. The top level objective, manage radioactive metallic waste, has five primary objectives. These are shown as optimize for land disposal, optimize for reuse, waste form stability, minimize worker exposure, and cost. The land disposal objective requires volume reduction and in some cases may benefit from lowering the disposal classification by concentration averaging. The reuse objective has two subobjectives, free release and controlled reuse such as using the metal in new reactor construction. The waste form stability, worker exposure and cost are also primary objectives.

The reuse objective could be achieved by transferring some of the metallic waste to the commercial scrap metal industry for processing but this option is dismissed from consideration due to strong opposition within the scrap metal industry and generally low public acceptance [3].

The cost of managing radioactive waste is a significant factor in the total decommissioning costs that can be reduced through waste minimization and volume reduction. Because of Korea's high unit disposal costs for radioactive waste, these costs are expected to be considerably higher than other countries. The high cost and limited disposal capacity in Korea has required that a target amount of waste

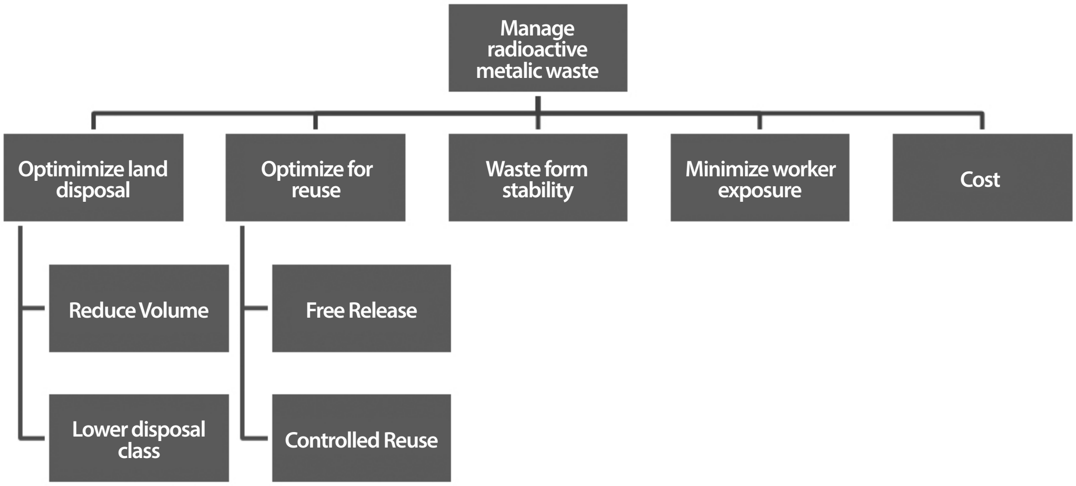

Fig. 1. Objectives Hierarchy for Managing Radioactive Metallic Waste.

to be disposed is designated as a maximum of 14,500 drums for each nuclear power plant [4]. This makes volume reduction a strong consideration in this analysis. There is limited cost data for the options considered in this paper so it is not possible to directly compare the costs of options and subjective evaluation of costs was used in AHP. In general, high unit disposal costs and higher front-end costs of melting was considered in the pairwise comparisons.

Metal waste from bulky components could be disposed of directly in the repository facility with or after processing and cutting. The direct disposal option while the simplest from a technology perspective produces a large volume of waste. Therefore, only options that include volume reduction are being considered in this study. One treatment option, melting metallic waste into ingots results in both decontamination, volume reduction the potential for reuse or a stable waste form. Although it is a more complex technology it has been used internationally with success.

Our previous study evaluated melting technology applicable to radioactive metallic waste management for the Kori Unit 1 [5]. The conceptual design and process flow of the melting facility considering the location of the NPP and repository in Korea was presented. The results of this study are used as the basis for the evaluation of the melting technology treatment option in this paper.

Melting technology is generally regarded as a promising technology for metallic waste treatment. Several European countries, including Germany, Sweden, and France, have applied melting technology in the treatment of VLLW and LLW metallic waste. It has been shown that melting can limit the occurrence of radioactive contamination, reduce the amount of waste for disposal and treatment, and allow the recycle valuable metals. In addition, the scale of melting operations is suitable for the large quantities of decommissioning metallic waste. However, there is still insufficient infrastructure in Korea for establishing melting facilities and currently there are no regulatory guidelines. Implementation of melting technology will require further development and a regulatory basis for this treatment option to be used.

2. Radioactive Metallic Waste

2.1 Waste Classification in Korea

The classification of radioactive waste in Korea is defined as follows [6]:

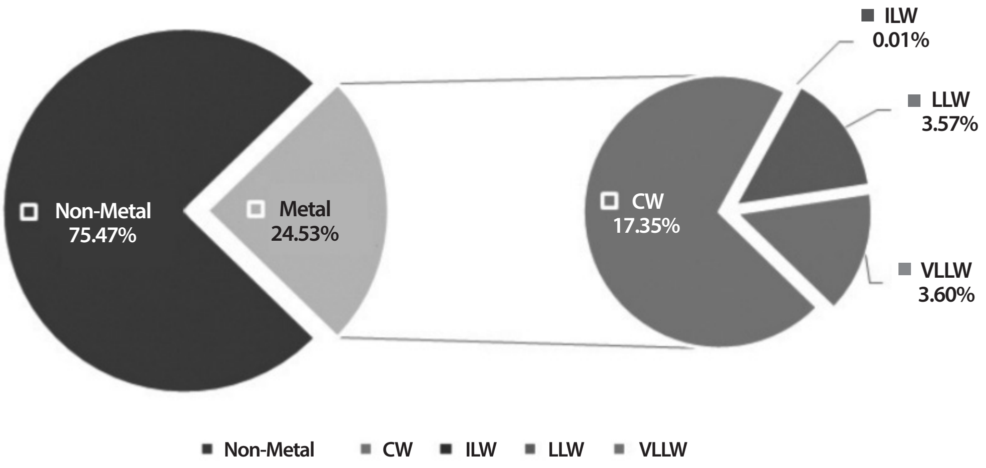

Fig. 2. Estimate of Metallic Waste from Decommissioning Kori 1 [5].

- ILW: Radioactive concentration among the intermediate and low level radioactive waste is more than the specified concentration in NSSC Notice No. 2014-003, Table 2.
- LLW: Radioactive concentration among the intermediate and low level radioactive waste is 100 times or more the permissible concentration of clearance and less than the specified concentration in NSSC Notice No. 2014-003, Table 2.
- VLLW: Radioactive concentration among the intermediate and low level radioactive waste is more than the permissible concentration of clearance and 100 time less than the concentration of clearance.
- Clearance Level Waste (CW): Radioactive concentration less than the permissible concentration of clearance in NSSC Notice No. 2014-003.

2.2 Estimated Metallic Waste Inventory for Kori-1

An estimate of metallic waste for Kori Unit 1 decommissioning is shown in Fig. 2 [5]. During the decommissioning period, large quantities of metallic wastes are generated as CW, LLW and VLLW.

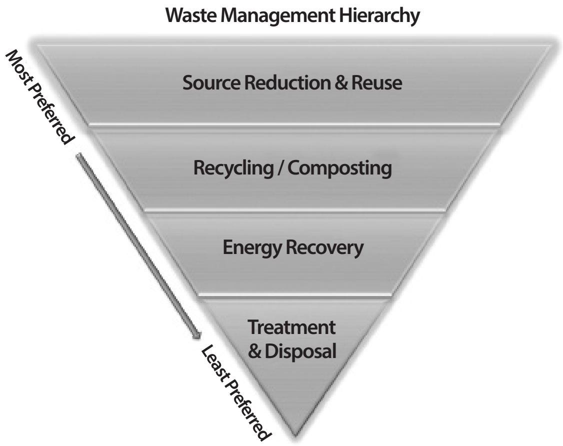

Fig. 3. General Waste Management Hierarchy [7].

3. Methodology

3.1 General Waste Management Hierarchy

Options and criteria are developed from the objectives hierarchy. The options for management of radioactive metallic waste will be evaluated against the set of criteria. The options can be considered as a subset of the general waste management hierarchy shown in Fig. 3 [7].

This general hierarchy is considered in the options development and evaluation. The primary objective of waste management is reduction at the source and for the purposes of this study, melting technology gives the ability to recycle radioactive metallic waste which is preferable to land disposal. This approach is appropriate for the preliminary screening of options and selection of the most appropriate option. A similar approach was used by Sandia National Laboratories when the US Department of Energy was considering recycling and melting technology as options for the large quantities of metallic waste from reactors and nuclear material production and fabrication facilities [8].

3.2 Options in this Study

Two options are selected from the objectives hierarchy to be combined with treatment options:

- Optimize for land disposal
- Optimize for reuse or free release

Two treatment options considered are:

- Volume reduction by physical methods
- Melting

3.3 Treatment Option Descriptions

Volume reduction by physical methods in this paper is defined as a process performed on metal waste that is to be packaged for disposal in containers. The sectioning of large components such as the reactor vessel, steam generator, tanks and metal structures must be performed regardless of the treatment (decontamination, volume reduction by cutting, or by melting is used for the final size reduction. The current method most widely used for volume reduction is mechanical cutting. Other methods such as thermal or laser cutting are therefore not considered.

The criteria used to evaluate the options are also derived from the objectives hierarchy previously shown in Fig. 1. The criteria are as follows:

- Potential for worker exposure (containment)
- Waste form stability
- Minimize secondary waste generation
- Volume reduction
- Lowering the classification of the radioactive waste
- Cost (unit disposal cost and melting capital costs)

The final options to be evaluated are:

- Land disposal with physical volume reduction
- Land disposal with melting technology applied
- Controlled reuse with melting
- Free release with melting

3.4 Ranking

The Analytic Hierarchy Process (AHP) is a tool for complex decision making. It reduces complex decisions to a series of pairwise comparisons, and then synthesis the results. In this study, the AHP evaluated the criteria and options as shown in Fig. 4. The AHP method involved two steps. First, the relative importance of the criteria were ranked. For example, in this study the "criteria minimize worker exposure" was ranked more important than the "waste form stability". The pairwise comparison was performed for all the combinations of criteria taken two at a time. Then a similar pairwise comparison was made for each pair of options against each of the criteria. For example "melting and controlled release" was compared to "physical volume reduction" based on the performance for the "minimize worker exposure" criteria. This was repeated for all pairs of options against each of the criteria. The AHP then synthesized all these pairwise comparisons into the overall ranking of the options.

For this study the evaluation criteria and alternative options have been previously defined. Ranking the options against the criteria was informed by Buckentin et al. 1996 [8] and Seo et al. 2017 [5]. Summary rankings adapted from Buckentin et al. 1996 [8] are shown in Table 1.

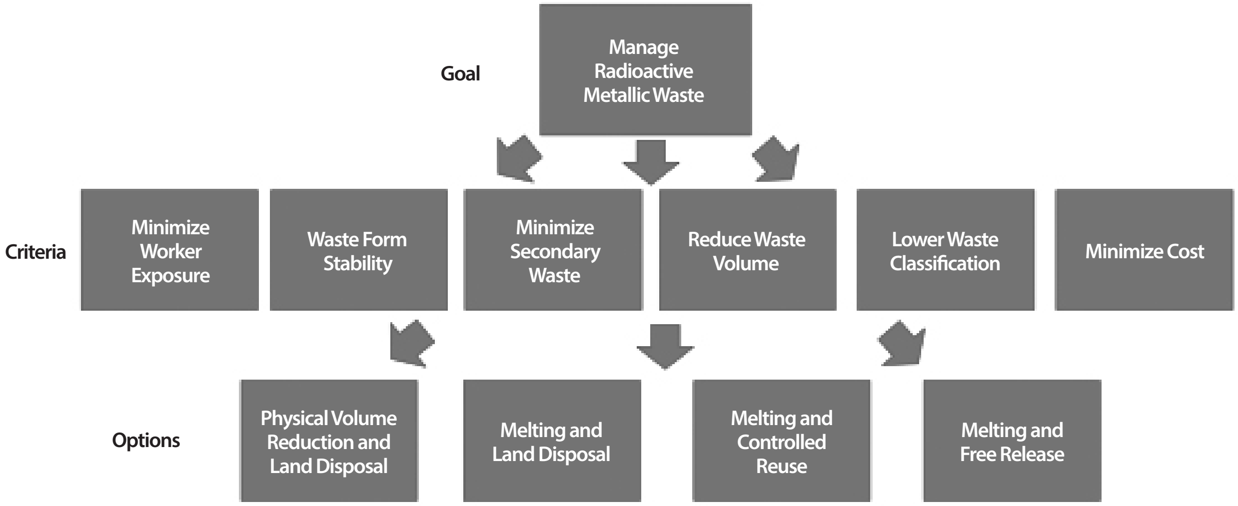

Fig. 4. Structure of Analytic Hierarchy Decision Model.

Table 1. Safety and Environmental Ratings of Radioactive Disposition Methods (Rated 1-best to 5-worst) [8]

	Personnel Exposure		Residual Hazards			
	Limit Physical Contact	Limit Inhalation Hazards	Volume Reduction	Waste Long Term Stability	Limit Process Dust and Fumes	Potential to Retain Resource Value
Size Reduction Land Disposal	5	4	2	3	3	5
Plasma Arc Centrifugal Melting	1	1	1	1	1	1
Electric-Arc Melting	4	5	1	2	5	3
Air Induction Melting	3	4	1	2	4	3
Vacuum Induction Melting	2	1	1	2	1	2
Vacuum Induction Melting with Electroslag Remelting	1	2	1	1	2	1

The ratings from Table 1 were used to inform the subjective pairwise ranking of options against the criteria in the AHP. Personal exposure criteria in the AHP was based on the worst case of the “Limit Physical Contact” and “Limit Inhalation Hazards” and “Limit Dust and Fumes” from Table 1.

Table 1 Notes

Personal Exposure [8]:

Size reduction and the five melting techniques require more or less size reduction and produce a range of dust and fumes which drives the ratings in Table 1 for physical contact, inhalation hazards and process dust and fumes.

Size Reduction, Packaging and Burial was ranked unfavorably because of the necessity of manually torch cutting the scrap into pieces, followed by the repeated contact necessary to catalogue and sort the pieces into containers.

Plasma Arc Centrifugal Melting avoids exposure, as feed stock can be contained in drums and the process is completely enclosed.

Electric Arc Melting furnaces require finely divided scrap to avoid electrode damage and as such require substantial feed stock preparation. In addition, this process generates a great deal of dust and fume.

Air Induction Melting generates about 20% of the dust generated by *Electric Arc Melting*, but still requires size reduction of scrap.

Vacuum Induction Melting followed by *Electroslag Remelting*, exposure risks are low because the scrap metal is reduced to a monolithic, decontaminated ingot.

Residual Hazards [8]:

Size Reduction, Packaging and Burial reduces the volume of the metal only in the sense that its compactness is increased. The packaged waste is moderately stable provided the storage containers are not breached.

Plasma Arc Centrifugal Melting produces an ingot that is completely dense and very stable. Because the process is completely enclosed, capture and containment of process dust is facilitated.

Electric Arc Melting also renders the metal completely dense, but as by product produces contaminated waste in the form of spent refractory, slag, and process dust.

Air Induction Melting produces a completely dense ingot and a somewhat lesser amount of spent refractory.

Vacuum Induction Melting ranks better because the vacuum enclosure lends itself to the containment of process dust. When *Vacuum Induction Melting* is followed by *Electroslag Remelting*, spent refractory from the vacuum induction furnace can be recycled as ESR slag and thus rendered completely dense and stable.

Table 2. Overall Results of AHP

Options	Normalized Score (0 to 1)	Ranking
Controlled Release/Melting	.2869	1
Free Release/Melting	.2869	1
Land Disposal/Physical Volume Reduction	.2717	3
Land Disposal/Melting	.1545	4

Potential to Retain Resource Residual Value [8]:

Volume Reduction, Packaging and Burial rank unfavorably because die material is not available for reuse.

Plasma Arc Centrifugal Melting does not fully decontaminate the material.

Electric Arc Melting and *Air Induction Melting* are better at decontamination, but ingots may contain contamination with a detrimental effect on the material properties.

Vacuum Induction Melting is not a complete decontamination process.

Vacuum Induction Melting followed by *Electroslag Remelting* produces a decontaminated ingot that has physical properties equal to or better than those of the original material.

4. Results

The results of the pairwise comparisons for criteria are summarized as follows: Reducing worker exposure was given the highest importance in the criteria pairwise ranking (.627) followed by cost and volume reduction with equal importance since they are not independent (.151) and finally waste form stability and lower waste classification criteria rated lowest relative importance (.0353). Normalized rankings are given in parentheses for a 0 to 1 scale.

The results of the overall ranking of the options in the AHP is shown in Table 2.

The results are internally consistent within the AHP model and controlled reuse and free release with melting were both ranked to be of equal merit and the most desirable options.

These results were driven by the potential to reduce worker exposure for some melting technologies compared to physical volume reduction, and volume reduction advantage of melting as compared to physical volume reduction by cutting. Melting generally performs better than physical volume reduction for some of the melting technologies. No cost benefit was assigned in the ranking to differentiate between free release and controlled release as the economic value and public acceptance issues related to free release will require further study. Therefore, these two options are assigned an identical ranking in the AHP and the results reflect that choice.

Land disposal with melting was ranked lower than the other three options. This is driven by the high unit disposal cost combined with a higher cost for implementing melting technology over physical volume reduction. Currently the unit disposal costs for LLW and VLLW are the same in Korea. Therefore any benefit from lowering waste classification by melting is not realized at this time.

5. Conclusions

There will be a large amount of radioactive contaminated metal produced by the decommissioning of Kori 1 power plant and subsequent NPP decommissioning in Korea. Melting radioactive metal waste offers several benefits when compared to volume reduction by physical cutting. It can be performed on a scale suitable for the quantities of metallic waste from decommissioning and it produce useful output products subject to controlled use within the Korean nuclear industry and potentially for free release.

The use of melting technology for treatment of radioactive metallic performs well when considering personnel exposure, residual hazards, and ability to reduce waste volume, waste classification and preliminary considerations of cost. Additional research for implementation of melting technology for radioactive metallic waste from decommissioning in Korea should include more detailed studies of economic, national policy, public acceptance, and risk management issues.

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