Preliminary Evaluation of Decommissioning Wastes for the First Commercial Nuclear Power Reactor in South Korea

Kyomin Lee, Joohee Kim, Sangho Kang

***Abstract*—**The commercial nuclear power reactor in South Korea, Kori Unit 1, which was a 587 MWe pressurized water reactor that started operation since 1978, was permanently shut down in June 2017 without an additional operating license extension. The Kori 1 Unit is scheduled to become the nuclear power unit to enter the decommissioning phase. In this study, the preliminary evaluation of the decommissioning wastes for the Kori Unit 1 was performed based on the following series of process: firstly, the plant inventory is investigated based on various documents (i.e., equipment/ component list, construction records, general arrangement drawings). Secondly, the radiological conditions of systems, structures and components (SSCs) are established to estimate the amount of radioactive waste by waste classification. Third, the waste management strategies for Kori Unit 1 including waste packaging are established. Forth, selection of the proper decontamination and dismantling (D&D) technologies is made considering the various factors. Finally, the amount of decommissioning waste by classification for Kori 1 is estimated using the DeCAT program, which was developed by KEPCO-E&C for a decommissioning cost estimation. The preliminary evaluation results have shown that the expected amounts of decommissioning wastes were less than about 2% and 8% of the total wastes generated (i.e., sum of clean wastes and radwastes) before/after waste processing, respectively, and it was found that the majority of contaminated material was carbon or alloy steel and stainless steel. In addition, within the range of availability of information, the results of the evaluation were compared with the results from the various decommissioning experiences data or international/national decommissioning study. The comparison results have shown that the radioactive waste amount from Kori Unit 1 decommissioning were much less than those from the plants decommissioned in U.S. and were comparable to those from the plants in Europe. This result comes from the difference of disposal cost and clearance criteria (i.e., free release level) between U.S. and non-U.S. The preliminary evaluation performed using the methodology established in this study will be useful as a important information in establishing the decommissioning planning for the decommissioning schedule and waste management strategy establishment including the transportation, packaging, handling, and disposal of radioactive wastes.

***Keywords*—**Characterization, classification, decommissioning, decontamination and dismantling, Kori 1, radioactive waste.

I. Introduction

THE Korean Hydro & Nuclear Power Co., Ltd (KHNP) must submit the final decommissioning plan (FDP) to the Nuclear Safety and Security Commission (NSSC) within 5 years after the permanent shut down of Kori Unit 1(hereafter Kori-1). After that, the NSSC will be on the process of assessment of the safety of decommissioning for FDP, and, when approved by the NSSC, the decommissioning and dismantling of Kori-1 will get started. The Kori-1 has selected the immediate dismantling after the permanent shutdown (DECON), since it is expected that it would be less expensive than other deffered dismantling (SAFSTOR) options, and minimize the potential for increased radioactive waste burial costs or unavailability of a burial site. In developing the decommissioning plan for Kori-1 based on the DECON alternative, the exact estimation of the expected wastes is one of the most important information to be required. In this study, the preliminary evaluation of the decommissioning wastes to be potentially generated from the Kori-1 decommissioning was carried out considering the new classification criteria [4], and waste management strategies established in this study.

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II. Reference Plant

The Kori-1, the first commercial nuclear power plant (NPP) in South Korea, is selected as the reference reactor. The Kori-1, which is a two-loop Westinghouse pressurized water reactor (PWR) type with 587 MWe, began the commercial operation in 1978. Since 1978, it had been operated with planned preventative maintenance every 15 months, and was refurbished in 2007 for an additional operating license extension. Technical information about Kori Unit 1 is provided in [1].

III. Methodology

Calculation of the decommissioning waste amount to be generated during the dismantling operations of the Kori-1 is carried out by the methodology illustrated in Fig. 1. Firstly, to perform the accurate estimate of the amount of wastes, it is required that a thorough and comprehensive inventory of all the site system components and structures subject to potential radioactive contamination be estimated. Secondly, the radiological conditions (i.e., inner and/or outer surface contaminations and volumetric contaminations) of decommissioning wastes including structures, systems, and components (SSCs) are established using a calculation model and engineering judgement based on operating data and decommissioning experiences, which will be used to estimate the amount of decommissioning wastes that are divided into waste categories including exemption waste (EW), very low-

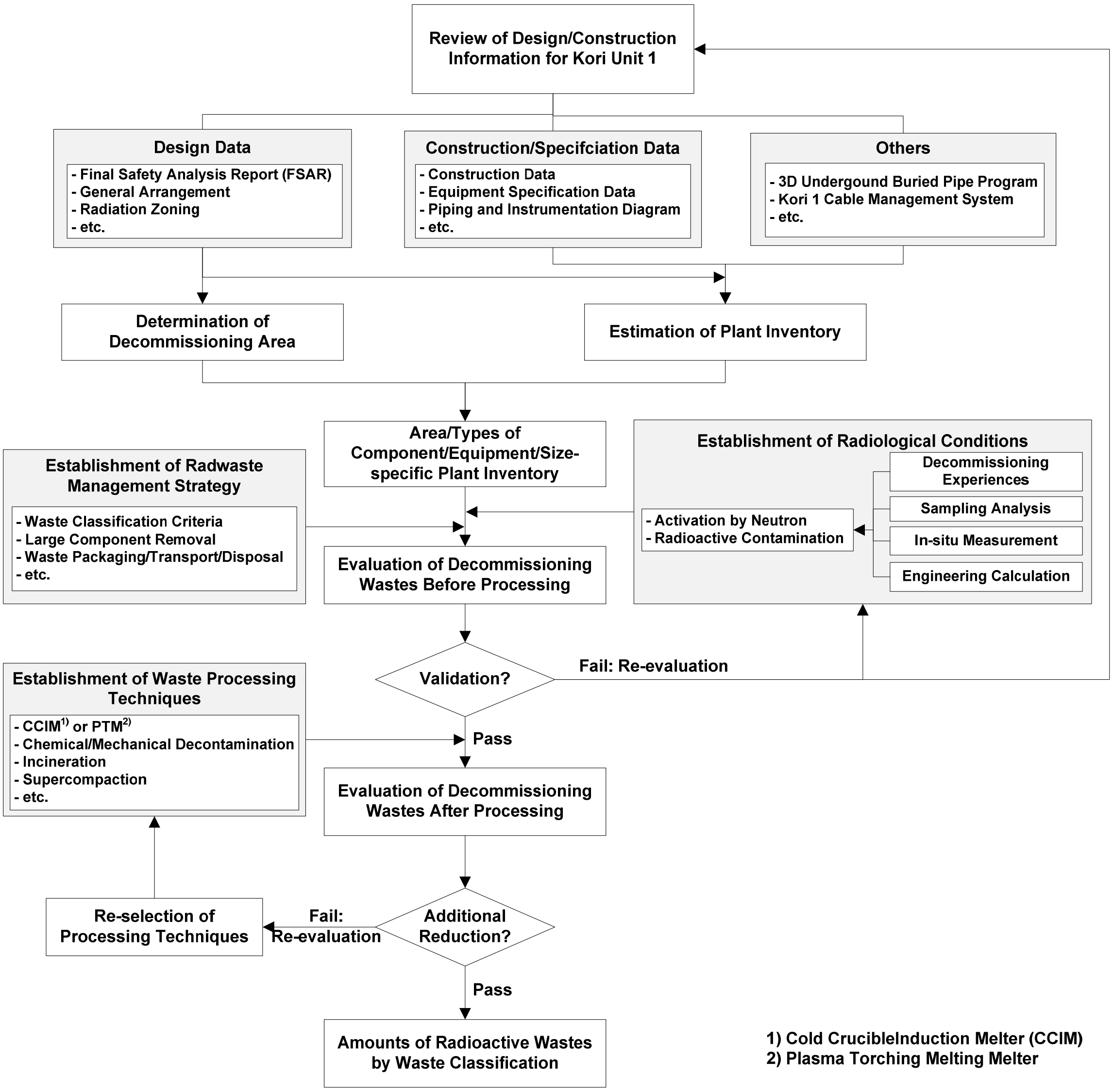


Fig. 1 Flow scheme of evaluating the decommissioning wastes for Kori Unit 1

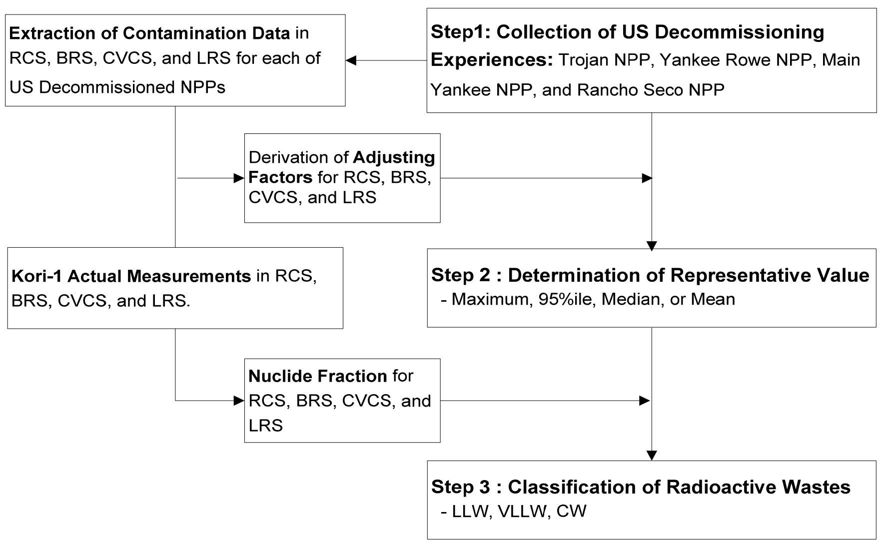


Fig. 2 Flow Diagram of Determining the Radiological Conditions for Kori-1 Systems

level waste (VLLW), low-level waste (LLW), Intermediate-level waste (ILW), and high-level waste (HLW)). Thirdly, the waste management strategies are established including the radioactive waste classification and criteria, the large components removal options (i.e., one-piece removal vs. segmentation), and packaging. In this study, the radwaste transport and disposal concepts are not dealt with.

Forth, the waste processing technologies are used to minimize disposal of radioactive waste. Finally, the waste amount by classification of metals, concrete, resigns from the system decontamination, cable, and others generated from the Kori 1 decommissioning is estimated using the DeCAT program, which was developed by KEPCO-E&C for a decommissioning cost estimation. In the case that the result (or estimation) of the processing-before-decommissioning wastes between Kori-1 and the international decommissioning experiences has a significant difference, the re-evaluation of wastes will be performed based on re-evaluation of the radiological condition and/or plant inventory. Also, considering the capacity of the disposal facility, if necessary, an addition waste processing could be taken into account.

A. Plant Inventory Estimation

The evaluation of the overall plant inventories of the SSCs is performed using the plant operator databases, variable drawings, a reliable valve/piping/equipment list, specification and so on. The lack of the necessary data required to evaluate the inventory (e.g., equipment weights and volume, its location,) is compensated by use of application of sound hypothesis and the informed engineering judgements.

The following categories of elements have been used to estimate total plant inventories in the Kori -1:

- Mechanical and piping system: all process fluid system with its equipment, piping, valve, and accessories;
- Structural and various steel: cranes, liners, supports and miscellaneous steel;
- Air cleanup system: its associated ducts, equipment, dampers and accessories;
- Electrical equipment and cable: cable, cable tray and conduits, and all electrical and I&C equipment;
- Building and structure concrete
- Others: dry active waste (DAW), and hazardous materials (e.g., asbestos containing material (ACM), lead, PCB)

In this study, it is assumed that there would be no expected soil waste that needs to be excavated from the site of the Kori-1 in order to meet the unrestricted site release criteria, because: 1) several data points taken beyond the site boundary indicate that there is no significant soil contamination which is distinguishable from the background levels and 2) the employee interviews and documentation reviews indicated there had been no spill and leakage event during the plant operations. It should be noted that the soil contamination that may be found during the decommissioning of Kori-1 will lead to the significant increase of the waste amount.

The amounts (or volume) of the concrete to be scabbled are estimated based on penetration and spreading of activity, and levels of activity.

In this study, the spent fuels are assumed to be transported to the onsite interim spent fuel storage installation (ISFSI) from the spent fuel storage pool after enough cooling time of more than 5 years and stored in it. Therefore, it is not considered in estimating the decommissioning wastes.

B. Establishment of Radiological Conditions

The total volume of decommissioning wastes to be disposed of as radioactive waste depends on both the radiological conditions and waste processing technology(that will be addressed in Section III.E), which will have an significant impact on cost for decommissioning waste management

Radiological conditions falls into two categories: 1) neutron-activated material and 2) contaminated material including activated corrosion products and/or fission products. Neutron-activated materials are reactor components and concrete structures surrounding the pressure reactor vessel (RPV). Their radioactive level is derived by using the engineering calculation (i.e., MCNP/FISPACT coupling code). The level of contamination can determined by acquiring site-specific radiological characterization data, but since the limited amount of data is only available at this point when the Kori 1 had been still operated (as of May 1, 2017) before permanent shutdown, the appropriate combination of Kori-1 measurement data and the previous U.S. decommissioning experiences from [13], [17]-[21] is used as an alternative method.

As illustrated in Fig. 2, the radioactive levels of the contaminated materials are first estimated based on the characterization data surveyed during the decommissioning of U.S. commercial NPPs, which is then adjusted with the results of the actual measurement/sampling for Kori-1. Estimated results of the volume and/or surface contaminations for the SSCs in RCAs of the Kori-1 are given in Tables I-III.

The electrical equipment and cabling include cables, cable trays and conduits, as well as all electrical equipment are conservatively assumed to have the same level of contamination in the areas where they are located, since they are expected to have only external surface contamination.

C. Radioactive Waste Classification

The activated and/or contaminated materials were classified by combining all the specific activities of various nuclides, which is called the sum of the fraction rule. The sum of the fractions is calculated by dividing each nuclide's concentration by the specific limit for the corresponding nuclide. Table IV presents the waste classification criteria specified in the Notice of NSSC No. 2014-03 in South Korea [4]. As stated in Table I, the highest category belongs to high level waste (HLW), but is not considered in this evaluation since spent nuclear fuels are only fall within this category. Moreover, the analysis results in this study show that any component in RPV internals does not meet the requirement for the HLW classification.

D. Establishment of Radwaste Management Strategy

The one-piece removal of large components such as steam generators and RPV is recently preferable, as it yields significant benefits in terms of dose to the workforce, time for removal, waste volume and decommissioning cost, though it might be balanced by an increase in disposal costs [5], [6].

TABLE I
EXPECTED CONTAMINATION FOR MAJOR KORI-1 ACTIVATED COMPONENTS [3]

Components		Total Inventory (Bq)	Radwaste Classi-fication
Core: Center line	Baffle Plate	3.08E+16	ILW
	Barrel	3.56E+16	ILW
	Baffle Former	5.84E+14	ILW
	Thermal Shield	9.53E+15	ILW
Core: Above	Upper Support Assembly	1.27E+08	VLLW
	Upper Core Plate	5.71E+12	LLW
	Guide Tube	2.65E+10	VLLW
	Upper Support Column	7.71E+10	VLLW
	Thermo-couple Column	N/A[1)]	VLLW
	Hold Down Spring	N/A[1)]	VLLW
Core: Below	Lower Core Plate	5.81E+12	LLW
	Core Support Plate	1.26E+10	VLLW
	Secondary Core Support Plate	N/A[1)]	VLLW
	Secondary Core Support Column	N/A[1)]	VLLW
	Core Support Tube	N/A[1)]	VLLW
Reactor Pressure Vessel		6.71E+15	LLW
Primary Concrete	56% of Primary Concrete: Inner	1.14E+16	LLW
	44% of Primary Concrete: Outer		VLLW

1) Based on the engineering judgement

TABLE II
EXPECTED CONTAMINATION FOR MAJOR KORI-1 SYSTEMS

Systems	Contamination (Bq/g)	Radwaste Classi-fication
Condenser Air Removal System	1.74E-01	CW
Auxiliary Steam System	4.87E+00	VLLW
Steam Generator Blowdown System	6.14E-01	VLLW
Boron Recovery System	2.61E+03	LLW
Component Cooling Water System	1.59E+00	VLLW
Condensate System	1.64E-01	CW
Chemical & Volume Control System	1.42E+04	LLW
Circulating Water System	3.88E-01	CW
Main Feedwater System	2.33E-01	VLLW
Main Steam	3.23E-03	CW
Primary Makeup Water System	2.85E+03	LLW
Reactor Coolant System	8.55E+02	LLW
Refueling Water System	2.61E+02	LWW
Residual Heat Removal System	9.48E+02	LLW
Service Cooling Sea Water System	3.12E-01	CW
Station Drain System	7.88E+03	LLW
Spent Fuel Pit Cooling/Cleanup System	6.77E+04	LLW
Steam Generator	7.66E+02	LLW
Safety Injection System	9.61E+01	LLW
Containment Spray System	4.72E+01	LLW
Condenser	3.22E-01	CW
Waste Disposal System	6.21E+03	LLW

TABLE III
EXPECTED CONCRETE SURFACE CONTAMINATION FOR MAJOR KORI-1 BUILDINGS/STRUCTURES

Building/Structure	Contamination (Bq/cm^2)		Radwaste Classi-fication
	Min.	Max.	
Containment Building	3.84E+00	1.53E+02	LLW - CW
Auxiliary Building[1)]	6.34E-02	1.69E+03	LLW - CW
Turbine Building	2.67E-03	2.84E-01	CW

1) Include spent fuel area and waste storage area

TABLE IV
RADIOACTIVE WASTE CLASSIFICATION CRITERIA

Radwaste Classification	Radwaste Classification Criteria	
High Level Waste (HLW)	Greater than 4,000 Bq/g (Concentration of Alpha Emitter with $T_{1/2}$ > 20 year) and 2 kW/m^3 of Heat Generation Rate	
Intermediate Level Waste (ILW)	Disposal Criteria <	$\sum_{i=a}^{n} \frac{A_i}{DC_i} > 1$
Low Level Waste (LLW)	≤ Disposal Criteria	$\sum_{i=a}^{n} \frac{A_i}{CW_i} > 100 \cap \sum_{i=a}^{n} \frac{A_i}{DC_i} \le 1$
Very Low-Level Waste (VLLW)	≤ Clearance Criteria × 100	$1 < \sum_{i=a}^{n} \frac{A_i}{CW_i} \le 100$
Clean Waste (CW)	≤ Clearance Criteria	$\sum_{i=a}^{n} \frac{A_i}{CW_i} \le 1$

Ai: Concentration (Bq/g) of the ith radionuclide in Radiowaste. DCi : Upper limits of Concentration (Bq/g) of the ith radionuclide for Disposal Criteria (DC). CWi : Upper limits of Concentration (Bq/g) of the ith radionuclide for Clean Waste (CW).

For the Kori-1, however, the segmentation option for these large components is selected, since the disposal facility in South Korea does not take into account the storage space for one-piece removal, which is the most critical issue of the variable factors to be considered [7].

Waste containers are classified with steel drums, concrete containers, HIC, and polyethylene containers. The steel drums are classified into 200L and 320L drums, and the concrete containers classified into circular concrete containers and rectangular concrete containers. In this study, except for the HLW and ILW, it is assumed that all the wastes generated during the Kori-1 decommissioning including large components are packaged into 200L drums of the above variable wastes containers, which is loaded into a 16 pack concrete disposal container prior to disposal.

This assumption will make all the decommissioning wastes to be segmented into small sizes which are suitable for placement into theses drums. While the result may cause not only unreasonably high labor costs and schedule extension but also significant increase of the worker exposure during segmentation activities, it is not considered in this study. It is clear that the wastes volume would be adjusted due to the voids in the packaging container in order to estimate the number of the 200L drums. The void fractions vary significantly based on the different shapes and physical characteristics of the wastes. Based on the decommissioning experiences, it is assumed that the void fractions range from 10 to 30%. In addition, it is noted that in this study the impact of the payload efficiency due to loading weight limitation is not taken into consideration, which could lead to increase of the number of waste containers.

TABLE V
SUMMARY OF WASTE PROCESSING TECHNOLOGIES USED FOR THE KORI-1 DECOMMISSIONING

Technologies	Melting/PTM	Abrasion	RPV/SGs/PZR Segmentation	Chemical Decontamination	CCIM	Super-compactor	CCRS
Material Applied	Metal/Non-Combustible	Small Metal	Large Metal	Small Metal	Combustible (e.g., Resin)	Compactable (e.g. DAW)	Cable
Volume Reduction	5.0	10.0	8.5/9.8/5.6	20.0	30.0	5.0	5.0
Secondary Wastes 1)	2.25%	2.50%	N/A	0.50%	0.00%	0.00%	0.00%

Note: CCIM: Cold Crucible Induction Melter and CCRS: Copper Cable Recycling System
1) Ratio of the generated secondary wastes to total radioactive wastes to be dealt with

TABLE VI
EXPECTED DECOMMISSIONING WASTES GENERATED DURING KORI-1 DECOMMISSIONING

Waste Classification	Waste Types	Decommissioning Wastes (ft^3)		200L Drum (EA)	
		Gen.	Dis.	Gen.	Dis.
CW	Cable, Concrete, Metal, etc.	139,526	147,687	n/a	n/a
ILW	Small Metal	291	291	347	347
	Resin, Cutting Swarf and Filter	545	545	85	85
LLW	Cable	763	1	119	0.1
	Concrete - Debris	8,083	8,083	1,488	1,488
	Concrete - Scabbled	1,213	1,213	189	189
	DAW	4,453	3,324	2,456	565
	Hazard Material	381	17	65	3
	Asbestos	16	14	65	2
	Large Component	29,380	3,718	5,408	579
	Large RPV	7,023	827	1,293	152
	Small Metal	120,651	7,181	22,207	1,118
	Metal - Spent Fuel Racks	17,320	1,003	3,188	156
	Resin, Cutting Swarf and Filter	664	22	103	3
VLLW	Cable	2,931	4	457	1
	Concrete - Debris	6,618	6,618	1,218	1,218
	Concrete - Scabbled	3,536	3,536	551	551
	Hazard Material	776	34	132	6
	Asbestos	4,573	152	712	24
	Small Metal	222,775	27,150	41,004	4,228
	Metal - Spent Fuel Racks	-	1,003	-	156
	Resin, Cutting Swarf and Filter	-	-	-	-
Total Wastes 1)		5,369,716	5,269,674	n/a	n/a
Radioactive Wastes		442,393	64,736	81,085	10,872
Fraction of Radwastes (%)		8.2	1.23	n/a	n/a

Total wastes include all the waste including CW, VLLW, LLW, and ILW.

E. Establishment of Waste Processing Technology

In general, the decontamination and dismantling (D&D) technologies have been selected on the basis of previous experience on international decommissioning projects and national segementation projects, considering the various factors: safety, performance, cost-effectiveness, secondary wastes, etc. The volume reduction resulted from D&D technologies used is based on KHNP's experimental results or data from various literatures [2]. Table V presents the decontamination and waste processing technologies, and the corresponding performances and secondary wastes generation for each of the waste types generated during the Kori-1 decommissioning. The processing of the contaminated and/or activated materials that are classified as ILWs or HLWs is not considered in this study.

IV. ESTIMATION OF DECOMMISSIONING WASTES

Table VI has shown that the preliminary evaluation results performed in this study including the estimated radioactive wastes amount before/after the waste processing and the resulting number of waste drums to be disposed of in the disposal facility for the Kori-1.

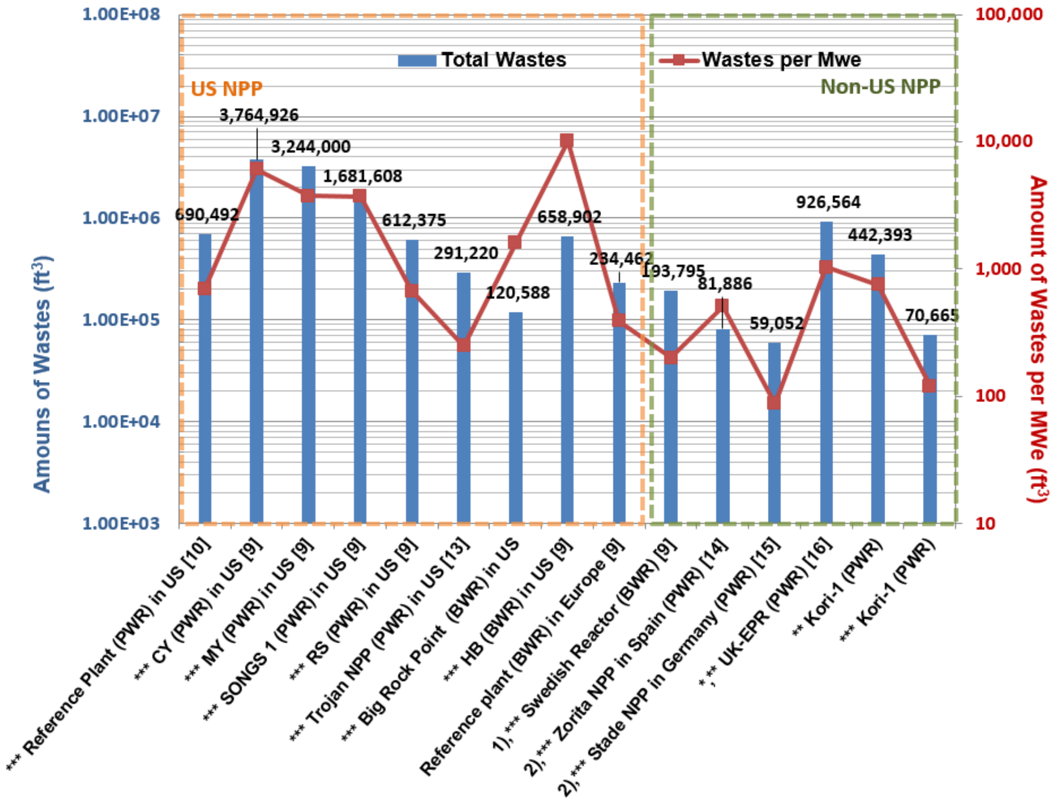
As can be seen in Table VI, the expected amounts of decommissioning radioactive wastes were less than about 8.5% and 1.5% of the total wastes generated (i.e., sum of clean wastes and radwastes) before and after waste treatment/processing, respectively. After treatment/processing of the wastes, it was found that the amount of radioactive wastes was decreased by a factor of about 7, or to about 15% (64,736 ft^3 vs. 442,393 ft^3). That is, more than 80% of the radioactive wastes before processing could be cleared immediately for subsequent use or for (conventional) disposal by the waste treatment/processing. The reduction of the wastes was mainly attributed to declassification and/or the volume reduction of metal wastes such as carbon or alloy steel and stainless steel, which accounts for about 78% of total radioactive wastes. As a simple method for estimating the decommissioning wastes, the following equation, which is used to adjust the amount of materials for various design power levels, could be used, where the scaling factor is determined based on the mass of PWR pressure vessels.

$$Generated\ Wastes = W_{ref} \cdot \left(\frac{P}{P_{ref}}\right)^{2/3} \quad (1)$$

where W_{ref}= Generation of Wastes in Reference Reactor; P= Power Rating of Kori Unit 1; P_{ref} = Power Rating of Reference Reactor (900 ~ 1,300 MWe PWR). It is provided in the IAEA document that the amount of potentially radioactive material generated from the typical PWR (i.e., 900 ~ 1,300 MWe PWR) is 6,200 ton [8]. Assuming a density of 280 lbs/ft^3 for the metal and 70 lbs/ft^3 for all other wastes [9], the total number of the 200L drums generated is estimated to be about 13,800, which is used as generation of wastes in Reference reactors in the above equation. Based on the waste amount suggested by IAEA, the resulting decommissioning wastes for the Kori-1 with 587 MWe power level can be estimated to be 8,109 to 10,362 drums when a 900 ~ 1,300MWe PWR generate the same amount of wastes. Therefore, it was found that the expected waste amount estimated based on the waste generation in an IAEA reference reactor and the above equation (i.e., scaling factor) was comparable to those estimated in this study (10,362 drums verse 10,872 drums). On the one hand, the Korea Radioactive Waste Agency (KORAD) assumed the total amount of decommissioning wastes per a reactor to be 14,500 drums in performing a study on optimized waste management options for LILW disposal [11].

V. Comparison of Decommissioning Radioactive Waste Volume Estimate

Fig. 3 compares the volume of radioactive waste expected to be generated during the decommissioning of a Kori-1 to that from selected decommissioning projects in the U.S. [9], [10], [13] and from the plants to be decommissioned (or decommissioned) in Europe [9], [14]-[16].



1) Averaged over 3 Oskarsham Units and 3 Forsmark Units in Sweden
2) Estimated based on the waste density of 280lbs/ft³ forMetal and 70 lbs/ft³ for other wastes
* Packed waste produced volume considering Packaging Specifications
** Before waste processing of decontamination
*** After waste processing of decontamination

Fig. 3 Comparison of Decommissioning Radioactive Wastes between Kori-1 and Plants in U.S. and Europe

It is reasonable that the expected volume of waste from the decommissioning of the Kori-1 is considerably less than that from U.S. plants (i.e., upto about fifty (50) times) on the key basis that:

- significant amounts of the wastes that would be classified as VLLWs or LLWs in the U.S. would meet the clearance criteria in Europe and be disposed of as conventional waste [9].
- higher disposal costs of wastes in South Korea make much more wastes to be decontaminated to clearance levels, compared to the U.S. where decontamination to free release (i.e., not detectable activity) levels is typically not cost-beneficial [9].
- the volume of radioactive waste could be reduced by use of volume reduction processes, such as melting, compaction, incineration, filtration and evaporation.
- As discussed earlier, it is noted that no soil contamination is not considered particularly.

On the other hand, Connecticut Yankee (CY), Maine Yankee (MY), San Onofre Nuclear Generating Station Unit 1 (SONGS-1), and Humboldt Bay (HB) led to significant amount of wastes since all (or most) of the above ground radiologically controlled area (RCA) concrete were disposed of as radioactive waste as well as soil remediation due to radioactivity content needed to perform. For Rancho Seco (RS) and Trojan NPP, the RCA building was decontaminated to the site release limits and left them in place at license termination, thereby resulting in relatively less radioactive waste for these plants [9].

As can be shown in Fig. 3, it was found that the (expected) decommissioning wastes from the plants in Europe were comparable to Kori-1, between which the defference of wastes was found to be within 20 percent particularly for the same PWR type after processing, since, as in South Korea, due to higher waste disposal costs, the clearance is preferred. For example, in Germany, in order to achieve unconditional clearance of metal scrap, total costs of 9 to 15 EUR/kg may be estimated which includes decontamination, release measurement and personnel. Costs for reuse of recycling in the nuclear field (i.e. melting under radiological control) may amount to around 12 to 15 EUR/kg. However, Costs for final disposal can be estimated in the range of 50 to 250 EUR/kg including conditioning, waste package, interim storage and final storage depending on the activity contents and the type of waste container chosen to a large extent [12]. Clearance is, therefore, the cheapest option and can be applied for nearly the entire mass of the plants.

VI. Conclusion

The preliminary evaluation of decommissioning wastes potentially generated during the Kori-1 decommissioning was performed using the methodology established in this study.

It was found that only a few percent of the expected total amount of decommissioning wastes would need to be disposed of as radioactive wastes in a repository, and more than 80% of the radioactive wastes could be cleared immediately for subsequent use or for (conventional) disposal by the waste treatment/processing.

Also, within the range of availability of information, the preliminary results of the evaluation were compared with results from the previous study, or international references and documents including actual decommissioning wastes from the previous decommissioning experiences. The comparison results have shown that the radioactive waste amount from Kori Unit 1 decommissioning were significantly less than those from the plants decommissioned in U.S., but were comparable to those (i.e., particularly for the same PWR type as Kori 1) in European countries. This result come from the difference of disposal cost and clearance criteria (i.e., free release level) between U.S. and European contries.

The preliminary evaluation performed in this study will be useful as a basic data in establishing the decommissioning planning including the decommissioning schedule establishment, waste management strategy (e.g., the transportation, packaging, handling, and ultimate disposal of radioactive wastes), and so on.

In the future, the more accurate and reasonable decommission wastes that will be disposed of in a disposal facility will evaluated considering the optimized waste management strategy based on the cost-benefit analysis. To end it, the key parameters to influence the decommissioning wastes are going to be derived by performing the sensitivity analysis.

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