X Congreso Regional Latinoamericano IRPA de Protección y Seguridad Radiológica
"Radioprotección: Nuevos Desafíos para un Mundo en Evolución"
Buenos Aires, 12 al 17 de abril, 2015
SOCIEDAD ARGENTINA DE RADIOPROTECCIÓN

Radiological Characterization of Decommissioning Wastes from Korean 1400 MWe PWR: Activated Reactor Internals

Kyo Min Lee[1] and Sang Ho Kang[1]

[1] KEPCO Engineering & Construction Company Inc.
2354 Yonggudaero, Giheung-gu, Yongin-si, Gyeonggi-do, South Korea 446-713

ABSTRACT

The structural materials (i.e., reactor internals, reactor pressure vessel) surrounding the reactor core are exposed to fission neutrons during lifetime of a nuclear power plant, resulting in high concentration of activation products. Knowledge of the extent and level of this activation is very important in planning the cutting, conditioning, packaging, storage and disposal of the reactor as part of decommissioning after a permanent shutdown. In this study, the estimation of the activation product inventory inside the reactor vessel was carried out taking into account the geometry, material composition and operating history of the Korean 1400 MWe reactor, and the radiological characteristics for waste classification was evaluated. A coupled transport and activation analysis code system, MCNP/FISPACT, was used for the source term analysis. The neutron trasport calculation for the spatial distribution of the neutron flux spectra was performed with the MCNP code, and the nuclide inventory calculation for the radioactive waste clarification during decommissioning stage was performed with the FISPACT code. The specific activities of the radionuclides of interest in the activated material, which were calculated as a function of time, were compared with the specific activity limits listed in the Korean standard Notice of Nuclear Safety and Security Commission No. 2014-03, which has recently been revised regarding disposal of radioactive wastes. The results showed that the components such as the core shroud, core support barrel, and lower support structure located at the immediate vicinity of the core were classified as intermediate level waste (ILW) regardless of the cooling time of the waste. It is expected that radiological characteristics and radwaste classification evaluated in this study will be useful to establish the decommissioning strategy for Korean 1400 MWe reactor.

1. INTRODUCTION

Since the start of commercial operation of Kori Unit 1 in 1978, 23 nuclear power plants (NPP) are in operation in Korea: 19 Pressurized Water Reactors (PWRs) and 4 Pressurized Heavy Water Reactors (PHWRs) [1]. These NPPs will need to be decommissioned when they reach the end of their design life if longer operation is not justified.

Decommissioning of a NPP requires the disposal of the large volume of activated metals, since the structural materials surrounding the reactor core is irradiated by high neutron fluxes during its lifetime, thereby resulting in high concentration of activation products. These activated materials consist of reactor pressure vessel (RPV) and its internal components such as core baffles, core barrels, and core support structures and it is known that these reactor internals take about 99% of the total activity generated from decommissioning of a NPP [2].

Information on the extent and level of activation is very important for planning and impementation of decommissioning activities such as cutting, conditioning, packaging, storage and disposal and plays an important role in establising radiation protection programs, identification of contamination, assessment of potential risks, and cost estimation.

---

[1] Author's e-mail: kyominlee@kepco-enc.com

In this study, an estimation of the activation product inventories for the major components surrounding the reactor core of a Korean 1400 MWe PWR was carried out by using the MCNP/FISPACT coupling system. It takes into account the Korean 1400 MWe PWR design-specific geometry, material compositions and the operating history. The resultant radiological characteristics of the materials were classified based on the specific activity criteria presented in Notice of the Nuclear Safety and Security Commission (NSSC) No. 2014-03 (Radioactive Waste) in Korea [3].

2. REFERENCE REACTOR

In this study, the Korean 1400 MWe reactor is selected as the reference reactor, which is planned to start its commercial operation in June 2015 in Korea for the first time. This reactor, which is a 4,060 MW_{th} evolutionary PWR based on well proven Korean Standard Nuclear Power Plant (KSNP) design, incorporates a number of design modifications and improvements to meet the utility’s needs for enhanced safety and economic goals and to address the new licensing issues such as mitigation of severe accidents [4].

3. NEUTRON ACTIVATION PRODUCT INVENTORY ANALYSIS

3.1. MCNP/FISPACT Coupling Model

A coupled transport and activation code system MCNP/FISPACT was used to calculate the neutron-induced activity inventory. Neutron transport calculations used to determine the spatial distribution of the neutron fluxes were performed using MCNPX code [5], which is capable of simulating the transport of neutron in 3-dimensional geometry with point-wise nuclear cross-section. The radioactive inventory calculations used for radwaste classification at the time of decommissioning were performed by FISPACT code [6]. It calculates the neutron activation and generates the gamma ray sources using activation cross-section data with the “VITAMIN-J” 175 energy group structure in EAF-2007 data file.

Calculation of the activation products using MCNP/FISPCT coupling code system is carried out by a two-step approach as shown in Figure 1. First, the neutron flux spectra for selected regions of the geometry model are calculated using MCNP code, which is used by FISPACT code to collapse the 175 group activation cross-section into an effective one-group data. Secondly, the activation products for a region of interest are calculated using the average neutron fluxes provided by the preceding MCNP calculation in the selected zones/materials based on the material compositions and activation cross-sections.

3.2. Material Compositions

The reactor internals are divided into four (4) major parts: 1) Upper Guide Structure (UGS) Assembly; 2) Lower Support Structure (LSS) Assembly; 3) Core Support Barrel (CSB) Assembly; 4) Core Shroud (CS) Assembly. All major components are made of Type 304 stainless steel (SS). Parts that not fabricated from Type 304 SS are bolts and dowel pins,

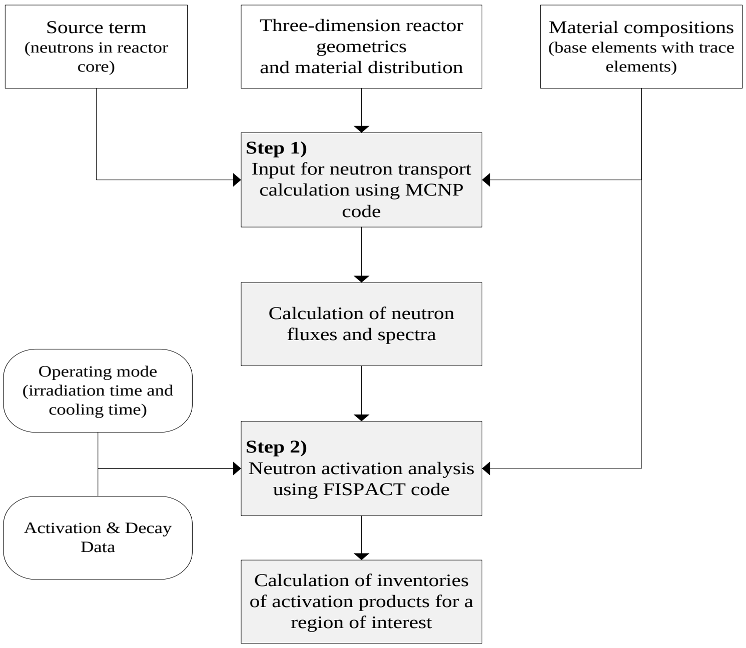


Figure 1 Flow Scheme of MCNP/FISPACT Activation Analysis

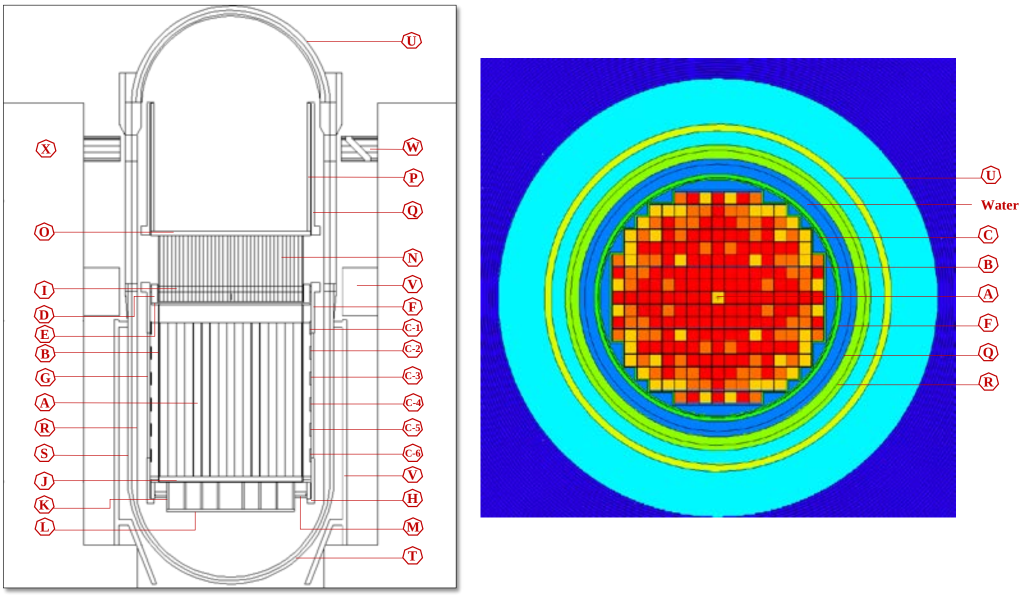
which is made of Type 316 SS, and hold-down ring, which is made of Type 415 (Grade F6NM) SS. However, very small components such as nuts and bolts or complicated geometric configuration are not specifically modeled for simplification since it is not easy to model the complicated geometries in the MCNP code as well as they have no effect on the accuracy of calculation due to their size. Material compositions of the major components surrounding the reactor core are given in Table 1. In determining the compositions, the types and contents of trace elements listed in NURER/CR-3474 [7] were taken into consideration. The trace elements, of which information impacts on the uncertainty in assessing of the activation inventory, can be more important than the major constituents of the metals in terms of waste classification [8].

3.3. Neutron Transport Calculations

Three-dimensional MCNP model for Korean 1400 MWe reactor was developed to estimate the spatial and energy distributions of neutron fluxes in RPV and its internals. As addressed in Section 3.2, the geometric approximations in modeling the major complex components of the reactor were made to reduce engineering efforts and computing times while facilitating reasonably accurate calculations. Figure 2 illustrates axial and radial cross-sectional views of the MCNP model for Korean 1400 MWe reactor. As shown in Figure 2(b), the reactor core is composed of 241 fuel assemblies, which consists of 236 fuel rods and 5 guide tubes welded to the spacer grids. The fuel assemblies, which are composed of fuel rods, claddings, grids, guide tubes, and coolant, are modeled as homogeneous regions in the MCNP code. Density of the coolant in the reactor core is assumed to be 0.713 g/cm^3, considering the design temperature and pressure during normal operation. The RPV inner radius and the active core height are 231.46 cm and 381 cm, respectively. The total neutron

Table 1 Element Compositions in Reactor Pressure Vessel and Internals

Reactor Pressure Vessel (ρ=7.82g/cc)				RPV Internals (ρ=7.92g/cc): UGS, LSS, Core Barrel, Core shroud Assemblies			
Base Metal: SA-508 Gr. Class 1 [9]		Trace Elements: NUREG-3474 [8]		Base Metal: Type 304 [10]		Trace Elements: NUREG-3474 [8]	
Nuclides	Composition (wt.%)	Nuclides	Composition (wt.%)	Nuclides	Composition (wt.%)	Nuclides	Composition (wt.%)
C	2.50E-01	Li	3.00E-05	Cr	1.81E+01	Li	1.30E-05
Mn	1.20E+00	N	8.40E-03	Mn	1.51E+00	N	4.52E-02
Si	1.50E-01	Sc	2.60E-05	Fe	6.95E+01	Sc	3.00E-06
P	2.50E-02	Ti	2.00E-04	Ni	9.85E+00	Ti	6.00E-02
S	2.50E-02	Co	1.22E-02	-	-	Co	2.31E-01
Cr	2.50E-01	Cu	1.27E-01	-	-	Cu	3.08E-01
Ni	4.00E-01	Zn	1.00E-02	-	-	Zn	4.57E-02
Mo	4.50E-01	Nb	1.88E-03	-	-	Nb	8.90E-03
V	5.00E-02	Ag	2.00E-04	-	-	Mo	2.60E-01
Fe	9.72E+01	Sb	1.10E-03	-	-	Ag	2.00E-04
-	-	Cs	2.00E-05	-	-	Sb	1.23E-03
-	-	Ce	1.00E-04	-	-	Cs	3.00E-05
-	-	Sm	1.70E-06	-	-	Ce	3.71E-02
-	-	Eu	3.10E-06	-	-	Sm	1.00E-05
-	-	Lu	2.00E-05	-	-	Eu	2.00E-06
-	-	Hf	2.10E-05	-	-	Lu	8.00E-05
-	-	Ta	1.30E-05	-	-	Hf	2.00E-04
-	-	Th	1.80E-05	-	-	Th	1.00E-04



Point	Components
A	Active Core
B	CS Plate
C	CS Rings (Ring no. 1 ~ 6)
D	Guide Lug & Gusset
E	
F	CSB Nozzle Cylinder
G	CSB (core region)
H	CSB Lower Flange
I	Fuel Alignment Plate (FAP)
J	Bottom Plate
K	LSS Support Beams
L	LSS Bottom Plate
M	Raised Bottom Plate
N	CEA Guide Tubes
O	UGS Support Plate
P	UGS Cylinder
Q	Upper CSB
R	RPV Cladding
S	RPV (core region)
T	Lower RPV Head
U	Upper RPV Head
V	RPV Insulator
W	Upper & Lower Shield Plug
X	Primary shield concrete

(a) Axial cross sectional view (b) Radial cross sectional view

Figure 2 MCNP Model for Korean 1400 MWe Reactor

flux in the full core is 3.0701×10^{20} neutrons/sec, which is calculated based on the average number of both prompt and delayed neutrons (i.e., 2.418) from a fission for U-235 atom [11], the rated thermal power of 4,060 MW_{th}, and the 60-year life time. For the fission energy spectrum, the Watt fission spectrum built in MCNP code is used.

The normalized neutron flux distribution in the Korean 1400 MWe reactor estimated using the MCNP code is shown in Figure 3. As can be seen in Figure 3, the maximum neutron fluxes are found at the reactor core periphery, and the neutron fluxes in the components far from the core region are orders of magnitude less than the flux in the reactor core. These components are influenced by the fast neutrons escaped out of the reactor core region.

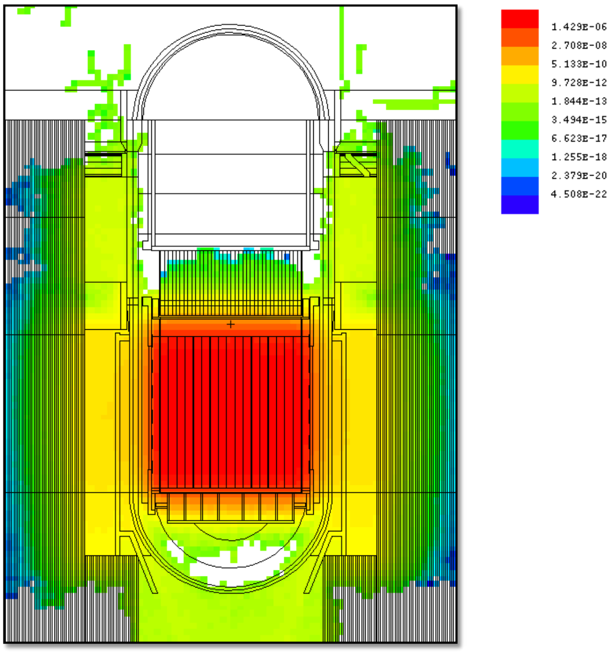


Figure 3 Normalized Neutron Flux Distribution on X-Z Plane for MCNP Model

3.4. Activation Analysis

For the activation analysis of the reactor components, it is assumed that Korean 1400 MWe reactor is operated for 60 years with a capacity factor of 95 percent which leads to about 57 effective full power years (EFPYs) calculated assuming a refueling period of 1 month per each 18-month fuel cycle. Also, throughout the entire lifetime of the reactor, the low burnup fuel assemblies are assumed to be located on the periphery of the core to maximize the core leakage to maximize the activation of structures outside of the core. Consequently, it is found that the calculation of activation products have produced more conservative radionuclide inventories than expected at the end of the operating lifetime.

As shown in Figure 1, the FISPACT code calculations require materials composition, energy-dependent neutron fluxes, and the operating history (i.e., irradiation and cooling times) as input data. The irradiation (or neutron production) and cooling times can be determined based

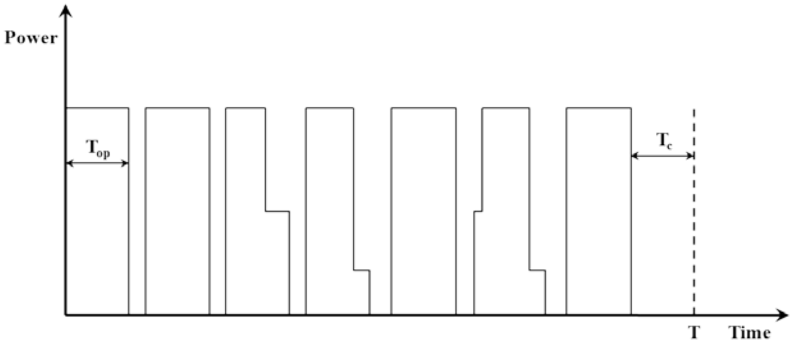


Figure 4 General Irradiation and Cooling Model Used for Estimating Radioactive Inventories (T_{op}: operating period, T_c: refueling period)

on the operation mode over the core lifetime of 60 years. As displayed in Figure 4, the fuel cycle (i.e., irradiation time) is assumed to be 18 months: 17 months with continuous irradiation, and 1 month for refueling period (i.e., cooling time) during which radioactive decay is considered.

Figure 5 shows the radioactivities in various structural materials of the Korean 1400 MWe reactor estimated with time elapsed since the start of operation of the plant. As can be seen in Figure 5, the fluctuation of the radioactivities during operation period is attributed with production and depletion of the short-lived nuclides such as Mn-56 during reactor operation and refueling periods, respectively. Figure 6 indicates the specific radioactivity due to dominant nuclides during reactor cooling after reactor operation of 60 years at the major reactor components, i.e., the core shroud plate (Type 304 SS), and RPV (SA-508 Gr. Class 1).

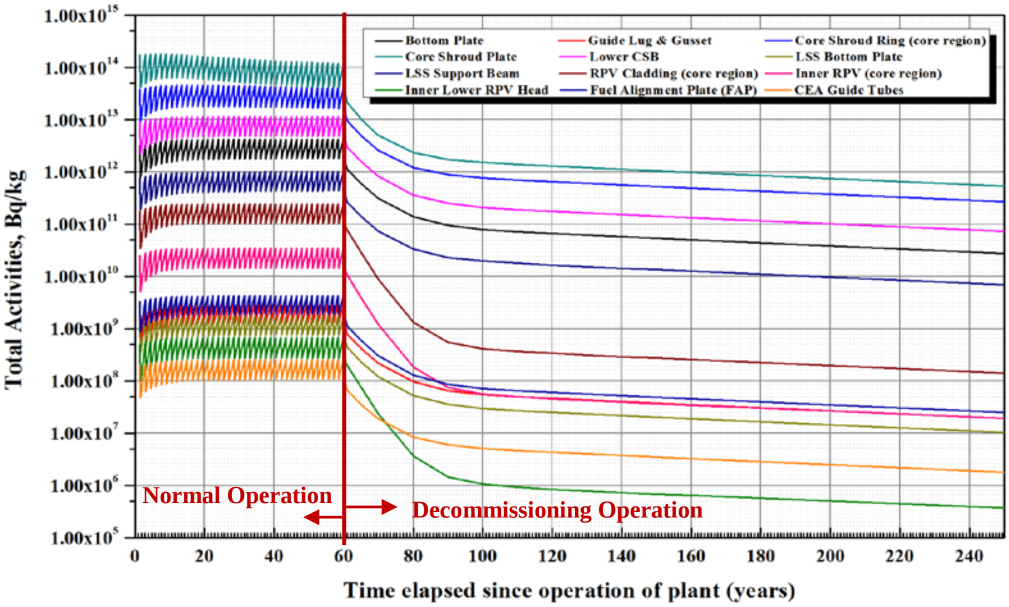
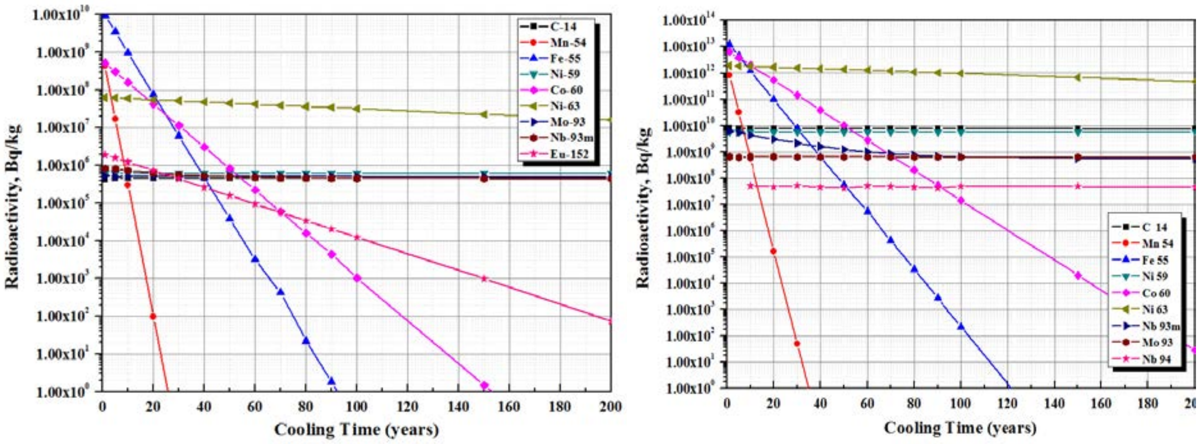


Figure 5 Total Activities as a Function of Time



(a) Inner RPV (core region)

(b) Core Shroud Plate (core region)

Figure 6 Specific Activities of Major Radionuclides as a Function of Time

In Figure 6, it is found that the Fe-55, Co-60, Mn-54, and Ni-63 are the most important radionuclides from the point of view of a immediate dismantling (DECON). In the long-term, the total activity is determined by the specific activity resulted from the activation reaction of $^{62}Ni(n,\gamma)^{63}Ni$, which takes most of the total activity, and to a smaller extent Ni-59, C-14, Mo-93, Nb-93m, and Nb-94.

4. RADIOLOGICAL CHARACTERISTICS AND WASTE CLASSIFICATION

In classifying the radioactive levels, the surface contamination of the reactor materials are not taken into account because the surface contamination is relatively very low compared to those due to activation of structures [12]. The activated 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 2 presents the waste classification criteria specified in the Notice of NSSC No. 2014-03 in Korea. As stated in Table 2, 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.

As a result of activation analysis, at the time of permanent shutdown, it was found that almost all components immediately adjacent to the active core, i.e., CS assembly, lower CSB, were classified as ILW. Other components farther away from the active core, i.e., upper CSB, LSS assembly, RPV, were classified as VLLW or CW. The detailed analysis has indicated that Nb-94 was the only dominant nuclide that makes the components be classified as ILW due to its long half-life of 2.03E+04 years. The waste classification is not changed even with a long cooling time. It is, therefore, recognized that Nb-94 becomes a principle discriminator in the aspect of ILW waste classification. For CW, VLLW, and LLW classes, it was evaluated that

Co-60, Mn-56, and Mn-54 were the most dominant nuclides in determining the waste classification at the time of permanent shutdown. After the permanent shutdown, Ni-63, C-14, and Nb-94 contribute dominantly as the cooling time increase, because of their long half-lives.

Table 2 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)	$\le$ 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)	$\le$Clearance Criteria $\times 100$	$1 < \sum_{i=a}^{n} \frac{A_i}{CW_i} \le 100$
Clearance Waste (CW)	$\le$ Clearance Criteria	$\sum_{i=a}^{n} \frac{A_i}{CW_i} \le 1$

A_i : Concentration (Bq/g) of the i^{th} radionuclide in Radiowaste

DC_i : Upper limits of Concentration (Bq/g) of the i^{th} radionuclide for Disposal Criteria (DC)

CW_i : Upper limits of Concentration (Bq/g) of the i^{th} radionuclide for Clearance Waste (CW)

Table 3 summarizes the radiological characteristics and radioactive waste classifications for the activated reactor internal components.

4. CONCLUSION

In this study, an estimation of the activation product inventory of the RPV and its internals was carried out using the MCNP/FISPACT coupling system as a function of cooling time after permanent shutdown of Korean 1400 MWe reactor. The radiological characteristics for waste classification were also assessed. The resultant radioactivity concentrations, decay heat generations, and gamma doses for a specific region of each of the activated components were varied depending on levels of neutron fluxes and neutron energy spectrum. The specific activities of the relevant radionuclides in the activated metal wastes were compared with the specified limits of the specific activities listed in the Korean criteria. It was found that almost all components immediately adjacent to the active core were classified as ILW regardless of cooling time, whereas other components located farther away from the active core were classified as VLLW or CW. Where, it is very important to realize the fact that the variation in material composition of a base metal can affect the waste classification of the components.

It is expected that radiological characteristics and radwaste classification evaluated in this study will be very useful to establish the decommissioning planning for the transportation, packaging, handling, and ultimate disposal of radioactive wastes.

Table 3 Radiological Characteristics and Radwaste Classifications

Structure Component	Activity concent-ration (Bq/kg)	Heat Generation (kw/kg)	Gamma Dose (Sv/hr)	Radioactive Waste Classification				
				At Shut-down (S/D)	50 yrs after S/D	100 yrs after S/D	150 yrs after S/D	200 yrs after S/D
Core Shroud (CS) Assembly								
CS Plate	1.20E+14	2.73E-05	3.40E+04	ILW	ILW	ILW	ILW	ILW
CS Rings no.1	1.24E+13	2.59E-06	3.50E+03	ILW	ILW	ILW	ILW	ILW
CS Ring no. 4	4.14E+13	8.84E-06	1.16E+04	ILW	ILW	ILW	ILW	ILW
CS Ring no. 6	2.68E+13	5.67E-06	7.56E+03	ILW	ILW	ILW	ILW	ILW
Guide Lug	3.15E+09	6.78E-10	9.22E-01	LLW	VLLW	CW	CW	CW
Bottom Plate	4.27E+12	8.98E-07	1.23E+03	ILW	ILW	ILW	ILW	ILW
CS Top Plate	3.66E+11	7.55E-08	1.03E+02	ILW	ILW	ILW	ILW	ILW
Core Support Barrel (CSB) Assembly								
CSB Nozzle Cylinder	5.04E+11	1.08E-07	1.49E+02	ILW	ILW	ILW	ILW	ILW
CSB (core region)	1.14E+13	2.42E-06	3.29E+03	ILW	ILW	ILW	ILW	ILW
CSB Lower Flange	2.11E+12	4.45E-07	6.10E+02	ILW	ILW	ILW	ILW	ILW
Upper CSB[1]	n/a	n/a	n/a	*CW*	*CW*	*CW*	*CW*	*CW*
Lower Support Structure (LSS) Assembly								
LSS Support Beams	1.02E+12	2.11E-07	2.88E+02	ILW	ILW	ILW	ILW	ILW
LSS Bottom Plate	1.74E+09	3.58E-10	4.92E-01	LLW	VLLW	CW	CW	CW
Raised Bottom Plate	7.52E+10	1.56E-08	2.13E+01	LLW	LLW	VLLW	VLLW	VLLW
Upper Guide Structure (UGS) Assembly								
Fuel Alignment Plate (FAP)	4.39E+09	9.14E-10	1.26E+00	LLW	VLLW	CW	CW	CW
Guide Tubes (above FAP)	2.59E+08	5.36E-11	7.28E-02	LLW	CW	CW	CW	CW
Guide Tubes (below FAP)	7.74E+10	1.58E-08	2.15E+01	LLW	LLW	VLLW	VLLW	VLLW
UGS Support Plate[1]	n/a	n/a	n/a	*VLLW*	*VLLW*	*VLLW*	*VLLW*	*VLLW*
UGS Cylinder[1]	n/a	n/a	n/a	*CW*	*CW*	*CW*	*CW*	*CW*
Reactor Pressure Vessel (RPV)								
RPV Cladding (core region)	2.46E+11	5.69E-08	7.05E+01	LLW	VLLW	VLLW	VLLW	VLLW
RPV (core region)	3.48E+10	8.07E-09	1.00E+01	LLW	VLLW	VLLW	CW	CW
Inner Lower RPV Head	6.80E+08	1.60E-10	1.99E-01	LLW	CW	CW	CW	CW
Upper RPV Head[1]	n/a	n/a	n/a	*CW*	*CW*	*CW*	*CW*	*CW*

1) Although the quantitative estimation for these components which are much further from the neutron source was not performed in this study, their waste classification could be conservatively determined based on the results of activation analysis of specific components adjacent to them. It is considered as resonable since, as shown in Figure 3, not only the reduction in the neutron flux can be an order of magnitude over just a few centimeters of water but also spectral changes can occur over samll distance, to which activation is proportaional. From the exeperiences, it was also found that movement of the core barrel reduced some activation levels in the level of the thermal shield and/or RPV.

5. REFERENCES

1. http://www.khnp.co.kr, Korea Hydro & Nuclear Power (KHNP) (2015).
2. EPRI, "*Life of Plant activity Estimates for a Nominal 1000 Mwe Pressurized Water Reactor and Boiling Water Reactor,* 2012 Technical Report 1025314, North Oaks, U.S. (2012).
3. NSSC Notice 2014-03, *Acceptance Criteria for Clearance Waste and Radioactive Waste Classification*, *Nuclear Safety and Security Commissionin* (2014).
4. H. G. Kim, "*The Design Characteristics of Advanced Power Reactor 1400*, IAEA-CN-3S09 (2003).
5. Denise B. Pelowitz, "*MCNPX User's Manual, version 2.5.0*", LA-CP-05-0369, LANL, California, U.S. (2005).
6. R. A. Forrest, "*FISPACT-2007: User manual*", UKAEA FUS 534, Oxfordshire, U.K. (2007).
7. J. C. Evans, et al., "*Long-Lived Activation Products in Reactor Materials*", USNRC, NUREG/CR-3474 (1982).
8. EPRI, "*Trace Impurities and Activation Products in Base Metal*, 2012 Technical Report 1025313, North Oaks, U.S. (2012).
9. R. G. Williams III, C. J. Gesh, R. T. Ragh, "*Compendium of Material Composition Data for Radiation Transport Modeling*, PNNL-15870, Springfield, U.S. (2006).
10. J. E. Bringas, *"Handbook of Comparative World Steel Standards"*, Third Edition, ASTM DS67B, U.S. (2004).
11. J. R. Lamarsh, "*Introduction to Nuclear Engineering*", Third Edition, New York, U.S. (2001).
12. IAEA, "*Radiological Characterization of Shut Down Nuclear Reactors for Decommissioning Purposes*", Technical Report Series No. 389, Vienna, Austria (1998).