Technical Paper https://doi.org/10.7733/jnfcwt.2016.14.4.343

Activation Analysis of Dual-purpose Metal Cask After the End of Design Lifetime for Decommission

설계수명 이후 해체를 위한 금속 겸용용기의 방사화 특성 평가

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(Received August 2, 2016 / Revised September 5, 2016 / Approved September 27, 2016)

The Korea Radioactive Waste Agency (KORAD) has developed a dual-purpose metal cask for the dry storage of spent nuclear fuel that has been generated by domestic light-water reactors. The metal cask was designed in compliance with international and domestic technology standards, and safety was the most important consideration in developing the design. It was designed to maintain its integrity for 50 years in terms of major safety factors. The metal cask ensures the minimization of waste generated by maintenance activities during the storage period as well as the safe management of the waste. An activation evaluation of the main body, which includes internal and external components of metal casks whose design lifetime has expired, provides quantitative data on their radioactive inventory. The radioactive inventory of the main body and the components of the metal cask were calculated by applying the MCNP5·ORIGEN-2 evaluation system and by considering each component's chemical composition, neutron flux distribution, and reaction rate, as well as the duration of neutron irradiation during the storage period. The evaluation results revealed that 10 years after the end of the cask's design life, ^{60}Co had greater radioactivity than other nuclides among the metal materials. In the case of the neutron shield, nuclides that emit high-energy gamma rays such as ^{28}Al and ^{24}Na had greater radioactivity immediately after the design lifetime. However, their radioactivity level became negligible after six months due to their short half-life. The surface exposure dose rates of the canister and the main body of the metal cask from which the spent nuclear fuel had been removed with expiration of the design lifetime were determined to be at very low levels, and the radiation exposure doses to which radiation workers were subjected during the decommissioning process appeared to be at insignificant levels. The evaluations of this study strongly suggest that the nuclide inventory of a spent nuclear fuel metal cask can be utilized as basic data when decommissioning of a metal cask is planned, for example, for the development of a decommissioning plan, the determination of a decommissioning method, the estimation of radiation exposure to workers engaged in decommissioning operations, the management/reuse of radioactive wastes, etc.

Keywords: PWR spent nuclear fuel, Dual-purpose metal cask, Dry storage, Radioactive characterization analysis, Dcontamination·Decommission

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한국원자력환경공단에서는 국내 경수로 원전에서 발생한 사용후핵연료를 건식으로 저장하기 위하여 안전성을 최우선으로 국내/외 기술기준을 준수하여 금속겸용용기를 개발하였다. 이러한 금속용기는 50년 동안 주요 안전성요소(구조, 열제거, 격납, 임계방지, 방사선차폐 등)에 대한 건전성을 유지하고, 운영기간 중 유지보수 과정에 폐기물의 발생을 최소화 하고 이를 안전하게 관리할 수 있도록 설계하였다. 본 논문은 설계수명이 종료된 금속용기 본체 및 내/외부 구조물에 대한 방사화 평가를 통해 정량적인 방사능 재고량에 대한 정보를 제공한다. 본 논문에서는 금속용기 본체 및 구성품의 방사화 방사능 재고량은 MCNP5 · ORIGEN-2 평가체계를 이용하여 계산하였으며, 각 구성품의 화학조성, 중성자속 분포, 반응률 및 저장기간 동안 중성자조사 기간을 반영하여 평가하였다. 평가결과, 설계수명 이후 10년 경과시 모든 금속재질에서 ^{60}Co의 방사능이 기타 핵종들에 비하여 가장 큰 방사능을 띄는 것으로 나타났으며, 중성자차폐체인 수지에서는 수명직후 ^{28}Al 및 ^{24}Na등의 고에너지 감마선을 방출하는 핵종은 반감기가 짧아 0.5년 이후에는 무시할 수 있는 수준으로 나타났다. 또한, 사용후핵연료 제거 후 캐니스터 및 금속용기 본체에 대한 표면 선량률 평가결과, 상당히 낮은 값을 나타내어, 해체 시 작업자가 받는 피폭선량은 무시할 수 있는 수준으로 평가되었다. 본 평가방법은 사용후핵연료 금속겸용용기 해체 시 계획의 수립 및 해체작업 종사자의 피폭선량 예측, 방사성폐기물의 관리/재활용 등의 기본자료로 활용할 수 있을 것으로 사료된다.

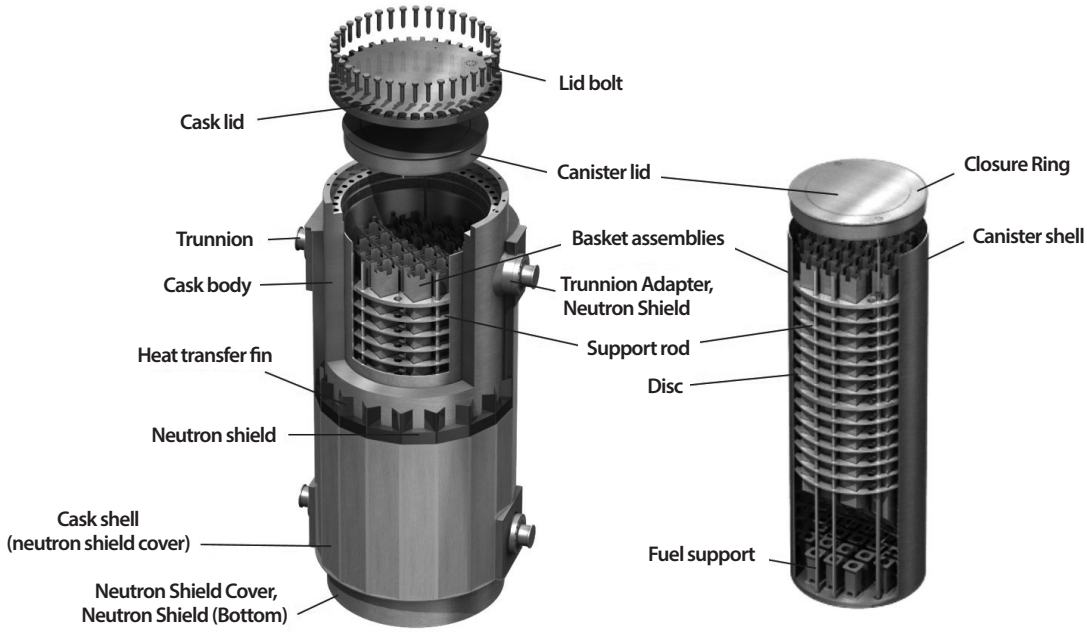
중심단어: 경수로 사용후핵연료, 금속 겸용용기, 건식저장, 방사화 평가, 제염 · 해체

1. Introduction

The Korea Radioactive Waste Agency (KORAD) has developed a dual-purpose metal cask (hereinafter, “metal cask”) for the dry storage of spent nuclear fuel that has been generated by domestic light-water reactors. The metal cask has been designed in compliance with international and domestic technology standards, and safety was the most important consideration in developing its design [1]. The metal cask has been designed to maintain its integrity for 50 years in terms of major safety factors (e.g., structure, heat removal, confinement, prevention of criticality, radiation shielding, etc.). Furthermore, the cask ensures the minimization of waste generated by maintenance activities during the storage period as well as the safe management of wastes. A metal storage cask for spent nuclear fuel has the following design features, including aspects related to decommissioning and decontamination:

- Easy recovery of spent nuclear fuel after the design life;
- Simple operations for the separation and removal of structures activated after the recovery of spent nuclear fuel;
- Easy decontamination of the external surface of the canister and the main body;
- Minimization of the generation of secondary radioactive wastes.

When the metal cask is used to store spent nuclear fuel for 50 years, which is its design life, the main body and components of the cask become activated due to irradiation with neutrons emitted from the spent nuclear fuel. When the design lifetime of the metal cask has ended, data from the radionuclide inventory of its canister, main body, and components provide very important information for decommissioning. The activity levels of radionuclides are directly related to the selection of the decommissioning method [2]. An activation evaluation of the main body and internal/external components of metal casks whose design lifetime has ended provides quantitative data on their radioactive inventory. This study can be utilized as basic data necessary for the decommissioning of the metal cask (i.e., estimation of exposure doses to workers during decommissioning operations, determination of a decontamination technology, assessment of residual radioactivity at facilities/sites, etc.) [3].



(a) Cask (b) Canister

Fig. 1. Arrangement of the dual-purpose metal cask.

2. Main Discussion

2.1 Cask specifications and description

The metal cask is an independent cylinder and is vertically stored on a concrete or metallic pad. The cask consists of the following:

- The cylindrical body, composed of a forged carbon steel containment vessel, maintains containment by a bolt fastened forged carbon steel cask lid. Fuel is loaded in the basket assembly for the canister and sealed through welding within the containment vessel, and containment integrity regarding radioactive material is maintained within the internal space, which is filled with helium.
- The canister is composed of the basket assembly, with a capacity of 21 bundles, a disc that supports the basket assembly, support rod, canister shell, canister baseplate, canister lid, and closure ring. The canister lid and closure ring are sealed by welding after loading with spent nuclear fuel.
- Neutron shielding resin is filled between the cask body and neutron shield cover, and is located on the cask body side and bottom surfaces.
- The basket assembly that supports the spent nuclear fuel transfers heat to the cask body. A neutron absorber is installed on the four external sides of the basket cell for absorbing neutrons, to satisfy the nuclear criticality safety requirements.
- One trunnion pair is installed on the upper portion of the cask to allow convenient lifting of the cask in an upright position. The lower trunnion acts as the contact point for rotating and fastening the metal storage cask under transport conditions.

Table 1 shows the major features of a metal cask that are subject to evaluation in this study (Fig. 1)

Table 1. A characteristics of metal cask

Component	Dimension
Cask Body (mm)	Ø2,404 × 5,285
Cask Lid (mm)	150THK. × Ø1,956
Basket Assembly (mm)	241 × 241 × 4,550
Spent Nuclear Fuel	-
- Burnup [MWD/MTU]	45,000
- Enrichment [wt%]	4.5
- Cooling Time [yr]	10
- Loading Fuel Type	21 WH & CE type
Disc (mm)	Ø1,630 ×20, Ø1,630 ×50
Support Rod (mm)	Ø50 × 4,565
Fuel Support (mm)	216 × 216 × 425
Canister (mm)	Ø1,686 × 4,880
Design Lifetime [yr]	50

2.2 Computation code and methodology

The metal cask is mostly made of stainless steel and carbon steel except for its neutron shield. Table 2 shows the chemical composition of materials constituting a metal cask [4]. In addition, 'Reference 5&6' suggests that the content of cobalt (Co) as an impurity is a critical factor for an activation analysis, and thus Co was included in the present assessment. So, in the present study, the value obtained by reflecting the content of Co as an impurity was compared with the value obtained by not reflecting it, and a conservative value from between the two values was applied to the activation analysis [5,6]. And, Table 3 lists radionuclides most frequently generated by neutron irradiation.

Additionally, the metal cask complies with the stringent 'Nuclear Quality Assurance Requirements (KEPIC or ASME)'. All materials, except for special materials, will be

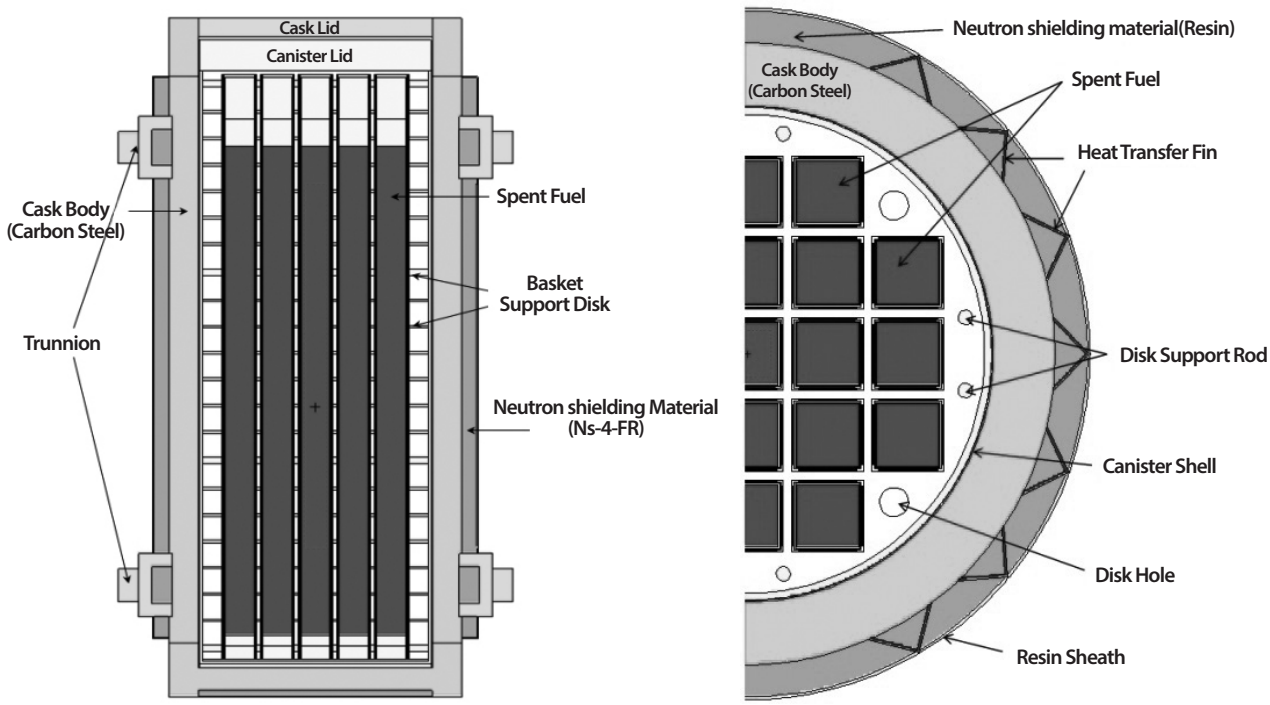
Table 2. Weight fraction (%) for chemical composition of metal cask

Composition	Basket, Support disk	Canister shell, Canister lid	Cask body	Cask lid
	SA-240 304	SA-240 316L	SA-350 LF.3	SA-182 GR.F6NM
C	0.00080	0.00030	0.002	0.0008
N	0.00100	0.00100	-	-
Si	0.00750	0.00750	0.00275	0.0060
P	0.00045	0.00045	0.00035	0.0003
S	0.00030	0.00030	0.0004	0.0003
Cr	0.19000	0.17000	0.0030	0.1275
Mn	0.02000	0.02000	0.0090	0.0075
Fe	0.68745	0.65545	0.9418	0.8054
Ni	0.09250	0.12000	0.0350	0.0450
Mo	-	0.02500	0.0012	0.0075
Cu	-	-	0.0040	-
Nb	-	-	0.0002	-
V	-	-	0.0003	-
Co	2214.0 ppm	2214.0 ppm	163.0 ppm	163.0 ppm

Table 3. Reaction formula for radionuclides in activated components

Activated radionuclides	Half life	Reaction formula
^{51}Cr	27.70 day	^{50}Cr(n,γ) ^{51}Cr
^{54}Mn	0.8556 yr	^{54}Fe(n,p) ^{54}Mn
^{55}Fe	2.73 yr	^{54}Fe(n,γ) ^{55}Fe
^{59}Fe	44.50 day	^{58}Fe(n,γ) ^{59}Fe
^{58}Co	70.86 day	^{58}Ni(n,p) ^{58}Co
^{60}Co	5.27 yr	^{59}Co(n,γ) ^{60}Co
^{14}C	5,730 yr	^{14}N(n,p) ^{14}C, ^{13}C(n,γ) ^{14}C
^{16}N	7.13 sec	^{15}N(n,γ) ^{16}N
^{3}H	12.33 yr	^{2}H(n,p) ^{3}H
^{24}Na	14.96 hr.	^{23}Na(n,γ) ^{24}Na
^{28}Al	2.2414 min.	^{27}Al(n,γ) ^{28}Al
^{59}Ni	76,000 yr	^{58}Ni(n,γ) ^{59}Ni
^{63}Ni	100.1 yr	^{62}Ni(n,γ) ^{63}Ni

manufactured and purchased in accordance with the Code (Reference 4). The material of the cask body should suppress the inclusion of impurities that may be present in the metal (S, P, etc.) in accordance with the Code (ASME Boiler and Pressure Vessel Code Section II Part A, SA-350/SA-350M, 'Chapter 5. Manufacture'). In addition, an analysis is performed in accordance with the code ('Chapter 6. Chemical Composition') to determine the chemical composition of the materials specified in "Table 1. Chemical Requirements' and issued to CMTR (Certified Material Test Report). Accordingly, it is considered that the amount of impurities contained in the cask body is very small. But, the content of Co is critical to the activation analysis of a metal cask. Therefore, a person ordering a metal cask must require the manufacturer to clearly describe the Co content (result of chemical analysis) in the CMTR. The neutron shield is a type of resin consisting of organic chemicals,



(a) Vertical section view of the metal cask (b) Horizontal section view of the metal cask

Fig. 2. Vertical and horizontal section of the dual-purpose metal cask.

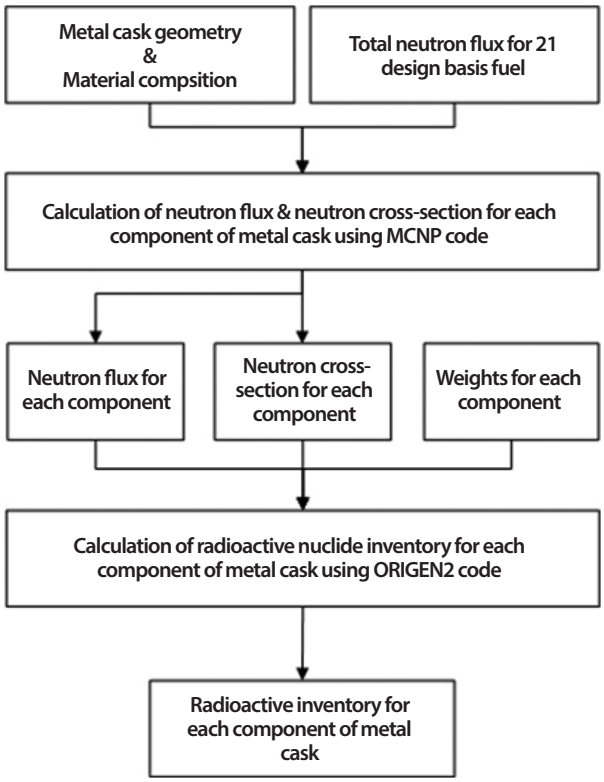


Fig. 3. Calculation procedure using MCNP and ORIGEN-2.

and its chemical composition includes Al, C, O, and H.

Estimating the radioactive inventory of the main body and components of a metal cask resulting from neutron irradiation can be conducted using computation codes. This study applies the MCNP5 computation code, which enables a realistic radiation transport analysis of three-dimensional geometrical structures [7]. It was used for calculating the neutron flux and reaction rate of the main body and components of a metal cask, as well as for detailed modeling. The total neutron flux emitted by the 21 bundles of design basis fuel at the initial stage of loading was evaluated using the ORIGEN-S module of the SCALE 6.1 computation code [8]. From among fuels generated from domestic light-water reactors, the selection of the design basis fuel was made based on the following conditions: the degree of burnup of 45,000MWD/MTU or less; ^{235}U enrichment degree of 4.5wt% or less; and a cooling period of at least 10 years. The total neutron flux emitted from one bundle of design basis fuel is 2.0967×10^{8} $cm^{-2}\cdot sec^{-1}$, and this was used as input data for a geometrical model developed using the MCNP5 computation code, for components of the metal cask (Fig. 2)

The neutron cross-section was then obtained by calculating the reaction rate of a parent nuclide activated by neutron flux and irradiation in the main body and each component of a metal cask, using input data such as chemical composition based on the material quality of the components of the metal cask, etc. Based on this method, the neutron cross-section of an activated parent nuclide was corrected in the light-water fuel library of the ORIGEN-2 computation code, and the radioactivity of the radionuclide was calculated again based on neutrons accumulated over the design lifetime [9]. The MCNP code includes libraries of (n,γ), (n,p), (n,d), (n,α), (n,^{3}He), etc. The calculation was done using the (n,γ) reaction cross-section, which represents the largest portion of the code. Figure 3 shows the method and process for estimating the inventory of radionuclides of the components of a metal cask after the end of the cask's design lifetime.

The following assumptions were applied in estimating the radionuclide inventory of a metal cask.

- 21 assembles of design basis fuel were stored during the design lifetime of 50 years.
- All the fuel will be removed when its design lifetime expires.
- It was assumed that the neutron flux at the beginning of the storage period of spent nuclear fuel was emitted constantly for 50 years.

The design basis fuel has a neutron flux of approximately 4.928×10^{8} $cm^{-2}\cdot sec^{-1}$ immediately after discharge from the nuclear reactor, 2.266×10^{8} $cm^{-2}\cdot sec^{-1}$ at 5 years, and 2.0967×10^{8} $cm^{-2}\cdot sec^{-1}$ at 10 years of cooling, respectively. Consequently, as no major change was expected in the amount released according to the cooling-off period, it was

Table 4. Neutron flux of main components by cooling time of spent nuclear fuel

(Unit : $cm^{-2}\cdot sec^{-1}$)

Component		Fuel cooling time after discharged from a reactor		
		Immediately	5 years	10 years
Canister	Basket	6.00×10^{5}	2.75×10^{5}	2.5446×10^{5}
	Disk	1.59×10^{5}	7.33×10^{4}	6.7827×10^{4}
	Bottom plate	1.09×10^{5}	5.03×10^{4}	4.6496×10^{4}
	Shell	2.77×10^{5}	1.27×10^{5}	1.1784×10^{5}
	Lid	3.38×10^{4}	1.57×10^{4}	1.4364×10^{4}
Cask body	Body (upper)	2.27	1.04	9.658×10^{-1}
	Body (middle)	6.15×10	2.83×10	2.617×10
	Body (lower)	1.39×10	6.39	5.9165
	Lid	1.77	8.16×10^{-1}	7.5209×10^{-1}
	Side resin	3.94×10^{4}	1.81×10^{4}	1.6780×10^{4}

hypothesized that a consistent amount would be released over 50 years.

In this study, an evaluation was conducted on the radioactive inventory of the components of a spent nuclear fuel metal cask over 10 years after its design lifetime using MCNP and ORIGEN-2. The results of the calculation of neutron flux in the main body and components of a metal cask, including the basket that is closest to the fuel, and the neutron shield that is farthest from the fuel, were between 2.54×10^{5} $cm^{-2}\cdot sec^{-1}$ and 9.66×10^{3} $cm^{-2}\cdot sec^{-1}$. The range of relative errors was 0.7% to 2%. In addition, we calculated the reduction of the component's neutron flux caused by the cooling of the spent nuclear fuel (Table 4). This result may mean that it is effective in reducing the activation level through the cooling period in the storage pool of spent nuclear fuel.

2.3 Results of Calculation

The reaction cross-section of major nuclides was calculated based on the neutron flux and reaction rate of each component of the metal cask. The calculation results replaced the corresponding value of the PWR library of the ORIGEN-2 computation code to reflect the operation period of the metal cask. The radioactive inventory was then calculated for each time point of decommissioning. The calculation results of reaction rates by major nuclides were greatly affected by the characteristics of the relevant nuclide, and the relative errors of the calculation were mostly below 2%.

Refer to Tables 5 ~ Table 12 for the radioactivity of major nuclides over time, from immediately after the design lifetime to various time points. The results of the evaluation of radioactive inventory of the main body and each component of a metal cask indicated that ^{54}Mn, ^{55}Fe, ^{60}Co, ^{59}Ni, and ^{63}Ni were the major radionuclides generated by elements of the stainless steel and carbon steel, which were the two major materials forming the metal cask. In particular, the radioactivity of ^{60}Co was found to be relatively larger in all the metal cask components, due to the electron capture and decay of Ni and Fe, the major metal elements of the steels, after neutron irradiation. From the neutron shield, light

Table 5. Specific activities of canister basket plate after design lifetime expiration

(Unit : $Bq \cdot g^{-1}$)

Nuclide	Duration after design lifetime expiration					
	Immediately	0.05yr	0.1yr	0.5yr	1.0yr	5.0yr
^{51}Cr	3.43×10^{-5}	2.17×10^{-5}	1.38×10^{-5}	3.56×10^{-7}	3.69×10^{-9}	4.95×10^{-25}
^{54}Mn	3.27×10^{-7}	3.14×10^{-7}	3.02×10^{-7}	2.18×10^{-7}	1.46×10^{-7}	5.69×10^{-9}
^{55}Fe	3.23×10^{-1}	3.18×10^{-1}	3.14×10^{-1}	2.82×10^{-1}	2.47×10^{-1}	8.51×10^{-2}
^{59}Fe	2.48×10^{-4}	1.88×10^{-4}	1.42×10^{-4}	1.49×10^{-5}	8.95×10^{-7}	1.51×10^{-16}
^{58}Co	5.03	4.20	3.52	8.40×10^{-1}	1.41×10^{-1}	8.58×10^{-8}
^{60}Co	6.05×10^{-2}	6.01×10^{-2}	5.97×10^{-2}	5.67×10^{-2}	5.30×10^{-2}	3.13×10^{-2}
^{59}Ni	3.65×10^{-2}	3.65×10^{-2}	3.65×10^{-2}	3.65×10^{-2}	3.65×10^{-2}	3.65×10^{-2}
^{63}Ni	4.32	4.31	4.31	4.30	4.28	4.16

Table 6. Specific activities of canister disk after design lifetime expiration

(Unit : $Bq \cdot g^{-1}$)

Nuclide	Duration after design lifetime expiration					
	Immediately	0.05yr	0.1yr	0.5yr	1.0yr	5.0yr
^{51}Cr	2.46×10^{-7}	1.56×10^{-7}	9.88×10^{-8}	2.55×10^{-9}	2.65×10^{-11}	3.55×10^{-27}
^{54}Mn	1.85×10^{-9}	1.78×10^{-9}	1.71×10^{-9}	1.24×10^{-9}	8.25×10^{-10}	3.23×10^{-11}
^{55}Fe	2.11×10^{-8}	2.09×10^{-8}	2.06×10^{-8}	1.85×10^{-8}	1.62×10^{-8}	5.57×10^{-9}
^{59}Fe	2.89×10^{-9}	2.18×10^{-9}	1.65×10^{-9}	1.73×10^{-10}	1.04×10^{-11}	1.75×10^{-21}
^{58}Co	7.56×10^{-8}	6.32×10^{-8}	5.28×10^{-8}	1.26×10^{-8}	2.11×10^{-9}	1.29×10^{-15}
^{60}Co	1.12×10^{-4}	1.12×10^{-4}	1.11×10^{-4}	1.05×10^{-4}	9.86×10^{-5}	5.82×10^{-5}
^{59}Ni	5.48×10^{-10}	5.48×10^{-10}	5.48×10^{-10}	5.48×10^{-10}	5.48×10^{-10}	5.48×10^{-10}
^{63}Ni	6.48×10^{-8}	6.48×10^{-8}	6.48×10^{-8}	6.46×10^{-8}	6.44×10^{-8}	6.25×10^{-8}

elements such as ^{3}H, ^{10}Be, ^{14}C, ^{28}Al, and ^{24}Na were mostly generated. Immediately after the design life, nuclides such as ^{28}Al and ^{24}Na had relatively greater radioactivity. However, since the half-life of the radioactivity of these nuclides (^{28}Al: 2.24min. and ^{24}Na: 14.96hr.) is very short, the level of their radioactivity is significantly reduced with a delay of decommissioning. After about 6 months, their radioactivity reaches an ignorable level.

Finally, to establish the decontamination and decommissioning procedures, the surface exposure dose rates of the main body of the cask and the canister, from which all of the spent nuclear fuel had been removed, were evaluated at the point of design lifetime expiration. However, because the inside of the canister, which comes in direct contact

Table 7. Specific activities of canister bottom plate after design lifetime expiration

(Unit : $Bq \cdot g^{-1}$)

Nuclide	Duration after design lifetime expiration					
	Immediately	0.05yr	0.1yr	0.5yr	1.0yr	5.0yr
^{10}Be	1.57×10^{-13}	1.57×10^{-13}	1.57×10^{-13}	1.57×10^{-13}	1.57×10^{-13}	1.57×10^{-13}
^{14}C	2.06×10^{-6}	2.06×10^{-6}	2.06×10^{-6}	2.06×10^{-6}	2.06×10^{-6}	2.06×10^{-6}
^{32}P	6.25×10^{-6}	2.58×10^{-6}	1.06×10^{-6}	8.94×10^{-10}	1.09×10^{-13}	5.63×10^{-28}
^{51}Cr	5.70×10^{-3}	3.61×10^{-3}	2.29×10^{-3}	5.92×10^{-5}	6.14×10^{-7}	8.23×10^{-23}
^{54}Mn	4.47×10^{-4}	4.29×10^{-4}	4.12×10^{-4}	2.98×10^{-4}	1.99×10^{-4}	7.78×10^{-6}
^{55}Fe	3.99×10^{-3}	3.93×10^{-3}	3.88×10^{-3}	3.49×10^{-3}	3.05×10^{-3}	1.05×10^{-3}
^{59}Fe	1.04×10^{-4}	7.88×10^{-5}	5.95×10^{-5}	6.27×10^{-6}	3.76×10^{-7}	6.34×10^{-17}
^{58}Co	9.31×10^{-4}	7.78×10^{-4}	6.51×10^{-4}	1.56×10^{-4}	2.60×10^{-5}	1.59×10^{-11}
^{60}Co	5.14×10^{-3}	5.11×10^{-3}	5.08×10^{-3}	4.82×10^{-3}	4.51×10^{-3}	2.66×10^{-3}
^{59}Ni	6.75×10^{-6}	6.75×10^{-6}	6.75×10^{-6}	6.75×10^{-6}	6.75×10^{-6}	6.75×10^{-6}
^{63}Ni	7.59×10^{-4}	7.59×10^{-4}	7.58×10^{-4}	7.56×10^{-4}	7.53×10^{-4}	7.31×10^{-4}

Table 8. Specific activities of canister shell after design lifetime expiration

(Unit : $Bq \cdot g^{-1}$)

Nuclide	Duration after design lifetime expiration					
	Immediately	0.05yr	0.1yr	0.5yr	1.0yr	5.0yr
^{10}Be	3.00×10^{-13}	3.00×10^{-13}	3.00×10^{-13}	3.00×10^{-13}	3.00×10^{-13}	3.00×10^{-13}
^{14}C	4.77×10^{-6}	4.77×10^{-6}	4.77×10^{-6}	4.77×10^{-6}	4.77×10^{-6}	4.77×10^{-6}
^{32}P	1.45×10^{-5}	5.97×10^{-6}	2.46×10^{-6}	2.07×10^{-9}	2.92×10^{-13}	2.97×10^{-27}
^{51}Cr	1.32×10^{-2}	8.35×10^{-3}	5.29×10^{-3}	1.37×10^{-4}	1.42×10^{-6}	1.90×10^{-22}
^{54}Mn	1.03×10^{-3}	9.93×10^{-4}	9.54×10^{-4}	6.89×10^{-4}	4.60×10^{-4}	1.80×10^{-5}
^{55}Fe	9.22×10^{-3}	9.10×10^{-3}	8.98×10^{-3}	8.07×10^{-3}	7.07×10^{-3}	2.43×10^{-3}
^{59}Fe	2.42×10^{-4}	1.82×10^{-4}	1.38×10^{-4}	1.45×10^{-5}	8.70×10^{-7}	1.47×10^{-16}
^{58}Co	2.15×10^{-3}	1.80×10^{-3}	1.50×10^{-3}	3.59×10^{-4}	6.01×10^{-5}	3.67×10^{-11}
^{60}Co	5.55×10^{-4}	5.51×10^{-4}	5.48×10^{-4}	5.20×10^{-4}	4.87×10^{-4}	2.87×10^{-4}
^{59}Ni	1.56×10^{-5}	1.56×10^{-5}	1.56×10^{-5}	1.56×10^{-5}	1.56×10^{-5}	1.56×10^{-5}
^{63}Ni	1.75×10^{-3}	1.75×10^{-3}	1.75×10^{-3}	1.75×10^{-3}	1.74×10^{-3}	1.69×10^{-3}

Table 9. Specific activities of canister lid plate after design lifetime expiration

(Unit : $Bq \cdot g^{-1}$)

Nuclide	Duration after design lifetime expiration					
	Immediately	0.05yr	0.1yr	0.5yr	1.0yr	5.0yr
^{10}Be	3.78×10^{-14}	3.78×10^{-14}	3.78×10^{-14}	3.78×10^{-14}	3.78×10^{-14}	3.78×10^{-14}
^{14}C	5.82×10^{-7}	5.82×10^{-7}	5.82×10^{-7}	5.81×10^{-7}	5.81×10^{-7}	5.81×10^{-7}
^{32}P	1.76×10^{-6}	7.27×10^{-7}	3.00×10^{-7}	2.52×10^{-10}	3.73×10^{-14}	4.41×10^{-29}
^{51}Cr	1.61×10^{-3}	1.02×10^{-3}	6.45×10^{-4}	1.67×10^{-5}	1.73×10^{-7}	2.32×10^{-23}
^{54}Mn	1.26×10^{-4}	1.21×10^{-4}	1.16×10^{-4}	8.40×10^{-5}	5.61×10^{-5}	2.19×10^{-6}
^{55}Fe	1.12×10^{-3}	1.11×10^{-3}	1.09×10^{-3}	9.84×10^{-4}	8.61×10^{-4}	2.97×10^{-4}
^{59}Fe	2.94×10^{-5}	2.22×10^{-5}	1.68×10^{-5}	1.77×10^{-6}	1.06×10^{-7}	1.79×10^{-17}
^{58}Co	2.62×10^{-4}	2.19×10^{-4}	1.83×10^{-4}	4.38×10^{-5}	7.33×10^{-6}	4.48×10^{-12}
^{60}Co	2.22×10^{-4}	2.20×10^{-4}	2.19×10^{-4}	2.07×10^{-4}	1.94×10^{-4}	1.15×10^{-4}
^{59}Ni	1.90×10^{-6}	1.90×10^{-6}	1.90×10^{-6}	1.90×10^{-6}	1.90×10^{-6}	1.90×10^{-6}
^{63}Ni	2.14×10^{-4}	2.14×10^{-4}	2.14×10^{-4}	2.13×10^{-4}	2.12×10^{-4}	2.06×10^{-4}

Table 10. Specific activities of cask body after design lifetime expiration

(Unit : $Bq \cdot g^{-1}$)

Nuclide	Duration after design lifetime expiration					
	Immediately	0.05yr	0.1yr	0.5yr	1.0yr	5.0yr
^{51}Cr	2.54×10^{-11}	1.61×10^{-11}	1.02×10^{-11}	2.66×10^{-13}	1.09×10^{-15}	1.46×10^{-31}
^{54}Mn	2.17×10^{-13}	2.09×10^{-13}	2.00×10^{-13}	1.45×10^{-13}	9.60×10^{-14}	3.95×10^{-15}
^{55}Fe	2.61×10^{-12}	2.57×10^{-12}	2.54×10^{-12}	2.28×10^{-12}	2.00×10^{-12}	6.88×10^{-13}
^{59}Fe	3.90×10^{-13}	2.96×10^{-13}	2.22×10^{-13}	2.31×10^{-14}	4.06×10^{-15}	6.85×10^{-25}
^{58}Co	1.09×10^{-11}	9.09×10^{-12}	7.60×10^{-12}	1.82×10^{-12}	3.04×10^{-13}	1.85×10^{-19}
^{60}Co	1.56×10^{-8}	1.55×10^{-8}	1.54×10^{-8}	1.46×10^{-8}	1.37×10^{-8}	8.07×10^{-9}
^{59}Ni	7.88×10^{-14}	7.88×10^{-14}	7.88×10^{-14}	7.88×10^{-14}	7.88×10^{-14}	7.88×10^{-14}
^{63}Ni	9.33×10^{-12}	9.32×10^{-12}	9.32×10^{-12}	9.29×10^{-12}	9.26×10^{-12}	8.98×10^{-12}

with the fuel, can be decontaminated, the contamination conditions were not taken into consideration for the evaluation. In addition, it was hypothesized that each of the cask is exposed to the external environment, without a separate shield and with only the top lid removed.

Immediately after the removal of the spent nuclear fuel, for each component part of the canister and the main body of the cask, the radioactivity of activation radionu-

Table 11. Specific activities of cask lid plate after design lifetime expiration

(Unit : $Bq \cdot g^{-1}$)

Nuclide	Duration after design lifetime expiration					
	Immediately	0.05yr	0.1yr	0.5yr	1.0yr	5.0yr
^{51}Cr	5.05×10^{-12}	3.20×10^{-12}	2.02×10^{-12}	5.49×10^{-14}	0.00	0.00
^{54}Mn	4.40×10^{-14}	4.22×10^{-14}	4.05×10^{-14}	2.85×10^{-14}	1.84×10^{-14}	8.82×10^{-16}
^{55}Fe	5.25×10^{-13}	5.18×10^{-13}	5.11×10^{-13}	4.59×10^{-13}	4.02×10^{-13}	1.39×10^{-13}
^{59}Fe	1.20×10^{-13}	9.11×10^{-14}	6.55×10^{-14}	5.97×10^{-15}	0.00	0.00
^{58}Co	2.15×10^{-12}	1.80×10^{-12}	1.51×10^{-12}	3.63×10^{-13}	6.02×10^{-14}	3.68×10^{-20}
^{60}Co	5.08×10^{-9}	5.04×10^{-9}	5.01×10^{-9}	4.75×10^{-9}	4.45×10^{-9}	2.63×10^{-9}
^{59}Ni	1.56×10^{-14}	1.56×10^{-14}	1.56×10^{-14}	1.56×10^{-14}	1.56×10^{-14}	1.56×10^{-14}
^{63}Ni	1.85×10^{-12}	1.85×10^{-12}	1.85×10^{-12}	1.84×10^{-12}	1.83×10^{-12}	1.78×10^{-12}

Table 12. Specific activities of cask resin after design lifetime expiration

(Unit : $Bq \cdot g^{-1}$)

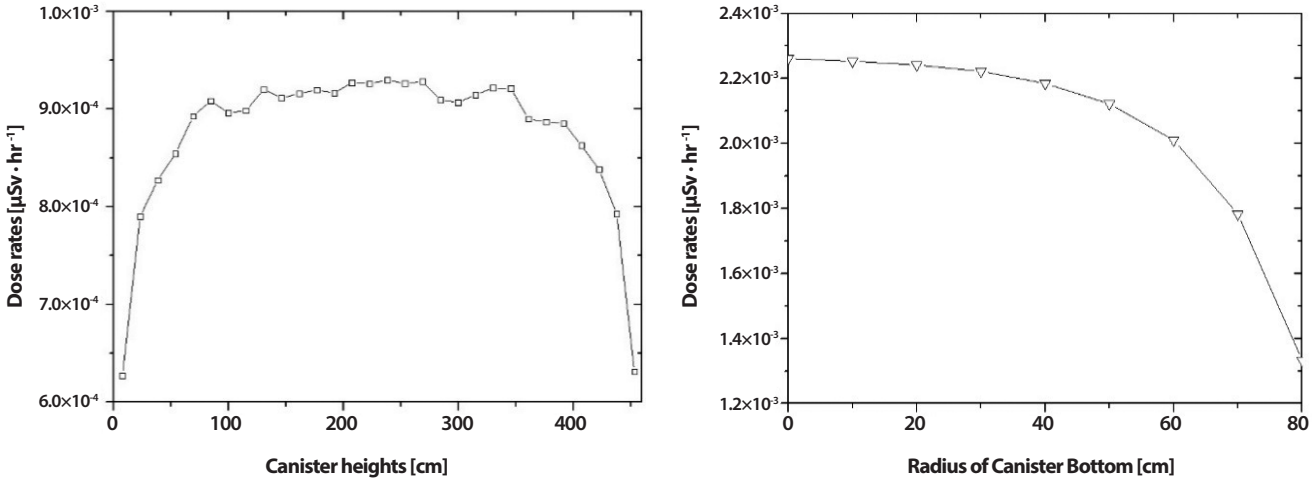
Nuclide	Duration after design lifetime expiration					
	Immediately	0.05yr	0.1yr	0.5yr	1.0yr	5.0yr
^{3}H	2.97×10^{-15}	2.97×10^{-15}	2.97×10^{-15}	2.91×10^{-15}	2.84×10^{-15}	2.24×10^{-15}
^{10}Be	2.24×10^{-17}	2.24×10^{-17}	2.24×10^{-17}	2.24×10^{-17}	2.24×10^{-17}	2.24×10^{-17}
^{14}C	1.83×10^{-12}	1.83×10^{-12}	1.83×10^{-12}	1.83×10^{-12}	1.83×10^{-12}	1.83×10^{-12}
^{24}Na	1.76×10^{-9}	2.82×10^{-18}	4.51×10^{-27}	0.00	0.00	0.00
^{28}Al	1.72×10^{-7}	0.00	0.00	0.00	0.00	0.00

clides was hypothesized to be distributed evenly within the material, and this was established as the radiation source term. Likewise, when the surface exposure dose rates were evaluated by using MCNP5, the surface exposure dose rates of the canisterⓐ and the main body of the caskⓑ amounted to a maximum of ⓐ2.262×10^{-3} $\mu Sv \cdot hr^{-1}$ and ⓑ4.089×10^{-5} $\mu Sv \cdot hr^{-1}$, respectively, and thus were evaluated to be very low compared to the effective dose limit (1 $mSv \cdot yr^{-1}$) for the public[1] (Fig. 4 ~ Fig. 5), (Table 13) [10].

3. Conclusion

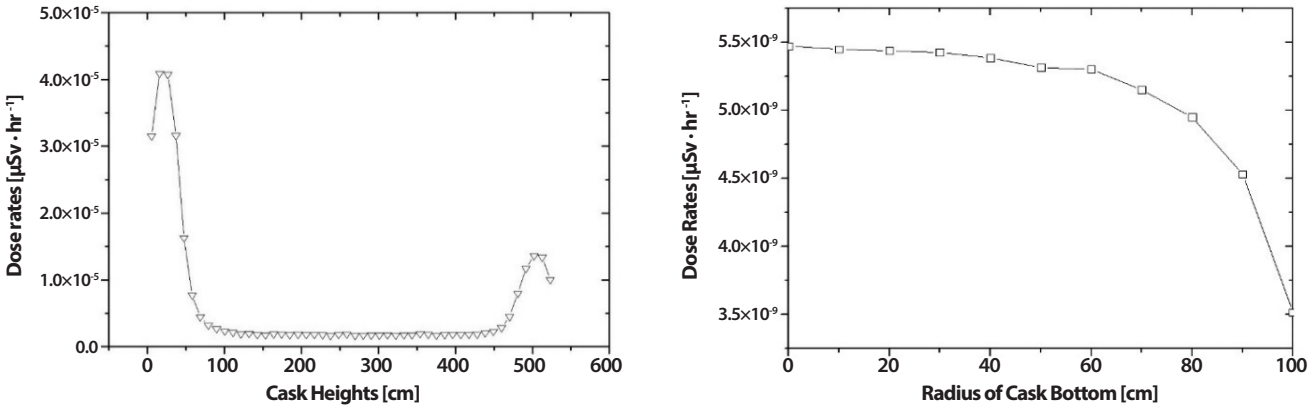
The radioactive inventory of a metal cask used for storing spent nuclear fuel, with a design lifetime of 50 years, was evaluated at the time point immediately after its design lifetimeended, and over the subsequent course of time. The radioactive inventory of the main body and components of the metal cask was calculated by applying the MCNP5·ORIGEN-2 evaluation system and by considering

[1] 2.262×10-3 (μSv·hr-1)×8760 (hr·yr-1) = 19.815 (μSv·yr-1)



(a) Canister shell body - Side (b) Canister shell body - Bottom

Fig. 4. Surface dose rates of canister shell in activated components after design lifetime.



(a) Cask body - Side (b) Cask body - Bottom

Fig. 5. Surface dose rates of cask body in activated components after design lifetime.

each component's chemical composition, neutron flux distribution, and reaction rate, as well as the duration of neutron irradiation during the storage period.

From the evaluation results, it was found that 5 years after end of the cask's design lifetime, ^{60}Co had greater radioactivity than other nuclides among the metal materials. In the case of the neutron shield, nuclides that emit high-energy gamma rays such as ^{28}Al and ^{24}Na immediately after the design lifetime had greater radioactivity. However, their radioactivity level became ignorable after 6 months due to their short half-life.

Based on the evaluations of this study it is believed that the nuclide inventory of a spent nuclear fuel metal cask can be utilized as basic data when the decommissioning of a metal cask is planned, for example, for the development of a decommissioning plan, the determination of a decom-

Table 13. Maximum dose rate of activated canister and cask body

Component		Dose rate [μSv·hr^{-1}]	Relative error [%]
ⓐ Canister	Shell (side)	9.296×10^{-4}	0.89
	Bottom	2.262×10^{-3}	0.45
ⓑ Cask body	Body (side)	4.089×10^{-5}	0.74
	Bottom	5.470×10^{-9}	0.40

missioning method, the estimation of radiation exposure of workers engaged in decommissioning operations, the management of radioactive wastes, etc. The surface exposure dose rates of the canister and the main body of the metal cask from which the spent nuclear fuel had been removed with expiration of the design lifetime of 50 years were evaluated to be at very low levels, and the radiation exposure doses to which radiation workers are subjected during the decommissioning process appeared to be at negligible levels.

In addition, it will be possible to use this evaluation method to predict the radiation exposure doses of radiation workers during the decommissioning of other component parts of the metal cask, and the obtained results later can be used as basic data for decommissioning storage casks. The confinement system of a storage cask is based on a dry process and limits any contamination risks to the inside of the canister. Therefore, the contamination of the metal cask body or its components during its design lifetime is highly unlikely. And, the most expensive part of the metal cask may be the cask body, which is a factor correlated with the economic feasibility of a spent fuel management project. Therefore, when a storage cask that has already been used in a nuclear power plant site for a short time is to be reused[2], the present activation analysis method and data regarding the storage cask may be useful in evaluating the possibility of the reuse.

Acknowledgements

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (20141710201731).

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[2] The term reuse herein means reusing only the main body of the cask after removing the canister for interim storage or disposal within the design lifetime of the cask.

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