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Review of Instant Release Fractions of Long-lived Radionuclides in CANDU and PWR Spent Nuclear Fuels Under the Geological Disposal Conditions

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Several countries, including Korea, are considering the direct disposal of spent nuclear fuels. The radiological safety assessment results published after a geological repository closure indicate that the instant release is the main radiation source rather than the congruent release. Three Safety Case reports recently published were reviewed and the IRF values of seven long-lived radionuclides, including relevant experimental results, were compared. According to the literature review, the IRF values of both the CANDU and low burnup PWR spent fuel have been experimentally measured and used reasonably. In particular, the IRF values of volatile long-lived nuclides, such as ^{129}I and ^{135}Cs, were estimated from the FGR value. Because experimental leaching data regarding high burnup spent nuclear fuels are extremely scarce, a mathematical modelling approach proposed by Johnson and McGinnes was successfully applied to the domestic high burnup PWR spent nuclear fuel to derive the IRF values of iodine and cesium. The best estimate of the IRF was 5.5% at a discharge burnup of 55 GWd tHM^{-1}.

Keywords: Disposal, Spent nuclear fuel, Instant release fraction, Fission gas release, High burnup

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1. Introduction

Korea Atomic Energy Research Institute (KAERI) has developed a KBS-3 type geological repository concept for the direct disposal of PWR and CANDU spent nuclear fuels with the KAERI Underground Research Tunnel (KURT) geological data [1]. Generally, the results of radiological safety assessment after the closure of the repository strongly depend on the source terms. The source terms from spent nuclear fuels are divided into an instant release and a congruent release [2]. In the used UO_2 fuel, most of radionuclides are uniformly distributed throughout the UO_2 matrix, but a few percentages of several radionuclides are located at the fuel/cladding gap and grain boundaries in the fuel. The latter is called instant release fraction (IRF) because these fractions of radionuclides are released quite rapidly upon contact with groundwater. On the other hand, the congruent release refers the process comprising the release of radionuclides from the UO_2 fuel matrix as the matrix itself corrodes or dissolves. According to the previous calculations [3], the IRF showed more significant effects than the congruent release, even though the IRF value was small.

According to Gray [4], it was common practice of performance assessment to assume that the average 2% values of radionuclides (e.g., ^{135}Cs, ^{129}I, and ^{99}Tc) were located in the gap and grain boundary regions. So far, the safety assessment for the geological repository carried out by KAERI assumed the IRF values [5]. When the Safety Case reports are prepared by the implementing organizations, the IRF values of radionuclides are assigned from the experimental results. The experimental results have shown that IRF values strongly depend on the linear power rating (LPR) and the discharge burnup of spent nuclear fuels. In this work, the authors reviewed three Safety Case reports published in Sweden, Finland, and Canada [3, 6, 7] and compared the IRF values of seven long-lived radionuclides including the relevant experimental results.

Various kinds of spent nuclear fuels are being generated from CANDU and PWR nuclear power plants in Korea. The burnups of PWR spent fuels continue to increase to improve economic benefits. It is known that a rim structure (i.e., High Burnup Structure, HBS) develops at a burnup exceeding 30 to 40 GWd tHM^{-1} [8, 9]. Because the experimental leaching data with a high burnup spent fuel are extremely limited, it is still not clear whether the radionuclides contained in the HBS may contribute to the IRF or not [10]. However, correlations between the Fission Gas Release (FGR) and the rapid release of some fission products such as ^{129}I and ^{137}Cs were proposed by Stroes-Gascoyne et al. [11] and Gray [5]. That is, the IRFs of the volatile long-lived nuclides such as ^{129}I and ^{135}Cs could be estimated from the measured FGR. For the high burnup PWR fuels, a modeling approach proposed by Johnson and McGinnes [12] that derives the IRF values of some mobile radionuclides such as ^{129}I and ^{135}Cs in high burnup fuels has been reviewed and applied to the domestic cases. Three different models for estimating the rim width were combined for the calculations [13, 14]. Finally, two leaching experiments from the 2010s that used the high burnup UO_2 fuels were reviewed, and the results are summarized [2, 15].

2. Instant Release Fractions in CANDU Fuels

The Nuclear Waste Management Organization (NWMO) published a post-closure safety assessment report in 2017 [7], where they assumed a geological repository for CANDU used fuels in crystalline rock. Under the disposal conditions, radionuclides in spent fuels may be released by instant release or congruent dissolution release when they contact groundwater after the repository is closed. In the safety assessment report [7, 16], the IRF was defined simply as the gap and grain boundary inventories and considered to be constant with time. The IRF values of key nuclides were determined based on the measurement data mostly obtained by Stroes-Gascoyne [17].

In Table 1, we summarize the IRFs of seven key

Table 1. IRFs of long-lived radionuclides in CANDU fuels

Radionuclides	Safety Case [7]	Lower Limit	Upper Limit	Measured Values (or Data Source)
^{14}C	Normal (0.027, 0.016)	0.0005	0.075	Normal (0.027, 0.016)
^{36}Cl	Normal (0.06, 0.01)	0.01	0.2	[22]
^{135}Cs	Normal (0.04, 0.01)	0.015	0.2	Normal (0.039, 0.019)
^{129}I	Normal (0.04, 0.01)	0.015	0.2	Normal (0.036, 0.024)
^{79}Se	Normal (0.006, 0.0015)	0.0023	0.03	(SKB data, [19])
^{90}Sr	Normal (0.025, 0.008)	0.001	0.05	Normal (0.025, 0.008)
^{99}Tc	Lognormal (0.01, 2)	0.0005	0.05	Normal (0.06, 0.01)

radionuclides that were used in the safety assessment [7]. In order to enhance the understanding of IRFs, the measured values are included. Stroes-Gascoyne [17] and Stroes-Gascoyne et al. [18] measured the IRFs of five long-lived radionuclides for five years using 15 fuel rods, which resulted in the current estimate of the IRFs of the major radionuclides in CANDU fuels. Stroes-Gascoyne [17] used crushed fuel samples for the leaching experiments. CANDU fuels were crushed for 3 hours and sieved for fuel particles < 20 μm and > 5 μm considering the average grain size of CANDU fuel is approximately 10 μm. Using the crushed samples, two kinds of leaching experiments, i.e., static and flow-through, were carried out. No particular advantage was found with flow-through experiments.

NWMO reviewed the measurement data and updated the IRF values as shown in Table 1 [16]. Since iodine and cesium behave like noble gases such as xenon, their inventories in gap strongly depended on the linear power rating. Generally, CANDU fuels have a lower burnup, but a higher linear power rating, than PWR fuels [14]. Thus, the IRF values of Cs and I are higher than those used by SKB for light water reactor fuels [19]. Strontium is not mobile in the UO_2 matrix at reactor temperature. However, a small fraction of the ^{90}Sr was measured, and it was due to the segregation of short-lived parents such as Rb and Kr, which are mobile in the UO_2 matrix at reactor temperatures [17].

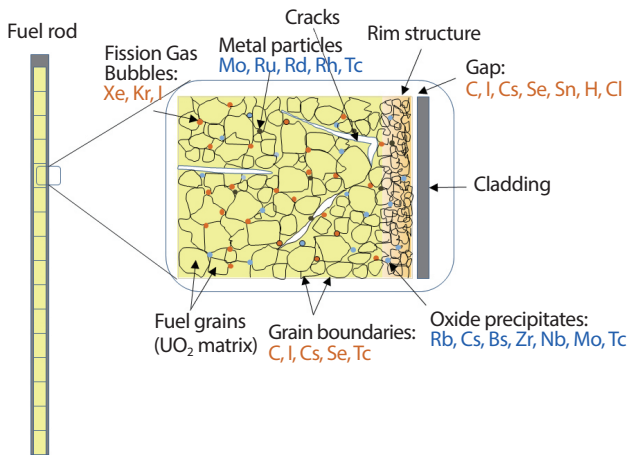

Fig. 1. Schematic of nuclides distribution in UO_2 pellet.

The IRF value of ^{14}C was taken from the measured data by Stroes-Gascoyne et al. [18], which showed no correlation with the fuel burnup and linear power rating. It was determined that the impurity level of nitrogen in the fuel, i.e., the main contributor of ^{14}C, varies between each fuel. The IRF value of ^{79}Se was estimated to be around 15% of FGR (4%), as determined by the SKB data [19]. The IRF value of ^{36}Cl, which was produced by the neutron activation of Cl impurities in UO_2 fuel, was derived from the measurement data by Tait et al. [20]. Tait et al. suggested the IRF value of ^{36}Cl for a typical CANDU LPR would be about 5% of the total inventory. Considering the LPR and burnups, the

Table 2. IRF recommended for volatile radionuclides in PWR spent fuel by SKB [19]

Radionuclides	PDF Type	Mean	Standard Deviation
^{36}Cl	Normal	0.13	0.093
^{135}Cs	Normal	0.043	0.031
^{129}I	Normal	0.043	0.031
^{79}Se	Normal	0.0065	0.0047

calculated IRF for ^{36}Cl was 0.06. Technetium was present in the used fuel that forms metallic precipitates, which means it is insoluble [21]. NWMO selected a large IRF value for ^{99}Tc considering the review of Garisto and Gierszewski [22]. The IRF was log-normally distributed with a geometric mean of 0.01, as shown in Table 1.

3. Instant Release Fractions in PWR Fuels

Two organizations, Swedish SKB and Finnish Posiva, prepared Safety Cases for the construction license, respectively. Both Safety Case reports [3, 6] were reviewed in terms of the IRF values used.

3.1 SKB Study

The SKB did not measure IRFs in PWR spent nuclear fuels, but instead collected a lot of evidence from previous studies on the IRF values that were used for the Safety Case. The IRF included a fraction of the nuclides located in the fuel-clad gap and grain boundaries as well as the inventory of the crud in the Swedish concept. That is, in the Safety Case report [19], the IRF [-] was defined as follows:

$$\mathrm{IRF} = \frac{I_{CRUD} + (F_{GGB} \cdot I_{UO_2})}{I_t} \quad (1)$$

Where I_t is the total inventory in a canister [mol canister^{-1}],

I_{CRUD} is the crud inventory [mol canister^{-1}],

F_{GGB} is the fraction of the UO_2 spent fuel inventory comprised of gap and grain boundary inventories [-], and

I_{UO_2} is the inventory in the UO_2 pellet [mol canister^{-1}].

Among the 45 radionuclides considered in the safety assessment, SKB assigned IRF values to 19 radionuclides. In Tables 2 and 3, the IRFs of seven key long-lived radionuclides are summarized. SKB did not directly measure the IRF values of the Swedish spent nuclear fuels, but instead used the FGR values of 0.043 for the PWR spent fuels. The FGR values were calculated and validated by the utilities in Sweden [23]. To estimate the F_{GGB} in equation (1), the rim inventories were not included.

There are no experimental data for ^{36}Cl with the PWR spent fuel. It is believed that ^{36}Cl is very mobile in UO_2. SKB used the value that Tait et al. [20] proposed for CANDU fuels. Tait et al. proposed using three times the amount of FGR, which was equivalent to 0.13 (= 0.043 × 3). ^{135}Cs and ^{129}I were also considered as mobile in the fuel. The upper bounding values of IRF for cesium and iodine were determined using the FGR data [24]. The SKB assigned the FGR of 0.043 to the IRF of cesium and iodine as shown in Table 2. The existing leaching data for ^{79}Se showed that the amount leached was less than the detection limit [25]. From the available data, SKB determined that the release of Se was less than 0.15 of FGR, which was equivalent to 0.0065.

Even though there were few leaching data for ^{14}C, SKB used a single point IRF value of 0.11 given in more recent publications [10]. Based on the existing experimental data, Johnson and Tait [26] concluded that the best estimate of IRF for ^{90}Sr is 0.0025 and the pessimistic estimate is 0.01.

Table 3. IRF for radionuclides in PWR spent fuel by SKB [19]

Radionuclides	PDF Type	Lower Limit	Best Estimate	Upper Limit
^{14}C	Single Point	0.11	0.11	0.11
^{90}Sr	Double Triangle	0	0.0025	0.01
^{99}Tc	Double Triangle	0	0.002	0.01

Table 4. Partitioning of some key radionuclides and IRF values used for the safety assessment by Posiva [6]

Radionuclides	Partitioning of Radioactivity				IRF Values
	Fuel Matrix	IRF	Zirconium Alloy	Other Metal Parts	
^{14}C	22.4%	5.5%	12.1%	60.0%	5.3%
^{36}Cl	73.6%	8.2%	18.2%	-	7.5%
^{135}Cs	95.0%	5.0%	-	-	5%
^{129}I	95.0%	5.0%	-	-	5%
^{79}Se	99.6%	0.4%	-	-	0.4%
^{90}Sr	99.0%	1.0%	-	-	1%
^{99}Tc	99.0%	1.0%	-	-	1%

It is known that fractions of the inventory of technetium are present in a metallic form as alloy inclusions. These metals are known to segregate from the matrix. In order to mobilize the metals in the metallic particles, oxidation is required. While Werme et al. [24] recommended the best estimate at 0.002 with triangle distribution, SKB recommended the double triangle distribution, as shown in Table 3.

3.2 Posiva Study

Finland's Posiva grouped radionuclides into four categories depending on their locations for the safety assessment of radionuclide release scenarios (Table 4). For the source term, Posiva assigned constant values to three categories except IRF as shown in Fig. 2.

Also, Posiva selected 41 long-lived radionuclides from 1,485 radionuclides for the safety assessment [6]. Among the 41 radionuclides, Posiva assigned the IRF values to 12 radionuclides, among which we summarized the values of seven key long-lived radionuclides in Table 4. The main safety assessment was carried out deterministically, but it was supplemented by a separate complementary probabilistic

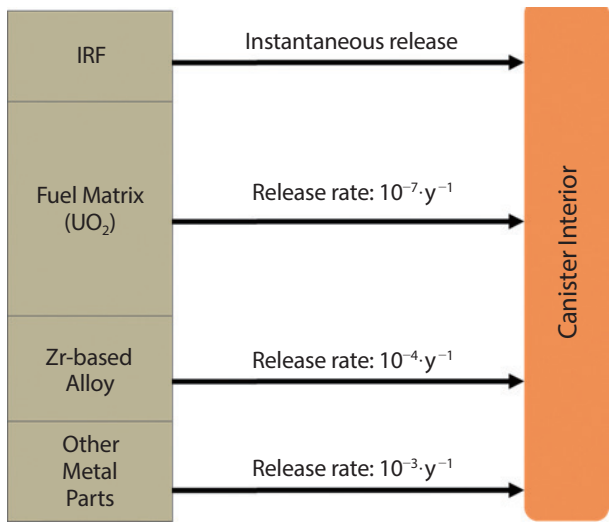

Fig. 2. Source terms used in the safety assessment of radionuclide release scenarios created by Posiva (slightly modified from Posiva 2013-01 [6]).

analysis. For the probabilistic analysis [27], log-uniform distributions of the IRF values were used. According to Posiva's definition of the IRF, the radionuclides located in the void spaces in the fuel rod such as the plenum, gap between the pellet and the cladding, grain boundaries in the fuel, cracks within the pellet, and pores accessible to water were expected to be released instantly after the breach of a disposal canister. The IRF values in Table 4 were determined based on the SKB data [19]. For the IRF of ^{36}Cl, Posiva assumed 10% of the ^{36}Cl inventory in the fuel matrix, while SKB assumed 3 times the amount of FGR.

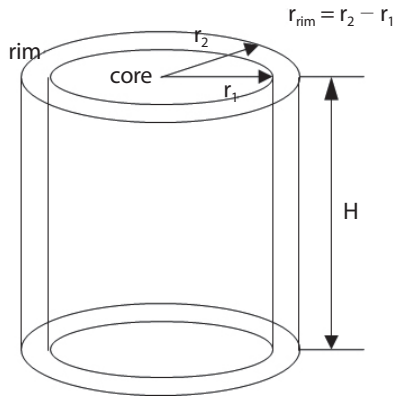

Fig. 3. Conceptual diagram of the rim structure.

4. Instant Release Fractions in High Burnup PWR Fuels

4.1 High Burnup Structure

The fission of ^{239}Pu in the rim region where ^{239}Pu concentrations increase as a result of capturing epithermal neutrons by ^{238}U can lead to a sharp increase in local burnup. This also causes remarkable microstructural changes called high burnup structure (HBS) or rim structure. According to Koo et al. [13], the characteristics of HBS are as follows:

(1) development of a subgrain microstructure whose typical size is 0.2 to 0.3 μm. The typical original grain size is around 15 μm. This means the original grain is subdivided into some 10,000 small grains,
(2) development of pores with a typical diameter of 1–2 μm,
(3) Xe depletion in the fuel matrix. According to Lassmann et al. [8], nearly all xenon that is swept out of the original grains is contained in the newly formed fission gas pores.

Generally, it is believed that the development of the HBS occurs above a local burnup called the threshold burnup for HBS. This threshold burnup corresponds to around 40 GWd tU^{-1}. Koo et al. [13] proposed a relationship between the rim burnup (Bu_{rim}) and the pellet average burnup based on the measured data relevant to the LWR operation as follows:

$$Bu_{rim} = 1.33 \times Bu_{avg} \quad (2)$$

where Bu_{avg} is the pellet average burnup [GWd tU^{-1}].

It is important to determine whether the radionuclides located in the rim structure will be included in the IRF or not. So far, volatile nuclides such as iodine and cesium in the rim structure are considered as IRF for conservative assessment. In this case, the estimation of the rim structure's thickness is very critical. Koo et al. [13] reviewed the data related to the rim width (r_{rim} marked in Fig. 3) and proposed two linear correlations, one for the best estimation (equation (3)) and the other for the pessimistic estimation (equation (4)):

$$r_{rim} = 3.55 \cdot Bu_{rim} - 185 \quad (3)$$

$$r_{rim} = 5.28 \cdot Bu_{rim} - 178 \quad (4)$$

where r_{rim} is the rim width [μm],
Bu_{rim} is the rim average burnup [GWd tU^{-1}].

Johnson et al. [14] pointed out that equation (4) overestimated the rim's thickness in fuel with the fuel average

burnup in the range of 30 GWd tU^{-1}. As a result, they proposed the following pessimistic equation (5) instead of equation (4):

$$r_{rim} = 5.44 \cdot Bu_{rim} - 281 \quad (5)$$

The above-mentioned three equations indicate the rim thicknesses as being 75 μm, 208 μm, and 117 μm, respectively, for the PWR fuel with an average pellet burnup of 55 GWd tU^{-1}. The difference in the rim thicknesses from the two pessimistic equations (4) and (5) is roughly 90 μm.

4.2 Modeling the Fraction of Fission Gas in the Rim Pore

The IRF values of some volatile radionuclides such as cesium and iodine are strongly related to the fission gas release (FGR). It is very important to estimate the amount of fission gas in the rim structure. Most of the fission gases are xenon (around 90%) and krypton (10%) [28]. In the rim region, it is known that a large part of fission gases (up to 90%) are contained in the pores resulting from changes in the microstructure.

According to Lassmann et al. [8], Xe depletion in the UO_2 matrix showed the following two interesting features:

(1) at a local burnup of 60–75 GWd tU^{-1}, the Xe concentration at about 1wt% deviates from the generated Xe concentration,

(2) at a high burnup above 120 GWd tU^{-1}, the Xe concentration does not fall below a concentration of approximately 0.25wt% and approaches an equilibrium.

By simply introducing a fitting constant for the loss term and assuming that the loss term of Xe from the matrix is proportional to the Xe concentration, Lassmann et al. proposed the following model:

$$\frac{dXe_m}{dBu_{rim}} = -\mathrm{a} \cdot Xe_m + \dot{c}_{Xe} \quad (6)$$

where Xe_m is the Xe concentration in the rim matrix [wt%],

Bu_{rim} is the local burnup [GWd tU^{-1}],

a is a fitting constant (=0.0584), and

$\dot{c}_{Xe}$ is the Xe creation rate [wt% (GWd tU^{-1})$^{-1}$] (=1.46×10^{-2} wt% per GWd tU^{-1}).

The analytical solution of equation (6) is as follows:

$$Xe_m = \dot{c}_{Xe}\left[\frac{1}{a} + (Bu_{rim}^0 - \frac{1}{a})^{e^{-a(Bu_{rim}-Bu_{rim}^0)}}\right] \quad (7)$$

where Bu_{rim}^0 is the threshold burnup for rim formation [GWd tU^{-1}].

To estimate the Xe fraction in the rim pores, Koo et al. [13] proposed an interesting model from the Lassmann's model given by equations (6) and (7). According to Koo et al., it is not expected that Xe gas is released from the rim matrix to the fuel exterior up as high as 100 GWd tU^{-1}. Then the Xe concentration in the rim pores (Xe_p) can be calculated by simply subtracting the Xe concentration in the rim matrix (equation (7)) from the total Xe creation ($\dot{c}_{Xe} \cdot Bu_{rim}$) as follows:

$$Xe_p = \dot{c}_{Xe} \cdot Bu_{rim} - \dot{c}_{Xe}\left[\frac{1}{a} + (Bu_{rim}^0 - \frac{1}{a})^{e^{-a(Bu_{rim}-Bu_{rim}^0)}}\right] \quad (8)$$

The fraction of Xe atoms retained in the rim pores (f_{rim}) can be calculated by using equations (7) and (8):

$$f_{rim} = \frac{Xe\ atoms\ retained\ in\ the\ rim\ pore}{total\ Xe\ atoms\ generated\ in\ the\ pellet} = \frac{Xe_p \cdot V_{rim} \cdot \rho_{rim}}{\dot{c}_{Xe} \cdot Bu_{avg} \cdot V_{pel} \cdot \rho_{pel}} \quad (9)$$

If the ratio of rim burnup to pellet average burnup is defined by B_r ($=\frac{Bu_{rim}}{Bu_{avg}}$), equation (9) can be expressed as follows:

$$f_{rim} = \frac{Xe_p}{Xe_m + Xe_p}\frac{V_{rim} \cdot \rho_{rim} \cdot B_r}{V_{pel} \cdot \rho_{pel}} = \frac{Xe_p}{Xe_m + Xe_p}\frac{r_{rim}(r_1+r_2)}{r_2^2}\frac{\rho_{rim} \cdot B_r}{\rho_{pel}} \quad (10)$$

where V_{rim} is the rim volume in a pellet [m^3],

V_{pel} is the pellet volume [m^3],

Table 5. IRF estimation for two volatile nuclides

Burnup		55 GWd tHM^{-1}			70 GWd tHM^{-1}	
		Best Estimate (%)	Bounding Estimate (%)		Bounding Estimate (%)	
Rim Width		Equation (3)	Equation (4)	Equation (5)	Equation (4)	Equation (5)
Fission Gas	Gap	2.5	3	3	6	6
	Rim	3	8	5	14	10
^{135}Cs		5.5	11	8	20	16
^{129}I		5.5	11	8	20	16

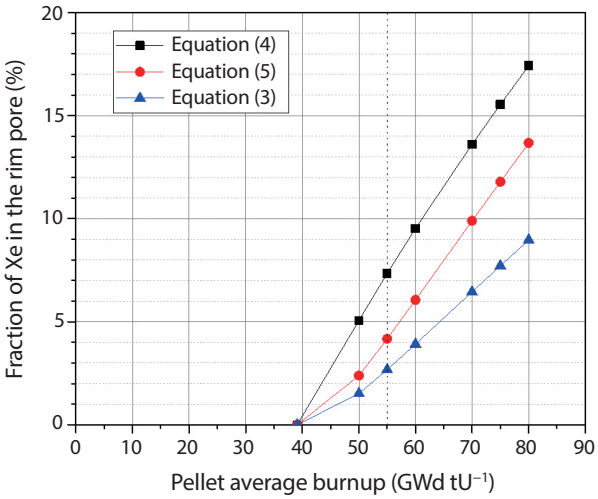

Fig. 4. Fraction of Xe atoms in the rim pore.

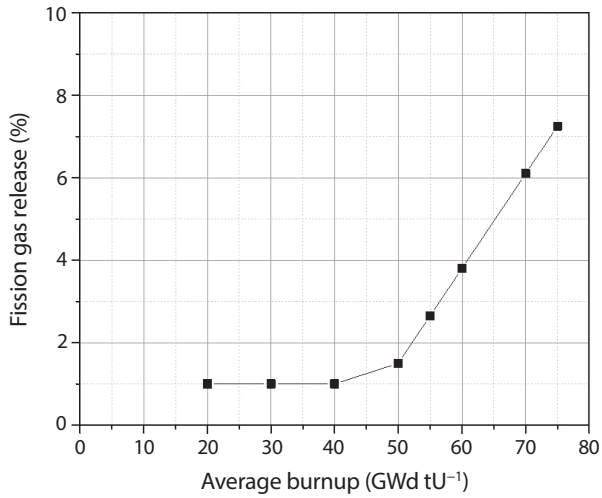

Fig. 5. Fission Gas Release from PWR fuel estimated by Vesterlund and Corsetti (1994).

ρ_{rim} is the density of the rim region [kg m^{-3}], and
ρ_{pel} is the density of a pellet [kg m^{-3}].

The rim volume (V_{rim}) in equation (10) is calculated by using the equation for the rim width (r_{rim}). Three cases of the fraction of Xe atoms are calculated with three different equations (3) to (5). The calculation results are presented in terms of the pellet average burnup rather than the rim burnup, as shown in Fig. 4. At a pellet average burnup of 55 GWd tU^{-1}, the best estimate (equation 3) of the rim width shows a fraction of Xe atoms in the rim pore around 2.7%, while two pessimistic estimates (equation 4 and 5) show around 7.3% and 4.2%, respectively.

4.3 Instant Release Fractions of Radionuclides in High Burnup Fuels

As mentioned above, some volatile radionuclides such as ^{129}I and ^{135}Cs behave like fission gas, i.e., Xe, in the UO_2 fuel. Thus, the average IRFs of those nuclides are derived using the FGR values for high burnup fuels according to the approach proposed by Johnson and McGinnes [12]. Johnson and McGinnes proposed that the best estimate of the average FGR for PWR fuels at an average burnup of 48 GWd tHM^{-1} is 1% while a bounding estimate is 2% based on the data of Vesterlund and Corsetti (See Fig. 5) [29]. KAERI has used the PLUS7 nuclear fuel with a reference

average burnup of 55 GWd tHM^{-1} [1] to design a geological repository for PWR spent nuclear fuel. In this study, we determined that the best estimate of the average FGR at 55 GWd tHM^{-1} is 2.5% and the bound estimate is 3%.

Johnson and McGinnes [12] proposed an approach to derive IRF values for high burnup PWR UO_2 from FGR because there have been a few experimental leaching data with high burnup fuels. They added the rim fraction (Rim in Table 5) given in equation (10) and FGR (Gap in Table 5) given in Fig. 5. In this study, we derived the IRF values of two volatile nuclides (iodine and cesium) at two different burnups by just following the approach. That is, the values for Gap were from Fig. 5 and those for Rim were from equation (10). The results of the calculation are given in Table 5. For the bounding values, we used two different equations for rim width estimation, as shown in Table 5. These large values of bounding estimates seem to be overestimated, but are meaningful in cases where few leaching data are available.

Johnson et al. [2] measured IRFs of volatile nuclides, ^{137}Cs and ^{129}I, through a collaborative study involving two Swedish institutes, SKB and Studsvik, and two Swiss institutes, Nagra and PSI, using a number of fuels irradiated to burnup of 50–75 MWd kgU^{-1}. They observed that the ratio of fractional release of cesium to FGR is in the range of 1:3 and the ratio of iodine appears to be on the order or slightly less than FGR. However, their results did not support the hypothesis that the radionuclides at grain boundaries in the rim region are easily leached.

Serrano-Purroy et al. [15] carried out static leaching experiments to measure the IRFs of fifteen radionuclides, including cesium, at a mean burnup of 60 GWd tU^{-1}. They prepared two samples from different radial positions, one (labelled CORE) from the center of the SNF and the other (labelled OUT) from the rim. A higher Cs IRF release was found for OUT than for the CORE sample. This effect was attributed to the thermal migration of cesium to the periphery of the spent nuclear fuel during irradiation. They concluded that the spent nuclear fuel in the HBS might be stabilized against oxidative dissolution compared to the core structure.

5. Conclusions

The instant release fractions of key long-lived radionuclides were investigated through a literature survey focusing on recent Safety Case reports prepared by Canada, Sweden, and Finland. The instant release fractions of CANDU spent nuclear fuels were measured at AECL Canada in the 1990s. Recently, Canada's implementing organization, NWMO, carried out a safety assessment with the IRF values of some key radionuclides from these measurement data. In Korea, it is expected that more than 600,000 bundles of CANDU SNF will be generated. Considering the linear power rates and discharge burnups of the domestic CANDU SNF, it is recommended to use the Canadian measurement data through some supplementary measurement data.

Sweden and Finland prepared a Safety Case report for the construction licenses in the 2010s. They did not directly measure the instant release fractions of their own spent nuclear fuel. Instead, in Sweden, the measured FGR was utilized to estimate two volatile radionuclides: iodine and cesium. Finland mostly used the IRF values proposed by Sweden's SKB with some modifications. For the low burnup PWR spent nuclear fuels, the IRF values of volatile long-lived nuclides such as ^{129}I and ^{135}Cs can be estimated from the FGR.

There are still ongoing studies on whether radionuclides in the rim structure of a high burnup spent nuclear fuel will be included in the IRF or not. Because leaching experimental data are extremely scarce with high burnup spent nuclear fuels, a mathematical modelling approach proposed by Johnson and McGinnes [12] was applied to the domestic high burnup PWR spent nuclear fuel to derive the IRF values of iodine and cesium. The best estimate of the IRF was 5.5% at a discharge burnup of 55 GWd tHM^{-1}. Finally, it is strongly recommended that the experimental

leaching data should be collected for high burnup spent fuels to understand completely the characteristics of the IRFs of major long-lived radionuclides.

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