Journal of Nuclear Materials 402 (2010) 108–115

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Changes of the surface-to-volume ratio and diffusion coefficient of fission gas in fuel pellets during irradiation

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ARTICLE INFO

Article history:
Received 10 September 2009
Accepted 6 May 2010

ABSTRACT

Short-lived fission gas release from fuel pellets during irradiation was investigated based on the experimental results of the gas-flow rigs irradiated in the Halden Heavy Water Reactor (HBWR).

The release-to-birth (R/B) rates of short-lived fission gas were measured by means of gas-flow measurement during the irradiation experiments. Surface-to-volume (S/V) ratios of fuel pellets and diffusion coefficients of short-lived fission gas release were evaluated from the obtained (R/B) values. The increase of (S/V) ratio agreed well with the point where the fuel temperature exceeded the threshold of 1% fission gas release. This indicates that the interlinkage of fission gas bubbles occurred there. The evaluated diffusion coefficients scattered in the range between 10^{-23} and 10^{-17} m^2/s, and the effects of fuel type (UO_2 or MOX) were not clearly observed. In addition, it is likely that the restructuring effect of fuel pellet on the diffusion coefficients of short-lived fission gas at least in the fuel pellet matrix is negligible in high burnup region where the rim structure forms in the fuel pellet.

1. Introduction

Release rate of volatile fission products from the fuel pellet is one of the most important factors to analyze the irradiation behaviour of fuel rods during irradiation. Since the amount of fission gas release (FGR) strongly affects the fuel design for high burnup, it is needed to investigate the effects of burnup, irradiation conditions such as temperature on FGR in detail, especially in the burnup region above 40 $MWd/kgUO_2$. The FGR from mixed-oxide (MOX) fuel is also becoming a recent subject to examine.

The Halden type gas-flow rig is often used to evaluate the release rate during irradiation of fuel rod. From release rate to birth rate ((R/B) ratio) measured in the gas-flow rig, we can obtain useful information about parameters of fission gas release, such as diffusion coefficient, surface-to-volume (S/V) ratio and so on.

These parameters have already been investigated by many researchers, and the data reported have been reviewed by White and Turnbull [1]. Recently, the fission gas release behaviour is being analyzed based on a fractal theory [2,3]. In these reports, however, the (S/V) ratio of fuel pellet was determined from the literature-derived diffusion coefficient in UO_2. In other words, the effect of fuel type (UO_2 or MOX) and burnup on the fission gas release behaviour could not be clearly reflected in the results. As a consequence, it is difficult to discuss the obtained data between different experimental series.

In this paper, the changes of (S/V) ratio and diffusion coefficient of fission gas in UO_2 and MOX fuel pellets are analyzed based on the results of the irradiation tests using gas-flow rigs in the Halden Heavy Water Reactor (HBWR) in Norway, and the effect of fuel type and burnup on the changes are investigated.

2. Outlines of the irradiation tests

In this study, the results of three irradiation experiments called IFAs-504, -633.1 and -655.1 were analyzed. In these irradiation experiments, the fuel pellets were irradiated in the HBWR as fuel rods in the test rigs which are called "Instrumented Fuel Assemblies (IFAs)". The outline of each irradiation experiment is summarized as follows. Characteristics of fuel pellets are presented in Table 1. The total plutonium contents in the MOX fuels of IFAs-633 and -655 were estimated as ~8 and ~16 wt.%, respectively.

2.1. IFA-504

The rig incorporated four gas flow rods. Rods 1 and 4 employed small grain size of about 6 μm. Rod 1 had solid pellets and rod 4 hollow ones. Rod 3 had also solid pellets doped with 0.35% niobia. The fuel rods with solid pellets were center-drilled for 7 cm length at each end to accommodate a thermocouple.

Under operating conditions, a sweep gas, such as helium or argon, could be flushed through the fuel rod and the exiting gas routed past a gamma spectrometer.

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doi:10.1016/j.jnucmat.2010.05.004

Table 1
Pellet characteristics in the fuel rods.

Fuel rod	Fuel type	^{235}U Enrichment (%)	Fuel density at fabrication (g/cm^3)	Grain size at fabrication (μm)
(a) IFA-504				
Rod 1	UO_2 (solid)	10	10.35 (94.4%TD)	~6
Rod 2				20–70
Rod 3	0.35%Nb_2O_3-doped UO_2 (solid)			26–35
Rod 4	UO_2 (hollow)			~6

Fuel rod	Fuel type	^{235}U Enrichment (%)	Pu fissile content (%)	Fuel density at fabrication (%TD)	Grain size at fabrication (μm)
(b) IFA-633.1					
Rod 1	UO_2	7.98	–	95.4	9.95
Rod 2	MOX	–	6.04	95.2	7.42
Rod 3	UO_2	7.98	–	95.4	9.95
Rod 4	MOX	–	6.04	95.2	7.42
Rod 5	UO_2	7.98	–	95.4	9.95
Rod 6	MOX	–	6.04	95.2	7.42
(c) IFA-655.1					
Rod 7	UO_2	~20	–	95	~9
Rod 8					~30
Rod 9					~9
Rod 10					~30
Rod 11	MOX	–	~14	95.9	~11 (homogeneous)
Rod 12				96.1	~8 (heterogeneous)

Fig. 1 shows the assembly-averaged linear heat rate history of the irradiation rig as a function of the assembly average burnup.

2.2. IFA-633.1

The rig consisted of six rods, three SBR-MOX and three UO_2 fuel rods. The UO_2 fuel was enriched to about 8% ^{235}U, and the MOX fuel contained about 6% fissile plutonium. These rods are each equipped with two thermocouples, one at each end. Four rods, two MOX and two UO_2, were also equipped with fuel stack elongation detectors while the remaining two are fitted with pressure transducers. Both ends of test rods are connected to a gas flow system by means of remotely controlled valves. Gaseous fission products could be flushed from the fuel rods, and it is possible to measure the amount of the unstable fission gases which are released from the fuel by using a gamma spectrometer connected to the gas flow system.

Fig. 2 shows the assembly-averaged linear heat rate history of the irradiation rig as a function of the assembly average burnup. The difference of linear heat rate between the fuel rods was less than about 4 kW/m throughout the irradiation period: the assembly-averaged linear heat rate can be treated as that of each fuel rod.

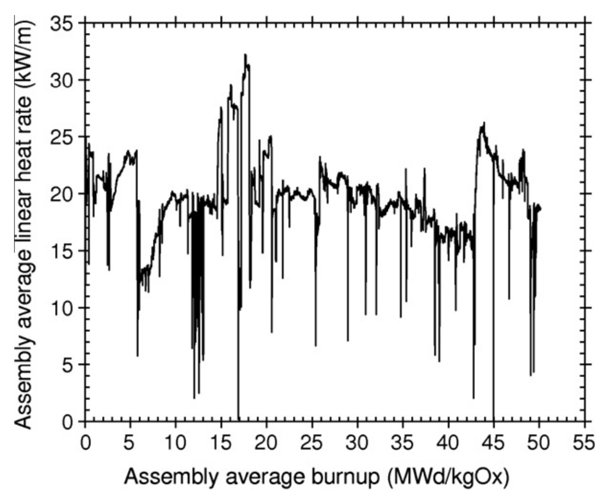

Fig. 2. Linear heat rate history of the irradiation rig IFA-633.1.

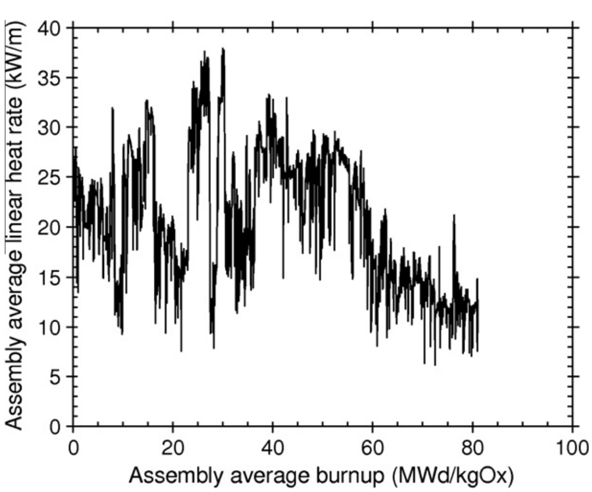

Fig. 1. Linear heat rate history of the irradiation rig IFA-504.

2.3. IFA-655.1

The rig contained 12 rodlets grouped into two axial clusters. In the upper cluster, gaseous fission products could be flushed from the fuel rods, and the fission gas release from the disks could be monitored by using a gamma spectrometer connected to the gas flow system.

The materials for irradiation were 1 mm thick disks of UO_2 enriched to about 20% ^{235}U and MOX containing about 14% fissile plutonium. The UO_2 disks were made of two grain sizes of about 9 and 30 μm. The MOX disks had homogeneous and inhomogeneous fuels, and the grain size of these MOX disks were about 10 μm. The fuel disks were placed between molybdenum disks to enhance the removal of heat in order to minimize the temperature gradient in the fuel and keep constant fuel temperature during irradiation. The target irradiation temperatures were set at 700 °C for rods 7, 8, 11 and 12 and at 500 °C for rods 9 and 10, respectively.

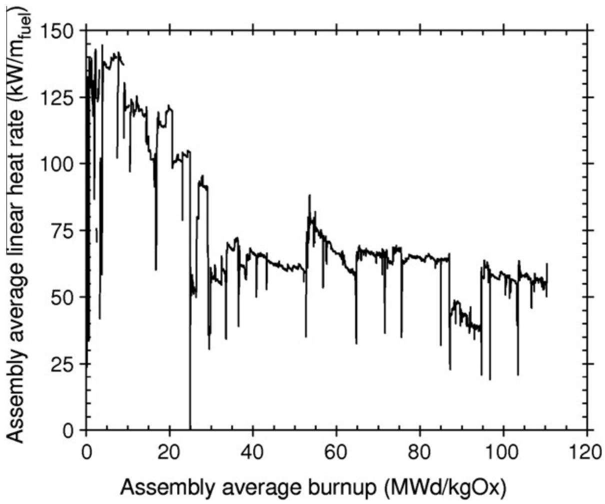

Fig. 3. Linear heat rate history of the irradiation rig IFA-655.1.

Fig. 3 shows the assembly-averaged linear heat rate history of the irradiation rig as a function of the assembly average burnup. As mentioned above, the fuel rods of IFA-655.1 contain fuel and molybdenum disks, and from the view point of fuel power, it is adequate to express a linear heat rate based on the length of not the fuel rod but the fuel disk stacks: a unit of kW/m$_{fuel}$ shows the linear heat rate of fuel disk stacks.

3. Analysis of experimental data

3.1. Ratio of release rate to birth rate (R/B) of short-lived fission gas

The ratios of release rate to birth rate in IFAs-504, 633.1 and 655.1 were evaluated based on the results of gas-flow measurement. Details of gas-flow measurement system are described elsewhere [1]. The (R/B) ratios of short-lived fission gas were calculated by using GARGAR code [4].

3.2. Evaluation of surface-to-volume (S/V) ratio and diffusion coefficient of short-lived fission gas during irradiation

The ratio of release rate to birth rate in the fuel pellet can be simply expressed as follows when it is assumed that fuel pellet consists of spherical grains of radius r and the release of fission gas is controlled by the diffusion of fission gas atoms in the grain [5]:

$$\left(\frac{R}{B}\right) = \frac{3}{r}\sqrt{\frac{D}{\lambda}}\left[\coth\left(r\sqrt{\frac{\lambda}{D}}\right) - \left(\frac{1}{r}\sqrt{\frac{D}{\lambda}}\right)\right], \tag{1}$$

where D is the diffusion coefficient; and λ, the decay constant of fission gas isotope. Since the term in square bracket approaches unity when (R/B) is sufficiently small, the equation can be approximated as follows by using a surface-to-volume ratio, (S/V) ratio, in the case of a sample with arbitrary shape [6],

$$\left(\frac{R}{B}\right) = \frac{S}{V}\sqrt{\frac{D}{\lambda}}. \tag{2}$$

Actually, a part of the fission gas is directly released from the surface of the fuel pellet due to recoil effect. In addition, diffusion of the precursors which decay into fission gas isotopes affects the fission gas release from the fuel pellet. Therefore, it is more appropriate to assume the following equation [3]:

$$\left(\frac{R}{B}\right)_{\text{meas}} = \left(\frac{R}{B}\right)_{\text{recoil}} + \frac{S}{V}\sqrt{\frac{\alpha D}{\lambda}}, \tag{3}$$

where $(R/B)_{\text{meas}}$ is the (R/B) obtained from gas flow analysis; $(R/B)_{\text{recoil}}$, the term which corresponds to the effect of recoil; and α, the precursor enhancement factor of fission gas isotope [7]. Eq. (3) can be rewritten as follows:

$$\ln\left[\left(\frac{R}{B}\right)_{\text{meas}} - \left(\frac{R}{B}\right)_{\text{recoil}}\right] = \ln\left(\frac{S}{V}\sqrt{D}\right) + \frac{1}{2}\ln\left(\frac{\alpha}{\lambda}\right). \tag{4}$$

Namely, the values of $(R/B)_{\text{recoil}}$, (S/V) ratio and diffusion coefficient D can be evaluated from the linear regression plot of $\ln\ [(R/B)_{\text{meas}} - (R/B)_{\text{recoil}}]$ against $\ln\ (\alpha/\lambda)$. Here, the value of $(R/B)_{\text{recoil}}$ is selected as the slope of linear regression line is equal to one-half, and the value of D can be obtained from the intercept of linear regression line and (S/V) ratio. The short-lived fission gas isotopes which are used for the analysis are ^{137}Xe, ^{138}Xe, ^{139}Xe, ^{85m}Kr, ^{87}Kr, ^{88}Kr, ^{89}Kr and ^{90}Kr.

Since the term $(R/B)_{\text{recoil}}$ shows the fission gas release due to recoil effect and the extent of recoil release should be independent on the fission rate of fuel, it is reasonable to consider that the value of $(R/B)_{\text{recoil}}$ only depends on the value of (S/V) ratio of fuel pellet. In other words, the value of $(R/B)_{\text{recoil}}$ may be normalized by using (S/V) ratio of fuel pellet.

4. Results

4.1. Evaluated results of $(R/B)_{recoil}$

The results of $(R/B)_{\text{recoil}}$ which were evaluated based on the Eq. (4) are presented in Figs. 4–6 for IFAs-504, -633.1 and -655.1, respectively.

4.2. Normalized $(R/B)_{recoil}$

Considering the mechanism of recoil release, it is reasonable to assume that the value of $(R/B)_{\text{recoil}}$ is proportional to the surface area on the fuel pellet. In order to evaluate values of (S/V) ratio of the fuel pellet, the value of $(R/B)_{\text{recoil}}$ per unit surface area on the fuel pellet, $(R/B)_{\text{recoil\_norm}}$, are introduced. Here, the value of $(R/B)_{\text{recoil\_norm}}$ corresponds to the effective range of fission gas release by recoil. In addition, since the fission energies of uranium and plutonium are nearly the same, it is adequate to assume that

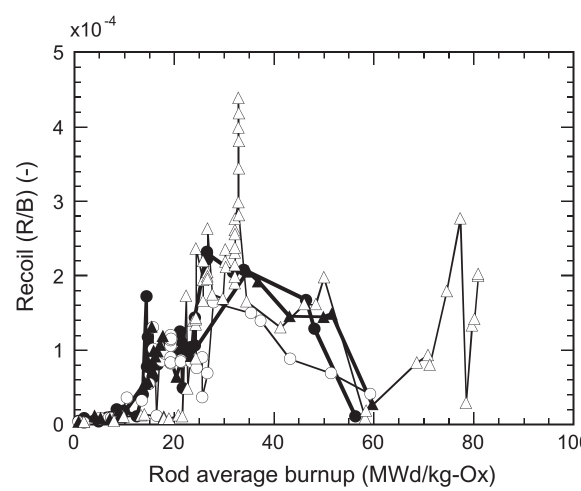

Fig. 4. The evaluated results of recoil (R/B) of IFA-504. ●: Rod 1, ○: Rod 2, ▲: Rod 3, △: Rod 4.

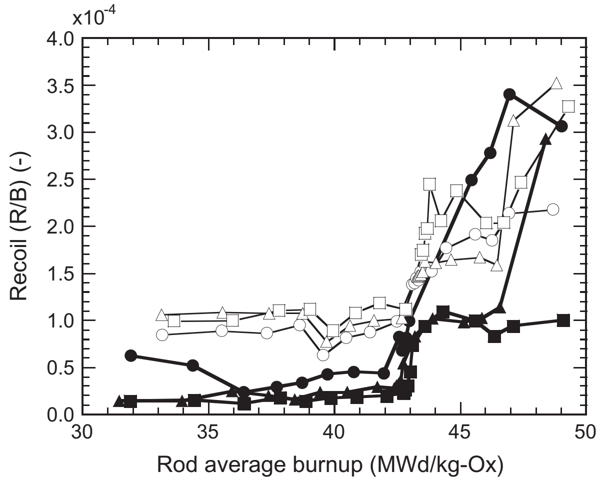

Fig. 5. The evaluated results of recoil (R/B) of IFA-633.1. ●: Rod 1, ○: Rod 2, ▲: Rod 3, △: Rod 4, ■: Rod 5, □: Rod 6.

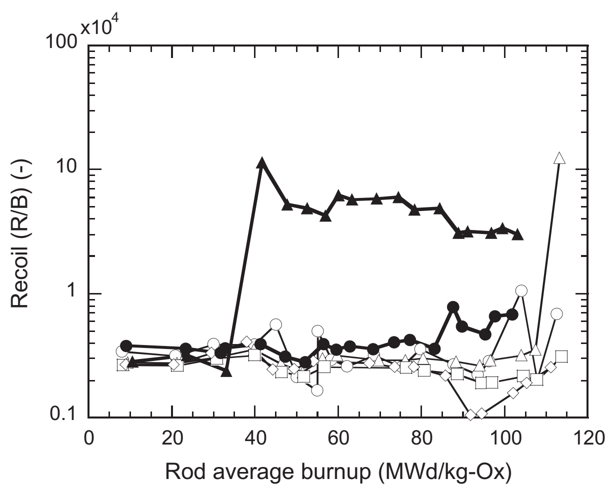

Fig. 6. The evaluated results of recoil (R/B) of IFA-655.1. ○: Rod 7, △: Rod 8, □: Rod 9, ◇: Rod 10, ●: Rod 11, ▲: Rod 12.

this value hardly depends on the fuel type and dimension of uranium-dioxide-based fuel (UO_2 or MOX) and irradiation condition.

The value of $(R/B)_{recoil\_norm}$, are evaluated by using the following equation:

$$\left(\frac{R}{B}\right)_{recoil\_norm} = \left(\frac{R}{B}\right)_{recoil} \Big/ \left(\frac{S}{V}\right) \quad (5)$$

In general, the actual value of (S/V) ratio differs from the value evaluated based on fuel geometry due to surface roughness, open porosity at surface and so on. In order to calculate the value of $(R/B)_{recoil\_norm}$, the accurate (S/V) ratio of a sample is needed. However, there are few reports in which (S/V) ratio of fuel sample is clearly shown.

Hirai et al. measured the diffusion coefficient in UO_2 and $(U,Gd)O_2$ fuels by using a gas-flow rig in the Harwell DIDO test reactor [8]. The value of $(R/B)_{recoil}$ can be calculated from their data and the results are given in Table 2. Here, the measured (R/B) ratios of ^{135}Xe, ^{85m}Kr, ^{88}Kr and ^{87}Kr at the startup of irradiation were used (as they mentioned in the Ref. [8], the data of these isotopes were used for a calculation of diffusion coefficient).

The value of (S/V) ratio of fuel pellet can be obtained from dividing the value of $(R/B)_{recoil}$, which is evaluated by using Eq. (4), by that of $(R/B)_{recoil\_norm}$.

4.3. Surface-to-volume ratio of fuel pellet

4.3.1. IFA-504

Fig. 7 shows the histories of fuel temperature and (S/V) ratio of fuel rods against fuel burnup. It can be seen that significant increases of (S/V) ratio occured at the burnups of approximately 15 and 22–27 MWd/kg-UO_2 for all fuel rods. Since these burnups corresponds to those where the fuel temperatures exceed the threshold of 1% fission gas release [9], so-called Vitanza threshold (the corresponding points are shown as the circles in Fig. 7a), it is suggested that some extent of the interlinkage of fission gas bubble occurred at these temperatures.

4.3.2. IFA-633.1

Fig. 8 presents the burnup dependence of (S/V) ratio of fuel pellet in IFA-633.1. In this figure, the (S/V) ratios can be separated into two groups, namely UO_2 (rods 3 and 5) and MOX (rods 2, 4 and 6). As for the rod 1 (UO_2), the (S/V) ratios are being located between these two groups.

At a burnup of about 43 MWd/kg-Ox, the significant increase of (S/V) ratios can be seen. At this burnup, the linear heat rates of the fuel rods increased intentionally, and it is estimated that the peak fuel temperatures of UO_2 and MOX rods reached about 1100 and 1050 °C, respectively. Since these temperatures are quite close to the threshold temperature of fission gas release [9], it is suggested that the interlinkage of fission gas bubbles occured due to the intentional fuel temperatures increase at this burnup. After the interlinkage occurred, the values of (S/V) ratio of UO_2 fuel pellets were nearly the same as that of MOX fuel pellets.

4.3.3. IFA-655.1

Fig. 9 shows the burnup dependence of (S/V) ratio of fuel in IFA-655.1. The (S/V) ratios of fuel disks hardly changed in rods 7–11 during irradiation. On the other hand, the (S/V) ratios of fuel disks in rod 12 (heterogeneous MOX fuel) clearly increases at the burnup of approximately 40 MWd/kg-Ox and show nearly constant value above this burnup.

Although the target irradiation temperatures of these fuel disks were set at 700 °C for rods 7, 8, 11 and 12 and at 500 °C for rods 9 and 10, only rod 12 experienced high temperature at 39 MWd/kg-Ox due to mal-operation of the gas flow system shortly after the reactor restart (the experienced temperature is estimated to be above 1000 °C). Since this temperature is close to the temperature at which fission gas release starts at this burnup, it is considered that the interlinkage of fission gas occurred to some extent.

Table 2
Normalized $(R/B)_{recoil}$ calculated from the data reported by Vitanza et al. [9].

Fuel type	Gd_2O_3 cont. (wt.%)	Burnup (MWd/t)	$(R/B)_{recoil}$ $(\times 10^{-5})$	Initial (S/V) ratio $(\times 10^2\ m^{-1})$	Normalized $(R/B)_{recoil}$ $(\times 10^{-9}\ m)$
UO_2	0	186	4.45	232	1.92
$(U,Gd)O_2$	4	204	9.17	281	3.26
	8	212	11.5	298	3.84
				Average	3.0 ± 1.0

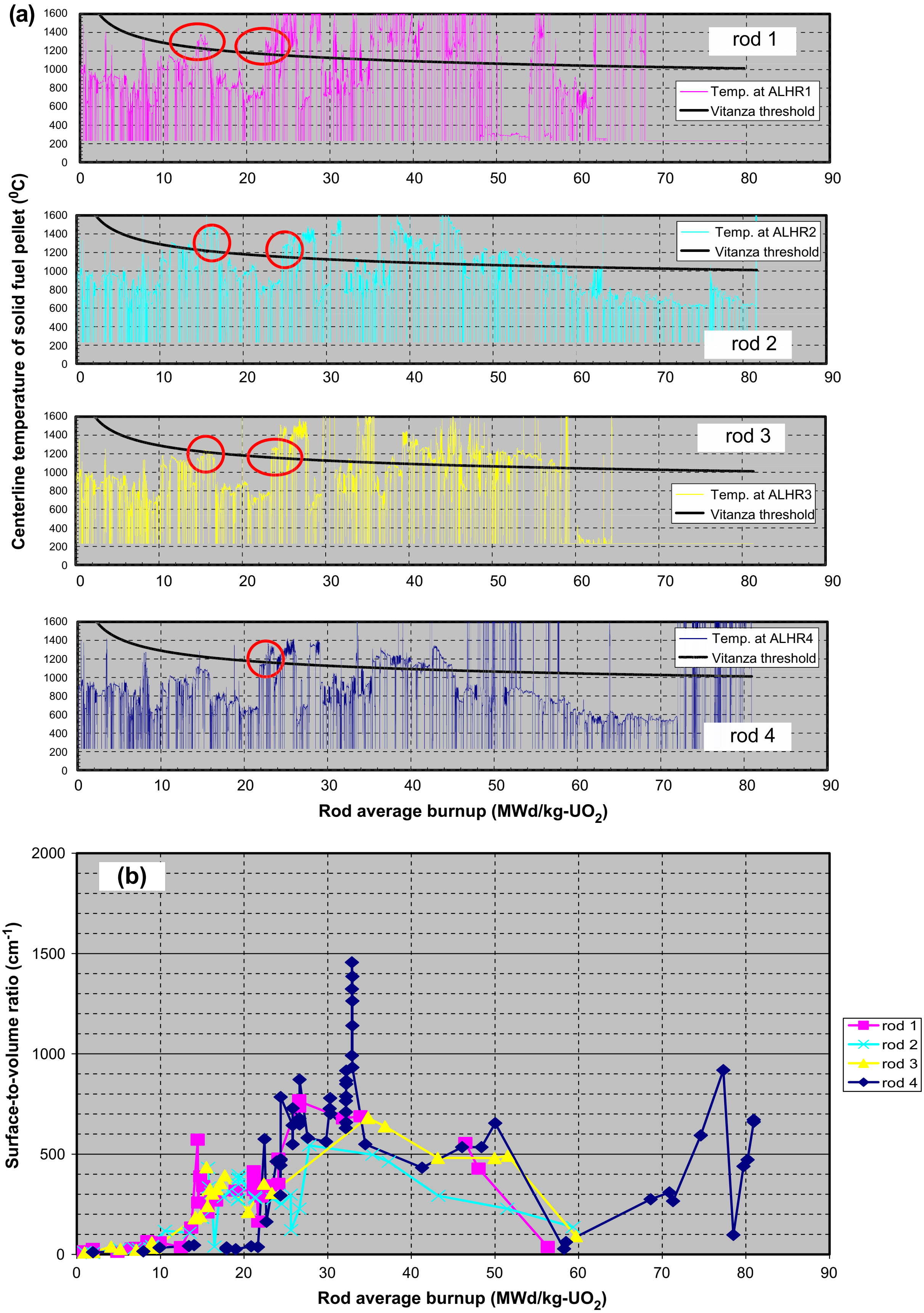

Fig. 7. Temperature histories and burnup dependence of the surface-to-volume ratios of fuel in IFA-504.

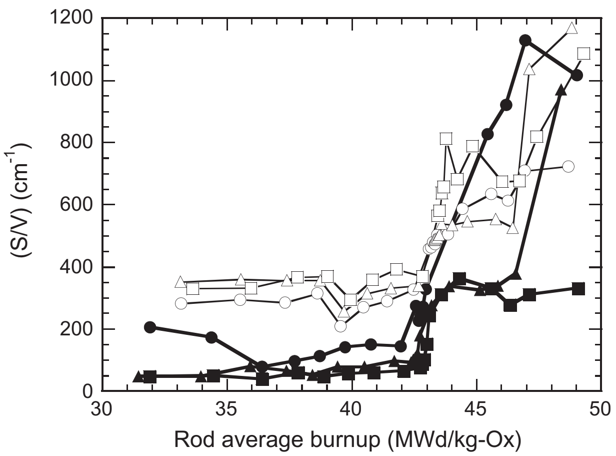

Fig. 8. Burnup dependence of the surface-to-volume ratios of fuel in IFA-633.1. ●: Rod 1, ○: Rod 2, ▲: Rod 3, △: Rod 4, ■: Rod 5, □: Rod 6.

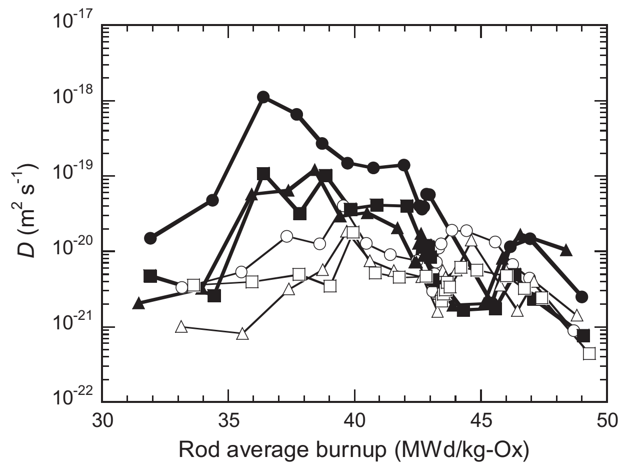

Fig. 11. Burnup dependence of the diffusion coefficient of fission gas in fuels for IFA-633.1. ●: Rod 1, ○: Rod 2, ▲: Rod 3, △: Rod 4, ■: Rod 5, □: Rod 6.

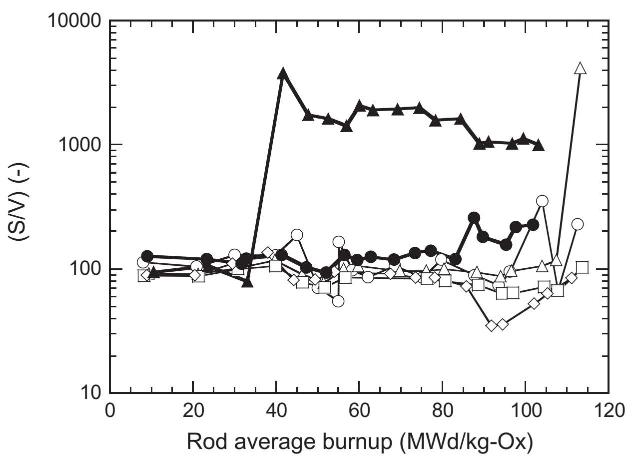

Fig. 9. Burnup dependence of the surface-to-volume ratios of fuel in IFA-655.1. ○: Rod 7, △: Rod 8, □: Rod 9, ◇: Rod 10, ●: Rod 11, ▲: Rod 12.

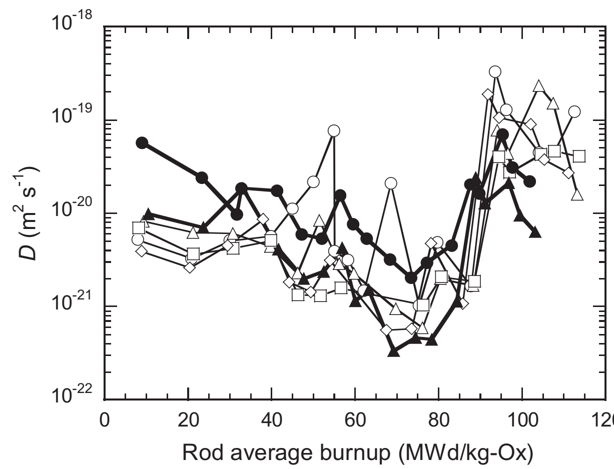

Fig. 12. Burnup dependence of the diffusion coefficient of fission gas in fuels for IFA-655.1. ○: Rod 7, △: Rod 8, □: Rod 9, ◇: Rod 10, ●: Rod 11, ▲: Rod 12.

4.4. Diffusion coefficient of short-lived fission gas

Figs. 10–12 summarize the burnup dependences of the diffusion coefficient of short-lived fission gas in the fuels of IFAs-504, -633.1 and -655.1.

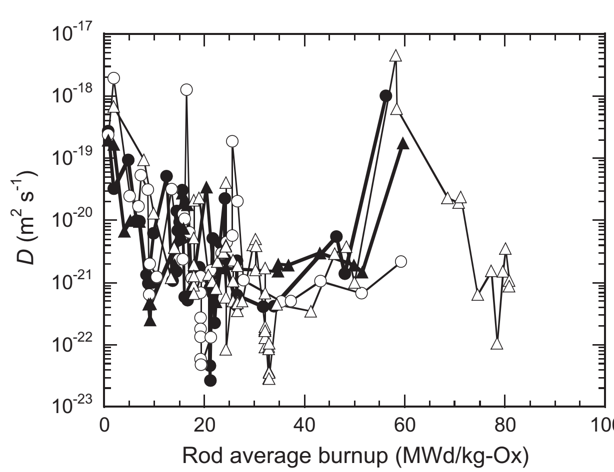

Fig. 10. Burnup dependence of the diffusion coefficient of fission gas in fuels for IFA-504. ●: Rod 1, ○: Rod 2, ▲: Rod 3, △: Rod 4.

As for the IFA-504 experiment (see, Fig. 10), diffusion coefficients of short-lived fission gas tend to decrease with increasing burnup in the burnup region up to ~30 MWd/kg-UO_2. These values are, however, 10^{-18}–10^{-23} m^2/s and comparable to the reported ones [1,9].

The diffusion coefficients of fission gas in the fuels of IFA-633.1 scatters between values of 10^{-18} and 10^{-22} m^2/s (see, Fig. 11), and it seems that the diffusion coefficients of each fuel rod do not change significantly in this burnup range when the data scatter range is taken into account. The diffusion coefficients of fission gas in the fuels of IFA-655.1 also scatters between values of 10^{-19} and 10^{-22} m^2/s irrespective of fuel type (see, Fig. 12).

5. Discussion

5.1. Changes in the equivalent sphere radius

The following relationship holds between the equivalent sphere radius, r, and (S/V) ratio:

$$r = \frac{3}{(S/V)}. \quad (6)$$

In the case of IFA-504 experiment, most values of (S/V) are in the range below about 100 cm^{-1} until the fuel pellets experienced the threshold temperatures of 1% fission gas release which are shown as the circles in Fig. 7a. The equivalent sphere radius which corresponds to this (*S*/*V*) value is 300 μm.

During irradiation, fuel pellet cracks radially due to thermal stress and is divided into fragments. In the case that fuel rod did not experience high temperature, a typical pellet fragment after base irradiation may be treated as a cube with a side of about 2 mm from the macrographs of pellet after irradiation (e.g. [10]). Due to the effect of surface roughness, it is considered that the actual (*S*/*V*) ratio of fuel fragments is larger than the geometrical (*S*/*V*) ratio. According to the (*S*/*V*) ratios which were measured and reported by Hirai et al. [8], it is estimated that the actual (*S*/*V*) ratios are about four-times larger than the geometrical ones. Accordingly, the actual (*S*/*V*) value of pellet fragment can be estimated as about 120 cm^{-1}. The equivalent sphere radius which corresponds to the value of 120 cm^{-1} is 0.25 mm, namely 250 μm. The equivalent sphere radius which is estimated based on the results of gas-flow measurement of this study, 300 μm, is quite close to that of the typical pellet fragment in the fuel rod which did not experience high temperature during irradiation, and it is suggested that significant interlinkage had not occurred in the fuel pellet until the fuel pellets experienced the threshold temperatures of 1% fission gas release.

On the other hand, after the fuel pellets experienced the threshold temperature of 1% fission gas release, the values of (*S*/*V*) ratio tend to increase due to the interlinkage of fission gas bubbles. Regarding the IFA-504 experiment, it seems that (*S*/*V*) ratio saturates to 500–600 cm^{-1}. This value corresponds to the equivalent sphere radius of around 50 μm. Considering that the grain size of fuel pellet is ~10 μm as fabricated and the (*S*/*V*) ratio of the grain is ~6000 cm^{-1}. Consequently, it is estimated that one tenth of grain surface area was connected to the outside of pellet during irradiation.

In the case of IFA-655.1 experiment, the estimated (*S*/*V*) ratios of both UO_2 and MOX fuel pellets excluding rod 12 are about 100 cm^{-1}. The (*S*/*V*) ratios of rod 12 increased to about 4000 cm^{-1} at a burnup of 40MWd/kg-Ox where the fuel temperature rose above 1000 °C for a short period. This value, 4000 cm^{-1}, corresponds to a equivalent sphere radius of 7.5 μm. This value agrees well with the grain size of about 10 μm at fabrication. As a consequence, it is likely that sudden increase of (*S*/*V*) ratio in rod 12 is caused by interlinkage of fission gas bubbles at grain boundary due to high temperature experience.

As for IFA-633.1 experiment, the (*S*/*V*) ratios are 50–150 and 300–400 cm^{-1} for UO_2 and MOX groups in the burnup range below 43 MWd/kg-Ox. These values correspond to the equivalent sphere radii of 200–600 μm and 75–100 μm, respectively.

On the other hand, the equivalent sphere radii are about 30 μm for rods 1, 3, 4 and 6 in the burnup range above 43 MWd/kg-Ox. It is considered that the interlinkage of fission gas bubbles occurred due to the intentional power increase of fuel rod at this burnup. In addition, the difference of equivalent sphere radius between UO_2 and MOX fuels tends to become small after the interlinkage of fission gas bubbles occur above 43 MWd/kg-Ox. Since it is estimated that the peak temperatures in both UO_2 and MOX fuels reached 1050–1100 °C at this power increase based on the measured fuel temperatures, it is likely that both fuels have nearly the same threshold temperature where the interlinkage of fission gas bubbles occurs around 43 MWd/kg-Ox. Considering this tendency, the difference of (*S*/*V*) ratio in the burnup range below 43 MWd/kg-Ox may be caused rather by the difference of pellet fabrication than by the difference of fuel types: pellet characteristics such as open porosity strongly depend on the sintering conditions (atmosphere, temperature, etc.) and what kinds of additives are used at fabrication.

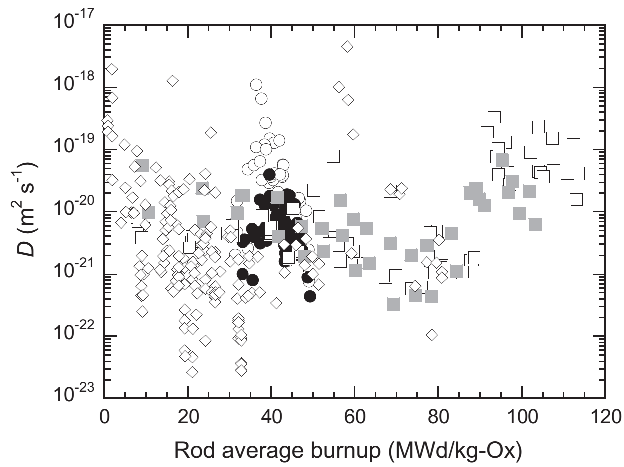

Fig. 13. Comparison of the diffusion coefficient of fission gas obtained from the irradiation experiment IFA-504, -633.1 and -655.1. ◇: IFA-504 (UO_2), ○: IFA-633.1 (UO_2), ●: IFA-633.1 (MOX), □: IFA-655.1 (UO_2), ■: IFA-655.1 (MOX).

5.2. Comparison of the evaluated diffusion coefficients of short-lived fission gas

Fig. 13 compares the diffusion coefficients of short-lived fission gas obtained from the three irradiation experiments, IFAs-504, -633.1 and -655.1. Since the evaluated diffusion coefficients agree well with each other, it is considered that the geometrical effect of fuel rod and/or pellet is negligible.

The evaluated diffusion coefficients are in the range between 10^{-18} and 10^{-23} m^2/s for these irradiation experiments, and comparable to the reported ones [1,9]. This also suggests that fuel type and burnup hardly affect the diffusion coefficient of short-lived fission gas in the temperature ranges of these experiments.

The effect of rim structure formation on fission gas release from fuel pellet has been discussed [11], particularly in the high burnup region, and the possibilities that the rim structure formation enhances the diffusion coefficient of fission gas are being pointed out. The evaluated diffusion coefficients, however, did not show clear increase even in the high burnup region above 70 GWd/t, where the rim structure formation begins to be observed in the irradiated fuel pellets [11]. Consequently, at least, it is considered that diffusion of short-lived fission gas in the fuel pellet matrix is hardly affected by the rim structure formation.

6. Conclusion

Short-lived fission gas release from fuel pellets during irradiation was investigated based on the experimental results of the gas-flow rigs irradiated in the Halden Heavy Water Reactor.

The release-to-birth (*R*/*B*) rates of short-lived fission gas were measured by means of gas-flow measurement during the irradiation experiments IFAs-504, -633.1 and -655.1. Surface-to-volume (*S*/*V*) ratios of fuel pellets and diffusion coefficients of short-lived fission gas release were evaluated from the obtained (*R*/*B*) values. The increase of (*S*/*V*) ratio agreed well with the point where the fuel temperature exceeded the threshold of 1% fission gas release. This indicates that the interlinkage of fission gas bubbles occurred there. The evaluated diffusion coefficients scattered in the range between 10^{-23} and 10^{-17} m^2/s, and the effects of fuel rod geometry, fuel type (UO_2 or MOX) were not clearly observed. Since the evaluated diffusion coefficients did not change significantly even in the burnup range where the rim structure forms, it is likely that the restructuring effect of fuel pellet on the diffusion coefficients of short-lived fission gas is negligible at least in the fuel pellet matrix.

Acknowledgments

The authors would like to thank Messrs B. Volkov and Ø. Brennvall for their experimental support in the gas flow measurements.

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