A Study of Mechanical Integrity of Coated Particle Fuel under High Burnup Irradiation

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ABSTRACT

In high temperature gas-cooled reactors (HTGRs), Tri-isotropic (TRISO)-coated fuel particles are employed as fuel. The TRISO coatings consist of a low-density, porous pyrolytic carbon (PyC) buffer layer adjacent to the spherical fuel kernel, followed by an isotropic PyC layer (inner PyC; IPyC), a silicon carbide (SiC) layer and a final PyC (outer PyC; OPyC) layer. In safety design of the HTGR fuels, it is important to retain fission products within particles so that their release to primary coolant does not exceed an acceptable level. From this point of view, the basic design criteria for the fuel are to prevent significant additional fuel failures during operation. In order to investigate fuel behavior under high burnup condition, irradiation tests were performed. The irradiation tests were carried out independently as 91F-1A capsule (at the Japan Materials Testing Reactor of Japan Atomic Energy Research Institute) and HRB-22 capsule (at the High Flux Isotope Reactor of Oak Ridge National Laboratory) irradiation tests. The fuel for the irradiation tests was called high burnup fuel, whose target burnup was 5 to 10%FIMA (% fission per initial metallic atom). In order to keep fuel integrity up to high burnup, thickness of buffer and SiC layers of the high burnup fuel particle were increased. During irradiation, fuel performance was monitored by fission gas concentration in sweep gas. The failure of coated particles was observed in both irradiation tests. The fuel failure behavior was analyzed by pressure vessel failure model, which evaluate failure probability of coating layers due to the internal pressure of fission gases and CO gas with burnup. The result showed that no tensile stresses acted on the SiC layers even at the end of irradiation and no pressure vessel failure occurred in the intact particles. This result implies that there were weak particles and they failed to the through-coatings failure during irradiation. The weak particles correspond to particles with defect in the SiC layer. The SiC-defected particle would be the particle with micro crack on the SiC layer surface. Since the high burnup fuel compact was high packing fraction, i.e., contained much coated fuel particles, to keep fissile materials, contact of the coated fuel particles would occur in fuel compaction process.

INTRODUCTION

In current high temperature gas-cooled reactors (HTGRs), Tri-isotropic (TRISO)-coated fuel particles are employed as fuel. The TRISO coatings consist of a low-density, porous pyrolytic carbon (PyC) buffer layer adjacent to the spherical fuel kernel, followed by an isotropic PyC layer (inner PyC; IPyC), a silicon carbide (SiC) layer and a final PyC (outer PyC; OPyC) layer as shown in Fig. 1. In safety design of the HTGR fuels, it is important to retain fission products within particles so that their release to primary coolant does not exceed an acceptable level. From this point of view, the basic design criteria for the fuel are to minimize the failure fraction of as-fabricated fuel coating layers and to prevent significant additional fuel failures during operation[(1)]. For the first-loading fuel of the High Temperature Engineering Test Reactor (HTTR), the fuel temperature is limited below 1495 °C during normal operation conditions and below 1600 °C during anticipated operational occurrences, and the fuel burnup is limited to 33 GWd/tM to meet the latter criterion.

In order to investigate fuel behavior under high burnup condition, irradiation tests were performed. The irradiation was carried out as 91F-1A and HRB-22 capsule irradiation tests. The fuel for the irradiation tests were called high burnup fuel, whose target burnup and fast neutron fluence were higher than those of the first-loading fuel of the High Temperature Engineering Test Reactor (HTTR)[(2)]. In order to keep fuel integrity up to high burnup over 5%FIMA (% fission per initial metallic atom), thickness of buffer and SiC layers of fuel particle were increased as shown in Table1. The fuel compacts were irradiated in the 91F-1A and HRB-22 capsules at the Japan Materials Testing Reactor (JMTR) of Japan Atomic Energy Research Institute (JAERI), and at the High Flux Isotope Reactor

(HFIR) of Oak Ridge National Laboratory (ORNL), respectively[3,4]. The various post-irradiation tests were also carried out. The results showed that there were no through-coatings failed particle at the beginning of irradiation, however, a few additional particle failures occurred during both irradiation tests. The post-irradiation tests of the fuels were also carried out and one through-coatings failed particle was found by X-ray radiography among the fuel irradiated in the 91F-1A capsule. This paper shows results of the irradiation and postirradiation test results of the high burnup fuels. Analytical result of a pressure vessel failure model is also presented and discussed in this paper.

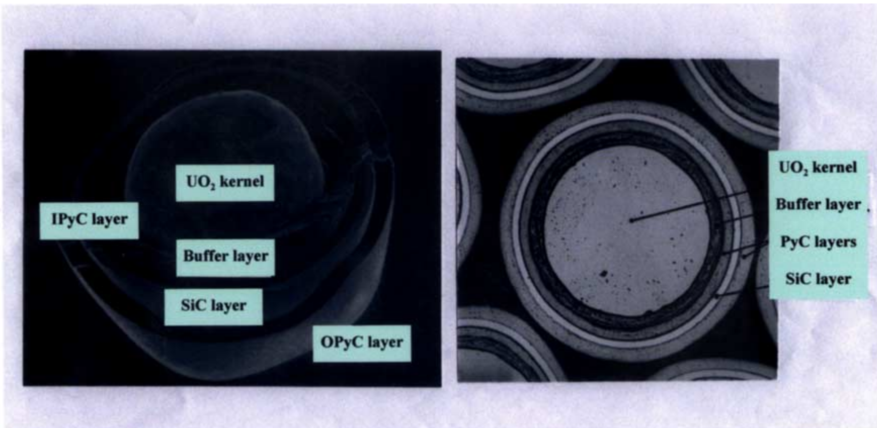

Fig. 1 TRISO-coated particle.

Table 1. Comparison of major specifications and irradiation target of high burnup fuel and first-loading fuel of the HTTR.

	High burnup fuel	First-loading fuel of the HTTR
Kernel diameter (μm)	550	600
Buffer layer thickness (μm)	90	60
SiC layer thickness (μm)	35	25～30
Target burnup (GWd/t)	50～100	33
Fast neutron fluence ($10^{25}m^{-2}$)	3～5	1.5

EXPERIMENTS

Fuel Fabrication

The fabrication process of the high burnup fuel irradiated in the capsules was basically same as the first loading fuel of the HTTR[2]. Table 2 shows measured dimensions of as-fabricated coated fuel particles[5]. The diameter of the UO_2 fuel kernel was measured by the Particle Size Analyzer (PSA). The thickness of the buffer and the IPyC layers were measured by optical microscopy. The thickness of the SiC and the OPyC layers were measured by X-ray microradiography. The optical anisotropy factors (OPTAF) were 1.00 for both the IPyC and OPyC layers, then PyC layers were properly deposited.

Table 2. Dimensions of the irradiated coated fuel particles.

	HRB-22		91F-1A	
	Mean value (μm)	Standard deviation (μm)	Mean value (μm)	Standard deviation (μm)
Kernel diameter	544	9.1	551	9.9
Buffer thickness	97.4	13	97.3	12
IPyC thickness	32.9	3.4	32.1	3.4
SiC thickness	33.7	1.6	34.2	1.7
OPyC thickness	39.3	3.1	38.6	3.7

The fuel compacts contained the TRISO-coated fuel particles and the dummy SiC-kerneled coated particles (diluted fuel compacts). The total packing fraction was nearly 35 %. The free uranium fraction of the fuel compacts was measured by the deconsolidation followed by the acid leaching. The solution was analyzed for uranium by fluorometric analysis. The measured values showed that no through-coatings-failed particle was present in the sampled fuel compacts. The SiC-failure fraction of the fuel compact was measured by two methods: by the burn/leach method and by the burn/X-ray microradiography. No SiC-failed particle was observed in the sampled fuel compacts. In the burn/X-ray microradiography, four fuel compacts were burned in the same way as in the burn/leach method. In one particle, crack was observed on the surface of the SiC layer by optical microscopy and scanning electron microscopy (SEM). If the crack ran through the SiC layer, the buffer and IPyC layers would be burned off during the burning of the fuel compact. Since the X-ray microradiograph showed no anomaly in the buffer and the IPyC layers, it was concluded that the cracks did not run through the SiC layer.

Irradiation Test

The HRB-22 capsule consisted of a doubly contained, single purge cell with 12 fuel compacts held in a graphite fuel body. The twelve compacts were enclosed in a fuel body fabricated from fine grain graphite, grade 2020 graphite. The radial gap between the graphite fuel body and the inconel containment was sized to maintain the temperature as uniformly as possible over the length of the capsule by machining a steeped outer surface to the sleeve. The temperature of the graphite fuel body was monitored by 24 thermocouples (TCs). The capsule includes facility for introducing a purge gas. Capsule temperatures were adjusted by changing the composition of the sweep gas flowing in the gap between the graphite fuel body and the inconel pressure vessel. A mixture of helium and neon was used to control the temperature. The irradiation was conducted in position RB-3B of the Removal Beryllium (RB) facility for 4 reactor operating cycles starting with HFIR cycle 325. The reactor was operated at a nominal

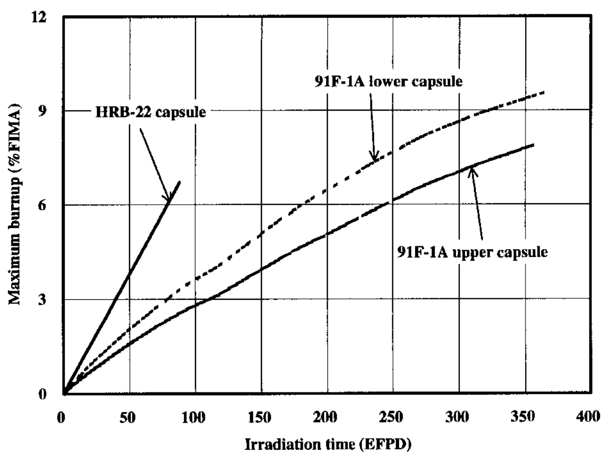

Fig.2 Burnups in irradiation tests.

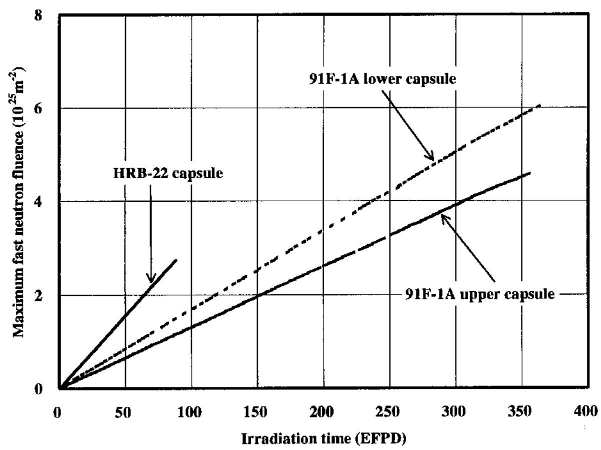

Fig.3 Fast neutron fluences in irradiation tests.

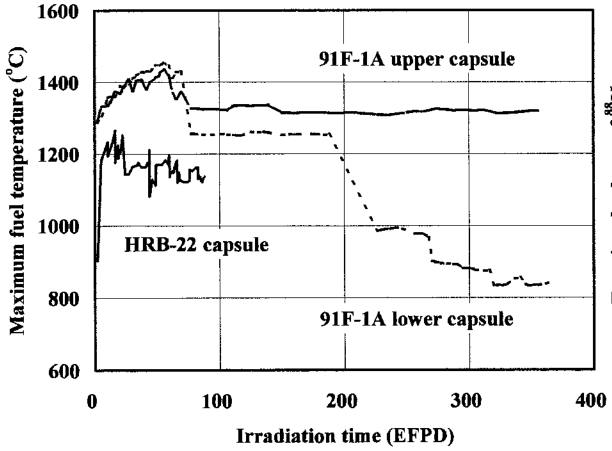

Fig. 4 Maximum fuel temperatures in irradiation tests.

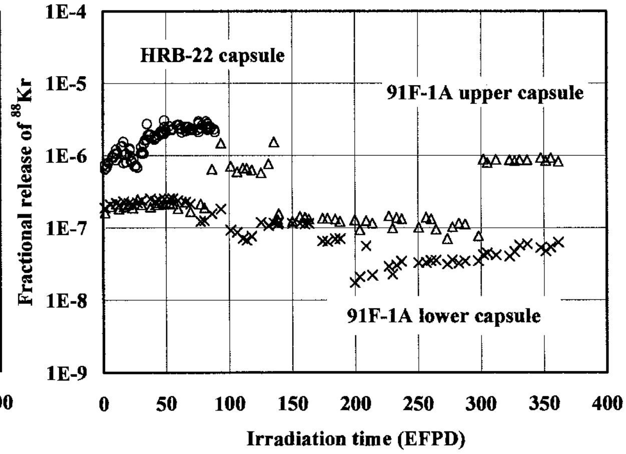

Fig. 5 Measured fractional releases in irradiation tests.

power of 85 MW_t throughout most of the irradiation period.

The 91F-1A irradiation rig consisted of two capsules, upper and lower, which were irradiated and monitored independently. Each capsule contained two fuel compacts which were held in a graphite sleeve, which in turn was housed in a double wall container. Temperatures were controlled by adjusting the gas pressure between the two walls. The fuel and graphite temperatures were measured by W/Re and N-type TCs, respectively. The irradiation was conducted in position M-7 for 16 reactor operating cycles starting with JMTR cycle 104. The reactor was operated at a nominal power of 50 MW_t throughout most of the irradiation period.

Burnups and fast neutron fluences for the fuel compacts are shown in Figs. 2 and 3, respectively. The fuel temperatures were evaluated based on measured TC temperatures. Time-dependent maximum fuel temperatures are shown in Fig. 4. The fuel temperature of the lower capsule in the 91F-1A was decreased after 80 effective full power days (EFPD) because the W/Re TC was failed during irradiation. The release rate-to-birth rate ratio (R/B) is an important measure of the performance of the coated particle fuel. A sample of the sweep gas was obtained in a bottle using the grab sample apparatus. The sample was obtained by first evacuating the bottle and grab sample manifold, and then backfilling the system with the sweep gas. The type and activity of radioactive fission gas in the grab sample was measured using γ-spectroscopy. The γ-rays were detected by an intrinsic Ge detector. In the 91F-1A irradiation test, sweep gas was sampled from both inner capsules independently. The measured (R/B) values were shown in Fig. 5 during HRB-22 and 91F-1A capsule irradiation tests.

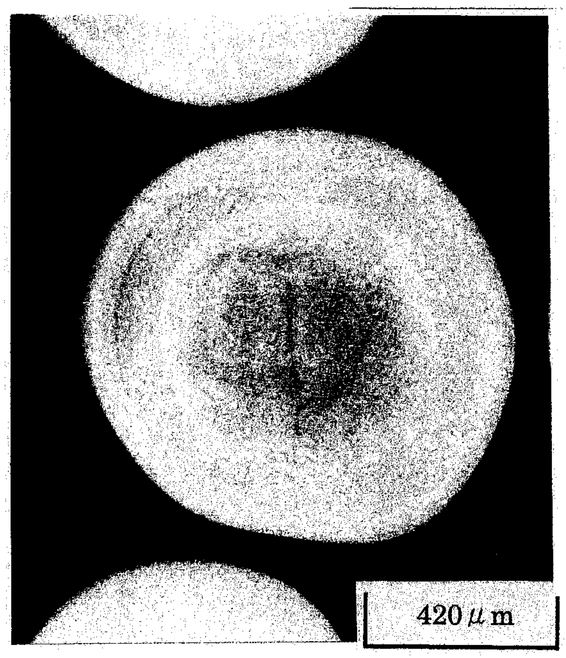

Fig. 6 Microradiograph of a failed particle.

Postirradiation Examination

No damage, degradation and loose particles were found in visual examination of the irradiated fuel compacts. The coated fuel particles were recovered from the fuel compacts by electrolytic deconsolidation. As postirradiation examinations, coated fuel particles were examined by X-ray microradiography, ceramograpy, SEM and shielded electron probe microanalyzer (EPMA).

In the postirradiation examination of the 91F-1A fuel, one failed particle was found among the deconsolidated coated fuel particles. X-ray microradiograph of the failed particle is shown in Fig. 6. A line is a crack on the particle surface and the fuel kernel was leached during the deconsolidation. It means that the crack penetrates all coating layers, i.e., the through-coatings failed particle. Figure 7 shows SEM observations of whole particle view and expanded view of the failed particle. The outer surface of the particle is OPyC layer washed by nitric acid during deconsolidation.

For other particles, no corrosion of the SiC layer by fission product palladium or carbon monoxide was observed. All fuel kernels retained their full original diameter and smooth circular shape with minor internal porosity and no kernel migration was observed.

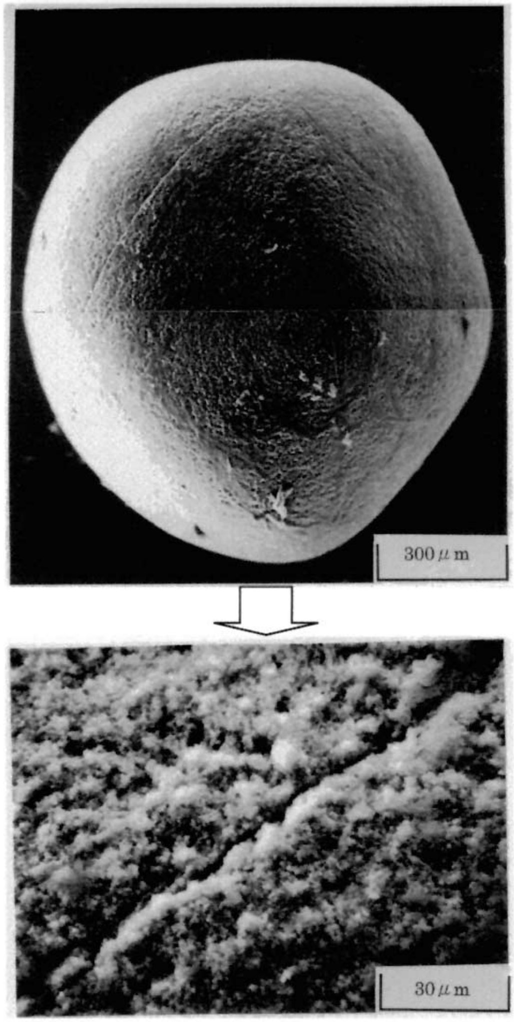

Fig. 7 SEM observation of a failed particle and expanded view of crack.

RESULTS AND DISCUSSIONS

Fission Gas Release

The fission gas release fraction, (R/B), was evaluated by a model developed in JAERI to investigate fuel failure behavior during irradiation[6]. In the model, fractional release is written as follows.

$$(R/B)=((f_{k,r}\times f_{m,d})+(f_{k,d}\times f_{m,ad}))\times \phi_k+(f_{m,r}+f_{m,d})\times \phi_c \quad (1)$$

Fractional release from the through-coatings failed particle is expressed by the following equation that includes pre-cursor effect[7].

$$f_{k,d}=3\left(\frac{1}{\Gamma_1}\left(\frac{\coth\sqrt{\mu_1}}{\sqrt{\mu_1}}-\frac{1}{\mu_1}\right)+\frac{1}{\Gamma_2}\left(\frac{\coth\sqrt{\mu_2}}{\sqrt{\mu_2}}-\frac{1}{\mu_2}\right)\right)\times f_{BU} \quad (2)$$

$$\Gamma_1=1-\frac{\mu_1}{\mu_2},\quad \Gamma_2=1-\frac{\mu_2}{\mu_1},\quad \mu_i=\frac{\lambda_i}{D'_i} \quad (3)$$

The diffusion coefficients of Kr and Xe-isotopes and their parents in the UO_2 fuel kernel are determined based on experimental data[8]. The release fraction increases with burnup in general, because the irradiation-enhanced diffusion occurs as a result of burnup. The burnup correction factor is introduced based on experimental observation[9].

The recoil release fraction from kernel is calculated by the following equation[10].

$$f_{k,r}=\left(\frac{3}{4}\right)\left(\frac{R_{ec}}{a}\right)-\left(\frac{1}{16}\right)\left(\frac{R_{ec}}{a}\right)^3 \quad (4)$$

Fractional release from the fuel compact matrix is divided into two components; namely, the in-graphite grain diffusion and the graphite grain boundary diffusion releases.

$$f_{m,d}=\alpha\times f_{m,gd}+(1-\alpha)\times f_{m,ad} \quad (5)$$

Both fractional releases are calculated by the analytical solution of the basic diffusion equation.

$$f_{m,d} = 3\sqrt{\frac{D'}{\lambda}}\coth\left(\sqrt{\frac{\lambda}{D'}} - \sqrt{\frac{D'}{\lambda}}\right) \tag{6}$$

The release fraction from the fuel compact by fission recoil of the contaminated uranium in the fuel compact matrix is calculated based on the fuel compact geometry, which is assumed to be infinite hollow cylinder, and recoil distance of the fission product.

$$f_{m,r} = \frac{R_{ec}(3(r_i + r_o) - 2R_{ec})}{6(r_o^2 - r_i^2)} \tag{7}$$

The comparison of measured and calculated (R/B)s during the HRB-22 and the 91F-1A capsule irradiation test is shown in Figs. 8 and 9, respectively. In the HRB-22 capsule irradiation test, no additional failure occurred between 0 to 30 EFPD and the fractional release varied in accordance with change of the fuel temperature. The calculated results give relatively good agreement with the measured (R/B)s when there were two through-coatings failed particles at the beginning of irradiation. Since there were 3.2×10^4 of the fuel particles in the HRB-22 capsule, the failure fraction was 6.3×10^{-5} at the beginning of irradiation. The failure fraction reached to 1.9×10^{-4} at the end of irradiation because additional fuel particle failures were observed at 30.4, 32.6, 59.7 and 83.3 EFPD by the ionization chamber monitoring during irradiation. In the 91F-1A capsule irradiation test, the calculated results give relatively good agreement with the measured (R/B)s when there was no failed particle at the beginning of irradiation. During irradiation, additional failure occurred and the failure fraction reached to 5.3×10^{-5} at the end of irradiation in both inner capsules. Since there were 1.0×10^4 of the fuel particles in each inner capsule, the number of failed particle is estimated to be 0 or 1. In these calculations, 2×10^{-6} of the uranium contamination fraction was employed based on the fabrication data[2,6].

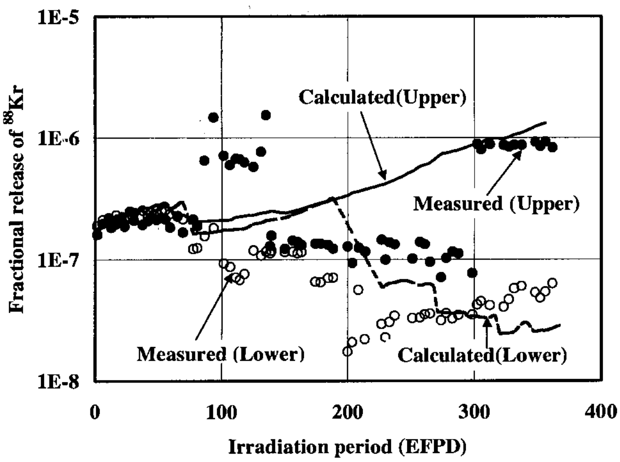

Fig. 8 Comparison of measured and calculated fractional releases in HRB-22 capsule irradiation test.

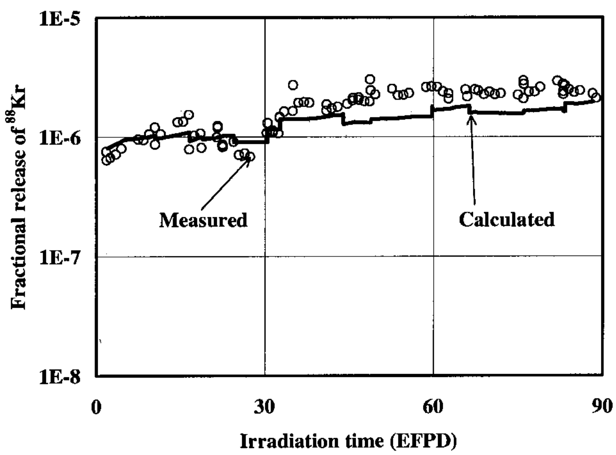

Fig. 9 Comparison of measured and calculated fractional releases in 91F-1A capsule irradiation test.

Failure Fraction

Based on the irradiation experiences[11,12], possible mechanisms that caused additional four particles failure during irradiation are kernel migration, SiC corrosion by Pd and pressure vessel failure by internal pressure. However, kernel migration and SiC corrosion was not observed in the postirradiation examination. Through the SEM observation shown in Fig. 7, the pressure vessel failure is considered to be the most probable failure mechanism under the irradiation.

A pressure vessel failure model under high burnup condition has been developed based on the following essential assumptions[13].

(1) The failure probability of each coating layer is described by a Weibull distribution with microscopic surface

flaws considered to be critical failure initiation sites.

(2) The stresses act on the coating layers of the fuel particle are assumed to be caused by pressure of fission gases and CO gas from UO_2 kernel and by fast neutron-induced shrinkage of the PyC layers.

(3) Two types of failed particles are categorized, i.e., through-coatings failed particle and SiC-failed particle. The through-coatings failed particle results in IPyC, SiC and OPyC layer failure. The SiC-failed particle has failed IPyC and SiC layers but an intact OPyC layer. The gaseous fission products are released from through-coatings failed particle. On the other hand, since OPyC layer is capable of retaining the gaseous fission products, the SiC-failed particle does not release the gaseous fission products. The failure probability that as-fabricated SiC-failed particle becomes the through-coatings failed particle is also modeled.

The fracture strength distribution of coating layers is expressed by a Weibull distribution. The failure probability of each layer is calculated by the following basic equation.

$$f_i(t) = 1 - exp(-\ell n2 \times (\frac{\sigma_i(t)}{\sigma_{0,i}})^{m_i}) \tag{8}$$

The tensile stress is introduced into the coatings due to the pressure of fission gases and CO gas as burnup proceeds. On the other hand, the IPyC and OPyC layers undergo irradiation-induced shrinkage as a result of fast neutron exposures. Consequently, the OPyC layer places a compressive load on the SiC layer, which counteracts the SiC tensile stress due to internal pressure. Similarly, the IPyC layer acts to reduce the SiC tensile stress by tending to contract while maintaining contact with the inner SiC surface. The shrinkage of the PyC layers results in tensile stresses on themselves. Based on above-mentioned behavior, failure probability of each coating layer is modeled as follows.

It is assumed that the IPyC layer fails by tensile stress only in the SiC layer failed particle. When the SiC layer is intact, the IPyC layer is supported by the SiC layer, which is much stronger than the PyC layer, and the IPyC failure does not occur (f_{IPyC}=0). For the SiC-failed particle, in which the SiC layer can not support the IPyC layer, tensile stress due to internal gas pressure would cause failure of the IPyC layer (f'_{IPyC}). The SiC layer fails by internal gas pressure in high burnup irradiation condition. The compressive stress caused by the IPyC and the OPyC layers shrinkage mitigates the stress on the SiC layer. When the OPyC layer is intact, the failure probability of the SiC layer (f_{SiC}) is evaluated based on tensile stress which is a balance of the stress due to internal gas pressure and the compressive stresses by both the IPyC and the OPyC shrinkage. Since a compressive load by the OPyC layer can not be expected, the tensile stress of the SiC layer and the failure probability in the OPyC-failed particle (f'_{OPyC}) becomes larger than that in the OPyC intact particle. The OPyC layer fails only by tensile stress. When the SiC layer, which is inside of the OPyC layer, is intact, the failure of the OPyC does not occur (f_{OPyC}=0) because it is supported by the stronger SiC layer. In the SiC-failed particle, the failure of the OPyC layer occurs by the internal gas pressure (f'_{OPyC}).

Based on above-mentioned failure probabilities of coating layers, probability that the intact particle becomes the through-coatings failed particle (F_{TC}) can be expressed as follows.

$$F_{TC} = f'_{IPyC} \times f_{SiC} \times f'_{OPyC} \tag{9}$$

In the fabrication of coated fuel particles, a few particles are made as initially SiC-failed particles. In this model, the SiC-failed particle is defined as a particle that has failed SiC layer but has an intact OPyC layer. The probability that as-fabricated SiC-failed particle becomes the through-coatings failed particle (F'_{TC}) is written as following equation.

$$F'_{TC} = f'_{OPyC} \tag{10}$$

The tensile stress induced in the coating layer is calculated based on a thick-walled spherical pressure vessel model[14]. The internal pressure generates from stable gaseous fission products and CO gas due to excess oxygen by UO_2 fission. The internal pressure is calculated by following equations.

$$P = \frac{nRT}{V} \tag{11}$$

$$n = n_{FP} + n_O \tag{12}$$

The number of free oxygen atoms is calculated by the experimentally obtained equation[15].

$$log((n_O/F)/t_i^2) = -0.21 - \frac{8500}{T} \tag{13}$$

The number of stable noble gases is calculated by the following equation[16].

$$n_{FP} = 0.31 \times FxFR \tag{14}$$

The model formalism describes the j-layer stress contribution from PyC shrinkage as a function of anisotropic irradiation-induced strains[17] and creep in the PyC layers.

At first, the stresses on the SiC layers in the intact particles were evaluated as shown in Fig. 10. The result shows that no tensile stresses act on the SiC layers even at the end of irradiation and no pressure vessel failure occurred in the intact particles. Therefore, it is difficult to consider the intact particle failed by the internal pressure buildup during the irradiation.

The possibility that the SiC-failed particle failed to the through-coatings failed particle during the irradiation was investigates by the analysis. The evaluated failure probabilities that the as-fabricated SiC-failed particle fails to the through-coatings failure at the end of irradiation were 28 % for the compact-6 of HRB-22 irradiation test and 0.05 % for the 91F-1A irradiation test. The result shows that additional through-coatings failures could occur for as-fabricated SiC-failed particles in the fuel compact. This prediction implies that there were weak particles and they failed to the through-coatings failure during irradiation. The weak particles correspond to particles with defect in the SiC layer. Judging from the fact that there were two as-fabricated through-coatings failure particles in the HRB-22 capsule, the SiC-defected particles, for example particles with micro crack on the SiC layer were considered to be contained in fuel compacts.

Based on the fabrication experiences

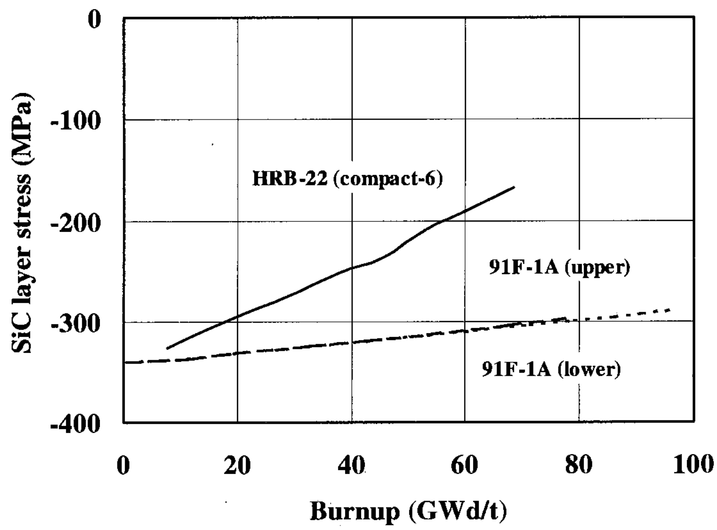

Fig. 10 Evaluated stress on the SiC layer in irradiation tests.

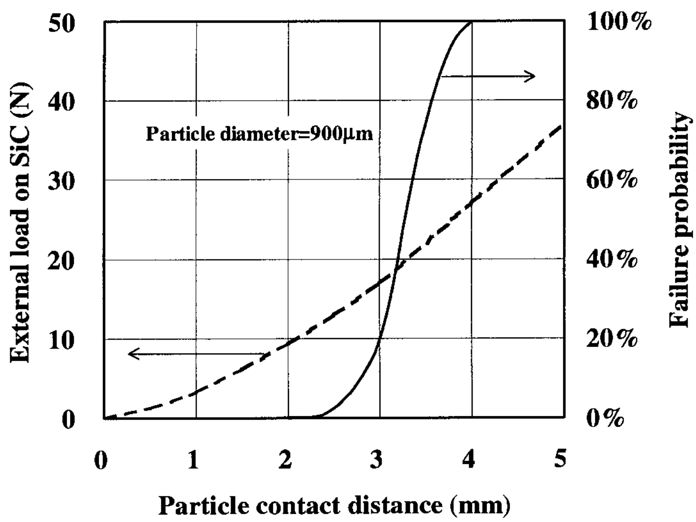

Fig. 11 Evaluated failure probability of the SiC layer in compaction.

of the first-loading fuel of the HTTR, the as-fabricated SiC-defect occurred in the compaction process mainly by the direct contact with neighboring particles in the fuel compact. Because the packing fraction of coated particles in a fuel compact is as high as 35 vol% in a high burnup fuel to keep the amount of uranium, although about 30 vol% in the first-loading fuel compact, the probability of direct contact with neighboring particles would be increased. In order to evaluate the as-fabricated defect probability of SiC-layer by the direct contact of particles, $f_{contact}$, the following model is investigated.

$$f_{contact}(P_{ex}) = 1 - exp(-\ell n2 \times (\frac{P_{ex}}{P_0})^{m_P}) \tag{15}$$

When the diameter of the particles, d, is the same, the external load on the particle is written as follows[14].

$$P = (\frac{1}{2})^{(\frac{1}{2})} \times (\frac{\delta}{1.54})^{(\frac{3}{2})} \times E \times d^{(\frac{1}{2})} \tag{16}$$

The external load and as-fabricated defect probabilities of SiC-layer are shown in Fig. 11 as a function of distance between particles. In the calculation, mean strength and Weibull modulus are employed as 20 N and 8, respectively[13]. The modulus of elasticity of the SiC is assumed to be 300 GPa[11] and the diameter is 900 μm. The result shows that when the particles contact distance becomes larger than 1 or 2 μm, the SiC failure would occur during compaction. It means that the increase of packing fraction would easily result in small increase of the particle distance, and the brittleness of the SiC could increase of as-fabricated SiC failure probability in the high burnup fuel compact.

CONCLUSIONS

1. The capsule irradiation tests and the postirradiation tests of the high burnup fuel were successfully carried out to investigate fuel behavior under high burnup condition.
2. The comparison of measured and calculated (R/B)s during the HRB-22 and the 91F-1A capsule irradiation test was carried out. In the HRB-22 capsule irradiation test, there were two through-coatings failed particles at the beginning of irradiation. During the irradiation, additional four fuel particle failures were observed by the ionization chamber monitoring. In the 91F-1A capsule irradiation test, the calculated results gave relatively good agreement with the measured (R/B)s when there was no failed particle at the beginning of irradiation. The result also showed that one additional failure occurred in each inner capsule during irradiation.
3. A through-coatings failed particle was observed in PIE of 91F-1A fuel. Through the SEM and EPMA observations, it was considered that the failure occurred by internal pressure.
4. A pressure vessel failure model showed that no tensile stresses acted on the SiC layers even at the end of irradiation and no pressure vessel failure occurred in the intact particles. Therefore, it is difficult to consider the intact particle failed by the internal pressure buildup during the irradiation.
5. Additional through-coatings failures could occur for as-fabricated SiC-failed particles in the fuel compact. This prediction implies that there were weak particles and they failed to the through-coatings failure during irradiation. The weak particles correspond to particles with defect in the SiC layer.
6. Because the packing fraction of coated particles in a fuel compact is as high as 35 vol% in a high burnup fuel, the probability of direct contact with neighboring particles would be increased. The external load and as-fabricated defect probabilities of SiC-layer are modeled. The result shows that when the particles contact distance becomes larger than 1 or 2 μm, the SiC failure would occur during compaction. It means that the increase of packing fraction would easily result in small increase of the particle distance, and the brittleness of the SiC could increase of as-fabricated SiC failure probability in the high burnup fuel compact.]

ACKNOWLEDGEMENTS

The authors wish to express their gratitude to Mr. T. Saito, Department of JMTR, Mr. A. Ishikawa and Mr. H. Sekino, Department of Hot Laboratory, Dr. M. J. Kania, Mr. P. L. Rittenhouse and Dr. F. C. Montgomery, who were members of the ORNL HTGR Fuels Program, for their support to the irradiation tests. The authors wish to express their gratitude to Mr. O. Baba, director of Department of HTTR Project, and Mr. Iyoku, head of HTTR reactor development division, for their encouragement to this study.

NOMENCLATURE

(R/B)	: fractional release of fission gases from fuel compact.
$f_{k,r}$	: recoil release fraction from kernel.
$f_{m,d}$	: fractional release from fuel compact matrix.
$f_{k,d}$	: fractional release from kernel by diffusion.
$f_{m,ad}$	: fractional release by grain boundary diffusion.
ϕ_k	: fraction of through-coatings failed particle.
$f_{m,r}$	: recoil release fraction from fuel compact matrix.
ϕ_c	: uranium contamination fraction in fuel compact matrix.
λ_i	: decay constant of nuclide i (s^{-1}).
D'_i	: reduced diffusion coefficient of nuclide i in the fuel kernel (m^2/s).
R_{ec}	: recoil distance (m).
a	: kernel diameter (m).
α	: fraction of fission product generated at in-grain.
$f_{m,gd}$	: fractional release by in-grain diffusion.
r_o, r_i	: outer and inner radius of fuel compact (m).
f_i	: failure probability of i-layer at irradiation time t.
$\sigma_i(t)$	: stress on the i-layer at irradiation time t (MPa).
$\sigma_{0,i}$	: strength of the i-layer (MPa).
m_i	: Weibull modulus for the i-layer strength.
f'_{IpyC}	: failure probability of the IPyC layer in the SiC failed particle.
f_{SiC}	: failure probability of the SiC layer in the OPyC intact particle.
f'_{OPyC}	: failure probability of the OPyC layer in the SiC failed particle.
P	: internal pressure (MPa).
n	: mole number of stable gaseous fission products and free oxygen atoms (mol).
R	: gas constant (J/mol·K).
T	: irradiation temperature (K).
V	: free volume in buffer layer (m^3).
n_{FP}	: mole number of stable gaseous fission products (mol).
n_O	: mole number of free oxygen (mol).
FR	: fractional release of stable gaseous fission products from fuel kernel.
F	: fission number (fission).
t_i	: irradiation time (days).
P_{ex}	: external load during pressing (N).
P_o	: mean strength against external load (N).
m_P	: Weibull modulus against external load.
d	: diameter of the particles (m).
δ	: distance between particles (m).
E	: modulus of elasticity of SiC (Pa).

REFERENCES

1. Saito, S., Tanaka, T., Sudo, Y., Baba, O., et al., "Design of High Temperature Engineering Test Reactor (HTTR)", JAERI-1332, Japan Atomic Energy Research Institute, 1994.
2. Sawa, K., Tobita, T., Mogi, H., Shiozawa, S., Yoshimuta, S., Suzuki, S., Deushi, K., "Fabrication of the First-Loading Fuel of the High Temperature Engineering Test Reactor", J. Nucl. Sci. Technol., Vol. 36, 1999, p. 683.
3. Sawa, K., and Minato, K., "An Investigation of Irradiation Performance of High Burnup HTGR Fuel," J. Nucl. Sci. Technol., 36, 1999, p. 781.
4. Minato, K., Sawa, K., Fukuda, K., Baldwin, C. A., Gabbard, W. A., Kimball, O. F., Malone, C. M., Montgomery, F. C., Myers, B. F., Packan, "HRB-22 Capsule Irradiation Test for HTGR Fuel," JAERI-Research 98-021, Japan Atomic Energy Research Institute, 1998.
5. Minato, K., Kikuchi, K., Sawa, K., Tobita, T., et al., "Preliminary Characterization of HTGR Fuel for HRB-22

Capsule Irradiation Test (JAERI/US DOE Collaborative Irradiation Test for HTGR Fuel)", JAERI-Tech 95-056, Japan Atomic Energy Research Institute, 1996.
6. Sawa, K., Minato, K., Fukuda, K., "Development of an Evaluation Method of Fission Product Release Fraction from High Temperature Gas-cooled Reactor Fuel", JAERI-Research 96-063, Japan Atomic Energy Research Institute, 1996 (in Japanese).
7. Friskney, C. A., and Speight, V., "A Calculation on the In-pile Diffusional Release of Fission Products Forming a General Decay Chain", J. Nucl. Mater., 62, 1976, p. 89.
8. Ogawa, T., Fukuda, K., Kashimura, S., Tobita, T., Minato, K., Yamamoto, K., Suzuki, H., Matsushima, H., "Release of Short-lived Noble Gases from HTGR Fuel with Failed Coated Fuel Particles and Contaminated Matrix, JAERI-M 86-146, Japan Atomic Energy Research Institute, 1986 (in Japanese).
9. Myers, B. F., "Fuel Design Data Manual", GA-901866/F, GA Technologies, 1987.
10. Krohn, H. and Finken, R., "FRESCO-II, Ein Rechenprogramme zur Berechnung der Spaltproduktfreisetzung aus Kugelformigen HTR-Brehnelementen in Bestrahlug und Ausheizaxperimenten," Jul-Spez-212, Kernforschungsanlage Juelich, 1983.
11. Verfondern, K. (Ed.), "Fuel Performance and Fission Product Behaviour in Gas-cooled Reactor," IAEA-TECDOC-978, International Atomic Energy Agency, 1997.
12. Fukuda, K., Ogawa, T., Kashimura, S., Hyashi, K., Tobita, T., Kobayashi, F., Minato, K., Kikuchi, H., Murakami, H., Kikuchi, T., Ikawa, K., Iwamoto, K., "Research and Development of HTGR Fuels", JAERI-M 89-007, Japan Atomic Energy Research Institute, 1996 (in Japanese).
13. Sawa, K., Shiozawa, S., Minato, K., Fukuda, K., "Development of a Coated Fuel Particle Failure Model under High Burnup Irradiation", J. Nucl. Sci. Technol., 33, 1996, p. 712.
14. Utoguchi, T. (Ed.), "Zairyo Rikigaku", Shokabo, 1982 (in Japanese).
15. Proksch, E. and Strigl, A., "Production of Carbon Monoxide during Burn-up of UO_2 Kerneled HTR Fuel Particles," J. Nucl. Mater., 107, 1982, p. 280.
16. Lindemer, T. B., "Measurement and Interpretation of CO and Kr + Xe in Irradiated ThO_2-Containing HTGR Fuel Particles", J. Amer. Ceram. Soc., 60, 1977, p. 409.
17. Kaae, J. L., "The Mechanical Behavior of BISO-coated Fuel Particles during Irradiation. Part I: Analysis of Stresses and Strains Generated in the Coating of a BISO Fuel Particle during Irradiation", Nucl Technol., 35, 1977, p. 359.