

New Concept of Accident Tolerant Fuel Assembly Composed of SiC Block for KAMADO-BWR

by

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(Received on April 12, 2022 and accepted on May 27, 2022)

Abstract

We propose a new concept of accident tolerant fuel assembly composed of an SiC block for current commercial BWRs or ABWRs, which is called the "KAMADO-BWR" assembly. The KAMADO-BWR assembly is designed as one type of replacement fuel assembly for commercial BWRs or ABWRs. Conventional UO₂ fuel pellets are enclosed in many holes (fuel stacks) in the SiC block. The melting point of SiC and UO₂ is higher than 3000 K and these ceramic materials scarcely produce hydrogen with light water coolant. Most of the heat generated at the fuel pellets is significantly transferred through the SiC block, and it is removed by the two-phase flow of light water coolant inside or outside the SiC block. The thermal hydraulic and neutron reaction properties of the KAMADO-BWR assembly, such as maximum temperature, critical heat flux (CHF), infinite multiplication factor (*k*-inf) and peaking power ratio were estimated with analytical methods, and they were equivalent to those of the commercial BWR fuel assembly. It is possible to lower the maximum fuel temperature by increasing the number of fuel stacks and decreasing the power density of each fuel stack in the assembly, which can improve the safety margin. Accordingly, the KAMADO-BWR assembly is expected to be one candidate for the accident tolerant and replacement fuel assemblies for commercial BWRs or ABWRs.

Keywords: KAMADO-BWR, SiC block, Accident tolerant fuel (ATF), Critical heat flux (CHF), Replacement fuel

1. Introduction

The severe accident of the Fukushima Daiichi has shown that under such extreme conditions, nuclear fuel claddings generated hydrogen at high temperature over 1400 K by reactions with water or steam. Large amount of the generated hydrogen exploded and caused serious damage to the plant.

Recently, attention to accident tolerant fuel (ATF) is increasing, which has more resistant to fuel failure and hydrogen generation. SiC based cladding tubes, chromium coated tubes on zirconium alloy or other various ATF designs have been proposed and their related researches and developments are progressing^{1, 2)}.

We have been proposing a new concept of fuel assembly and core that is called the KAMADO (a classical hot range in Japanese), in which we make use of the solid heat transfer and multiple heat paths to coolant^{3 - 5)}. The KAMADO concept is applied to commercial BWRs, and two types of fuel assemblies are constructed as shown in Fig. 1. The fuel pellets are enclosed in many holes in an SiC block, and the generated heat at the fuel pellets is transferred through the SiC block to the two-phase flows similar to the BWR fuel assembly. The fuel pellets in Fig. 1 (a) are equivalent to the BWR 9×9 type, and (b) are equivalent to the BWR 11×11 type. These fuel

concepts can improve accident tolerance with an SiC block instead of metal claddings to prevent generating hydrogen.

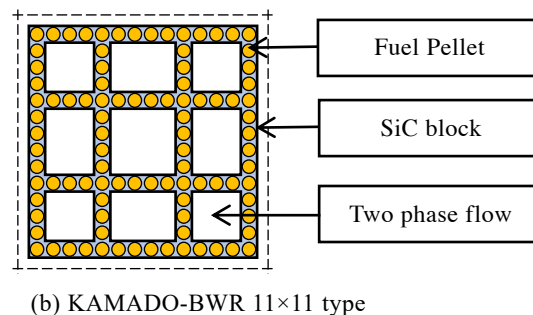
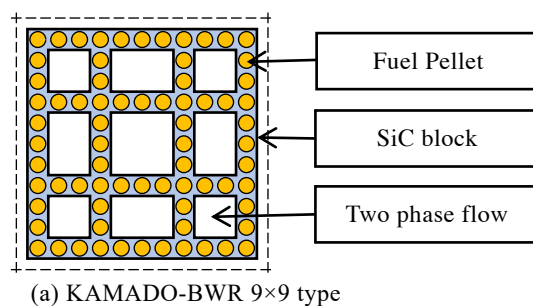


Fig. 1 KAMADO-BWR fuel assemblies.

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In this paper, results of temperature, thermal hydraulic, mechanical and neutron reaction analyses for the KAMADO-BWR fuel assembly are described. SiC materials, fabrication methods, thermal conductivity, super-critical heat flux and severe accident cases for the fuel assemblies are also discussed.

2. Fuel temperature analyses

The specifications of the KAMADO-BWR fuel assembly are listed in Table 1. Common items of the KAMADO-BWR such as assembly outer dimensions are the same as those of the commercial BWR 9×9-B fuel assembly⁶⁾. The KAMADO-BWR fuel assembly can be used as a replacement fuel assembly for commercial BWRs or ABWRs.

Table 1 Specifications of the KAMADO-BWR fuel assembly.

Item	Value
KAMADO-BWR common	
Assembly outer dimension	139.0 mm × 139.0 mm
Assembly height	3.710 m
Assembly pitch	152.4 mm
Assembly generation power	4.31 MW
Plant pressure	7.02 MPa
Saturated temperature	560 K
Coolant mass flow	17.6 kg/s
(a) 9×9 type	
Pellet diameter	9.6 mm
Number of fuel stacks	72
Fuel pitch	12.6 mm
Uranium weight	168 kg
(b) 11×11 type	
Pellet diameter	8.2 mm
Number of fuel stacks	96
Fuel pitch	9.93 mm
Uranium weight	162 kg

Since the specifications of BWR 11×11 such as the fuel pellet diameter is not still published, the values of PWR 17×17 are used here that are closed to those of BWR 11×11.

The fuel temperature distribution was calculated with the finite element analysis system LISA⁷⁾. Assuming that the axial power peaking ratio to the average power rate was realistic value 1.4, the horizontal temperature distributions at the axial peaking position are shown in Fig. 2. Since the thermal conductivity of SiC is high (200 W/m/K), the maximum temperature on the fuel pellets center is (a) 1313 K in the BWR 9×9 type and (b) 1128 K in the BWR 11×11 type, respectively. The thermal conductivity of UO₂ fuel pellet was set to 2.54 W/m/K, which is a conservative value. The temperature of the SiC block is suppressed to 580 K close to the temperature of the two-phase flow (560 K). The heat transfer coefficient h from the SiC block to the two-phase flow is 94 kW/m²/K for the BWR 9×9 type or 89 kW/m²/K for the BWR 11×11 type respectively, which is calculated with the Jens-Lottes equation⁸⁾

in Eqs. (1),

$$\Delta T = \frac{0.82}{e^{63}} q_w^{\frac{1}{4}}, \quad q_w = \frac{W}{A}, \quad h = \frac{q_w}{\Delta T} \quad (1)$$

where ΔT is the difference between the assembly surface temperature and coolant saturated temperature (K), q_w is the heat flux at the assembly surface (kcal/m²/h), p is the pressure (ata), W is the assembly generation power (kcal/h), and A is the heat transfer area (m²).

The Comparison between Fig. 2 (a) and (b) shows that the maximum temperature on the fuel pellet center can be reduced by decreasing the diameter of the fuel pellets and increasing the number of fuel stacks.

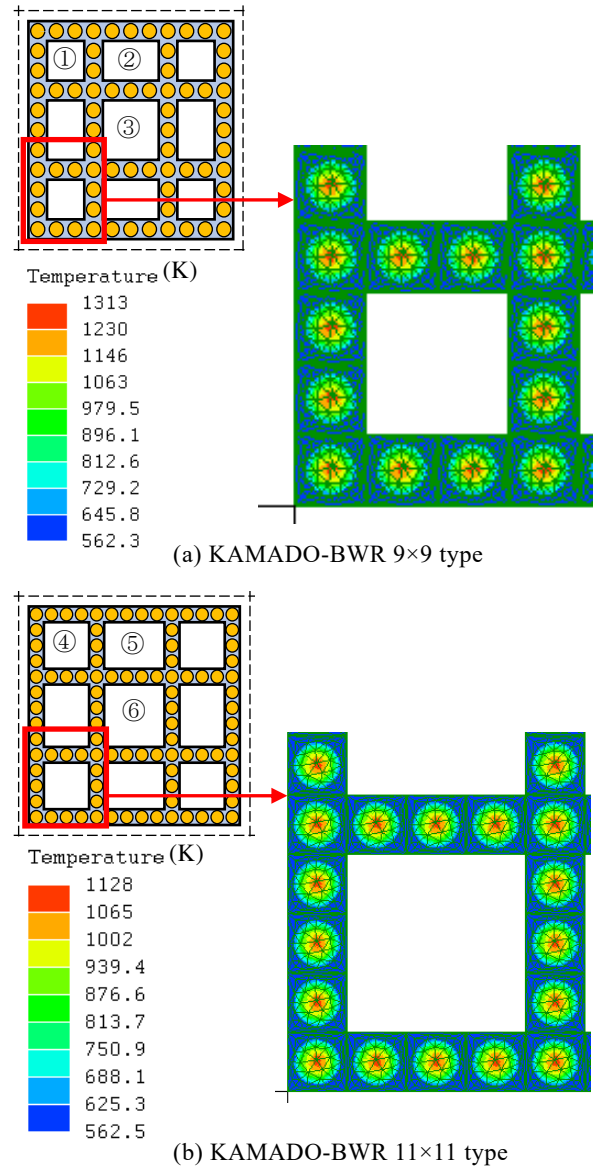


Fig. 2 Temperature distributions in the KAMADO-BWR.

3. Thermal-hydraulic analyses

The pressure drop F_p (Pa/m) with friction pressure of the fuel assembly in the single-phase flow of water is generally

expressed by the Darcy–Weisbach equation ⁹⁾ in Eq. (2),

$$F_p = \frac{f}{D} \frac{\rho_m U^2}{2} \quad (2)$$

where f is the coefficient of friction, D is the equivalent hydraulic diameter (m), U is the fluid velocity (m/s) and ρ_m is the water density (kg/m³). The f is calculated by the Nikulase equation in Eq. (3) that can be applied with $10^5 < Re < 10^8$, where Re is the Reynolds number,

$$f = 0.0032 + 0.221Re^{-0.237} \quad (3).$$

The U is calculated from the coolant mass flow and the flow path area inside of the fuel assemblies. The U values are 2.60, 3.04 and 2.41 (m/s) for the BWR 9×9, KAMADO-BWR 9×9 type and 11×11 type respectively. As the F_p depends on the D shown in Table 2 for each flow path ① - ⑥ in Fig. 2, and the F_p calculated with Eq. (2) are listed in Table 2.

In the KAMADO-BWR, friction pressure of the fuel assembly is about 1/2 - 1/4 of that in the BWR 9×9. The static pressure multiplied by height is 26.8 kPa for 3.71 m. The pressure drop in the two-phase flow with friction pressure is about 100 times higher than that in water ⁹⁾, which is on the order of MPa in the BWR 9×9 fuel assembly.

The critical heat flux (CHF: q_c) in the two-phase flow was evaluated by the Katto's equation ¹⁰⁾ in Eq. (4),

$$\frac{q_c}{GH_{fg}} = c \left(\frac{\sigma \rho_m U^2}{G^2 L} \right)^{0.043} D/L \quad (4)$$

$$C = 0.25 \quad L/D < 50,$$

$$= 0.25 + 0.0009(L/D - 50) \quad 50 \leq L/D < 150,$$

$$= 0.34 \quad L/D \geq 150$$

where L is the assembly height (m), G is mass velocity (kg/m²/sec), H_{fg} is the heat of vaporization (kJ/kg), σ is the surface tension (N/m) and C is the coefficient changing with L/D .

The q_c is 2.15 MW/m² for the BWR 9×9 and 3.79 - 5.51 MW/m² for KAMADO-BWR according to the flow path shown in Fig. 2. The Details are summarized in Table 2.

Table 2 Pressure drop and CHF for each flow path.

Type	D (m)	F_p (kPa/m)	q_c (MW/m ²)	Q (MW)
BWR	0.0147	2.4253	2.1451	19.7
(a)-①	0.0253	1.6928	4.2244	16.6
(a)-②	0.0303	1.3662	4.7387	18.6
(a)-③	0.0379	1.0515	5.5101	21.6
(b)-④	0.0298	0.9156	3.7920	16.7
(b)-⑤	0.0340	0.7825	4.1426	18.3
(b)-⑥	0.0397	0.6529	4.6100	20.3

The CHF of the KAMADO-BWR is larger than that of the BWR, but it is necessary to consider the heat transfer area. The critical heat output Q of the assembly multiplied by the

heat transfer area in the fuel assembly is 19.7 MW for the BWR 9×9, and 16.6 - 21.6 MW for the KAMADO-BWR. The Q can be adjusted by changing the dimensions of flow path in the KAMADO-BWR assembly. Accordingly, the CHF of the KAMADO-BWR is equivalent to that of the BWR 9×9.

4. Mechanical stress analyses

In terms of structural strength, the tensile strength of SiC (approximately 200 MPa) is equivalent to that of metal materials (200 - 500 MPa). During the assembly loaded in the BWR, the reactor pressure (7 MPa) applies compressive stress to the SiC block and fuel stacks. The stack internal pressure by enclosed He is set to 1 MPa during manufacturing and 2 MPa during operation. The calculation results of the KAMADO-BWR 9×9 and 11×11 types with LISA are shown in Fig. 3 (a) and (b). Although there are some tensile stresses (positive values), most of them are compressive stresses (negative values). The compressive stress is not a problem in terms of the compressive stress limit of SiC (2000 MPa or more).

During unloading the assembly from BWR, the tensile stress on the SiC block is generated by the enclosed He pressure (1MPa) inside the fuel stack. The maximum stress is 3.5 MPa for the KAMADO-BWR 9×9, and 4.7 MPa for the KAMADO-BWR 11×11 types, respectively as shown in Fig. 4 (a) and (b). There are sufficient margins for the tensile strength (approximately 200 MPa).

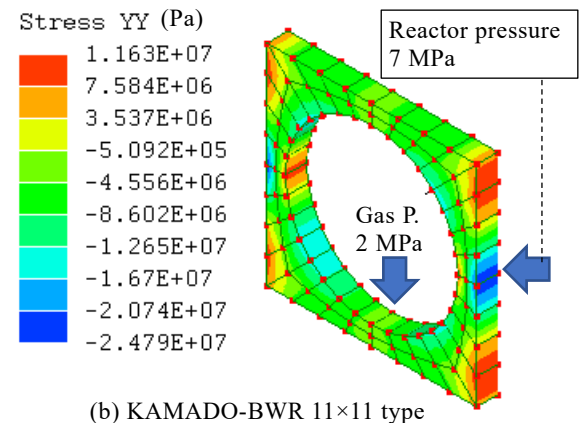
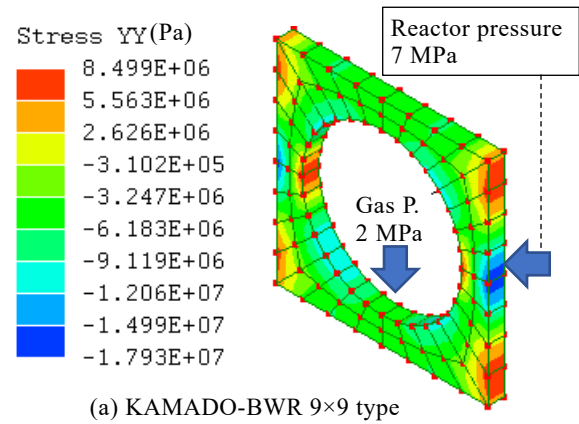


Fig. 3 Stress distributions on SiC block during loading.

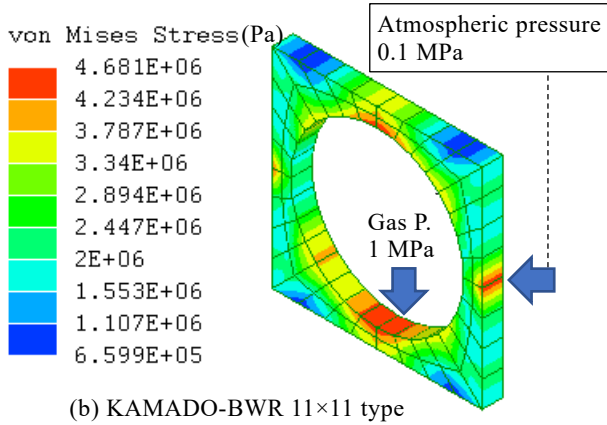
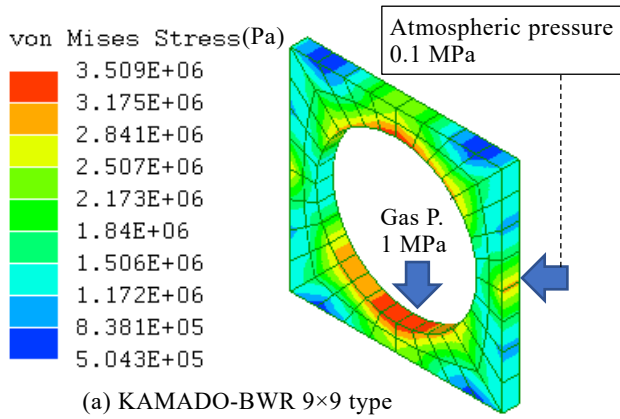


Fig. 4 Stress distributions on SiC block during unloading.

5. Neutron reaction analyses

In neutron reaction calculations, the compositions of UO_2 fuel with 4% enrichment are listed in Table 3. The Monte Carlo codes MVP3¹¹⁾ and MVP-BURN¹²⁾ were used for these calculations.

Table 3 Fuel nuclide composition¹³⁾.

Nuclide	Number density (1/barn/cm)
^{234}U	8.0530E-6
^{235}U	8.8880E-4
^{236}U	5.4190E-6
^{238}U	2.1040E-2
O (Natural)	4.4380E-2

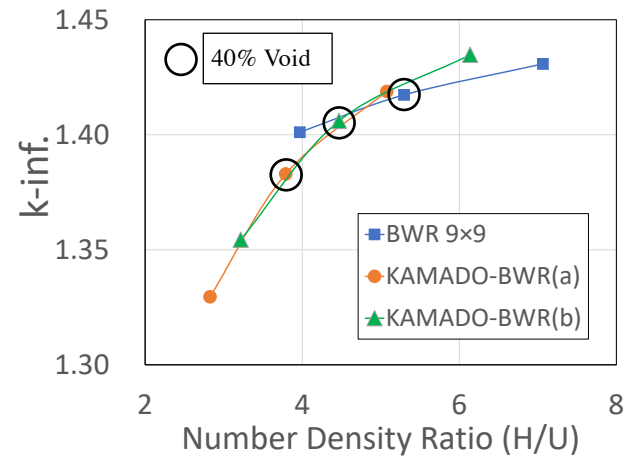
Infinite neutron multiplication factors ($k\text{-inf.}$) of the fuel assemblies for the commercial BWR 9×9, the KAMADO BWR 9×9 and 11×11 type with void ratios (0, 40, 70%) at the beginning of life (BOL) are summarized in Table 4, assuming that ^{235}U enrichment for all the pellets in three assemblies is homogeneous, 4% here.

The $k\text{-inf.}$ depends on the nuclide number density ratio of hydrogen to uranium (H/U), as shown in Fig.5. Comparing the values at 40% void ratio, the $k\text{-inf.}$ increased as the H/U increase, in ascending order of the KAMADO-BWR 9×9 type, 11×11 type and commercial BWR 9×9. The $k\text{-inf.}$ and H/U can be adjusted by U loading weight of pellets or water area in

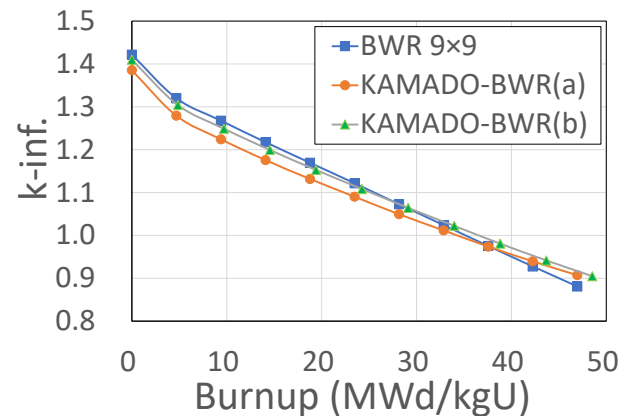
each SiC block. It is also necessary to consider the effect of doped Gd concentration and the average void ratio.

Table 4 $k\text{-inf.}$ at BOL with void ratios.

Assembly type	Void (%)	H/U	$k\text{-inf.}$
BWR 9×9	0	7.0661	1.4308
	40	5.2965	1.4173
	70	3.9694	1.4011
(a) KAMADO-BWR 9×9 type	0	5.0771	1.4189
	40	3.7908	1.3830
	70	2.8261	1.3296
(b) KAMADO-BWR 11×11 type	0	6.1389	1.4348
	40	4.4689	1.4060
	70	3.2164	1.3544

Fig. 5 Changes of $k\text{-inf.}$ with H/U at BOL.

The $k\text{-inf.}$ of the fuel assembly for the KAMADO-BWRs is almost the same as that for the commercial BWR as burnup increases (Fig. 6). The $k\text{-inf.}$ for the KAMADO-BWRs is less than that for the commercial BWR at BOL, while the $k\text{-inf.}$ for the KAMADO-BWRs becomes greater at the end of life (EOL), because of the higher Pu conversion ratio for them.

Fig. 6 Changes of $k\text{-inf.}$ with burnup.

The power distributions of the fuel stack in the KAMADO-BWR are shown in Fig.7, where the void ration is

40% inside and 0% outside the fuel assembly. They are slightly higher at the corner stacks due to the effect of the outside moderator. Although there are further issues such as the effect of Gd fuel, these peaking factors (1.17 or 1.14) may be smaller than that of the commercial BWR fuel assemblies.

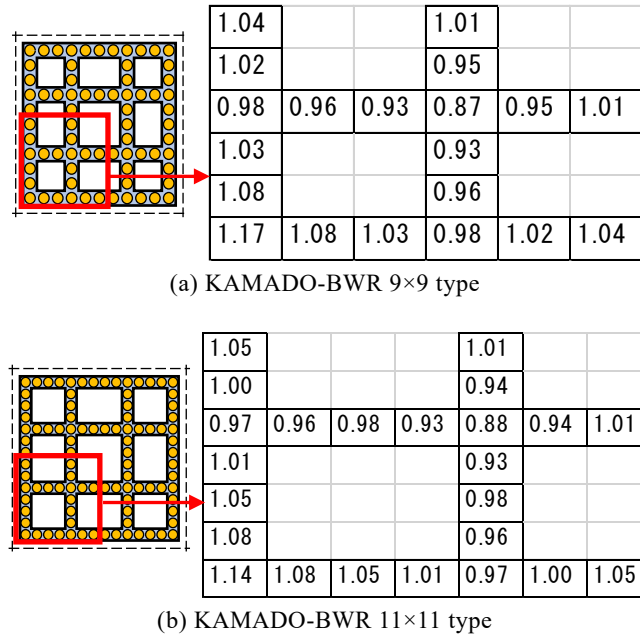


Fig. 7 Stack power distributions in KAMADO-BWR fuel assemblies.

6. Discussions

SiC materials, fabrication methods, SiC thermal conductivities, superior CHF, severe accident cases for the KAMADO-BWR and application to PWRs are discussed.

6.1 SiC material

SiC materials are known to have high strength but be fragile. For this reason, SiC / SiC composite materials in SiC fibers are researched and developed¹⁴⁾. In addition, there are various methods for manufacturing SiC parts or blocks, such as atmospheric pressure sintering method, hot press method, hot isotropic press (HIP) method, chemical vapor deposition (CVD) method, reaction sintering (RS) method and others. Since the mechanical performance of SiC differs depending on these methods, it is necessary to pay careful attention to the results of research and development for the SiC manufacturing methods¹⁵⁾.

6.2 Fabrication method

SiC parts or blocks can be produced by powder sintering method such as hot press method. However, it is known that some processes such as welding and other joining method is difficult for SiC materials. A trial method without joining processes to fabricate the KAMADO-BWR fuel assembly is suggested and shown in Fig. 8.

The fabricating procedures are as follows:

- 1) manufacture an SiC block with necessary holes for fuel stacks by the powder sintering method,
- 2) insert fuel pellets into the holes in the SiC block,

- 3) cover the block with a seal of swollen graphite that can withstand high temperature,
- 4) put a lid on the seal and tighten them with bolts and nuts.

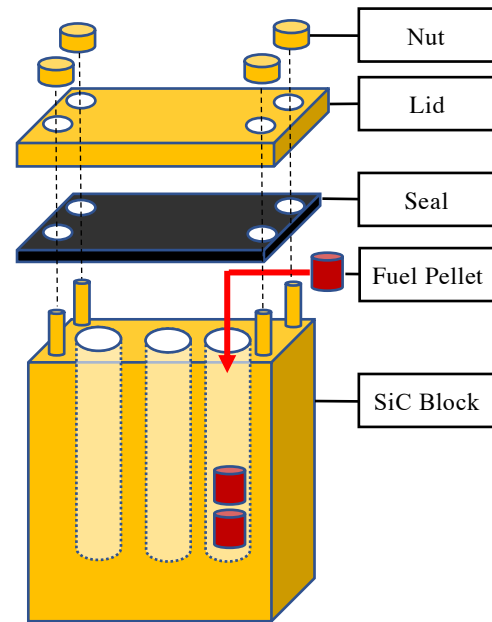


Fig. 8 Fabrication method for KAMADO-BWR fuel assembly.

6.3 Thermal conductivity

It has been reported that the thermal conductivity of SiC deteriorates as irradiation damages in it are accumulated¹⁶⁾. We analyzed the temperature distribution when the thermal conductivity of SiC was reduced to 20 W/m/K, which is 1/10 of that in as-fabricated fresh conditions. Comparing with results in the previous temperature analysis shown in Fig. 2 (a), the maximum fuel temperature (1137 K) increased by 39 K at the same assembly power (4.31 MW) as shown in Fig. 9. The temperature increment is slight.

It has been also reported that the thermal conductivity deterioration with irradiation damages depends on the method of manufacturing SiC matrices or making SiC / SiC composite materials¹⁷⁾.

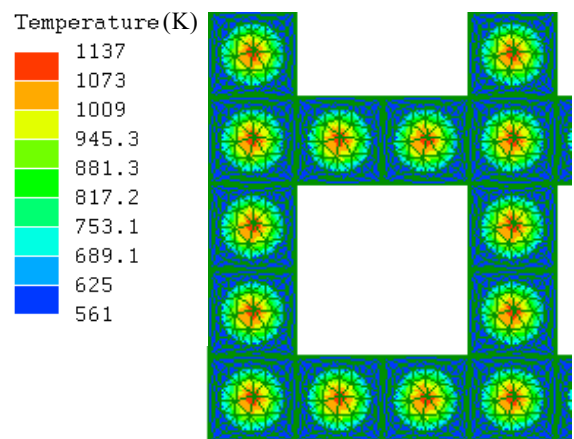


Fig 9 Fuel temperature distribution in KAMADO-BWR 9×9 type at reducing SiC heat conductivity to 20 W/m/K.

6.4 Superior CHF

If the heat flux to the two-phase coolant inside the KAMADO-BWR fuel assembly exceeds the critical heat flux q_c during operation, and if the coolant becomes only steam, major parts of the heat generated at fuel pellets can be removed through the surfaces surrounding the fuel assembly.

The cooling performance by steam was evaluated by the Dittus-Boelter formula⁹⁾ in Eq. (5),

$$h = 0.023Re^{0.8}Pr^{0.4}\lambda/D \quad (5)$$

where Pr is the Prandtl number, λ is the thermal conductivity of steam, and D is the value at flow pass ② in Fig. 2. The h is calculated to be 10.3 kW/m²/K, while the coolant becomes the two-phase flow outside the fuel assembly and the cooling performance is still maintained to be high (94 kW/m²/K). The maximum fuel temperature (1171 K) increased by 73 K at the same assembly power (4.31MW) as shown in Fig. 10. The temperature increment is not large.

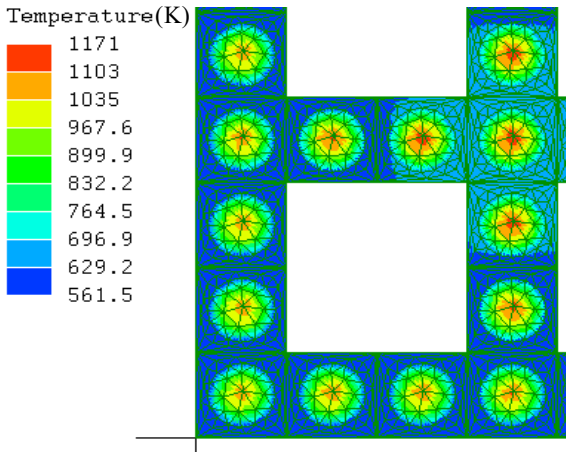


Fig 10 Fuel temperature distribution in KAMADO-BWR 9×9 type beyond CHF condition.

If the heat transfer capability of the flow path is reduced inside the fuel assembly and is maintained outside it, the cooling performance can be ensured. Moreover, if the thermal conductivity of SiC also was reduced to 20 W/m/K, the maximum fuel temperature (1230 K) increased by 132 K at the same assembly power. Consequently, the temperature increment is not significant on the fuel integrity.

6.5 Severe accident

When the cooling water was exhausted in case of the severe accidents, the temperature distribution in the KAMADO-BWR fuel assembly was evaluated assuming the fuel decay heat decreased to 1/10 of the fuel fission reaction energy. There is no cooling inside the assembly, and simple evaluation outside the assembly was carried out with the radiative cooling formula in Eq. (6),

$$h = \sigma_{SB}T^3 \quad (6)$$

where σ_{SB} is the Stefan-Boltzmann constant and T is the surface temperature (K). Assuming that the surface temperature of the assembly is 1500 K, the h becomes 191 W/m²/K. Using the h , the maximum temperature at fuel pellets is 1881 K and the minimum temperature is 1569 K (Fig. 11).

The fuel decay heat in the KAMADO-BWR fuel assembly can be also sufficiently removed by conduction of radiant heat through the SiC block to the coolant. Hence it may be possible to prevent fuel melting in case of severe accidents.

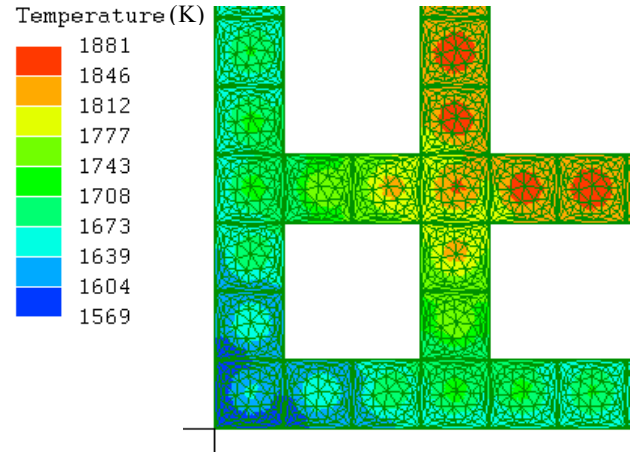


Fig 11 Fuel temperature distribution in KAMADO-BWR 9×9 type during severe accident.

6.6 Application to PWR

Another KAMADO concept can be also applied to commercial PWRs, and the PWR 17×17 type fuel assembly is shown in Fig. 12. The assembly necessarily includes an in-core instrumentation thimble and control rod guide thimbles at the fixed locations in the commercial PWRs. The fuel pellet diameter is 7.8 mm, smaller than 8.2 mm diameter of the commercial PWR fuel pellet, and the number of fuel stacks is 252 less than 264 rods in each PWR assembly. There are still manufactural and mechanical issues to be confirmed, such as stability on inserting or drawing control rods.

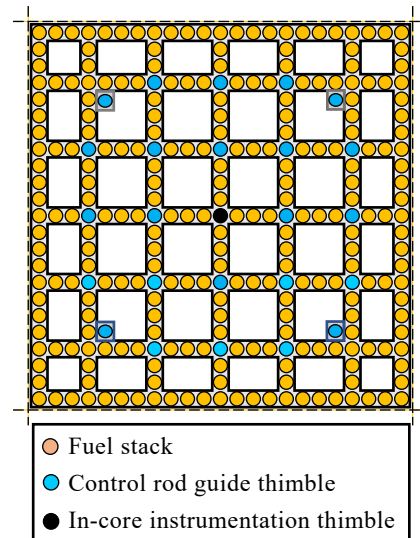


Fig 12. KAMADO-PWR 17×17 type fuel assembly.

7. Conclusions

A new concept of the accident tolerant fuel assembly for the KAMADO-BWR is proposed, and the assembly is composed of an SiC block and conventional UO_2 fuel pellets. The melting point of SiC and UO_2 is higher than 3000 K and these ceramic materials scarcely produce hydrogen with light water coolant. The considerable thermal conductivity of SiC also provides the significant heat transfer from the pellets to the coolant.

Analytical results of the fuel assembly temperature, mechanical stress, thermal-hydraulics and neutron reaction prove that both the KAMADO-BWR 9×9 and 11×11 type assemblies have satisfactory performance equivalent to the commercial BWR 9×9 assembly.

The maximum temperature on the fuel pellet center can be reduced by decreasing the diameter of the fuel pellets and increasing the number of fuel stacks. If the thermal conductivity of SiC deteriorating due to irradiation damage accumulation, the increment in the maximum fuel temperature is slight.

As the friction pressure in the KAMADO-BWR fuel assembly is much less than that in the commercial BWR 9×9 fuel assembly, the pressure drop of flow path in the KAMADO-BWR also becomes the less.

Though the stress on the SiC block is compressive during the reactor operation or tensile while unloading the fuel assemblies, stresses in these conditions are much less than the limit of structural strength of SiC.

Since the KAMADO-BWR 9×9 and 11×11 type assembly have the smaller H/U ratio than that of the commercial BWR 9×9 assembly, the k_{inf} of the KAMADO-BWR assemblies is less at BOL, while it becomes greater at EOL than that of the commercial BWR because of higher Pu conversion ratio.

Additionally, SiC materials, fabrication methods, SiC thermal conductivities, superior CHF, severe accident cases for the KAMADO-BWR fuel assemblies and application to the PWR 17×17 type assembly are discussed. They are appropriately verified or confirmed.

Accordingly, the concept of KAMADO-BWR assembly is expected to be one candidate of the accident tolerant and replacement fuel assemblies for commercial BWRs or ABWRs.

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