Proceedings of the Korean Nuclear Society Spring Meeting
Gyeongju, Korea, 2004

PCMI Analysis of DUPIC Fuel by Orthogonal Array Tables

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Abstract

The effects of material properties on the pellet clad mechanical interaction(PCMI) of DUPIC fuel were evaluated. Modified material models of the DUPIC fuel were employed in the performance evaluation code to estimate the ridge height, plastic strain of the cladding, and the interfacial stress between the pellet and the cladding. The optimum condition of fuel fabrication parameters for the mitigation of the PCMI of the DUPIC fuel was presented by a statistical analysis by orthogonal array tables.

Introduction

The DUPIC(Direct Use of spent PWR fuel in CANDU reactors) technology is a kind of dry re-fabrication process which can reuse fissile elements in the spent fuels of pressurized light water reactors(LWR) without the separation of sensitive nuclear materials such as plutonium[1]. The saving of uranium resources and the reduction of accumulated spent fuel are the benefits of the dry re-fabrication process[2]. The proliferation resistance is strictly maintained during the fabrication process of the DUPIC fuel.

Because DUPIC fuel contains solid fission product elements, its material properties are different from those of the fresh UO_2 fuel[3,4]. The DUPIC fuel also differs from the high burnup oxide fuel because it does not contain fission gas elements or volatile fission products. The material properties such as thermal conductivity, thermal expansion coefficient, creep rate, Young's modulus and hot hardness of simulated DUPIC fuel have been measured to evaluate the irradiation performance of the DUPIC fuel.

Pellet clad mechanical interaction(PCMI) is closely related to the structural integrity of fuel element during the irradiation[5]. The effect of changed material properties on the PCMI behavior should be checked using the fuel performance evaluation code. Orthogonal array table is one of the simplest statistical methods to evaluate the dependency of some important parameters upon the changing variables when many variable contribute complicatedly[6]. In this study, PCMI behavior of the DUPIC fuel were analyzed using modified ELESTRES code with varying fabrication parameters according to orthogonal array design.

Experimental Procedures

Material properties was characterized using simulated fuel consisting of natural UO_2 powder blended with stable chemical additives simulating the composition of the spent fuel corresponding to discharge burnup of 27,300 MWd/tU. The composition of the simulated fuel

was obtained by the calculation of ORIGEN code. After three cycles of oxidation and reduction, the milled powder was compacted into cylindrical pellets and sintered at 1700°C for 4 hours in a H_2 atmosphere. Thermal diffusivity and thermal expansion of the simulated DUPIC fuel was measured by the laser flash method and by a push rod type dilatometer(DIL402C, Netzsch), respectively. Creep rate was measured by a compressive creep test at 1500, 1600, 1700°C in a H_2 atmosphere. Young's modulus of the simulated DUPIC fuel was measured by a resonance ultrasound spectroscopy(RUS) and hot hardness and fracture toughness were measured by a high temperature micro-Vickers hardness tester (QM-2, Nikon). Scanning electron microscopy was employed to observe the microstructure of the simulated DUPIC fuel after milling, sintering and hot hardness test.

Results and Discussion

Based on the measured thermal and mechanical properties of the simulated DUPIC fuel, thermal and mechanical properties of the simulated DUPIC fuel were measured to modify the material models in the performance evaluation codes such as ELESTRES for the CANDU fuel element. The changed material properties result in important changes in the irradiation behavior such as centerline temperature, fission gas release (FGR) and pellet cladding mechanical interaction(PCMI). Fig 1(a) shows that the thermal conductivity of the simulated DUPIC fuel was lower than UO_2 due to the presence of the solid solution elements such as Zr, Nd, Ce, etc.[7] It has been reported that the thermal conductivity reduced as the target burnup of the simulated fuel increased[8,9]. Thermal conductivity of the DUPIC fuel was fitted with the Harding-Martin equation[10].

The coefficient of the thermal expansion of the simulated DUPIC fuel is larger than that of UO_2 as plotted in Figure 1(b)[11]. The decrease in thermal conductivity and the increase in thermal expansion are not desirable for the fuel performance.

As for the view of the PCMI, compliant fuel is desirable for preventing the cladding from severe mechanical interaction. But Figure 2 and Figure 3 shows that the simulated DUPIC fuel is not softer than UO_2. Creep rate as shown in Figure 2(a), Young's modulus as shown in Figure 2(b), and Vickers hardness as shown in Figure 3(a) exhibit that time dependent deformation and time independent deformation are more difficult in the simulated DUPIC fuel. Solid solution hardening and precipitation hardening occur in the simulated DUPIC fuel.

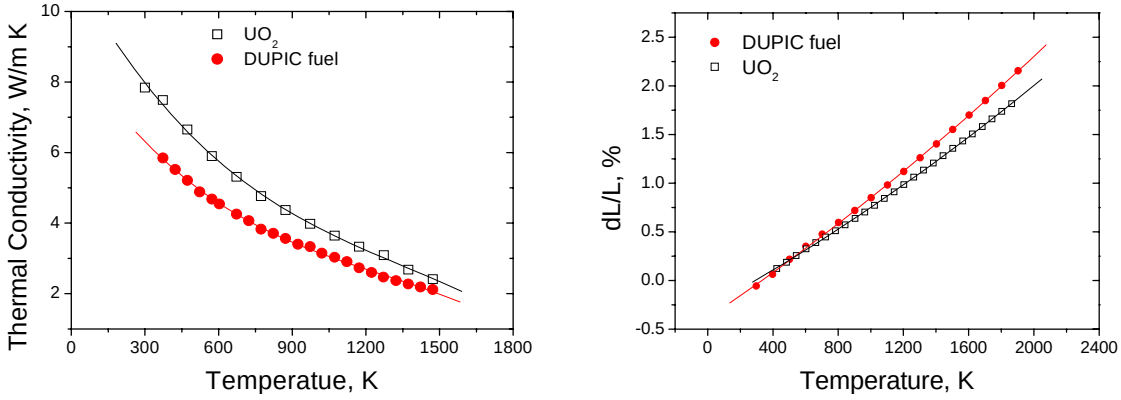
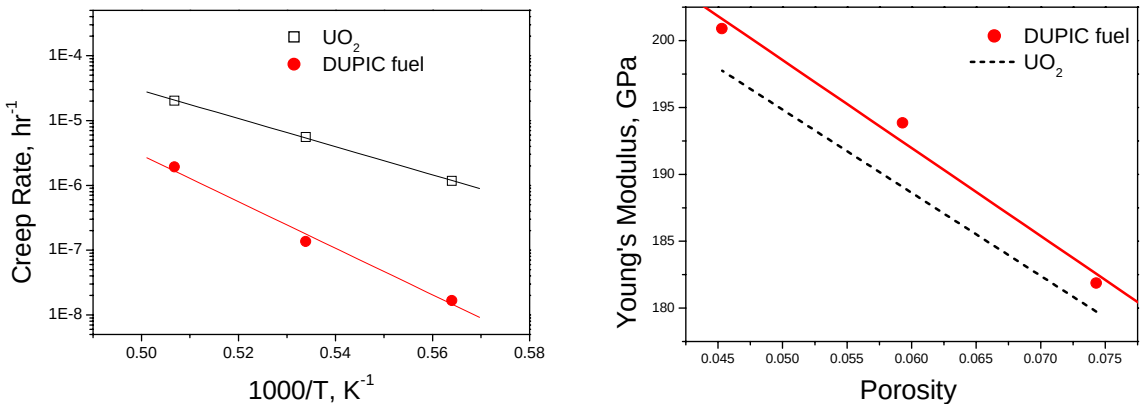
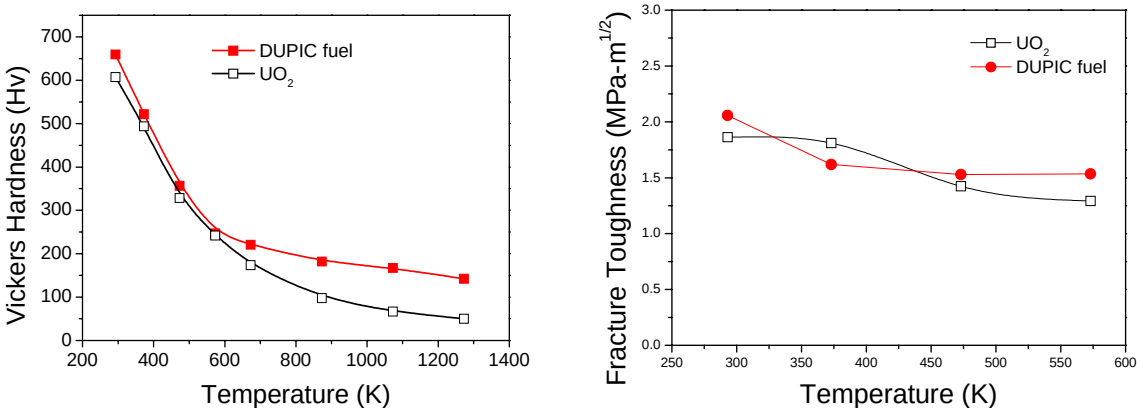


Figure 1. (a) Thermal conductivity and (b) thermal expansion of UO_2 and the simulated DUPIC fuel with temperature.



(a) **(b)**

Figure 2. (a) Creep rate and (b) Young's modulus of UO_2 and the simulated DUPIC fuel.



(a) **(b)**

Figure 3. (a) Hot hardness of UO_2 and the simulated DUPIC fuel measured by the high temperature microvickers hardness test and (b) the fracture toughness of UO_2 and the simulated DUPIC fuel obtained by the indentation crack length method.

From the hot hardness test as shown in Figure 3(a), the high temperature yield strength of the simulated DUPIC fuel can be calculated by the empirical relationship between the hardness and yield strength. Fracture toughness can also be calculated from a hot hardness test by the indentation crack length method. For brittle materials, fracture toughness is formulated as a function of the crack length, Young's modulus and hardness as follows[12].

$$K_C = 0.028\,(H/E)^{-1/2} \cdot H \cdot a^{1/2} \cdot (c/a)^{-3/2}$$

where H is the hardness, E is the Young's modulus, a is indent diagonal distance, and c is the crack length. The simulated DUPIC fuel has a comparable fracture toughness to UO_2 as shown in Figure 3(b). Because the DUPIC fuel is designed to be utilized in existing CANDU reactors, the ELESTRES code has been used for the fuel element performance evaluation of the DUPIC fuel[13,14]. Some important material models adopted in the ELESTRES code were modified one by one to measure their contribution to the fuel performance.

Figure 4 shows the calculated results of the centerline temperature and sheath plastic strain by the modified ELESTRES code when one of the material models such as thermal conductivity and thermal expansion are changed for the DUPIC fuel. The change in thermal conductivity resulted in the most remarkable changes of the centerline temperature and sheath plastic strain, while the other factors did not exhibit quite such an influencing deviation.

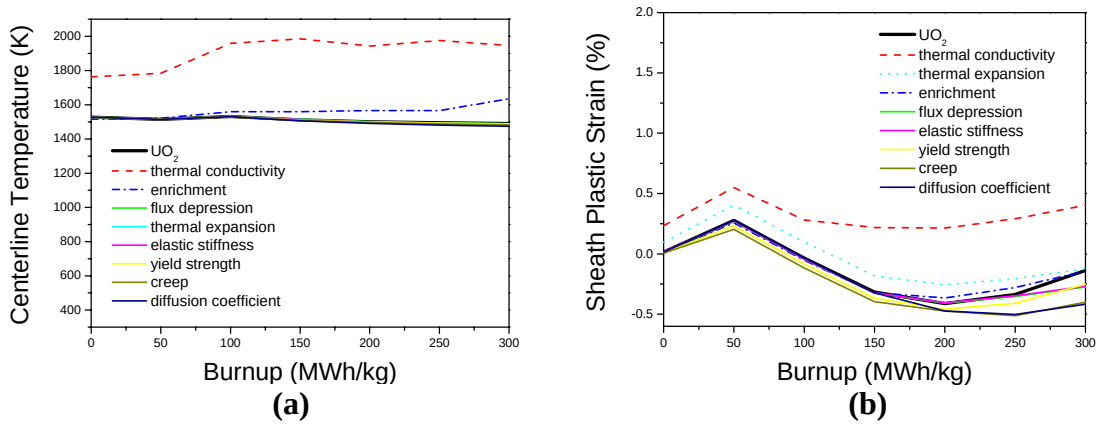


Figure 4. The effect of the performance variables on (a) the centerline temperature and (b) plastic strain of the sheath of the DUPIC fuel with burnup at a linear heat rate of 40 kW/m.

Parametric analysis was carried out using modified ELESTRES codes to suggest the optimum fabrication variables within the ranges of the fuel fabrication specifications. Orthogonal array design(OAD) involving three fabrication factors with three levels was employed as shown in Table 1[6]. Fuel density, gap clearance and grain size were selected as important fabrication variables influencing the performance of the DUPIC fuel. As shown in Figure 5(c), the fuel density was the most controlling factor for the increase of the hoop strain due to the strong PCMI. It is recommended to decrease the fuel density and to increase the gap clearance to reduce the PCMI of the DUPIC fuel. Although the decrease in the fuel density may result in a rise of the centerline temperature of the DUPIC fuel, Figure 5(e) shows that the effect of the recommended change of the fabrication parameter within the fuel specification is acceptable compared to the melting point of the DUPIC fuel.

From Table 2 to Table 6, analysis of variance (ANOVA) for each performance characteristics calculated by using OAD are presented. Sum of squared deviations, degree of freedom, variance, Fisher test factor(F) and percentage contribution are calculated for each fabrication factor. As a result of ANOVA analysis, factors with high variance or high F value were considered as significant factors controlling the performance related values such as hoop strain, internal pressure and central temperature of DUPIC fuel element. For example, hoop strain at pellet end is mainly controlled by the variation of fuel density as shown in Table 4, and internal gas pressure is mainly controlled by the variation of grain size of fuel pellet as shown in Table 5.

Table 1. Fabrication factors and their levels used in the orthogonal array design.

Fabrication Factors	Level 1	Level 2	Level 3
Fuel Density	10.30 g/cm^3 (95.5%)	10.45 g/cm^3 (96.9%)	10.60 g/cm^3 (98.2%)
Gap Clearance	40 μm	80 μm	120 μm
Grain Size	5 μm	15 μm	25 μm

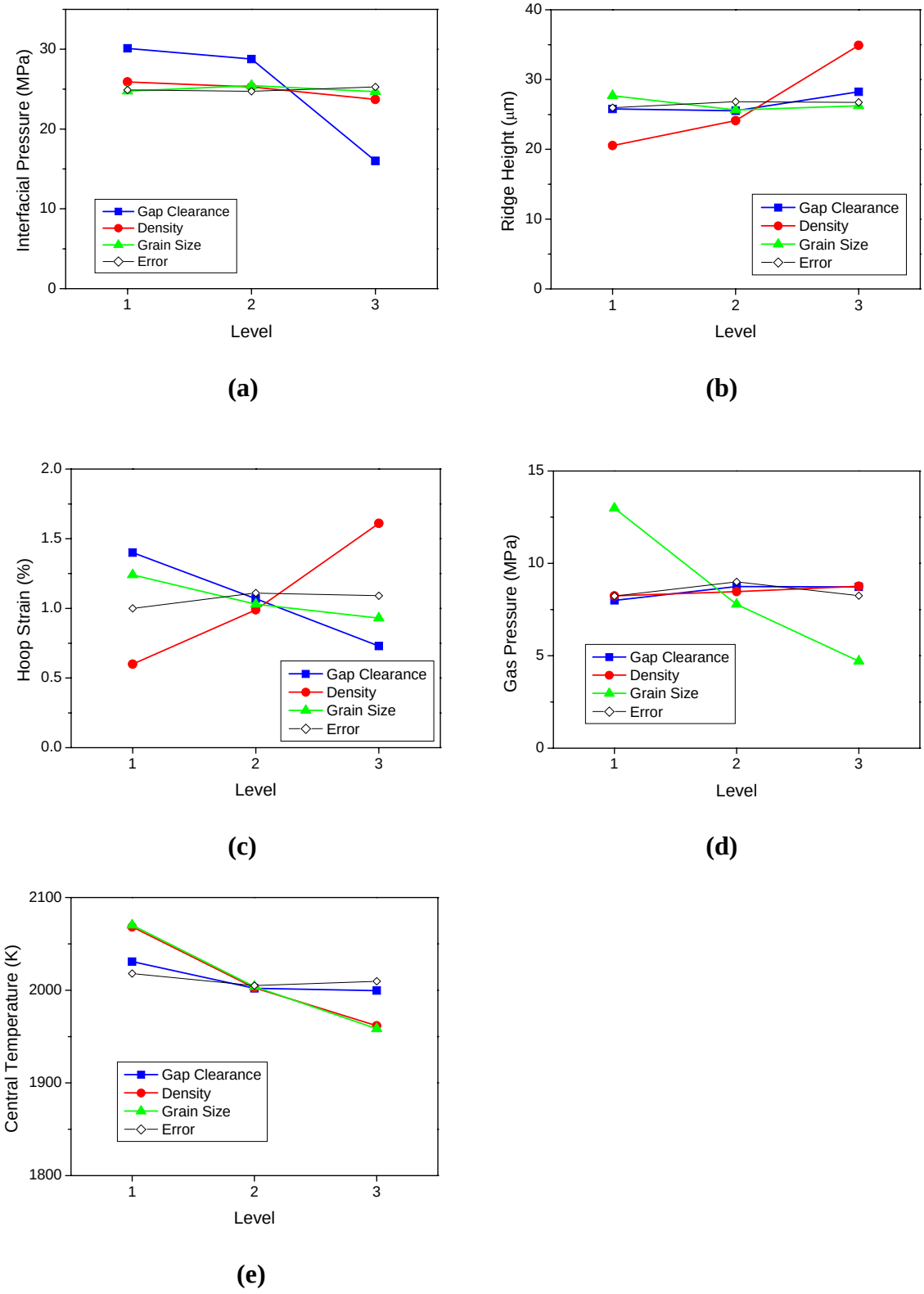


Figure 5. Statistical variation of the (a) interfacial pressure between pellet and cladding, (b) ridge height at the pellet end, (c) hoop strain at pellet end, (d) internal gas pressure, and (e) central temperature of the DUPIC fuel with the levels in orthogonal array design.

Table 2. ANOVA analysis for interfacial pressure between the pellet and cladding.

Fabrication Factors	Sum of squares	D.O.F.	Variance	F	Contribution(%)
Fuel Density	7.6	2	3.8	15.8	2.0
Gap Clearance	364.2	2	182.1	753.3	97.5
Grain Size	1.1	2	0.5	2.2	0.3
Error	0.5	2	0.2		0.1

Table 3. ANOVA analysis for ridge height at pellet end.

Fabrication Factors	Sum of squares	D.O.F.	Variance	F	Contribution(%)
Fuel Density	335.8	2	167.9	248.9	94.0
Gap Clearance	13.4	2	6.7	10.0	3.8
Grain Size	6.5	2	3.3	4.9	1.8
Error	1.3	2	0.7		0.4

Table 4. ANOVA analysis for hoop strain of cladding at pellet end.

Fabrication Factors	Sum of squares	D.O.F.	Variance	F	Contribution(%)
Fuel Density	1.6	2	0.8	69.6	65.1
Gap Clearance	0.7	2	0.3	29.7	27.7
Grain Size	0.2	2	0.1	6.7	6.2
Error	0.0	2	0.0		0.9

Table 5. ANOVA analysis for internal gas pressure.

Fabrication Factors	Sum of squares	D.O.F.	Variance	F	Contribution(%)
Fuel Density	0.4	2	0.2	0.4	0.4
Gap Clearance	1.1	2	0.5	0.9	1.0
Grain Size	104.8	2	52.4	90.1	97.5
Error	1.2	2	0.6		1.1

Table 6. ANOVA analysis for central temperature of pellet.

Fabrication Factors	Sum of squares	D.O.F.	Variance	F	Contribution(%)
Fuel Density	17370.9	2	8685.4	66.8	45.1
Gap Clearance	1828.2	2	914.1	7.0	4.8
Grain Size	19029.6	2	9514.8	73.1	49.4
Error	260.2	2	130.1		0.7

The results of OAD and ANOVA show that DUPIC pellets with large gap, large grain and low pellet density are recommended to reduce strong PCMI during normal operational condition. The central temperature, internal gas pressure and plastic strain of cladding at pellet end were compared between a DUPIC fuel with small gap-high density and large gap-low density. Although a DUPIC fuel with small gap and high density showed a little lower central temperature as shown in Figure 6(a), it has much higher plastic strain of cladding at pellet end as shown in Figure 6(b).

If the ratio of maximum level-averaged value of performance data during irradiation to safety limit is called a safety margin ratio, Figure 7 shows the safety margin ratio of a DUPIC fuel with large gap, large grain and lower pellet density and the other one with small gap, small grain and higher pellet density with respect to central temperature, internal gas pressure, and plastic strain of cladding at pellet end. While the safety margin ratio of central temperature did not increases so much, the safety margin ratio of internal gas pressure and plastic strain of cladding at pellet end are remarkably different between each condition. This result exhibits the importance of the optimization of fabrication design parameter of the DUPIC fuel to reduce the strong PCMI propensity.

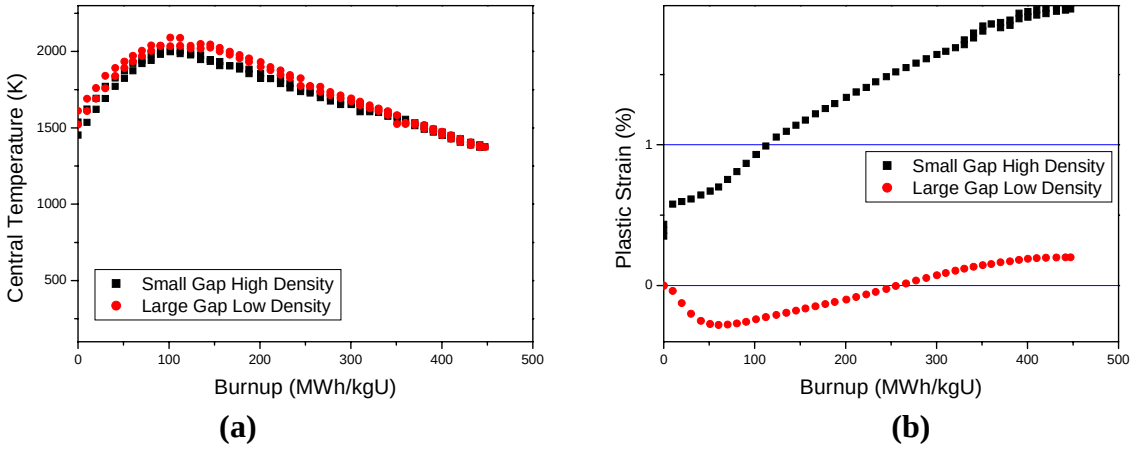


Figure 6. Comparison of (a) central temperature, (b) internal pressure, and (c) plastic strain of cladding between a rod with small initial gap and high pellet density and the other one with large initial gap and low pellet density.

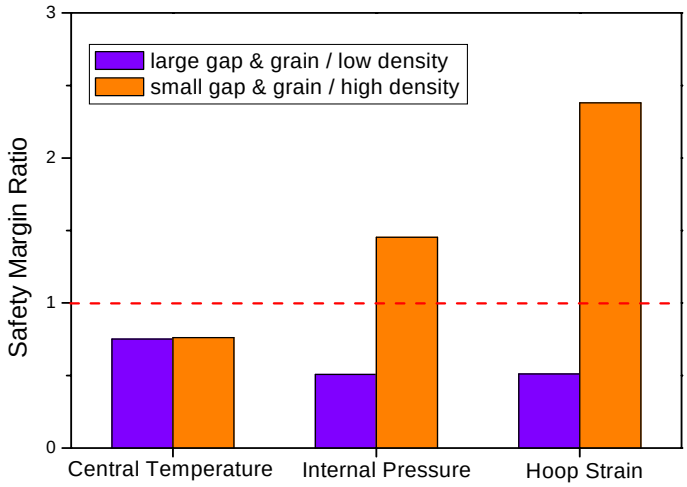


Figure 7. Comparison of safety margin ratio of a rod with large initial gap, large grain and low pellet density and the other one with small initial gap, small grain and high pellet density.

Conclusions

DUPIC fuel has a stronger propensity of pellet cladding mechanical interaction than UO_2 fuel mainly due to the decrease in thermal conductivity. Orthogonal array design analysis by using a modified performance code employing material models of DUPIC fuel showed that the fabrication parameters such as fuel density, initial gap and grain size should be optimized to mitigate PCMI of the DUPIC fuel.

Acknowledgements

This study was carried out as a research project of the National Nuclear R&D Program sponsored by the Ministry of Science and Technology (MOST).

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