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Irradiation Behavior Analyses of Oxide Fuel Pins for SFR High Breeding Cores

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As a possible concept for commercialized Sodium-cooled fast reactor (SFR) core fuel, annular mixed oxide (MOX) fuel with oxide dispersion strengthened ferritic steel (ODS) cladding was considered with low breeding ratio as a standard, break-even breeding cores, and cores with high breeding ratio (high breeding cores). Some calculations of fuel pin irradiation performance of (U,Pu) oxide fuel and minor actinides bearing oxide fuel were conducted by a fuel performance analysis code CEDAR developed in JAEA to understand the steady state irradiation behavior of fuel pins for the cores with high breeding ratio.

The fuel temperature profiles, fuel and cladding deformation profiles, and radial temperature distribution at end of life (EOL) were evaluated. Those results show that the MOX fuel pin having the specifications and irradiation conditions used in this investigation would be irradiated moderately up to approximately 250GWd/t with well integrity. The difference toward to 10.4 mm fuel pins, critical behavior will not being estimated. The temperature of MA bearing oxide fuel was tended to be higher than that of (U, Pu) oxide fuel. However, it is concluded that the effect of MA or difference toward to fuel behavior is restrictive considering its obtained results.

Keywords：Fast Reactor, Mixed Oxide Fuel, High Breeding Ratio, CEDAR, Fuel Performance

高増殖比 **SFR** における酸化物燃料ピンの照射挙動解析

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実用化段階のナトリウム冷却高速炉の燃料概念として、中空の混合酸化物（MOX）燃料と酸化物分散強化型フェライト鋼被覆管による燃料ピンを、標準の低増殖炉心、break-even 炉心 ((高速炉)平衡期炉心)、高増殖炉心に適用することが検討されている。高増殖炉心における燃料ピンの定常運転時の照射挙動を理解するため、U,Pu 酸化物燃料とマイナーアクチニド含有燃料の照射挙動計算を、JAEA で開発した燃料ピン挙動解析コード"CEDAR"を用いて実施した。

燃料温度履歴、燃料と被覆管の変形履歴、照射末期における径方向温度分布を評価した結果、本研究で検討した燃料仕様と照射条件において、MOX 燃料ピンは 250GWd/t まで健全に照射できる見通しが得られた。また、φ10.4mm の太径ピンでは、問題となるような挙動は解析されなかった。MA 含有燃料の温度は、U,Pu 酸化物燃料よりも高くなる傾向が示されたが、MA による燃料挙動への影響は限定的であるという評価結果となった。

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1. Introduction

The Fast Reactor Cycle Technology Development (FaCT) project has been being conducted in Japan. In the FaCT project, fuel pin concepts consisting of MOX annular fuels and oxide dispersion strengthened martensitic steel (ODS) cladding have been being considered to be one of possible concepts for the sodium cooled reactor cores, which include standard cores with low breeding ratio, break-even breeding cores, and cores with high breeding ratio (high breeding cores). The high breeding cores in the FaCT project have thick axial blanket with shorter core fuel column length and smaller diameter driver fuel pins than those of standard cores.

In this work, to understand the steady state irradiation behavior of the small diameter annular MOX fuel pin, some calculations of fuel pin irradiation performance of (U,Pu) oxide fuel and minor actinides bearing oxide fuel were conducted by a fuel performance analysis code CEDAR developed in JAEA.

2. Outline of CEDAR

A pellet type MOX fuel performance analysis code "CEDAR" (Code for Thermal and Deformation Analysis of Reactor fuel pin) was used[1)]. This code has been developed by JAEA. CEDAR is an R-Z system code that has been verified by results obtained from irradiation tests in experimental reactors such as Joyo; the range of burnup is ~130GWd/t, of LHR is ~440W/cm, and of cladding inner surface temperature is ~923K. CEDAR models the thermochemical and mechanical behaviors of a fuel pin during irradiation using 10 axial nodes, each having 26 radial nodes, 20 of which are for the fuel region and 6 for the cladding region. Fuel property correlations in CEDAR code include (U,Pu) oxide fuel and minor actinides bearing oxide fuel. Mass transports in the axial direction are not taken into consideration, except for FP gases released into the plenum space and fuel-cladding gap. The stress-strain analysis procedure based on the generalized plane strain is applied to the mechanical analysis, and the finite difference analysis procedure is applied to the thermochemical analysis. Table 1 shows the evaluated behaviors. Fig.1 and Fig.2 show the geometrical model and flow chart of CEDAR, respectively.

3. Calculation conditions

Table 2 shows designed fuel specifications and irradiation conditions in the case of high breeding core. A fuel pin having annular type MOX pellets with the ODS cladding was taken for this investigation. This fuel pin had lower and upper plenum regions. And the outer diameter is relatively small, 9.3 mm, compared with previous evaluation condition (10.4 mm in diameter) [2)]. The irradiation time was taken as 2557 days (4 cycles). The maximum neutron fluence was taken as $5.02\times10^{23}n\cdot cm^{-2}$, then the maximum local burnup was evaluated to be as 227 GWd/t. The condition of coolant inlet temperature was taken as 668 K.

Calculations were conducted at the following 5 axial positions; X/L = 0.9, 0.7, 0.5, 0.3, and 0.1. Axial distribution conditions at BOL and EOL of LHR and cladding midwall temperature are shown in Fig. 3 and Fig. 4, respectively. Profile conditions of LHR and cladding midwall temperature at each axial position of the calculations are shown in Fig. 5 and Fig. 6, respectively.

Fuels considered in the present study are MA bearing oxide fuel with 3% of Am content and (U,Pu) oxide fuel.

These conditions are based on the current results of feasibility studies on a commercialized fast reactor cycle system in Japan[2)].

4. Results and discussions

4.1 (U,Pu) oxide fuel

Deformation profiles of fuel outer radius and cladding inner radius during irradiation at X/L = 0.5 are shown in Fig.7. It was cleared that the fuel was contacted to cladding in the early stage of irradiation. Figure 8 shows the cladding deformation by swelling or swelling with creep after irradiation. The swelling defined as a ratio of diameter change. As shown in Fig. 8, maximum swelling was seen at X/L = 0.1, and then no swelling was estimated at X/L = 0.5, 0.7, 0.9. On the other hand, the deformation by creep was evaluated all the calculated position, the effect was depended on neutron fluence. Therefore, maximum deformation of cladding with swelling and creep was expected at X/L = 0.3. The fuel-cladding mechanical interaction (FCMI) was considered based on these results, it is expected that the contact pressure was not strong to cause the considerable cladding deformation. Therefore, it is concluded that the MOX fuel pin having the specifications and irradiation conditions used in this investigation would be irradiated moderately up to approximately 250GWd/t with well integrity.

4.2 MA bearing oxide fuel (3% Am)

For calculation of MA bearing oxide fuel, 3% of Am content is newly applied as a calculation parameter on the specification and irradiation condition of (U, Pu) oxide fuel shown in Table 3. Thermal effect would be considered for the use of Am by using the thermal conductivity correlation that considered the effect of Am contents [3)]. As is shown in Fig. 9, thermal conductivity is apt to be decreased with increasing Am content. Figure 10 shows temperature profile for fuel inner, outer and cladding inner surface at X/L = 0.5 during irradiation. Figure 11 also shows deformation profiles of fuel outer and cladding inner radius at X/L = 0.5 during irradiation. It was cleared that the fuel was contacted to cladding in the early stage of irradiation, and therefore, good correlation was seen in the behavior between gap closure and temperature change at fuel outer surface position. It is the same tendency as (U, Pu) oxide fuel for the axial position at X/L = 0.5. The cladding deformation after irradiation is shown in Fig. 12. Similarly, it was seen that the cladding deformation by swelling or swelling with creep were almost the same as (U, Pu) oxide fuel calculation results shown in Fig. 8. In the meantime, fuel inner surface temperature of MA bearing oxide fuel (3% Am) and (U, Pu) oxide fuel were compared and shown in Fig. 13. The temperature of MA bearing oxide fuel was tended to be higher than that of (U, Pu) oxide fuel. However, it can be said that the effect toward to fuel behavior is restrictive considering its Am content.

5. Conclusion

Some calculations of fuel pin irradiation performance of (U,Pu) oxide fuel and minor actinides bearing oxide fuel were conducted by a fuel performance analysis code CEDAR developed in JAEA to understand the steady state irradiation behavior of fuel pins for the cores with high breeding ratio.

The fuel temperature profiles, fuel and cladding deformation profiles, and radial temperature distribution at EOL were evaluated. Those results show that the MOX fuel pin having the specifications and irradiation conditions used in this investigation would be irradiated moderately up to approximately 250GWd/t with well integrity. The difference toward to 10.4mm fuel pins, critical behavior will not being estimated. The temperature of MA bearing oxide fuel was tended to be higher than that of (U, Pu) oxide fuel. However, it is concluded that the effect of MA or difference toward to fuel behavior is restrictive considering its obtained results.

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Table 1　Behaviors evaluated by CEDAR

Evaluated fuel behaviors
Temperature distribution
Stress-strain state
Restructuring (pore migration)
Fission gas release
Pu migration
Oxygen migration (O/M ratio distribution)
Chemical reaction between fuel components and FPs in the fuel-cladding gap (JOG formation and its effect on gap conductance)
Swelling
Hot-pressing
Creep deformation
Cracking
Evaluated cladding behaviors
Temperature distribution
Stress-strain state
Void swelling
Creep deformation
Cladding wastage
Creep damage

Table 2 Designed oxide fuel specifications and irradiation conditions (High breeding core)

Item		Unit	Value
Fuel	Type		Annular pellet
	Inner diameter	mm	2.32
	Outer diameter	mm	7.81
	Density	%TD	95
	Pu cont.	wt.%	23.1
	O to M ratio	-	1.95
Fuel column length		mm	750
Plenum	upper	mm	100
	lower	mm	1100
Cladding	Material		ODS
	Inner diameter	mm	8.02
	Outer diameter	mm	9.3
	Thickness	mm	0.64
Irradiation duration		day	2556.8 (1cycle:639.2)
Max. LHR		W/cm	419
Max. Cladding midwall temperature		K	942
Max. Neutron fluence (>0.1MeV)		n/cm^2	5.02E23
Max. Burnup (local position)		GWD/t	227
Coolant	Material		Sodium
	Inlet temperature	K	668

Table 3 Designed MA bearing fuel specifications and irradiation conditions (High breeding core)

Item		Unit	Value
Fuel	Type		Annular pellet
	Inner diameter	mm	2.32
	Outer diameter	mm	7.81
	Density	%TD	95
	Am cont.	wt.%	3
	O to M ratio	-	1.95
Fuel column length		mm	750
Plenum	upper	mm	100
	lower	mm	1100
Cladding	Material		ODS
	Inner diameter	mm	8.02
	Outer diameter	mm	9.3
	Thickness	mm	0.64
Irradiation duration		day	2556.8 (1cycle:639.2)
Max. LHR		W/cm	419
Max. Cladding midwall temperature		K	942
Max. Neutron fluence (>0.1MeV)		n/cm^2	5.02E23
Max. Burnup (local position)		GWD/t	227
Coolant	Material		Sodium
	Inlet temperature	K	668

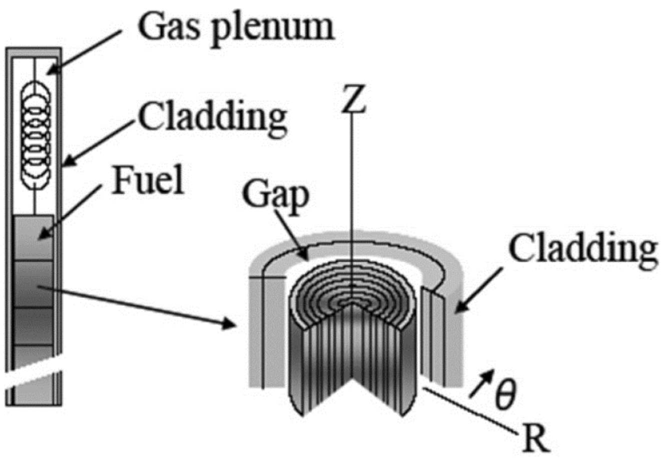

Fig.1 Geometrical model of CEDAR

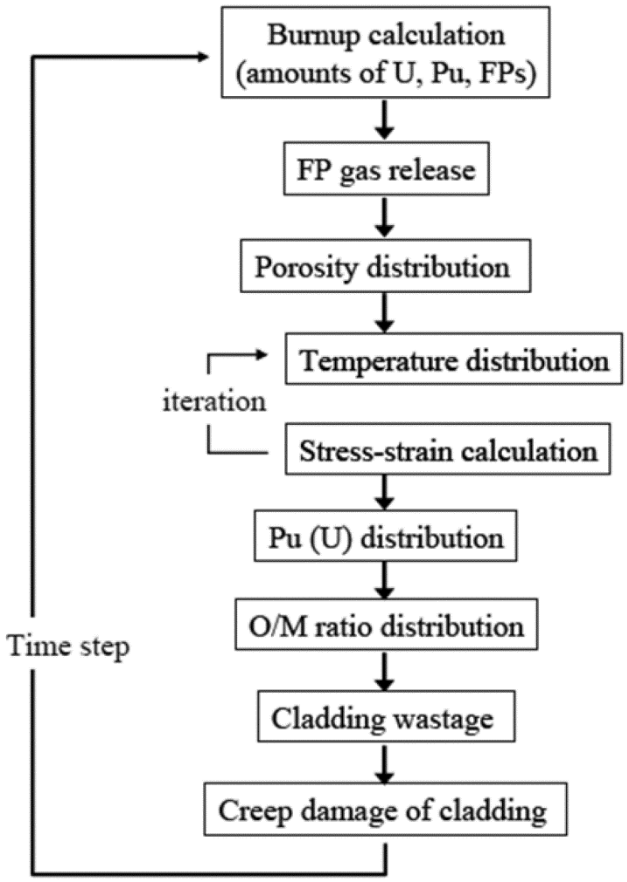

Fig.2 Flow chart of CEDAR

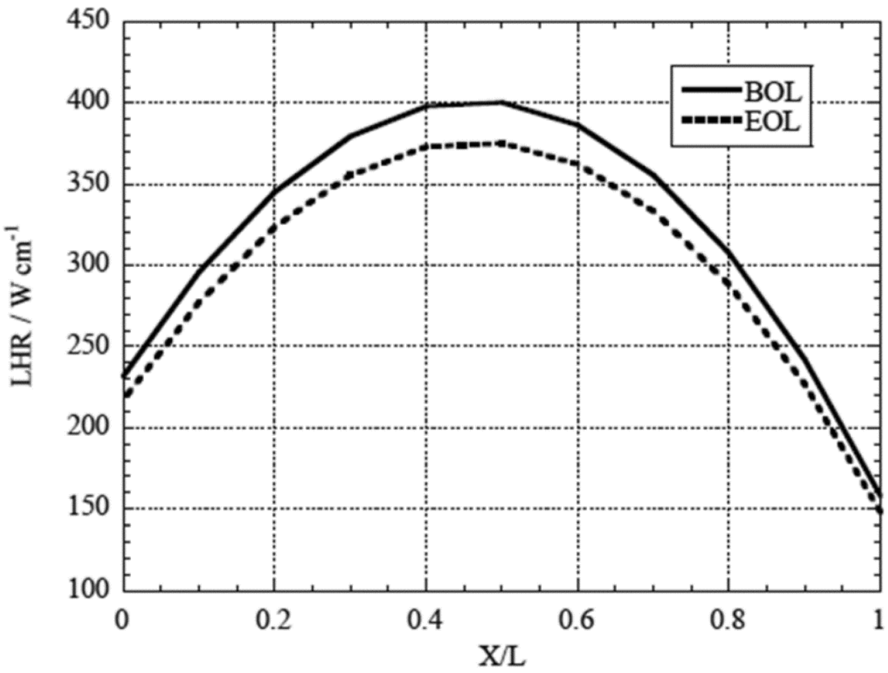

Fig.3 Axial distribution condition of LHR

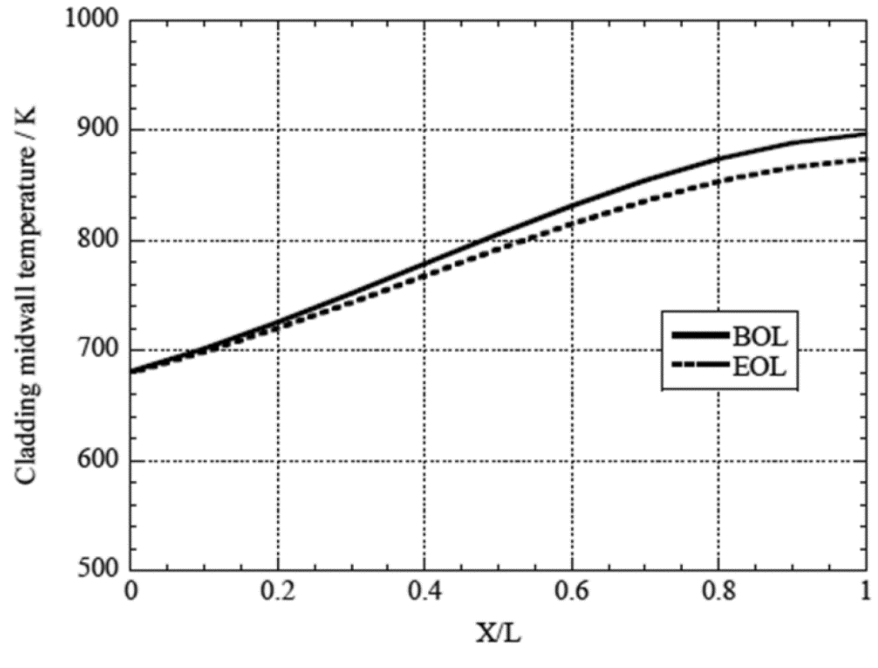

Fig.4 Axial distribution condition of cladding midwall temperature

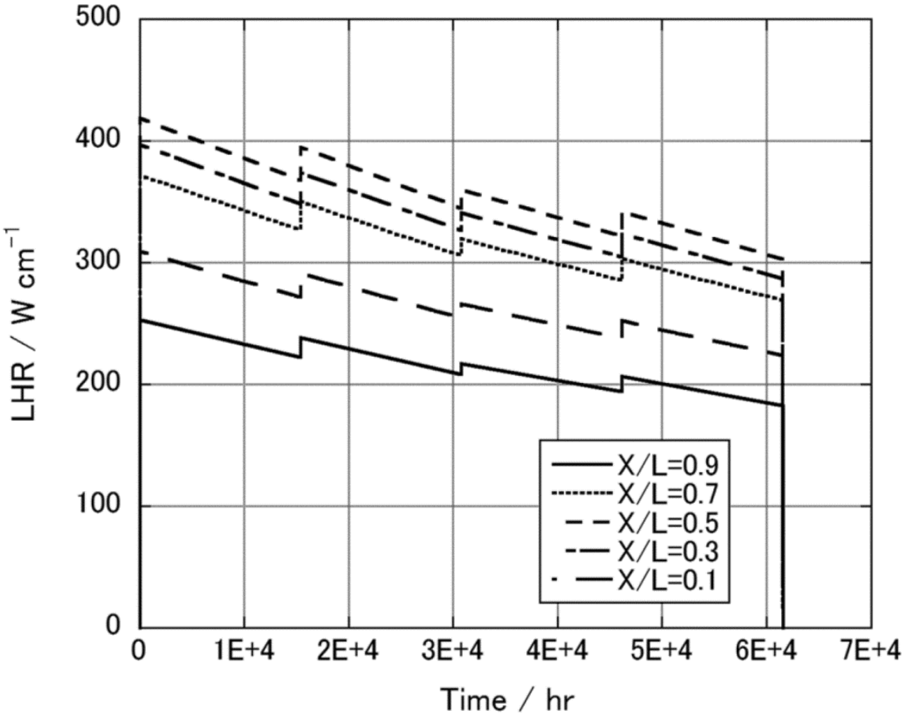

Fig.5 Profile condition of LHR

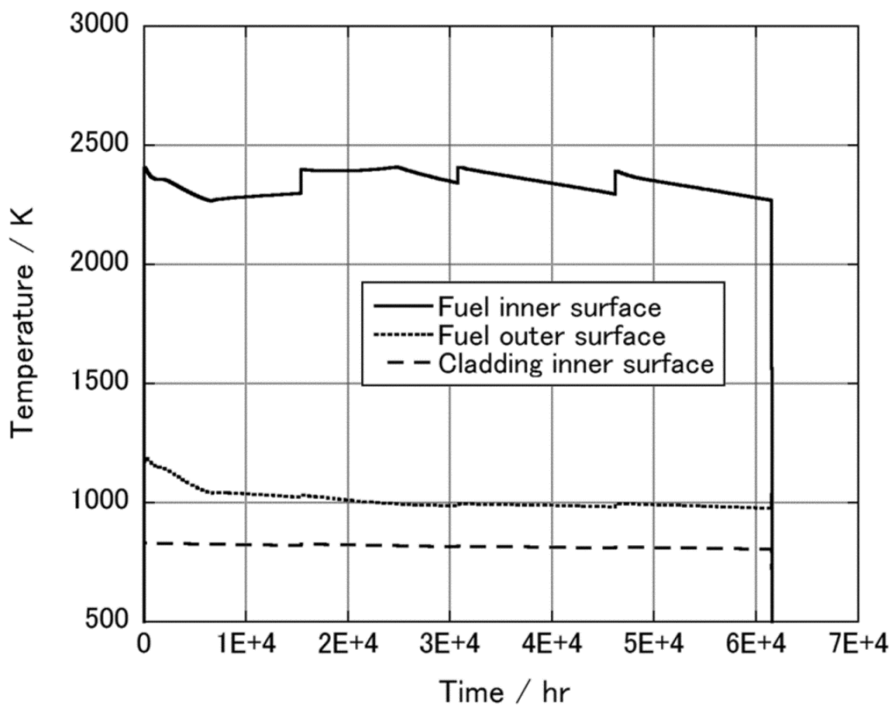

Fig.6 Temperature profiles at X/L=0.5 for oxide fuel

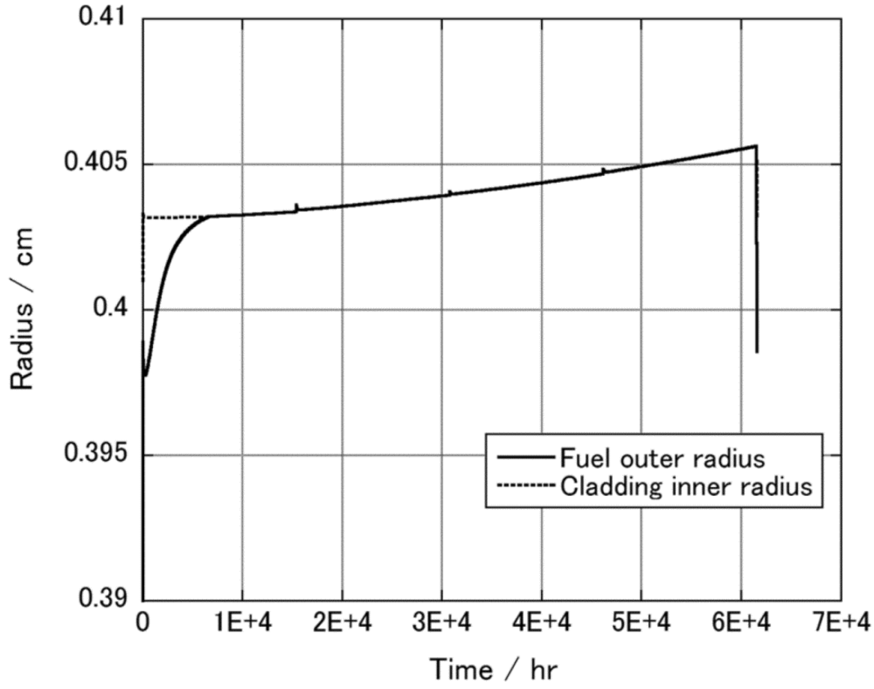

Fig.7 Deformation profiles of fuel and cladding at X/L=0.5 for oxide fuel

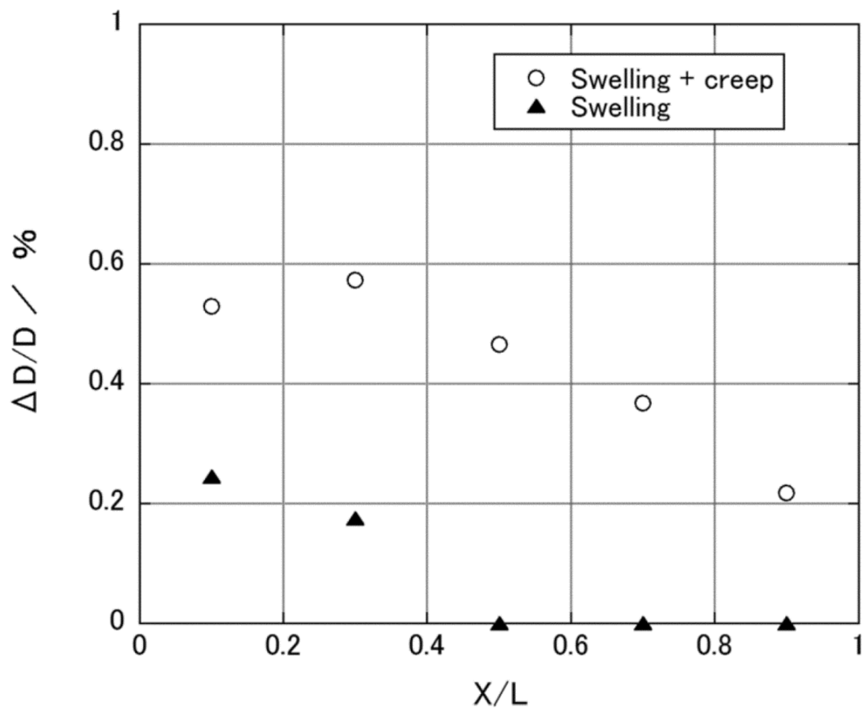

Fig.8 Cladding deformation after the irradiation for oxide fuel

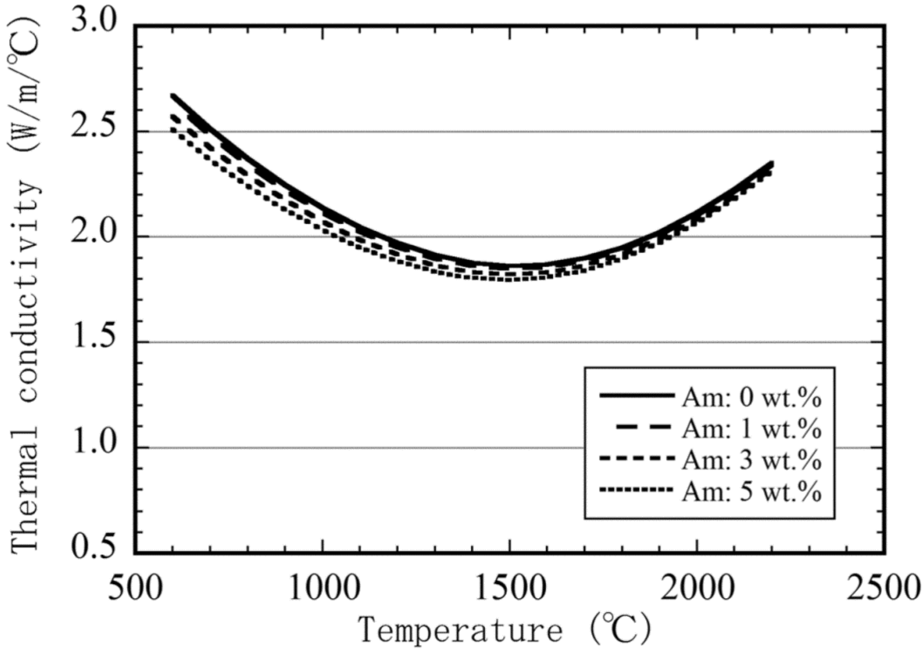

Fig.9 Thermal conductivity for Am bearing oxide fuel

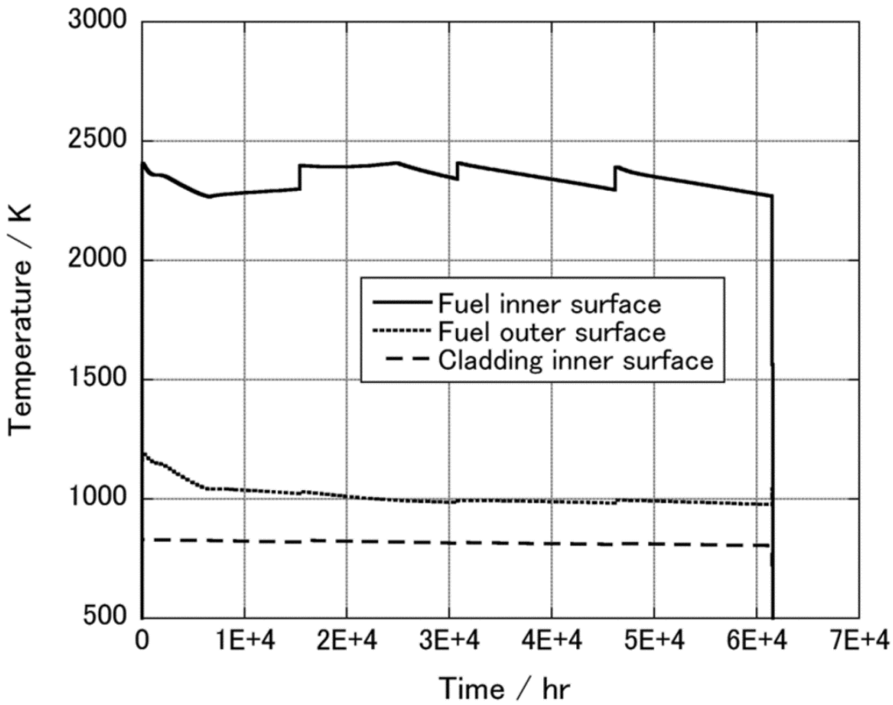

Fig.10 Temperature profiles at X/L=0.5 for Am bearing oxide fuel

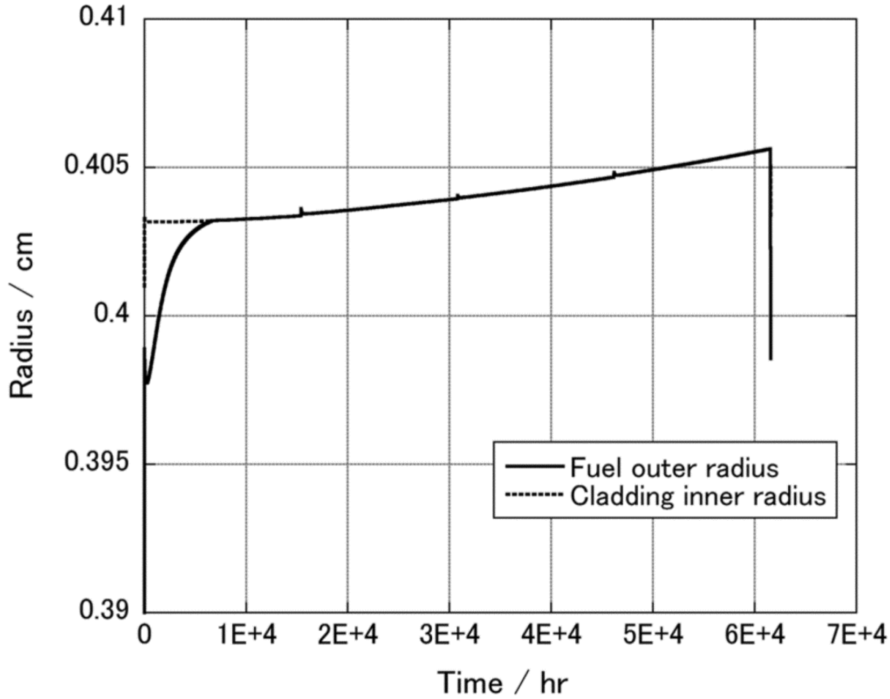

Fig.11 Deformation profiles of fuel and cladding at X/L=0.5 for Am bearing oxide fuel

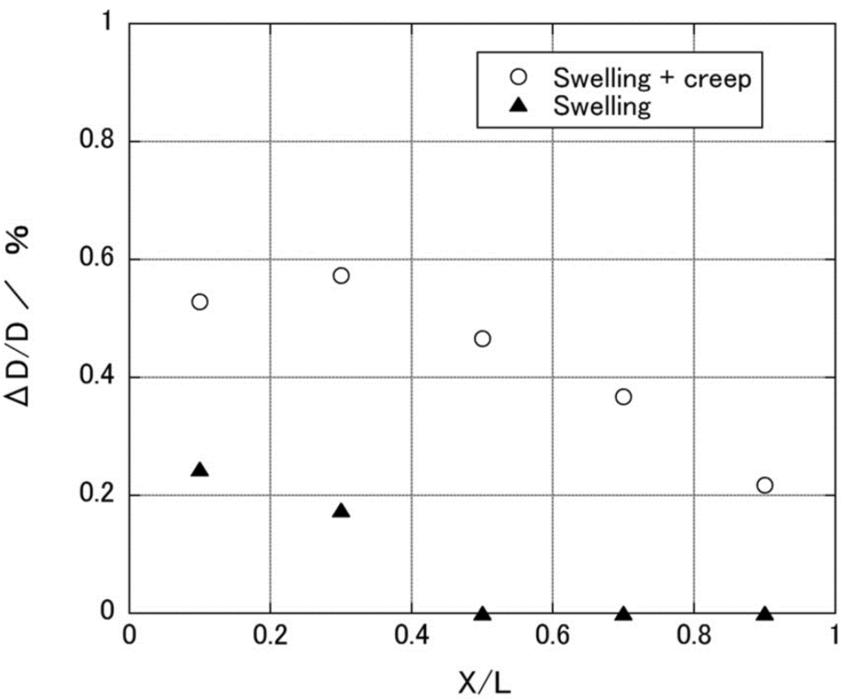

Fig.12 Cladding deformation after the irradiation for Am bearing oxide fuel

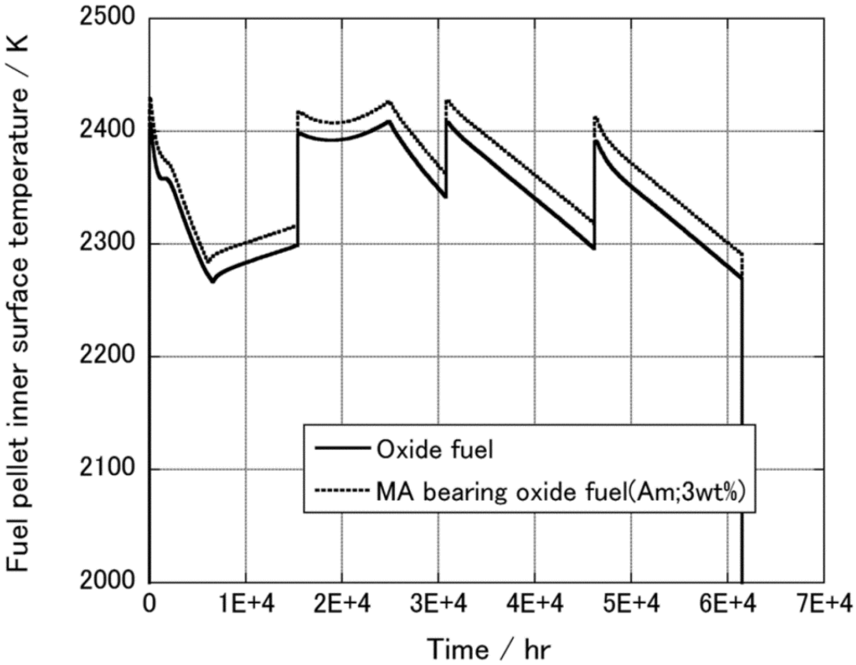

Fig.13　Histories of fuel center temperatures