JAEA-Technology
2013-009

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June 2013
Japan Atomic Energy Agency
日本原子力研究開発機構

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(Received March 11, 2013)

Metallic fuel, U-Pu(TRU)-Zr, is a fuel candidate for Sodium-cooled fast reactor (SFR) selected as a possible promising future nuclear reactor system in Generation-IV international forum (GIF). Design studies were performed in the Japanese feasibility study on commercialized fast reactor cycle system, and the irradiation behavior of metallic fuel is under investigation through analytical fuel performance code calculations with preliminary analytical models.

As fuel temperature at overpower events is a major interest, some calculations of U-Pu(TRU)-Zr fuel irradiation performance were conducted by a simplified calculation program developed in JAEA. The calculated fuel temperature at the maximum power of overpower events, 110%-120% of steady state power, was around 1100K in maxim. It is clear that this temperature was low enough to avoid fuel melting in the event.

Keywords：Fast Reactor, Metallic Fuel, Overpower, Fuel Temperature, Calculation Code

JAEA-Technology 2013-009

ナトリウム冷却高速炉金属燃料の過出力時における燃料温度解析

日本原子力研究開発機構　次世代原子力システム研究開発部門
燃料材料技術開発ユニット

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(2013 年 3 月 11 日　受理)

U-Pu(TRU)-Zr,を成分とする金属燃料は、第 4 世代原子力システム国際フォーラム (GIF)において有望な原子炉として選定されたナトリウム冷却炉(SFR)の候補燃料である。金属燃料の設計研究は日本における高速増殖炉サイクルの実用化戦略調査研究で実施され、照射挙動に関して挙動解析コードを用いた予備評価を実施中である。

過出力事象時の温度解析は燃料健全性評価上重要であるため、U-Pu(TRU)-Zr 燃料の照射挙動評価を JAEA で開発した簡易計算プログラムを用いて実施した。過出力事象時の最大出力、すなわち定常運転時の 110－120%の出力条件において、燃料温度は最高で 1100K と評価され、燃料溶融が回避できることが示された。

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1. Introduction

Sodium-cooled fast reactors (SFR) were selected in Generation-IV international forum (GIF) as a possible promising future nuclear reactor system with superior safety, sustainability and economic competitiveness.$^{1)}$ Fuel candidates for SFR in GIF collaborative program include U-Pu(TRU)-Zr metallic fuel as well as oxide fuel.$^{2)}$

Design studies of metallic fuel core for SFR were performed in the Japanese feasibility study on commercialized fast reactor cycle systems. The significant outcome of the studies is an attractive core and fuel concept which achieves high burnup and high outlet temperature of reactor vessel.$^{3)}$ The irradiation behavior of metallic fuel of the design studies is under investigation through analytical fuel performance code calculations with preliminary analytical models of metallic fuel.

In the present work, analytical code calculations of metallic fuel pin irradiation performance are conducted with major interest on fuel temperatures during overpower events.

The irradiation behavior models and fuel properties for the analytical code were selected based on the information of metallic fuel characteristics including fuel properties and irradiation behavior obtained from open literatures and collaborative research activities with the Central Research Institute of Electric Power Industry.

2. Outline of calculation program

A simplified calculation program for U-Pu(TRU)-Zr metallic fuel pin performance analysis has been developed. This program is an R-Z system and models the thermal 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. Mass transports in the direction are not taken into account, except for FP gases released into the gas plenum of the fuel pin. The program is limited to analyses of fuel pins having a smear density not over around 75%TD. Table 1 shows the evaluated behaviors. Some conservative and simplified models as follows were incorporated into the program;

1) for the FP gas release, the fractional release rate under irradiation was taken as the constant value of 90 %,

2) for the fuel and cladding mechanical analyses, the fuel-cladding contact pressure under irradiation was taken as the constant value of zero, because it was reported that no considerable contacts between fuel and cladding were obtained in the case of fuels having a smear density of less or equal to 75%TD.$^{4)}$ Only the stress-strain analysis of cladding due to the plenum gas pressure were conducted,

3) for the fuel restructuring and fuel constituents migrations, they were not taken into account,

4) for the fuel thermal conductivity, metallic fuel slug effective thermal conductivity is considered. The effective thermal conductivity model consists of solid fuel slug thermal conductivity with 100% TD and contribution of porous fuel microstructure filled with gas and liquid sodium due to gas swelling and sodium ingress under irradiation. The correlations of solid fuel thermal conductivity and contribution of porous fuel

microstructure are found elsewhere.[5)6)7)] The volume fractions of gas-filled porosity and sodium-infiltrated porosity are treated as variants in the present work. The specific conditions in the calculation are described later.

The finite difference analysis procedure is applied to the thermal analysis, and the stress-strain analysis procedure based on the generalized plane strain is applied to the mechanical analysis of cladding. Figures 1 and 2 show the geometrical model and flow chart of the program, respectively.

3. Calculation conditions

3.1 Fuel pin specifications and irradiation conditions

Table 2 shows fuel specifications and irradiation conditions for this investigation. A fuel pin having a metallic U-Pu-Zr slug with the ODS cladding was taken for this investigation. The bonding material filling the fuel-cladding gap was sodium. The level of bonding sodium was up to the top of the fuel column. The time of overpower events were selected as the time when the fuel temperature was maximum during the steady state irradiation. Aiming at the selection of time of overpower event, fuel pin behavior calculation of steady state irradiation was made. The irradiation time was taken as 2205 days (3 cycles). The maximum neutron fluence was taken as $5.50\times10^{23}\mathrm{n\cdot cm^{-2}}$, then the maximum local burnup was evaluated to be as 140 GWd/t. The coolant inlet temperature was taken as 668K. 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 Figs. 3 and 4, respectively. Profile conditions of LHR and cladding midwall temperature at each axial position of the calculations are shown in Figs. 5 and 6, respectively.

These conditions are based on the current results of feasibility studies on a commercialized fast reactor cycle system in Japan.[3)]

After selecting the time of overpower events, fuel temperature calculation of the events was made. Maximum power during the overpower events were selected as 110%, 116% and 120% of steady state power. The value of 116% was based on the typical overpower factor of an existing fast reactor design and other values were selected for the sensitivity study. Fuel temperature calculation was made assuming equilibrium heat transfer condition which gives the highest fuel centerline temperature.

3.2 Effective thermal conductivity models of metallic fuel

As described above, the effective thermal conductivity model consists of solid fuel slug thermal conductivity with 100% TD and contribution of porous fuel microstructure filled with gas and liquid sodium. The fraction of swelled volume filled with sodium was reported to be from 0.25 to 0.28 in some case of U-Pu-Zr fuel. In the present study, following two cases are selected aiming at a sensitivity study. One is 0.25 of the fraction as a case of sodium ingress and the other is no sodium ingress as conservative case.

4. Results and discussions

The fuel temperature is irradiation performance of most interest in the present study. Figure 7 and 8 show the fuel centerline temperatures during steady state irradiation, calculated using effective thermal conductivity models without sodium ingress into the swelled metallic fuel and with sodium ingress, respectively. The axial positions of these temperatures are X/L = 0.5 and 0.7 of the fuel column. These positions are axial positions where the calculated fuel temperatures are maximum. Axial distributions of fuel centerline temperature are indicated in Fig.9, which shows the position of maximum temperature is around X/L = 0.5 and 0.7 of the fuel column.

The time of maximum fuel temperature was calculated to be 8856 hr of irradiation time as indicated in Figs. 7 and 8. Therefore, overpower fuel temperature calculations were made at this time. Figures 10 and 11 show the calculated fuel centerline temperatures for 110%, 116% and 120% of steady state power. Fuel temperatures become high in comparison with those of steady state irradiation, but they are about 1100K in maximum for the case of no sodium ingress into the swelled metallic fuel and about 1000K in maximum for the case of sodium ingress. They are well below the melting point of U-Pu-Zr metallic fuel.

5. Conclusion

Some calculations of metallic fuel irradiation performance were conducted by a simplified calculation program developed in JAEA to understand the behavior of a U-Pu(TRU)-Zr fuel pin. The major interest of the investigation is calculated fuel temperatures in typical overpower events with 110%-120% of steady state power.

Calculated fuel temperature at the maximum power of overpower event was around 1100K in maximum and low enough to avoid fuel melting in the event.

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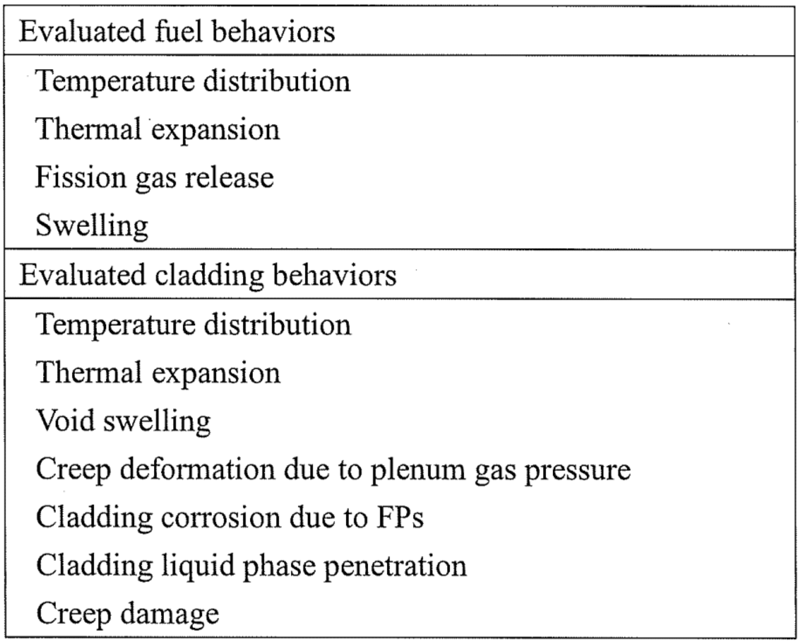
Table 1 Behaviors evaluated by the calculation program



Evaluated fuel behaviors
Temperature distribution
Thermal expansion
Fission gas release
Swelling
Evaluated cladding behaviors
Temperature distribution
Thermal expansion
Void swelling
Creep deformation due to plenum gas pressure
Cladding corrosion due to FPs
Cladding liquid phase penetration
Creep damage

Table 2 Designed fuel specifications and irradiation conditions

Item		Unit	Value
Fuel	Type		Slug
	Outer diameter	mm	6.496
	Density	%TD	100
	Pu cont.(including MA)	wt.%	11.47
	Zr cont.	wt.%	6.0
Fuel colum length		mm	750
Plenum	upper	mm	1350
Cladding	Material		ODS
	Inner diameter	mm	7.5
	Outer diameter	mm	8.5
	Thickness	mm	0.5
Bonding	Material		Sodium
	Filling level	mm	up to fuel column
Irradiation duration		day	2205 (1cycle : 735)
Max. LHR		W/cm	347
Max. Cladding midwall temperature		K	878
Max. Neutron fluence(>0.1MeV)		n/cm^2	5.50E23
Max. Burnup (local position)		GWD/t	140
Coolant	Material		Sodium
	Inlet temperature	K	668

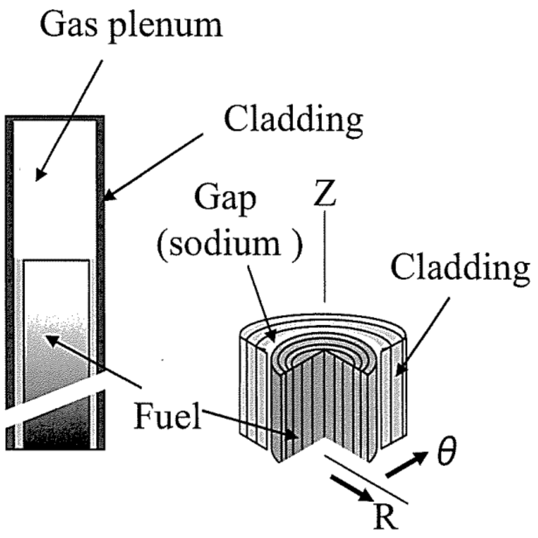


Fig.1 Geometrical model of the calculation program

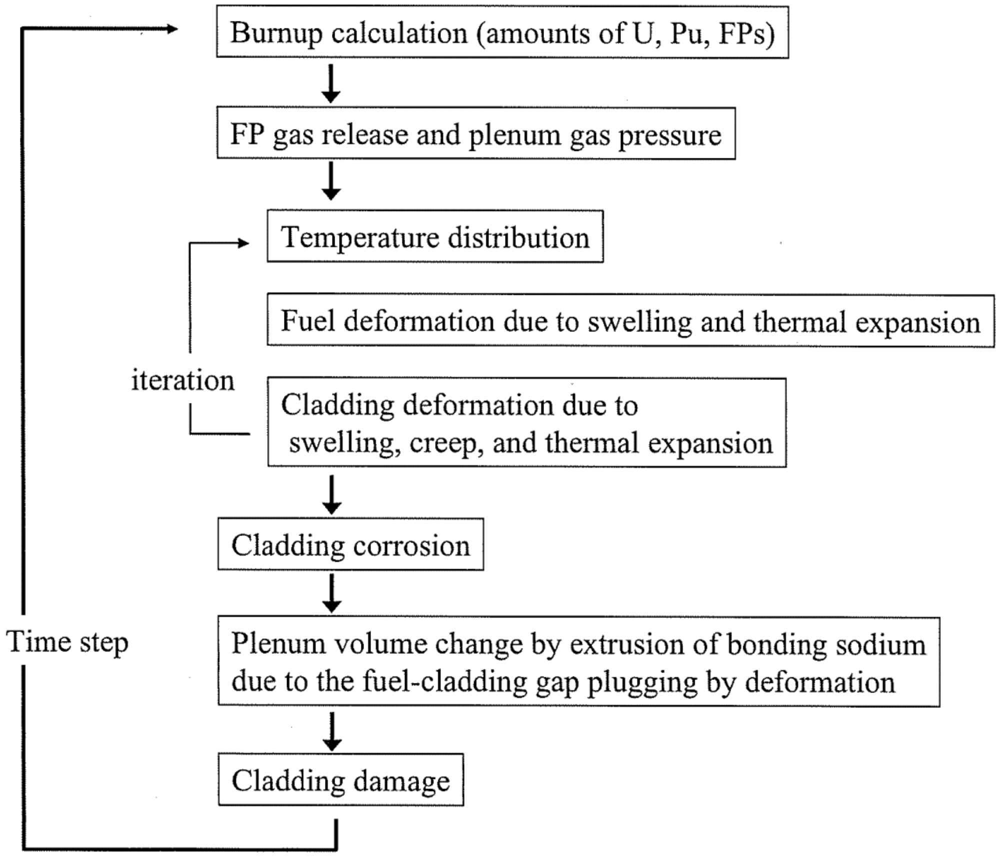


Fig.2 Flow chart of the calculation program

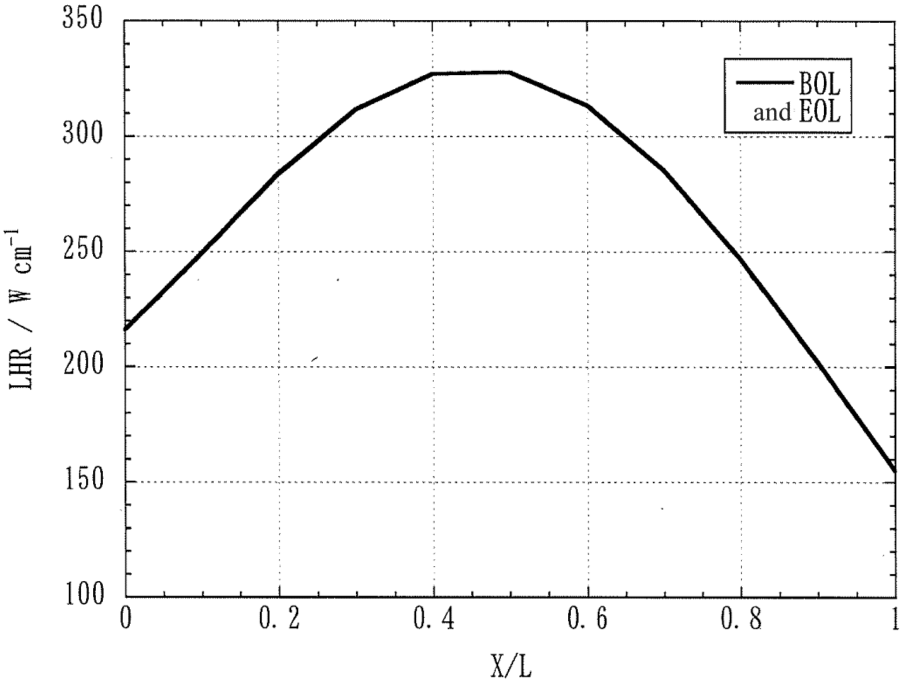


Fig.3 Axial distribution condition of LHR

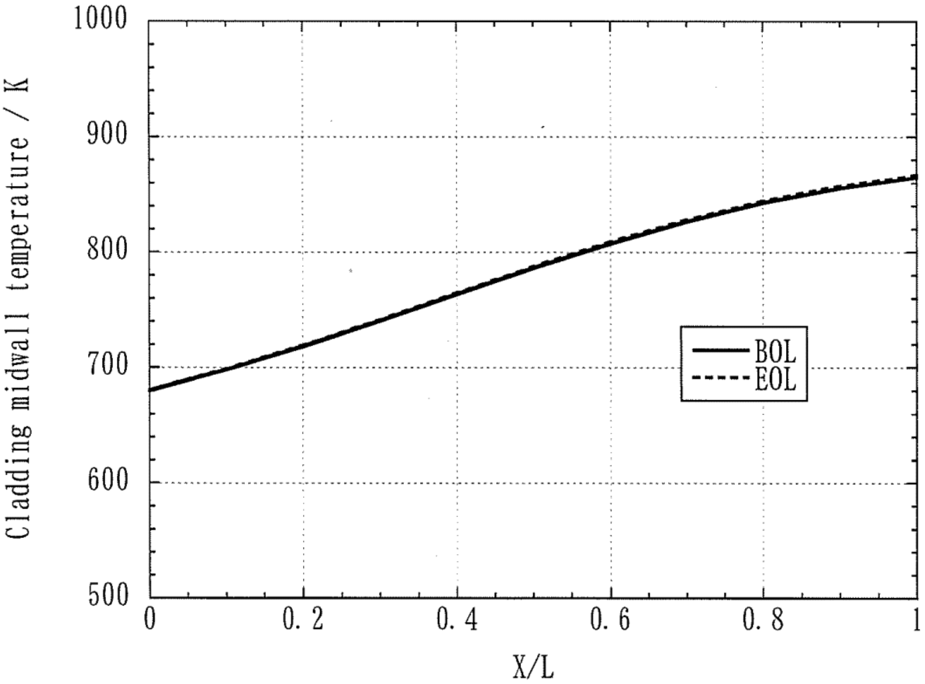


Fig.4 Axial distribution condition of cladding midwall temperature

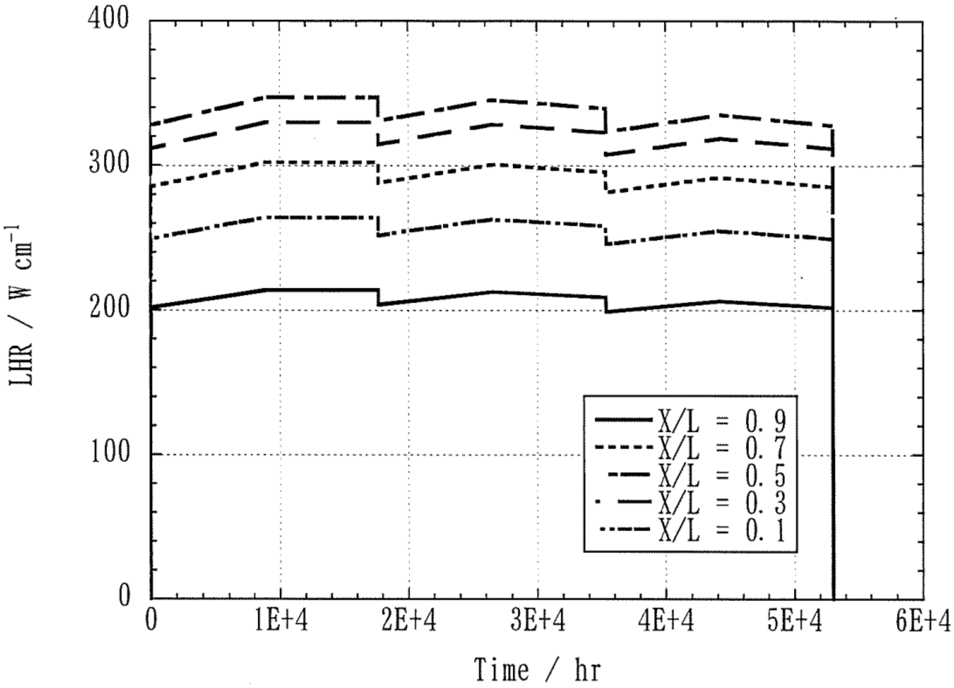


Fig.5 Profile condition of LHR

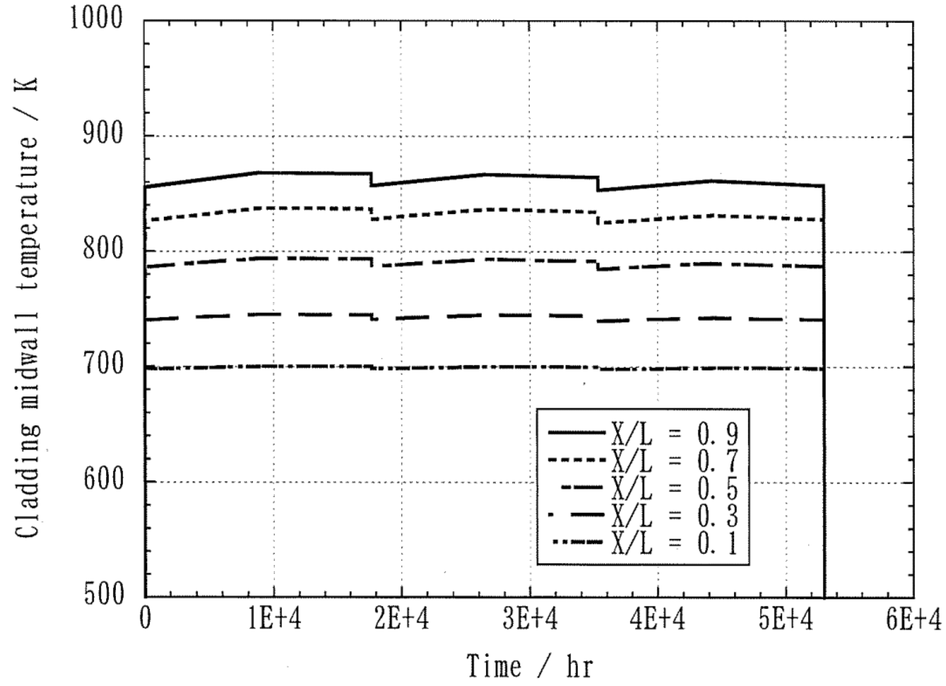


Fig.6 Profile condition of cladding midwall temperature

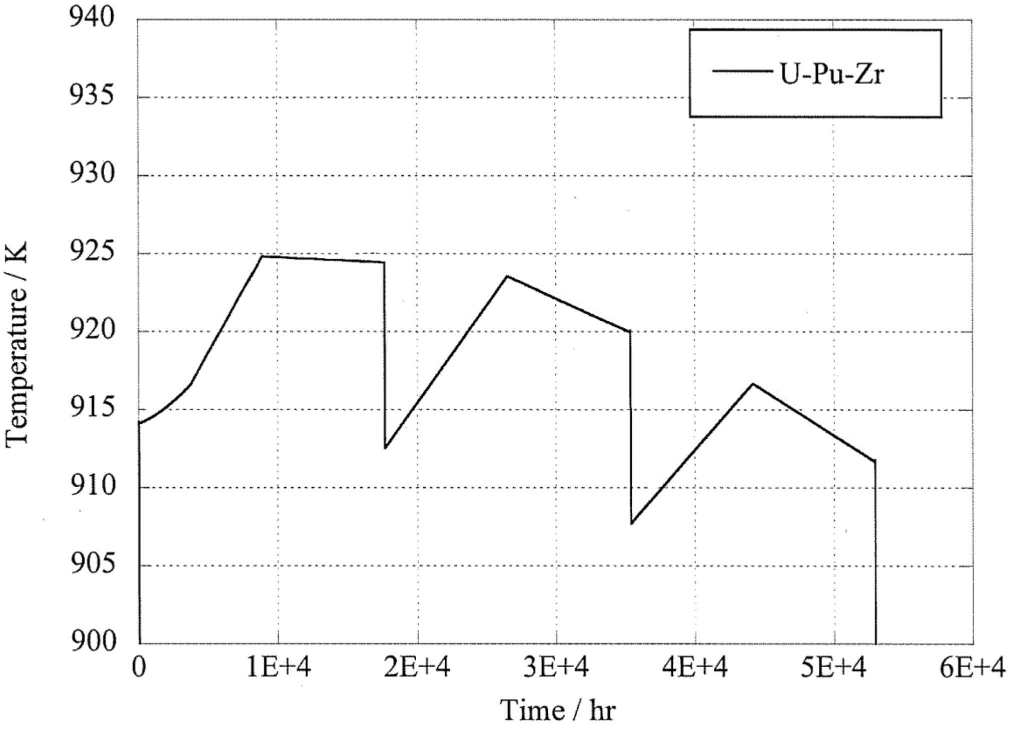


Fig.7 History of fuel centerline temperature at X/L=0.5 and 0.7, effective thermal conductivity model without sodium ingress into the fuel

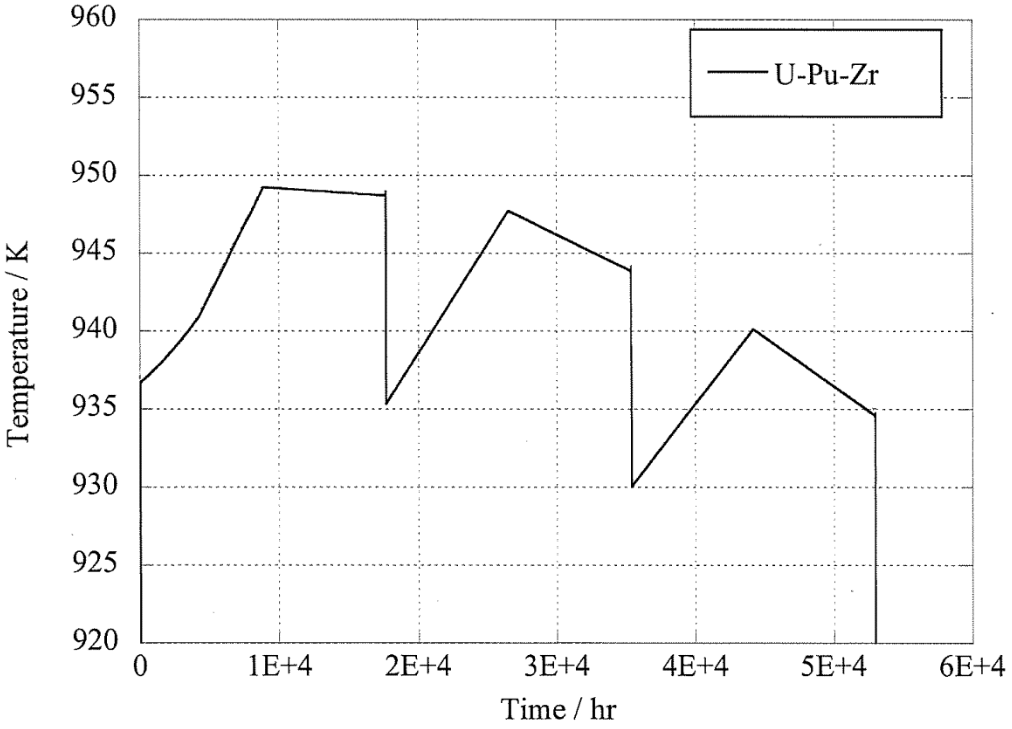


Fig.8 History of fuel centerline temperature at X/L=0.5 and 0.7, effective thermal conductivity model with sodium ingress into the fuel

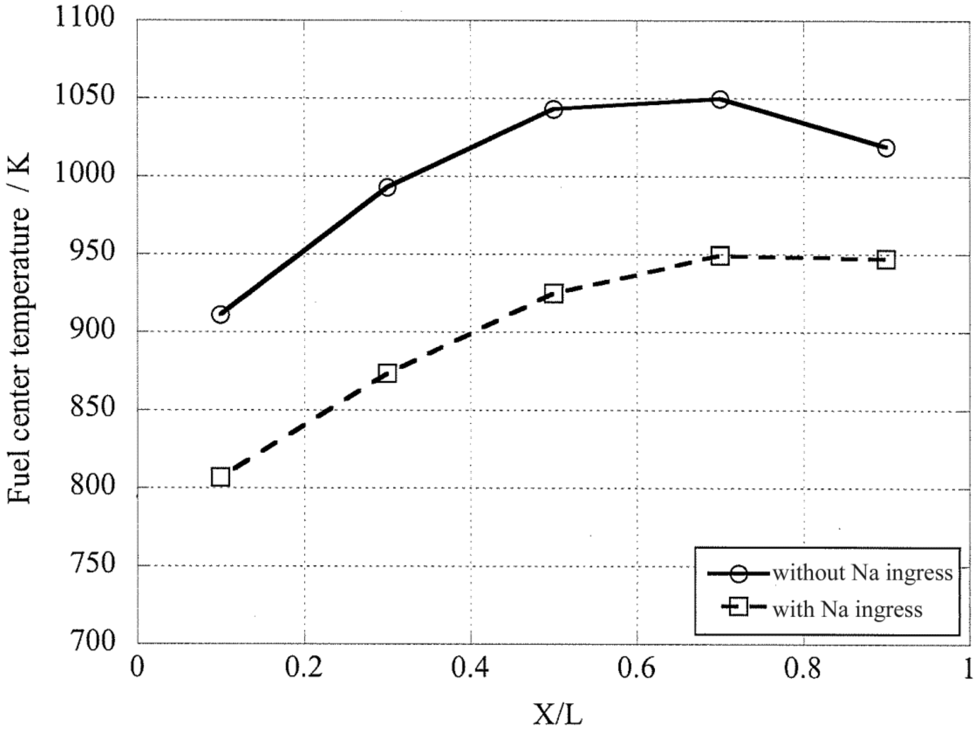


Fig.9 Axial distributions of U-Pu-Zr fuel centerline temperatures at the maximum power in steady state irradiation (8856h)

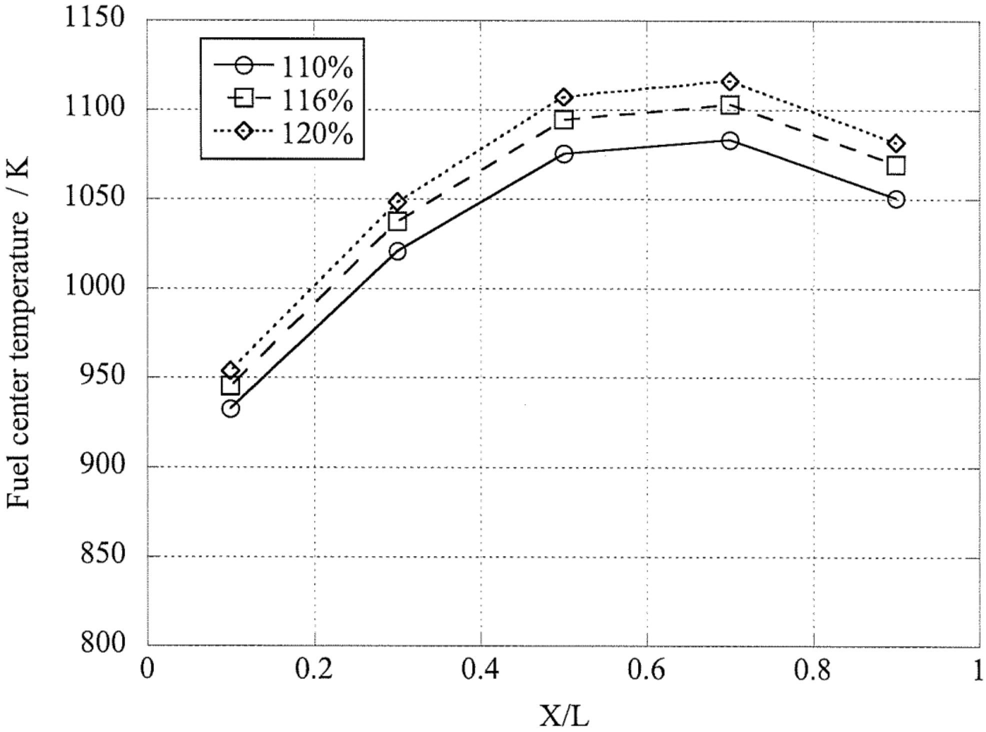


Fig.10 Axial distributions of U-Pu-Zr fuel centerline temperatures at 110, 116, 120% overpower conditions, effective thermal conductivity model without sodium ingress into the fuel

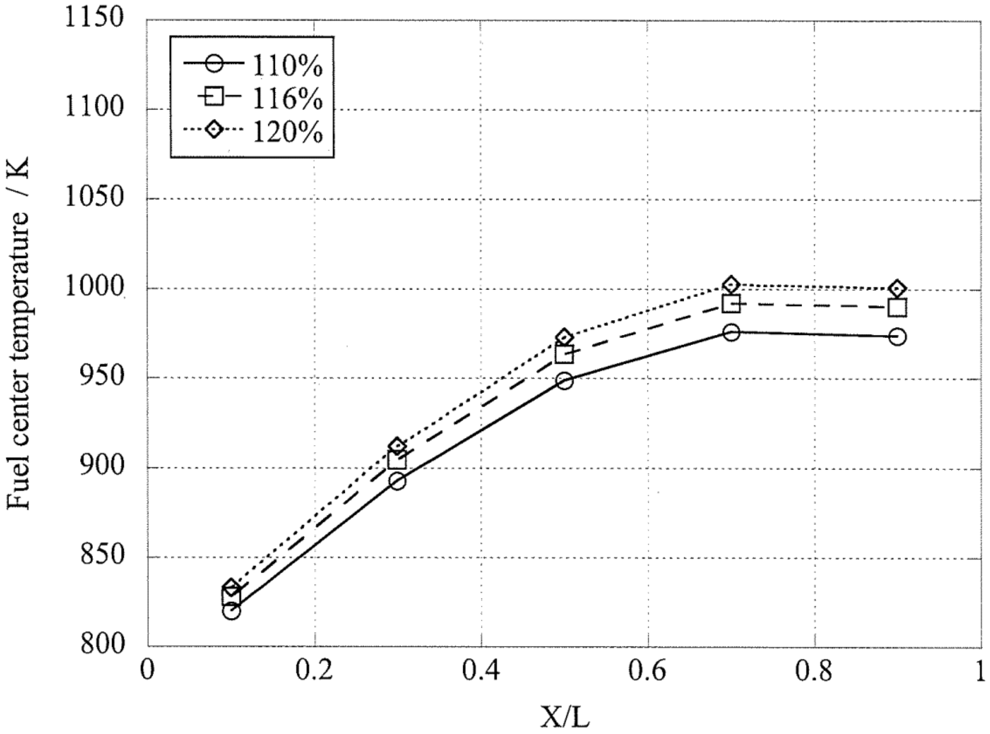


Fig.11 Axial distributions of U-Pu-Zr fuel centerline temperatures at 110, 116, 120% overpower conditions, effective thermal conductivity model with sodium ingress into the fuel