A Design Study of High Breeding Ratio Sodium Cooled Metal Fuel Core without Blanket Fuels*

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Abstract

The metal fuel core is superior to the mixed oxide fuel core because of its high breeding ratio and compact core size resulting from hard neutron spectrum and high heavy metal densities. Utilizing these characteristics, a conceptual design for a high breeding ratio was performed without blanket fuels. The design conditions were set so a sodium void worth of less than 8 \$, a core height of less than 150 cm, the maximum cladding temperature of 650 °C, and the maximum fuel pin bundle pressure drop of 0.4MPa. The breeding ratio of the resultant core was 1.34 with 6wt% zirconium content fuel. Applying 3wt% zirconium content fuel enhanced the breeding ratio up to 1.40.

Key words: Sodium Cooled Fast Reactor, Metal Fuel Core, Breeding Ratio, Zr-Content, Bundle Pressure Drop, Sodium Void Worth, Nuclear Reactor, Nuclear Energy, Nuclear Engineering

1. Introduction

A sodium-cooled fast breeder reactor (SFR) core using metal fuel is one of the promising candidates for advanced SFR core concept, because it has several advantages to the mixed oxide fuel core, *i.e.*, a small inventory and a high breeding ratio resulting from hard neutron spectrum and high heavy metal densities. On the contrary, the maximum cladding temperature with metal fuel is limited due to cladding compatibility concerns, which forces limitations upon the core outlet temperature.

In order to overcome the disadvantage, JAEA has carried out a conceptual metal fuel core design study⁽¹⁾⁽²⁾ to achieve an identical core outlet coolant temperature with that of the mixed oxide fuel core as a part of the Fast reactor Cycle Technology development project (FaCT)⁽³⁾. In the FaCT project, the conditions of the core design have been determined from the viewpoints of near-future feasibility of the fast breeder reactor systems, that is, they have been given from the practical fuel specifications based on the present irradiation test results, the plant design requirements, and the SFR deployment scenario in Japan.

However, the fuel specifications could be more flexible by accumulating irradiation test results in future, by considering other possible SFR deployment scenarios, and so on. Setting the design conditions more flexibly, it is expected that there may be many attractive concepts that characterize the merits of the metal fuel cores, such as high breeding ratio, small fuel-inventory, compact core size, low sodium void worth (hereinafter, void worth),

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high transmutation rate of the minor actinides (MA) and so on. For example of the conceptual high breeding ratio core designs, Riyas *et al.* reported the breeding ratio of 1.61 with the radial and axial blanket fuels⁽⁴⁾. The breeding ratio consisted of the internal conversion ratio of 1.12 and the external of 0.49. Dubberley *et al.* reported a high internal conversion ratio of 1.05 and the breeding ratio of 1.22 with axial blanket fuels⁽⁵⁾. A conceptual high breeding ratio core design without blanket fuels may be as a basic concept for the higher breeding ratio core design with blanket fuels. It also has other interests, when compared with those concepts with blanket fuels, such as the simplification of pyrometallurgical reprocessing system.

In the present paper, we concentrate to study the conceptual high breeding ratio core design without blanket fuels by setting the design conditions flexibly. The present conceptual core design is aimed to specialize in high breeding ratio. The small fuel inventory, low void worth and high MA-transmutation core designs will be reported in future papers, and the merits and demerits among them will be discussed.

2. Design Conditions

The design conditions in the present study are shown in Table 1. The maximum core height was given from the viewpoint of protection from creep deformation under the fuel slug's own weight. The value was set as a tentative value based on the irradiation test results of 124.4 cm-length fuel pins at ANL⁽⁶⁾. The outer diameter of the fuel pins was based on manufacturing and irradiation test results. The Zr-content of the fuel was basically set at the same range as in the FaCT project, 6 – 10 wt%. The 3wt% zirconium content fuel⁽⁷⁾ reported by Crawford *et al.* was dealt with as an optional condition. The fuel transuranium (TRU) isotopic composition is based on the metal fuel fast reactor core equilibrium after the multi recycling of the metal fuel core.

Table 1 Current core design conditions

Item		Design conditions
Plant Spec.	Core thermal output	3,530 MWt
	Core coolant flow rate	18,000 kg/s
Advanced Fuel Spec.	Fuel type	U-TRU-Zr alloy
	Fuel TRU composition	Metal fuel FBR multi-recycle*1
	Fuel pin outer diameter	< 8.5 mm
	Fuel Zr-content	3 ~ 14 wt%
	Core height	< 150 cm
	Spacer wire diameter	> 0.8mm
Flexible Conditions	Breeding ratio	As high as possible
	Core outlet/inlet temperature	Design output
	Operation cycle length	Design output
	Maximum fast neutron*2 fluence	5x10 ²³ n/cm ²
	Void worth	< 8 \$
	Bundle pressure drop	< 0.4MPa
	Maximum cladding temperature	< 650 °C
	Cladding hoop stress	< 120MPa

*1 ²³⁸Pu/²³⁹Pu/²⁴⁰Pu/²⁴¹Pu/²⁴²Pu/²³⁷Np/²⁴¹Am/²⁴³Am/²⁴⁴Cm/²⁴⁶Cm
= 1.1/66.0/25.2/2.4/2.4/0.4/1.6/0.5/0.4/0.1

*2 E > 0.1 MeV

In the present design, we consider thermal-hydraulic and fuel integrity conditions. The maximum fast neutron fluence and the maximum cladding temperature have been given as a target value of the ODS-steel claddings in the FaCT project. The core inlet and outlet temperatures were design outputs and allowed to be lower than those of the FaCT metal fuel core in order to satisfy the maximum cladding temperature. It is because the power swing

is expected larger as the breeding ratio becomes large. As the fuel integrity conditions, cladding hoop stress was set less than 120MPa, so the gas plenum length was given by taking into consideration of the inner pressure of the maximum burnup fuel pin.

In order to construct a design of the core consisting of the large fuel volume ratio subassemblies of long fuel pins, the bundle pressure drop condition was set as 0.4 MPa. It was determined from the roughly estimated value of the maximum bundle pressure drop of the prototype reactor MONJU. The bundle pressure drop was estimated by the MIT formula⁽⁸⁾. Flow rate of the peak power subassembly was estimated to satisfy the maximum cladding temperature.

The maximum void worth was given from the viewpoint of preventing the super-prompt criticality in the initiation phase of core disruptive accident caused by the unprotected loss of flow (ULOF) accident. The envelope diameter of shielding region and the operating cycle length were design outputs.

For convenience of discussion in the present study, Fig. 1 shows the configurations of the FaCT metal fuel core with high reactor outlet temperature. The core consists of 2-radial regions without blanket fuels and its breeding ratio is 1.03. There are 150 and 495 subassemblies in the inner and the outer cores, respectively. The fuel Zr-content of the inner core was 10 wt% and the outer core was 6 wt%. The Pu-enrichment is common to both cores (hereinafter Pu-enrichment 1-region core). The core outlet temperature is 550 °C, which was obtained by a reduction of the radial peaking factor, and by creating a stable power profile.

**Figure 1 Configurations of the FaCT metal fuel core
(high reactor outlet temperature type)**

3. Conceptual High Breeding Ratio Core Design

3.1 Tentative Core Design

In order to obtain a high breeding ratio, the tentative core specifications were selected so that the neutron leakage is as small as possible. That is, a core height of 150 cm and a wire wrapped spacer diameter of 0.80 mm were selected. The Pu-enrichment and the operation cycle length were adjusted so that maximum of the fast neutron fluence was approximately 5×10^{23} n/cm² and that the minimum of the effective multiplication factor was not too small. All other specifications were the same as those for the FaCT core.

Table 2 shows major specifications and characteristics of the tentative and the FaCT cores. The breeding ratio of the tentative core was much larger than that of the FaCT core, 1.32, without blanket fuels. The void worth was approximately 7.5 \$, which satisfied the void worth condition. The operation cycle length was approximately 840 days, approximately 1.1 times longer than that of the FaCT core. The discharge burnup was

approximately 54 GWd/t. The radial peaking factor was 1.94, which was approximately 50% larger than that of the FaCT core. This indicates that the radial power distribution was not flattened in the tentative core. With the exception of the bundle pressure drop, the tentative core design satisfied the conditions in Table 1. The pressure drop was 1.06 MPa. Therefore, for the construction of the conceptual high breeding ratio core design, it was found that the tentative core had to be adjusted so that the pressure drop would be less than 0.4 MPa.

Table 2 Major specifications and characteristics of tentative and FaCT cores

Item	Unit	Tentative core	FaCT metal fuel core
Core height	cm	150	75
Zr-content (Inner core/outer core)	wt%	10.0/6.0	
Spacer wire diameter	mm	0.80	1.00
Operation cycle length	days	840	745
Pu-enrichment	wt%	8.7	12.2
Breeding ratio	–	1.32	1.03
Discharge burnup	GWd/t	53.8	96.6
Pu-fissile inventory	t/GWe	6.8	4.7
Maximum linear heat rating	W/cm	259	347
Void worth	\$	7.52	6.15
Peak bundle power	MW	10.6	7.3
Bundle pressure drop	MPa	1.06	0.22
Core outlet temperature	°C	532	550

In order to reduce the bundle pressure drop under the condition of a 150 cm-height core, we considered two manners; to reduce the peak fuel pin bundle power (hereinafter peak bundle power) and to enlarge the flow area. For reduction of the peak bundle power, we considered 1) applying the Pu-enrichment 2-region core, 2) adjusting the subassembly number ratio between the inner and outer cores, and 3) increasing subassembly number.

For the 2-region core, the Zr-content of the fuels was set as 6 wt% in both the inner and the outer cores. It is because the lower Zr-content fuel is preferred to obtain higher breeding ratio due to its higher heavy metal densities. The Pu-enrichment was determined so that the maximum linear heat rating of the inner core was nearly equal to that of the outer core. In Sec. 3.2, the better core type for the high breeding ratio core will be chosen between Pu-enrichment 1-region core or the 2-region one with the Zr-contents of 6-10wt%. Application of the 3 wt% Zr-content fuel will be considered to the better core type.

3.2 Effect of the Subassembly Number Ratio between Inner and Outer Cores

The neutronic characteristics of the Pu-enrichment 1-region and 2-region cores were discussed with the subassembly number ratio between the inner and the outer cores parametrically changed. The results are shown in Fig. 2.

As the subassembly number ratio becomes larger, the breeding ratio decreases. Although the breeding ratio of the Pu-enrichment 1-region core is a slightly larger than the Pu-enrichment 2-region core, the difference is small.

The dependence of the void worth is, however, different between the 1-region and 2-region cores. For the 1-region core, the Zr-content of the inner core is larger than that of the outer core. The core averaged zirconium content increases with the subassembly number ratio, and the void worth increases. On the other hand, for the 2-region core, the void worth is nearly constant because the core averaged zirconium content is independent of the subassembly number ratio. Therefore, the dependence of the void worth is different.

The discharge burnup of the Pu-enrichment 1-region core is less than 55 GWd/t, although that of the 2-region core is approximately 70 GWd/t. This indicates that the

radial power distribution of the 2-region core is more flattened than that of the 1-region core, as shown in Fig. 3. In the 1-region core, the maximum power density in the inner core is 20% larger than that of the outer core. While in the 2-region core, the maximum power density in the inner core is nearly equal to that in the outer core.

Figure 2 Effect of subassembly number ratio upon core characteristics
(wire diameter = 0.85 mm)

Figure 3 Radial distribution of power density

The operation cycle length was set so that the maximum of the fast neutron fluence would be approximately 5×10^{23} n/cm². Because of the difference of the radial power distribution, the operation cycle length of the 2-region core is much longer than that of the 1-region core. The operation cycle length of the 1-region core takes the maximum of 850 days at a subassembly number ratio of 0.30. That of the 2-region core is more than 1,000 days and it increased with the subassembly number ratio.

The bundle pressure drop of the 2-region core is smaller than that of the 1-region core. It is because the peak bundle power of the 2-region core is smaller. Although there were no results satisfying the bundle pressure drop condition, it was found that the Pu-enrichment 2-region core was more adopted for reduction of the peak bundle power and the bundle pressure drop than the Pu-enrichment 1-region core. Therefore, the Pu-enrichment 2-region core was selected for the conceptual high breeding ratio core design.

3.3 Effect of Subassembly number and Wire Diameter

As the subassembly number becomes larger, the peak bundle power and the bundle pressure drop decrease. Because the void worth increases with the subassembly number, the maximum wire diameter is reduced as the subassembly number becomes larger. Therefore, the wire diameter was also changed parametrically. The results are shown in Fig. 4. In the survey, the neutron fluencies and the core thermal output were fixed, so the power densities decrease as the subassembly number increases.

The breeding ratio increases slightly as the subassembly number becomes larger. For the 819 subassembly cores, the breeding ratio is approximately 1.33, while for the 645 subassembly cores, it is approximately 1.31.

The void worth increases with the subassembly number. The maximum wire diameter becomes smaller as the subassembly number increases. For the 645 subassembly core, the void worth condition was satisfied with 0.95 mm-diameter wire, while for the 819 subassemblies core, the maximum value of the wire diameter was 0.90 mm.

Figure 4 Effect of wire diameter upon core characteristics

The radial peaking factor is independent on the subassembly number. It means the peak bundle power decreases with the subassembly number. Therefore, the bundle pressure drop also decreases. The bundle pressure drop of the 819 subassembly core with 0.90 mm-diameter wire is 0.36 MPa.

Because there is a margin in the bundle pressure drop of the 819 subassembly core with 0.90 mm-diameter wire, we considered to apply the smaller diameter wire and to reduce the subassembly number. From Fig. 4 (c), the bundle pressure drop of 819 subassembly core is expected to be 0.4 MPa with 0.85 mm-diameter wire. In order to find the minimum subassembly number to satisfy the bundle pressure drop condition efficiently, dependence of the bundle pressure drop upon the subassembly number was roughly estimated as shown in Fig. 5. From the figure, it is found that the bundle pressure drop is 0.4 MPa as the subassembly number is approximately 770.

Figure 5 Rough estimate of bundle pressure drop

Table 3 lists the characteristics of these candidates. The breeding ratio of the 765 subassembly core with 0.90 mm-diameter wire is nearly equal to that of 819 subassembly core with 0.85 mm-diameter wire core; however, the Pu-fissile inventory of 765 subassembly core is 5% smaller. Therefore, the 765 subassembly core was found to be the best high breeding ratio core.

Table 3 Comparison of characteristics between candidates of high breeding ratio cores

Item	Unit	Applying 0.85 mm diameter wire	Reduction of S/A number
Number of S.A.	–	819	765
Wire diameter	mm	0.85	0.90
Refueling batch	–	3	
Breeding ratio	–	1.33	1.32
Discharge burnup	GWd/t	65.9	66.4
Burnup reactivity	% $\Delta k/kk'$	–4.9	–4.8
Pu-f inventory	t/GWe	8.4	7.9
Core equivalent diameter	m	5.8	5.6
Sodium void worth	\$	7.7	7.9
Core outlet temperature	°C	516	516
Bundle pressure drop	MPa	0.40	0.40

3.4 Effect of Refueling Batch

In the previous section, the 765 subassembly core was selected as the best of the high breeding ratio core. Because the absolute value of the burnup reactivity is large, it should be improved by an increase of refueling batch. The power swing was expected to decrease and the core outlet temperature was expected to increase.

Figure 6 shows the effect of the refueling batch. In the survey shown in Fig. 6(a) – (e), the major core specifications were fixed except for the refueling batch and the operation cycle length. The subassembly number ratio between the inner and the outer cores was adjusted in Fig. 6 (f).

By an increase of the refueling batch from 3 to 6, the breeding ratio increases from 1.32 to 1.35. Although the void worth is slightly increased, the void worth condition is satisfied. By the increase of the refueling batch, the absolute value of the burnup reactivity is reduced. The core outlet temperature increases from 516 °C to 520 °C; however, the bundle pressure drop also increases. Hence, it was necessary to adjust the subassembly number ratio in order to satisfy the bundle pressure drop condition. Figure 6(f) shows dependence of the bundle pressure drop, it was found that the bundle pressure drop condition is satisfied as the subassembly number ratio is 0.46. The breeding ratio of the adjusted core was 1.34, the Pu-fissile inventory 7.6 t/GWe, and the core outlet coolant temperature 519°C. Thus, this was selected as the resultant high breeding ratio core with 6 wt% Zr-content fuel. Figure 7 shows R-Z model of the resultant high breeding ratio core.

Figure 6 Effect of Refueling batch upon core characteristics

Figure 7 R-Z model of the resultant high breeding ratio core

3.5 Specifications of High Breeding Ratio Core

Table 4 shows the major specifications and the characteristics of the resultant high breeding ratio core without blanket fuels. In the table, those of the core adopting 3wt% Zr-content fuel are also listed. The specifications of the 3 wt% Zr-content fuel core are obtained by replacing the fuel Zr-content from 6 wt% to 3 wt% and by adjusting the subassembly number ratio between the inner and outer cores for satisfying the bundle pressure drop conditions.

By adopting the 3wt% Zr-content fuel, the breeding ratio is enhanced up to 1.40. It is because the Pu-enrichment of the 3wt% Zr-content fuel is lower than that of the 6wt% Zr-content fuel due to its higher heavy metal densities. Although the Pu-enrichment of the 3wt% Zr-content fuel core is lower, the Pu-f inventory is almost the same as that of the 6wt% Zr-content fuel core. It is because the higher heavy metal densities of the 3 wt% Zr-content fuel.

Although the Pu-enrichment 1-region core may satisfy the design conditions by adopting 3 wt% Zr-content fuel, the Zr-content of the inner core must be larger than 3wt%. Therefore, the Pu-enrichment 1-region core adopting 3wt% Zr-content fuel is not expected better than the Pu-enrichment 2-region core in the right hand side column in Table 4.

Table 4 Major specifications and characteristics of high breeding ratio cores

Item	Unit	Highest breeding ratio core	
		6 wt% Zr-content fuel	3 wt% Zr-content fuel
Fuel Zr-content (IC/OC)	wt%	6.0/6.0	3.0/3.0
Fuel Pin Outer Diameter	mm	8.5	
Spacer Wire Diameter	mm	0.90	
Core Hight	cm	150	
S.A. Number (IC/OC/total)	–	240/525/765	276/489/765
Refueling Batch	–	6	
Core Thermal Output	MWth	3530	
Operation Cycle Length	days	650	680
Fuel Pu-enrichment (IC/OC)	wt%	7.4/8.3	6.9/7.6
Breeding Ratio	–	1.34	1.40
Burnup Reactivity	%Δk/kk'	–2.8	–3.3
Discharge Burnup	GWd/t	68.5	65.7
Pu-fissile Inventory	t/GWe	7.6	7.6
Sodium Void Worth	\$	8.0	7.6
Core Outlet Temperature	°C	519	515
Bundle Pressure Drop	MPa	0.39	0.39
Hoop Stress	MPa	112	112

4. Conclusion

An attractive metal fuel core concept of high breeding ratio core without blankets was established taking into consideration of thermal-hydraulic and fuel integrity conditions. In order to pursue for the breeding capability of the metal fuel core, the design conditions were flexibly set on the basis of the recent fuel irradiation test results.

In order to satisfy the conditions on the bundle pressure drop of < 0.4 MPa and the void worth of < 8 \$, the Pu-enrichment 2-region core was more adopted than the Pu-enrichment 1-region core. The 765 subassembly core with 0.90 mm-diameter wire was selected as the high breeding ratio core design with the Zr-content 6 wt% fuel. Its breeding ratio was 1.34. By adopting 3wt% Zr-content fuels, the breeding ratio was enhanced up to 1.40.

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