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LMFBR Design and its Evolution: (1) Fuel Design of LMFBR

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Current LMFBR fuel design study for future system in Japan aims at achieving high burnup and high outlet temperature to get advantages of economics and resource utilization. Primary fuel integrity limiting features of such design study are core material dimensional stability, high temperature cladding strength, and fuel smeared density. In the current fuel design study, ferritic steels, Oxide Dispersion Strengthened(ODS) ferritic steel cladding and PNC-FMS ferritic-martensitic steel sub-assembly duct, are selected as reference because of its possible stability at high neutron dose corresponds to high burnup. Feasible fuel design is achieved by such core material selection, fuel smeared density definition and design evaluation with appropriate design margin.

Effort to realize the excellent performance of LMFBR fuel design will be continued through such fuel design study work.

KEYWORDS:LMFBR, Fuel design, Oxide fue1, Metal fuel, Ferritic steel, High burnup

I. Introduction

The advanced core for the next generation is considered to be a core with superior characteristics in safety, economics, resource utilization, environmental burden reduction, and proliferation resistance. Fast reactors are promising concepts to satisfy these demands with engineering consistency. Current LMFBR fuel design study for future system in Japan aims at achieving high burnup and high outlet temperature to get advantages of economics, resource utilization etc. High burnup concept reduces amount of recycle fuel for unit electric power generation. This reduces fuel cycle cost and demand of capacity of fuel recycle facilities such as fuel fabrication facility and fuel reprocessing facility. High outlet temperature concept gives high thermal efficiency in power conversion. An LMFBR core design for high burnup and high outlet temperature gives challenging condition of fuel design.

The objective of LMFBR fuel design is to realize the maximum fuel and core performance for high burnup and high outlet temperature concept in consistent with fuel integrity and reliability. The fuel design attains the objective by applying the knowledge and technology related to fuel specification determination, fuel design criteria, and fuel design evaluation.

The present paper describes examples of such fuel design effort in oxide fuel core and metal fuel core.

II. Typical designs

The sodium cooled oxide fuel core concepts and metal fuel core concepts are under investigation as a part of the Feasibility Study on Commercialized Fast Reactor Cycle System in Japan.[1)] Typical designs are indicated below.

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1. Oxide fuel core design

A preliminary conceptual design study of sodium-cooled oxide fuel core has been performed to establish medium scale advanced core concepts. A medium scale sodium-cooled oxide fuel core is one of the attractive concepts of commercialized fast reactor core in view of flexibility in increasing reactor vessel size within an acceptable level.

(1) Oxide Fuel Core Design Conditions

The 750MWe core design study is performed in viewpoints of core neutronic performance and thermal hydraulics. Major core design conditions are as follows:

- Core thermal output : 1785MWth
- Core outlet/inlet temperature : 550/395°C
- Fuel pin bundle pressure drop : 0.2MPa
- Fuel burnup (discharge average) : 150GWd/t

High burnup and high outlet temperature targets are specified as 150GWd/t and 550°C of core outlet temperature in the present design.

The thermal output corresponds to 750MWe of plant electricity output under the 550°C of core outlet temperature. The core outlet temperature of 550°C is the maximum acceptable temperature under the condition of cladding maximum temperature as 700°C with engineering uncertainties. The bundle pressure drop is as low as 0.2MPa and this contributes the natural circulation capability of plant primary system.

TRU isotopic composition is indicated below, which corresponds to the composition of oxide fuel fast reactor core equilibrium cycle after the multi recycle of the core fuel.

TRU isotopic composition :
Pu238/239/240/241/242/ Np237/Am241/243/Cm244
=1.1/54.1/32.1/4.3/3.9/ 0.5/2.0/1.0/1.0

Fission product content of as-fabricated fuel is assumed to be 2 vol.%, that corresponds to the low decontamination factor reprocessing application.

As regards the fuel pin design conditions, maximum fuel pin linear power and fuel smeared density are common value as 430W/cm and 82%TD, respectively.

Cladding and sub-assembly duct materials are ODS(Oxide dispersion strengthened) martensitic steel[2)] and PMC-FMS(ferritic/martensitic steel[3)] which withstand neutron dose of high burnup fuel. In the present design study, tentative limit value of fast neutron dose is selected as around 5×10^{27}n/m^2(E>0.1MeV), which corresponds to around 250 dpa and to the target of current irradiation tests planed in Japan for these materials.

A target of breeding capability is break even breeding without radial blankets. This aims at reducing fuel cycle cost by achievement of high internal conversion ratio. A core with high internal conversion ratio has a potential to attain breeding break even without radial blankets, which lead to low fuel cycle cost. The present design study is directed to large fuel pin diameter as one of the most effective ways of achieving high internal conversion ratio.

(2) Oxide Fuel Core Specifications and Characteristics

Table 1 shows the major core specifications and characteristics. Figure 1 shows the core configuration. As shown in Table 1, the core studied here is feasible under the condition of 150GWd/t of discharge average burnup, around 18 months of operation cycle length and given bundle pressure drop. The peak neutron dose is around 5×10^{27}n/m^2(E>0.1MeV). The core reveals break even breeding capability without radial blankets. Coolant void reactivity is limited as low as 5.5$ with the core fuel column length of 1m, which are reasonable values from the core safety viewpoints. The core concept here has a potential for reasonable achievement of target burnup and breeding capability. Some important characteristics should be discussed. The fuel pin diameter of around 10mm, which is larger than a conventional value, makes a contribution to high internal conversion ratio as 0.82 which attains break even breeding capability without radial blankets. This feature also indicates that the replacement of part of radial shielding assemblies with radial blankets can meet the requirement for higher breeding capability such as 1.2. In other words, the core studied here has flexibility for requirement for breeding capability with little influence on core and fuel specifications.

A potential of around 26 months of operation cycle length, which is quite longer than the target length, is achieved by the high internal conversion ratio. This feature is advantageous to improving operation rate and power cost.

As no radial blankets are loaded, as much as 100GWd/t of burnup averaged over core and blanket regions (hereinafter referred to as average burnup) is achieved, which is invaluable to improvement of fuel cycle cost.

Table 1 Specifications and characteristics of 750MWe MOX fuel core

Items	Values
Specifications	
Operation cycle length (EFPM)	26
Fuel reload batch (batches)	4
Core diameter (m)	3.7
Core column length (m)	1.0
Axial blanket length (top/bottom) (cm)	30/30
Fuel pin diameter (mm)	10.4
Fuel pins (pins/[S/A])	217
Fuel smeared density (%TD)	82
Fuel volume fraction (%) (100% dens.fuel)	37.6
Subassembly pitch (mm)	186.1
Characteristics	
Pu enrichment (Pu/HM) (%)	21.0*
Discharge burnup (GWd/t)	
averaged over core	149
averaged over core + blanket	101
Burnup reactivity swing (%Δk/kk')	2.9
Breeding ratio (Core/Total) (--)	0.82/1.04
Core void reactivity ($)	5.5

* Average of inner and outer cores

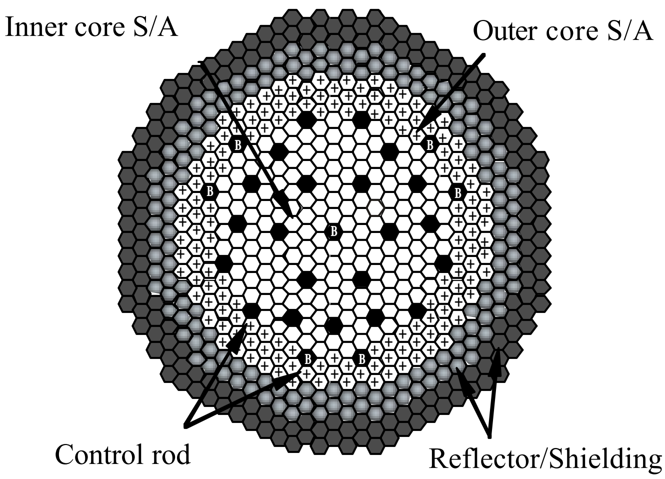

Fig. 1 Core configuration of 750MWe MOX fuel core

2. Metal fuel core design

A preliminary conceptual design study of sodium cooled metal fuel core has been performed to establish high outlet temperature core concept with metal fuel. Metal fuel has a cladding temperature limit lower than that of oxide fuel due to fuel cladding compatibility concerns. Therefore, the target core outlet temperature identical with that of oxide core is a challenge of metal fuel core design study.

(1) Metal Fuel Core Design Condition

The 500MWe core design study is performed in viewpoints of core neutronic performance and thermal hydraulics. Major specifications are selected as indicated below.

- Core thermal output : 1,190MWth
- Core outlet/inlet temperature : 550/395°C
- Fuel pin bundle pressure drop : 0.2MPa
- Fuel : U-TRU-Zr (10wt.%)

Cladding and sub-assembly duct materials are ODS and PNC-FMS, same as those of oxide fuel. As regards the burnup, the tentative limit of core material fast neutron dose is applied and corresponding burnup is evaluated.

Fuel smeared density is 75%TD and fuel composition including TRU isotopic composition is same as oxide core. Cladding maximum temperature is limited to 650°C due to metal fuel-steel cladding compatibility issues at high temperature.

Target core inlet and outlet temperatures are 395°C and 550°C, respectively, which are same as oxide core design.

(2) Metal Fuel Core Specification and Characteristics

Table 2 and Figure 2 show the major fuel specifications/ core characteristics and core configurations, respectively.

The core has three driver fuel regions and no axial and radial blanket. The three driver regions have individual fuel pin diameter with identical Pu enrichment as 14wt.% Pu/(U+Pu). Such core concept achieves stable radial power profile and low radial power peaking factor of the core.

Burnup reaches 107GWd/t with around 5×10^{27}n/m^2(E>0.1MeV) of fast neutron dose tentative limit. Refueling batch is selected as 4.4 batches in average of whole core with 18 months of operation cycle length. Bunrup reactivity swing is as low as 0.6% Δk/kk'. Core internal conversion ratio reaches 1.03 of breeding ratio with 107GWd/t of burnup and without axial and radial blanket.

The core requires thick outer core configuration to have a low radial power peaking factor. Figure 3 shows the radial power profile of the core. The radial power profile corresponds to low radial peaking factor and very stable even the core burnup is as high as 107GWd/t.

The thermal hydraulic design[4)] shows the possible achievement of 550°C of core outlet temperature with 650°C of cladding temperature, which is lower than 700°C of cladding maximum temperature in oxide core. This is due to stable radial power profile and low radial power peaking factor of the core described above and application of grid spacers in fuel pin bundle design.

Table 2 Major Specifications and Characteristics of 500MWe Na cooled metal fuel core

Core dia. /column length	**2.8m／100cm**
Fuel pins in S/A	**169 pins/ S/A**
Fuel pin diameter	**9.2/9.7/10.3mm***
Sub-assemblies	**58/60/138***
Pu enrichment	**14wt%**
Burnup reactivity swing	**0.6%Δ k/kk'**
Breeding ratio	**1.03**
Operation cycle length	**18 months**
Core refueling butch	**4.4 batches (ave.)**
Burnup (discharge ave.)	**107 GWd/t**
Core radial peaking factor (S/A power)	**1.3**
Max. neutron dose	**5.3×10^{27}n/m^2 (E>0.1MeV)**

* : inner / intermediate / outer cores

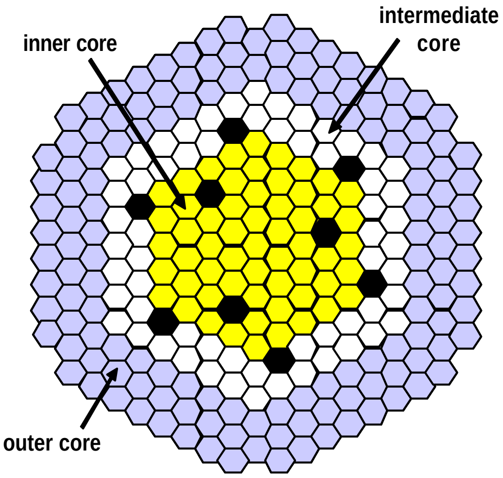

Fig. 2 500MWe 3 region(individual fuel pin diameters) core configuration

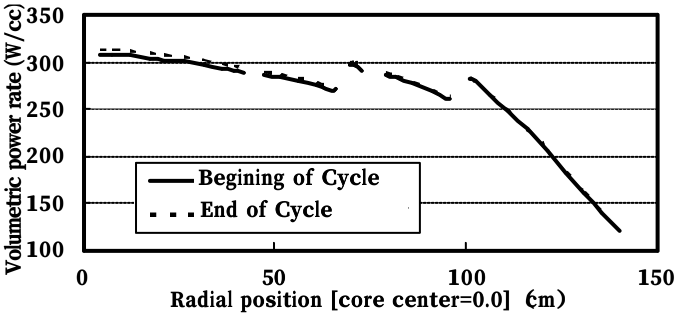

Fig. 3 Radial Power Profile of Core in figure 2

III. Fuel Design Consideration

Primary fuel integrity limiting features of LMFBR design study are core material dimensional stability, high temperature cladding strength, and fuel smeared density.

Each of them requires fuel design consideration such as fuel specification determination, fuel design criteria, and fuel design evaluation. Typical designs described above contain examples such consideration.

1. Fuel Specification Determination

Consideration of fuel specification determination provides possible ranges and options of various specification items such as core material and fuel density.

(1) Core Material

In a fast reactor core, core material dimensional stability is one of the most critical life limiting factors of fuel. This is due to the high fast neutron flux in the core. Fast neutron irradiation to the material causes significant deformation such as cladding diameter change and sub-assembly duct expansion due to void swelling and irradiation creep. In general, the void swelling has greater contribution to the deformation in high burnup condition or high neutron fluence condition. Therefore, application of fuel structural material with insignificant swelling up to high neutron fluence is essential to achieve high burnup.

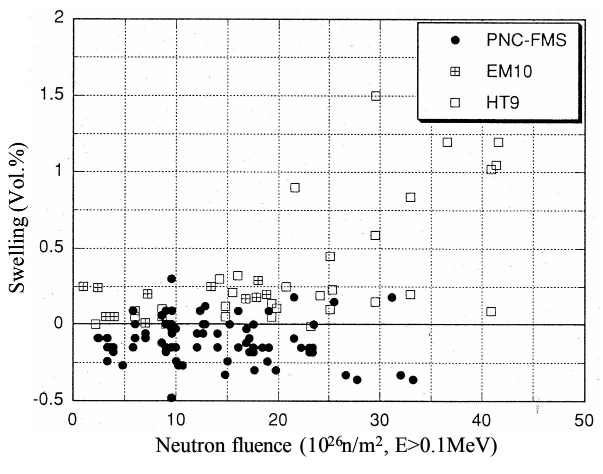

Fig. 4 Swelling of Ferritic Steels (384-688°C)

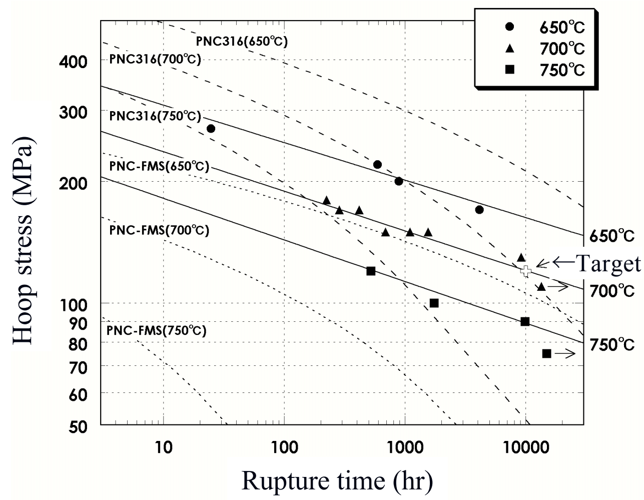

Fig. 5 Creep Rupture Strength of ODS Ferritic Steel (In air)

Ferritic steels are well-known as swelling resistant material. Figure 4 shows such characteristic of ferritic steels. The volume change due to swelling is insignificant in these ferritic steels. Among them, PNC-FMS reveals least swelling up to high neutron fluence condition. Selection of PNC-FMS as core material specification is reasonable in the high burnup fast reactor core design study.

Ferritic steel has disadvantage of low strength at high temperature. Fuel cladding temperature is higher than sub-assembly duct temperature in LMFBR core design. PNC-FMS is applicable to sub-assembly duct since the temperature range during irradiation is acceptable for strength of PNC-FMS. However, swelling resistant material with higher strength than PNC-FMS is required for cladding application. ODS is appropriate material for the cladding since it has both of high strength up to high temperature and swelling resistant characteristics due to oxide dispersion in the ferritic matrix. Figure 5 shows the excellent high temperature strength of ODS in comparison with conventional ferritic steels.

(2) Fuel density

Fuel smeared density is one of the primary specifications for high burnup fuel. Fuel Cladding Mechanical Interaction (FCMI) is fuel pin integrity limiting feature at high burnup. Fuel swelling becomes significant at high burnup and may cause severe FCMI. To accommodate such behavior, fuel specification of limited fuel smeared density is most effective measure. Accumulated experience of irradiation tests leads to the fuel smeared density specifications as 82%TD for oxide fuel and 75%TD for metal fuel in high burnup fuel design.

2. Fuel Design Criteria and Fuel Design Evaluation

As regards the fuel design criteria, there are two categories. One is fuel structural design criteria and material design base standard. The other is fuel design limits. The material design base standards of PNC-FMS and ODS have been established based on extended out-of-pile test data and limited irradiation test data. Accumulation of irradiation test data for those materials is in progress. Continual revision of material design base standards will be made as the high dose date become available. The fuel design limits are based on fuel irradiation behavior in tight connection with fuel integrity limiting features such as fuel melting and FCMI. They are available for current reactors and will be revised as high burnup data are accumulated.

The fuel design evaluation includes thermal and mechanical analyses which confirm the fuel integrity applying the fuel design criteria. As far as fuel design analytical methods are concerned, trial improvement such as statistical treatment of design parameter uncertainties is under investigation in design evaluation work of cladding high temperature integrity(thermal creep damage), cladding diameter change and sub-assembly duct expansion.

IV. Conclusion

Current LMFBR fuel design study for future system in Japan aims at achieving high burnup and high outlet temperature. Primary fuel integrity limiting features of such design study are core material dimensional stability, high temperature cladding strength, and fuel smeared density. In the current fuel design study, ferritic steels, Oxide Dispersion Strengthened(ODS) ferritic steel cladding and PNC-FMS ferritic-martensitic steel sub-assembly duct, are selected as reference because of its possible stability at high neutron dose corresponds to high burnup. The ODS ferritic steel is applied to cladding because of its superiority of high temperature strength. Feasible fuel design is achieved by such core material selection, fuel smeared density definition and design evaluation with appropriate design margin.

Effort to realize the excellent performance of LMFBR fuel design will be continued through such fuel design study work.

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