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ARTICLE

MA Transmutation Core Concept for a Metal-Fueled Sodium-Cooled Fast Reactor

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We have developed a conceptual framework for a minor actinide (MA) transmutation core for a metal-fueled sodium-cooled fast reactor (FR) that is suitable for a scenario in which light water reactors (LWRs) and FRs coexist. First, a target value was established for the amount of MA transmutation that would eliminate the transfer of MA to high-level radioactive waste (HLW) under the assumption of a coexistence scenario. Subsequently, a conceptual framework was established for a metal-fueled FR core that could achieve the desired MA transmutation target. MAs extracted from LWR spent fuels were loaded into the axial blanket (AB) in order to mitigate the impact of MAs on reactivity feedback. By setting the MA enrichment of the AB to 20 wt%, a transmutation amount of 185 kg/GWe/year was achieved, which satisfied the target. Ultimately, the fuel integrity during an unprotected transient over power (UTOP), was validated through transient analysis.

KEYWORDS: coexistence scenario, sodium-cooled fast reactor, metal fuel core, minor actinides (MAs), transmutation, sodium void reactivity, doppler coefficient, UTOP

1. Introduction

The core concept of transmuting minor actinides (MAs) using fast reactors (FRs) has been studied with the objective of reducing the toxicity of high-level radioactive waste (HLW). There are two primary methods: homogeneous recycling, in which MA is transmuted alongside Pu in the core fuel, and heterogeneous recycling,[1,2] in which MA oxide is loaded into target fuel assemblies situated in the core fuel region or at the periphery of the core. This results in two methods for MA loading in the metal-fueled FR core: homogeneous loading and heterogeneous loading. The maximum MA content for homogeneous loading is 4%, with a corresponding limit of 75 kg/GWe/year[3] for MA transmutation. Heterogeneous loading is the solution to increasing the transmutation amount. Taking into account the fact that stable U-MA-Zr alloy could not be manufactured metallurgically,[4] we studied an MA transmutation metal-fueled core in which U-Pu-MA-Zr alloy accompanied with Pu and MA was heterogeneously loaded into the axial blanket.

In France, a scenario was considered where light water reactors (LWRs) and fast reactors (FRs) coexist, assuming a continuous supply of natural uranium during the transition from LWRs to FRs. In this study, we assume a scenario in which LWRs and FRs coexist for a certain period during the introduction of FRs.[5] We evaluated a target value for the MA transmutation amount that would transmute all MAs produced in LWRs by metal-fueled FRs and prevent the generation of MA waste. We also developed a concept of a metal-fueled core to achieve this MA transmutation goal.

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II. Coexistence Scenario of LWRs and FRs

1. Coexistence Scenario

A number of issues must be considered when assuming the long-term use of LWRs in Japan, starting with the accumulation of spent fuels from MOX-fueled LWRs (LWR-MOX). This indicates that the capacity of spent fuel (SF) in pool and interim storage facilities is reaching its limit. Secondly, the Pu composition contained in the spent fuel of LWR-MOX is subject to degradation. When the Pu vector loaded in a LWR-MOX is degraded, the ratio of fissile Pu (Puf) to the total amount of Pu decreases. Conversely, the ratio of the amount of the parent nuclides (i.e., the amount of even-numbered Pu isotopes, such as Pu-240 and Pu-242) to the amount of total Pu increases. It is therefore necessary to determine how to burn the degraded plutonium extracted from the LWR-MOX spent fuel and restore the Pu isotope ratio in order to prevent the unnecessary accumulation of this material, which is difficult to use in FRs. It is also worth noting that the volume of high-level waste (HLW) produced by reprocessing LWR spent fuels is expected to increase. Thus, the processing and disposal of MA presents a significant challenge.

To address these challenges, we propose a coexistence scenario for LWRs and FRs, as illustrated in **Fig. 1**. The first step is to use the characteristics of metal fuel cores to restore the composition of plutonium recovered from LWR spent fuel. This allows for the recycling of plutonium in LWR-MOX, while preventing the unnecessary accumulation of plutonium. Secondly, all MAs produced from LWRs are transmuted in a metal-fueled FR. This will result in a reduction in the radiotoxicity of HLW.

Next, we determine the capacity for each reactor type in the coexistence scenario and set a target for transmuting MA in the FR. We then develop a metal-fueled core concept to achieve the MA transmutation goal.

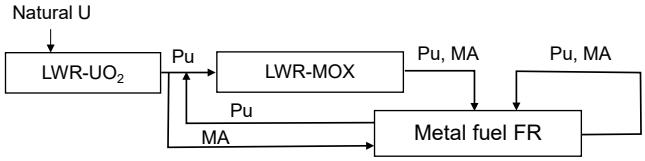


Fig. 1 Coexistence scenario with LWRs and metal-fueled FRs

2. Setting Capacity for Each Reactor Type in Coexistence Scenario

The following steps outline the procedure for developing a coexistence scenario:

The first step is to evaluate the fuel loading/discharged weight breakdown for each reactor type. **Table 1** provides a breakdown of fissile and fertile Pu, which have significantly different nuclear characteristics. We utilized specifications for two types of LWR fuel assemblies[6] and evaluated the annual data regarding the amount of Pu isotopes[7] produced (as a unit of electrical output) for the LWR-UO_2 loading BWR STEP-III fuels and the LWR-MOX based on a fully MOX ABWR loading BWR STEP-II based MOX fuels. We also evaluated the annual data of the amount of Pu isotopes produced for the FR using the specifications of the innovative metal-fueled small core developed in the United States.[8] In LWR-MOX, the amount of fissile Pu is reduced by almost half due to burnup, while the amount of the fertile nuclide Pu increases by 5%. This indicates that the isotopic composition of Pu is degrading. As shown in Table 1(c), in the metal-fueled SFR, the amount of fissile Pu is increased by 28% and the fertile Pu is decreased by 8%. This indicates that the Pu isotope composition in LWR-MOX can be restored by utilizing the metal-fueled SFR.

Secondly, the data provided in the fuel loading/discharged weight breakdown was used to determine the capacity of each reactor type in order to achieve a balanced Pu ratio.

Thirdly, the total capacity was set at 35 GWe in accordance with national policy.

Finally, based on the capacity of each reactor type in Fig. 1, a target value for MA transmutation was set to ensure that all MAs produced in LWRs are transmuted in the metal-fueled SFR.

In line with Japan's nuclear policy goal of achieving 20-22% of the total power capacity from nuclear energy and assuming a total domestic nuclear power capacity of 35 GWe, the capacity for each reactor type, i.e., the LWR-UO_2, LWR-MOX, and FR is 10 GWe, 14 GWe, and 11 GWe, respectively. These capacities ensure the balanced utilization of plutonium, including an even number of nuclides exchanged between each reactor type. The target amount of MA transmutation has been set at 100 kg/GWe/year or more, contingent upon the condition that all MAs produced in the LWR would be transmuted in the FR and there would be no generation of MA waste.

Table 1 Fuel loading/discharged weight [t/GWe/year]

(a) LWR-UO_2

	Load	Discharged
Pu-fissile	0.0	0.13
Pu-fertile	0.0	0.07

(b) LWR-MOX

	Load	Discharged
Pu-fissile	0.69	0.37
Pu-fertile	0.33	0.35

(c) Metal-fueled SFR

	Load		Discharged		
	Core	Blanket	Core	Blanket	Total
Pu-fissile	0.94	0.0	0.76	0.44	1.20
Pu-fertile	0.88	0.0	0.77	0.03	0.81

III. Core Concept and Performance

1. Design Limits and Methodology

To achieve the target for transmuting MA as established in Section II.2 and ensure compatibility with the coexistence scenario, we aim to develop a small MA transmutation metal-fueled core concept. **Tables 2** and **3** list details regarding the design conditions, constraints and a goal. The design conditions are based on a small sodium-cooled metal-fueled fast reactor with an electrical output of 311 MW, which was developed in the United States.[8] The continuous operation period has been adjusted to achieve an average discharge fuel burnup of approximately 106 GWd/t for the core fuel. These are the conditions for the reactor core that form the basis of Natrium™,[9] which is currently undergoing licensing for operation in 2030. The design limits were set in accordance with the findings of research conducted in Japan. The Pu enrichment is set to 25wt% or less in order to avoid eutectic reactions between the metal fuel and the fuel rod cladding. The sodium void reactivity was set at a level of 8 $ or less.

Table 2 Design conditions

Item	Specification
Output	311 MWe/ 840 MWt
Core equivalent diameter	3.4 m
Fuel assembly pitch	161.4 mm
Core temperature (In/out)	360°C/ 499°C
Core fuel type	U-TRU-Zr

Table 3 Design limit and goal

Item	Specification
Pu enrichment	≦25 wt%
Sodium void reactivity	≦8 $
MLHGR	≦500 W/cm
Ave. dis. fuel burnup (Core fuel)	- 106 GWd/t

Our study utilized the following analysis methods. We use UFLIBJ40,[10] which is the 70-group nuclear constant set for fast reactors based on JENDL-4.0. The effective cross-section is calculated using SLAROM-UF.[11] The equilibrium cycle core's characteristics are calculated using the two-dimensional RZ system of CITAION-Burn.[12] Reactivity coefficients are calculated using the perturbation calculation code PERKY.[12] However, given the significant impact of transport effects on the reactivity of the gas expansion module (GEM), the reactivity of GEM is calculated using the triangular mesh of the three-dimensional transport calculation code MINISTRI.[13]

2. Design of MA Transmutation Metal-Fueled Core

We have developed a concept for a small metal-fueled core that loads MA homogeneously, accompanied by Pu recovered from the spent fuel of LWR, into the core fuel. Based on manufacturing and irradiation experience, the MA content is approximately 4 wt%, and the MA transmutation amount is about 75 kg/GWe/year.

Figure 2 shows a horizontal cross-section of the metal-fueled core, which features a radial heterogeneous configuration, with internal blankets loaded with depleted uranium arranged in the core fuel region containing Pu. GEMs, which are passively negative reactivity insertion modules, are loaded on the periphery of the core.

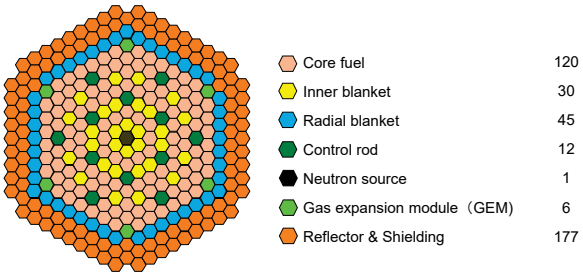
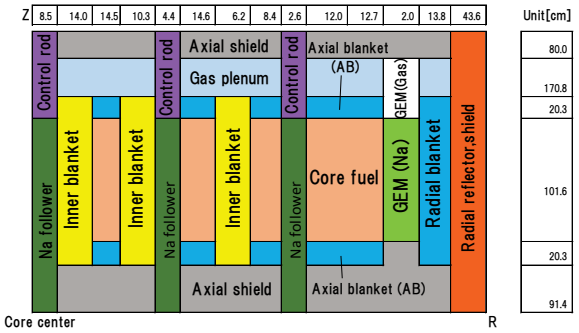
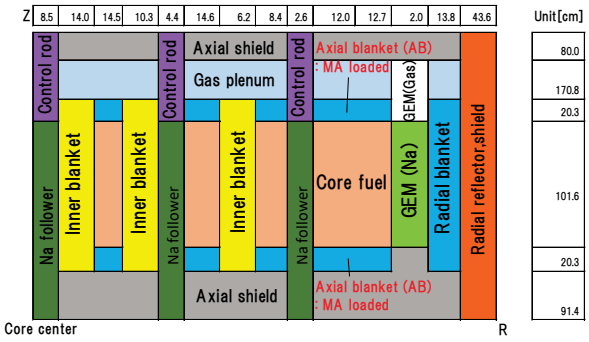


Fig. 2 Horizontal cross-section of metal-fueled core

Figure 3 illustrates the vertical cross-section view of the revised design of the MA transmutation core. Figure 3(a) depicts a vertical cross-sectional view of the reference core with an axial blanket (AB) set in the MA homogeneous loading core previously mentioned. The fuel in the AB of the reference core is a depleted uranium and zirconium alloy, i.e., U-Zr. Figure 3(b) depicts a vertical cross-section of the MA transmutation metal-fueled core. The addition of MA recovered from LWRs to the AB has a negligible impact on the reactivity coefficient. As the U-MA-Zr alloy cannot be manufactured metallurgically, an U-Pu-MA-Zr alloy with Pu is added instead. We will maximize the MA content in the AB, within the limits of void reactivity. **Table 4** provides a summary of the key nuclear characteristics for the cores under evaluation. In the reference core, the Pu enrichment was 22.3 wt%, the MA content was 4.2 wt%, and the sodium void



(a) Reference core



(b) MA transmutation metal-fueled core

Fig. 3 Vertical cross-section of metal-fueled core (2D R-Z)

Table 4 Comparison of key nuclear characteristics

Item	Unit	Reference core	MA trans. metal-fueled core
Cycle length	EFPD	580	722
Pu enrichment/ MA content @ Core fuel	wt%	22.3/4.2	19.8/4.2
Pu enrichment/ MA content @ AB	wt%	0/0	20/20
Sodium void reactivity	$	6.0	7.6
Doppler coefficient (Core fuel)	Tdk/dT	-1.76×10^{-3}	-1.63×10^{-3}
MA transmutation amount	kg/GWe/y	76	185
Breeding ratio	–	1.22	1.14

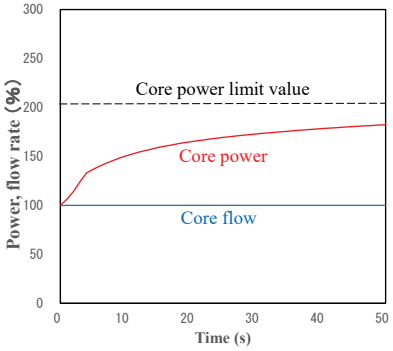
reactivity was 6.0 $. Additionally, the Doppler coefficient of the core fuel was -1.76×10^{-3} Tdk/dT. For the MA transmutaion metal-fueled core, the MA content was set at 20 wt% to achieve a sodium void reactivity of 7.6 $, which is within the design limit. The Doppler coefficient was found to be equivalent to that of the reference core, with a value of -1.63×10^{-3} Tdk/dT. The MA transmutation amount reached the target of 185 kg/GWe/year, and it is projected that the facility capacity for each reactor type evaluated in Chapter II, which demonstrates the coexistence scenario of LWRs and FRs, will be achieved

3. Safety Evaluation for Typical ATWS

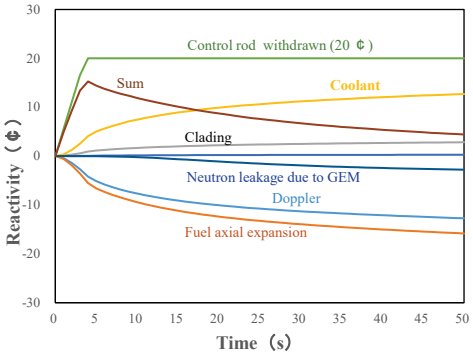
The safety of the MA transmutation metal-fueled core, as discussed in the previous sections, was evaluated for a typical anticipated transient without scram (ATWS).

The potential for unprotected loss of flow (ULOF) is outlined below. As previously stated in Section 2, six GEMs are loaded at the peripheral position. A negative reactivity of -40 ¢ was inserted during ULOF, and boiling of the coolant sodium can be prevented based on the results of a nearly identical core.[14)]

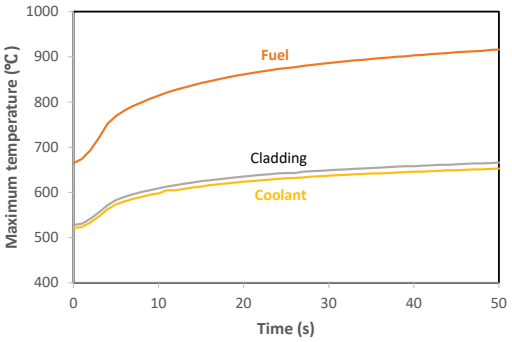
A transient analysis was conducted to verify the integrity of the fuel for the unprotected transient over power (UTOP). This analysis assumed a rod stop mechanism, which limits the amount of control rod withdrawal, as proposed in PSID (Preliminary Safety Information Document) of the advanced metal fuel fast reactor.[15)] The transient analysis was performed by dividing the equilibrium cycle core into core fuel assemblies, inner blanket fuel assemblies, radial blanket fuel assemblies, GEM assemblies, and other non-heat generating assemblies, using a plant dynamics code based on the point kinetics.[16)] The reactivity considered was the Doppler reactivity at the end of the equilibrium cycle, fuel temperature reactivity, coolant temperature reactivity, cladding temperature reactivity, wrapper tube temperature reactivity, GEM reactivity, and accident reactivity. It was conservatively assumed that the radial expansion reactivity of the fuel assemblies, the core support plate reactivity, and the reactivity due to the thermal expansion of the control rod drive mechanism and reactor vessel were not taken into account. As mentioned above, it was assumed that the accident reactivity due to the unexpected withdrawal of the control rod would be limited by the rod stop mechanism. The reactivity insertion rate was assumed to be 5.5 ¢ /s based on the UTOP analysis results shown in the PSID.[15)] The reactivity insertion was limited to 20 ¢ to ensure the safety of the fuel. The analysis results are shown in **Figs. 4**(a),(b) and (c). Figure 4(a) illustrates the alterations in core power and flow rate. The peak core power was below 200%. Based on the results of the TREAT overpower test [17)] using EBR-II's spent metal fuel, it was determined that the integrity of the cladding can be ensured. As illustrated in Fig. 4(b), the breakdown of the reactivity transition resulted in a negative Doppler reactivity equivalent to that of the base core. [14)] Therefore, the design principle of loading MA in the AB was a sound decision. Figure 4(c) shows the trends in maximum temperatures of the metal fuel, cladding and coolant sodium.



(a) Alterations in core power and flow rate



(b) Breakdown of the reactivity



(c) Changes in fuel, cladding, and coolant sodium temperatures

Fig. 4 Results of transient analysis for UTOP

IV. Conclusion

Toward a scenario where fast reactors and light water reactors can coexist, we have developed a core concept for a metal-fueled fast reactor that can eliminate MA waste emissions. The capacity ratio of LWRs and FRs was determined under conditions that do not generate unnecessary Pu in the cycle scenario, with the objective of achieving a target MA transmutation amount of 100 kg/GWe/year or more. We developed a core concept in which MA-containing metal fuel with low Pu enrichment is loaded into the axial blanket, which has a small effect on the safety-related reactivity

coefficient, and set the MA enrichment within the limit of sodium void reactivity. The MA transmutation amount was 185 kg/GWe/year, which met the target. The Doppler coefficient of the core is equivalent to that of the base metal-fueled core, and through a transient analysis of the scram failure overpower event UTOP, the fuel integrity was verified to be maintained.

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