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ARTICLE

Inherent Safety Fast Reactor Concept of KAMADO-FR2 Design of Ultra-Long Life Core and Reuse of LWR Spent Fuels

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We designed an ultra-long-life core (ULLC) and reactor concept, KAMADO-FR2, with metal U-Pu-10Zr fuels to effectively use uranium and plutonium resources. Metal fuel assemblies are loaded in a pressure vessel containing carbon dioxide (CO_2) at 3 MPa. We studied the ultra-long-life core and achieved the core burnup of 256 MWd/kgHM with Pu/(U+Pu) 8% enrichment fuels by the conversion ratio 0.96, which can extend the utilization of nuclear fuel resources effectively without reprocessing and can reuse light water reactor (LWR) spent fuel assemblies.

KEYWORDS: fast reactor; ULLC, inherent safety, metallic fuel, MVP, reuse, spent fuel

I. Introduction

As part of the mission of nuclear power generation, it is necessary to address long-term resource issues, safety, and the economy.[1)] We are proposing a new concept, KAMADO, originating from the name of a Japanese traditional cooking range with inherent safety by providing the fuel assembly with a means of removing the decay heat of the fuel.[2,3)]

The environment of the nuclear fuel cycle is changing; increasing plutonium production is no longer necessary, and measures are needed to utilize existing plutonium and uranium resources effectively. Considering this background, we have constructed a new fast reactor concept, KAMADO-FR2 (Fast Reactor revision 2), which can effectively utilize nuclear fuel resources without reprocessing. In this concept, fuel assemblies of metal fuels (U-Pu-10Zr) are loaded in a pressure vessel containing carbon dioxide (CO_2) at 3 MPa. The pressure vessel is installed in the reactor water pool at atmospheric pressure, as shown in **Fig. 1**. The fuel assembly is cooled by CO_2 gas, and an inverted U-shaped decay heat cooling pipe is installed in the fuel assembly. The water in the decay heat cooling pipes becomes steam during operation and becomes a two-phase flow or water during shutdown. When the cooling performance of CO_2 gas flow is lost, the decay heat of the fuel assembly is removed by two-phase flow or water from the reactor water pool via the decay heat cooling pipe, which ensures inherent safety. The reactor water pool also cools the surface of the pressure vessel. Graphite neutron reflectors surround the fuel assembly. Under the condition of 900 MWe electrical output, KAMADO-FR2 realizes an ultra-long life core (ULLC) of 256MWd/kgHM or more with Pu 8% enrichment fuels. Additionally, this core can reuse LWR spent fuels without any special treatment.

The KAMADO-FR2 concept corresponds to the effective use of plutonium and uranium resources with nuclear non-proliferation and the solution of LWR spent fuel accumulation in Japan.

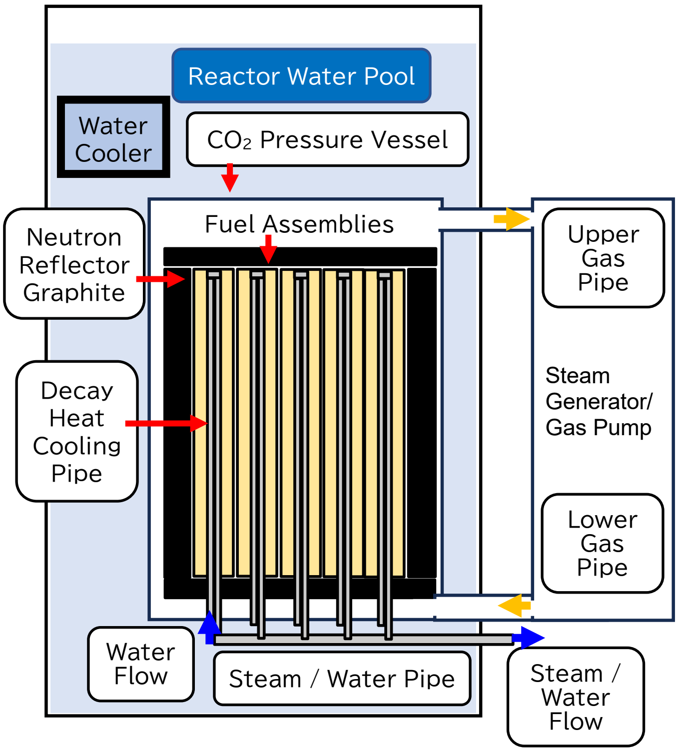

Fig. 1 Concept of KAMADO-FR2 reactor (vertical view)

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II. Fuel Assembly and Core Concept

The external shape of the fuel assembly of this concept is the same as the PWR 17×17 fuel assembly, and the fuel assembly consists of a stainless-steel frame, metal fuel (U-Pu-10Zr) plates covered with stainless-steel, and decay heat cooling pipes (**Fig. 2**). Metal fuel plates are widely used in experimental reactors.[4-6] The decay heat cooling pipe extends to the bottom of the pressure vessel and is directly connected to the reactor water pool. The pool water of about 0.2 MPa (higher than atmospheric pressure) at the bottom of the pressure vessel is supplied from the reactor water pool to the decay heat cooling pipes without any power equipment. During fuel exchange, the pressure vessel, including the fuel assemblies, is submerged in water, and water is replaced with CO_2 gas during reactor operation.

The outlet temperature of the coolant was set to 673 K (400°C), considering the liquid phase formation temperature of the metal (U-Pu-10Zr) fuel (approximately 923 K[7]). The temperature distribution within the fuel assembly was analyzed using the finite element analysis system LISA.[8] The maximum fuel temperature was 851K during operation, which confirmed that the fuel temperature was below the liquid phase formation temperature (**Fig. 3**).

The steam flow rate, two-phase flow, and pressure loss must be evaluated to evaluate the decay heat cooling pipe performance. The following Darcy–Weisbach Equation gives the pressure loss Δp (Pa) due to the pipe walls in a steady flow through a pipe, where f is the friction loss coefficient, L is pipe length, D is pipe diameter, ρ is fluid density, and V is fluid velocity,

$$\Delta p = f\frac{L}{D}\frac{\rho V^2}{2} \qquad (1).$$

Assuming the mass velocity of steam or two-phase flow is 100 kg/m^2/s, the steam velocity is 91 m/s, and the pressure loss is 0.03 MPa, which is lower than atmospheric pressure. Since the pressure loss of two-phase flow is estimated to be the same or smaller than that of steam under the same mass velocity. This evaluation shows that 100 kg/m^2/s mass velocity can be achieved for steam or two-phase flow. With the same mass velocity in the event of reactor shutdown, the heat transfer coefficient (h) from the decay heat cooling pipe to the two-phase flow is 48 kW/m^2/K, which was calculated using the following Jens-Lottes equation,[9] where q_w is heat flux and p is pressure,

$$h = \frac{1}{0.79}q_w^{3/4}\exp\left(\frac{p}{6.2\times 10^6}\right) \qquad (2).$$

Even if the cooling performance of CO_2 gas flow is lost, the maximum fuel center temperature is lower than 862K with the decay heat cooling pipes and the natural circulation of CO_2 gas (110 W/m^2/K) after reactor shutdown (decay heat of 6%) (**Fig. 4**).

Considering the coolant outlet temperature, the turbine efficiency is 36%, and the thermal output is 2500 MWt. Based on the heat removal performance of the fuel assemblies, the average output of the fuel assemblies was set at 10 MW, and the number of assemblies was set at 252. With nine control element assemblies, the core equivalent diameter of the 261 assemblies is 3.92 m (**Fig. 5**). **Table 1** shows the fuel assembly and core specifications.

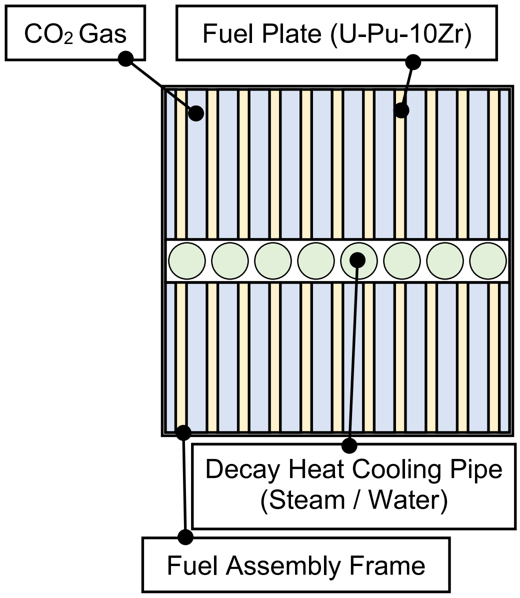


Fig. 2 Concept of fuel assembly (horizontal view)

Table 1 Specifications of the KAMAD-FR2 fuel and core

Items	Values
Assembly dimension	214 mm×214 mm×3700 mm
Assembly thermal power	10 MW
Plant gas pressure	3 MPa
CO_2 inlet/outlet temp.	453 K/673 K
Fuel type	U-Pu-10Zr
Pu enrichment	8%
Pu vector (^{239}Pu/^{240}Pu/^{241}Pu/^{242}Pu)	58/24/14/4% (From reprocessed LWR fuel)
U enrichment	0.3% (Depleted uranium)
Fuel plate thickness	6 mm
Number of fuel plates	11×2
Decay heat cooling pipe diameter	22.25 mm
Coolant velocity	100 m/s
Thermal/Electric Power	2500/900 MW
Number of fuel assemblies	252
Equivalent core diameter	3.92 m
Neutron reflector thickness	1 m (Graphite)

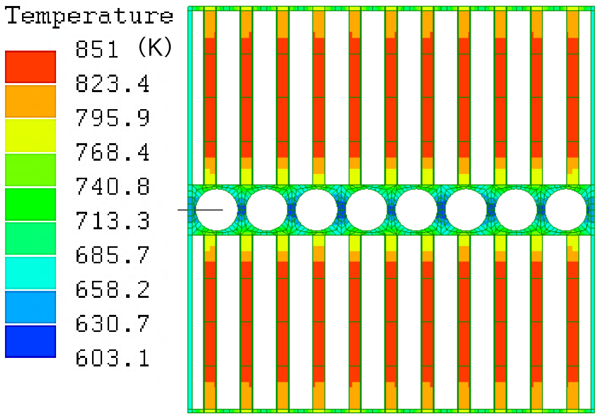


Fig. 3 Temperature distribution in the fuel assembly at full power

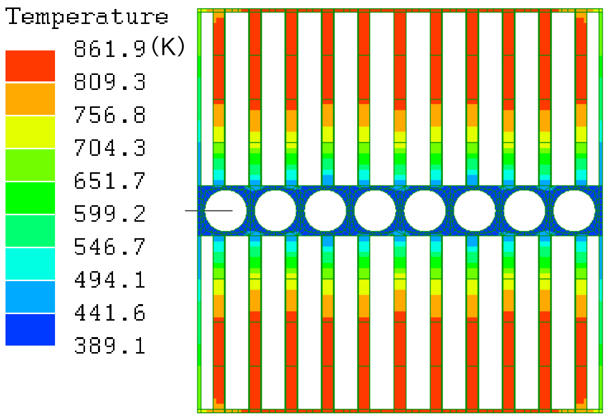
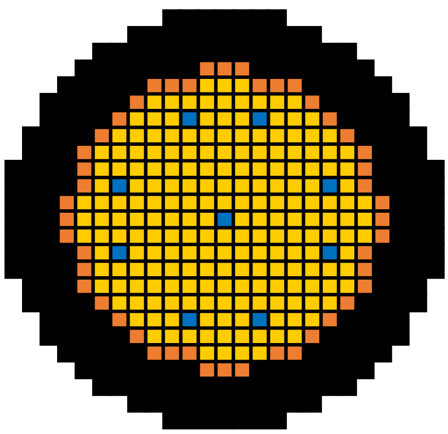


Fig. 4 Temperature distribution in the fuel assembly at LOF (Loss of flow)



Assembly type	Number of assemblies	
Metal fuel	204	252
Metal fuel (Periphery)	48	
Control element	9	
Graphite reflector	228	

Fig. 5 Configuration and assembly types in the standard reactor

III. Core Neutronic Performance

When water flows in the decay heat cooling pipes and the core is submerged during fuel exchange, the fuel assembly multiplication factor (k_∞) was evaluated using MVP 3.0.[10] The k_∞ increases as the number density ratio of hydrogen to heavy metal (H/HM) increases (**Fig. 6**). To escape the k_∞ increase, the surfaces of fuel plates are coated with 0.02 mm of B_4C. The neutron absorption performance of ^{10}B allows the reactivity of the fuel assembly to be lower when submerged than when in operation. As the proportion of thermal neutrons increases in the core periphery due to the neutron moderation effect of the graphite reflector, the neutron absorption rate of ^{10}B coated on fuel plates becomes greater. Boron could be mixed with U-Pu-Zr fuel instead of coated, but the coexistence of boron and U-Pu-Zr should be confirmed.

Burn-up dependence of core effective multiplication factor (k_{eff}) was calculated with MVP-BURN[11] considering coating of B_4C on fuel plates. The core k_{eff} at the beginning of the cycle (BOC) varies greatly depending on the Pu enrichment (7, 8, 9%). Still, the difference decreases with burnup (**Fig. 7**). With Pu 8% enrichment fuels, the core can burn up to an ultra-high burn-up of 256 MWd/kgHM (End of cycle, EOC) with 45 EFPY (Effective Full Power Year).

U-10Zr fuels with ^{235}U 9% enrichment can burn up to 227 MWd/kg and achieve the integrated conversion ratios of 0.87 as well as 0.96 for U-Pu-Zr fuels, as shown in **Fig. 8**.

Table 2 and **Fig. 9** show the weight compositions of actinide nuclides in U-Pu-10Zr fuels, which are averaged for the entire core. at BOC and EOC. ^{235}U decreases, while Pu (except ^{241}Pu) increases with burnup.

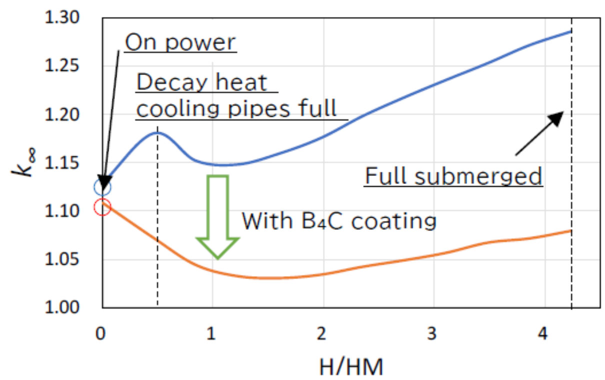


Fig. 6 Changes of fuel assembly k_∞ with H/HM

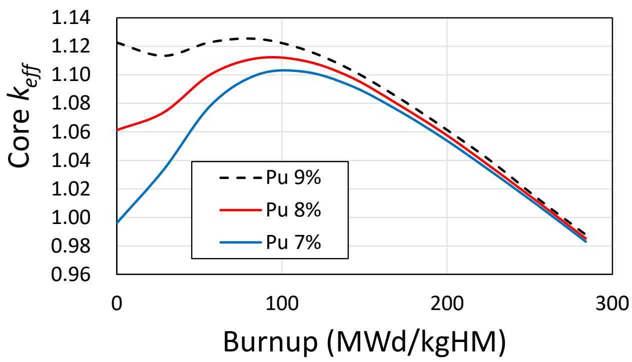


Fig. 7 Changes of core k_{eff} for Pu enrichment of U-Pu-Zr fuels with core burn-up

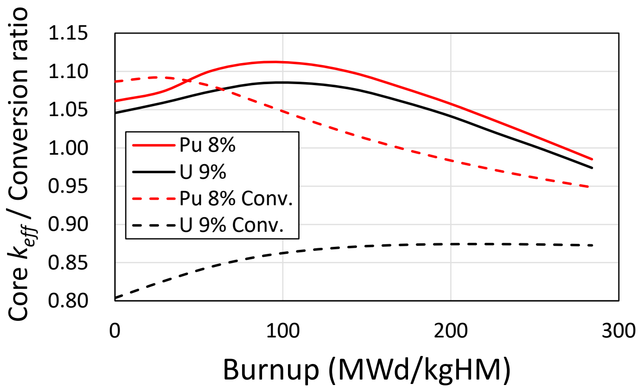


Fig. 8 Changes of core k_{eff} and integrated conversion ratio of U-Pu-Zr and U-Zr fuels with core burn-up

Table 2 Core averaged weight compositions of actinide nuclides in U-Pu-10Zr fuels at BOC and EOC

Nuclides	BOC 0MWd/kgHM (g/cm^3)	EOC 256MWd/kgHM (g/cm^3)
^{235}U	0.03924	0.00272
^{238}U	13.03989	9.12436
^{237}Np	-	0.00979
^{238}Pu	-	0.02763
^{239}Pu	0.65975	0.83383
^{240}Pu	0.27296	0.39045
^{241}Pu	0.15925	0.04712
^{242}Pu	0.04550	0.05211
^{241}Am	-	0.03275
^{242m}Am	-	0.00136
^{243}Am	-	0.01460

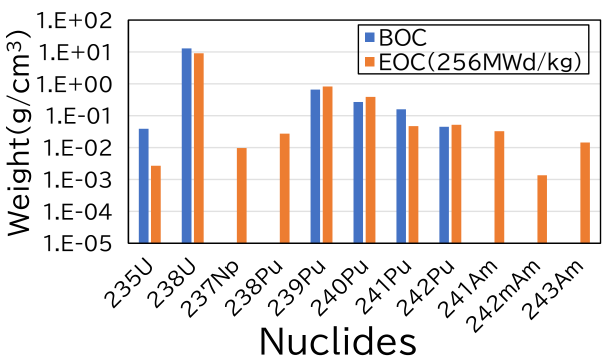


Fig. 9 Core averaged weight compositions of actinide nuclides in U-Pu-10Zr fuels at BOC and EOC

IV. Reuse of PWR Spent Fuel Assemblies

The external shape of the KAMADO-FR2 fuel assembly is the same as that of the PWR17×17 fuel assembly, so the fresh or spent PWR17×17 fuel assemblies can also be loaded in the peripheral locations of the core (48 fuel assemblies, **Fig. 5**) instead of the KAMADO-FR2 fuel assemblies.

When PWR spent fuel assemblies with burnup of 45 MWd/kgU are reloaded in the peripheral regions of the core, they can achieve an additional burnup of 29.8 MWd/kgU over a 5 EFPY period. The spent fuels have slightly negative reactivity (less than 3%) over five years.

The fast neutron fluxes (over 10^2 eV) mainly account for the total fluxes in the core center. In contrast, the thermal neutron fluxes (under 10^2eV) share a significant part in the core periphery because of the graphite reflector and its moderation effects (Fig. 5 and **Fig. 10**). As shown in Fig. 10 (a), the contribution of thermal neutrons to the nuclear fission reaction rates is 62%, more than half, and burnup of the loaded PWR spent fuel is progressing with thermal neutrons. The PWR spent fuel rod's linear heat rate (LHR) is 7.6 kW/m, approximately half that of normal PWR fuel.

Loaded PWR fuel assemblies are cooled with CO_2 gas. When the CO_2 gas cooling flow function is lost, the decay heat of loaded PWR fuel assemblies is removed by the natural circulation of CO_2 gas and through the graphite neutron reflector adjacent to the PWR fuel assembly, which has a heat cooling function to keep the fuel claddings at a low temperature. As the LHR of the reused spent PWR fuel rod is low, it is considered that the fuel integrity can be maintained even during the LOF event. However, a detailed safety analysis is required.

Table 3 and **Fig. 11** show the weight compositions of actinide nuclides in the PWR spent fuel before (Beginning of cycle: BOC) and after reusing (End of cycle, EOC). ^{235}U decreases, but Pu increases with burnup. The nuclide composition calculations are based on the case where the PWR spent fuels are loaded into the periphery of the KAMADO-FR2 core at BOC, but the PWR spent fuels can be loaded into the KAMADO-FR2 core at any time and be replaced every after 5 EFPY. **Figure 12** shows an image of reusing PWR spent fuels. If the PWR spent fuel pit and KAMADO-FR2 reactor are installed in one large water pool, the PWR spent fuel is easy to load and unload in the peripheral locations of the KAMADO-FR2 core.

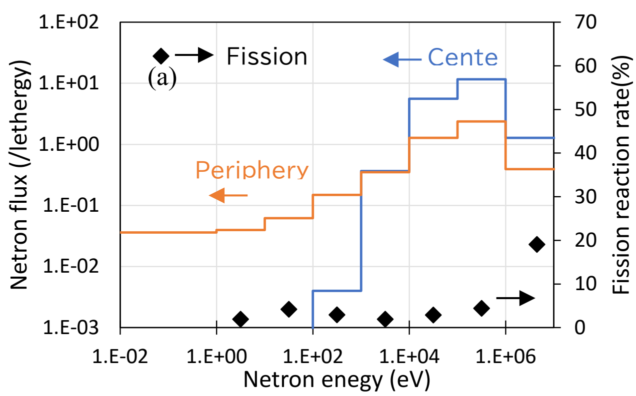


Fig. 10 Neutron energy spectra at core center and periphery, and fission reaction rates in PWR spent fuel region

Table 3 Weight compositions of actinide nuclides in spent PWR fuels at BOC and EOC

Nuclides	BOC 45MWd/kgHM (g/cm^3)	EOC 75MWd/kgHM (g/cm^3)
^{235}U	0.05294	0.01577
^{238}U	8.54984	8.16528
^{237}Np	0.00524	0.00730
^{238}Pu	0.00262	0.00694
^{239}Pu	0.05227	0.12284
^{240}Pu	0.02506	0.07345
^{241}Pu	0.01568	0.01627
^{242}Pu	0.00816	0.01334
^{241}Am	0.00040	0.00172
^{242m}Am	0.00001	0.00003
^{243}Am	0.00185	0.00347

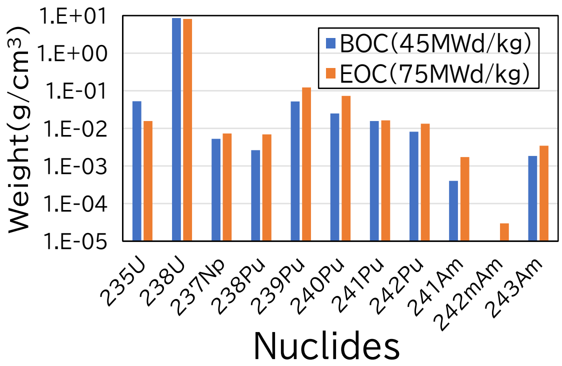


Fig.11 Weight compositions of actinide nuclides in spent PWR fuels at BOC and EOC

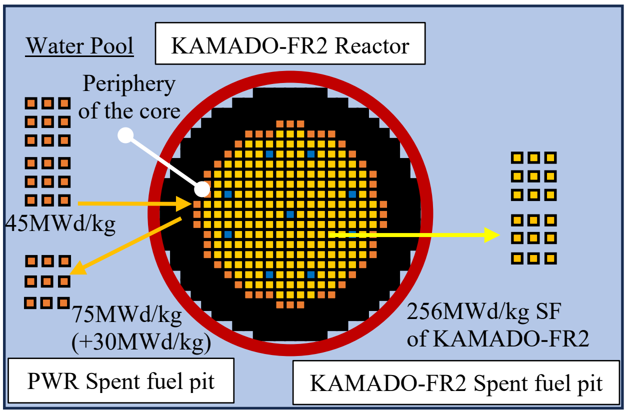


Fig. 12 Image of reusing PWR spent fuels

V. Discussions

1. Integrity of the Metal Fuel

The results have been reported that U-Pu-Zr fuel pin could get to peak burnups as high as 18% fima in the EBR-II, and that metal fuel expanded with swelling phenomenon as its burnup increased.[7)]

Plate fuels are widely used in experimental reactors, such as the Kyoto University Research Reactor (KUR) shown in Fig. 13.[6)] The KUR uses an aluminum-covered U_3Si_2 pre-curving plate fuel assembly. However, the irradiation of metal (U-Pu-10Zr) fuel plates covered with stainless steel has not been sufficiently performed and reported.

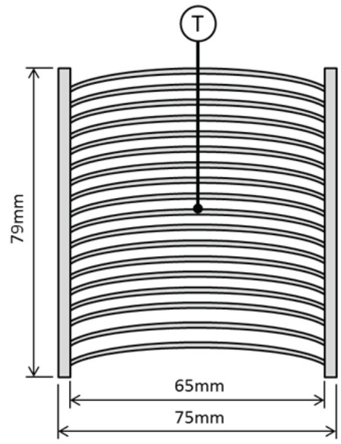


Fig. 13 Cross-sectional view of the KUR fuel assembly[6)]

The expansion caused by swelling of the U-Pu-Zr fuel plate could be absorbed by pre-curving the plate fuels, like the mechanism of research reactor fuel plates. However, the integrity of the metal (U-Pu-10Zr) fuel plate must be verified through irradiation tests.

In the Fast Reactor Cycle Technology Development (FaCT) project, 9Cr and 12Cr-ODS steel cladding tubes are researched, aiming for a maximum burnup of 250 MWd/kg.[12)]

Several factors must be evaluated and addressed for the long-term use of metallic U-Pu-Zr fuel up to 256 MWd/kgHM and 45 EFPY. However, it is possible to repair and replace fuel cladding that deteriorates during irradiation and continue to use the U-Pu-Zr fuel portion.

2. Integrity of the Reused PWR Spent Fuel

The reuse of LWR spent fuel also poses the issue of fuel integrity. Increasing the fuel burnup in light water reactors involves the following challenges:

- Corrosion of the cladding tubes and the amount of hydrogen absorbed.
- Increased release of fission gas (FP gas) leads to an increase in the internal pressure of the fuel rods.
- In-reactor creep and irradiation growth of cladding.

When using CO_2 gas, corrosion and hydrogen absorption are less problematic, but the fuel rods' internal pressure and the cladding tubes' deterioration are issues. These factors need to be evaluated and addressed in the future. However, perforating the cladding tube, adjusting the fuel rod gas pressure, changing FP gas with He, and overpacking the fuel rod cladding are possible.

3. Disposal of Spent Fuels

After the original spent fuel of the KAMADO-FR2 fuel (256 MWd/kgHM) and reused PWR spent fuel (75 MWd/kgU) are cooled and stored in the spent fuel pit for several years, they are expected to be transported to a disposal facility. Since a large amount of Pu remains in these spent fuels, the storage or utilization of the remaining Pu will be an issue for physical protection or a topic for fuel recycle research.

4. Power Reactivity Coefficient

When core power generation increases and the fuel temperature rises, the Doppler coefficient acts negatively, while the coolant density coefficient of CO_2 acts positively. Further study, including safety analysis, is required regarding the total reactivity coefficient for core power generation.

VI. Conclusion

We developed the concept of "KAMADO-FR2", which can achieve a high burnup of 256 MWd/kgHM with Pu 8% enrichment metal fuels. Temperature distribution analysis of the fuel assembly showed acceptable temperature distribution during operation and accidents, which ensures inherent thermal safety. KAMADO-FR2 can use 12.9 tons of Pu with a 900 MWe unit and can significantly contribute to the utilization of separated plutonium. Although a 900 MWe ordinary LWR requires 4700 tons of natural uranium for 45 years, KAMADO-FR2 requires only 148 tons of depleted uranium. When PWR spent fuel assemblies were reloaded in the peripheral locations of the reactor core, an additional burnup of 29.8 MWd/kg could be achieved over a 5 EFPY burnup period.

The KAMADO-FR2 concept corresponds to the effective use of plutonium and uranium resources with nuclear non-proliferation and handling (reuse) of LWR spent fuels in the medium to long term.

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