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ARTICLE

Once-through high burnup fuel management strategy with dual neutron energy spectrum core in high-temperature gas-cooled reactor

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Because of the excellent neutron economy of a graphite moderator, a high-temperature gas-cooled reactor (HTGR) has the flexibility to burn fuel with a small quantity of fissile material or to incinerate fissile material with very high burnup. The utilization of an HTGR with a once-through high burnup fuel management strategy may meet the social demands for a stable energy resource, high fuel-utilization efficiency, and non-proliferation features. In the strategy investigated in this study, the fuel blocks irradiated up to the designed burnup value are reloaded to the additional irradiation zone to achieve higher burnup and fuel utilization efficiency. A dual neutron energy spectrum core layout was proposed to implement the fuel management strategy; in addition to the original fuel zone of a reference HTGR core design (driver zone), the outer reflector blocks were replaced with fuel blocks called the "efficiency zone" for additional irradiation. The impact of neutron energy on the burnup extension in the efficiency zone has also been investigated by changing the fuel pin pitch inside the fuel block to change the moderator-to-fuel ratio. Numerical simulations showed that extended burning in the efficiency zone with the pin-pitch unchanged for 1 extra irradiation batch could increase discharge fuel burnup from 125.9 GWd/t to 140.4 GWd/t. The proliferation resistance of the discharged fuel also improved due to rise in Pu-238 ratio from 5.1 to 7.3%. Moreover, increasing the pin-pitch of the fuel blocks and 2-batch additional irradiation in the efficiency zone could potentially increase the burnup and Pu-238 ratio of the discharged fuel.

Keywords: high-temperature gas-cooled reactor; high burnup; fuel management strategy; waste reduction

1. Introduction

A high-temperature gas-cooled reactor (HTGR) has great neutronic and passive safety properties. Because of the excellent neutron economy of a graphite moderator, the HTGR has the flexibility to burn fuel with a small quantity of fissile material, such as natural uranium, or to incinerate fissile material with a very high burnup, called "deep burning" [1]. It may be possible to re-irradiate once-irradiated fuel in an HTGR by adjusting the moderator-to-fuel ratio to generate adequate thermal energy neutrons. In addition, the graphite and silicon carbide spherical layers of the tri-structural isotropic (TRISO) particle fuel used in an HTGR encapsulates the fuel material inside multiple barriers, which can prevent the release of radioactive fission products under accident conditions or possibly even after disposal in a deep geological repository [2]. The highly robust TRISO particle fuel that has been widely used in advanced HTGR design is comparatively difficult to reprocess compared to the conventional UO_2 pellets used in light water reactor because of its complex structure, which may downgrade the material attractiveness of the HTGR fuel to both state and non-state actors, increasing the proliferation resistance [3,4]. Therefore, the utilization of HTGRs with a once-through high burnup fuel management strategy may meet the social demands for a stable energy resource, high fuel utilization efficiency, high-level-waste minimization, and excellent safety, security, and non-proliferation features.

The objectives of this study are to clarify the impacts of fuel management strategy with dual neutron energy spectrum core for a block-type HTGR on extension of burnup and fuel utilization efficiency by adding an extra-irradiation zone.

2. Methodology

2.1. Fuel management strategy and dual neutron energy spectrum core

In the strategy investigated in this study, once the fuel blocks are irradiated up to the designed burnup value, they are reloaded to the additional irradiation zone to achieve higher burnup and fuel utilization efficiency. The prismatic-block type HTGR core was divided into two fuel zones, the "driver zone" like the reference active core, and the additional "efficiency zone," for more irradiation by longer fuel residence time (**Figure 1**).

In this study, the outer reflector region of the reference core design was selected to be replaced with the efficiency

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zone to study the feasibility of the fuel management strategy. GTHTR300, a block-type HTGR designed by the Japan Atomic Energy Agency (JAEA), was used as the reference core design for this study [5]. A dual neutron energy spectrum core model based on the reference core model shown in **Figure 2** was used to simulate the fuel management strategy. The impact of neutron energy on the burnup extension in the efficiency zone has also been investigated by changing the fuel pin pitch inside the fuel block to change the moderator-to-fuel ratio.

Numerical simulations were performed to evaluate the basic burnup characteristics of the efficiency zone and the impacts of the strategy on the core burnup characteristics. The burnup calculation code MVP-BURN used for the numerical simulation was coupled with the continuous-energy Monte Carlo neutron transport code MVP (version 3) and JENDL 4.0 nuclear data. The procedures are described in the following sections.

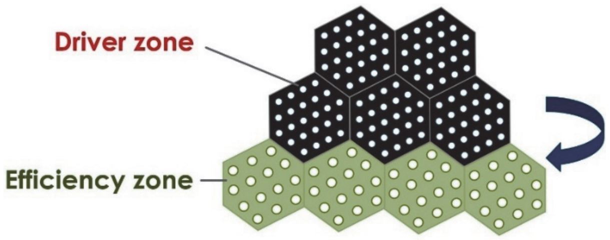
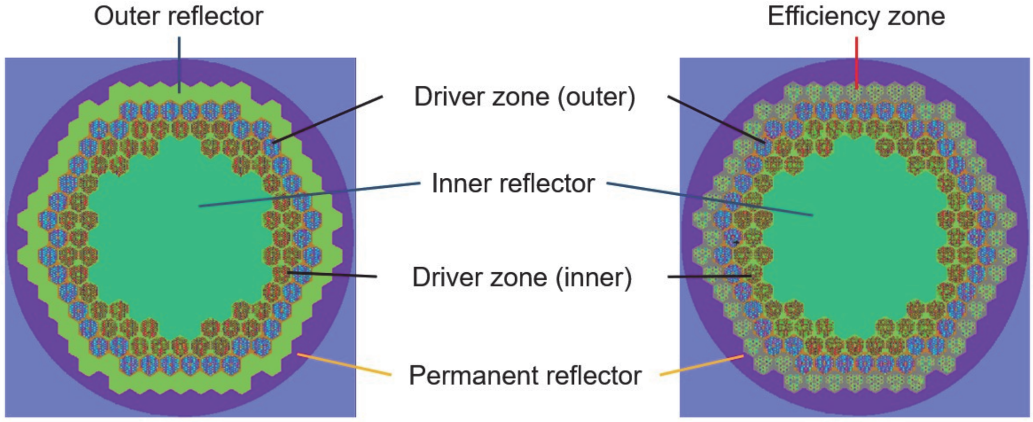


Figure 1. Concept of the fuel management strategy with dual neutron energy spectrum core.

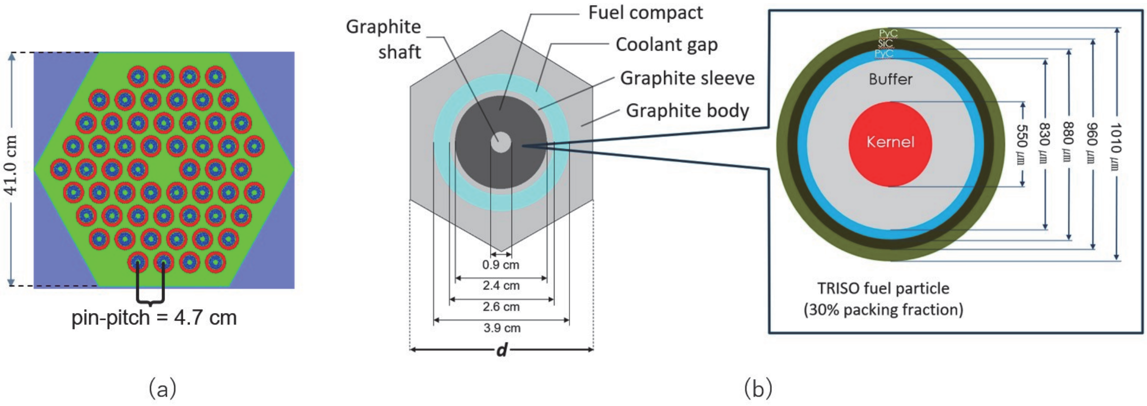
2.2. Investigation of the basic burnup characteristics of the efficiency zone

First, the basic burnup characteristics of the efficiency zone were studied by performing a burnup simulation using a pin-cell model. The pin-cell model represents a single fuel-pin unit in a fuel block, with a coolant gap between it and the graphite body in the form of a regular hexagon, as shown in **Figure 3**. Here, the apothem (side-to-side length of a hexagon) of the pin-cell model represents the distance between adjacent fuel pins (pin pitch) in a fuel block described as *d* in the figure, which is the main parameter of this study. The apothem is defined as the cell equivalent (c.e.) pin-pitch, which is calculated from the pin-pitch of the fuel block volume ratio of the coolant, graphite moderator, and fuel pin. For example, the fuel block of the GTHTR300 had a pin-pitch of 4.7 cm. Thus, the pin-cell model representing it would have a c.e. pin-pitch of 5.5 cm. The pin-cell model is used to perform a parametric survey as the burnup calculation can be done with little computational time due to its simplicity.



(a) (b)

Figure 2. Two-dimensional core model of HGTR: (a) reference core and (b) dual neutron energy spectrum core.



(a) (b)

Figure 3. Pin-cell model: (a) dimensions of fuel block of GTHTR300 as reference and (b) pin-cell model.

A parametric survey was performed using the pin-cell model with the pin-pitch as the variable to investigate the basic neutronic properties of extended irradiation in the efficiency zone with different neutron energy. First, a benchmark calculation was performed to verify the validity of the pin-cell model in comparison with the reference core with specifications as shown in **Table 1**. The burnup period and linear heat rate were set to obtain the average design burnup of the GTHTR300, which was 120 GWd/t after operating at 600 MW for 730 effective full-power days (EFPDs) with two fuel batches. The burnup period was set to 1460 EFPD for a one-batch fuel burnup calculation for simplicity.

Table 1. Major specifications of GTHTR300 [5].

Thermal power	600 MW
Irradiation time per batch	730 EFPD
Fuel batches	2
Fuel type and enrichment	UO2, 14 wt%
Packing fraction of fuel compact	30%
Fuel pin-pitch in block	4.7 cm
Average discharge burnup	120 GWd/t
Residual fuel enrichment at discharge	4.4%

2.3. Evaluation of the impacts of the strategy on core burnup characteristics

The feasibility and impacts on the core characteristics of the fuel management strategy were evaluated by running burnup calculations with the 2D core models as shown in Figure 2. The reference core model (Figure 2(a)) had a driver zone with fuel blocks that has a pin-pitch of 4.7 cm. The fuel blocks were graphite blocks with fuel pins and coolant gaps, and the reflector blocks were simplified as solid hexagonal prismatic graphite blocks with the coolant channels omitted. The 2D core model was defined as a cylinder with mirror reflective vertical boundaries, so only the radial neutron leakage was considered. The dual neutron energy spectrum core model (Figure 2(b)) had a driver zone which is the same as the reference core and an efficiency zone instead of the outer reflector region.

The driver zone had 90 fuel blocks and 2 irradiation batches (1460 EFPD), while the efficiency zone had 48 blocks and 1 irradiation batch. The efficiency zone had the same pin-pitch as the driver zone which is 4.7 cm, so there are 57 fuel pins per block. All the fuel blocks irradiated for 2 batches in the driver zone may be shuffled directly to the efficiency zone for 1 extra irradiation batch. To simulate the fuel management strategy with MVP-BURN, the initial fuel composition of the efficiency zone was set to be the final fuel composition of the inner driver zone of the reference core after the fuel was irradiated for 2 irradiation batches. The burnup and actinide composition in the efficiency zone after 1 irradiation batch was evaluated, although the burnup calculation was performed for 2 irradiation batches in the simulation.

Next, the pin-pitch of fuel blocks in the efficiency zone was changed from 4.7 cm to 5.9 cm to study the impacts of neutron energy in the efficiency zone on the core burnup characteristics. Other specifications of the dual neutron energy spectrum core were kept constant, so the efficiency zone had 48 fuel blocks and the number of fuel pins per block decreased from 57 to 33, resulting in a decrease in total fuel inventory. In this case, inventory balance between the driver zone and the efficiency zone was not considered and it is assumed that only fuel from the efficiency zone would be discharged. The burnup and actinide composition after 1 and 2 extra irradiation batch in the efficiency zone were evaluated to demonstrate the potential extension of burnup and fuel utilization efficiency by extra irradiation in a softer neutron energy spectrum and longer fuel residence time.

3. Results

3.1. Neutronic characteristics of the efficiency zone fuel with cell calculation

The burnup simulation using the pin-cell model showed that the reactivity penalty by the irradiated fuel could be reduced by increasing the moderator-to-fuel ratio of the efficiency zone. The burnup results for the driver zone showed that the residual fuel enrichment at 121 GWd/t was 4.4%, which was consistent with the value calculated with the full core model of the GTHTR300, thus confirming the validity of the pin-cell model. The fuel composition obtained from the irradiated driver fuel in the driver zone was used as the initial fuel composition. For the efficiency zone, the *k-inf* (infinite multiplication factor) showed significant increases with wider pin-pitches at the initial burnup step (starting at 121 GWd/t), but a sharper decrease in *k-inf* was observed for the same increase in burnup (**Figure 4**).

The initial value of *k-inf* increased with the pin-pitch, although the degree of increase in *k-inf* diminished as the pin-pitch became wider. The increase in *k-inf* could be attributed to the decrease in the resonance capture probability due to an increase in the moderator-to-fuel ratio. On the other hand, the neutron flux distribution in **Figure 5** shows that there is less of a shift in the neutron flux from a fast and resonance region to a thermal region when the c.e. pin-pitch changes from 7.3 cm to 9.1 cm, compared to that from 5.5 cm to 7.3 cm, implying that the reactivity gain effect obtained by the widening of the pin-pitch becomes smaller at wider pin-pitches.

However, the decrease in *k-inf* for the same increase in burnup was larger for wider pin-pitches in the efficiency zone. At 156 GWd/t, a 7.3 cm c.e. pin-pitch gave the highest *k-inf*, while a 9.1 cm c.e. pin-pitch resulted in the lowest *k-inf*, which was worse than the *k-inf* for a c.e. pin-pitch of 5.5 cm. This was likely due to wider pin-pitches having a worse conversion factor (less U-238 being transmuted into Pu-239 through a capture reaction) because of a lower

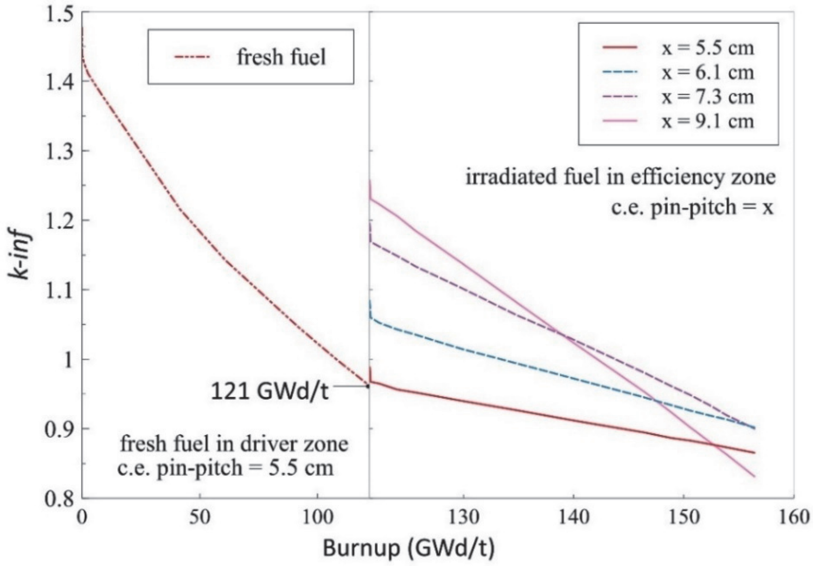


Figure 4. Burnup characteristics of fresh fuel in the driver zone and irradiated fuel in the efficiency zone with different pin-pitches.

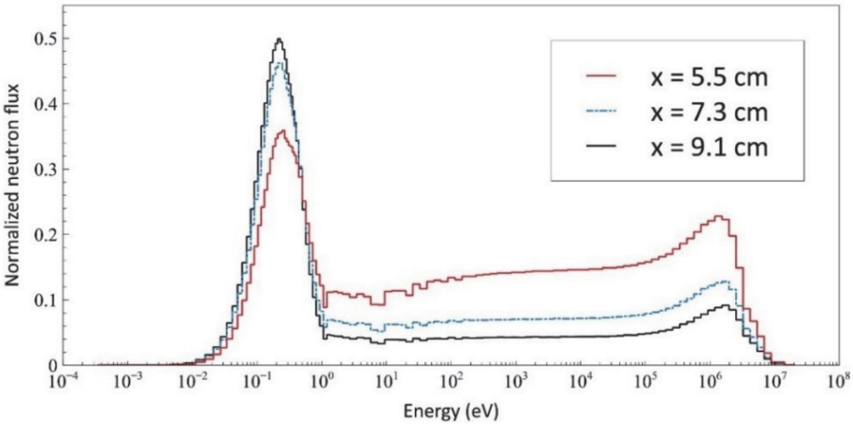


Figure 5. Neutron energy spectra for different pin-pitches.

resonance capture probability. Thus, at some point, an efficiency zone with a wider pin-pitch will have less fissile nuclide as burnup progresses. This result suggests that there is an optimal value for the pin-pitch of the efficiency zone that would maximize its neutronic performance, depending on the maximum achievable burnup in the zone, which could be evaluated by performing a burnup calculation with the 2D core model. The next section discusses the evaluation of the impact of an efficiency zone consisting of fuel blocks with a pin-pitch of 5.9 cm (c.e. pin-pitch of 7.2 cm) on the overall core neutronic performance.

3.2. Impact of the fuel management strategy on overall core performance

Burnup calculations with the 2D core model showed that replacing the outer reflector region with the efficiency zone had little impact on the core reactivity for the same thermal power output and irradiation period (**Figure 6**). The largest decrease in *k-eff* (effective multiplication factor) compared to the reference case was observed in the initial step, which was approximately -3.6% Δ*k*/*kk*’ with an error of less than 0.03%. The differences in *k-eff*

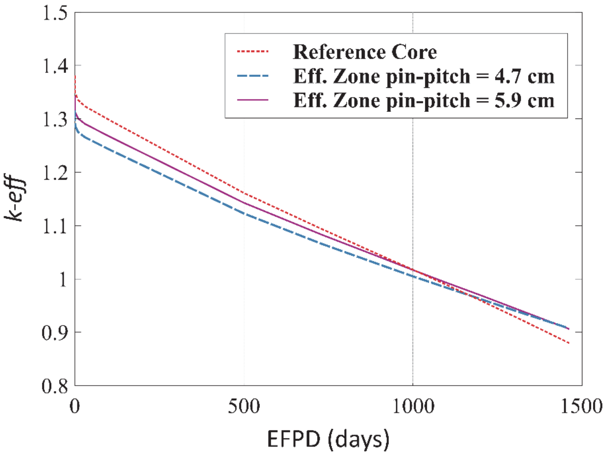


Figure 6. Reactivity change with burnup of the reference core and dual neutron energy spectrum core.

diminished as burnup progressed, and *k-eff* became larger than that of the reference case at some point for the one-batch calculation result. Moreover, the reactivity penalty is projected to be reduced further when the pin-pitch of the fuel blocks in the efficiency zone was widened to 5.9 cm, which was -2.1% $\Delta k/kk'$ in the initial step. Considering that the actual core design was meant for two fuel batches, we could estimate the *k-eff* value of the two-batch core assuming that the *k-eff* changes linearly with burnup. The two-batch core *k-eff* at the beginning-of-cycle (BOC) would be the average value of the one-batch core *k-eff* at 10 EFPD (the time step at which xenon equilibrium is reached) and 730 EFPD, while at the end-of-cycle (EOC) the two-batch core *k-eff* would be the average value of the one-batch core *k-eff* at 730 EFPD and 1460 EFPD. The two-batch core *k-eff* estimate is listed in **Table 3**. The estimation showed that while the two-batch *k-eff* for the dual neutron energy spectrum core models at BOC were lower than that of the reference case, their *k-eff* values were sufficiently larger than one, and both cores with an efficiency zone had a higher two-batch *k-eff* at EOC compared to the reference case. Thus, it was presumed that criticality could still be achieved by adjusting the amount of burnable poison in the core. This estimation suggested that the implementation of the fuel management strategy would not have a significant negative effect on the core operation in terms of criticality. This is likely because of the low neutron importance of the efficiency zone as it is located near the circumference of the core. Besides, as suggested in the results in 3.1, widening the pin-pitch would increase the fuel reactivity in the efficiency zone due to a decrease in resonance capture probability.

Results of burnup and estimated actinide composition after extended burning in the efficiency zone is shown in **Table 4**. The burnup of once-irradiated fuel was increased from 125.9 GWd/t to 140.4 GWd/t after 1 batch of extended burning in the efficiency zone with a pin-pitch of 4.7 cm. However, the burnup of the driver zone decreased from 125.9 GWd/t to 117.2 GWd/t and from 116.5 GWd/t to 89.2 GWd/t in the inner and outer parts respectively. The decrease in burnup was because the reactor power was kept constant, so the average burnup of the whole core is the same regardless of the fuel management strategy. The outer driver zone suffered a larger loss in power density as it is located nearer to the efficiency zone, which resulted in a larger drop in fuel burnup.

Table 2. Two-batch core *k-eff* estimation.

Core	*k-eff* at BOC	*k-eff* at EOC
Reference	1.214	0.987
Reference w/ Efficiency Zone	1.170	0.987
Dual Neutron Energy Spectrum Core	1.192	0.995

Table 3. Burnup and estimated actinide composition in the efficiency zone.

Pin-pitch in the efficiency zone fuel blocks	4.7 cm	5.9 cm	
Extra irradiation time (days)	730	730	1460
Burnup (GWd/t)	140.4	145.7	166.1
Residual U-235 enrichment	2.6%	1.9%	1.1%
Pu-238 isotopic ratio	7.3%	8.7%	12.3%

Results in Table 4 also suggested that the dual neutron energy spectrum core design can increase fuel utilization in the efficiency zone due to increased power density. When the pin-pitch of the efficiency zone fuel blocks increased from 4.7 cm to 5.9 cm, the burnup slightly improved to 145.7 GWd/t after 1 batch of extended burning in efficiency zone, and the average power density in the efficiency zone increased from 0.202 $\mathrm{kW/cm^3}$ to 0.264 $\mathrm{kW/cm^3}$. Extended burning in the efficiency zone for 2 batches is projected to achieve a burnup of 161.7 GWd/t and 1.1% of residual U-235 enrichment. However, since the amount of fuel inventory in the efficiency zone is lower compared to the reference core design, the actual values would differ for a dual neutron energy spectrum core design that considers inventory balance between the driver zone and the efficiency zone.

The proliferation resistance of discharged fuel may be evaluated with isotopic ratio of Pu-238 due to its high decay heat which would hinder the production of nuclear explosive devices (NED) [6]. U-235 transmutation led to a buildup of Np-237 and Pu-238 with extended burning in the fuel management strategy. After 1 batch of extended burning in the efficiency zone with a pin-pitch of 4.7 cm, the residual U-235 enrichment in the efficiency zone was reduced from 3.6% to 2.6%, and the Pu-238 isotopic ratio raised from 5.1% to 7.3%. This improvement is significant as the Pu-238 isotopic ratio for medium technology NED to be technically unfeasible is >6% as proposed in Ref. [7]. Moreover, 1-batch extended burning with an efficiency zone pin-pitch of 5.9 cm is projected to further improve the Pu-238 isotopic ratio to 1.9% and 8.7%, while a 2-batch extended burning could potentially attain a Pu-238 isotopic ratio of 12.3% in the efficiency zone, which is close to the criterion of >15% Pu-238 for high technology NED to be technically unfeasible. The raise in Pu-238 isotopic ratio when the pin-pitch is widened is attributed to the drop in resonance capture probability of U-238 which led to a fall in Pu-239 production rate.

4. Conclusion

The impacts of a fuel management strategy with dual neutron energy spectrum core for a block-type HTGR on extension of burnup and fuel utilization efficiency by adding an extra-irradiation zone have been clarified in this study.

Pin-cell calculations showed the effects of the pin-pitch on the basic burnup characteristics of the efficiency zone. Widening the pin-pitch of the efficiency zone could increase the reactivity of the fuel irradiated, but the improvement would become smaller and the reactivity would drop as the burnup increases. The burnup calculation results showed that a c. e. pin-pitch of 7.3 cm in the efficiency zone would have the least negative effect on the reactivity when the burnup exceeds 150 GWd/t.

Burnup calculations with the 2D core model showed that adding the efficiency zone had a negligible effect on the overall core reactivity. The fuel management strategy was shown to improve fuel utilization and non-proliferation feature of the discharged HTGR fuel.

- Extended burning in the efficiency zone with a pin-pitch of 4.7 cm for 1 extra irradiation batch fulfills the fuel inventory balance requirement for fuel shuffling. The burnup increased from 125.9 GWd/t to 140.4 GWd/t. The residual U-235 enrichment reduced from 3.6% to 2.6% and Pu-238 isotopic ratio increased from 5.1% to 7.3%.
- A dual neutron spectrum core design with 5.9 cm pin-pitch in the fuel blocks of the efficiency zone was projected to further improve the fuel utilization and non-proliferation feature of the discharged fuel, though further study would be required on the inventory balance between the driver zone and the efficiency zone.

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References

[1] C. Rodriguez, A. Baxter, D. McEachern, M. Fikani and F. Venneri, Deep-burn: making nuclear waste transmutation practical, N*ucl. Eng. Des*. 222 (2003), pp. 299-317.

[2] B.P. Van den Akker, On the Disposition of Graphite Containing TRISO Particles and the Aqueous Transport of Radionuclides via Heterogeneous Geological Formations, (2012), Ph.D. dissertation, U.C. Berkeley.

[3] P. Paviet-Hartmann, M.R. Stacey, S. Bakhtiar and G. Cerefice, Analysis of nuclear proliferation resistance reprocessing and recycling technologies, *Proceedings of ICONE19, 19th International Conference on Nuclear Engineering* (2011), Chiba, Japan, May 16-19 (2011).

[4] T. Aoki, H. Sagara and C.Y. Han, Material attractiveness evaluation of inert matrix fuel for nuclear security and non-proliferation, *Ann. Nucl. Energy* 126 (2019), pp. 427-433.

[5] K. Kunitomi, S. Katanishi, S.Takada, X. Yan and N. Tsuji, Reactor core design of gas turbine high temperature reactor 300, *Nucl. Eng. Des*. 230 (2004), pp. 349-366.

[6] G. Kessler, C. Broeders, W. Hoebel, B. Goel and D. Wilhelm, A new scientific solution for preventing the misuse of reactor-grade plutonium as nuclear explosive, N*ucl. Eng. Des*. 238 (2008), pp. 3429-3444.

[7] Y. Kimura, M. Saito and H. Sagara, Evaluation of proliferation resistance of plutonium based on decay heat, *J. Nucl. Sci. Technol.* 48 (2011), pp. 715-723.