The object of this study is a small modular gas-cooled fast reactor (GFR) fuelled by UN-PuN with minor actinides (MA) addition. The problem solved in this study is the identification of the impact of MA addition on the criticality, fuel burnup stability, and nuclear waste transmutation of the small modular GFR. The parameters studied include k-eff, macroscopic cross-section, conversion ratio (CR), heavy nuclides inventory, and the probability of radiopharmaceutical isotope production. The study was conducted using SRAC-COREBN computational analysis, and the MA used in this study were Pa-231, Am-241, and Np-237. The results obtained that the MA addition, on average, results in a decrease in k-eff, the magnitude of which depends on the type and concentration of MA. Macroscopic cross-section analysis reveals shifts in values, such as an increase in the Macroscopic cross-section absorption, particularly in the case of Am-241. Then, an increase in the macroscopic cross-section of fission is passed at high energies. The CR > 1 and inversion ratio of heavy nuclide approximately are observed at 50% in all configurations. Furthermore, the evolution of fission products such as Tc-99, Rh-105, and I-135 suggests the chance production of radiopharmaceutical isotope. Interpretation of the results show that adding MA effect k-eff and CR because isotopes such as Am-241, Np-237, and Pa-231 actively participate in fission and conversion of fissile material using fast neutron spectrum. A key feature of obtained results is a stable burnup profile, where the MA effectively functions in target transmutation without disrupting the consumption of the primary fissile fuel. These findings could be a technical basis for supporting national energy security and sustainable nuclear waste management

Keywords: conversion ratio, GFR, COREBN, k-eff, minor actinide, radiopharmaceutical, SMR, transmutation

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IDENTIFICATION OF IMPACT OF MINOR ACTINIDE ADDITION ON BURNUP PROCESS AND HEAVY NUCLIDE EVOLUTION IN UN-PUN FUELED SMALL MODULAR GAS-COOLED FAST REACTORS

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1. Introduction

The progression of nuclear technology advancement will continue to be in parallel with the increasing global demand for energy and the growing interest over long-lived radioactive waste have urged the development of leading nuclear reactor concepts [1]. Researchers are developing Generation IV nuclear reactors to provide nuclear power systems that are

more safe, more efficient, and more sustainable [2]. One of the possible contenders receiving significant global attention is the gas-cooled fast reactor (GFR), which offers high thermal efficiency, the capability to operate at elevated outlet temperatures, and a fast neutron spectrum that enables fuel breeding and minor actinide transmutation [3, 4].

The principal purpose of GFR improvement within the framework of Generation IV reactors is a closed fuel cycle implementation. The enhancement of the efficiency of fissile material utilization while simultaneously reducing long-lived radioactive waste, is the main reason why the system is designed [5]. The fission of plutonium by fast neutrons and neutron capture by U-238 enables the concurrent occurrence of plutonium burning and breeding processes. The process's effectiveness is strongly determined by the reactor core design, including the distribution of material, core configuration, and fuel composition [6]. The application of plutonium management strategies specifically designed for Generation IV systems have the potential to directly contribute to the strategic goals of these reactors, particularly sustainability, safety, and waste minimization [7]. Within the framework, the management of minor actinides (MA) plays a crucial role in promoting the concept of a closed fuel cycle and decommissioning the nuclear energy system [8].

A small modular reactor (SMR) is a small nuclear reactor with a power capacity below 300 MW designed for high modularity and ease of assembly process [9]. The idea of integrating the SMR concept into a gas-cooled fast reactor system is attracting increasing research attention. First, this modular concept offers flexibility in integration with the electricity grid, and potential application in areas with limited energy infrastructure. Furthermore, the advantages of gas-cooled fast reactors with the fast neutron spectrum characteristics of GFR support efficient fuel utilization and effective nuclear waste management [10]. Hence, small modular GFR can be utilized as a transmutation facility or the process of converting long-lived isotopes (MA) into short-lived or even useful isotopes through exposure to neutron flux can be carried out by introducing MA isotopes into fuel in reactor core. Therefore, research on identification of impact of minor actinide addition on burnup process and heavy nuclide evolution in UN-PuN fueled small modular gas-cooled fast reactors is relevant for further research.

2. Literature review and problem statement

The paper [11] presents the result on neutronic analysis of 200MWth GFR design with Uranium-Plutonium nitride (UN-PuN) fuel using the SRAC code. The results show that the UN-PuN fuel can sustain long-term operation without refueling. However, this study still uses the JENDL3.2 nuclear database, so it is possible that improvements are needed to the fission product and minor actinoid data.

The paper [12] presents the result of comparation of UN-PuN and Thorium nitride (ThN) fuels in a 300MWTh GFR design for 20 years of operation without refueling. This study found that these fuels can achieve a burnup time of over 20 years with an excess reactivity of approximately 1%. Both UN-PuN and ThN fuels have similar average power densities, but UN-PuN fuel has a lower maximum power density than ThN fuel. However, this study is still limited to criticality (*k-eff*) and power density values, so further analysis of their burnup characteristics is needed.

The paper [13] shows neutron analysis using the MCNP code. This study compared Uranium-Plutonium carbide (UC-PuC) and UN-PuN fuels with plutonium contents of 5–25%. The results showed that the effective multiplication factor (*k-eff*) value increased along with increasing plutonium content. Furthermore, the *k-eff* reached 1.2 at 20% fissile plutonium, a supercritical state that can disrupt reactor operation. These results demonstrate the potential of nitride and carbide fuels to support fast spectrum reactors, and determining the appropriate percentage of fissile fuel can also improve fuel efficiency in reactors.

The paper [14] presents a study of 300MWTH GFR with UN-PuN fuel using SRAC with an additional COREBN module. The results of this design optimization study obtained the most optimal results with a *k-eff* value of 1.0031841 at a fuel fraction of 64%. However, this study still produces optimization at a fairly high fuel fraction, so that readjustments to the configuration are needed to obtain a better configuration.

The paper [15] presents neutronic studies on thorium nitride-fueled GFRS using the OpenMC code with the ENDF/B-VII.1 nuclear library. The study shows that the thorium nitride-fueled GFR can maintain critical conditions for up to 15 years of operation, demonstrating stable burnup performance.

The paper [16] presents examining the influence of fuel geometry and configuration on the neutronic characteristics of GFRs. This study compared hexagonal and square Uranium carbide (UC) fuel pins using the SRAC code and CITATION. The results show that the hexagonal configuration provides better reactor efficiency.

The paper [17] compared heterogeneous core configurations using three and five variations of UN-PuN fuel GFRs using OpenMC. The results showed that a configuration with a five percent variation provided better neutronic performance than a configuration with a three percent variation. Therefore, geometry determination is a consideration in neutronic calculation simulations.

The study [18] related to plutonium-based fuels has also been validated in generation IV reactors such as MSRs, where a high PuF_3 composition in the RGP affects neutron characteristics, leading to increased Macro XS for fission, absorption, and total reaction. Meanwhile, a paper [19] demonstrated the incorporation of minor actinides (MA) in PWR-type reactors. In this study, americium (Am) has been shown to be effective as a burnable poison in PWRs and VVER-1200s, with characteristics similar to Gd_2O_3. Another study [20] demonstrated that the addition of minor actinides (MA) to GFRs, such as Np-237 and Am-241, decreased the *k-eff* value but did not significantly affect the power distribution. Recent paper [21] research has shown that certain fuel rod configurations using MA produce the desired critical values. However, the addition of Am-241 is likely to lead to subcritical conditions at the end of combustion. Furthermore, research has shown that the burnup of Np-237 and Am-241 produces radiopharmaceutical fission products such as Tc-99m, Sr-89, Y-90, Sm-153, and I-131.

All this allow to conclude that it is expedient to conduct research devoted to evaluating the influence of minor actinides (Pa-231, Am-241, and Np-237) in UN-PuN on key neutronic performance in small modular GFR burnup. A way to overcome these difficulties can be to perform a more detailed burnup analysis for UN-PuN fuel on small modular GFR using SRAC-COREBN and JENDL4.0 as nuclide database. This approach was used in [14, 22]. The hope is to ensure that minor actinides addition in UN-PuN fuel in small modular GFR support efficient fuel utilization and effective nuclear waste management.

3. The aim and objectives of the study

The aim of this study is to identify the impact of minor actinides (Pa-231, Am-241, and Np-237) in UN-PuN on key neutronic performance in small modular GFR burnup. This will allow more efficient fuel utilization and enhanced operational reliability of the proposed GFR system.

To achieve these aims, the following objectives are accomplished:

– to simulate the *k-eff* value and macroscopic cross-section shifts to determine reactivity control;

– to analyze the conversion ratio (CR) and the evolution of heavy nuclide inventory throughout the burnup period;

– to assess the potential of radiopharmaceutical isotope production resulting from neutron spectrum changes.

4. Materials and methods

The object of this study is small modular GFR fueled UN-PuN with addition of minor actinides (MA).

This study only focuses on the scope of neutron parameters which will be simulated computationally and the analysis is based on established nuclear data libraries. The main hypothesis of this study is that addition of minor actinides improving initial reactivity control, while ensuring fuel burnup stability, and enabling long-term radioactive waste transmutation.

This study is conducted under several assumptions. The reactor was assumed to operate under steady-state conditions, and the neutron energy spectrum is represented using a 107-group structure in the fast energy range. Nuclear database was taken from the JENDL-4.0. Thermal-hydraulic feedback effects was not coupled in the present model, and the geometry of the core was assumed to remain unchanged during burnup. Furthermore, several simplifications were adopted in the present analysis. The neutronic behavior of the reactor is modelled using the multigroup neutron diffusion approach in three-dimensional (XYZ) geometry.

The core design was based on a previously developed design in the study by [14]. The reactor design specifications used in this study are presented in Table 1.

Table 1

Reactor specification

Parameter	Specification
Power	300 MW
Core geometry	Cylinder pancake
Burn-up period	10 years
Fuel material	Uranium-plutonium nitride (UN-pun)
Fuel pin cell	Hexagonal
Active height core	100 cm
Active diameter core	240 cm
Cladding	Silicon carbide
Coolant	Helium
Density (gr/cm^3)	14.32
Pin pitch (cm)	1.45

The reactor model used maintains the configuration of pancake cylinder core with a diameter of 300 cm and height of 100 cm, as shown in Fig. 1. The core consists of fuel assemblies and reflector regions arranged to maintain a fast neutron spectrum. The reflector region surrounds the active core to reduce neutron leakage and enhance neutron economy.

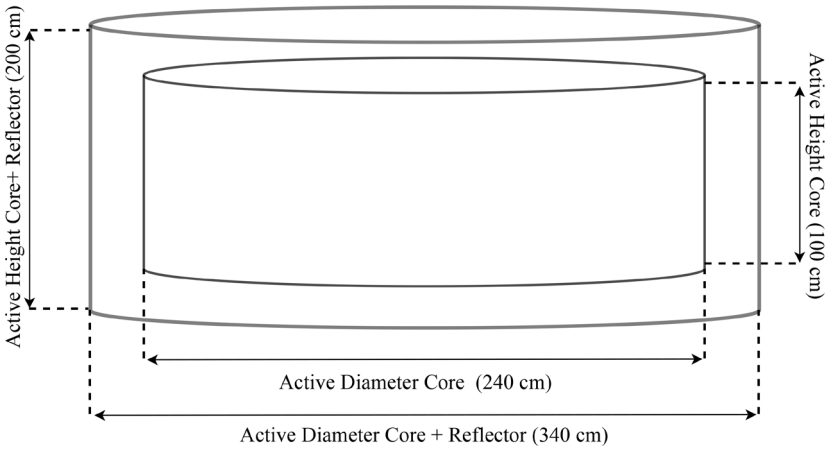

Fig. 1. Reactor core geometry

The fuel used in this study is uranium-plutonium nitride (UN-PuN) with the uranium used being natural uranium consisting of two main isotopes, U-235 and U-238 with natural abundances of 0.72% and 99.28%, respectively. Meanwhile, the plutonium used is waste plutonium from operating nuclear power plants. Minor actinides, including americium, neptunium, and protactinium, are loaded into the fuel matrix in selected cases to assess their influence on neutronic behavior during burnup. The fuel composition is uniformly distributed within the fuel region for each analyzed configuration. The hexagonal fuel pin was used in this study, as shown in Fig. 2.

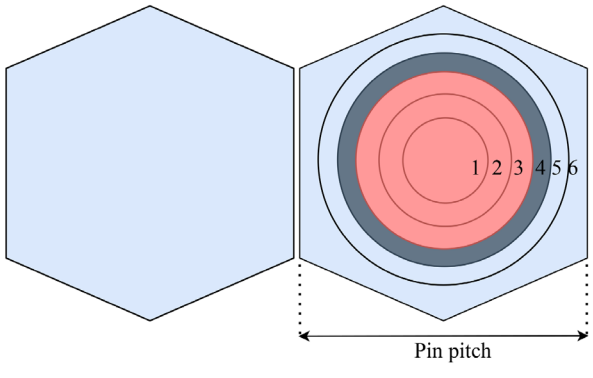

Fig. 2. Hexagonal fuel pin

The neutronic calculation using SRAC-COREBN was divided into two steps. The first step involves burn-up calculations at the cell (fuel pin) using the PIJ module in SRAC and the JENDL-4.0 employed as nuclear data library. The PIJ input contains information on the material fuel used, the atomic number density, the energy group, the geometrical buckling, the power level, and the burn-up period.

SRAC (standard reactor analysis code) is a computational system for neutronic analysis of various reactor types developed by JAEA. In SRAC, neutron flux distributions are obtained by solving the multigroup neutron diffusion equation,

which describes neutron balance considering production, absorption, and leakage within the system [23]. The multigroup neutron diffusion equation can be expressed mathematically in equation (1)

$$-\vec{\nabla}.D_g\vec{\nabla}\phi_g+\Sigma R_g\phi_g=\frac{\chi_g}{k_{eff}}\sum_{g^i}^{g^n}\nu_{g^i}\Sigma f_{g^i}\phi_{g^i}-\sum_{g^i}^{g^n}\Sigma_{sg}\to g^i\phi_{g^i}. \quad (1)$$

Output of PIJ calculation consist of homogenized macroscopic cross-section data tabulated in the MACRO file (PDS format). These data are subsequently converted into PS format using the PDStoPS utility, which serves as input for the COREBN module.

The second stage involves 3-dimensional core burn-up calculations using the COREBN code. COREBN is an additional code of the SRAC system for multi-dimensional core burn-up calculations based on diffusion theory and interpolation of macroscopic cross-sections tabulated to local parameters such as burn-up degree, moderator temperature, and so on. COREBN requires macroscopic cross-section data in PS format generated from PIJ calculations. Additional input parameters include reactor operating conditions such as thermal power, operation time, core geometry configuration, fuel loading pattern, control rod configuration, and non-fuel structural components. These operating states are defined through the HIST state code prior to executing COREBN [24]. The computational scheme of SRAC-COREBN is presented in Fig. 3.

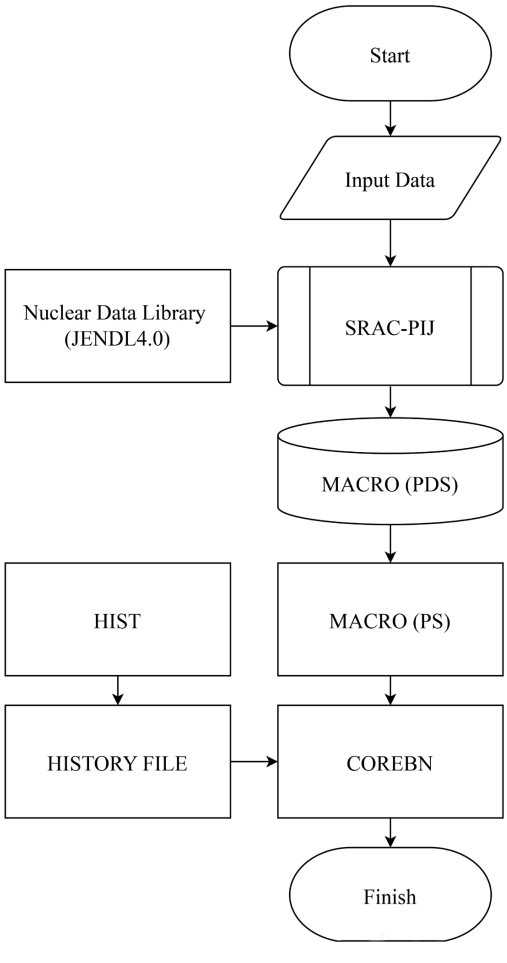

Fig. 3. SRAC-COREBN calculation scheme

The output of the COREBN code will contain the effective multiplication factor (*k-eff*) and macroscopic cross-section shift to determine reactivity control, conversion ratio (CR) to see the evolution of the heavy nuclide inventory throughout the burning period, and the change in atomic density of the isotope as a potential value for radiopharmaceutical isotope production resulting from changes in the neutron spectrum.

5. Results on the impact of minor actinides addition into UN-PuN fuel in small modular gas cooled fast reactor

5. 1. Effective multiplication factor (*k-eff*) value and macroscopic cross-section shifts during burnup

This study focuses on the analysis of minor actinide transmutation within a heterogeneous configuration effecting burnup. This is based on previous research which showed that heterogeneous configurations have the advantage of reducing power peaking, thereby increasing safety margins [22]. The initial stage involved neutronic assessment of the homogeneous core configuration of the 300 MW GFR employing UN-PuN fuel with plutonium fractions ranging from 6% to 15%. The homogeneous core represents a configuration with uniform fuel composition across all fuel pins. The outcomes of the homogeneous-core assessment subsequently served as the basis for determining the baseline plutonium composition that satisfies the design reactivity criteria.

Fig. 4 presents the *k-eff* values of the homogeneous core throughout the reactor operation period. In general, the increase in the effective multiplication factor (*k-eff*) with increasing plutonium fraction indicates that *k-eff* is strongly influenced by the amount of fissile material in the fuel. Plutonium plays a major role in the fission reaction in the fast neutron spectrum, so increasing its fraction directly increases the probability of fission. The downward trend in *k-eff* over the burn-up period across all configurations indicates plutonium consumption as the primary fuel, where the fission contribution decreases due to the accumulation of fission products and the resulting neutron spectrum shifts. The optimal plutonium fraction is identified through the *k-eff* behavior, specifically the fraction that maintains critical condition ($k\text{-}eff = 1$) during burn-up period. A critical condition means a stable neutron population capable of sustaining reactor power. This indicates that the reactor can preserve a steady fission reaction, making it an important indicator in core design evaluation.

Plutonium fractions of 6–8% fuel correspond to a condition of subcriticality ($k\text{-}eff < 1$) throughout the operation period, indicating a reduction in neutron production within the reactor. This condition is non-ideal, as it is insufficient to sustain the fission reaction. In contrast, for plutonium fractions of 9–15%, the *k-eff* values are in a supercritical state ($k\text{-}eff > 1$). Based on these results, a plutonium fraction of 10% is selected as the representative average fuel composition, as it exhibits the most stable *k-eff* behavior and remains closest to the critical condition.

Subsequently, the determination of the heterogeneous configuration was carried out by constructing four scenarios, as presented in Table 2. The variation was implemented by adjusting the plutonium percentage in each core zone while maintaining an average fuel composition identical to that of the optimal homogeneous configuration.

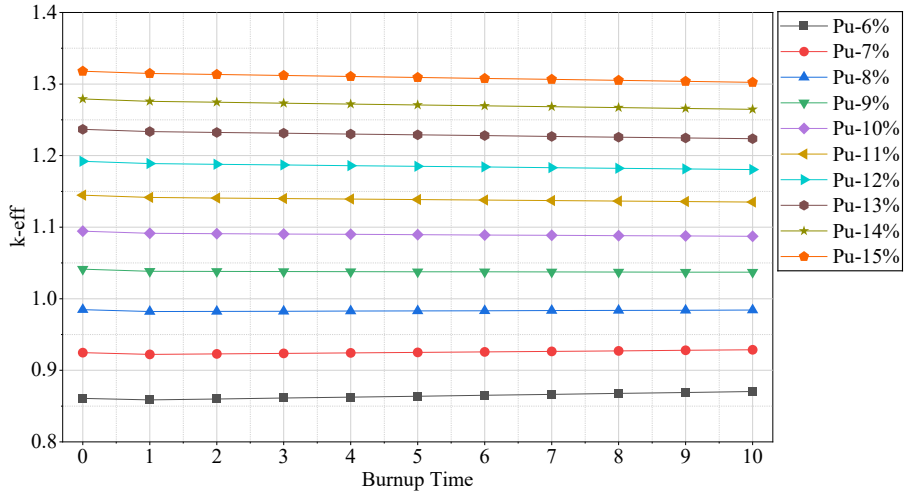

Fig. 4. *K-eff* values for the homogeneous core configuration

Table 2

Plutonium percentages in the heterogeneous core

Case	Plutonium percentage (%)		
	U1	U2	U3
1	6	10	14
2	7	10	13
3	8	10	12
4	9	10	11

Fig. 5 displays *k-eff* result for all four heterogeneous configurations, exhibiting a reduction in *k-eff* at the beginning of operation compared to homogeneous configuration. The *k-eff* are able to maintain ≈ 1 throughout the operational period, signifying that the system can sustain a critical state. This behavior indicates that all configurations possess the capability to maintain the fission reaction. Based on this stability *k-eff*, the configuration in case 1 is selected as the optimum condition for the next step, namely the loading of minor actinides (MA) into fuel. The minor actinides considered in this study are Am-241, Np-237, and Pa-231.

The MA addition scenario is carried out by introducing the isotopes Am-241, Np-237, and Pa-231 as single isotope into selected configuration. To identify the neutronic characteristics associated with each MA, the isotopes Am-241, Np-237, and Pa-231 are varied from 1% to 5%. For comparison purposes, this study maintains a constant total heavy metal (HM) content, ensuring that the resulting reactivity changes originate solely from the intrinsic neutronic behavior of the respective MA.

Fig. 6 presents the *k-eff* values after the addition of minor actinides, namely Am-241, Np-237, and Pa-231. All *k-eff* values at the early burn-up period are relatively lower than the *k-eff* values of the heterogeneous core in case 1 without minor actinides. In Fig. 6, *a*, the addition of Pa-231 generally yields the lowest *k-eff* values compared to the cases with Am-241 and Np-237. In Fig. 6, *b*, the addition of Am-241 results in higher initial *k-eff* values compared to the Pa-231 addition. Furthermore, for the case with Np-237 addition, the *k-eff* values are higher than those obtained with the other minor actinides, as shown in Fig. 6, *c*.

As a comparison of the *k-eff* values, the optimized results from each case are compiled into a single graph, as shown in Fig. 7. The calculation results indicate that the *k-eff* values gradually decrease as burn-up progresses for all scenarios, although with different patterns and rates of decline.

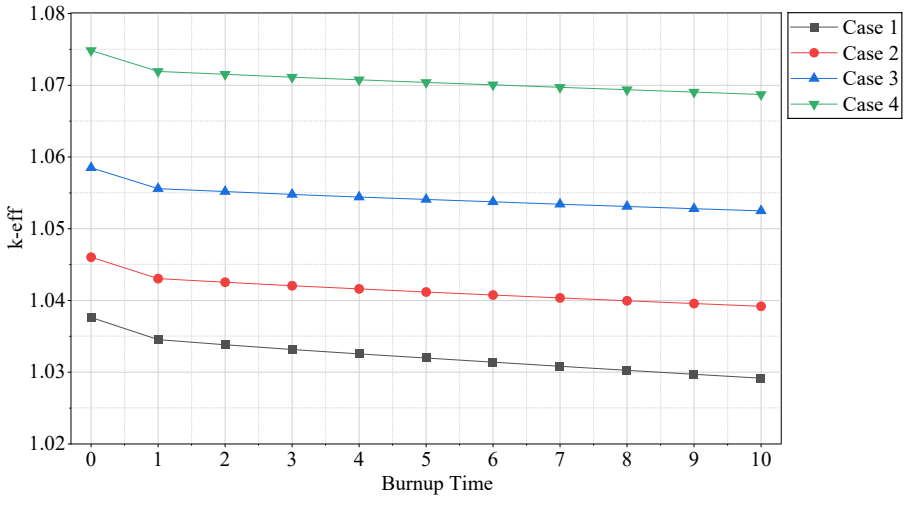

Fig. 5. *K-eff* values for the heterogeneous core configuration

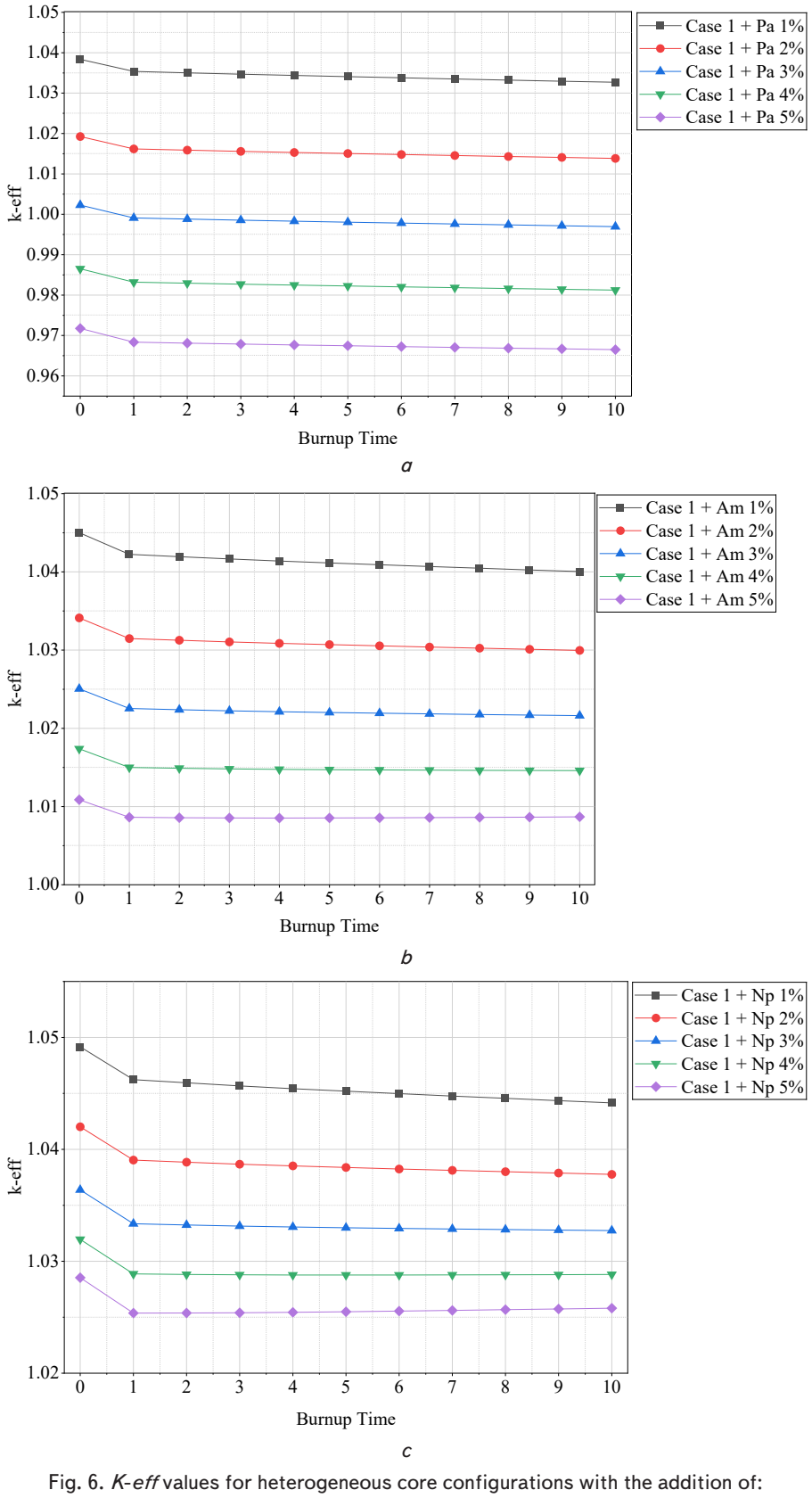

Fig. 6. *K-eff* values for heterogeneous core configurations with the addition of: *a* – Pa-231; *b* – Am-241; *c* – Np-237

Fig. 7 shows the homogeneous Pu-10% case has the highest *k-eff* with a relatively small decrease, indicating better reactivity stability. In contrast, the heterogeneous core configuration in case 1 displays a lower initial *k-eff* and a more significant reduction compared to the homogeneous core, suggesting a higher sensitivity to burn-up. The addition of minor actinides such as 5% Am, 5% Np, and 2% Pa results in lower *k-eff* values compared to the case without MA.

The next analysis is the macroscopic cross-section shift during burnup period. Fig. 8 shows value of absorption, scattering, and fission macroscopic cross-section for each optimized case. These values are parameters that represent the probability of a reaction on a neutron interacting with the material.

Fig. 8, *a* present the value of macroscopic absorption ($\sum a$) for each optimized configuration. The $\sum a$ values of the heterogeneous configuration (case 1) are slightly higher than those of the homogeneous Pu-10% configuration, particularly in the intermediate to fast energy groups. In contrast, the heterogeneous cases with minor actinide (MA) additions exhibit a more significant increase in $\sum a$ across the entire energy spectrum, with the largest rise occurring in the Am-5% case.

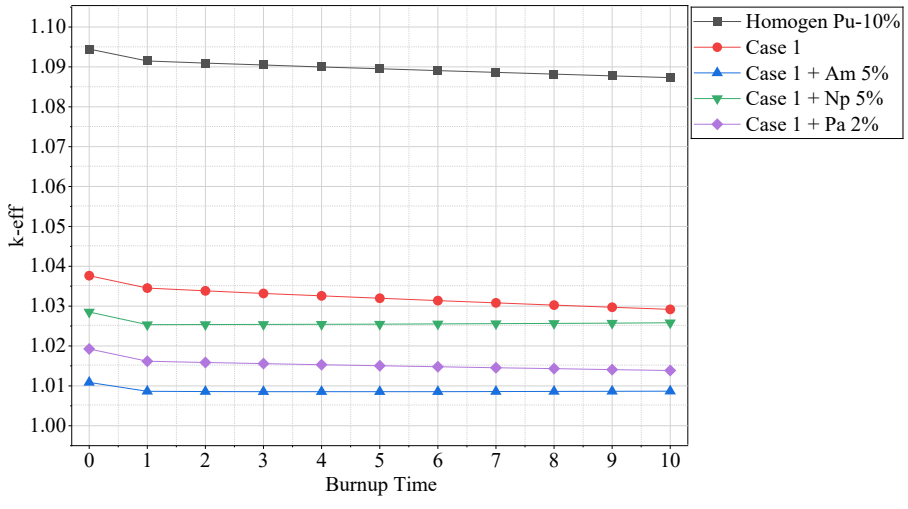

Fig. 7. Comparison of *k-eff* values for each case

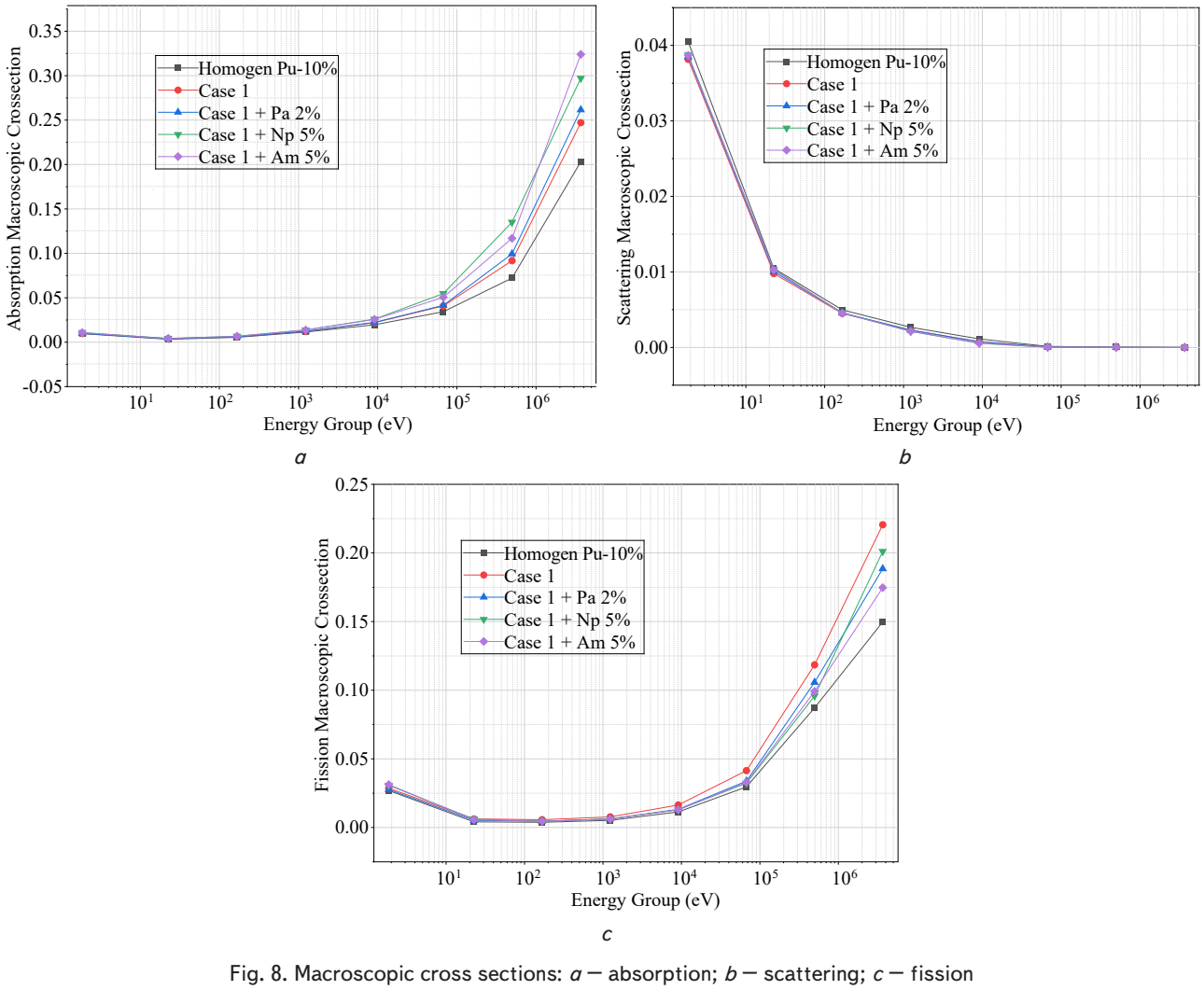

Fig. 8. Macroscopic cross sections: *a* — absorption; *b* — scattering; *c* — fission

Fig. 8, *b* illustrates the value of macroscopic scattering ($\sum s$) for all optimal configurations. Overall, $\sum s$ exhibits nearly identical patterns across all energy groups for the homogeneous, heterogeneous, and addition of MA cases.

Fig. 8, *c* shows the variation of macroscopic fission ($\sum f$) for each optimal configuration. The heterogeneous configuration in case 1 (without MA) demonstrates slightly higher $\sum f$ values than the homogeneous Pu-10% configuration, particularly in the fast energy group.

5. 2. Conversion ratio and evolution of heavy nuclides

Fig. 9 demonstrates that the conversion ratio increases with burn-up for all fuel variations. Cases with MA additions consistently show higher conversion ratios compared to both the homogeneous configuration and the heterogeneous case 1. This shows that the addition of MA to small modular GFRs does not affect the breeder properties of GFR, where the reactor consumes more fissile material than it consumes.

The calculation results in Table 3 show the changes in nuclide mass that directly affect the CR in Fig. 9. The comparison between the number of fertile nuclides converted into fissile nuclides during the operating period provides an overview of the fuel regeneration efficiency in the reactor.

The inversion ratio across all configurations remains within ≈ 50% (as shown in Table 4), indicating that the fissile depletion rate remains consistent even with the incorporation of minor actinides. In addition, the decrease in for all cases confirms that the breeding process proceeds effectively, in agreement with the conversion ratio (CR) values greater than 1. There is no indication that the MAs undergo excessively rapid or excessively slow depletion, meaning that they function effectively as burnable absorbers while simultaneously participating in transmutation mechanisms without introducing significant reactivity penalties.

5. 3. Potential production of radiopharmaceutical isotopes

The next analysis for the probability of radiopharmaceutical isotopes production. Radiopharmaceutical materials are usually used for medical purposes, so their decay time or half-life is very short, lasting just days, hours, minutes, or even seconds. Fig. 10 present radiopharmaceutical isotopes production during operation period.

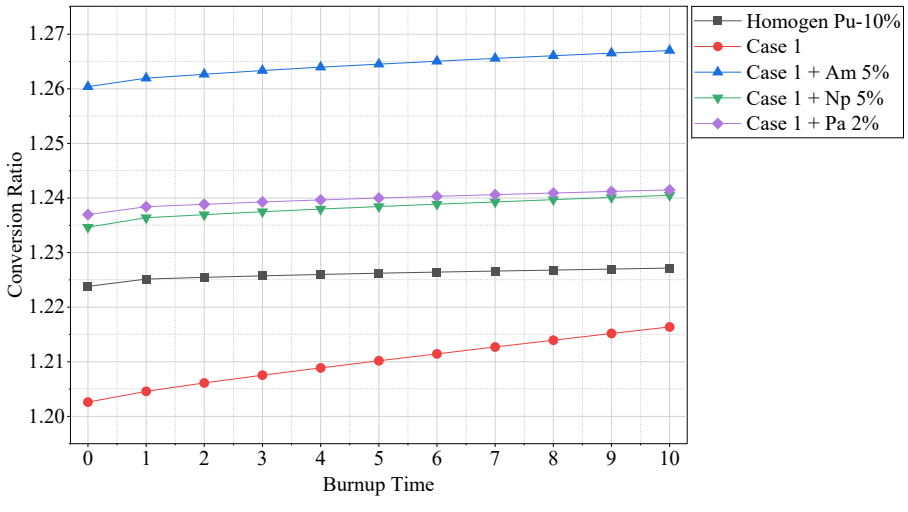

Fig. 9. Comparison of conversion ratio for each case

Table 3

Heavy nuclide inventory (grams)

Isotope	Period	Case				
		Homogeneous Pu-10%	Case 1	Case 1 + Am 5%	Case 1 + Np 5%	Case 1 + Pa 2%
U-235	INITAL	5.46E+05	5.43E+05	5.18E+05	5.20E+05	5.23E+05
	FINAL	2.66E+05	2.65E+05	2.53E+05	2.54E+05	2.55E+05
U-236	INITAL	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	FINAL	1.31E+03	1.31E+03	1.15E+03	1.12E+03	1.28E+03
U-238	INITAL	7.53E+07	7.49E+07	7.15E+07	7.17E+07	7.21E+07
	FINAL	3.74E+07	3.73E+07	3.55E+07	3.57E+07	3.59E+07
Pu-239	INITAL	4.98E+06	5.03E+06	4.79E+06	4.80E+06	4.83E+06
	FINAL	2.52E+06	2.54E+06	2.42E+06	2.42E+06	2.44E+06
Pu-240	INITAL	2.05E+06	2.08E+06	1.97E+06	1.83E+06	1.99E+06
	FINAL	1.02E+06	1.03E+06	9.84E+05	9.87E+05	9.93E+05
Pu-241	INITAL	9.67E+05	9.78E+05	9.30E+05	9.33E+05	9.38E+05
	FINAL	4.54E+05	4.57E+05	4.37E+05	4.39E+05	4.40E+05
Pu-242	INITAL	3.31E+05	3.34E+05	3.18E+05	3.19E+05	3.21E+05
	FINAL	1.66E+05	1.67E+05	1.60E+05	1.60E+05	1.61E+05
Inversion ratio		49.86%	49.80%	49.82%	49.81%	49.86%

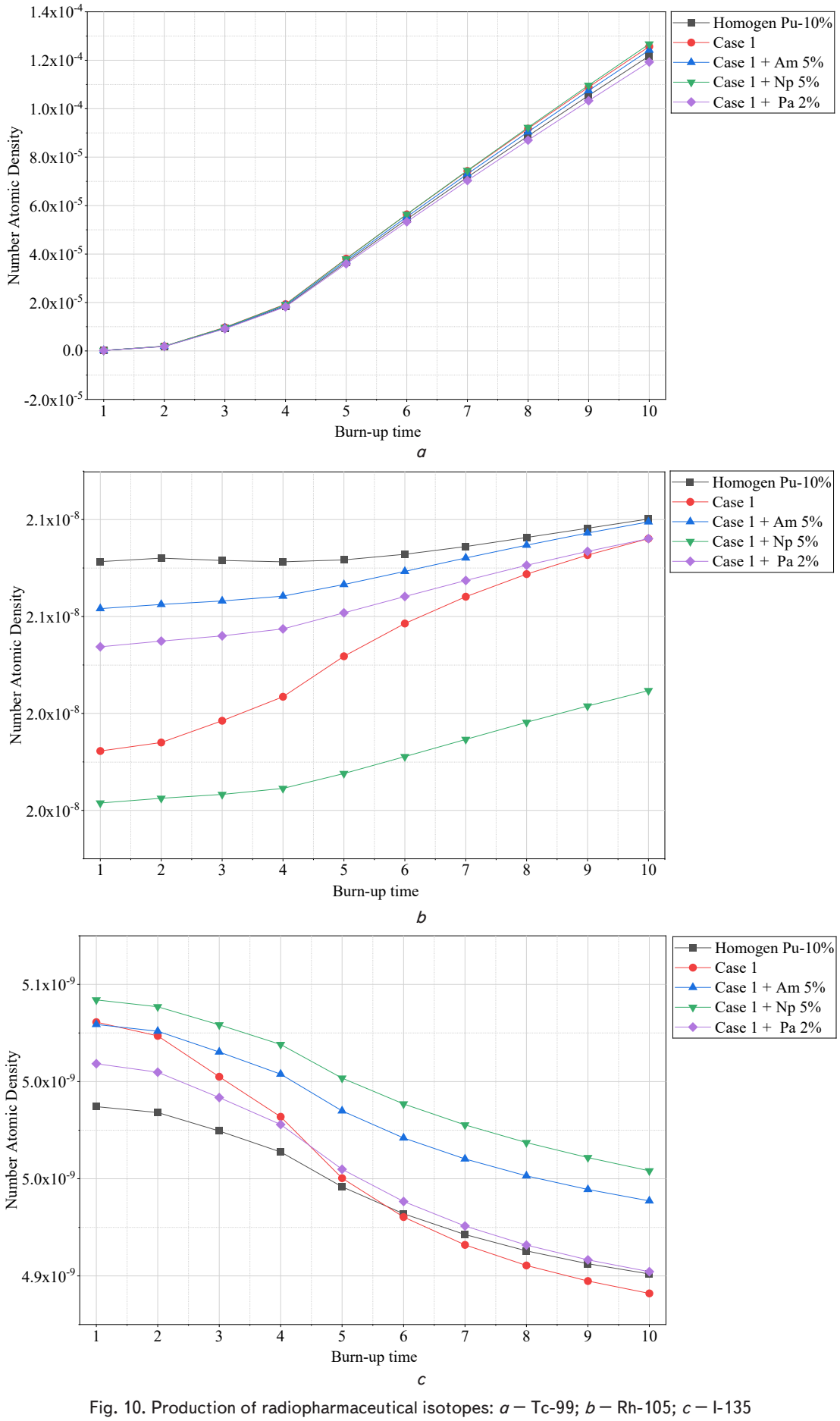

Fig. 10. Production of radiopharmaceutical isotopes: *a* – Tc-99; *b* – Rh-105; *c* – I-135

The observed trend in Tc-99 (Fig. 10, *a*), the concentration of Tc-99 increases significantly with burn-up. This trend is consistent with the formation mechanism of Tc-99, which originates from the fission of heavy isotopes such as U-235 and Pu-239, as well as from the decay of Mo-99. In fast-spectrum reactors, the yield of Tc-99 is generally higher than in thermal reactors due to the larger fission cross sections of fissile isotopes at high energies. From a radiopharmaceutical perspective, Tc-99 is an important indicator for the potential production of Tc-99m, the most widely used medical isotope for diagnostic imaging.

Furthermore, Fig. 10, *b* shows that the atomic density of Rh-105 increases steadily throughout the burn-up period. The differences among configurations are clearly observable, the Am-241 and Np-237 additions exhibit the highest concentrations of Rh-105, while the homogeneous 10% and heterogeneous case-1 configurations produce the lowest values. These differences are closely associated with the fission contribution from Am-241 and Np-237, which have larger fission cross sections in the fast spectrum compared to the fertile isotopes in the primary fuel. The enhanced production of Rh-105 in the MA cases is also influenced by spectral shifts that increase the probability of the Pd $\rightarrow$ Rh capture pathway. Similar behavior was also observed for I-135, which is used as an indicator of I-131 formation (Fig. 10, *c*). Higher I-135 production in the configuration with minor actinides indicates an increased fission rate, ultimately increasing the potential for the formation of medically valuable radioactive isotopes.

6. Discussion on the impact of minor actinides addition into UN-PuN fuel in small modular gas cooled fast reactor

The addition of minor actinides to UN-PuN fuel showed a decrease in *k-eff* values during combustion compared to the case without minor actinides, as shown in Fig. 6. For the addition of Pa-231 (Fig. 6, *a*), at concentrations of 1% and 2%, the *k-eff* values remained within the critical region throughout the burnup period. In contrast, the 3% Pa case failed to maintain criticality until the end of burnup. At higher concentrations (4–5%), the *k-eff* values failed to reach criticality at any point during fuel cycle. These results indicate that Pa-231 acts as an early neutron absorber, limiting the availability of neutrons for fission reactions.

In contrast, in the case of Am-241 addition, the *k-eff* values showed a significant reduction compared to the reference configuration, as presented in Fig. 6, *a*. This is consistent with the high neutron absorption cross section of Am-241, which directly reduces the initial system reactivity. This is consistent with research [19] showing that Am-241 is a neutron absorber. Furthermore, the *k-eff* value for the case with the addition of Np-237 is higher than that obtained with the other minor actinides, as shown in Fig. 6, *c*. This indicates that although Np-237 absorbs neutrons, a portion of its isotopic population can contribute to fission via the (n, γ) reaction that converts Np-237 to Pu-239. Consequently, the addition of Np-237 increases the criticality of the system more effectively than Am-241 or Pa-231. These results indicate that minor actinides generally reduce the reactivity of the system, although the magnitude changes during combustion remain within a relatively controlled range.

For the macroscopic cross-section, changes are quite noticeable in the macroscopic absorption ($\sum a$) and macroscopic fission ($\sum f$). Meanwhile, the macroscopic scattering ($\sum s$) has almost identical values for all cases. The macroscopic absorption ($\sum a$) value for the heterogeneous configuration (case 1) is slightly higher than for the homogeneous Pu-10% configuration, especially in the intermediate to fast energy range (Fig. 8, *a*). This is consistent with previous studies of heterogeneous configurations. This increase indicates a shift in the flux distribution resulting from the distribution of fissile-to-fertile nuclides in the heterogeneous geometry, which increases the probability of neutron capture by U-238. In contrast, the heterogeneous case with the addition of minor actinides (MA) shows a more significant increase across the spectrum, with the largest increase occurring in the Am-5% case. This increase is consistent with the characteristics of MA, which has high capture in the fast spectrum. This result aligns with the comparative *k-eff* trend, where Am-5% results in the largest reduction in *k-eff* due to increased neutron loss through absorption mechanisms.

The heterogeneous configuration in case 1 (without MA) shows slightly higher macroscopic fission values ($\sum f$) than the homogeneous configuration of Pu-10%, especially in the fast energy group. This increase indicates that the distribution of fissile isotopes in the heterogeneous geometry increases the probability of fission in certain regions. In the case with the addition of minor actinides, the $\sum f$ also increases compared to the homogeneous configuration. This is due to the ability of Np-237 and Am-241 to undergo fission at the fast energy spectrum. However, the magnitude of the increase in the configuration with MA remains relatively smaller than the corresponding increase shown in Fig. 8, *a*.

Fig. 9 shows that all cases with MA addition consistently exhibit higher conversion ratios compared to the case without MA addition. This suggests that, in the fast neutron spectrum, certain minor actinides contribute to fission reactions and fissile isotope conversion, thus generating additional neutrons. The increase observed in Fig. 8, *c* for the configuration with MA addition supports breeding behavior, where fission neutrons produced by minor actinides increase the neutron number, thereby increasing the probability of neutron capture by U-238. This demonstrates consistency between the conversion ratio trend and the macroscopic cross-sectional pattern presented in Fig. 8.

Based on the analysis of the heavy nuclide inventory and conversion ratios (CR), the addition of minor actinides (Am-241, Np-237, Pa-231) exhibits stable burnup behavior and does not interfere with the consumption of the primary fissile fuel. Table 3 shows inversion ratio in all configurations remains within $\approx$ 50%, indicating that the fissile depletion rate remains consistent even with the incorporation of minor actinides. Furthermore, the decrease in the mass of heavy nuclide in all cases suggests that the breeding process is effective, corresponding to conversion ratio (CR) values greater than 1. There is no indication that the masses are depleting too rapidly or too slowly, meaning they are effectively functioning as a burnable poison while simultaneously participate in the transmutation mechanism without incurring significant reactivity penalties. Overall, the MA addition in all configurations demonstrates a stable burnup confirm the possibility of radiopharmaceutical isotope production as shown in Fig. 10.

These results indicate that small modular GFR with minor actinide management not only contribute to energy

production and waste transmutation but also have the potential to support radiopharmaceutical production as an additional benefit. However, this study still has several limitations. The analysis is based on simulation results using the SRAC code, which uses solutions to the diffusion equation involving modelling assumptions and steady-state reactor conditions. Consequently, the results obtained represent theoretical neutronic behavior of the proposed reactor configuration based on multigroup diffusion calculations. Furthermore, sensitivity analysis on nuclear data uncertainty may be conducted to assess the impact of cross-section variations on reactivity and burnup predictions.

7. Conclusions

1. The addition of minor actinides (Pa-231, Np-237, and Am-241) into UN-PuN proven to shift the *k-eff* curve downwards compared to the configuration without MA and the magnitude depends on the type and concentration of minor actinides. This indicates that the addition of MA can affect criticality. Meanwhile, macroscopic cross-section shift analysis is noticeable seen in $\sum a$ and $\sum f$. This indicates that minor actinides can function effectively as neutron absorbers, with $\sum a$ increasing as *k-eff* decreases. For the $\sum f$, it indicates the ability of Np-237 and Am-241 to undergo fission at the fast energy spectrum.

2. Conversion ratio (CR) analysis shows that CR > 1 for all configurations, with an increase in plutonium breeding efficiency in the case of MA addition. This is supported by inventory evolution data showing stability of U-235 and Pu-239 burnup fractions, meaning MA does not overburden the primary fuel consumption. These results differ from standard UN-PuN fuel because the use of UN-PuN with MA addition provides a higher metal density, allowing for an inversion ratio of approximately 50%, extending the core life cycle.

3. Evaluation of isotope production potential shows that the fast neutron spectrum modified by the presence of AM additions is capable of producing Tc-99, Rh-105, and I-135, which can be seen from the increase in atomic density. From a radiopharmaceutical perspective, Tc-99 is an important indicator for the potential production of Tc-99m, the most widely used medical isotope for diagnostic imaging. Similar behavior was also observed for I-135, which is used as an indicator of I-131 production.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Manuscript has associated data in a data repository.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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Authors' contributions

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