Neutronic Analysis of an Over-coated TRISO-particle Bed Reactor for Micro Reactor Applications

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Keywords : Over-coated TRISO-particle Bed Reactor (OTBR), High-Temperature Gas-cooled Reactor (HTGR)

1. Introduction

High-temperature gas-cooled reactors (HTGRs) have gained considerable attention among Gen-IV designs, particularly for micro-reactor applications that demand the highest level of safety. Their high thermal efficiency, potential uses in hydrogen production and process heat supply, and the exceptional safety performance of TRISO fuel make them highly attractive options.

A key design requirement for micro-reactors is extremely simplified operation. In this regard, the fuel-shuffling schemes typically used in pebble-bed or prismatic reactors are impractical, as they introduce significant complexity in operation, maintenance, and inspection.

Furthermore, concerns remain regarding the structural integrity of pebbles during re-circulation and the potential failure of TRISO particles during pebble or compact fabrication, which raises issues such as tritium release. In addition, the considerable release of ^{110m}Ag at fuel temperatures around 1600 °C [1] poses a challenge for maintenance.

One possible way to address these challenges is to adopt a stationary fuel scheme by simply applying an additional graphite coating to TRISO particles. Direct cooling of individual TRISO particles may help maintain lower fuel temperatures and reduce the release of ^{110m}Ag. The main objective of this study is therefore to assess the neutronic feasibility of an Over-coated TRISO-particle Bed Reactor (OTBR) as a 20 MWth micro-reactor. For the neutronic analyses, the Serpent 2.2.1 Monte Carlo code with the ENDF/B-VII.1 library was employed.

2. Description for Over-coated TRISO-particle

Fig. 1 (left) shows the configuration of a conventional TRISO particle, which consists of a 500 μm UCO kernel, a porous graphite buffer, an inner pyrolytic carbon (IPyC) layer, a SiC layer, and an outer pyrolytic carbon (OPyC) layer. The right-hand figure illustrates the over-coated TRISO, where an additional graphite coating is introduced. The detailed geometry and densities of the TRISO particle constituents are summarized in Table I.

It should be noted that the thickness of the graphite over-coat is expressed by Eq. (1), which defines the volume fraction (V.F) of the TRISO particle within the over-coating layer. For example, 100% TRISO V.F represents a conventional TRISO particle without an over-coat, whereas the right-hand figure in Fig. 1 represents the case of 10% TRISO V.F. The packing fraction (P.F) of over-coated TRISO particles was set to 60% under the assumption of random distribution, with CO_2 coolant occupying the remaining 40% of the volume. For the neutronic calculations, an isothermal condition of 900 K was assumed, and the thermal scattering law of graphite was applied to the buffer, PyC, and over-coat layers.

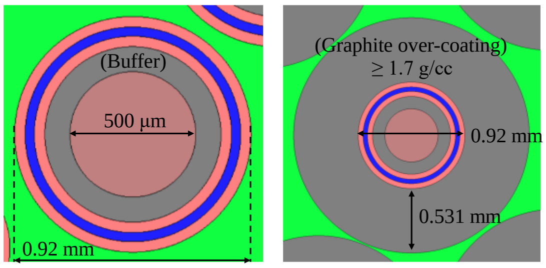

Fig. 1. Conventional TRISO (L) and Over-coated TRISO (R)

Table I: Material densities

Material	$UC_{0.5}O_{1.5}$	Over-coat	CO_2
ρ (g/cm^3)	10.8	1.7	1.84 E-3
Material	Buffer	SiC	PyC
ρ (g/cm^3)	1.05	3.18	1.9
Size	95 μm	35 μm	40 μm

$$TRISO\ V.F\ (\%) = \left(\frac{OPyC\ radius}{Over-coat\ radius}\right)^3 \times 100 \quad (1)$$

3. Neutronic Analyses of Over-coated TRISO-particle Bed Reactor (OTBR)

3.1 Sensitivity Analyses with a Square Lattice model

To investigate the neutronic characteristics of the graphite over-coat and determine the appropriate coating thickness, lattice calculations were conducted using a square lattice model of a single TRISO particle with reflective boundary conditions, as shown on the right side of Fig. 2. To represent the 60% P.F of a single TRISO particle in the square lattice, the outermost surface of the sphere was truncated, while maintaining equivalent neutronic properties to those of the explicit model on the left. The left-hand model depicts a TRISO cluster with 60% P.F in a 5 cm cube, which serves as the basic unit for the 3D reactor model.

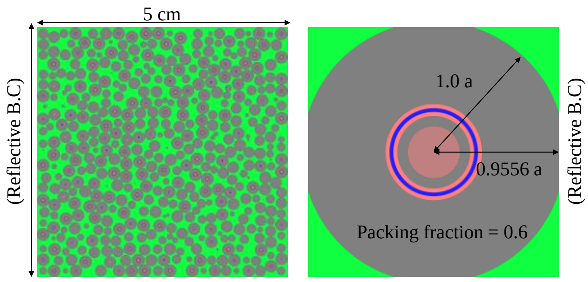

Fig. 2. TRISO cluster (L) and single TRISO-particle (R) model for square lattice calculation

Fig. 3 presents the infinite neutron multiplication factor for 10 wt.% LEU+ and 19.75 wt.% HALEU as a function of TRISO V.F. Both cases exhibit a maximum near 1% V.F, followed by a sharp decline up to 15% V.F due to insufficient moderation. Notably, the multiplication factor increases again after 40% V.F as the harder spectrum reduces parasitic absorption, although the 10 wt.% LEU+ case remains subcritical. Fig. 4 illustrates the neutron spectrum for 19.75 wt.% HALEU, showing the typical HTGR spectrum at 5% TRISO V.F.

Figs. 5 and 6 show depletion calculations with different TRISO V.F values for both fuel enrichments to estimate the maximum achievable discharge burnup without leakage. An average power of 20 W/cc in the square lattice was assumed. For 10 wt.% LEU+, a discharge burnup of 70–80 MWd/kgU was achieved near 5% V.F, which is typical of large-scale HTGRs, but it decreases significantly at higher V.F, as summarized in Table II. A similar trend was observed for 19.75 wt.% HALEU, although the discharge burnup increases again beyond 20% V.F due to higher k-inf and reduced fission product poisoning in the harder spectrum. Consequently, a discharge burnup of 86.06 MWd/kgU was achieved at 100% V.F with an extended lifetime.

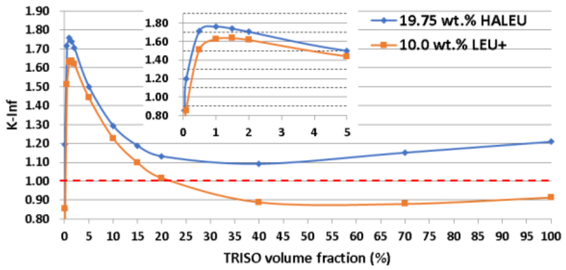

Fig. 3. K-inf as a function of TRISO V.F.

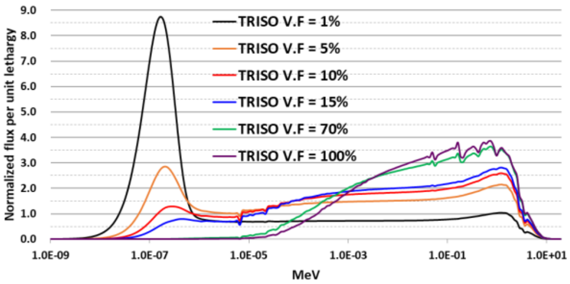

Fig. 4. Neutron spectra depending on the TRISO V.F.

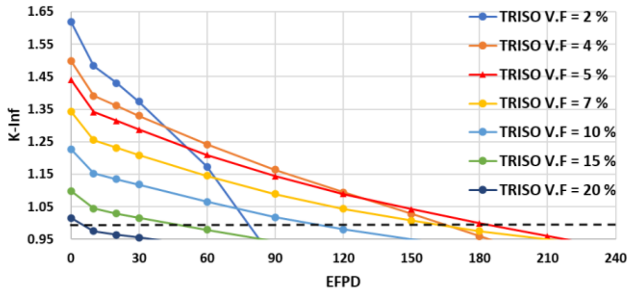

Fig. 5. Depletion calculation of 10 wt.% LEU+

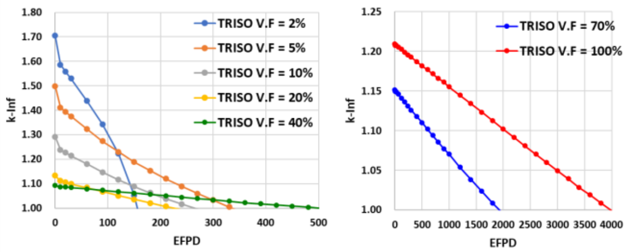

Fig. 6. Depletion calculation of 19.75 wt.% HALEU

Table II: Depletion analyses of 10% LEU+

TRISO V.F	Initial k-inf	Lifetime (d)	Discharge Burnup (MWd/kgU)
2%	1.61920	78	84.56
4%	1.49964	162	87.79
5%	1.44100	180	78.03
7%	1.34199	156	48.23
10%	1.22742	105	22.78

Table III: Depletion analyses of 19.75 wt.% HALEU

TRISO V.F	Initial k-inf	Lifetime (d)	Discharge Burnup (MWd/kgU)
2%	1.70501	156	168.77
4%	1.55986	308	166.53
5%	1.49842	336	145.60
10%	1.29178	264	57.25
20%	1.13291	226	24.48
70%	1.15132	1,927	59.62
100%	1.20919	3,974	86.06

Figs 6 and 7 show the fuel, moderator, and isothermal temperature coefficients evaluated for both enrichments by perturbing the temperature from 900 K to 1000 K. The moderator includes the buffer, PyC, SiC, and over-coat. The moderator temperature coefficient (MTC) becomes less negative with larger TRISO V.F due to weaker moderation, as spectrum hardening near the thermal peak at elevated temperature primarily drives reactivity reduction. Conversely, the fuel temperature coefficient (FTC) becomes more negative as the epithermal spectrum dominates. However, in the case of 19.75 wt.% HALEU, once TRISO V.F exceeds 15%, the FTC becomes less negative because the spectrum shifts further into the fast region (as shown in Fig. 4). Thus, a favorable temperature coefficient of about –3 to –4 pcm/K is obtained above 70% V.F.

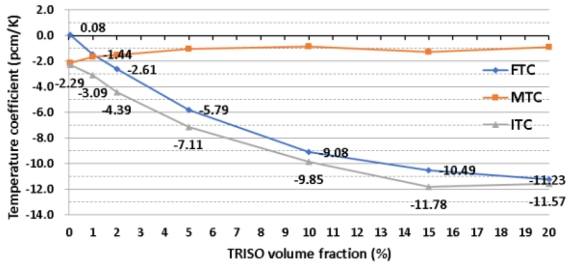

Fig. 6. Temperature coefficients with 10.0 wt.% LEU+

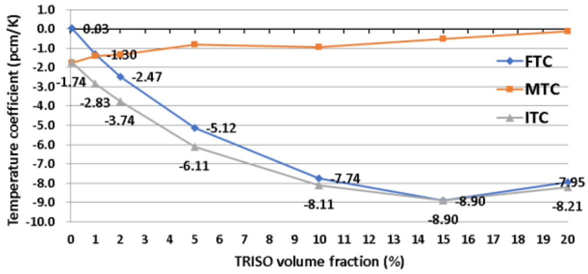

Fig. 7. Temperature coefficients with 19.75 wt.% HALEU

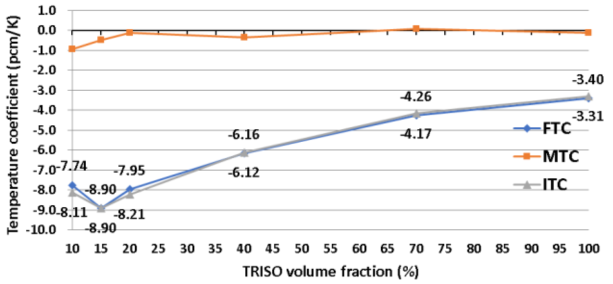

Fig. 8. Temperature coefficients with 19.75 wt.% HALEU

3.2 Explicit 3D Model of OTBR for Micro Application with 12 wt.% HALEU

Based on the neutronic characteristics obtained from lattice calculations, an explicit 3D reactor model of the OTBR was established, as shown in Fig. 9. As described in Section 2, the active core was modeled by repeating the basic TRISO cluster unit of 5 cm cube. Owing to sufficient particle randomness, the neutronic properties are nearly identical to those of a fully explicit 3D model, whereas the latter requires huge computation time due to inefficient surface tracking of the vast number of particle surfaces in each unit cell.

The reactor adopts a simple cylindrical geometry, with the active core surrounded by a 100 cm graphite reflector (1.8 g/cc) to reduce neutron leakage. Because the reactor lifetime with 10 wt.% LEU+ was insufficient in the preliminary depletion calculation using the square-lattice model (Fig. 5), it was therefore decided to use 12 wt.% HALEU as the reference fuel for the 3D reactor design.

Fig. 10 shows the effective neutron multiplication factor for various core heights and diameters (1.2 m, 1.5 m, and 2.0 m). The density of the graphite over-coat was increased to 1.85 g/cc, which enhanced reactivity by up to 4000 pcm compared to 1.7 g/cc. The effective multiplication factor is strongly dependent on core size, especially at the significantly moderated 5–10% V.F range. Severe neutron leakage arises from the inherently low fissile inventory, requiring core sizes of several meters to ensure sufficient economy. The yellow line in Fig. 10 indicates the HALEU inventory for the 2.0 m core.

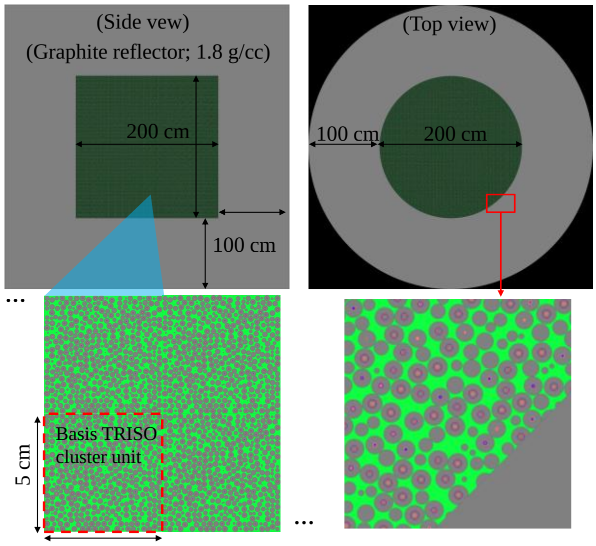

Fig. 9. Description for 3D model of OTBR

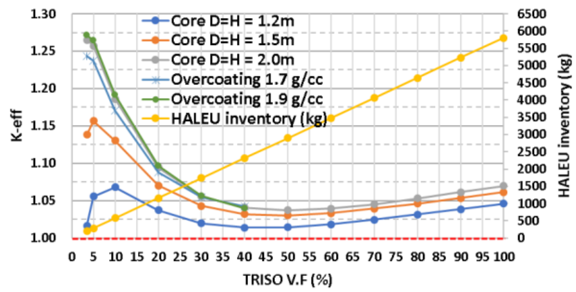

Fig. 10. K-eff as a function of TRISO V.F (12 wt.% HALEU)

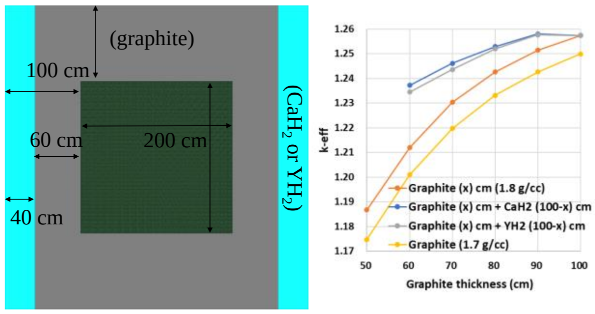

Fig. 11. Sensitivity analysis for reflector (5 % TRISO V.F)

For the 2.0 m core with 5% TRISO V.F, a sensitivity analysis was performed by varying the reflector thickness. Without any reflector, k-eff is only 0.76033, indicating substantial leakage even with the 2.0 m core. As shown in Fig. 11, the saturation thickness of graphite is nearly 100 cm, owing to its low number density and absorption cross section, which is a disadvantage for micro-reactor applications and shielding. To improve shielding performance, hydrides such as CaH_2 or YH_2, which exhibit forward scattering, may be applied as an outer reflector by partially replacing the radial graphite.

Fig. 12 compares the neutron multiplication factors from the square lattice model and the 3D OTBR model with a 100 cm graphite reflector, highlighting the significant neutron leakage in compact cores. To achieve sufficient lifetime and burnup with 12 wt.% HALEU, a core size of at least 2.0 m is required.

Fig. 13 and Table IV present the depletion results for various TRISO V.F values in the 2.0 m OTBR at 20 MWth. Depletion was modeled on average across the fuel zone without sub-dividing it. The maximum lifetime with meaningful discharge burnup was obtained at 9% TRISO V.F. With a 700 μm UCO kernel, the lifetime could be extended beyond 200 days at 7.5% V.F with comparable burnup, as the larger kernel provides higher fuel inventory with similar moderation (graphite thickness). Although the longest lifetime was observed at 100% V.F, the burnup is limited due to insufficient excess reactivity.

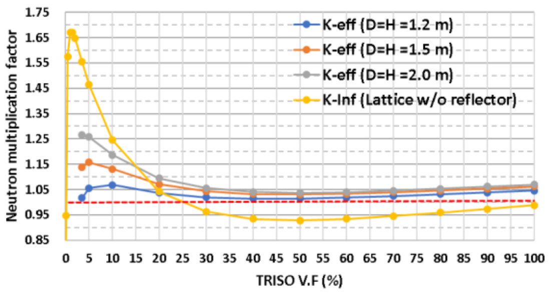

Fig. 12. Comparison of K-eff and K-inf (12 wt.% HALEU)

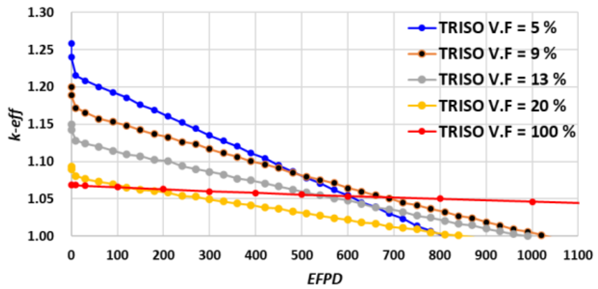

Fig. 13. Depletion calculation of 2.0 m active core size OTBR

Table IV: Depletion analyses of 2.0 m active core size OTBR

TRISO V.F	Initial k-eff	Life time (d)	Discharge Burnup (MWd/kgU)	HALEU inventory (kg)
5%	1.25844	808	55.50	291
9%	1.19980	1030	39.33	524
13%	1.14945	990	26.23	755
20%	1.09366	854	14.69	1163
100%	1.06882	4176	14.39	5804

3.3 Miniaturization Strategy of OTBR with 19.75 wt.% HALEU

To achieve a compact core design with an active height of about 1.2 m, 19.75 wt.% HALEU was applied, along with a 100 cm graphite reflector. As shown in Fig. 14, sufficient excess reactivity can be obtained even with this compact size due to the higher fissile content. Fig. 15 and Table V present depletion results for the 1.2 m core, showing that the maximum lifetime and burnup occur at 100% TRISO V.F, which provides the highest excess reactivity among the cases.

An advantage of the TRISO-bed reactor is the ability to arrange the particles in a regular face-centered cubic (FCC) structure, whose theoretical packing fraction is about 74%. For the 1.2 m core design with 100% TRISO V.F., adopting a practical P.F. of 65% using the FCC structure—rather than the randomly distributed 60% shown in Table V—results in a discharge burnup of 56.44 MWd/kgU and a core lifetime of 3,869 days, with a slightly enhanced initial k_{eff} of 1.17296 and a proportionally increased fuel inventory, the latter being the primary contributor to the extended core lifetime. This trend is also observed for P.F. values of 70% and 74%.

One possible approach to achieve burnup levels comparable to the 86.06 MWd/kgU reported in Table III is to adopt a traveling-wave concept by stacking LEU+ fuel in the upper region of the active core and utilizing burnable absorbers into the TRISO particles.

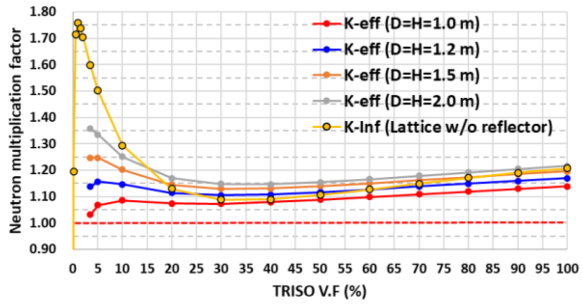

Fig. 14. Comparison of K-eff and K-inf (19.75 wt.% HALEU)

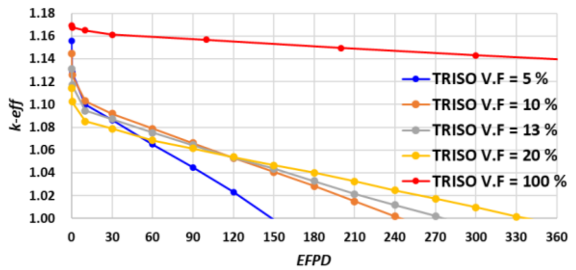

Fig. 15. Depletion calculation of 1.2 m active core size OTBR

Table V: Depletion analyses of 1.2 m active core size OTBR

TRISO V.F	Initial k-eff	Life time (d)	Discharge Burnup (MWd/kgU)	HALEU inventory (kg)
5%	1.15594	148	47.48	62
10%	1.14489	244	38.69	126
13%	1.13143	276	33.72	163
20%	1.11441	337	26.77	252
100%	1.16922	3467	55.15	1257

A more compact design with a 1.0 m active core was also investigated, and the corresponding depletion results are summarized in Table VI for various TRISO V.F. values. It is noteworthy that, with the over-coated configuration (e.g., 5% TRISO V.F.), the discharge burnup drops sharply due to the low excess reactivity, which is primarily driven by substantial neutron leakage resulting from the significantly reduced fissile inventory.

In contrast, for 100% TRISO V.F., the discharge burnup is slightly lower than that of the 1.2 m core but still provides a reasonable lifetime because of the sufficient excess reactivity. Consequently, achieving an effectively miniaturized TRISO-based microreactor requires adopting the 100% TRISO V.F. configuration. This design choice, however, should not be mistaken as an attempt to pursue a fast-spectrum reactor; rather, it aims to maximize the fissile inventory. Since the primary objective is microreactor application—intrinsically less suited to fast reactors—using a moderating reflector such as graphite remains effective for securing core economy than a conventional heavy-mass reflector typical of fast reactors. Fig. 16 illustrates the fission reaction rate spectrum for the 1.0 m core with 100% TRISO V.F., showing that approximately 43% of fission reactions occur below 1 eV.

Table VI: Depletion analyses of 1.0 m active core size OTBR

TRISO V.F	Initial k-eff	Life time (d)	Discharge Burnup (MWd/kgU)	HALEU inventory (kg)
5%	1.06699	17	9.55	36
8%	1.08507	52	17.68	58
13%	1.08157	75	15.92	94
20%	1.07352	99	13.63	146
100%	1.13810	1584	43.58	727

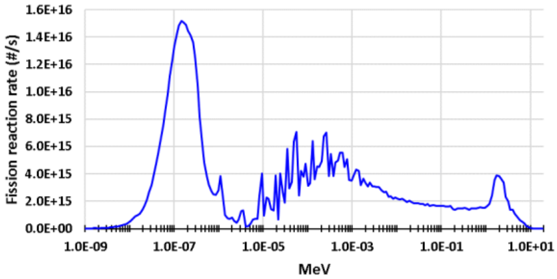

Fig. 16. Fine-energy-group fission reaction rate of the 1.0 m active core with 100% TRISO V.F

4. Conclusion

The neutronic feasibility of the OTBR has been assessed for micro-reactor applications. Due to the intrinsic challenges of miniaturizing HTGRs, arising from their limited fissile inventory and high neutron leakage, a core size of about 2.0 m with 12 wt.% HALEU is required to achieve adequate lifetime and burnup. With 19.75 wt.% HALEU, the core size can be reduced to about 1.2 m, achieving a considerable lifetime. However, a key challenge for the OTBR remains the potentially high pressure drop in the coolant gas caused by direct cooling of the large number of particles.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government(MSIT) (RS-2023-00260898) and Korea Energy Technology Evaluation and Planning (KETEP) grant funded by the Korean Government (MTIE) (RS-2024-00439210).

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[1] Stempien, John D., Lu Cai, and Paul A. Demkowicz. *AGR TRISO Fuel Fission Product Release Data Summary*. No. INL/RPT-23-74651-Rev000. Idaho National Laboratory (INL), Idaho Falls, ID (United States), 2023.