INFLUENCE OF THE ABSORBENT ELEMENTS (Gd_2O_3) DISTRIBUTION IN AN iPWR TYPE FUEL ASSEMBLY ON THE CELL NEUTRONIC PARAMETERS

GEORGETA ROXANA BEZDEDEANU, CRISTINA ALICE MĂRGEANU, ANDREEA ŞERBĂNESCU

Institute for Nuclear Research (RATEN ICN) Piteşti, Romania
e-mail: roxana.bezdedeanu@nuclear.ro

Abstract

The present study aims to evaluate the impact of the placement of an iPWR type fuel assembly elements containing consumable poison (Gd_2O_3) on neutronic parameters at the lattice cell level. For this analysis, the NuScale Power Module was used, which is an innovative iPWR design based on PWR technology. The NuScale fuel assembly is represented as a 17×17 matrix of elements, comprising 232 fuel elements UO_2 with 4.55% U^{235} enrichment, 32 fuel elements of mixed oxides (UO_2 and consumable poison, Gd_2O_3, at a concentration of 2% and 8%, respectively), as well as 24 guide tubes and one instrumentation tube. The DRAGON code's PSP module was utilized for the fuel elements, tubes (guide/instrumental), and fuel assembly's geometric modeling. All calculations were carried out using the deterministic DRAGON code and the IAEA's nuclear data library. The main parameters of interest for this study were, as follows: burnup evolution of the infinite multiplication factor (k_{inf}), maximum discharge burnup (B_{max}), and reactivity coefficients. The values of B_{max} ranged between 39500 and 39900 MWd/tHE. The increase in the amount of consumable poison led to a decrease in the maximum burnup by up to 370 MWd/tHE compared to fuel compositions containing 2% Gd_2O_3. The results of the analysis indicate that the utilization of various arrangements for the placement of fuel elements with consumable poison in the NuScale fuel assembly did not significantly affect the primary neutronic parameters.

Keywords: *iPWR-type SMR fuel assembly, Criticality, Safety parameters, Gd_2O_3, DRAGON code*

Introduction

In recent years, the trend in small modular reactor (SMR) technology development has been towards the water-cooled integral pressurized water reactor (iPWR) type. The innovative and unique characteristics of iPWR-type SMRs provide an enhanced safety margin, thus offering the potential to expand the use of safe, clean, and reliable nuclear energy to a broad range of energy applications. Currently in the world, there are about eleven (11) iPWR-type SMRs concepts and designs that are in various phases of development: under construction, licensed or in the licensing review process, the development phase, and conceptual design phase, [1]. Several nuclear industry companies, including NuScale, AREVA, Babcock & Wilcox (mPower), General Atomics, and Westinghouse (IRIS), are actively promoting various designs of SMRs, [2]. Additionally, national research institutes in countries such as Argentina, China, Japan, Korea, and Russia are developing additional designs of SMRs, [3, 4].

For this study, the NuScale Power Module (NPM) was considered, which is an innovative iPWR design based on PWR technology without using primary coolant pump, so natural circulation is used as primary heat transfers. With a thermal power of 160 MW per module, NuScale has its modularity and flexibility to increase power up to 12 modules in on facility, and advantages due to small footprint, [5, 6]. Financial budget for SMR is also lower than for a large NPP because it eliminates uses of pumps and several pipelines [6, 7] as well as simpler manufacture and transport of reactor component. In addition, there are reduced probability for some accidents such as Loss of Coolant Accident (LOCA) or Loss of Flow Accident (LOFA) which based on primary coolant pump and pipeline failure [8-10].

The objective of this paper is to examine the consequences of placing iPWR type fuel assembly elements that have consumable poison (Gd_2O_3) on neutronic parameters at the lattice cell level. Five geometric configurations were investigated concerning the arrangement of consumable poison elements in the iPWR type fuel assembly. The configuration *Case_5_ref*, which follows the conventional arrangement of 32 consumable poison elements in the fuel assembly, [11-14], was selected as the reference configuration for the current investigation.

For the lattice cell assessment, 2-D neutron transport calculations were performed to estimate the following neutronic parameters: the infinite multiplication factor (k_{inf}), the maximum burnup at discharge (B_{max}), and the reactivity coefficients of the fuel (Doppler effect, αT) and of the moderator (αT_{mod}).

The neutron transport calculations were performed using DRAGON (version 5, [15]), a collision probability code, and an appropriate nuclear data library based on the ENDF/B-VII evaluated nuclear data [16, 17].

NuScale's description

The reactor building is a Seismic Category I structure that is reinforced by concrete that will withstand the effects of aircraft impact, environmental conditions, natural phenomena, design basis accidents, and design basis threats. The reactor building also provides radiation protection to plant operation and maintenance personnel (see Fig. 1, [18]).

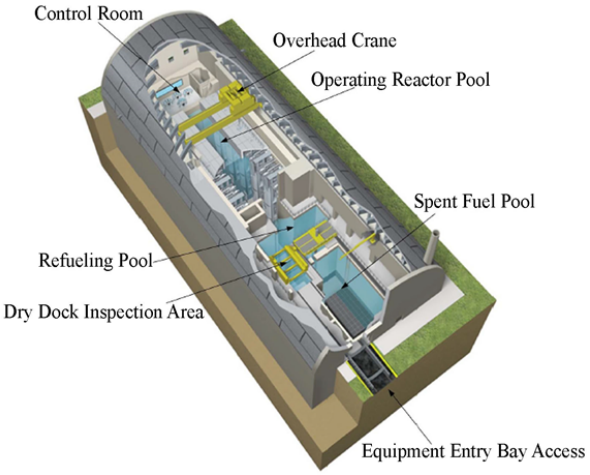


Fig. 1. Reactor building view, [18]

NuScale is a typical Pressurized Water Reactor (PWR) Small Modular Reactor with a thermal power output of 160 MW. The basic configuration of a single NuScale Power Module is shown schematically in Fig. 2.

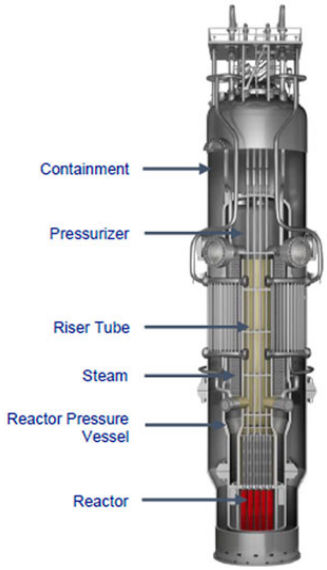


Fig. 2. NuScale Power Module, [19, 20]

The integrated design contains the nuclear core, two interwoven helical coil steam generators (SG), and a pressurizer (PZR) within the reactor pressure vessel (RPV) and is housed in a steel containment vessel (CNV). The RPV is about 17.8 m long and 3.0 m in diameter. The core is surrounded by a stainless steel heavy neutron reflector which improves fuel utilization by preventing the neutrons radially escape from the core. The reflector also provides the core envelope and directs the flow through the core.

The reactor core consists of an array of 37 half-height typical LWR fuel and 16 control rod assemblies followed by a riser tube, where two helical coil steam generators wrap around it. Feedwater is pumped into the tubes where it boils to generate superheated steam. Pressurizer heaters and sprays are located in the upper head of the vessel to provide pressure control. The modules are operated below-grade level in a 28,000 m^3 steel-lined pool of water, [21].

Fuel element and fuel assembly description

To perform the proposed analysis, NuFuel HTP2™ was the iPWR type fuel assembly considered.

The fuel assembly (FA) is arranged in 17 × 17 square lattice, with 21.4 cm width and 200 cm active height, as shown in Fig. 3, [21]. The shorter height is the only significant difference between the NuScale fuel assembly and other PWR fuel designs. Fuel assembly is supported by five spacer grids, 24 guide tubes, top and bottom sides of a nozzle, which together provide a structural framework for the 264 fuel rods. Each fuel assembly also includes a central instrumentation tube.

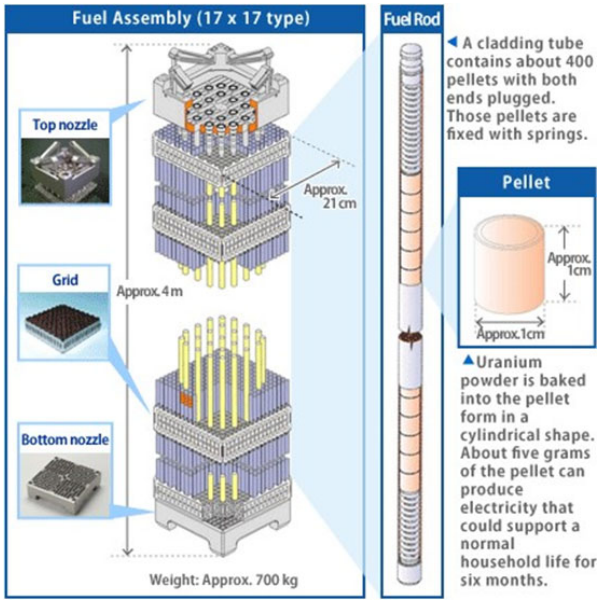


Fig. 3. iPWR-type SMR fuel assembly, [21]

The fuel elements constituting the iPWR type fuel assembly contain enriched uranium oxide up to 4.95% or a mixed oxide of uranium and gadolinium (with a concentration of up to 8%).

Fig. 4 schematically presents the two types of FAs: one with uranium oxide and the other with mixed oxides of uranium and gadolinium.

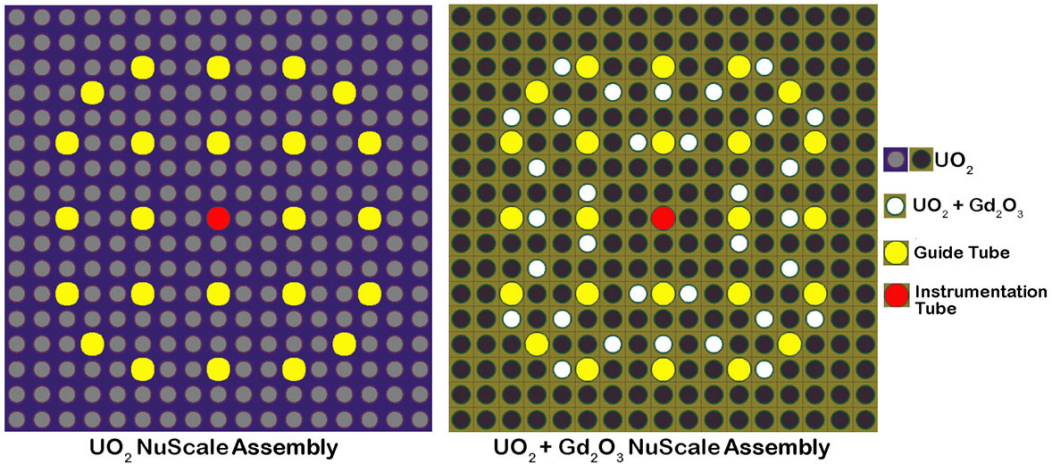
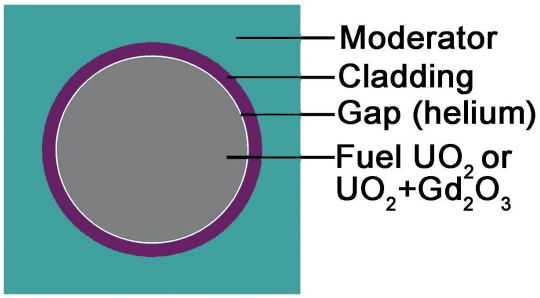


Fig. 4. iPWR-type SMR Fuel Assembly fueled (DRAGON plots)

Methodology and key parameters

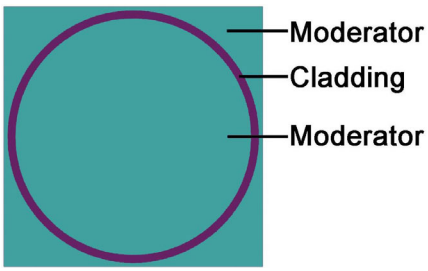
The first step in the neutronic analysis process involves, prior to performing any calculations, developing the model of the fuel pin, guide tube, and instrumentation tubes in a cubic lattice by using a lattice cell code called DRAGON. The fuel pin cell comprises a fuel rod with a radius of 0.40575 cm, surrounded by helium gas and cladding made of M5 material [16], which has thicknesses of 0.00825 cm and 0.061 cm, respectively. The height of every iPWR type fuel pin cell is 200 cm. Fig. 5 displays the modelling of the fuel pin cell and the main data of fuel pin cell, [22, 23].



		Material	Radius
1	Fuel pellet	UO2/UO2+Gd2O3	0.40575
2	Gap between pellet - cladding	Helium	0.41400
3	Cladding	M5	0.47500
4	Moderator	Water (H2O)	—

Fig. 5. DRAGON model for iPWR-type SMR fuel pin cell

The guide tubes and instrumentation tube have identical geometries, despite each has different functions. A guide tube is a part of the structure designed to provide a channel for neutron absorber rods (control rods), burnable absorbers rods, and neutron source rods. An instrumentation tube is designed to provide a place for neutron detectors or in-core instrumentation and other measuring installation. These tubes were modeled in a similar manner to the fuel pin cell, but only replacing the fuel rod with water as additional neutron moderation. The model of these tubes and their composition are shown in Fig. 6.



		Material	Radius
1	Moderator	Water (H2O)	0.57150
2	Cladding	M5	0.61200
3	Moderator	Water (H2O)	

Fig. 6. DRAGON model for iPWR-type SMR guide and instrumentation tubes

The next step is to model the iPWR type fuel assembly with the DRAGON code by constructing a 17×17 square lattice consisting of 264 fuel pins, 24 guide tube and one instrumentation tube cells.

In Fig. 7, five different fuel assembly types consisting of UO_2 and UO_2+Gd_2O_3 fuel rod configurations are summarized. There are two concentrations of gadolinium in UO_2+Gd_2O_3 mixed oxides fuel, namely 2% and 8% Gd_2O_3, the UO_2 fuel enrichment in U^{235} being 4.55%.

All neutronic calculations on the five fuel assemblies were carried out considering three different scenarios, namely:
(i) standard operating conditions,
(ii) perturbed fuel temperature and
(iii) perturbed moderator temperature.

In standard operating conditions, the temperature of the fuel, cladding, and moderator are set to 600°K, while in perturbed fuel temperature conditions, the fuel temperature increases from 600°K to 900°K, and the cladding and moderator temperatures are 600°K, respectively. The perturbed moderator temperature scenario consists of decreasing the moderator temperature from 600°K to 300°K, while keeping the cladding and fuel temperatures at 600°K.

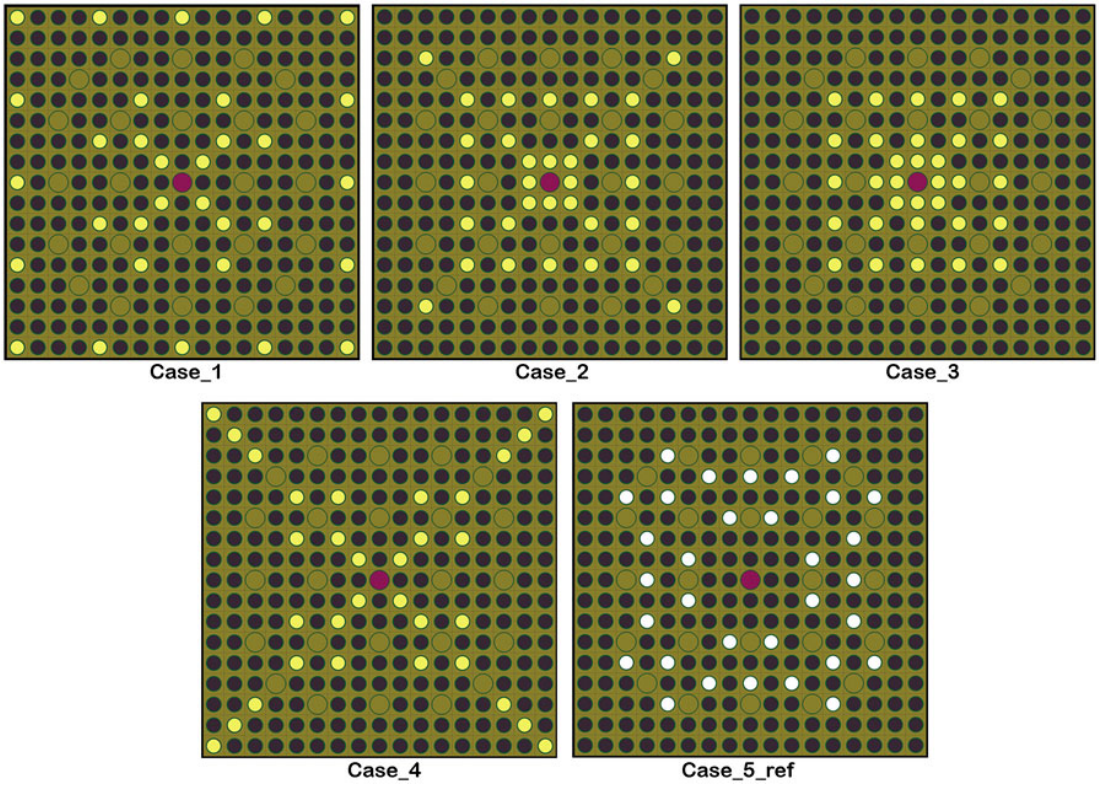


Fig. 7. Considered fuel assembly configurations, DRAGON plots

The main neutronic parameters considered in this paper were, as follows: the infinite multiplication factor (k_{inf}), the maximum discharge burnup (B_{max}), and the reactivity coefficients of the fuel (Doppler effect, αT) and of the moderator (αT_{mod}).

As is known, the reactivity of an initially supercritical cell decreases with burning, due to the consumption of fissile isotopes and the accumulation of "*poisons*" (Xe, I), the cell becoming subcritical. The maximum burnup (B_{max}) is defined as the burning degree for which the considered cell is still critical, k_{inf} =1.0. It is determined by linear interpolation, following the method: B_1 and B_2 corresponding to k_1 and k_2 are established, for which $k_1 > 1$ and $k_2 < 1$, then calculate B_{max} using formula:

$$B_{\max} = \frac{B_1(1-k_1) - B_2(1-k_2)}{k_1 - k_2} \quad (1)$$

Temperature coefficients are perceived as instantaneous disturbances obtained by changing the fuel or the moderator temperature. The Doppler effect is highlighted by the reactivity of the cell, when the fuel temperature changes from its standard value. To calculate the change in reactivity (Δρ) we should determine k_{inf} value both for the reference and perturbed case (fuel temperature increased to 900°K). Fuel density was considered 10.54 g/cm^3 for all scenarios. The coefficient of fuel temperature reactivity (αT) is calculated by using the following formulas:

$$\Delta\rho = \frac{k_{pert} - k_{ref}}{k_{pert} \cdot k_{ref}} \quad (2)$$

$$\alpha T = \frac{\Delta\rho}{\Delta T} \quad (3)$$

Moderator temperature reactivity coefficient, (αT_{mod}), is a measure of how the reactivity of a nuclear reactor changes depending on the moderator temperature variations. It was determined using the formulas given below:

$$\Delta\rho = \frac{k_{ref} - k_{\mathrm{mod}}}{k_{ref} \cdot k_{\mathrm{mod}}} \quad (4)$$

$$\alpha T_{\mathrm{mod}} = \frac{\Delta\rho}{\Delta T} \quad (5)$$

where: $\Delta\rho$ - reactivity change, [$\Delta k/k$]; k_{ref} - multiplication factor at normal condition; k_{pert} - multiplication factor at perturbed condition, fuel temperature is 900°K; k_{mod} - multiplication factor at perturbed condition, moderator temperature is 900°K; αT - Doppler temperature coefficient reactivity [$\Delta k/k/K$]; αT_{mod} - moderator temperature coefficient reactivity, [$\Delta k/k/K$]; ΔT - temperature change.

For the iPWR type SMR, the temperature reactivity coefficients can vary based on the type of fuel and moderator, and other specific characteristics of the reactor. Overall, they are expected to be as small as possible to ensure system stability and nuclear reaction control.

Criticality and neutronic safety parameters calculation for the iPWR type fuel assembly was done by means of the deterministic code DRAGON, using the IAEA's nuclear data library on 172 neutron energy groups.

Main cell results and discussions

In Fig.8, k_{inf} evolution during the burnup is represented, for fuel assemblies containing 2% and 8% gadolinium oxide.

For the fuel with 2% Gd_2O_3, the value of k_{inf} at the beginning of the burnup ranged between 1.16 and 1.19, while k_{inf} value ranged between 1.07 and 1.12 for the fuel with 8% Gd_2O_3. The lowest k_{inf} value is associated to the reference assembly, *Case_5_ref,* the highest k_{inf} value being obtained for the configuration referred to *Case_3*, for both poison concentrations, 2% and 8%.

For all the fuel assemblies analysed, the value of B_{max} ranged between 39500 and 39900 MWd/tHE. Increasing of the consumable poison amount led to a decrease in the maximum burnup by up to 0.9% for the fuel composition containing 8% Gd_2O_3 compared to the one containing only 2% Gd_2O_3, as can be seen in Fig. 9.

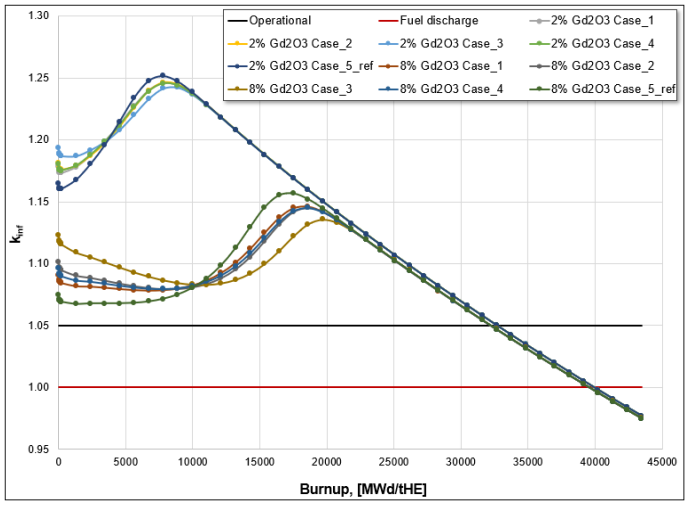


Fig. 8. Evolution of k_{inf} with burnup for iPWR type fuel assemblies containing gadolinium oxide

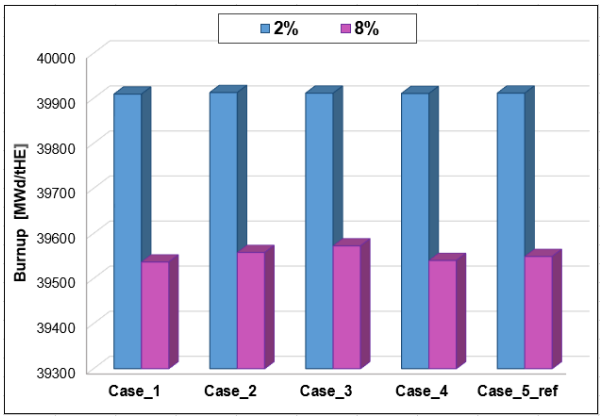


Fig. 9. Maximum burnup [MWd/tHE]

The Doppler coefficient gives the change in reactivity per unit of temperature change that occurs in the fuel. To calculate the change in reactivity (Δρ), first the standard conditions are considered (temperature 600°K for the cladding, fuel, and moderator). Then calculations are carried out for the perturbed fuel temperature condition, where the fuel temperature is set to 900°K, while the cladding and moderator temperature is kept at 600°K.

The results obtained for the Doppler coefficient αT are presented in Table 1. This table includes also the values of k_{inf} calculated for the standard and perturbed conditions, and the calculated value of Δρ.

The Doppler coefficient values for the fuel compositions with 2% Gd_2O_3 concentration were between -2.4291×10^{-5} and -2.4368×10^{-5}, up to 1.5% lower in absolute value than the reference value. For the fuel compositions with 8% Gd_2O_3 concentration, the Doppler coefficient values were higher in absolute value by up to 9.5% compared to the *Case_5_ref* value.

When the temperature of the moderator (water) increases, it becomes less dense and slows down fewer neutrons, leading to a decrease in the number of neutrons available for nuclear reactions. The corresponding results for the change of moderator temperature, namely the moderator reactivity coefficient, αT_{mod}, are displayed in Table 2.

The moderator reactivity coefficient values obtained for the fuel compositions with 2% Gd_2O_3 concentration vary between -9.67×10^{-7} and -1.55×10^{-6}, while those for the fuel compositions with 8% Gd_2O_3 concentration vary in the range -4.05×10^{-5} and -2.68×10^{-5}.

Table 1. The Doppler coefficient for iPWR type fuel assemblies

	k_{pert}	k_{ref}	$\Delta\rho$ [Δk/k]	αT [Δk/k/K]	k_{pert}	k_{ref}	$\Delta\rho$ [Δk/k]	αT [Δk/k/K]
	$UO_2 + 2\% Gd_2O_3$				$UO_2 + 8\% Gd_2O_3$			
Case_1	1.1683	1.1783	-7.2969x10^{-3}	**-2.432** x10^{-5}	1.0809	1.0903	-7.9587 x10^{-3}	**-2.653** x10^{-5}
Case_2	1.1713	1.1814	-7.3105 x10^{-3}	**-2.437** x10^{-5}	1.0917	1.1012	-7.9153 x10^{-3}	**-2.638** x10^{-5}
Case_3	1.1832	1.1935	-7.2708 x10^{-3}	**-2.424** x10^{-5}	1.1132	1.1229	-7.7894 x10^{-3}	**-2.596** x10^{-5}
Case_4	1.1705	1.1806	-7.2873 x10^{-3}	**-2.429** x10^{-5}	1.0866	1.0960	-7.9188 x10^{-3}	**-2.640** x10^{-5}
Case_5_ref	1.1550	1.1650	-7.3820E-03	**-2.461** x10^{-5}	1.0666	1.0748	-7.2060 x10^{-3}	**-2.402** x10^{-5}

Table 2. The moderator reactivity coefficient for iPWR type fuel assemblies

	k_{ref}	k_{mod}	$\Delta\rho$ [Δk/k]	αT_{mod} [Δk/k/K]	k_{ref}	k_{mod}	$\Delta\rho$ [Δk/k]	αT_{mod} [Δk/k/K]
	$UO_2 + 2\% Gd_2O_3$				$UO_2 + 8\% Gd_2O_3$			
Case_1	1.1683	1.1783	-7.2969x10^{-3}	**-2.432** x10^{-5}	1.0809	1.0903	-7.9587 x10^{-3}	**-2.653** x10^{-5}
Case_2	1.1713	1.1814	-7.3105 x10^{-3}	**-2.437** x10^{-5}	1.0917	1.1012	-7.9153 x10^{-3}	**-2.638** x10^{-5}
Case_3	1.1832	1.1935	-7.2708 x10^{-3}	**-2.424** x10^{-5}	1.1132	1.1229	-7.7894 x10^{-3}	**-2.596** x10^{-5}
Case_4	1.1705	1.1806	-7.2873 x10^{-3}	**-2.429** x10^{-5}	1.0866	1.0960	-7.9188 x10^{-3}	**-2.640** x10^{-5}
Case_5_ref	1.1550	1.1650	-7.3820E-03	**-2.461** x10^{-5}	1.0666	1.0748	-7.2060 x10^{-3}	**-2.402** x10^{-5}

The comprehensive results of the moderator temperature coefficient reactivity indicate negative values for all modelled fuel assemblies, and they fall within an acceptable range, [23]. Negative values for both moderator and fuel temperature coefficients are desirable because of its good self-regulating effect.

The analysis carried out has shown that considering diverse configurations of integral burnable absorber fuel (UO_2 + Gd_2O_3) within the iPWR type fuel assembly did not result in a notable variation for the main neutronic parameters considered: infinite multiplication factor (k_{inf}), maximum discharge burnup (B_{max}) and temperature reactivity coefficients.

Conclusions

A comparative neutronic analysis on the main parameters of interest at lattice cell level was presented in present work for iPWR type fuel assemblies containing enriched UO_2 or mixed oxides of uranium and burnable poison, Gd_2O_3. To perform proposed analysis, the NuScale fuel assembly was selected.

The neutronic cell calculations for the iPWR type fuel assembly were performed across three distinct scenarios (standard and perturbed) utilizing the deterministic code DRAGON code. The considered iPWR type fuel assembly, with Gd_2O_3 burnable absorber concentrations of 2% and 8%, and featuring various loading pattern arrangements, was simulated using the code's PSP module.

The maximum burnup (B_{max}) values ranged between 39500 to 39900 MWd/tHE. The augmentation of the consumable poison quantity resulted in a reduction of the maximum burnup by up to 370 MWd/tHE compared to fuel compositions containing only 2% Gd_2O_3.

The overall calculation results indicate that the temperature reactivity coefficients exhibit a relatively low discrepancy compared to the standard assumed, specifically ranging from -1.0% to -1.5% Δk/k/K for a 2% gadolinia concentration. However, the analysis performed for fuel compositions with 8% Gd_2O_3 concentration reveals a greater difference when compared the temperature reactivity coefficients with the one associated to the standard fuel assembly, the differences being between -7.5% and -9.5% Δk/k/K.

It was found that the different loading patterns arrangement of integral burnable absorber fuel (UO_2 - Gd_2O_3) in the iPWR type fuel assembly did not significantly affect the main cell neutronic parameters.

References

[1] Zeliang, C., Mi, Y., Tokuhiro, A., Lu, L., Rezvoi, A. (2020) "Integral PWR-Type Small Modular Reactor Developmental Status, Design Characteristics and Passive Features: A Review", *Energies*, Vol. 13(11), 2898; https://doi.org/10.3390/en13112898.
[2] Lindner, J. (2011) "Status and Future Potential of Small Modular Reactors (SMRs)", Joint ICTP-IAEA School of Nuclear Energy Management, International Centre for Theoretical Physics (ICTP), Trieste, Italy.
[3] International Atomic Energy Agency (2020) "Advances in Small Modular Reactor Technology Developments", 2020 Edition, A Supplement to: IAEA Advanced Reactors Information System (ARIS), http://aris.iaea.org.
[4] International Atomic Energy Agency (2022) "Advances in Small Modular Reactor Technology Developments", 2022 Edition, A Supplement to: IAEA Advanced Reactors Information System (ARIS), https://aris.iaea.org/Publications/SMR_booklet_2022.pdf.

[5] Ingersoll, D.T., Carelli, M.D. (2020) ″Handbook of Small Modular Nuclear Reactors″, Second Edition, Woodhead Publishing Series in Energy.
[6] International Atomic Energy Agency (2013) ″Evaluation of Advanced Thermohydraulics System Codes for Design and Safety Analysis of Integral Type Reactors″, IAEA TECDOC No. 1733, Vienna, Austria.
[7] Nuclear Energy Agency (2011) ″Current Status, Technical Feasibility and Economics of Small Nuclear Reactors″, https://www.oecd-nea.org/ndd/reports/2011/current-status-small-reactors.pdf
[8] Khan, S.U., Peng, M., Zubair, M. (2011) ″Study on the Evaluation and Simulation of Steady State Behavior and Reactor Safety Concept for Integral Pressurized Water Reactor″, *Information Technology Journal*, Vol. 10(5), pp. 983-991.
[9] Ingersoll, D.T., Carelli, M.D. (2014) ″Handbook of Small Modular Nuclear Reactors″, Woodhead Publishing.
[10] Ingersoll, D., Colbert, C., Bromm, R., Houghton, Z. (2014) ″NuScale Energy Supply for Oil Recovery and Refining Applications″, *Proc. ICAPP 2014*, USA, 2344–2351
[11] Zuhair, Z., Luthfi, W., Dwijayanto, R.A.P., Suwoto, S. (2021) ″Study on criticality and neutronic safety parameters of NuScale fuel assembly″, *Urania Jurnal Ilmiah Daur Bahan Bakar Nuklir*, Vol. 27(3), pp. 165 – 176.
[12] Zuhair, Z., Luthfi, W., Widiawati, N., Suwoto, S., Setiadipura, S. (2023) ″Study on Neutronic Characteristics of NuScale Reactor Core with Thorium Coating″, *Proc. AIP Conf.* 2893, 040007, https://doi.org/10.1063/5.0173455
[13] Suwoto, S., Adrial, H., Luthfi, W., Setiadipura, T., Zuhair, Z. (2022) ″Neutronic Investigation of Integral Burnable Absorber (UO_2-Gd_2O_3) Different Pattern Arrangement on NuScale Reactor Fuel Assembly″, *Proc. ICONSTA Conf.,* DOI:10.1063/5.0192826.
[14] NuScale Power (2023) ″VOYGR SMR Plants″, https://www.nuscalepower.com/en/products/voygr-smr-plants
[15] Marleau, G., Hébert, A., Roy, R. (2018) ″A user guide for DRAGON Version5″, IGE-335, Inst. de Génie Nucléaire, École Polytechnique de Montréal, Canada.
[16] Nuclear Energy Agency (1998) ″WIMS-D5″, OECD/NEA Data Bank Documentation, Package ID No. 1507/02 Online, http://www.nea.fr/html/dbprog
[17] Leszczynski, F., López Aldama, D., Trkov, A. (2007) ″WIMS-D library update: final report of a coordinated research project″, STI/PUB/1264, International Atomic Energy Agency, Vienna, Austria, http://www-nds.iaea.org/wimsd
[18] NuScale Power, LLC (2012) ″NuScale Plant Design Overview″, report NP-ER-0000-1198, www.nrc.gov/docs/ml1221/ml12216a392.pdf
[19] Langdon, K. (2019) ″NuScale Small Modular Reactor (SMR) Overview″, INPRO Dialogue Forum on Opportunities and Challenges in Small Modular Reactors, Ulsan, Rep. of Korea
[20] Pramuditya, S. personal blog (2009) ″Standard PWR nuclear fuel assembly (17x17) technical specification″, https://syeilendrapramuditya.wordpress.com/2009/04/14/standard-pwr-nuclear-fuel-assembly-17x17-technical-specification/
[21] Kecek, A., Tuček, K., Holmström, S., Van Uffelen, P. (2016) ″Development of M5 Cladding Material Correlations in the TRANSURANUS Code″, *JRC Technical Reports EUR 28366 EN*
[22] NuScale Power, LLC (2020) ″NuScale Standard Plant Design Certification Application″, Final Safety Analysis Report, Rev.5, Chapter 4 - Reactor, Part 2, Tier 2.
[23] NuScale Power, LLC (2019) ″NUFUEL-HTP2™ Fuel and Control Rod Assembly Designs″, TR-0816-51127-NP, Rev.3, www.nrc.gov/docs/ML1935/ML19353A719.pdf