RADIOLOGICAL CHARACTERISTICS OF SPENT NUCLEAR FUEL FROM SMALL MODULAR REACTORS UNDER CONSIDERATION FOR DEPLOYMENT IN UKRAINE

by

Olena KHOTIAINTSEVA [1,2*], ***Volodymyr KHOTIAINTSEV*** [2,3], ***and Volodymyr GULIK*** [1]

[1] Institute for Safety Problems of Nuclear Power Plants, Kyiv, Ukraine
[2] Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden
[3] Taras Shevchenko National University of Kyiv, Kyiv, Ukraine

Scientific paper
https://doi.org/10.2298/NTRP2302088K

Small modular reactors represent a promising technology for power generation, offering solutions to the energy crisis and mitigating greenhouse gas emissions. As Ukraine considers the deployment of NuScale, UK SMR, and SMR-160, it is crucial to address the safe management of spent nuclear fuel. This study focuses on evaluating the radiological characteristics of spent nuclear fuel from the selected small modular reactors and for comparison, from the VVER-1000 reactor. Using the Monte Carlo code Serpent, depletion calculations were performed for an assembly in an infinite 2-D geometry, and the activity, decay heat, and inhalation toxicity of the spent nuclear fuel were assessed. We determined the main nuclides contributing to the radiological characteristics and quantified the mass content of these nuclides. The total number of spent nuclear fuel assemblies produced during the entire life of each small modular reactor type was estimated. The radiological characteristics assessed for the three small modular reactors do not exceed those observed for VVER-1000 reactors currently operating in Ukraine. So, spent nuclear fuel generated by the selected small modular reactors will introduce no new challenges to Ukraine's radioactive waste management system. The results of this work provide valuable insights for identifying the optimal small modular reactor technologies for Ukraine concerning safe spent nuclear fuel management.

Key words: small modular reactor, spent nuclear fuel management, NuScale, SMR-160, UK SMR, Serpent, spent nuclear fuel characteristic

INTRODUCTION

By 2050, global energy consumption will increase by almost 50 % [1]. Looking for ways to meet the growing need for energy through clean and innovative solutions, many countries of the world, including Ukraine, plan to increase the use of renewable sources and nuclear energy. Small modular reactors (SMR) can effectively contribute to the decarbonization of the power sector [2]. The SMR are reactors with electric power up to 300-500 MW. The SMR offer a range of anticipated benefits, including simpler designs, enhanced safety and reliability [3], the ability to work on a balancing power market, power generation for a wider range of users, and applications like commercial hydrogen production, district heating, and water desalination. Their modular designs and compact footprints potentially provide advantages in terms of construction, operation, and maintenance, allowing for placement in locations unsuitable for larger nuclear facilities. Furthermore, SMR are engineered with passive safety features, relying on natural circulation, convection, gravity, and self-pressurization [4].

Ukraine is an industrial country with a powerful energy sector largely based on nuclear power. Nuclear power plants (NPP) provide about half of the country's electricity. Currently, 15 NPP units are operated in Ukraine, of which 13 are VVER-1000 and 2 are VVER-440. However, most Ukrainian nuclear units have been in operation for decades and will soon need to be replaced [5]. Due to the war, many fossil plants in Ukraine have been damaged or destroyed. At present, *Ukraine is considering the possibility of building up to 20 SMR instead of thermal generation units destroyed during the war* [6]. Preliminary agreements have been reached on co-operation with the American company NuScale and the British Rolls-Royce to introduce SMR technologies in Ukraine [7]. In 2029, the implementation of SMR projects is expected to begin after

* Corresponding author, e-mail: olenakhot@gmail.com

the completion of the technology certification and licensing procedures [7].

In addition to generating electricity and heat, NPP produces spent nuclear fuel (SNF) and other forms of radioactive waste, requiring an appropriate infrastructure for their safe management. In Ukraine, there are four operating NPP. The biggest Zaporizhzhya NPP – now under Russian control – has an *on-site* spent fuel dry storage facility. Khmelnytska, Rivne, and South Ukraine NPP are to use the Centralized Spent Fuel Storage Facility (CSFSF) at the Chornobyl zone. The CSFSF has not been damaged during the military operations in the Chornobyl Exclusion Zone of the Russian army and is completely ready for operation [7]. The SNF from the closed Chornobyl NPP is stored at the wet interim storage facility ISF-1 and the dry interim storage facility ISF-2, both at the Chornobyl NPP site.

The SNF management is an integral part of the nuclear fuel cycle, its back-end. To choose appropriate SMR concepts for Ukraine, it is necessary to analyze fuel cycle performance, from fuel mining and fabrication to radioactive waste disposal, and environmental impacts. Not all elements of the fuel cycle are present in the fuel cycle of Ukraine. At present, Ukraine buys Westinghouse fuel and has no reprocessing and final disposal. After the used fuel is unloaded from the reactor, it is stored underwater at the reactor site in a spent fuel pool for several years. Then the spent fuel may be moved to a dry storage facility at the NPP site, or transported to the centralized dry storage facility. Ukraine has chosen the so-called *deferred solution*, which provides for long-term safe storage without final disposal or reprocessing. Studies of the possibility of SNF disposal are at the initial stage in Ukraine [5]. In the Republic of Serbia, research is underway to identify a new location for the radioactive waste disposal, as the current storage site near Belgrade, known as Vincha, is unsuitable. This effort aims to align with international standards, meet stringent spatial requirements, and adhere to national planning priorities for managing radioactive waste [8]. The application of a digital twin of a radioactive waste repository [9] promises substantial benefits for the construction of such facilities, including enhanced management capabilities and safety, cost reduction, and more efficient response to accidents.

At the moment there are many different SMR projects in the nuclear power market, which are based both on traditional and well-tested reactor technologies and on technologies that have not yet been tested. A variety of SMR technologies means a variety of wastes. Since non-water SMR introduce new materials as fuels, coolants, and moderators, they provide new issues for radioactive waste management [10].

Since each country is responsible for the management of SNF produced on its territory, Ukraine needs to consider various SMR technologies and then consider how to manage the produced SNF, taking into account the already existing structure and experience of SNF management in Ukraine. Spent fuel and waste management for the majority of water-cooled SMR is similar to that for the LWR operating in Ukraine. Therefore, from the point of view of SNF management, the light water SMR are preferable for Ukraine. At the same time, light water SMR have key differences from the large light water reactors: power rating, footprint, simpler design, more significant inner safety, integral design (NuScale), natural primary circulation (NuScale, SMR-160), no soluble boron in the primary circuit (Rolls-Royce SMR), integrated dry spent fuel storage and transportation system (SMR-160).

In this work, we investigate the characteristics of spent fuel from three light water SMR: VOYGRTM (NuScale Power Corporation, USA), UK SMR (Rolls-Royce SMR Ltd, UK) and SMR-160 (Holtec International, USA). The considered SMR projects differ in design, nominal power, fuel assembly length, and characteristics of nuclear fuel irradiation. All these factors can affect the composition of the SNF and, as a result, the SNF management. The considered SMR projects include their solutions for on-site SNF management. Evaluating these solutions should be based on independent data on the characteristics of the SMR SNF. The goal of this study is to estimate and compare the key properties of the SNF, which affect the SNF management, for the three SMR. We also compare the data on the SMR with similar data on the VVER-1000 reactors that operate in Ukraine.

MATERIALS AND METHODS

In this work, the Monte Carlo code Serpent was used to perform depletion simulation in the infinite 2-D geometry. The ENDF/B-VII.1 nuclear data were used in the simulations. Reflective or periodic boundary conditions are applied on the assembly faces, which means that instead of a real reactor core, an infinite periodic structure of identical fuel assemblies (FA) is simulated. So, no leakage of neutrons and variation of the neutron flux in the axial direction are taken into account. Such a 2-D depletion simulation is applied for various SMR types [11, 12] and gives a sufficiently accurate assessment of the SNF composition in the middle part of the assembly in height, except the assemblies that remain on the core-periphery for a significant part of the irradiation period [11]. Another simplification is to keep all parameters constant during the calculation. The reports [13, 14] comprehensively discuss the effect of the aforementioned simplifications on the spent fuel composition in water-cooled reactors and present the results of sensitivity studies on the modeling and simulation input parameters. We model FA of NuScale, SMR-160, UK SMR, as well as VVER-1000 FA. For the SMR, we consider standard LWR fuel UO_2 with enrichment less than 4.95 % in a

Table 1. Some key properties of NuScale SMR, SMR-160 and UK SMR

Property	NuScale	SMR-160	UK SMR
Thermal power [MW] [4]	250	525	1358
Number of FA in the core [4]	37	57	121
Linear thermal power [Wcm^{-1}]	33784	24893	40083
Active fuel length [cm]	200 [4]	370 [15]	280 [4]
Initial enrichment (% ^{235}U)	4.55	4	4.55
Fuel rods with gadolinium	16 rods 8 % Gd_2O_3 [11]	–	40 rods 8 % Gd_2O_3 [16]
Discharge burnup [MWd/kgU] [4]	45	45	55
Boron concentration in water [ppm]	650	650	–
Coolant density [gcm^{-3}]	0.753 [11]	0.761	0.705

17 17 square configuration [4]. The key simulation parameters [4, 11, 15, 16] are presented in tab. 1. The latest publicly available data on 2022 have been used. For the NuScale FA, the initial enrichment of 4.55 % ^{235}U is taken from the report [11]. For the SMR-160 FA, the initial enrichment of 4.0 % ^{235}U equals the average enrichment according to [4]. The initial enrichment of 4.55 % ^{235}U for UK SMR FA is a reasonable value less than maximum enrichment 4.95 % according to [4]. Actual core fuel loading patterns usually include several FA types with different initial enrichment and burnable poison content (see, for example, [17, 18]). In this study, we simulate the NuScale and UK SMR fuel assemblies with rods containing gadolinium, and the SMP-160 FA without rods containing gadolinium. For the VVER-1000, the FA of the TVS-A design and 390GO type was simulated. The key parameters correspond to the benchmark [19]: linear thermal power is 51845 Wcm^{-1}, active fuel length is 355 cm, average initial enrichment is 3.9 % ^{235}U, 6 fuel rods with 5 % Gd_2O_3, boron concentration in water is 525 parts per million (ppm), coolant density is 0.724 gcm^{-3}. For the VVER-1000 FA we consider 55 MWday per kilogram of uranium (MWd/kgU) burnup at discharge. We assume that 650 ppm soluble boron for the NuScale SMR and SMR-160 considered in the simulation approximately matches the average boron concentration over the cycle. According to [4], the average core water temperature is 282 °C for SMR-160 and 310 °C for UK SMR, at a pressure of 15.5 MPa in both cases. The coolant densities for the SMR-160 and UK SMR were derived by applying bilinear interpolation techniques to data from the NIST Compressed Water and Superheated Steam tab. [20].

Figure 1(a)-1(c) shows fuel and control rod patterns for square SMR assemblies and 1(d) hexagonal VVER 1000 assembly. Fuel rods containing gadolinium are marked in dark green. For the VVER-1000 FA, fuel rods with an initial enrichment of 4 % are marked in yellow, and in light green – with an initial enrichment of 3.6 %. In an SMR assembly, the initial enrichment of all fuel rods is the same: 4.55 %, 1(a) and 1(b), and 4 %, 1(c).

The depletion simulation was performed in burnup steps from 0.1 to 5 MWd/kgU up to the discharge burnup values specified above. Cooling of the used fuel was simulated in time steps from 50 to 365 days up to 10 years.

In this work, we assess the radiological characteristics of the SNF. The code Serpent calculates the total activity, decay heat, and radiotoxicity as the sum of the radiological characteristics of each nuclide calculated by the formulas

$$A_i(t) \quad N_i(t) V \lambda_i \tag{1}$$

$$D_i(t) \quad A_i(t) \varepsilon_i \tag{2}$$

$$R_i(t) \quad A_i(t) DCF_i \tag{3}$$

Here $A_i(t)$ [Bq] is the activity of the i-th nuclide at the moment of time t, $N_i(t)$ – the number density of the i^{th} nuclide at the moment of time t, V – the volume (in the case of 2-D calculation, is the cross-sectional area) of the fuel assembly, λ_i – the decay constant, $D_i(t)$ – the decay heat of the i^{th} nuclide, ε_i – the decay energy, $R_i(t)$ – the radiotoxicity, and DCF_i – the specific radiotoxicity (dose conversion factor, in $SvBq^{-1}$). For each nuclide, the decay constant, decay energy, and specific inhalation toxicity were obtained from the ENDF nuclear data files used in the simulations. In the next section, we also calculate the expected total number of SNF assemblies produced during the life of the plant.

RESULTS AND DISCUSSION

The SNF radiological characteristics depend on many parameters and conditions of reactor operation [14]: discharge burnup, cooling time, initial enrichment, concentrations of soluble boron and burnable poison, fuel density, moderator density, and specific power (specific power is the power per unit mass of initial heavy metals). A particularly important parameter is the discharge burnup. Figures 2 and 3 illustrate the dependence of the activity and decay heat of spent fuel on the cooling time; for greater burnup (UK SMR and VVER-1000), the level of activity and decay heat is significantly higher.

Explanation of the differences in radiological characteristics between the reactor assemblies with

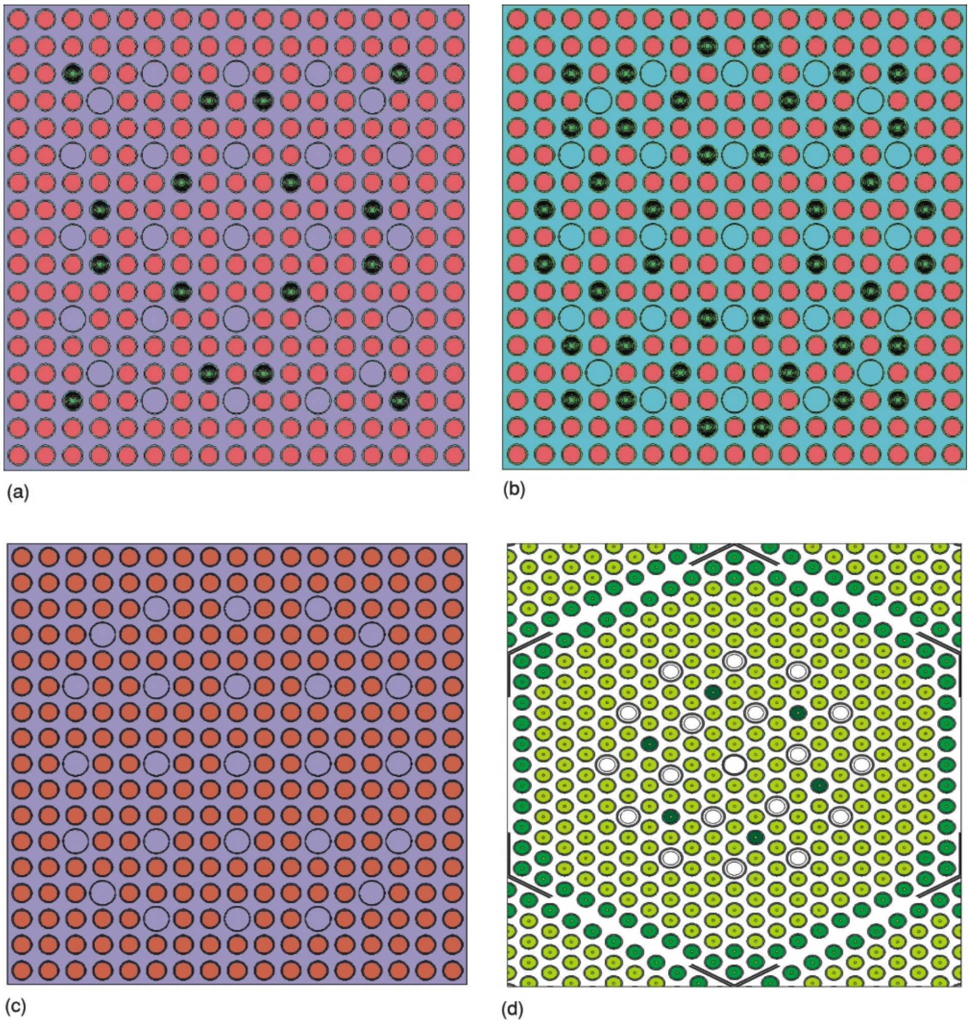

Figure 1. Geometry of the computational model plotted by Serpent: (a) – NuScale FA, (b) – UK SMR FA, (c) – SMR-160 FA, and (d) – VVER-1000 TVS-A

identical discharge burnup is less evident. This effect, most pronounced during several first years of cooling, diminishes with time. For instance, after 1 year, NuScale FA exhibits 19 % higher activity and 17 % more decay heat than SMR-160 FA, but after 7 years, this gap narrows to 4 % and 1 %. At identical discharge burnup and similar coolant density (see tab. 1 for NuScale and SMR-160 fuel assemblies), the effect can result from distinctions due to the presence of gadolinium rods in the NuScale FA and differences in initial enrichment and linear thermal power. Notably, our additional computation for NuScale FA at the same linear power of 24893 Wcm^{-1} as for SMR-160 FA has revealed that NuScale FA exhibits slightly lower radiological characteristics compared to SMR-160 FA. The difference decreases from 1 % to almost 0 % for activity and from 3 % to 1 % for decay heat throughout 10 years of cooling. These differences in radiological characteristics result from greater initial enrichment and the presence of gadolinium rods in the NuScale FA. Returning to the dependencies shown in figs. 2 and 3, we can conclude that somewhat higher radiological characteristics for the NuScale FA compared to the SMR-160 FA are caused by higher specific power, which affects predominantly short-lived nuclide composition (for the considered SMR assemblies, specific power values are approximately proportional to linear thermal power values, because of very close values of mass of initial heavy metals per unit length). This aligns with previous findings [14], that the gamma source related to ^{144}Pr follows a power law relationship of $p^{0.65}$, where p is specific power. For the calculations corresponding to figs. 2 and 3, ^{144}Ce (the half-life is 285 days) and its short-lived daughter ^{144}Pr (the half-life is 17.3 minutes), contribute about 1/3 to the activity and decay heat after one year of cooling but less than 1 % after 7 years. However, the contributions for the NuScale FA are greater than for the SMR-160 FA. The same reasons are likely to explain similar differences in radiological characteristics between UK SMR and VVER 1000 FA, see figs. 2 and 3.

The values per fuel assembly depend on its dimensions. The SMR-160 FA is longer than the NuScale FA, therefore, with the same burnup, the radiological characteristics of the SMR-160 FA are higher. Radiotoxicity, activity, and decay heat are im-

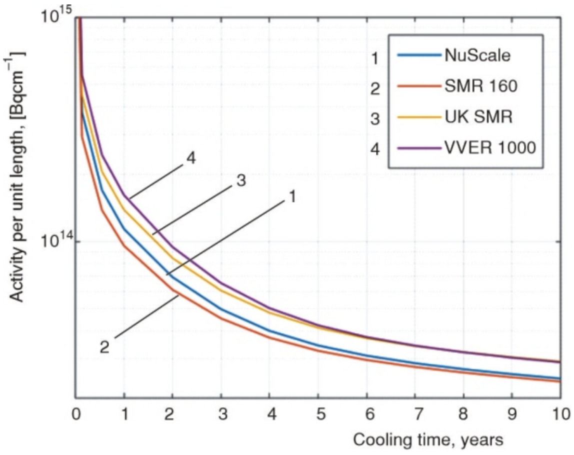

Figure 2. Activity per unit length of the FA up to 10 years after discharge

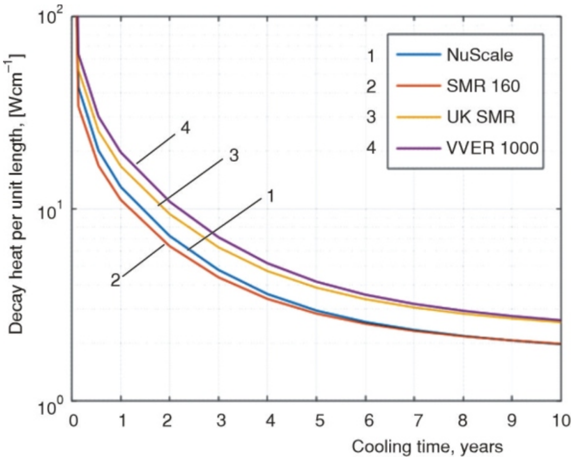

Figure 3. Decay heat per unit length of the FA up to 10 years after discharge

portant characteristics for near-term spent fuel handling, transportation, and storage, as well as for long-term waste disposal planning. For the final geological disposal, radiological characteristics should be analyzed on the time scale of centuries and millennia, which can be the next research step. Table 2 presents spent fuel radiological characteristics calculated per assembly after discharge and 7 years of cooling in the spent fuel pool.

The radiological characteristics of spent fuel and the risks associated with them come from two groups of isotopes – fission products and transuranic elements. However, not all of them are equally important. We have figured out the main contributors to the radiological characteristics, together with their percentage contributions to radiotoxicity, activity, and decay heat. They are transuranic isotopes ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{241}Am, ^{244}Cm, and fission products ^{90}Sr, ^{90}Y, ^{134}Cs, ^{137}Cs, ^{137m}Ba, ^{147}Pm, ^{154}Eu. Each of them contributes at least 2 % to one or more radiological characteristics. The data in tab. 3 are presented for the NuScale FA. For the SMR-160, UK-SMR, and VVER-1000 fuel assemblies, the list of nuclides contributing more than 2 % to the radiological characteristics remains unchanged. For the UK SMR and VVER-1000, which undergo deeper burnup, the contributions of nuclide ^{244}Cm to toxicity and decay heat increase by a factor of nearly 1.5 and 2.0, respectively; the contributions of other isotopes differ less.

Table 2. Total inhalation toxicity, activity, and decay heat per assembly after discharge and 7 years of cooling

Characteristic	NuScale	SMR-160	UK SMR
Toxicity [10^{-10} Sv]	1.18	2.41	2.43
Activity [10^{-15} Bq]	5.72	10.19	9.56
Decay heat [W]	466.9	855.2	856.5

Table 3. The nuclide contributions that exceed 2 % of inhalation toxicity, activity, and decay heat for NuScale spent fuel assembly after discharge and 7 years of cooling

Isotope	Toxicity [%]	Activity [%]	Heat [%]
^{238}Pu	38	–	8
^{239}Pu	3	–	–
^{240}Pu	6	–	–
^{241}Pu	21	19	–
^{241}Am	14	–	3
^{244}Cm	16	–	7
^{90}Sr	–	14	5
^{90}Y	–	14	25
^{134}Cs	–	3	11
^{137}Cs	–	19	7
^{137m}Ba	–	18	24
^{147}Pm	–	5	–
^{154}Eu	–	–	3

Table 4 shows masses of the main isotopes per unit mass of initial heavy metals for NuScale SMR, UK SMR, SMR-160, and VVER-1000. Besides short-lived and medium-lived fission products shown in tab. 3, tab. 4 includes also the isotopes with a very long half-life, ^{99}Tc, ^{135}Cs, ^{129}I, ^{107}Pd, ^{93}Zr.

Planning of the SNF storages (on-site, regional, or centralized) for each of the SMR types requires the number of SNF assemblies N_{FA} produced during the entire life of the plant. This number can be roughly estimated using the available data on the basic parameters of the reactor. The thermal energy E released by the reactor during its lifetime t can be found as follows

$$E = P_{th}\eta t \tag{1}$$

where P_{th} is the nominal reactor thermal power and η – the capacity factor. Knowing the average fuel burnup B, which is the energy released per unit mass of uranium, we then find the total mass of uranium $m_{U,tot}$ required to produce the energy E

$$m_{U,tot} = \frac{E}{B} \tag{2}$$

We assume that the average burnup is the same as specified in tab. 1. Once $m_{U,tot}$ is known, the corresponding number of assemblies N_{FA} is given by

$$N_{FA} = \frac{m_{U,tot}}{m_{U,FA}} \tag{3}$$

Table 4. Mass content of the isotopes in the fuel assemblies (mg/g of initial heavy metals)

Isotope	Half-life	NuScale	SMR-160	UK SMR	VVER-1000
^{238}Pu	87.7 y	0.26	0.31	0.40	0.38
^{239}Pu	2.41 y	5.91	5.73	6.11	6.21
^{240}Pu	6.56 y	2.62	2.65	3.07	3.11
^{241}Pu	14.2 y	1.13	1.10	1.33	1.37
^{241}Am	4.33 y	0.52	0.52	0.61	0.61
^{244}Cm	18.1 y	0.04	0.05	0.10	0.13
^{90}Sr	28.79 y	0.61	0.58	0.71	0.69
^{90}Y	64.6 h	1.5 $^{-4}$	1.5 $^{-4}$	1.8 $^{-4}$	1.7 $^{-4}$
^{134}Cs	2.06 y	0.02	0.01	0.02	0.03
^{137}Cs	30.17 y	1.37	1.34	1.68	1.70
^{137m}Ba	2.55 min	2.1 $^{-7}$	2.0 $^{-7}$	2.6 $^{-7}$	2.6 $^{-7}$
^{147}Pm	2.62 y	0.03	0.03	0.04	0.04
^{154}Eu	8.59 y	0.02	0.02	0.03	0.03
^{99}Tc	2.11 y	1.04	1.05	1.23	1.20
^{135}Cs	2.3 y	0.69	0.74	0.78	0.58
^{129}I	1.6 y	0.21	0.21	0.26	0.27
^{107}Pd	6.5 y	0.28	0.30	0.39	0.42
^{93}Zr	1.53 y	0.97	0.95	1.14	1.11

where $m_{U,FA}$ is the mass of uranium per fuel assembly. We calculated this value from the Serpent FA models. Table 5 shows the results evaluated using eqs. (1)-(3).

It should be noted that the results of this study offer just a general understanding of the expected SNF characteristics, which can vary within certain limits. The SMR projects continue to evolve with time to allow higher burnup at discharge and better utilization of nuclear fuel. Depending on the in-core management, the parameters of SNF assemblies will vary due to different individual in-core histories. The results presented above are an example of SNF characteristics, based on the applied assumptions and currently available input data.

Compared to large reactors, SMRs have smaller cores; that can lead to increased neutron leakage and greater inhomogeneity of the neutron field within the core. Burnup calculations performed in an infinite geometry (considering separate fuel assembly with reflective or periodic boundary conditions) do not take into account neutron leakage and the heterogeneity of the neutron field. Consequently, the error in such calculations for SMR could be greater than for large reactors. To accurately assess these effects, it is necessary to carry out 2-D and 3-D full-core calculations. Such an extensive analysis is beyond the scope of this work and has not been carried out by other authors, to the best of our knowledge. However, in large light water reactors neighbor assemblies can also impact the neutron spectrum and create strong inhomogeneity of the neutron field. The previous investigation has revealed [13] that neighbor assemblies typically impact the assembly total fissile content by approximately 1 %, for UO_2 fuel; frequently, the results obtained by disregarding neighbor assemblies were close to those obtained from more comprehensive neighbor models.

According to [21], the lower SNF discharge burnup for light water SMR can result in a greater amount of spent fuel per unit of energy produced, compared to conventional large reactors. However, the quantity of fission products per unit of energy produced remains the same, while the quantity of transuranic elements per unit of energy produced (such as ^{238}Pu, ^{241}Pu, ^{241}Am, ^{244}Cm, which contribute significantly to radiological characteristics) decreases rapidly with decreasing burnup [14]. As a result, lower discharge burnup of SMR SNF can lead to reduced decay heat, activity, and toxicity, thereby facilitating the handling and storage, while also reducing associated costs.

All SMR projects considered in this study incorporate on-site dry storage facilities for the entire duration of reactor operation. However, it may be desirable to transport SNF from SMR as it accumulates, to a centralized storage facility. If SMR are deployed at multiple locations throughout Ukraine, a comprehensive plan for SNF transportation throughout the country will need to be developed. Since the CSFSF in the Chornobyl Exclusion Zone is designed to store SNF from existing large reactors, it will need to be expanded or new storage facilities will need to be constructed. Furthermore, in light of the plans to deploy SMR in Ukraine, expediting the resolution of the final geological disposal issue is essential. A comprehensive and timely addressing of SMR SNF management issues will help to gain the necessary support of local communities and contribute to the development of nuclear energy in Ukraine.

CONCLUSIONS

At present, Ukraine considers the possibility of deployment of water-cooled SMR in the near future, VOYGRTM (NuScale Power Corporation, USA), UK

Table 5. The total number of SNF assemblies produced during the SMR lifetime, at the capacity factor of η = 0.95

Value	NuScale SMR t = 60 y P_{th} =250 MW B = 45 MWd/kgU	SMR-160 t = 80 y P_{th} =525 MW B = 45 MWd/kgU	UK SMR t = 60 y P_{th} =1358 MW B = 55 MWd/kgU
$m_{U,tot}$ [kg]	116000	324000	514000
$m_{U,FA}$ [kg]	250	470	350
N_{FA}	464	690	1470

SMR (Rolls-Royce SMR Ltd, UK) and SMR-160 (Holtec International, USA). Operating nuclear reactors in Ukraine, are of the VVER type. In this work, we perform 2-D infinite-core depletion calculations of the SMR fuel assemblies and the VVER-1000 assembly using the Monte Carlo code Serpent. Main SNF characteristics affecting the SNF management were evaluated: activity, decay heat, and inhalation toxicity (per unit length of the assembly and assembly), the contributions of nuclides that exceed 2 % of activity, decay heat, and inhalation toxicity, and mass content of these nuclides per unit mass of heavy metals. We also evaluated the total number of SNF assemblies produced during the entire life of the plant, for each SMR type. From the obtained results, the following conclusions can be made.

The inhalation toxicity, activity, and decay heat per unit length of the SNF assembly, are close for the considered SMR and the VVER-type reactors. Therefore, SNF from the considered SMR will not create new issues for radioactive waste management in Ukraine. For the three SMR, the evaluated radiological characteristics do not exceed those for large VVER-1000 reactors currently operating in Ukraine.

Compared to UK SMR and VVER-1000 SNF, NuScale and SMR-160 SNF fuel assemblies exhibit lower inhalation toxicity, activity, and decay heat per unit length, and require shorter cooling time in the used fuel pool before moving to dry cask storage.

Among the studied SNF assemblies with identical discharge burnup (45 MW/kgU for NuScale and SMR-160, and 55 MW/kgU for UK SMR and VVER-1000) the NuScale and VVER-1000 assemblies exhibit noticeably higher radiological characteristics throughout several initial years of cooling in the pool. These differences are related to significantly higher specific power for NuScale and VVER-1000 compared to SMR-160 and UK SMR, correspondingly. The effect of specific power on the radiological characteristics dominates over the effect of other distinctions between the studied assemblies with identical discharge burnup (in initial enrichment, burnable poison content, and coolant density), at least during the first 5 years of cooling. The power-dependent alterations in the nuclide composition of SNF assemblies can be of potential importance for safeguard measures and nondestructive testing of the SMR SNF.

The three SMR significantly differ in total number of SNF assemblies produced during the entire life of the plant, mainly due to different reactor heat power and active length of the fuel assembly. This could be important for the siting of plants (including on-site dry storage) as well as options for the development of decentralized and centralized SNF management in Ukraine.

The estimates of SNF characteristics obtained in this work can help to evaluate the NuScale, UK SMR, and SMR-160 projects under consideration for construction in Ukraine in terms of SNF management and their inclusion in the radioactive waste management scheme in Ukraine, to reasonably inform the public about the risks associated with SMR radioactive waste, and to prepare public opinion for the introduction of new SMR technologies in Ukraine.

ACKNOWLEDGMENT

This work was funded by ISN/NDF Global Threat Reduction programs (Grant Agreement#1012-NRT).

AUTHORS CONTRIBUTIONS

O. Khotiaintseva: conceptualization, formal analysis, investigation, methodology, software, writing – original draft, review and editing. V. Khotiaintsev: conceptualization, investigation, methodology, writing – review and editing. V. Gulik: formulation of the problem, conceptualization, writing – review and editing.

REFERENCES

[1] ***, The International Energy Outlook (IEO), 2021 https://www.eia.gov/outlooks/ieo/, Release Date: October 6, 2021

[2] Sichen, Gao., *et al*., Small Modular Reactors Enable the Transition to a Low-Carbon Power System Across Canada, *Renewable and Sustainable Energy Reviews, 169* (2022), Nov., 112905

[3] Playbell, I., Economy, Safety and Applicability of Small Modular Reactors, *Proceedings*, *Institution of Civil Engineers – Energy, 170* (2017), 2, pp. 67-79

[4] ***, Advances in Small Modular Reactor Technology Developments, IAEA, 2022, p. 424

[5] ***, Report on Nuclear and Radiation Safety in Ukraine for 2020, State Nuclear Regulatory Inspectorate of Ukraine, 2021, p. 89

[6] ***, Interfax-Ukraine: Ukrainian News Agency, https://en.interfax.com.ua/news/economic/898157.html

[7] ***, SE "NNEGC Energoatom", https://www.energoatom.com.ua/app-eng/small-reactors.html

[8] Stefanović, N. D., *et al*., The Spatial and Planning Aspect of Solving the Issue of Radioactive Waste Disposal in the Republic of Serbia, *Nucl Technol Radiat, 36* (2021), 1, pp. 38-49

[9] Xu, H., *et al*., A Digital Twin Framework for Construction and Operation of the Radioactive Waste Repository, *Nucl Technol Radiat, 37* (2022), 3, pp. 180-192

[10] ***, Advanced Modular Reactors: Technical Assessment. Nuclear Innovation and Research Office, UK, 2021, p. 55

[11] Keto, P., *et al*., Waste Management of Small Modular Nuclear Reactors in Finland, VTT Research Report, VTT-R-00076-22, 2022

[12] Bakir, G., Analysis of Thorium and Transuranium Utilization in Small Modular Reactor, *Nucl Technol Radiat, 37* (2022), 3, pp. 175-180

[13] Hu, J., *et al*., Developing Spent Fuel Assembly Standards for Advanced NDA Instrument Calibration - NGSI Spent Fuel Project, Technical Report ORNL/

TM-2013/576, Oak Ridge National Laboratory, Oak Ridge, TN, USA, 2014

[14] Broadhead, B. L., Recommendations for Shielding Evaluations for Transport and Storage Packages, Technical Report NUREG/CR-6802, ORNL/TM -2002/31, Oak Ridge National Laboratory, Oak Ridge, TN, USA, 2003

[15] ***, Advances in Small Modular Reactor Technology Developments, IAEA, 2014, p. 150

[16] ***, Status Report – UK SMR (Rolls-Royce and Partners), United Kingdom, 2019/09/30, p. 25

[17] Preston, M., *et al*., Possibilities for Monitoring the Composition of an iPWR Core Using Ex-Core Neutron Detectors, Annual Meeting Proceedings, 2023, https://resources.inmm.org/annual-meeting-proceedings/possibilities-monitoring-composition-ipwr-core-using-ex-core-neutron

[18] Suk, P., *et al*., Simulation of a NuScale Core Design with the CASL VERA Code, *Nuclear Engineering and Design 371* (2021), Jan., 110956

[19] Lötsch, T., *et al*., The X2 benchmark for VVER-1000 Reactor Calculations, International Conference „Novel Vision of Scientific & Technical Support for Regulation of Nuclear Energy Safety: Competence, Transparency, Responsibility", Kyiv, Ukraine, March 2017

[20] ***, https://www.nist.gov/system/files/documents/srd/NISTIR5078-Tab3.pdf

[21] Nicholas, R., *et al*., Impact of Thermal Spectrum Small Modular Reactors on Performance of Once-Through Nuclear Fuel Cycles with Low-Enriched Uranium, *Annals of Nuclear Energy, 101* (2017), March, pp. 166-173

Received on July 24, 2023
Accepted on September 18, 2023

Олена КОТИЈАИНЦЕВА, Володимир КОТИЈАИНЦЕВ, Володимир ГУЛИК

РАДИЈАЦИОНЕ КАРАКТЕРИСТИКЕ УТРОШЕНОГ НУКЛЕАРНОГ ГОРИВА МАЛИХ МОДУЛАРНИХ РЕАКТОРА У РАЗМАТРАЊУ ЗА УПОТРЕБУ У УКРАЈИНИ

Мали модуларни реактори представљају обећавајућу технологију за производњу електричне енергије, нудећи решења за енергетску кризу и ублажавање емисија гасова стаклене баште. Пошто Украјина разматра распоређивање NuScale, UK SMR и SMR-160, од кључне је важности да се позабави сигурносним управљањем истрошеним нуклеарним горивом. Ова студија фокусира се на процену радијационих карактеристика утрошеног нуклеарног горива из одабраних малих модуларних реактора и, ради поређења, из реактора VVER -1000. Користећи Монте Карло код Serpent, извршени су прорачуни осиромашења за гориви склоп у бесконачној 2-D геометрији и процењена је активност, топлотно слабљење и инхалациона токсичност утрошеног нуклеарног горива. Одредили смо главне нуклиде који доприносе радијационим карактеристикама и квантификовали масени садржај ових нуклида. Процењен је укупан број утрошених склопова нуклеарног горива насталих током читавог животног века сваког малог модуларног типа реактора. Радијационе карактеристике процењене за три мала модуларна реактора не прелазе оне уочене за реакторе VVER-1000 који тренутно раде у Украјини. Отуда, утрошено нуклеарно гориво произведено у одабраним малим модуларним реакторима неће представљати нове изазове за украјински систем управљања радиоактивним отпадом. Резултати овог рада пружају драгоцене увиде за идентификацију оптималних технологија малих модуларних реактора за Украјину у погледу сигурносног управљања утрошеним нуклеарним горивом.

Кључне речи: мали модуларни реактор, управљање утрошеним нуклеарним горивом, NuScale, UK SMR, SMR-160, Serpent, карактеристика утрошеног нуклеарног горива