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Research Article

Small nuclear power plants for power supply in arctic regions: assessment of spent nuclear fuel radioactivity*

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Abstract

The purpose of the present study is the investigation of mass composition of long-lived radionuclides accumulated in the fuel cycle of small nuclear power plants (SNPP) as well as long-lived radioactivity of spent fuel of such reactors. Analysis was performed of the published data on the projects of SNPP with pressurized water-cooled reactors (LWR) and reactors cooled with Pb-Bi eutectics (SVBR). Information was obtained on the parameters of fuel cycle, design and materials of reactor cores, thermodynamic characteristics of coolants of the primary cooling circuit for reactor facilities of different types. Mathematical models of fuel cycles of the cores of reactors of ABV, KLT-40S, RITM-200M, UNITERM, SVBR-10 and SVBR-100 types were developed. The KRATER software was applied for mathematical modeling of the fuel cycles where spatial-energy distribution of neutron flux density is determined within multi-group diffusion approximation and heterogeneity of reactor cores is taken into account using albedo method within the reactor cell model. Calculation studies of kinetics of burnup of isotopes in the initial fuel load (^{235}U, ^{238}U) and accumulation of long-lived fission products (^{85}Kr, ^{90}Sr, ^{137}Cs, ^{151}Sm) and actinoids ($^{238,239,240,241,242}Pu$, ^{236}U, ^{237}Np, ^{241}Am, ^{244}Cm) in the cores of the examined SNPP reactor facilities were performed. The obtained information allowed estimating radiation characteristics of irradiated nuclear fuel and implementing comparison of long-lived radioactivity of spent reactor fuel of the SNPPs under study and of their prototypes (nuclear propulsion reactors). The comparison performed allowed formulating the conclusion on the possibility in principle (from the viewpoint of radiation safety) of application of SNF handling technology used in prototype reactors in the transportation and technological process layouts of handling SNF of SNPP reactors.

Keywords

Arctic regions of Russia; small nuclear power plants; reactors; spent nuclear fuel; fuel cycle; radioactivity

Introduction

The need to develop alternative energy sources and to implement of upgrades of power generation infrastructure in Arctic regions was included among the priority tasks implementation of which is aimed at the achievement of main purposes of state policy of the Russian Federation in the Arctic regions (Strategy of development of Arctic zone 2015). The above priority direction determines the realistic prospects of practical implementation of projects of small nuclear power plants (SNPP) in the area of provision of energy supplies for remote territories of Arctic regions of the RF. Remoteness of potential sites for construction of SNPPs from the main centers of machine

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building for nuclear industry and sites where handling of spent nuclear fuel (SNF) is performed predetermines the necessity to establish on SNPP site the infrastructure for handling irradiated fuel.

The study is dedicated to the assessment of radioactivity of SNF which was performed on the basis of mathematical simulation of fuel cycles of SNPP reactors of different types and of prototype reactor facilities. Radionuclides producing main contribution in SNF radioactivity during the stages of irradiated fuel handling after its cooling down in reactor SNF storage facilities including the following: β-active ^{85}Kr ($T_{1/2}$ = 10.9 years), ^{90}Sr ($T_{1/2}$ = 28.6 years), ^{137}Cs ($T_{1/2}$ = 30.1 years), ^{151}Sm ($T_{1/2}$ = 90 years) and α-active ^{238,239,240,241,242}Pu, ^{236}U, ^{237}Np, ^{241}Am ($T_{1/2}$ = 433 years), ^{244}Cm ($T_{1/2}$ = 18.1 years) were examined in the studies and in the analysis of results.

Small power reactor facilities

Currently a number of research institutes (Dollezhal Research and Design Institute of Energy Technologies (NIKIET), IPPE) and design bureaus (Afrikantov Experimental Design Bureau for Mechanical Engineering (OKBM), OKB Gidropress) developed on the basis of existing experience of nuclear-powered shipbuilding several options of design of shipboard nuclear propulsion facilities of different types and configurations which can be used for covering prospective power demand from potential consumers in Arctic regions of the RF (Adamov 2015, Voropay et al. 2015, Melnikov et al. 2015, Petrunin et al. 2015, Saneev et al. 2011). Reactor facilities which, in the opinion of the authors, according to the combination of factors (availability of a prototype, degree of preparedness to practical implementation, duration of fuel cycle, possibility of operation in the cogeneration mode, possibility of operation in stand-alone mode, etc.) refer to the most priority types of reactor facilities: RITM-200M; KLT-40S; ABV; UNITERM; SVBR-100; SVBR-10. Versions of design of the above listed reactor facilities were divided into two classes in accordance with coolant used in the primary cooling circuit. The first class includes design projects based on the application of thermal pressurized light water reactors with pressurized water as the coolant. Facilities with fast reactors of SVBR-100 and SVBR-10 types cooled with molten Pb-Bi eutectic alloy refer to the second class of reactor facilities.

The following two reactor facilities are regarded as prototype facilities for the class of light water reactors: shipboard reactor facility of OK-900A type on “Siberia” nuclear-powered icebreaker which was operated from 1978 to 1992 and generated 84 GW·day of thermal power during the first Arctic navigation (1978 – 1980), as well as reactor facility of KLT-40 type used to power “Sevmorput” nuclear lighter carrier. Two cores of KLT-40 reactor were spent during the period from 1988 to 1999 with average power output equal to 78 GW·day (Makarov et al. 2000). Nuclear reactor of Project 705K submarines (NSM) with designed power capacity of ~ 25 GW·day which were operated during the period 1970 to 1996 (Ignatiev et al. 2007) can be regarded as prototypes of the class of liquid-metal cooled reactors.

Research methodology

Simplified mathematical models of reactor cores (RC) of the reactors under examination with description of neutronics processes using KRATER software complex (SW) (Naumov et al. 1996) based on the algorithm of numerical solution of neutron balance equations in the reactor in multi-group (10 groups) diffusion approximation and equations of kinetics of ^{235}U and ^{238}U burnup and accumulation of actinoids, as well as stable and long-lived fission reaction products were developed for estimating production of radioactive nuclei in nuclear reactors. KRATER software has library of group neutronics constants for 59 elements. Values of constants correspond to the data in ENDF/B-6 library (Naumov et al. 1996), while those for fission product yields and half-lives are in correspondence with ENDF-349 (England and Rider 1994) publication. Neutron balance equations are solved jointly for the sequence of time steps of fuel burnup into which reactor core fuel cycle is split. Fuel cycle (FC) of reactor core is represented by reactor operation on medium power level during the whole duration of the fuel cycle. Development of mathematical models of the FC presupposes determination of material composition and geometry of the reactor core, neutron reflectors, as well as power generation parameters of the reactors.

FC parameters and characteristics of cores of reactors under study used as the input data for constructing mathematical models are presented in Tables 1 – 3 (Adamov 2015, Makarov et al. 2000, Ignatiev et al. 2007, Alekseev et al. 2016, Vatulin et al. 2005, Voronkov et al. 2009, Egorov 2016, Klimov 2013, Knyazevsky et al. 2014, Samoylov et al. 2005, IAEA-TECDOC-1536 2012). Installed thermal power, capacity factor (CF) and time of installed power operation are the main design parameters of the reactor core.

Models of pressurized SNPP reactors and pressurized water prototype reactors

Heterogenous core of channel type of reactor facility OK-900A consists of 241 pressure channels (PC) each of which represents Ø60×1 mm pipe made of zirconium-niobium alloy containing fuel rod bundle consisting of 61 rods (54 fuel rods and seven absorber rods (AR)). Cross-section of pressure channel is shown in Fig. 1a.

Mathematical model of OK-900A reactor facility was developed on the basis of the data in Tables 1–3 in one-dimensional cylindrical reactor geometry and reactor cell. Radial non-uniformity of neutron flux density distribution in the pressure channel is accounted for using the model of multi-zone annular cell into which pressure channel with

Table 1. Parameters of fuel cycles of SNPP reactor installations and their prototypes.

SNPP or shipboard reactor facility	Installed thermal power, MW	Power generation capacity, GW·day	Time of installed power operation, years	CF	Fuel cycle duration, years	Time between core refueling, years
ABV	45	131.5	8.0	0.8	10	10–12
UNITERM	30	181	16.5	0.8	20.6	25
KLT-40S	150	137.5	2.51	0.65	3.9	4
RITM-200M	175	291.7	4.57	0.65	7.03	10-12
KLT-40, “Sevmorput” nuclear lighter carrier	135	78	1.58	~0.3	~5.5	~6
OK-900A, “Siberia” nuclear icebreaker*	171	84	1.35	~0.6	2.3	4
SVBR-100	280	631	6.18	0.9	6.9	8
SVBR-10	43.3	243	15.4	0.8	19	20–21
NSM, Project 705K	150	25	0.46	~0.09	~5.0	–

* Reactor unit no. 2, “Siberia” icebreaker during 1978 – 1980 fuel irradiation campaign.

Table 2. Characteristics of SNPP reactors and their prototypes.

SNPP or shipboard reactor facility	Uranium load, t	Mass of fuel composition, t	Average uranium enrichment with ^{235}U isotope, %	Fuel composition	Average fuel burnup depth, g/cm^3
ABV	1.4	1.9	16.5	UO_2 in aluminum-silicon matrix	0.43
UNITERM	1.58	2.52	19.7	UO_2 in zirconium matrix	0.665
KLT-40S	1.53	2.09	17.4	UO_2 in aluminum-silicon matrix	0.429
RITM-200M	3.2	4.28	17.5	UO_2 in aluminum-silicon matrix	0.429
KLT-40, “Sevmorput” nuclear lighter carrier	0.167	0.84	90	Uranium-zirconium alloy	0.35
OK-900A, “Siberia” nuclear icebreaker*	0.513	0.95	40.6	UAl_3 in aluminum matrix	0.38
SVBR-100	9.188	10.4	16.5	UO_2	0.62
SVBR-10	4.037	4.58	18.7	UO_2	0.62
NSM, Project 705K	0.182	0.4	89	UBe_{13} in beryllium matrix	< 0.1

Table 3. Characteristics of cores of SNPP reactors and their prototypes.

SNPP or shipboard reactor facility	Number of fuel assemblies (FA grid pitch, cm)	Fuel rod diameter, mm (fuel cladding material)	Number of fuel rods in the core	Reactor core diameter/height, m
ABV	121 (10)	6.8×0.5 (alloy Э-110)	9317	1.155/1.3
UNITERM	265 (7.2)	5.8×0.5 (alloy Э-110)	14310	1.231/1.1
KLT-40S	121 (10)	6.2×0.5 (alloy Э-635)	12342	1.155/1.3
RITM-200M	199 (10)	6.2×0.5 (steel)	20467	1.48/1.65
KLT-40, “Sevmorput” nuclear lighter carrier	241 (7.2)	5.8×0.5 (alloy Э-110)	12787	1.155/1.0
OK-900A, “Siberia” nuclear icebreaker*	241 (7.2)	5.8×0.5 (steel)	12787	1.155/1.0
SVBR-100	61 (20)	12×0.4 (steel)	12078	1.646/0.9
SVBR-10	27 (20)*	12×0.4 (steel)	5373	1.086/0.9
NSM, Project 705K	**	11×0.5 (steel)	4200	0.885/0.928

* calculated value
** not used in the present study

water is transformed (Fig. 1c). Results of calculations of isotopic composition by the end of fuel cycle are presented in Table 4 where specific α- and β-activities of SNF are determined as the ratio of total activity to the mass of fuel composition. There the sum of activities of nuclides under study (^{85}Kr, ^{90}Sr, ^{90}Y, ^{137}Cs, ^{137m}Ba, ^{151}Sm) is understood as the total activity.

UNITERM SNPP reactor is the closest to the investigated prototype with regard to reactor core design. This rector has design of pressure channels similar to OK-900A reactor (Fig. 1b), but, however, number of channels and height of fuel kernel are increased to 265 pieces and to 110 cm, respectively. Other measure aimed at the increase of fuel load and power yield is the application of ceramic-metal fuel composition instead of UAl_3+Al intermetallide. Volume fraction of UO_2 particles in the fuel kernel amounts to ~60%, while uranium concentration is increased from 2.2 to ~ 5.6 g/cm^3. Results of calculations of mass composition of long-lived ac-

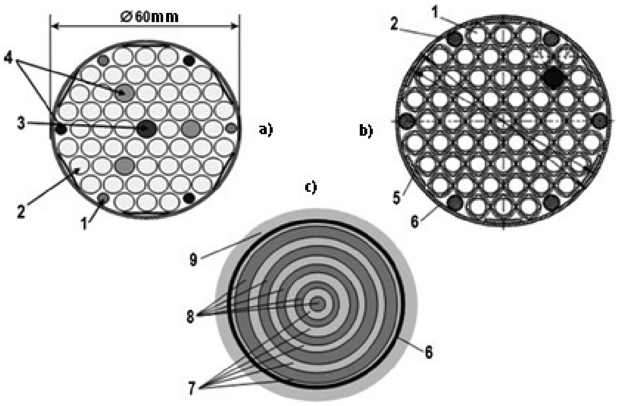

Figure 1. Cross section of pressure channel of light water reactor core: a) pressure channel 10-14-3M of icebreaker OK-900A reactor core У (Vatulin et al. 2005); b) pressure channel of UNITERM reactor core (IAEA-TECDOC-1536); c) model of fuel cluster of ship propulsion nuclear reactors. 1 – brace of spacer grid; 2 – fuel rod; 3 – operational neutron source; 4 – burnable absorber rod; 5 – tabular displacer; 6 – casing; 7 – coolant; 8 – fuel layers; 9 – interchannel water.

tinides and fission products performed using KRATER SW for UNITERM reactor are presented in Table 4.

The next group of reactor facilities under investigation with cognate accepted design and technological solutions with regard to reactor core is formed by ABV, KLT-40S and RITM-200M. Fuel cycle of these reactor facilities differs from the prototype ones by large values of power generation capacity and time of installed power operation (see Table 1). This feature requires increased fuel loads which is achieved by increasing fuel volume and uranium content. Reactor cores of the examined reactor facilities have cassette type configuration and are assembled of hexagonal fuel assemblies (cassettes) (Figs. 2a, 2b).

Heterogenous structure of cassette-type reactor cores is accounted for in mathematical models of fuel cycles using five-zone elementary cylindrical reactor cell (Fig. 2c). Compositions of zones of reactor cells are preset using atomic concentrations of elements determined according to the data on reactor core characteristics (see Tables 2, 3). Results of studies of mass composition of long-lived radionuclides and their activities by the end of fuel cycle of ABV, KLT-40S and RITM-200M reactors are presented in Table 4.

Models of SVBR-type reactors

Two projects of fast reactors with lead-bismuth coolant SVBR-10 and SVBR-100 intended for application as power sources in remote regions of Russia were developed in our country. Fuel cycle of SVBR-100 reactor was investigated in (Voronkov et al. 2009) using rigorous calculation methods and isotopic composition of actinoids was determined by the end of fuel residence campaign (Table 5). However, isotopic composition of fission products was not investigated in this paper which does not permit performing comparison of this reactor with other reactor types. Therefore, the need to develop mathematical model of the fuel cycle and to perform investigation of SNF of SVBR reactor remains.

Structure of reactor core and its radial reflector is shown in Fig. 3 (radial reflector is the steel structure with Pb-Bi-coolant with thickness equal to 25 cm). Reactor geometry is represented with one-dimensional cylindrical model. Accounting for the heterogeneity of the reactor

Table 4. Comparison of masses and activities of long-lived radionuclides in reactor core by the end of fuel cycle of light-water SNPP reactors and their prototypes * (KRATER software).

Parameter	Reactor facilities					
	KLT-40, ”Sevmorput” nuclear lighter carrier	OK-900A, “Siberia” nuclear icebreaker	UNITERM	ABV	KLT-40S	RITM-200M
Mass of ^{235}U, kg	51.7	100	108	88	119	243
Mass of ^{237}Np, kg	1.01	1.12	3.34	2.02	2.47	5.38
Mass of ^{238}Pu, kg	0.345	0.21	0.82	0.526	0.606	1.32
Mass of ^{238}U, kg	14.9	296	1220	1128	1224	2544
Mass of ^{239}Pu, kg	0.41	4.21	12.4	9.77	13.3	28.7
Mass of ^{240}Pu, kg	0.16	1.11	4.39	3.49	3.79	8.24
Mass of ^{241}Pu, kg	0.13	0.92	3.40	2.57	3.22	7.15
Mass of ^{241}Am, kg	0.004	0.043	0.87	0.31	0.156	0.636
Mass of ^{244}Cm, kg	0.001	0.01	0.036	0.025	0.027	0.0575
Mass of ^{85}Kr, kg	0.074	0.079	0.098	0.093	0.116	0.221
Mass of ^{90}Sr, kg	1.68	1.825	3.03	2.40	2.68	5.45
Mass of ^{137}Cs, kg	2.78	3.12	5.66	4.42	4.91	10.1
Mass of ^{151}Sm, kg	0.01	0.026	0.036	0.028	0.041	0.087
Total a-activity, PBq	0.222	0.19	0.817	0.50	0.548	1.225
Specific a-activity, TBq/kg	0.26	0.20	0.324	0.263	0.265	0.286
Total b-activity**, PBq	35.7	39.4	68	53.6	60	122
Specific b-activity**, TBq/kg	42.5	41.6	27	28.3	28.9	28.5

* ^{236}U and ^{242}Pu masses omitted
** ^{241}Pu not accounted for

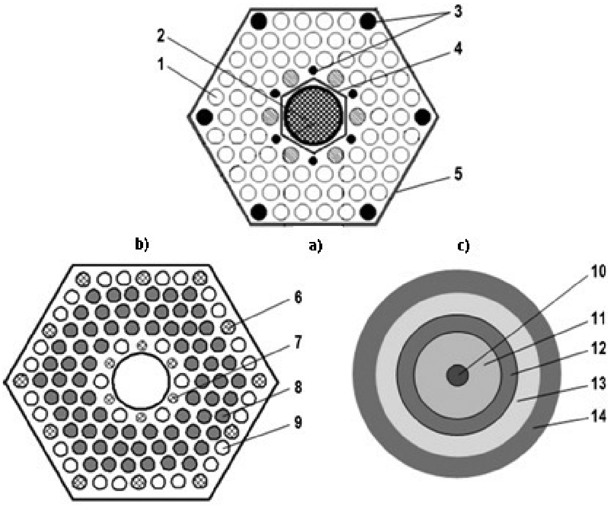

Figure 2. Cross-section of fuel assembly of cassette-type core of SNPP reactors: a) cassette of ABV-6 reactor (IAEA-TEC-DOC-1536); b) Cassette of KLT-40S reactor (Alekseev et al. 2016); в) Model of cylindrical reactor cell; 1 – fuel element; 2 – absorber element; 3 – burnable absorber rod; 4 – internal tube; 5 – external tube; 6 – burnable absorber rods (BAR) or operational neutron sources (ONS) with external diameter equal to 6.2 mm; 7 – BAR or ONS with external diameter equal to 4.6 mm; 8 – "heavy" fuel element; 9 – "light" fuel element; 10 – burnable absorber; 11 – fuel; 12 – fuel cladding; 13– coolant (water); 14 – structural materials.

core is achieved using the model of elementary cylindrical reactor cell where caisson pipe intended for arrangement of absorber rods of reactor control and safety system is separated.

Mode of operation at nominal thermal power with generation of 243 GW·day and time of installed power operation equal to 15.4 years was examined for calculating isotopic composition of SVBR-10 reactor core. Rector core is configured using the same fuel assemblies as in SVBR-100 reactor. Number of FAs was taken to be equal to 27.

Results of investigation of isotopic composition and activity of SNF by the end of fuel cycle of SVBR-10 and SVBR-100 reactors are presented in Table 5.

Results and discussion

Main results of the study provided in Tables 4 and 5 represent the data on mass isotopic composition and activity of long-lived actinoids and radiation dose shaping ^{85}Kr, ^{90}Sr and ^{137}Cs fission products (FP) (including daughter products of decay of ^{90}Y and ^{137m}Ba) and ^{151}Sm in SNF of SNPP reactor facilities of two classes with different coolant technology (Table 4 contains results for SNPP reactors of ABV, KLT-40S, RITM-200M, UNITERM types and their prototypes – reactor facilities of nuclear powered icebreakers equipped with light-water reactors; Table 5 contains respective data for liquid-metal SNPP reactors of SVBR-10 and SVBR-100 types and their prototype – reactor facility of Project 705K NSM).

The authors regard the comparison of total specific activities of radiation dose shaping FPs within each class of SNPP reactor facilities to be of utmost scientific and practical interest, because this comparison allows formulating judgement about possible differences in radiation conditions of handling SNF of SNPP reactor facilities and their prototypes. In case of light water reactor types specific activities of long-lived fission products in SNF of all SNPP reactors have the values of activity of about

Table 5. Comparison of masses and activities of long-lived radionuclides in the reactor core by the end of fuel cycle of liquid metal SNPP fast reactors and of their prototype – reactor of Project 705K NSM (masses of ^{236}U and ^{242}Pu are not presented).

Parameter	Intermediate neutron reactor of Project 705K NSM (KRATER SW)	Fast SNPP reactors	
		SVBR-10 (KRATER SW)	SVBR-100 (KRATER SW and (Voronkov et al. 2009))
Mass ^{235}U, kg	126.4	504	941
Mass ^{237}Np, kg	0.87	3.0	6.77
Mass ^{238}Pu, kg	0.082	0.31	0.814
Mass ^{238}U, kg	16.48	3113	7220
Mass ^{239}Pu, kg	1.33	111	331
Mass ^{240}Pu, kg	0.086	4.75	16.4
Mass ^{241}Pu, kg	0.062	0.175	0.53
Mass ^{241}Am, kg	0.001	0.013	0.0368
Mass ^{244}Cm, kg	0.000003	0.00001	0.000022
Mass ^{85}Kr, kg	0.0252	0.143	0.472
Mass ^{90}Sr, kg	0.559	4.11	11.98
Mass ^{137}Cs, kg	0.917	7.61	21.83
Mass ^{151}Sm, kg	0.042	0.685	1.71
Total a-activity, PBq	0.056	0.597	1.49
Specific a-activity, TBq/kg	0.142	0.13	0.143
Total b-activity, PBq	11.9	92.1	263
Specific b-activity, TBq/kg	30	20	25

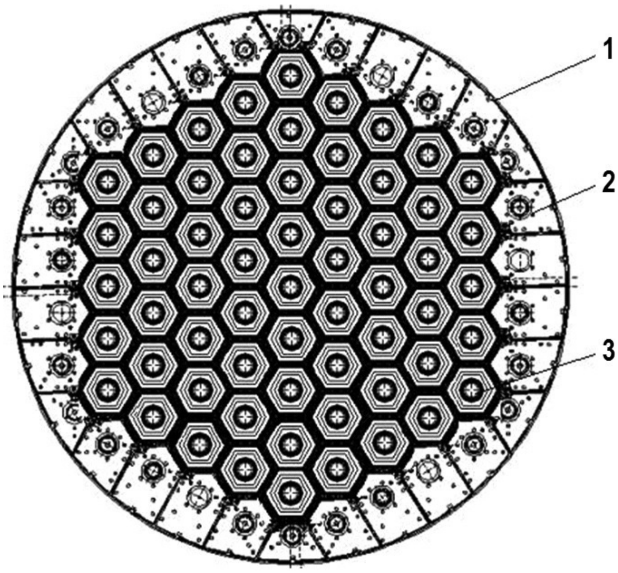

Figure 3. Cross-section of SVBR-100 reactor core (Konyukhov 2015): 1 – casing of extractable block; 2 – element of side reflector; 3 – fuel assembly.

27 TBq/kg, while those for prototype reactor facilities are equal to ~42 TBq/kg. Thus, it is evident that intensity of sources of ionizing radiation emitted in decays of ^{85}Kr, ^{137}Cs and ^{137m}Ba is by approximately 1.5 lower for SNF of SNPP reactor facilities compared to their prototypes. It follows from the above that handling SNF of SNPP reactor facilities will be performed at time moments after cooling SNF down in reactor spent fuel storage facilities at lower levels of ionizing radiation than those for SNF of prototype reactor facilities. In our opinion this fact allows formulating the conclusion on the possibility (from the viewpoint of ensuring radiation safety) of application of the SNF handling infrastructure used at present on prototype reactor facilities with SNF handling technology for SNPP reactor facilities currently under development.

In case of liquid-metal fast reactors specific β-activity (and, consequently, gamma-activity of ^{137}Cs→^{137m}Ba decay chain as well) of SNF of reactor facility of SVBR type is also lower than that for the prototype (reactor facility of Project 705K NSM) by 1.2 – 1.5 times. Conclusion similar to that for SNPP reactor facility with light-water reactors can be formulated in this case.

As to the analysis of mass composition of actinoids in SNF of light-water SNPP reactors, significant accumulation of plutonium isotopes in SNF (from 7 kg per ton of uranium in the case of ABV reactor to 9 kg/t for RITM-200M) has to be noted, which is explained by high (about 2%) burnup of ^{238}U because of high values of power yield by cores of reactor facilities of this class. This result is rather hard to predict, if the fact is taken into account of a lower specific content of ^{239}Pu in spent nuclear fuel of commercial reactors of VVER-440 and VVER-1000 types, where less enriched fuel is used compared to SNPP reactors. The determined high concentration of ^{239}Pu in SNF of SNPP reactor facility with VVER type reactors allows formulating the conclusion on the advisability of radiochemical reprocessing of SNF of SNPP reactor facilities.

Conclusions

Mathematical models were developed of neutronics processes in reactor cores of SNPP of the following two classes: on the basis of light-water reactors and liquid-metal fast reactors, as well as of prototype reactor facilities. Calculation study was performed of accumulation of long-lived radiation dose shaping fission products and actinoids in SNF of these reactors.

Analysis of specific activity of long-lived radiation dose shaping fission products (^{85}Kr, ^{90}Sr, ^{137}Cs) established that this parameter characterizing intensity of sources of ionizing radiation is lower for SNF reactors of SNPP than for SNF of prototype reactors, which allows forecasting the possibility, in accordance with conditions for ensuring radiation safety, of application of SNF handling infrastructure currently used for prototype reactors for handling SNF of SNPP reactors at time moments after extraction of SNF after cooling down in on-site reactor spent fuel storage facilities.

Significant accumulation of ^{239}Pu in SNF of light-water SNPP reactors (7 – 9 kg per ton uranium) was discovered based on the analysis of mass composition of long-lived actinoids, which exceeds concentration of ^{239}Pu equal to ~ 5.5 kg per ton uranium in SNF of commercial reactors of VVER-440 and VVER-1000 types, which is the indication of the advisability of reprocessing SNF of SNPP reactors.

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