Approaches to definition of radiation characteristics of constructional elements at core assemblies during operation and decommissioning of fast reactors

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Abstact. In the analysis of nuclear and radiation safety of existing and designed BN reactors considerable attention is paid to the problems associated with the formation of radioactive waste (RW) during their operation and decommissioning.

This paper describes the approaches to determine radiation characteristics of non-fuel compositions and structural elements of fuel assemblies (FA) and non-fuel assemblies of the core. The latter include the control and protection system (CPS) assemblies and in-vessel storage shielding assemblies. During the operation of BN reactor CPS assemblies are replaced, with subsequent transfer to RW, and in-vessel storage shielding assemblies are transferred to RW on reactor decommissioning.

Development of the approaches to determine radiation characteristics of the structural elements of the BN reactor core assemblies is an actual problem and some developments in this direction are presented within the framework of this work.

The radiation characteristics of irradiated structural elements depend on:

- the value and the spectrum of neutron flux at the location of irradiated structural elements;
- the irradiation history (the irradiation time, the number of irradiation intervals (cycles between refueling));
- the type of assemblies (weight fractions of elements and isotopes in construction materials such as steel, boron carbide; impurities in the assembly).

The calculation of the radiation characteristics for any user-defined assemblies on the core load map is provided with modern nuclear data libraries and computer codes. For this purpose, the procedure was developed for automatic selection of all the necessary data on decay energy, quantities of isotopes, activity and gamma radiation spectrum in the axial layers and entire assembly. It is also possible to define RW categories in the assembly axial layers for the selected cooling times range.

The analysis of the present study results indicates the important aspects of the radiation characteristics of the considered assembly types that need to be taken into account at all stages of BN reactors lifecycle.

Key words: core assemblies, activation isotopes, radiation characteristics, radioactive waste.

1. Introduction

In the analysis of nuclear and radiation safety of the operating and designed BN reactors much attention is paid to problems, connected with formation of radioactive waste during their operation and decommissioning.

This work provides the description of approaches to calculate of radiation characteristics of nonfuel compositions and constructional elements in fuel assemblies and in structure of nonfuel assemblies in the core. These are assemblies of the reactor control and safety system, and also shielding assemblies of in-vessel storage.

Radiation characteristics of irradiated constructional elements depend from:

- Neutron flux value and spectrum in the location of the irradiated constructional elements;

- Irradiation history (irradiation time, numbers of irradiation and decay intervals);

- Types of assemblies (weight fractions of elements and isotopes in steel constructional materials at assemblies and B_4C).

2. Description of code and calculation model

Authors of the report have developed the program complex ACMAR [1] with interfaces for data transmission from neutron and physical calculation to the code. In this code, there is an opportunity to use various libraries with modern data when calculating radiation characteristics for any given assemblies in a cartogram of the core. At the same time, the structure of assemblies by the height is simulated in details, including of material composition of different elements: heads, wrappers, adapters, bottom nozzles, etc. The code provides calculation: energies release; activities of isotopes; gamma radiation spectrum (15 and 127 groups), and also the radioactive waste category of assembly materials and their volumes. In the figure 1 there is block-scheme of developed program ACMAR.

For more detailed analysis the listed characteristics are calculated in zones on assembly height (to 200 zones) and sum on whole assembly. The possibility of analysis of characteristics change during storage for the chosen time intervals after radiation of assembly in the reactor is provided.

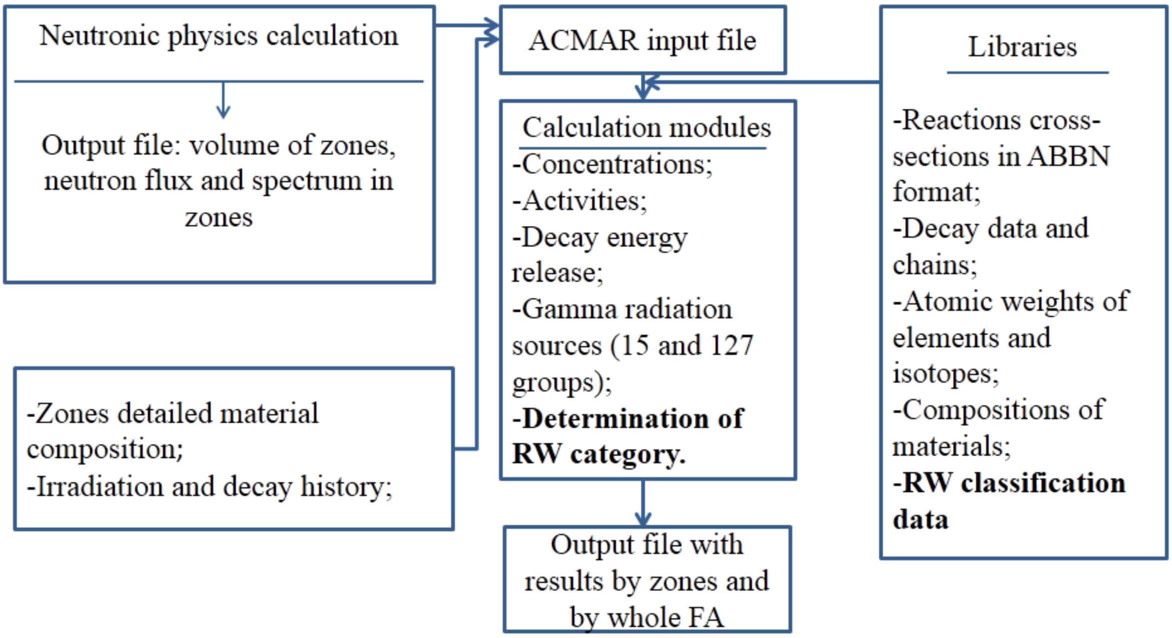

Figure.1 Schematic block diagram of ACMAR code

The obtained data are necessary for:

- Nuclear and radiation safety analysis;

- Definitions of dose budget on personnel at operations with assemblies;

- Determination of volumes and classes of radioactive waste at operation and decommissioning of the BN reactor;

- Developments of approaches to operations with radioactive waste;

- Developments of requirements to containers for transportation and disposal of radioactive waste;

- Determination of disposal cost of radioactive waste etc.

The main nuclear reactions for calculation of activation isotopes are:
$Co^{59}(n,\gamma)Co^{60}$; $Ni^{60}(n,p)Co^{60}$; $Fe^{54}(n,p)Mn^{54}$;
$Ni^{58}(n,\gamma)Ni^{59}$; $Cr^{50}(n,\gamma)Cr^{51}$; $Fe^{54}(n,\alpha)Cr^{51}$;
$Fe^{58}(n,\gamma)Fe^{59}$; $Co^{59}(n,p)Fe^{59}$; $Fe^{54}(n,\gamma)Fe^{55}$;
$Ni^{62}(n,\gamma)Ni^{63}$; $Ni^{58}(n,p)Co^{58}$; $Mn^{55}(n,\gamma)Mn^{56}$;
$Zr^{92}(n,\gamma)$ $Zr^{93}(Nb^{93m})$; $Nb^{93}(n,\gamma)Nb^{94}$; $Nb^{93}(n, n')Nb^{93m}$ and so on.
Depending on steel grade the content of main and impurities elements varies. Nowadays the works directed to development of the low-activated perspective steel grades are actively conducted. Using ACMAR it is possible to estimate the contribution of radionuclides which are formed as a result of activation processes to radiation characteristics of radioactive waste and to estimate advantage of perspective steel.
Based on test model of the BN sodium reactor of big power with MOX fuel [2] assemblies with the largest content of iron – steel shielding assemblies (SSA) and reactor control and safety system assemblies (CSSA) were analyzed. Two options with perspective EK-181 steel and EK-164 steel were considered.
In neutron and physical calculation it was accepted that the BN reactor is in the steady conditions, duration of one interval of reactor operation between refueling is 330 eff. days, outage duration was accepted 35 days. Radiation time of SSA - 12 irradiation intervals, assemblies of CSSA - 2 irradiation intervals.

3. Analysis of results

Preliminary results of a contribution of radionuclides to summary activity of assemblies for various time intervals are presented in tables 1-4. Change of characteristics was carried out in details, for providing results the most important points were chosen: 0 years – end of radiation in the reactor, 10, 50 and 100 years. By the received results, the considered assemblies were referred to various categories.

TABLE 1: CONTRIBUTION OF RADIONUCLIDES TO SUMMARY ACTIVITY OF STEEL SHIELDING ASSEMBLIES MADE FROM EK-181 STEEL FOR VARIOUS COOLING TIME

Nuclides	**Cooling, years**			
	0	**10**	**50**	**100**
^{51}Cr	1	0	0	0
^{54}Mn	1	0	0	0
^{55}Fe	4	62	1	0
^{56}Mn	6	0	0	0
^{57}Mn	0	0	0	0
^{59}Ni	0	0	1	3
^{59}Fe	1	0	0	0
^{60}Co	1	38	48	0
^{63}Ni	0	0	41	85
$^{93\mathbf{m}}Nb$	0	0	6	3
^{93}Mo	0	0	0	1
^{94}Nb	0	0	2	7
^{137}La	0	0	0	1
^{182n}Ta	7	0	0	0

TABLE 2: CONTRIBUTION OF RADIONUCLIDES TO SUMMARY ACTIVITY OF STEEL SHIELDING ASSEMBLIES MADE FROM EK-164 STEEL FOR VARIOUS COOLING TIME

Nuclides	**Cooling, years**			
	0	**10**	**50**	**100**
^{51}Cr	6	0	0	0
^{54}Mn	1	0	0	0
^{55}Fe	10	45	0	0
^{56}Mn	52	0	0	0
^{58}Co	4	0	0	0
^{59}Ni	0	0	2	3
^{59}Fe	3	0	0	0
^{60}Co	2	37	2	0
^{63}Ni	0	14	86	88
^{93}Mo	0	0	2	2
$^{93\mathbf{m}}Nb$	0	3	6	3
^{94m}Nb	5	0	0	0
^{94}Nb	0	0	2	3
^{99m}Tc	7	0	0	0

^{182m}Ta	13	0	0	0
^{182}Ta	32	0	0	0
^{183m}W	21	0	0	0
^{185} W	2	0	0	0
^{187} W	6	0	0	0
^{188} Re	1	0	0	0
others	4	0	1	0
Sum	100	100	100	100
%	100	0,53	0,002	0,0007
RW category	HLW		ILW	

^{99}Mo	9	0	0	0
others	1	1	0	1
Sum	100	100	100	100
%	100	1,7	0,2	0,14
RW category	HLW			

The analysis of tables 1 – 2 shows, that the activity decay is much faster in case of SSA made from EK-181 than for SSA made from EK-164. After 10 years of cooling the activity of EK-181 assembly is 0.53% of initial activity, and for EK-164 – 1.7%. After 50 years activity of EK-181 assembly is 0.002%, EK-164 – 0.2%. After 100 years 0.0007% and 0.14% respectively.

RW category for EK-181 assemblies will change from HLW to ILW between 10 to 50 years, for EK-164 after 100 years. Conducting additional calculations we adjusted, that RW category for EK-181 will change after 28 years, and for EK-164 after 110 years.

TABLE 3: CONTRIBUTION OF RADIONUCLIDES TO ACTIVITY OF CSSA MADE FROM EK-181 FOR VARIOUS TIME

Nuclides	**Cooling, years**			
	0	**10**	**50**	**100**
^{51}Cr	1	0	0	0
^{55}Fe	1	57	1	0
^{56}Mn	2	0	0	0
^{59}Ni	0	0	1	3
^{60}Co	0	43	66	0
^{63}Ni	0	0	24	86
^{93m}Nb	0	0	7	4
^{94}Nb	0	0	1	5
^{137}La	0	0	0	1
^{182n}Ta	2	0	0	0
^{182m}Ta	5	0	0	0
^{182}Ta	22	0	0	0
^{183m}W	57	0	0	0
^{185} W	1	0	0	0
^{187} W	7	0	0	0
^{188} Re	1	0	0	0
others	1	0	0	1
Sum	100	100	100	100
%	100	0,08	0,003	0,00006
RW category	HLW		ILW	

TABLE 4: CONTRIBUTION OF RADIONUCLIDES TO ACTIVITY OF CSSA MADE FROM EK-181 FOR VARIOUS TIME

Nuclides	**Cooling, years**			
	0	**10**	**50**	**100**
^{51}Cr	6	0	0	0
^{52}V	1	0	0	0
^{54}Mn	2	0	0	0
^{55}Fe	4	45	0	0
^{56}Mn	54	0	0	0
^{58}Co	7	0	0	0
^{59}Ni	0	0	0	3
^{60}Co	1	45	4	0
^{63}Ni		7	82	89
^{93}Mo	0	0	1	2
^{93m}Nb	0	3	10	3
^{94m}Nb	4	0	0	0
^{94}Nb		0	1	2
^{99m}Tc	8	0	0	0
^{99}Mo	9	0	0	0
others	4	0	2	1
Sum	100	100	100	100
%	100	0,72	0,05	0,03
RW category	HLW			ILW

The analysis of tables 3 – 4 shows, that the activity decay is much faster in case of CSSA made from EK-181 than for CSSA made from EK-164. After 10 years of cooling the activity of EK-181 assembly is 0.08% of initial activity, and for EK-164 – 0.72%. After 50 years activity of EK-181 assembly is 0.003%, EK-164 – 0.05%. After 100 years 0.00006% and 0.03% respectively.

RW category for EK-181 assemblies will change from HLW to ILW between 10 to 50 years, for EK-164 after 50 years. Conducting additional calculations we adjusted, that RW category for EK-181 will change after 26 years, and for EK-164 after 55 years.

In tables 5 – 8 the results of the calculation of contribution of radionuclides to decay heat of irradiated assemblies for different cooling time are presented.

TABLE 5: CONTRIBUTION OF RADIONUCLIDES TO DECAY HEAT FORM SSA MADE FROM EK-181 STEEL FOR VARIOUS COOLING TIME

Nuclides	**Cooling, years**			
	0	**10**	**50**	**100**
^{52}V	3	0	0	0
^{54}Mn	1	0	0	0
^{56}Mn	18	0	0	0
^{59}Ni	0	0	0	1
^{59}Fe	2	0	0	0
^{60}Co	2	100	99	24
^{63}Ni	0	0	0	69
$^{93\mathbf{m}}$Nb	0	0	0	4
^{137}La	0	0	0	2
^{182n}Ta	4	0	0	0
^{182}Ta	55	0	0	0
^{183m}W	7	0	0	0
^{187} W	6	0	0	0
^{188} Re	1	0	0	0
others	1	0	1	0
Sum	100	100	100	100
%	100	0,6	0,003	0,00002

TABLE 6: CONTRIBUTION OF RADIONUCLIDES TO DECAY HEAT FORM SSA MADE FROM EK-164 STEEL FOR VARIOUS COOLING TIME

Nuclides	**Cooling, years**			
	0	**10**	**50**	**100**
^{52}V	1	0	0	0
^{54}Mn	1	0	0	0
^{56}Mn	85	0	0	0
^{58}Co	2	0	0	0
^{59}Fe	2	0	0	0
^{60}Co	4	99	44	0
^{63}Ni	0	0	16	22
$^{93\mathbf{m}}$Nb	0	0	2	1
^{93}Mo	0	0	0	1
^{94}Nb	0	0	38	75
^{99m}Tc	1	0	0	0
^{99}Mo	3	0	0	0
others	1	1	0	1
Sum	100	100	100	100
%	100	1,09	0,012	0,0063

TABLE 7: CONTRIBUTION OF RADIONUCLIDES TO DECAY HEAT FORM CSSA MADE FROM EK-181 STEEL FOR VARIOUS COOLING TIME.

Nuclides	**Cooling, years**			
	0	**10**	**50**	**100**
^{52}V	1	0	0	0
^{56}Mn	9	0	0	0
^{59}Fe	1	0	0	0
^{60}Co	1	100	99	10

TABLE 8: CONTRIBUTION OF RADIONUCLIDES TO DECAY HEAT FORM CSSA MADE FROM EK-164 STEEL FOR VARIOUS COOLING TIME

Nuclides	**Cooling, years**			
	0	**10**	**50**	**100**
^{52}V	1	0	0	0
^{54}Mn	1	0	0	0
^{56}Mn	85	0	0	0
^{58}Co	4	0	0	0

^{63}Ni	0	0	0	12
^{93m}Nb	0	0	0	1
^{94}Nb	0	0	0	76
^{182n}Ta	2	0	0	0
^{182}Ta	50	0	0	0
^{183m}W	26	0	0	0
^{183}Ta	1	0	0	0
^{187}W	8	0	0	0
^{188}Re	1	0	0	0
others	0	0	1	1
Sum	100	100	100	100
%	100	0,14	0,0007	0,00001

^{59}Fe	2	0	0	0
^{60}Co	2	100	69	0
^{63}Ni	0	0	10	27
^{93m}Nb	0	0	2	2
^{93}Mo	0	0	0	1
^{94}Nb	0	0	18	69
^{99m}Tc	1	0	0	0
^{99}Mo	3	0	0	0
others	1	0	1	1
Sum	100	100	100	100
%	100	0,52	0,004	0,001

The analysis of tables 5 – 8 shows, that the decay heat decrease is much faster in case of assemblies made from EK-181 than for assemblies made from EK-164. After 10 years of cooling the decay heat of EK-181 assembly is 0.6% of initial decay heat, and for EK-164 – 1.09%.

Initial decay heat of EK-181 assemblies is defined by ^{182}Ta, and for EK-164 by ^{56}Mn. After 10 and 50 years for EK-181 it is ^{60}Co. For EK-164 assemblies after 10 years it is ^{60}Co, after 50 years: ^{60}Co, ^{63}Ni, ^{94}Nb.

The material presented showed that using program complex ACMAR the radiation characteristics of non-fuel compositions and the structural elements of fuel, control and shielding assemblies can be calculated quite detailed. The data obtained are necessary for the study of innovative steels properties from the standpoint of radiation safety, developing approaches for the RW management during fast reactors operation and decommission.

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