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Forecasting System Requirements to the Materials of the Shell of Fuel Elements of Innovative Fast Reactors

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Abstract

Innovative nuclear energy system (INSS) designed to ensure effective use of uranium 238 and thorium 232 to produce energy. Maintain the neutron balance of this process requires the development and use of new types of nuclear fuel and structural materials. This requires the development of models to predict changes in their properties under the action of fields of different radiation, temperature, stress and exposure to various chemical substances. It is important achievement is not the limiting parameters, and the optimal combination of the properties of materials and their working conditions. In this paper parameters such as the fluence of fast neutrons, the reaction rate in the fuel rod cladding and the change of nuclide composition, in particular, developments of hydrogen and helium, influencing the change of the strength properties of steels, are calculated.

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1. Introduction

The main factor limiting the safe use of nuclear power plants is the radiation damageability of constructional materials. Swelling, creep, segregation of impurities and other widely known phenomena that occur in materials under irradiation by fast neutrons, lead to the degradation of their properties [1], and the change of the properties of steel largely depends on the accumulation of hydrogen and helium due to the interaction of nuclei with neutrons [2].

The passage of ionizing radiation through a solid occurs by the transfer of energy to the electrons and nuclei. As a result, in the kernel there are various violations of the electronic and atomic structures. Radiation defects depending on their type and number can significantly change the physico-mechanical properties of solids. The nature of radiation damage is determined primarily by the properties of the radiation,

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the type solids, as well as exposure conditions. The irradiation conditions influence differently on the different stages of radiation damage: for example, the radiation energy affects the stage of formation of the primary displaced atoms and the appearance of stages, temperature of irradiation on diffusion processes in the cascades and thermal annealing of radiation defects [3].

Currently there is no adequate understanding of the mechanisms of a considerable number of phenomena and processes occurring in metals and alloys under the influence of high-energy neutron irradiation [4]. In this regard, it is necessary to evaluate the system requirements to the materials of fuel pin claddings of fast neutron reactors, in particular, limits the accumulation of hydrogen and helium, which have a significant impact on the strength characteristics of steels and other structural materials under irradiation [3]. It is also important to consider the change of nuclide composition of steels under irradiation, as it not only leads to a change in the physical properties of steels, but also affects the allowable time of exposure not only from the point of view of changes of the strength properties, but also problem-solving treatment after irradiation, in particular the problems of storage, recycling opportunities and recycling of construction materials.

Modeling changes in the composition and properties of structural materials under irradiation is a necessary step in the development of the concept design reactor materials with desired properties. It is obvious that the process of designing a new reactor materials on the specified requirements should be built on the basis of use of modern methods and means of physical and chemical research, based on the use of neutron and x-ray spectroscopy; modern methods of monitoring and control of physical, thermodynamic and chemical state of the system and methods of computer simulation and numerical experiments as the most effective tool for the study of condensed matter. Of particular importance is the use of super-computer and information technology (including parallel programming) to simulate the change of properties of a wide class of the systems studied in various conditions.

This approach will allow to predict the nature and degree of changes in complex compositions on the basis of verified models of the microstructure and atomic dynamics of transport processes in them, as well as to carry out the adjustment of the operating characteristics of these objects by the given criteria by using alloying additives. This is the concept design of reactor materials with desired properties which can be productive for the design of nuclear reactors for different purposes.

2. MATERIALS AND METHODS

Since neutrons have no charge, they cause radiation defects only through interaction with the nuclei of the atoms of a solid body. The most probable mechanism of interaction of neutrons having energy in the range 100 eV $\leq$ E $\leq$ 2 MeV is elastic scattering on nuclei [3].

In structural materials cladding the embrittlement significantly influences the accumulation of hydrogen and helium. In the General case, the change of isotopic composition of material placed in the field of neutrons, is described by the Bateman's equations (or equations of burnout). There are many methods of modeling the changes of the isotopic composition of fuel in nuclear reactors. Engineering methods use the model of chains of nuclide transformations, often quite short. The formation of nuclides that are outside of these chains is not modeled. Precision methods to calculate the rates of reactions or the microscopic cross sections used codes based on the Monte Carlo subject to the pointwise representation of the cross section of neutron reactions on the energy of all nuclides which are present in modern libraries of evaluated nuclear data. In principle, the same method can be used to simulate the fading that is the change in isotopic composition of structural materials and to evaluate the generation rate of hydrogen and helium due to reactions (n,p) and (n,α). At the initial stage using a computer program based on the Monte Carlo calculated flux of neutrons in the shell of fuel (steel CHS-68) and jacket of TVS (steel EP-450) reactor type fast reactor and found the speed of the reactions (n,p), (n,α) on the nuclides originally included in the material of the shell and jacket of TVS. The isotopic compositions of the shell of fuel and jacket of TVS is shown in tables 1 and 2. The section of TVS in the plan shown in Fig. 1. The estimated model is an active part of the TVS of the reactor MBIR without limit switch. On the side faces is set to terms broadcast, on the end faces, reflection conditions.

In the framework of the described models has been carried out neutron-physical calculations of the most energy-intense TVS of the reactor MBIR. Based on nuclide composition of the steel and the neutron flux were calculated speeds of neutron reactions for all relevant nuclides included in the shell of fuel element and jacket of TVS. It should be noted that typically, when neutron-physical calculations of nuclear power very seriously considering changing the nuclide composition of fuel and structural materials are considered as neutron absorbers. It was acceptable at low burnup, the fuel and, consequently, at low integrated fluxes of neutrons, in which the nuclide composition of the steel did not change significantly. In modern power reactors, which have to meet very strict requirements of the economic indicators, the situation has changed and in

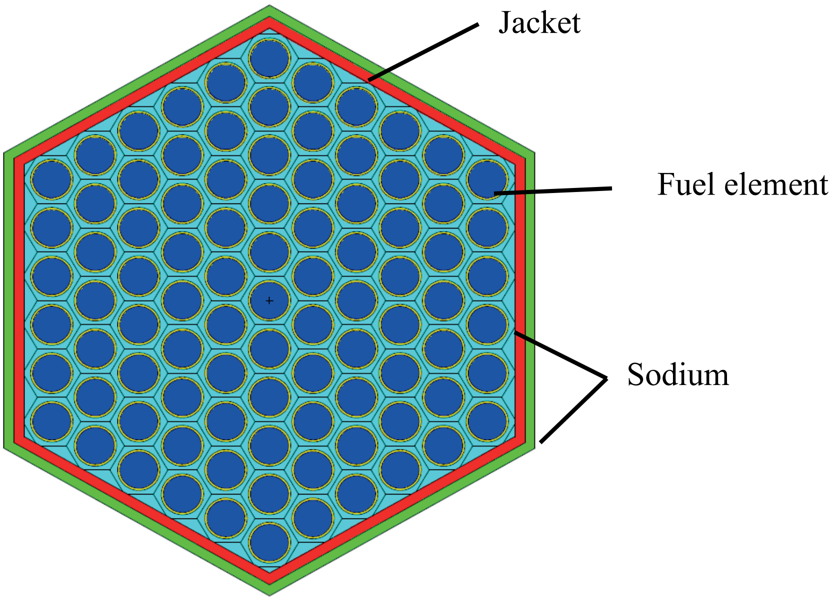

Figure 1: The section of TVS in the plan.

Table 1: Concentrations of nuclides in the material of the shell of fuel element, 10^{24} cm^{-3}.

Fe-54	3,08E-03	Mo-94	1,00E-04	Ti-48	2,91E-04
Fe-56	4,87E-02	Mo-95	1,72E-04	Ti-49	2,17E-05
Fe-57	1,17E-03	Mo-96	1,81E-04	Ti-50	2,13E-05
Fe-58	1,49E-04	Mo-97	1,03E-04	V	1,85E-04
Cr-50	6,51E-04	Mo-98	2,61E-04	B-10	3,48E-06
Cr-52	1,26E-02	Mo-100	1,04E-04	B-11	1,40E-05
Cr-53	1,42E-03	C-12	2,76E-04	S-32	1,68E-05
Cr-54	3,54E-04	Si-28	6,98E-04	S-33	1,33E-07
Ni-58	8,49E-03	Si-29	3,53E-05	S-34	7,44E-07
Ni-60	3,27E-03	Si-30	2,35E-05	S-36	3,53E-09
Ni-61	1,42E-04	Mn-55	1,46E-03	Co-59	1,60E-05
Ni-62	4,53E-04	P-31	3,05E-05	N-14	6,72E-05
Ni-64	1,15E-04	Ti-46	3,16E-05	N-15	2,47E-07
Mo-92	1,61E-04	Ti-47	2,88E-05	Al-27	8,75E-05

advance when selecting the structural materials to provide their changes under irradiation, in particular, due to the emergence of hydrogen and helium in very significant quantities.

Table 2: Concentrations of nuclides in the material of the jacket of TVS,10^{24} cm^{-3}.

Fe-54	4,09E-03	Mo-98	1,90E-04	S-36	4,42E-09
Fe-56	6,47E-02	Mo-100	7,58E-05	P-31	3,81E-05
Fe-57	1,55E-03	Si-28	7,75E-04	V-000	1,85E-04
Fe-58	1,98E-04	Si-29	3,93E-05	Nb-93	1,52E-04
C-12	4,73E-04	Si-30	2,61E-05	B-10	8,71E-06
Cr-50	5,13E-04	Mn-55	4,30E-04	B-11	3,50E-05
Cr-52	9,89E-03	Ni-58	1,10E-04	Ca-40	3,43E-05
Cr-53	1,12E-03	Ni-60	4,22E-05	Ca-42	2,29E-07
Cr-54	2,79E-04	Ni-61	1,83E-06	Ca-43	4,77E-08
Mo-92	1,17E-04	Ni-62	5,85E-06	Ca-44	7,37E-07
Mo-94	7,28E-05	Ni-64	1,49E-06	Ca-46	1,41E-09
Mo-95	1,25E-04	S-32	2,10E-05	Ca-48	6,61E-08
Mo-96	1,31E-04	S-33	1,66E-07		
Mo-97	7,52E-05	S-34	9,30E-07		

3. RESULTS

At the accepted parameters of the MBIR reactor with metal fuel as a result of calculations was obtained the following value of the density of neutron flux (reactor MBIR with fuel from uranium dioxide is expected to receive the maximum flux density is about 1.5 times smaller):

$$F = 7,6 \cdot 10^{15} \frac{n}{m^2 s}$$

This estimate is obtained under the assumption that average thermal power of fuel assemblies is 1.6 MW. In the TVS adjacent to the Central loop channel, the flux density will be higher and so will be acquired and a greater number of hydrogen and helium.

Knowing the flux density, concentration and sections were evaluated in the reaction (n,p), (n,α) resulting in the emergence of hydrogen and helium atoms. The results are shown in table 3.

To assess the accumulation of hydrogen and helium was chosen as iron, chromium and nickel because they comprise the largest share of the materials of shell of fuel element.

Using the speed of reactions, you can assess the accumulation of hydrogen and helium for 1 year: the rate of accumulation of hydrogen in the shell - 4.9 E-2 at.%, in

Table 3: The reaction rate in the shell of fuel element, $cm^{-3}\cdot s^{-1}$.

Nuclide	(n,p)	(n,α)
Fe-54	2,51E+11	2,90E+09
Fe-56	5,28E+10	2,26E+10
Fe-57	8,69E+08	1,21E+09
Fe-58	1,80E+06	1,10E+07
Cr-50	3,27E+10	2,31E+09
Cr-52	1,36E+10	1,74E+09
Cr-53	5,89E+08	1,23E+09
Cr-54	3,99E+06	1,93E+07
Ni-58	9,37E+11	8,08E+10
Ni-60	6,55E+09	5,58E+09
Ni-61	4,37E+08	3,66E+08
Ni-62	1,92E+07	2,64E+07
Ni-64	1,85E+05	1,43E+06

Table 4: The reaction rate in the jacket of TVS, $cm^{-3}\cdot s^{-1}$.

Nuclide	(n,p)	(n,α)
Fe-54	3,19E+11	3,64E+09
Fe-56	6,62E+10	2,83E+10
Fe-57	1,09E+09	1,52E+09
Fe-58	2,25E+06	1,37E+07
Cr-50	2,27E+10	1,59E+09
Cr-52	5,24E+08	6,66E+07
Cr-53	3,88E+09	8,14E+09
Cr-54	1,20E+07	5,73E+07
Ni-58	2,96E+10	2,54E+09
Ni-60	2,22E+08	1,89E+08
Ni-61	2,13E+08	1,79E+08
Ni-62	5,01E+06	6,86E+06
Ni-64	2,05E+05	1,55E+06

the jacket of TVS - 1.6 E-2 at.%; the rate of accumulation of helium in the shell - 6,3

E-3 at.%, in the jacket of TVS - 5.8 E-3 at.%. When the duration of exposure within a few years the concentration of the hydrogen and helium elements may reach very dangerous levels [2].

4. DISCUSSION

The calculations showed that the concentration of the hydrogen and helium produced in the structural materials of fast neutron reactors due to the interaction of neutrons with nuclei of iron, chromium and Nickel can reach values at which they exert significant influence on the strength properties and, accordingly, the allowable service life of structural materials in the neutron field. It is assumed that the estimate of the accumulation of hydrogen and helium in structural materials in the future will more accurately predict changes in the structure of materials in the process, and to adjust operational characteristics and original composition of the relevant materials based on the requirements of not only the strength characteristics, but taking into account the requirements for handling irradiated materials.

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