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CALCULATIONS OF RADIATION DAMAGE IN SPALLATION MODULE OF EAP-80

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Окно вакуумной трубы протонного ускорителя, используемого в подкритическом реакторе, является деталью, подвергающейся критическому анализу. Ожидается, что эта деталь будет подвергаться интенсивному протонному и нейтронному облучению. Надежность эксплуатации окна ускорителя влияет на осуществимость проекта подкритического реактора. Моделирование ядерных процессов в окне ускорителя было проведено с помощью программы MCNP/4B. Современные нейтронные и протонные данные были использованы в расчетах накопления радиационных повреждений в окне и некоторых деталях, расположенных около него. Полученные результаты демонстрируют, что окно ускорителя является деталью мишени реактора, в которой накапливаются самые большие дозы радиационных повреждений. Накопление газообразных атомов в конструкционных материалах мишени вызвано, в основном, действием протонного облучения.

INTRODUCTION

The structural materials of the EAP-80 (Energy Amplifier Prototype, 80 MWt thermal power) spallation module [1] are assumed to be exposed to high density particle fluxes both neutron and proton. The calculations of the radiation damage retention in structural components made of AISI 316 stainless steel were performed in a several steps:

- preparation of proton and neutron cross sections in a wide energy range from 0 to several hundred MeV;
- calculations of particle (both neutron and proton) spectra within certain components of interest;
- calculation of the number of displacements per atom (*dpa*) and of hydrogen and helium atoms accumulation in the structural matrix.

NUCLEAR DATA

For the *dpa* calculations two sources of nuclear data were used. The first is the data for stainless steel for energies up to 20 MeV, namely, the IRDF-90.2 (International Radiation Damage File) library. The second is the specially developed radiation damage library BISERM [2], covering projectile energies from 10 MeV to 1 GeV. Total displacement cross sections (the sum of elastic and nonelastic cross sections) for AISI 316 steel were considered (Fig.1). The cross sections for composite materials (such as AISI 316) were calculated in accordance with the corresponding weight fraction of elements. The concentrations of isotopes in natural mixture were used for the preparation of cross sections. Both libraries briefly discussed above were elaborated for incident neutrons.

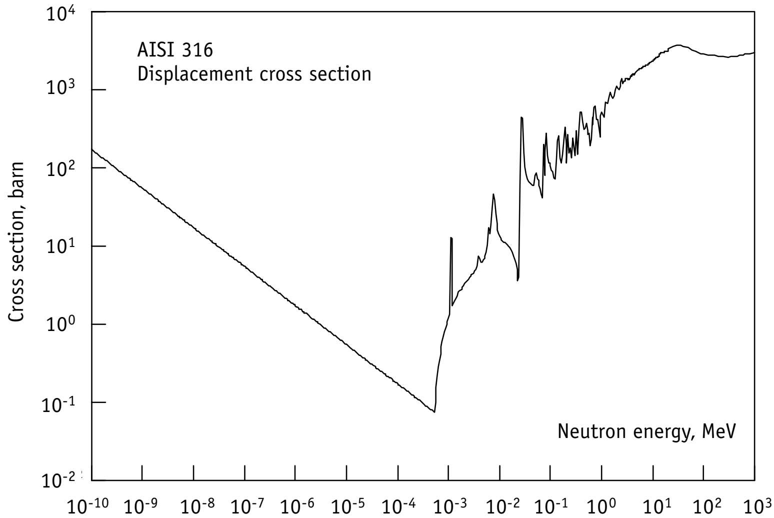

Fig.1. Neutron displacement cross section for AISI 316 stainless steel

Two sets of nuclear data were combined for the preparation of neutron gas production cross sections (H and He). IEAF-2000 (Intermediate Energy Activation File) [3] elaborated in collaboration with FZK (Forschungzentrum Karlsruhe, Germany) and INPE was used for gas production calculations in energy range from 0 to 150 MeV). The BISERM library data were applied for energies above 150 MeV. The IEAF-2000 data for high energies were based on the same CASCADE/INPE calculation as the BISERM data were. So, the combination of these libraries does not lead to jumps of cross sections at the 150 MeV points. The data prepared for the hydrogen and helium accumulation calculations are presented in Fig.2. It should be emphasised that hydrogen production cross sections were prepared as a sum of ^{1}H, ^{2}H and ^{3}H nuclide production data. As for helium data, the sum of ^{3}He and ^{4}He production cross sections was prepared for analysis.

Proton irradiation is supposed to be intensive in the reactor components locateds near the primary proton inlet point. Hence, the bulk of proton cross sections should be used for damage calculations. The preparation of the set of proton data was implemented using the

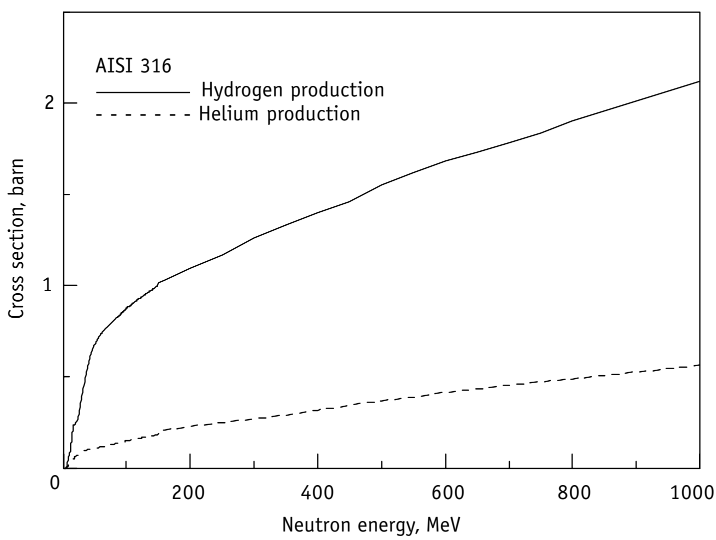

Fig.2. Neutron hydrogen and helium production cross sections for AISI 316 stainless steel

CASCADE/INPE code. The proton data cover the energy region from 10 MeV to 1 GeV.

Special attention was given to the preparation of the total neutron and proton cross sections for AISI 316 steel. The calculations of particle spectra above 20 MeV are based on the correct values for these cross sections. The NJOY processing code was applied for getting all the necessary data from the LA-150 (high energy Los Alamos library) data. The total cross sections above 150 MeV were calculated using the CASCADE/INPE code.

CALCULATIONS OF PARTICLE SPECTRA

Particle spectra were calculated for the window technology design of the EAP-80 reactor. The energy of the primary protons was taken to be 600 MeV. It was assumed that the most loaded components are located near the accelerator membrane. Hence, the calculations of the particle spectra were performed for the target window, as well as for the additional and external spheres of the spallation module. A slightly simplified spallation module design (Fig.3) was used for the simulation of the particle transport. The EAP-80 geometry parameters were used for calculations.

The calculations of particle spectra above 20 MeV were carried out with the help of the CASCADE/INPE code. A special routine was applied to simulate the heterogeneous allocation of the EAP-80 fuel, coolant and structural materials. A parabolic distribution of protons in the beam was considered. The neutron transport below 10.5 MeV in the CASCADE code is simulated on the basis of the multigroup transport approach. The internal data library used allows calculations of low energy neutron spectra to be performed with insufficient accuracy. The data presented in Fig. 1 demonstrate the importance of detailed information on the neutron spectra below 20 MeV. To reach the maximum accuracy in the low energy neutron spectra calculations consideration of all neutron histories was restricted to below 20 MeV in the CASCADE code in its turn. The low energy neutron source produced in this way was used in the low energy transport calculations.

The neutron spectra below 20 MeV were obtained by means of the MCNP/4B Monte Carlo code. The distribution of fuel was considered to be heterogeneous in the calculations. For the purposes of comparison the surface of the accelerator window was divided into 5 layers with a 2 cm step of longitudinal distance. Additional hemispheres were introduced for Pb-Bi liquid coolant flow profiling (Fig. 3). It is natural to expect that these additional stainless steel parts of the target should

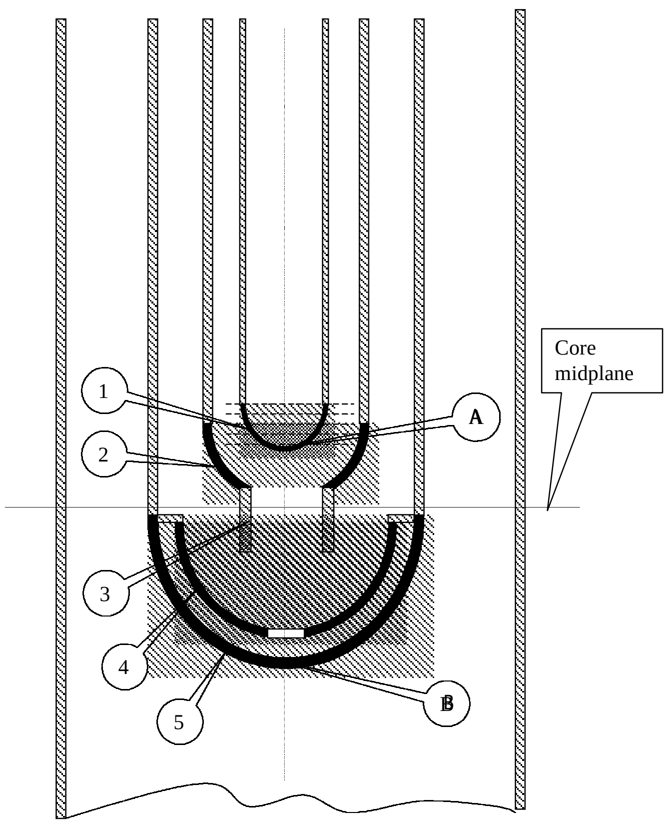

Fig.3. Principal scheme of the spallation region of the target. Division of the accelerator window (1 component, Cells 1-5) by five parallel planes is shown

accumulate damage, too. Because these parts are less important for the target safety they were roughly divided into cells. So, two intermediate hemispheres and an external one were divided into two cells, each with equal longitudinal length. An additional cylindrical cell, introduced into the design to arrange the raising coolant flow, was considered to consist of one cell. Two special points assumed to have the greatest *dpa* load were selected in the target design (points A and B, Fig.3).

For both codes a huge division of neutron spectra energies was used. Thus, about 8000 energy groups were considered for careful *dpa* calculations including all peaks in the energy dependence of the cross sections (Fig.1).

RESULTS OF RADIATION DAMAGE CALCULATIONS

As stated above, the initial proton energy was taken to be 600 MeV and the accelerator current was taken to be 3 mA. It was assumed that irradiation of materials could last 1 year. This time limit was chosen on the basis of traditional limits in commercial reactors.

The results of the *dpa* calculations are summarised in Table 1. Cell numbering corresponds to five main components of interest. Cells 1-5 belong to the target membrane, 6,7 – to the intermediate hemisphere, 8 – to the cylindrical part, 9,10 – to the additional hemisphere and 11, 12 to the external hemisphere. Points A and B are shown in Fig. 3. In Fig.4 particle spectra are presented for Cell 5. Point detector method was applied for the calculations of particle spectra in points A and B. The radius of the detector was chosen to be 1 mm for point A and 2 mm for point B.

The accelerator membrane was divided into five parallel planes with the longitudinal distance of 2 cm from each other (Fig. 3). Thus, Cells 1-5 were produced. The same technique was applied to divide the other elements with equal longitudinal lengths. Note that cell numbering proceeds down the longitudinal coordinate. Cylindrical component 3 of the target

Table 1

Accumulation of radiation damage dose in the target cells

Component number Fig.3	Cell number	Neutron radiation damage dose, dpa/year	Proton radiation damage dose, dpa/year	Total dose, dpa/year
1	1	6.6	1.3	7.9
1	2	7.5	1.4	8.9
1	3	7.7	1.5	9.2
1	4	8.6	1.7	10.3
1	5	11.0	3.3	14.3
1	**A**	28.8	7.2	36
2	6	7.8	0.8	8.6
2	7	9.3	0.7	10
3	8	10.9	0.7	11.6
4	9	9.0	0.3	9.3
4	10	8.5	0.06	8.6
5	11	8.9	0.2	0.2
5	12	8.1	0.01	8.1
5	**B**	7.1	0.003	7.1

is located along the beam axis. So, it was expected that the accumulation of damage in it was distributed uniformly. No division into cells was considered for component 3. The results obtained for gas production in various target components are summarised in Tables 2,3.

Table 2

Accumulation of hydrogen atoms in components

Component number in Fig.3	Cell number	Neutron hydrogen accumulation, appm/year	Proton hydrogen accumulation, appm/year	Total hydrogen accumulation, appm/year
1	1	47	704	751
1	2	156	710	866
1	3	230	795	1025
1	4	260	848	1108
1	5	534	1651	2185
1	**A**	982	3647	4629
2	6	72	368	440
2	7	133	336	469
3	8	247	260	507
4	9	76	98	174
4	10	76	12	88
5	11	57	70	127
5	12	57	13	70
5	**B**	81	10	91

Table 3

Accumulation of helium atoms in components

Component number in Fig.3	Cell number	Neutron helium accumulation, appm/year	Proton helium accumulation, appm/year	Total helium accumulation, appm/year
1	1	9.2	161	170
1	2	30	166	196
1	3	45	186	231
1	4	57	192	249
1	5	104	371	475
1	**A**	218	824	1042
2	6	14	83	97
2	7	26	72	98
3	8	48	52	100
4	9	15	19	34
4	10	15	2.1	17
5	11	11	13.5	25
5	12	11	0.3	11
5	**B**	16	0.2	16

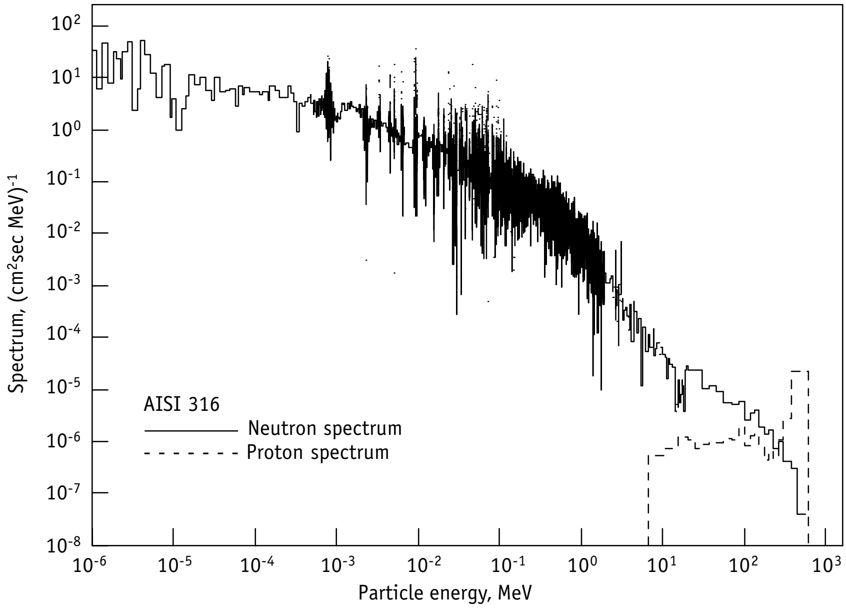

Fig.4. Neutron and proton spectra in Cell 5

As was expected, the maximum *dpa* rate is located in the central zone of the vacuum tube membrane. As the distance between the membrane layer position and central point of the membrane surface increases, the *dpa* dose rate decreases. It may be argued, that welding seam between the vacuum tube and the membrane is not intensively loaded. All the other components of the central part of the spallation module were found to accumulate a reasonable *dpa* dose. The location of the Cell 8 (along the beam axis) determines a higher dose in comparison with other coolant stream profiling components. The distribution of the *dpa* dose rate in the accelerator membrane is shown in Fig. 5.

Once the primary proton beam interacts with the target nuclei the scattering of protons takes place. This process leads to diffusion of protons to the peripheral zones of the target. Due to this fact, hydrogen accumulation in the intermediate sphere is greater than that for

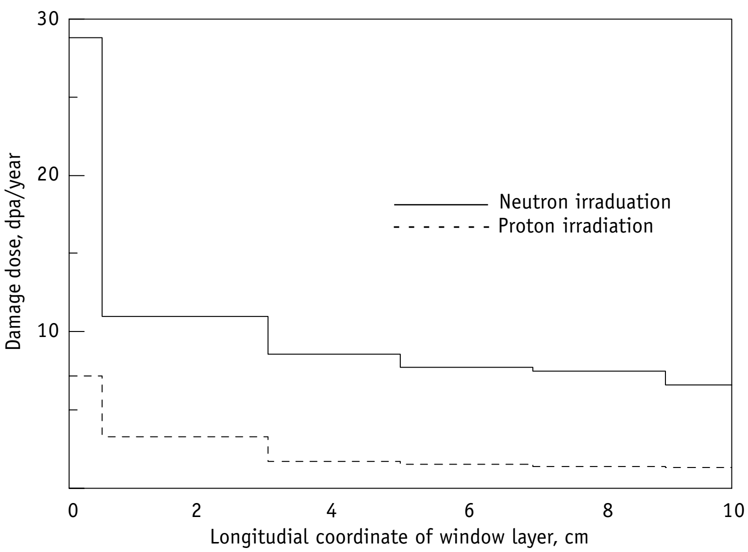

Fig.5. Distribution of *dpa* dose rate in vacuum tube membrane

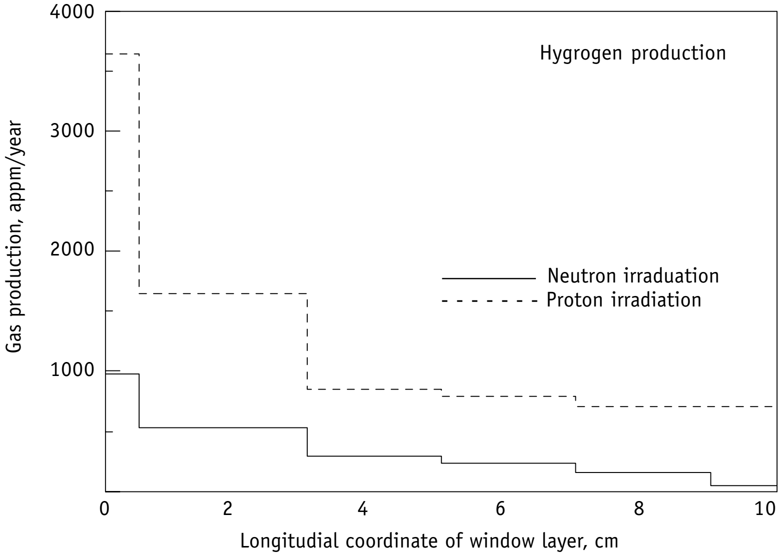

Fig.6. Distribution of hydrogen accumulation rate in vacuum tube membrane

components along the beam axis. The situation is reversed for neutron irradiation: the closer the cell is to beam axis, the greater is the accumulation of hydrogen. Fig. 6 reproduces the data for the hydrogen production rate in the target window.

High energy secondary neutrons produced in the target are spread mainly along the axis. The primary scattered protons and secondary protons produced in interactions diffuse out of the spallation region causing a higher gas accumulation in peripheral components. Distribution of the helium accumulation in the membrane is presented in Fig.7.

A detailed design of the EAP-80 spallation module in general should be based on material damage calculations. So far there are no fixed requirements for the maximum safety level of damage accumulated in the medium. Any experiments performed in the frameworks of investigations into material behaviour under irradiation can establish such values. It is important, therefore, to get detailed information on impact of each particle energy group

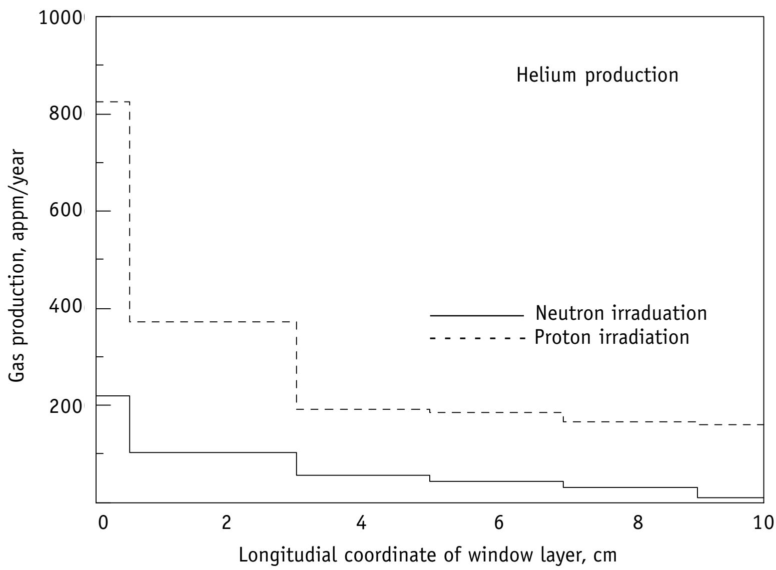

Fig.7. Distribution of the helium accumulation rate in the vacuum tube membrane

on the total damage produced. This information can clarify the importance of neutrons belonging to various energy groups. In this case the experimental data obtained at the facility available for damage investigations could be extrapolated for the EAP-80 design. Such a procedure is feasible and could be very fruitful in the case of proper neutron spectrum, produced by an experimental source. The calculations performed permit the role of each energy group to be emphasised for further analysis. The handling of the vacuum tube membrane seems to be the weakest point of the spallation module. The percentage of the total *dpa* produced by certain neutron energy groups in the target window is presented in Table 4.

The data presented in Table 4 allow some conclusions to be made. The first is that the *dpa* dose distribution in the window is very irregular. For example, point A belongs to Cell 5 but the *dpa* doses for these Cells are very different. Such distinctions were caused by the averaging procedure for neutron spectrum over Cell 5. Hence, the point cell (point detector) was found to represent a more precise *dpa* load. The second is that for point cell A more than 50% of dpa are produced by neutrons with energies from 1 to 10 MeV. The great importance of neutrons with energies from 20 to 100 MeV is accounted for by the peak in the damage cross section in this region (Fig.1).

The impact of various neutrons on the total hydrogen and helium production is presented in Tables 5 and 6. In terms of hydrogen production, low energy neutrons appeared to be less important than other neutron groups. This fact can be easily explained by the energy dependence of the hydrogen production cross section (Fig. 2). Taking into account that the threshold of this reaction is about 3 MeV, a low percentage of the total hydrogen production by neutrons with energies from 2 to 10 MeV is quite predictable. The main contribution to the total gas production is made by intermediate end high energy neutrons, namely, by 20-100 MeV and 100-600 MeV groups. Thus, low energy neutrons (energies less than 10 MeV) produce only a small share of the total gas damage in the window and, therefore, cannot be used for testing gas production in the materials planned to be used in EAP-80. Although the threshold of the helium production cross section is about zero, the role of neutrons with energies less that 4 MeV is negligible.

CONCLUSION

The results, obtained for radiation damage accumulation in some components of the EAP-80 spallation module, demonstrate that the most loaded cell in this device is target the window. Moreover, the distribution of defects in the window matrix is a non-linear function of the distance from the edge of membrane to the edge of vacuum tube. Even in the case of

Table 4

Percentage in the total *dpa* accumulation in the target membrane of different neutron energy groups

Cell №	0-0.1 MeV	0.1-1 MeV	1-2 MeV	2-4 MeV	4-10 MeV	10-20 MeV	20-100 MeV	100-600 MeV
	%							
1	12	62	14	6	2	1	2	1
2	11	56	14	6	2	1	8	2
3	11	54	14	6	2	1	9	3
4	10	51	14	6	3	1	11	4
5	8	42	12	9	7	3	13	6
A	3	16	8	17	28	13	13	2

Table 5

Relative contribution to the total hydrogen production of different neutron energy groups

Cell №	2-10 MeV	10-20 MeV	20-100 MeV	100-600 MeV
	%			
1	3	7	52	38
2	1	3	58	38
3	1	2	50	47
4	1	2	47	50
5	1	3	47	49
A	8	24	43	25

Table 6

Relative contribution to the total helium production of different neutron energy groups

Cell №	4-10 MeV	10-20 MeV	20-100 MeV	100-600 MeV
	%			
1	4	10	49	37
2	1	4	56	39
3	1	4	47	48
4	2	3	50	45
5	4	4	44	48
A	9	28	42	21

parabolic distribution of protons in the beam the peak of damage corresponds to the central point of the window surface.

The rate of the displacements per atoms formation in the window material is expected to be around 50 dpa/year. The total accumulation rate of hydrogen in the membrane is about 6000 appm/year (120 appm/dpa). For helium production rate this value is about 1300 appm/year (26 appm/dpa). The accumulation of gaseous atoms in the structural components is determined mainly by proton irradiation. The *dpa* dose rate depends on the neutron spectrum and, in part, on the proton spectrum.

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Calculations of Radiation Damage in Spallation Module of EAP-80\P. Pereslavtsev, D. Sahrai; Editorial board of journal "Izvestia visshikh uchebnikh zavedeniy. Yadernaya energetica" (Communications of Higher Schools. Nuclear Power Engineering) – Obninsk, 2001.-10 pages, 7 illustrations, 6 tables. – References, 3 titles.

One of the critical point of the subcritical reactor driven by the proton accelerator is the window of the accelerator vacuum tube. This component of the reactor is expected to be irradiated with intensive neutron and proton fluxes. The feasibility of the subcritical device is affected by the reliable performances of the window during machine operation. The simulation of the nuclear processes was implemented by MCNP/4B Monter-Carlo code. Modern neutron and proton nuclear data were used for the calculations of the radiation damage accumulation in the window and some components arranged near it. Results obtained demonstrate that the accelerator window is expected to be the most radiation damage loaded component of the EAP-80 spallation module. The accumulation of the gaseous atoms in the structural matrix is forced mainly by the proton irradiation.

УДК 51-72: 621.039.53

Simulation of Intercrystalline Corrosion on Surface Structure of Voronoy's Polyhedra \I.V. Pyshin; Editorial board of journal "Izvestia visshikh uchebnikh zavedeniy. Yadernaya energetica" (Communications of Higher Schools. Nuclear Power Engineering) – Obninsk, 2001.-6 pages, 3 illustrations. – References, 8 titles.

The intercrystalline corrosion model in 3 dimensions for loops with liquid alkali coolant is developed. The model component describing the liquid metal penetration to polycrystalline structure on faces but not edges is presented.

УДК 539.172

Calculation of Reaction Cross Section for Interaction of Elementary Particlies with Nuclei of Fussion Products and Transactinides\ A.P.Markin, V.S. Masterov, N.P. Savelyev; Editorial board of journal "Izvestia visshikh uchebnikh zavedeniy. Yadernaya energetica" (Communications of Higher Schools. Nuclear Power Engineering) – Obninsk, 2001.-10 pages, 7 illustrations, 6 tables. – References, 3 titles.

Results of calculations of reactions caused by protons, nucleons and light nuclides with intermediate energies and estimation of fast electrons (e,e') cross section for more important in view of transmutation of nuclei of fussion products (Cs, Sr, I, Tc) and transactinides (Np, Am, Cm).