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RADIATION DAMAGE OF THE TANTALUM COATING OF TUNGSTEN TARGET NEUTRON SOURCE

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Using the MCNPX program, a calculation of the radiation dose (in displacements per atom) and the distribution of the concentration of nuclear reaction products (hydrogen and helium) with depth of the tantalum coating of the tungsten target of the neutron source NSC KIPT, controlled by a high-energy electron accelerator with an energy of 100 MeV, was conducted.

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INTRODUCTION

In recent years, a number of works dedicated to the analysis of nuclear-physical and physico-mechanical characteristics of uranium [1-5] and tungsten [6-8] targets of the neutron source have been published at the NSC KIPT of the National Academy of Sciences of Ukraine. While the uranium target is still in the manufacturing stage, the tungsten target has already been operational for more than a year and a half at the stage of physical launch, which was carried out in 2021. The design of the target was described in detail in work [8]. During the operation of the neutron source (NS), the target is simultaneously irradiated with high-energy electrons with an energy of 100 MeV and neutrons from the subcritical assembly (SCA).

The change in the physical and mechanical properties of materials under irradiation is practically completely determined by the evolution of the microstructure. In turn, a key moment for understanding the microstructural evolution of the material under irradiation is the calculation of the spectra of primary knocked-out atoms (PKA) [9]. However, a more convenient characteristic for comparing different types of irradiation is the spectrum of cross-sections for the formation of radiation defects $d\sigma(E,T)/dT\,\nu(T)$, where $\nu(T)$ – is a cascade function, since in radiation materials science, it is not the knowledge of PKA spectra that is of interest, but the amount of radiation defects and their configuration [10]. It has been established that when irradiated with high-energy electrons with energies of hundreds of MeV, the main share of defects is created by PKAs with energies below 20 keV, and only a small part (about 15%) is formed by PKAs with energies above 40…50 keV. As a result, point defects or their smallest clusters will predominantly form in the material.

The development of electronic-photon rain, the appearance of braking gamma quanta in target plates leads to a change in the situation. High-energy PKA with energies exceeding 40 keV appear, which can lead to the formation of complex radiation defects in the form of dislocation loops and depleted zones [10].

To assess the resource of the target's operation, it is necessary to know the level of its radiation damage (RD), which also has two nuclear-physical components: the magnitude of the radiation dose (measured by the fraction of displaced atoms), and the level of concentration of nuclear reaction products (NRP) arising under irradiation.

The purpose of this work is to calculate the spectra of PKA necessary for assessing the level of RP of the tantalum protective coating of the tungsten target NS, which includes the dose of irradiation and the concentration level of the main NRP, such as helium and hydrogen.

1. CALCULATION OF THE NUMBER OF DISPLACEMENTS DURING IRRADIATION OF MATERIALS BY ELECTRONS

Using the MCNPX program [11], the calculation of radiation damage doses in Ta foils with a thickness of about 250…270 μm on the surface of tungsten was carried out.

Neutron Source plates of the NNTS KhFTI, irradiated with electrons with an initial energy of 100 MeV. The electron spectrum on the surface of the second tungsten plate is shown in Fig. 1. Calculations were performed using the IAEA nuclear cross-section library [12].

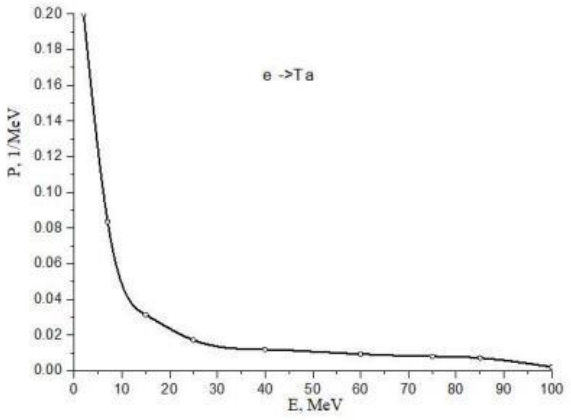

Fig. 1. The spectrum of electrons that reached the tantalum film on the second plate

When irradiating materials with electrons, recoil nuclei are generated with energy T that ranges from zero to T_{max}:

$$T_{max}(E) = E \cdot (E + 2E_0) \cdot 2 / (A\, m_p c^2), \quad (1)$$

where E is the initial energy of the electron; A is the atomic weight of the nucleus; $E_0 = m_e c^2$; m_e is the mass of the electron; m_p is the mass of the proton. When tantalum is irradiated with electrons with energy $E = 100$ MeV, the value of Tmax is 0.11 MeV.

The probability of the occurrence of a recoil atom with energy T is characterized by the spectrum of primary recoil atoms (PKA) $d\sigma(E,T)/dT$, the graph of this function for *Ta* at $E = 100$ MeV is represented by the black line in Fig. 2.

If the energy of the recoil nucleus T exceeds the threshold displacement energy Ed in this material, then a displaced atom is formed. If $T > 2.5\,E$d, then this atom can initiate a cascade of atom-atom collisions, as a result of which $\nu(T)$ displaced atoms are formed, where $\nu(T)$ is the cascade function:

$$\nu(T) = 1 \text{ when } E_d < T < 2.5E_d, \qquad (2)$$

$$\nu(T) = \frac{0.8T}{2E_d} \text{ при } T > 2.5E_d .$$

The probability of the occurrence of a displaced atom in the cascade from a PKA with energy T is characterized by the spectrum of damaging energies of recoil atoms: $\frac{d\sigma_D(E,T)}{dT} = \frac{d\sigma(E,T)}{dT}\nu(T)$ the graph of the function $d\sigma_D(E,T)/dT$ from energy T for Ta at E=100 MeV is shown by the red line in Fig. 2.

The probability of forming a displaced atom during electron scattering is irradiation characterized by the displacement cross-section σ_D:

$$\sigma_D(E) = \int_{E_d}^{T_{\max}(E)} \frac{d\sigma(E,T)}{dT}\nu(T)dT, \qquad (3)$$

The dependence of the defect formation cross-section σ_D on the energy of electrons E for *Ta* is presented in Fig. 3.

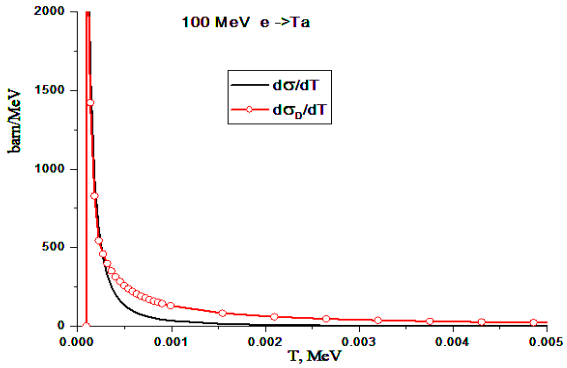

Fig. 2. Dependencies of the PKA spectra and damaging energies from the energy of recoil T for the electron energy value E= 100 MeV

Considering the electron spectrum $R(E)$in the second layer of the film *Ta* (see Fig. 1), one can calculate the resulting spectrum of damaging energies **dσD /dT** in this layer:

$$\frac{\mathbf{d\sigma_D}}{\mathbf{dT}} = \int_0^{E_0} P(E)\frac{d\sigma_D(E,T)}{dT}dE . \qquad (4)$$

The dependence **dσD/dT** on T for the film *Ta* in the second layer is presented in Fig. 4. This dependence describes the number of displaced atoms formed from PKA with energy T.

Based on the obtained results, a calculation of doses and the distribution of radiation damage in the tantalum coating on the surface of tungsten plates of the Neutron Source of the National Science Center "Kharkiv Institute of Physics and Technology", irradiated with electrons with an energy of 100 MeV, was carried out.

Fig. 5 shows the distribution of radiation damage dose in Ta on the surface of the second tungsten plate and inside it during irradiation for 1 year.

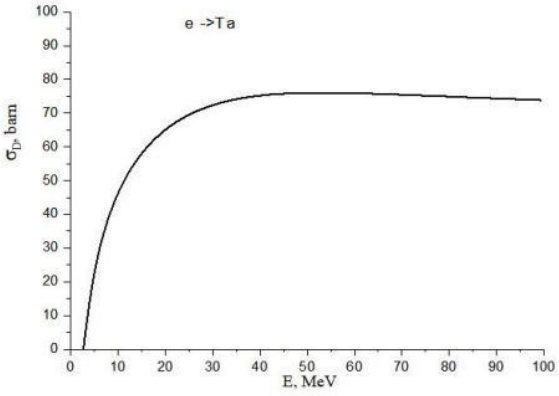

Fig. 3. The defect formation cross-section σ_D in Ta by electrons as a function of their energy

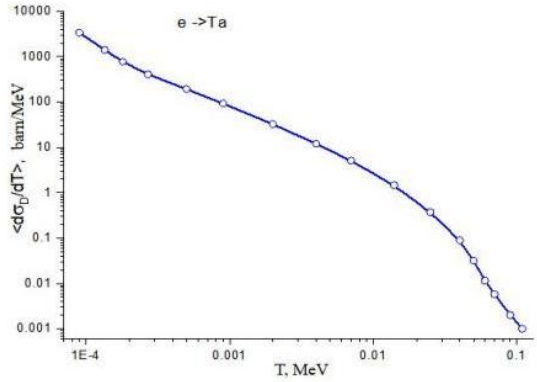

Fig. 4. The spectrum of damaging energies of PKA over the entire energy range T

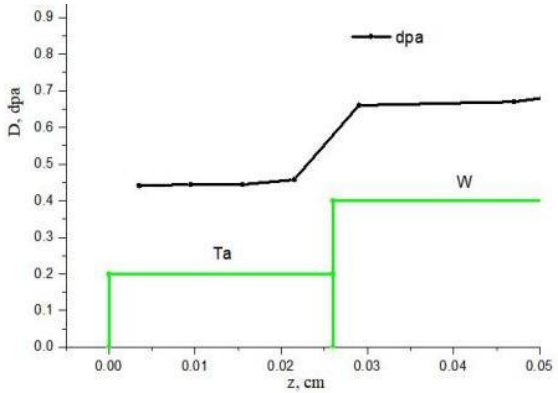

Fig. 5. Distribution of radiation damage doses in the second target plate, accumulated during one year of irradiation

2. ACCOUNTING FOR NEUTRON DAMAGE IN A SUBCRITICAL ASSEMBLY (SCA)

In work [6], it was shown that the contribution to the dose rate of radiation of the tungsten plate from neutrons of the SCA is 0.15 dpa/year.

The tantalum nuclei are little different from tungsten, but the threshold displacement energies differ significantly. For tungsten, it is 70 eV, while for tantalum it is 90 eV. Considering this, we find that for tantalum the damage rate from the SCA is 0.11 dpa/year.

Thus, the total dose rate (electrons + SCA) in tantalum on the second plate (where it is maximum) is 0.45 + 0.11 = 0.56 dpa/year. At the same time, the contribution to the damage dose from electron radiation is four times greater than that from neutrons of the SCA.

It should be noted that starting from the fourth plate, it is the neutrons of the SCA that will make the main contribution to the damage rate of the target [6].

3. HYDROGEN AND HELIUM PRODUCTION IN TA AND W NEUTRON-PRODUCING TARGET

Figs. 6 and 7 show the distribution of the proton beam in a tungsten target with a thickness of 2.5 mm or more, covered with a tantalum film with a thickness of 0.26…0.27 mm. The gap between the plates is filled with water, measuring 1.75 mm.

It can be seen that the proton beam falling from the water onto the tantalum coating sharply decreases at distances of about 0.1 mm from the surface of the coating, and then slightly increases in tantalum due to the (γ, p) reaction, after which the proton beam slowly decreases in tungsten and again sharply increases due to the recoil protons in the water.

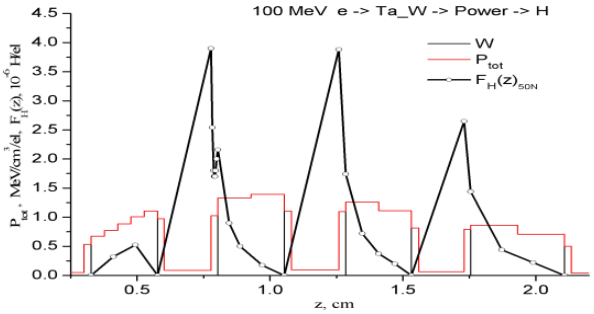

Fig. 6. Distribution of the proton beam in Ta and W

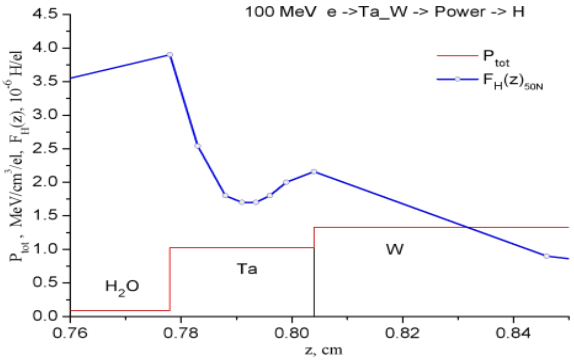

Fig. 7. Detailed distribution of the proton flow in tantalum on the second plate

Figs. 8 and 9 show the distributions of hydrogen concentrations that settled in the second plate of the target during one year of operation.

The large peak at the entrance of the beam into tantalum is due to hydrogen packed from water. The small concentration of hydrogen in tungsten is due to protons generated in tantalum and released into tungsten. Further increase in hydrogen concentration in tungsten occurs due to the (γ, p) reaction on tungsten nuclei, and the peak at the exit from tantalum is due to hydrogen scattered from water back into tantalum.

Fig. 10 shows the distributions of helium concentration that settled in the second plate target during one year of operation.

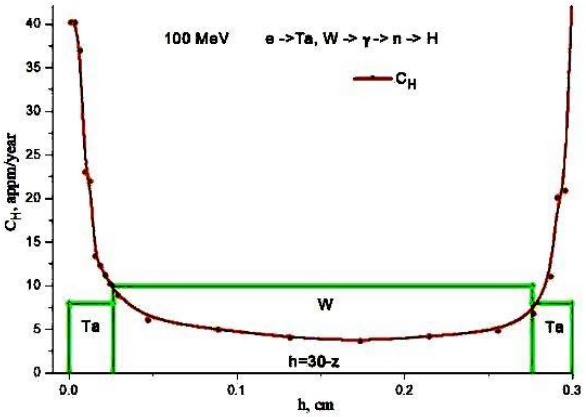

Fig. 8. Distribution of proton concentrations in tantalum and tungsten that settled in the second plate of the neutron-producing target during one year of operation

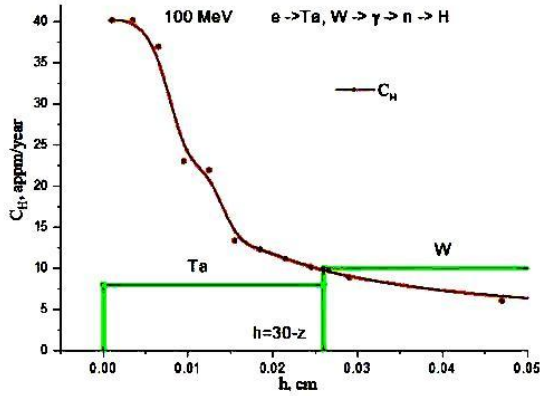

Fig. 9. Detailed distribution of proton concentration in tantalum in the second plate

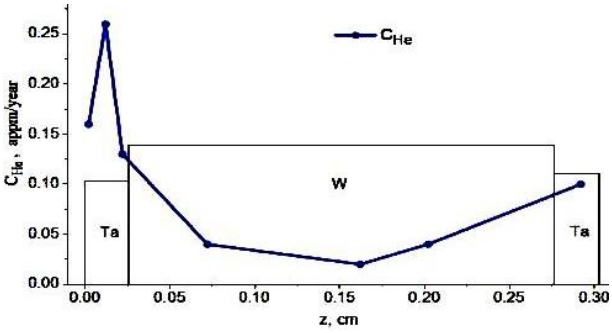

Fig. 10. Distribution of helium concentration in tantalum and tungsten in the second plate after one year of operation

In accordance with the calculations made, the dose accumulation rate in tantalum on the second plate is 0.56 dpa/year, and the maximum concentrations of hydrogen and helium in tantalum reach values C_H~40 appm/year and C_{He}~0.26 appm/year or C_H~$4\cdot 10^{-3}$ at.%/year and C_{He}~2.6 10^{-5} at.%/year.

The calculations carried out force us to answer the question: how significant are the values of defect concentrations (dpa) and gases for changing the physical and mechanical properties of the coating material (and thus the resources of the target). The analysis of works [13, 14] showed that a sharp change in the plastic characteristics of tantalum occurs at the doses not exceeding 0.1 dpa. At the same time, one of the decisive factors is the concentration of impurities in the metal, such as hydrogen, nitrogen, and oxygen.

CONCLUSIONS

An analysis of the radiation damage of the tantalum coating of the tungsten target of the neutron source NSC KIPT, which is under the influence of simultaneous irradiation with high-energy electrons with an initial energy of 100 MeV and neutrons from a subcritical assembly (SCA), has been conducted.

Using the MCNPX program, the radiation dose (number of displacements per atom) was determined, as well as its distribution along the length of the target plate assembly, and the concentration levels of nuclear reaction products - hydrogen and helium.

It was shown that the total dose accumulation rate (electrons + SCA) in the second plate (where it is maximum) is **0.56 dpa/year. The maximum concentration of gases does not exceed $4\cdot 10^{-3}$ at.%/year.**

Comparing these values with the results of radiation effects in reactors and ADS systems shows that such a level of damageability can lead to a significant loss of material ductility – radiation embrittlement during post-radiation mechanical tests, which in turn can affect the operational resource of the entire target.

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РАДІАЦІЙНЕ ПОШКОДЖЕННЯ ТАНТАЛОВОГО ПОКРИТТЯ ВОЛЬФРАМОВОЇ МІШЕНІ ДЖЕРЕЛА НЕЙТРОНІВ

В.В. Ганн, А.В. Ганн, Б.В. Борц, І.М. Карнаухов, О.О. Пархоменко

Із використанням програми MCNPX проведено обчислення дози опромінення (концентрації зміщень на атом), розподілу концентрації продуктів ядерних реакцій (водню та гелію) по глибині танталового покриття вольфрамової мішені нейтронного джерела ННЦ ХФТІ, керованого високоенергетичним електронним прискорювачем з енергією 100 МеВ.