GENERATION OF MeV-ENERGY PROTONS IN WWER REACTOR CORE

A.V. Gann, V.V. Gann*

National Science Center "Kharkov Institute of Physics and Technology", 61108, Kharkov, Ukraine

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The spectrum of fast protons, generated by fast neutrons of WWER-1000 reactor core in water, has been calculated using the Monte Carlo method. The main mechanism of fast proton generation in the moderator is found to be elastic scattering of fast neutrons on hydrogen nuclei. Fast protons with mean energy $1\,MeV$ flow towards the surface of cladding material at flux density $0.1\,\mu A/cm^2$. The process of hydrogen implantation into zirconium cladding is discussed in the article. Proton range distribution profile in cladding material is calculated. The role of this mechanism in the hydrogenation of zirconium under reactor irradiation is discussed.

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1. INTRODUCTION

Zirconium has been chosen as a structural material of reactor cores for water-cooled nuclear power reactors because of small cross-section of the thermal neutron absorption. Being in contact with the coolant, zirconium materials are oxidized and absorb hydrogen. Processes of hydrogen pickup change the mechanical properties of the core components. Investigation of reactor material hydrogenation during reactor operation is of great importance. The roles of various physical processes which control the transport of hydrogen into zirconium alloys are discussed in many works. The experimental data and phenomenological models describing the process of hydrogen absorption in zirconium alloys are presented in the review [1]. There are several ways of hydrogen transport into reactor core materials. One of those is (n, p) reaction on the nuclei of the material. For example, proton yield from the reaction of fission neutrons on zirconium nuclei equals to $0.38\,mb$ [2]. Therefore, only about $10\,ppm$ of hydrogen can be produced in zirconium cladding during one fuel cycle. Radiolysis of water is a more powerful mechanism of hydrogenation. H^+ ions penetrate through the cladding surface and diffuse over zirconium. Another mechanism of hydrogen transport from water to material is discussed in this paper. This mechanism is important for WWER-type reactors in which water serves as both moderating and cooling agent. Fast neutrons moving in the water are scattered by protons creating fast recoil protons, possessing the energy sufficient to penetrate into the material [3].

2. COMPUTER MODEL OF THE PROCESS

Let us consider a fuel assembly with the average enrichment of 3.9% of U^{235} (see Fig.1). This assembly has fuel rods, containing UO_2 or $UO_2 + Gd_2O_3$ pellets placed in claddings made of zirconium alloy. All the spaces between fuel rods as well as all tubes and central channels are filled with water. Fast neutrons produced during the fission of uranium are slowed down in water, diffuse to fuel rods, cause new fission or are absorbed by core materials.

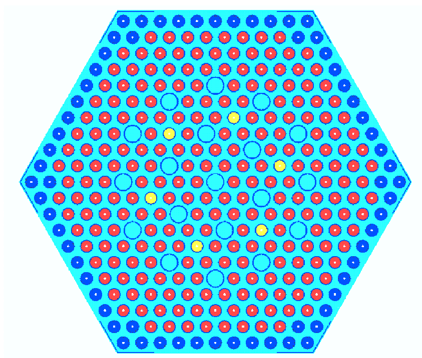

Fig.1. *Model of fuel assembly TVSA 390GO*

Fig.2 shows the spectrum of neutrons in water, obtained using the Monte Carlo method for criticality calculations of this assembly with mirror boundary conditions. When moving in water the fast neutrons collide with the hydrogen nuclei producing fast protons.The main mechanism of fast proton formation is elastic scattering of fast neutrons on hydrogen nuclei.

*Corresponding author E-mail address: gann@kipt.kharkov.ua

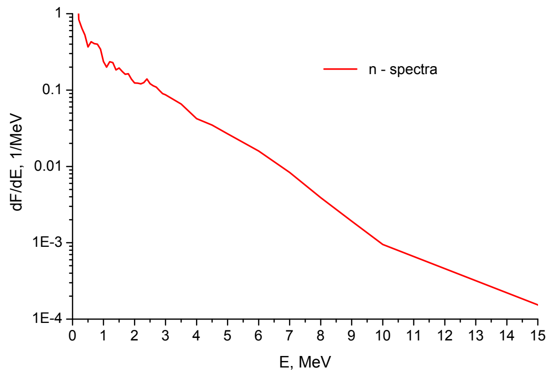

Fig.2. *Spectrum of neutrons in water*

The spectrum of recoil protons in water is shown in Fig.3. Recoil protons are slowed down in water and other core materials. Thus the density spectrum of the proton flux shifts to the lower energy, as shown in Fig.4. The mean energy of protons equals to 1 MeV, and the maximal energy is 10 MeV.

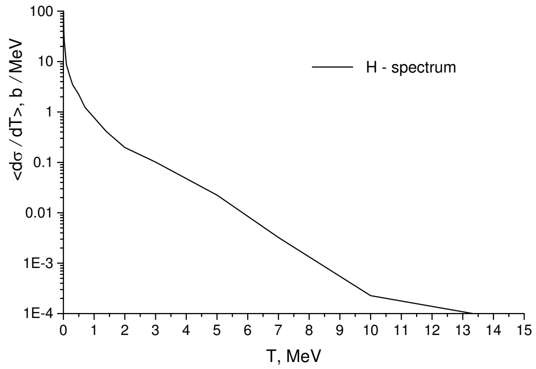

Fig.3. *Recoil protons spectrum*

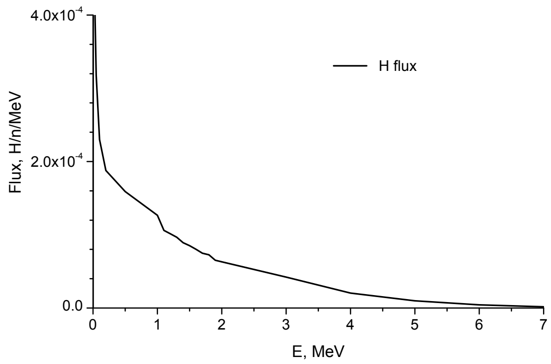

Fig.4. *Density spectrum of proton flux in water*

The spectrum of fast protons, produced in water by fast neutrons is shown in Fig.4 (using unit proton/neutron/MeV), as obtained using the Monte Carlo simulation. One can see that the ratio of proton flux to neutron flux at the surface of the zirconium cladding equals to $\varphi_p/\varphi_n = 0.0001$. The absolute value of proton flux at the surface of the cladding amounts to $0.1\,\mu A/cm^2$ at the nominal reactor power.

3. IMPLANTATION OF HYDROGEN INTO ZIRCONIUM CLADDING

The protons entering the zirconium cladding have a rather broad energy spectrum up to $10\,MeV$, and consequently different ranges in zirconium. The protons of low energy stop in the near-surface region and the fast protons reach a rather large depth. Dependences of the proton total flux on the depth are shown in Fig.5 and 6.

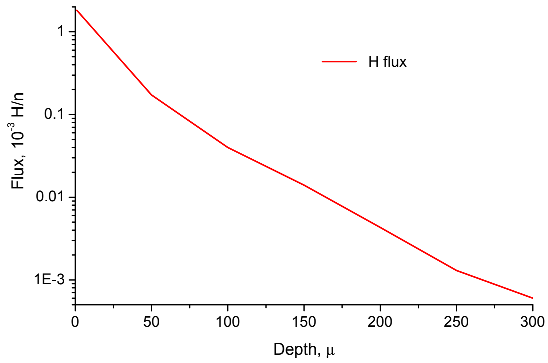

Fig.5. *Dependence of the proton total flux on the depth in zirconium*

As it follows from Fig.5, the protons penetrate zirconium to the depth of hundreds microns, although the proton flux density decreases rapidly with the depth. The dependence of the proton total flux in the near-the-surface region is shown in Fig.6. Such rapid decrease of the proton flux is caused by the large portion of low energy protons in the spectrum of protons coming to the outer surface of the cladding.

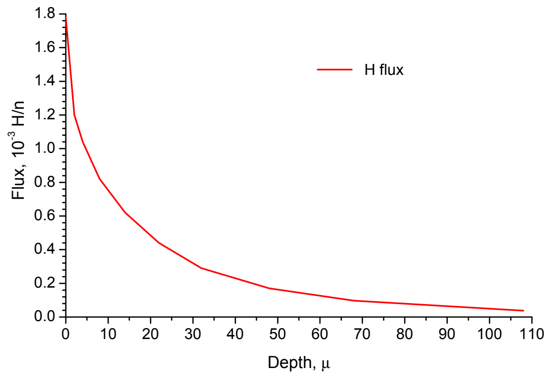

Fig.6. *Dependence of the proton flux in zirconium at the small depth*

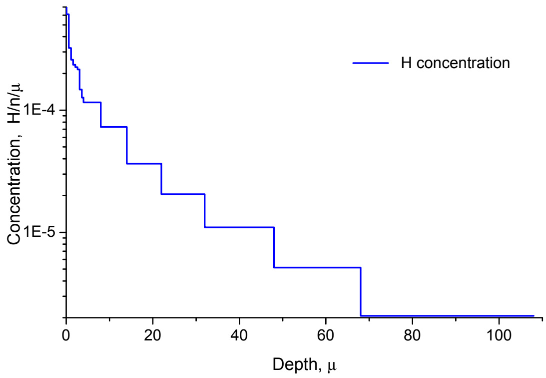

Fig.7. *Dependence of hydrogen concentration on the depth in zirconium*

Using the data from Fig.5 one can calculate the concentration profile of hydrogen implanted into the zirconium cladding of a fuel rod. Fig.7 shows the proton range profile. The range of fast protons averages $20\,\mu$, the maximal proton range is larger then $200\,\mu$. As mentioned above, the concentration of hydrogen implanted into zirconium decreases rapidly in the near surface region and comes to a simple exponential dependence at the large depth.

4. CONCLUSIONS

It follows from Fig.7 that the average rate of hydrogen accumulation in $40\,\mu$ layer amounts to $5 \cdot 10^{-5} H/n/\mu$, and the total concentration of hydrogen accumulated in this layer during the fuel cycle comes to $3 \cdot 10^{22} H/cm^3$, which corresponds to one hydrogen atom per one zirconium atom. Therefore, the discussed mechanism plays an important role in the process of zirconium hydrogenation during reactor irradiation.

References

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ГЕНЕРАЦИЯ ПРОТОНОВ МэВ-НЫХ ЭНЕРГИЙ В АКТИВНОЙ ЗОНЕ ВОДО-ВОДЯНОГО ЭНЕРГЕТИЧЕСКОГО РЕАКТОРА

А.В. Ганн, В.В. Ганн

Методом Монте-Карло рассчитан спектр быстрых протонов, возбуждаемых в воде быстрыми нейтронами активной зоны реактора ВВЭР-1000. Основным механизмом образования быстрых протонов в замедлителе является упругое рассеяние быстрых нейтронов на ядрах атомов водорода. Показано, что при номинальной мощности реактора поток быстрых протонов на оболочку твэла составляет величину порядка $0,1$ мкА/см^2, средняя энергия протонов составляет 1 МэВ, а максимальная энергия достигает 10 МэВ. Рассмотрен процесс имплантации водорода в циркониевую оболочку твэла. Рассчитан профиль пробегов протонов по толщине оболочки. Обсуждается роль рассмотренного явления в процессах наводораживания циркониевой оболочки твэлов в воде при реакторном облучении.

ГЕНЕРАЦIЯ ПРОТОНIВ МеВ-НИХ ЕНЕРГIЙ В АКТИВНIЙ ЗОНI ВОДО-ВОДЯНОГО ЕНЕРГЕТИЧНОГО РЕАКТОРА

А.В. Ганн, В.В. Ганн

Методом Монте-Карло розраховано спектр швидких протонів, що порушуються швидкими нейтронами у воді активної зони ректора ВВЕР-1000. Основним механізмом утворення швидких протонів у сповільнювачі є пружне розсіювання швидких нейтронів на ядрах атомів водню. Показано, що при номінальній потужності реактора потік швидких протонів на оболонку твела становить величину порядку $0,1$ мкА/см^2, середня енергія протонів 1 МеВ, а максимальна енергія досягає 10 МеВ. Розглянуто процес імплантації водню в цирконієву оболонку твела. Розраховано профіль пробігів протонів по товщині оболонки. Обговорюється роль розглянутого явища в процесах наводнення цирконієвої оболонки твелів у воді при реакторному опроміненні.