PROBABILISTIC ASSESSMENT OF THE REACTOR VESSEL LIFETIME

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Abstract

A simple and rapid method is proposed for assessing the reduction in the lifetime of steel walls of the reactor vessel under neutron irradiation. The method is based on modelling the number of radiation defects by the behaviour of a general time-dependent random process of death and birth and queuing theory. Necessary data for assessments: the estimated operating time of the reactor (in years), the actual operating time of the reactor, the accumulated fluence depending on time, the temperature on the walls of the reactor vessel, the neutron absorption cross section of the steel of the reactor walls, the energy of fast neutrons striking the walls. The main problem: getting this accurate data.

Keywords: *Neutron irradiation, Reactor vessel lifetime, Process of death and birth*

Introduction

The impact of neutron irradiation on the duration of the steady state of the walls of the reactor vessel (*RV*) is one of the main issues in nuclear energy. The safety and reliability of the operation of a nuclear power plant are associated with the reliability of predicting changes in the viscosity characteristics of the reactor vessel material. This problem is presented in detail in many studies [1-32]; it is associated with issues of safe operation of the reactor, extending the life of the reactor, and many other tasks. The procedure usually performed when considering problems of this kind is to measure the dependence of the change in the shift of the critical brittleness temperature (or radiation embrittlement coefficient) on the witness samples temperature.

Thus, a large amount of data was accumulated on the radiation embrittlement of low-alloy vessel steels, on the relationship between the critical temperature of embrittlement and the resulting fluence, and on other aspects of the problem under consideration, which was then used in predicting changes in the lifetime of *RV* materials. Probabilistic approaches to solving this problem have been considered; recent works have used Bayesian methods, approaches related to machine learning, etc.

This article proposes a simplified probabilistic approach to solving the problem of changing the lifetime of the walls of the *RV* under the influence of irradiation. This is an integral approach that does not take into account many details that do not have a decisive influence on the final result. As in experimental work, the influence of neutron fluence is considered important. Lattice atoms directly displaced by incident particles are defined as a primary knocked-out atom (PKA). PKAs have an energy spectrum even in the case of monochromatic irradiation; their energy varies from zero to a certain maximum value M_{max}. Getting into a solid body, a fast particle is involved in a complex process of interaction with electrons and atomic nuclei in the crystal lattice. The statistical approach is based on determining the probability of the interaction process occurring. The emerging defects in the crystal lattice and crystalline crystals are considered as a statistical system, subject to the general laws of the theory of random processes, statistical physics and non-equilibrium thermodynamics. It is assumed that at some random moment this system will change its structure under the influence of irradiation. It is assumed that these changes reduce the steel time of the *RV*.

In almost all studies investigating the phenomenon of radiation embrittlement under the influence of defects in the crystal structure, the shift in the embrittlement temperature under the influence of irradiation is chosen as an indicator characterizing the degree of embrittlement. In this article, such an indicator is chosen to reduce the time of stable functioning of the steel structure, the life time of steel *RV*. This indicator can be compared with the relative narrowing of *RV* steel, but with the opposite sign.

The article is structured as follows. The second section describes a mathematical model of the influence of radiation effects on the lifetime of the walls of the reactor vessel. The number of radiation defects is modelled by a model of a random process of death and birth. The queuing theory is used to describe the lifetime of a *RV*. In the third section, the dependences of the *RV* lifetime on the irradiation time are calculated. The fourth section discusses the results obtained.

Mathematical model of the influence of radiation effects on the lifetime of the walls of the reactor vessel

Radiation defects

The reaction cross section is taken as a measure of the probability density of events during the interaction of particle beams with a solid body: $\sigma = m/\varphi$, where m is the number of interactions per unit time, φ is the flow of particles.

Dimension of the interaction cross section is $[\sigma]=10^{-24}\text{cm}^2$. Different types of irradiation differ in the number and energy spectrum of primary knocked out atoms (*PKA*), which is characterized by the differential cross section $K_p(E,M)dM$, used to calculate *PKA* with energy M when the energy of the incident particle is E. The rate of formation of *PKA* with energy M is determined as follows: $P = \varphi \int_{M_d}^{M_{\max}} dMK_p(E,M)$, where φ is the flux density of incident particles. Here, only those *PKA*s that have received energy exceeding the threshold energy M_d required for displacement are considered; M_{max} is a certain maximum energy value.

Neutron irradiation leads to degradation of the original properties of the material. When a high-energy neutron collides with an atom in a crystal lattice, the atom is displaced or a cascade of displacements occurs in the lattice, depending on the amount of energy transferred by the neutron to the metal atom. The first atom hit by a neutron, striking other atoms, causes additional displacements in the lattice. The vacancy and its own interstitial atom formed as a result of the collision of a neutron with a lattice atom are called a Frenkel pair. As a result of the development of the cascade, volumes with a high concentration of vacancies are formed, surrounded at the periphery by zones with an increased density of interstitial atoms. In addition to displacements, large neutron fluxes, due to their energy, excite atoms and intensify their vibrations, which is accompanied by a local increase in temperature. An increase in temperature promotes radiation annealing, accompanied by the annihilation of vacancies and interstitial atoms. Further, in places where point defects accumulate, dislocation loops are formed precipitates of elements such as copper, nickel, manganese and silicon, segregation of elements such as phosphorus and tin at interphase boundaries and grain boundaries. The basis of theoretical models of the evolution of radiation-induced defects is the kinetic equations for the concentration of point defects in a medium containing sinks. It is assumed that the concentration of radiation point defects exceeds the concentration of thermally equilibrium defects. Vacancies and interstitial atoms, migrating along the lattice, can: firstly, recombine; secondly, to form clusters of defects of the same name and, thirdly, to become sinks, which can be dislocation networks, dislocation loops, pores and other extended defects. Consequently, the rate of change in the concentration of interstitial atoms and vacancies is equal to the difference in the rates of their formation and death, which can be described by kinetic equations [32]:

$$\begin{aligned} \frac{dC_v}{dt} &= G - R \cdot C_i \cdot C_v - C_v \sum j \cdot K_{jv} \\ \frac{dC_i}{dt} &= G - R \cdot C_i \cdot C_v - C_i \sum j \cdot K_{ij} \end{aligned} \quad (1)$$

where C_v, C_i are the average concentrations of vacancies and interstitial atoms; $G=\sigma_f \varphi$ - rate of introduction of freely migrating defects (σ_f - cross section for their formation, φ - irradiation intensity); $R = 4\pi RV_i (D_i+D_v)$ - recombination constant of point defects, where RV_i - radius of mutual recombination, $D_{i,v}=D_{0i,v}\exp(-E_{mi,v}/kT)$ - diffusion coefficients of interstitial atoms and vacancies, k - Boltzmann constant, T - absolute temperature, $E_{m\ i,v}$ - migration energy of interstitial atom and vacancy; $K_{ji,v}=S_{ji,v}D_{i,v}$ is the coefficient of absorption of point defects by sinks of type j, where $S_{ji,v}$ are quantities characterizing the power of sinks of type j for interstitial atoms and vacancies.

The embrittlement of steel walls of the *RV* is also influenced by impurities of phosphorus, copper and other elements, dilatation interactions between defects, the formation and evolution of partial and perfect dislocation loops, the formation of a dislocation network, the nucleation of pores and the evolution of the pore structure, radiation-induced segregation, and other reasons. Such influences can also be included in the consideration, but are not considered in this work.

In the last thirty to forty years, a significant number of scientific achievements have been made, such as the direct formation of self-interstitial atom clusters from cascades and their one-dimensional motion, dislocation displacement, and preferential formation of precipitates near dislocations. The change in drain force, how cascade calculations are included in the change in point defect concentration, how the recombination radius is specified, and how the point defect migration energies are selected have been calculated.

In addition, there are two critical issues in assessing the service life of pressure vessels, namely: (i) the effect of precipitation on radiation embrittlement, which is probably one of the main factors determining the service life of pressure vessels; (ii) the relationship between microstructure and macroscopic degradation.

Although all of the above aspects affect the results, their joint consideration faces significant mathematical and descriptive difficulties. In paper [43], an attempt was made to provide a three-level hierarchical description, where the kinetics of defect formation is considered at the first level of description, the formation of structures of these defects at the second level, and the influence of these structures on the lifetime of reactor materials at the third level.

In order to contribute to the assessment of the lifetime of *RV* materials, it is necessary to first consider the main factors of radiation embrittlement for modeling radiation damage. Nowadays, with the significant accumulation of test results worldwide, the understanding of the main factors contributing to embrittlement has been significantly enhanced. In addition to discussing the assessment of service life based on the number of irradiation defects, the model should also include radiation-induced microstructures resulting from the formation and evolution of defect clusters that are associated with embrittlement. Despite the abundance of details and features of the behavior of irradiated materials, the root cause of the processes occurring is still the irradiation of the *RV*.

In this paper, a deliberately simplified and coarse-grained description has been chosen. It is assumed that numerous factors of various complex processes can ultimately be reduced to the effect of irradiation.

Change in RV lifetime under irradiation

The behavior of a random process, for example, a branching random process [33], can be characterized using the generating function

$$F(s)=\sum_{k=0}^{\infty} p_k \cdot s^k,\ |s|\le 1 \tag{2}$$

where p_k is the probability that there are k particles in the system. Let us write the generating function in the form

$$\begin{aligned} &F(s)=p_0 Q(s)=\frac{Q(s)}{Q}=\frac{p_0}{p_0(s)},\\ &p_0=\frac{1}{Q},\ p_0(s)=\frac{1}{Q(s)},\ Q(s)=1+\frac{p_1 s}{p_0}+\ldots+\frac{p_n s^n}{p_0}+\ldots \end{aligned} \tag{3}$$

The value $p_0=F(s=0)$ describes the probability of degeneracy of the system, when there are no particles in the system. To illustrate how Eqs. (2) and (3) are fulfilled, we cite a large canonical ensemble [34-39].

In queuing theory (for example, [40]), the period of system occupancy, busy period, which can be compared with the lifetime of *RV* defects in the *M/G/1* model (an exponential distribution for the flow of requests entering the system, an arbitrary distribution of the time required to service a request in the system). The average time value of busy period is equal to

$$\overline{T}=\frac{\rho}{(1-\rho)},\ p_0=1-\rho,\ \rho=1-p_0=1-\frac{1}{Q} \tag{4}$$

where $\rho=d\psi(\theta)/d\theta_{\theta=0}$, the function ψ characterizes the entry of elements (defects) into the system. The reactor is operating and defects are accumulating in it. This is a busy period. Then annealing can occur - an empty period - there are no defects. Then the reactor starts working again - a busy period.

Let us assume that the same relationships are satisfied under the influence on the system, which we denote by parameter s. The average time value of the busy period under the influence of s on the system is equal to

$$\begin{aligned} &\overline{T}(s)=\frac{\rho(s)}{(1-\rho(s))},\\ &p_0(s)=1-\rho(s),\ \rho(s)=1-p_0(s)=1-\frac{1}{Q(s)}\\ &\frac{\overline{T}(s)}{\overline{T}}=\frac{\left(\frac{1}{p_0(s)}-1\right)}{\left(\frac{1}{p_0}-1\right)}=\frac{(F(s)-p_0)}{(1-p_0)}\le 1,\ F(s)\le 1 \end{aligned} \tag{5}$$

Here $T(s)$ is the average lifetime of the *RV* taking into account radiation effects. The proposed description is simplified. It is strictly valid for the large canonical ensemble [34]. But below we consider the stationary case, for which relations (2)-(5) are satisfied with a certain approximation. A consideration of the general non-stationary case using queuing theory is given in [41-44]. It is shown in [42] that the argument s from Eqs. (2), (3), and (5) is written as a function of s, the argument is replaced, $s\to D(\alpha=s)=f(s)\sim\exp(-U/k_B T_e)$. The function $Q(s)$ from Eqs. (2) - (5) turns out to be a function of the form $Q[D(\alpha)]$, where U is the additional potential energy received by the system, k_B is the Boltzmann constant, T_e is the absolute temperature. Below we consider the situation when $s=\exp(-U/k_B T_e)$, where U is the energy transferred to the *RV* by neutrons.

Model of "death-and-birth"

As in [45], we use the model of death and birth [33, 46]. We assume that the incoming flow G in Eq. (1) enters the system one particle at a time (particle birth). A hierarchical three-level model is considered in [47]. This work assumes that the lower levels of the hierarchy are already implicitly included in the description. The concentrations of vacancies and interstitial atoms depend on time in Eq. (1) (we assume a constant input flow). Let us replace the time-dependent expressions for concentrations with average effective constant values. Taking into account concentrations after the moment when they take on stationary values leads to the same result. The generating function (2) for the process of death and birth is equal to

$$\begin{aligned} &F(s,\tau,t)=\frac{1+(1-\xi-\eta)s}{1-\eta s}=\sum_{-\infty}^{\infty} P_n(t) z^n,\\ &\rho_1(t)=\int_0^t (\mu(\tau)-\lambda(\tau))d\tau \end{aligned} \tag{6}$$

$$\begin{aligned} &\xi=\frac{1-e^{-\rho_1}}{W},\ \eta=1-\frac{1}{W},\ W(\tau,t)=e^{-\rho_1}[1-K],\\ &K=\int_\tau^t e^{\rho_1(t,x)}\mu(x)dx,\\ &\overline{n}(t)=e^{-\rho_1(t)},\ Var(n(t))=e^{-\rho_1(t)}\left(2W-1-e^{-\rho_1}\right),\\ &P_0(t)=\xi(t)=1-\frac{e^{-\rho_1(t)}}{W} \end{aligned} \tag{7}$$

Here $\overline{n}$ is the total average number of particles in the system, $Var(n(t))$ is the dispersion of the number of particles.

Let us choose the parameter τ in Eqs. (6) and (7) equal to 1 year in order to consider already established stationary states. It is shown in [48] that the stationary mode is established in a time of about $3\cdot 10^7$ s, which is about 1 year. Which probabilities $\lambda(t)$ and $\mu(t)$ appear in Eqs. (6) and (7)? In [33] it says that any particle at moment t with probability $\mu(t)dt$ dies in the interval $(t,\ t+dt)$, while with probability $\lambda(t)dt$ is replaced by two new particles. For the flow G entering the system of defects from Eq. (1) $\lambda(t)\sim G/n(t)$, where $n(t)$ is the number of defects at time t. If we normalize the probability $\lambda(t)$ by dividing it by $\int_\tau^{T_f}\left(\frac{G}{n(t)}\right)dt$, where T_f is the total operating time of the reactor, we obtain that

$$\lambda(t)=\frac{G}{n(t)}\left(\int_\tau^{T_f}\frac{G}{n(t)}\right)^{-1} \tag{8}$$

In the stationary case $n(t)=const$. Then in Eq.(6) $\rho_1=0$, $\lambda=\mu$, and assuming the constant value of G, we obtain:

$$\lambda = \mu = \frac{1}{(T_f - \tau)} \tag{9}$$

The fluence is equal to $\Phi = \frac{dN}{dS}$, where dN is the number of particles penetrating into the sphere with cross section dS. Radiation intensity $\varphi=dF/dS$, with $F=dN/dt$ - the flux of ionized particles. Then $\Phi = \int \varphi dt$, since $\varphi=d(dN/dS)/dt$.

In Eq. (8) with $n(t)=const$, $\sigma_f\left[\Phi(T_f)-\Phi(\tau)\right]=\int_{\tau}^{T_f}\sigma_f\varphi dt$.

Results

The work [49] presents the dependences of the shift in the critical embrittlement temperature when witness samples are irradiated with a fluence of $17.8\cdot10^{18}$ n/cm^2, which corresponds to a reactor operating time of 18 years.

The total operating time of the reactor is assumed to be 40 years, and the value of τ is assumed to be τ = 1. In the practice of analyzing radiation embrittlement of materials of *VVER RV*s in Ukraine, the fluence of neutrons with energies above 0.5 MeV is used as a dose characteristic of fast neutrons; that is, it is assumed that neutrons with energies less than 0.5 MeV do not cause material damage.

For the stationary case, we have $K = \int_{\tau}^{t}\mu(x)dx = \frac{(t-\tau)}{(T_f=\tau)}$.

From Eqs. (5) - (8) for $\Delta T = T - T(s)$ we obtain:

$$\frac{\Delta T}{T} = \frac{1}{1+\frac{s}{1-s}\cdot\frac{1}{1+K}} = \frac{1}{1+\frac{s}{1-s}\cdot\frac{T_f-\tau}{T_f+t-2\tau}}, \tag{10}$$

$$s = \exp\left(-U/k_B T_e\right)$$

where U is the energy received by the walls of the reactor vessel during irradiation. The energy of the external field is added to the energy of the system as additional potential energy [50] in the grand canonical ensemble, for which Eqs. (3) and (10) are satisfied. The values vary: T_e - temperature in the reactor, σ_n - cross section for neutron absorption by the steel of reactor walls, E_n - neutron energy.

$$U = \Phi(t)\cdot\sigma_n\cdot E_n \tag{11}$$

Considering T_f = 40 years, E_n = 1 Mev, σ_n=1·10^{-26}cm^2, T_e=589K, in the interval t = 0-18 years, we accept a linear dependence of the form $\Phi(t) = 0.98889\cdot10^{18}\ t$ for the dependence of the fluence growth on time t [49]. The calculated curve of the relationship between the change in the average lifetime $\Delta T=T-T(s)$, to T, where T is the average lifetime of the *RV* without taking into account radiation effects, $T(s)$ - taking this into account, is shown in Fig. 1. For t = 18 years, $\Delta T/T$ = 0.631.

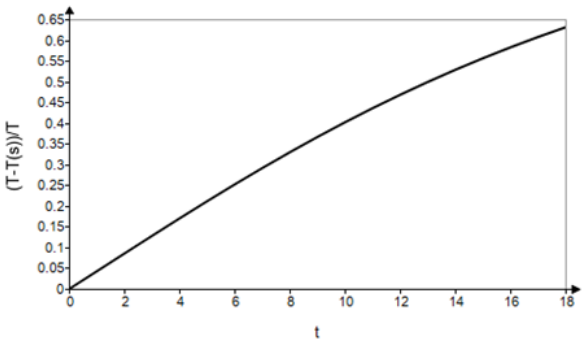


Fig. 1. Dependence of the ratio of changes in the average lifetime $\Delta T=T-T(s)$, to T
T_f=40 years, E_n=1 MeV, σ_n=1·10^{-26}cm^2, T_e=589 K,
$\Phi(t)$= 0.98889t ·10^{18} n/cm^2, in the interval t=0-18 years.

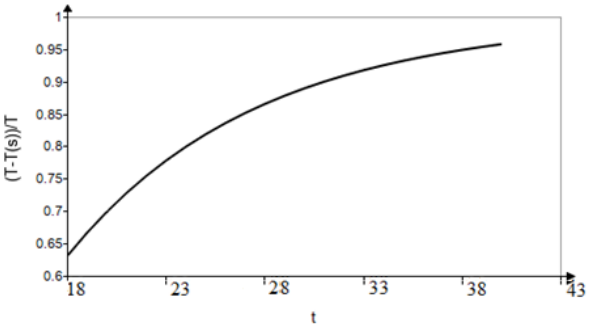


Fig. 2. Dependence of the ratio of changes in the average lifetime $\Delta T=T-T(s)$, to T
T_f=40 years, E_n=1 MeV, σ_n=1·10^{-26}cm^2, T_e=589 K,
fluence $\Phi(t)$=(17.8+1.78t)·10^{18} n/cm^2, in the interval
t=18-40 years. At t=40 years, $\Delta T/T$=0.958.
$\Phi(t)$= 6.3·10^{19} n/cm^2 achieved in t=43.19 years; $\Delta T/T$=0.969.

The dependence on the parameters is shown by replacing E_n (1 MeV in Fig. 2, it became 0.8 MeV in Fig. 3) and σ_n (1·10^{-26} cm^2 in Fig. 2, it became 0.25·10^{-26} cm^2 in Fig. 3). A significant change is visible - a decrease in the effect: $\Delta T/T$ for t=18 years it was 0.631 in Fig. 2, it is 0.196 in Fig. 3; for t=40 years: it was 0.958 in Fig. 2, it is 0.556 in Fig. 3. Changes in reactor core temperature also have an effect.

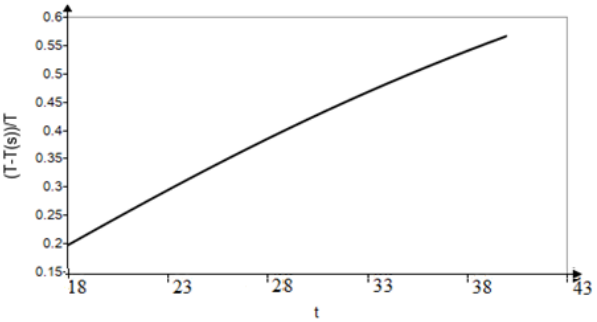


Fig. 3. Dependence of the ratio of changes in the average lifetime $\Delta T=T-T(s)$, to T
T_f=40 years, E_n=0.8 MeV, σ_n=0.25·10^{-26}cm^2, T_e=589 K,
fluence $\Phi(t)$=(17.8+1.78t)·10^{18} n/cm^2, in the interval
t=18-40 years. At t=40 years, $\Delta T/T$=0.566.
$\Phi(t)$= 6.3·10^{19} n/cm^2 achieved in t=43.19 years; $\Delta T/T$=0.608.

Other sources indicate other neutron fluence values. Thus, in [51], the estimated total maximum fluence of neutrons with E_n>0.5 MeV at the Khmelnitsky NPP Unit No.1, *RV* fluence for first ten fuel campaigns is $1.1\cdot10^{19}$ n/cm^2, with an average fluence accumulation rate of $1.1\cdot10^{18}$ n/cm^2 per campaign. At T_f=40 years and $\Phi(t=18)=19.98\cdot10^{18}$ n/cm^2 it became $\Delta T/T$=0.489 in 40 years; $\Delta T/T$ was 0.566 at $\Phi(t=18)=17.8\cdot10^{18}$ n/cm^2, E_n=0.8 *MeV* and $\sigma_n=0.25\cdot10^{-26}$ cm^2. At T_f=50 years, $\Delta T/T$=0.587, neutron absorption cross section by iron is $\sigma_n=10^{-26}$ cm^2; fast neutrons with energy E_n>0.5 MeV are taken into account.

If this rate of accumulation of the neutron fluence of the *RV* continues in the future, then the maximum permissible fluence specified in the technical safety justification for reactor plant *V-320* is equal to 5.7 10^{19} n/cm^2; it will be accumulated in about 50 years of operation, since the design service life of the *VVER-1000* vessel is 40 years.

Therefore, the task is to accurately determine such parameters as the energy of fast neutrons incident on the *RV*, neutron cross sections for the absorption of fast neutrons by the steels of the *RV* walls, fast neutron fluence, and temperature in the core. All these parameters significantly affect the change in the service life of the *RV*.

In [52], the relation obtained in [53] is given for the average energy of fast neutrons in a reactor of the form $\overline{E}_n(MeV) = 7.42R + 0.3$, where R is the ratio of the flux of neutrons with an energy greater than 3 MeV (Φ>3) to the flux of neutrons with an energy greater than 1 keV (Φ>0.001). In [48], R values were measured at different points of the reactor *OR*, *VVR* [52]: left channel; level of the core center – *LCC*; same place, 20 cm below *LCC*; same place, 20 cm above *LCC*; same place, 60 cm above *LCC*; right channel of *LCC*; niche, on the central horizontal axis; in graphite reflector of the reactor (the thickness of the graphite between the neutron detectors and the nearest fuel elements is 20-30 *cm*). The average value of R was found to be 0.153, so E_n=1.4357 MeV. The $\Delta T/T$ value calculated with this value E_n and temperature on the reactor walls T_e=290 ºC is shown in Fig. 4.

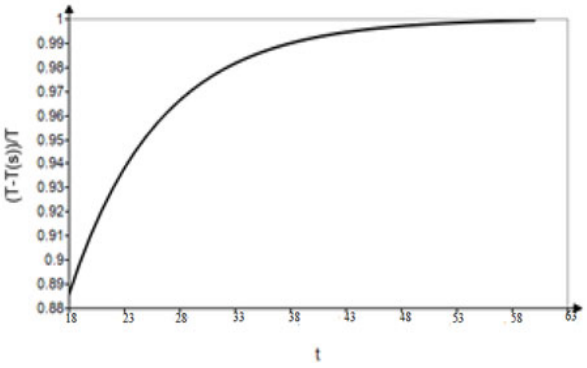


Fig. 4. Dependence of the ratio of changes in the average lifetime $\Delta T=T-T(s)$, to T
T_f=60 years, E_n=1.4357 MeV, $\sigma_n=1\cdot10^{-26}$ cm^2, T_e=563 *K*, fluence $\Phi(t)=(19.98+1.11t)\cdot10^{18}$ n/cm^2, in the interval t=18-60 years. At t=40 years, $\Delta T/T$=0.992. At t=18 years, $\Delta T/T$=0.885. At t=60 years, $\Delta T/T$=0.999.

Since $\Delta T/T=1-T(s)/T$, then, for example, at $\Delta T/T$=0.992, $T(s)=(1-0.992)T=0.008T$, the average lifetime of the *RV* under the influence of irradiation is reduced for t=40 years. In Fig. 5 compared to Fig. 4 the value of σ_n changes: E_n=1.4357 MeV, $\sigma_n=0.25\ 10^{-26}$ cm^2.

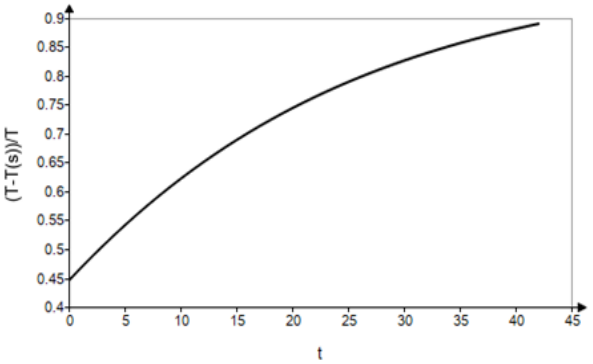


Fig. 5. Dependence of the ratio of changes in the average lifetime $\Delta T=T-T(s)$, to T
T_f=60 years, E_n=1.4 MeV, $\sigma_n=0.25\cdot10^{-26}$ cm^2, T_e=563 *K*, fluence $\Phi(t)=(19.98+1.11t)\cdot10^{18}$ n/cm^2, in the interval t=18-60 years. At t=40 years, $\Delta T/T$=0.764. At t=18 years, $\Delta T/T$=0.446. At t=60 years, $\Delta T/T$=0.890.

Similar results for Fig.4. But for Fig. 2, $\Delta T/T$=0.958 at t=40 years, $\Delta T/T$=0.969 at t=43.19 years. The maximum fluence is 6.3 10^{19} n/cm^2 at T_f=40 years, E_n=1 MeV, $\sigma_n=1\cdot10^{-26}$ cm^2; $\Phi(t)=(17.8+0.178t)\cdot10^{18}$ n/*cm*^{2}, occurs in t=43.19 years. For this period, $\Delta T/T$=0.969. For t=18 years, $\Delta T/T$=0.63, and for t=40 years, $\Delta T/T$=0.958.

For Fig. 3, when T_f=40 years, E_n=0.8 Me*V*, $\sigma_n=0.25\cdot10^{-26}$ cm^2, $\Phi(t)=(17.8+1.78t)\cdot10^{18}$ n/*cm*^{2}; in the time range t=18-40 years, $\Delta T/T$=0.196 for t=18 years, $\Delta T/T$=0.566 for t=40 years, and $\Delta T/T$=0.608 for t=43.19 years.

The comparison of Figs. 2, 2, and 4 shows a strong dependence of E_n and σ_n on neutron energy.

In the case of *VVER-440*, for t=50 years, the maximum fluence allowed is $3\cdot10^{20}$ n/cm^2. When $\sigma_n=1\cdot10^{26}$ cm^2, E_n=1 MeV, the time to reach the maximum fluence is 252 years. In this case $\Delta T/T$=1; for 152 years, $\Delta T/T$=0.97. If the fluence is allowed to be $1.6\cdot10^{20}$ n/cm^2, then the time to reach it will be 145 years. For the parameters in Fig. 5 and for t=145 years, we have the ratio $\Delta T/T$=0.994.

A similar characteristic of the fragility and durability of the *RV* metal is the relative elongation δ, shear fracture percentage. This parameter, like $\Delta T/T$, varies from 0 to 1 (from 0 to 100%). The value of δ at which brittle fracture of a metal sample occurs can be compared with the value of $T(s)$ at which the end of the metal's lifetime occurs. Fragility is the property of materials to collapse under the influence of external forces without residual deformation. Under significant impacts, destruction occurs at small values of δ and at large values of $\Delta T/T$ (small values of $T(s)$). The parameter δ is usually measured depending on the temperature, and the parameter $\Delta T/T$ is discussed above depending on the irradiation time t.

But the values of these parameters correspond to each other, characterizing the end of the service life of the steel. For heavily irradiated metals, the values of the parameters δ are very small, amounting to fractions of a percent. For example, if δ=0.002, then $T(s)$=0.002T, and $\Delta T/T$=0.998. Therefore, you can give preference to Fig. 4 with higher $\Delta T/T$ values and small values of $T(s)$.

Discussion

A simple approach to estimate the remaining lifetime of a *RV* after irradiation with fast neutrons is proposed. It is possible to relate this approach to the commonly used practice of measuring the critical brittleness temperature (*CBT*) and its shear. The simplicity of the approach can be both a disadvantage and an advantage of the method. The disadvantage is the lack of consideration of many features of the ongoing processes. But this may also be an advantage of the method, which does not take into account unimportant details, but in an integral form considers the important characteristics of the processes responsible for the main indicator of the reactor vessel - its lifetime.

It is assumed that the influence of various features of the processes, such as direct formation of clusters of self-interstitial atoms from cascades and their motion, displacement of dislocations and preferential formation of precipitates near dislocations, will ultimately be taken into account using neutron fluence, how it is done in the experiment. We assume that the results of complex processes caused by the initial irradiation can be reflected in the magnitude of the irradiation.

In [47], a three-level hierarchical description was used. Figure 4 of the present paper is very close to the result of [47] for the quadratic approximation in the equation for the energy of radiation damage. The estimations [47] show that the behaviour of the average lifetime as a function of the value of radiation influence strongly changes with the change of the parameter of non-equilibrium q of the non-equilibrium distribution for the lifetime. This parameter is generally unknown, and its incorrect choice can lead to significant errors. Therefore, a simplified description was adopted in the present paper, possibly to the detriment of some important details.

The value of $T(s)$ - the average lifetime of the *RV* taking into account radiation effects is not entirely clear: is this a real reduction in lifetime, or some conventional value? This value can be correlated with the change in the critical brittleness temperature. However, the latter value is also determined ambiguously. For example, an example of the spread of values was obtained within the framework of the IAEA project [55]. The corresponding results from all 8 laboratories are different.

To obtain more accurate results of the proposed approach, knowledge and strict consideration of the parameters of the problem are required. Thus, reactor steel is a complex alloy. For each component of this alloy, the neutron absorption cross sections for fast neutrons differ. Thus, in the case of Carbon, the neutron absorption cross section for fast neutrons is σ_n=0.0001·10^{-24} cm^2, and for Iron I σ_n=0.01·10^{-24} cm^2. It is necessary to take into account all components of steel *RV*, and write $\sigma_n=\Sigma\sigma_{ni}x_i$, where σ_{ni} is the neutron absorption cross section of fast neutrons of the i-th component, x_i is the fraction of the i-th component.

In a similar way, expressions for the neutron energy E_n should be written, taking into account the spectrum of fast neutrons and the contribution of this spectrum to the energy of neutrons incident on the walls of the *RV*. More precise and strict expressions for fluence are needed.

Generally, in the original relation for the lifetime (Eq. 4), one should consider not a single system, but a network of queuing theory systems. Each network system will describe a certain section of the *RV* wall. This approach was used in [45]. In a simple approximation, the factor $exp[-U/k_BT]$ includes c in the form $exp[-U/ck_BT]$, where c is the number of systems in the queuing network. It can be shown that $c \sim N_0$, where N_0 is the number of defects at the initial time. In this work, N_0=1 was assumed. However, the values of c and N_0 can take on other values, which can be used to correct the results obtained, taking, for example, the values of σ_n higher.

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