The article “**The prediction problems of VVER fuel element cladding failure theory**” (S.N. Pelykh*, M.V. Maksimov, S.D. Ryabchikov) is sent to “Nuclear Engineering and Design”.

Truly yours, Sergey Pelykh.

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1. Introduction

Development of methods for forecasting of VVER fuel element cladding integrity is imperative for Ukraine due to the great nuclear share (near 50 %) of electricity generation. In order to insure a high quality of electricity, the nuclear power plants should have the ability to follow load on a regular basis, including daily variations of the power demand (Yang, 2006).

Though no integrated data on cladding failure frequency during the last 5–10 years has been found in open publications, the following information concerning the period 1994–2006 is available:

— only 40 % of Ukrainian VVER-1000 reactors are operated with zero cladding failure frequency;

— in the whole world, in 2006 near 1 % of discharged VVER-1000 fuel assemblies had depressurized claddings, while in the most unsuccessful 2001 year – near 7 %;

— in Ukraine, the main suspected cause of cladding failure for VVER-1000 fuel is debris fretting, the share of failures with unknown causes is undetermined;

— in Russia, the main suspected causes of cladding failure for VVER-1000 fuel are: debris fretting and fretting wear on fuel element plugs in the bottom support grids – 20 % of all cases, and unknown causes – 80 % (2002–2006);

— in the whole world, the main suspected causes of cladding failure for PWR fuel are: grid to rod fretting – 55 % of all cases, debris fretting – 11 %, fabrication related failures – 5 %, crud/corrosion related failures – 4 %, and unknown causes – 25 % (IAEA, 2010).

The presently available VVER-1000 technological system controlling the hermeticity of fuel element cladding by a casual radiochemical analysis of water probes taken from the primary coolant circuit, does not allow to make the root cause analysis for cladding failures (Ovchinnikov and Semenov, 1988).

As a rule, the cause of cladding failure in VVER is not known reliably, hence, in order to guarantee the fuel operation safety and reliability, complex methods for controlling the cladding failure probability must be developed, considering different physical mechanisms leading to

cladding failure, including damage accumulation (Pelykh, 2013).

Taking into account the physical mechanism of cladding damage parameter $\omega(t)$ accumulation in VVER variable loading modes, let's consider the prediction problems of cladding failure theory, since the present fuel operation practice excluding a statistical service procedure for localization of untight cladding areas, fundamentally contradicts the current normative document demanding the control of cladding failures (SECNRS, 2008).

1.1. The normative method for forecasting of cladding failure due to damage accumulation

In order to understand the differences between different strength criteria discussed hereafter, let's look at the group of normative strength criteria for VVER-1000 fuel element cladding (Novikov et al., 2005) including the criteria SC1…SC5, each of them is used with the appointed normative safety coefficient K_{SC} (Table 1).

Table 1
Cladding normative strength criteria

Criterion	Definition	K_{SC}
SC1	$\sigma_\theta^{max} \le 250\,\text{MPa}$, where σ_θ^{max} is maximum circumferential stress	1.2
SC2	$\sigma_e^{max} < \sigma_0\,(T,\phi)$, where σ_e^{max} is maximum equivalent stress, Pa; σ_0 is yield stress, Pa; T is temperature, K; ϕ is neutron fluence, cm$^{-2}\cdot$s^{-1}	–
SC3	$P_c \le P_c^{max}$, where P_c is coolant pressure, Pa	1.5
SC4	$\omega(t) = \int_0^t \frac{dt}{t^{\lim}} + \sum_i \frac{n_i}{n_i^{\lim}} < 1$	10
SC5	$\varepsilon_{\theta,pl}^{max} \le 0.5\,\%$, where $\varepsilon_{\theta,pl}^{max}$ is cladding limit circumferential plastic strain	–

It can be seen that, omitting the SC3 and SC5 criteria, the strength of cladding under normal operation conditions is described by the SC1, SC2 and SC4 criteria only.

When a fuel element is operated in nonstationary regimes, quasi-static damage and fatigue damage are simultaneously accumulated in the cladding, therefore it is generally accepted, that the quasi-static cladding damage parameter $\omega_{q\text{-}s}$ originated from long slowly changing stresses and the

fatigue cladding damage parameter ω_{fat} originated from cyclic inelastic deformations, are distinguished. Thus when the damage accumulates, the limiting state is determined by summing up (Popov, 2000):

$$\omega = \omega_{q\text{-}s} + \omega_{fat}\,. \tag{1}$$

Generally speaking, the cladding material damage parameter can be considered as a structure parameter describing the material state (ω = 0, for an intact material and ω = 1, for a damaged material). The second possible approach is considering $\omega(\tau)$ as a characteristic of discontinuity flaw. That is when ω = 0, there are no submicrocracks in the cladding material. But if ω = 1, it is supposed that the submicrocracks have integrated into a macrocrack situated in some cross-section of the cladding.

The approach shown by Eq. (1) is used in the normative strength criterion SC4 (OECD, 2012):

$$\omega(t) = \int_0^t \frac{dt}{t^{\lim}} + \sum_i \frac{n_i}{n_i^{\lim}} < \frac{1}{K_{\text{SC4}}}\,, \tag{2}$$

where t is time; $t^{\lim}$ is the creep-rupture life under steady-state operation conditions; n_i is the number and $n_i^{\lim}$ is the limiting number of i-type power-cycles; K_{SC4} is the normative safety coefficient, K_{SC4} =10 (Alexeyev, 2008).

When calculating $\omega(t)$ using Eq. (2), after four years of VVER-1000 load according to 100–80–100 % N_{nom} and 100–50–100 % N_{nom} daily power-cycles (Novikov et al., 2005):

$$\omega_{q\text{-}s} \approx \frac{\omega_{fat}}{5} \;\; (\text{SC4})\,. \tag{3}$$

On the contrary, according to the experimental data obtained by two independent research groups (Sosnin et al., 1986) and (Kim et al., 2007), when a thin cylinder cladding is loaded at frequencies $\nu << 1\,\text{Hz}$, creep is the main physical process of deformation damage accumulation:

$$\omega_{q\text{-}s} >> \omega_{fat} \; (\text{Sosnin, 1986 and Kim, 2007}). \tag{4}$$

Hence, the SC4 criterion is not adequate. This inadequacy was pre-determined by the common practice of load acceleration used in experiments conducted in 60-70 years of the last century. But

this acceleration of cyclic loading changed the main physical mechanism of cladding deformation failure depending on frequency ν (Pelykh and Maksimov, 2011):

$$\begin{cases} \text{if } \nu \geq 1\,\text{Hz, then fatigue is dominant and creep is neglected;} \\ \text{if } \nu << 1\,\text{Hz, then creep is dominant and fatigue is neglected.} \end{cases}$$

The calculation model of $\omega(\tau)$ based on SC4 is uncertain due to:

— model incompleteness caused by eliminating, when determining the limiting components $n_i^{\lim}$ and $t^{\lim}$ for each fuel assembly, its real loading history as well as the real sequence of sets of its operating parameters. The following factors influencing the cladding creep strain rate are ignored specifically: fuel assembly rearrangement order, cladding corrosion rate, neutron fluence and spectrum, gas pressure in the inner fuel element volume, varying axial profiles of the coolant temperature and $\omega(t)$, disposition and movement of control elements of the reactor control system, parameters of reactor loading cycle, etc.;

— model inadequacy caused by neglecting the main physical mechanism of $\omega(\tau)$ accumulation at $\nu << 1\,\text{Hz}$ (creep), in particular, by setting the equal coefficient for $\omega_{\text{q-s}}$ and ω_{fat} in Eq. (1).

Considering this uncertainty, the SC4 criterion cannot be used for forecasting of cladding failure due to increase of $\omega(t)$ under variable loading. So the opinion that the value of $\omega(t)$ does not really limit the fuel element durability under maneuvering regimes is widely spread, and cladding depressurization by the mechanism of damage accumulation is considered to be prevented when the following two conditions are satisfied:

1. Circumferential stresses $\sigma_\theta(t)$ are not exceeding some established limiting value, e.g. according to the normative strength criterion SC1 (see Table 1):

$$\sigma_\theta(t) < \frac{250}{K_{\text{SC1}}}\,\text{MPa}, \tag{5}$$

where K_{SC1} is the normative safety coefficient, K_{SC1} =1.2.

2. Equivalent stresses $\sigma_e(t)$ are not exceeding the yield stress σ_0, e.g. according to the normative strength criterion SC2 (see Table 1):

$$\sigma_e(t) < \frac{\sigma_0(t)}{K_{\mathrm{SC2}}} = \sigma_0(t)\ \mathrm{MPa}, \tag{6}$$

where K_{SC2} is the normative safety coefficient for SC2, $K_{\mathrm{SC2}} = 1$.

1.2. The CET- method for damage parameter calculation

Though using conditions similar to Eq. (5) for cladding durability justification is a common practice (Suzuki, 2010), the calculated value of cladding axial segment volume-averaged $\sigma_\theta(t)$ does not take into account the mixed (intragranular and intergranular) nature of creep which is described by equivalent stress $\sigma_e(t)$ best of all (Popov, 2000).

So, in order to take into account the leading role of creep in the process of cladding damage parameter $\omega(t)$ accumulation at loading frequencies $\nu << 1\,\mathrm{Hz}$, it is reasonable to use the CET-method based on the experimentally proved creep energy theory (Sosnin et al., 1986), where $\omega(t)$ is found for the innermost cladding radial element having the maximum temperature as the integral function of $\sigma_e(t)$ (Pa) multiplied by the rate of equivalent creep strain $\dot{p}_e(t)$ (s^{-1}), and the CET-criterion is written as (Pelykh et al., 2013):

$$\omega(t) = A(t)/A_0 < \frac{1}{K_{\mathrm{SC4}}};\ \ A(t) = \int_0^t \sigma_e \cdot \dot{p}_e \cdot dt;\ \ A(t) \in [0; A_0], \tag{7}$$

where A_0 is specific dispersion energy $A(t)$ at the moment t_0 of cladding failure, MJ/m^3; the limiting component A_0 does not depend on the fuel element loading history, A_0 is determined by the cladding material properties only, and, for Zircaloy-4 alloy, the calculated value of A_0 is 55 MJ/m^3 (Pelykh et al., 2013).

Comparing Eq. (6) and Eq. (2), the CET-criterion has such advantages as:

— in contrast with SC4, the limiting component is constant for all sequences of sets of fuel operating parameters influencing $\omega(t)$:

$$A_0 = \mathrm{const};$$

— for any cladding material, having a verified software tool designed for analyzing the dynamic behavior of the corresponding nuclear fuel, the value of A_0 is easily found according to the limiting condition (Pelykh et al., 2013):

$$\lim(dA/dt)^{-1} \to 0 \text{ when } t \to t_0 . \quad (8)$$

The physical sense of Eq. (8) is that, according to the known experiments (Sosnin et al., 1986), the specific dispersion energy $A(t)$ comes equal to A_0 in the end of the rapid creep stage (third characteristic creep stage), at the moment when the $A(t)$ curve becomes vertical (Pelykh, 2013).

2. The proposed method for forecasting of cladding failure due to damage accumulation

Considering VVER-1000 fuel elements, the method for forecasting of cladding failure due to damage accumulation is described by the following algorithm:

1. Initialization of the calculation model by setting all the parameters describing:

— fuel element, fuel assembly and reactor core design;

— core power control algorithm including the layout of control elements used during the power maneuvering and core power control program defining the curves for reactor power, axial position of control elements, core coolant inlet temperature;

— fuel rearrangement model taking into account the fuel campaign duration;

— total isotopic composition of the fuel.

2. Choice of the number of axial segments and fixing the axial segment length. Choice of the number of fuel element groups distinguished by volume power-density irregularity coefficients k_v.

3. Choice of the software tool and, according to the core power control program, determination of irregularity coefficients $k_{v,i,j}$, where i is the axial segment number and j is the core cell number, in all axial segments of all fuel elements, for the fuel assemblies lying in the specified core segment containing one-sixth of all fuel assemblies, as well as one-sixth of all regulating units used for power maneuvering (Fig. 1).

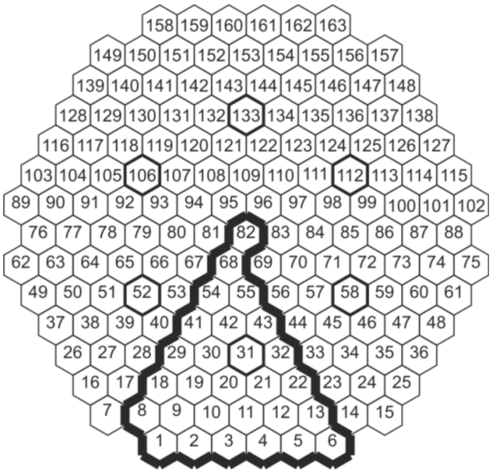

Fig. 1. Core segment: (numeral) cell number. The 10th regulating group cells and the segment are in bold

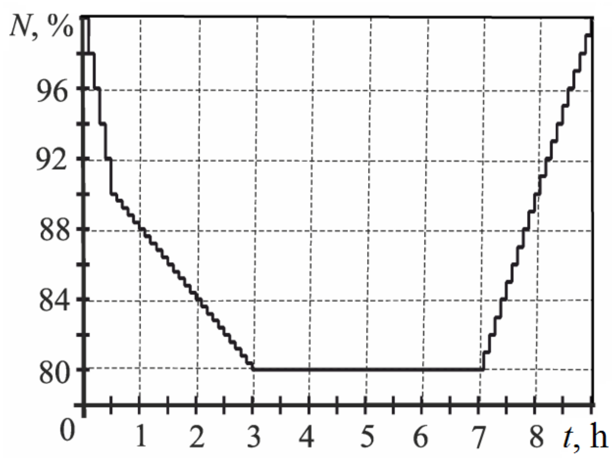

Fig. 2. Dependence of the core power on time

4. For each fuel assembly, clustering of all fuel elements into conditional groups depending on the value of $k_{v,i,j}$ in the most high-powered axial segment, based on the boundary minimum and maximum values of $k_{v,i,j}$ assigned for each conditional group.

5. As each fuel assembly is rearranged from one cell to another one, in order to take into account the variable number of fuel elements ingressed in a conditional group, the modified groups are formed. The number of fuel elements ingressed in a modified group is calculated using the conservatism principle: the vacancies in any modified group are filled, in the first place, by fuel elements from the conditional group with higher coefficients $k_{v,i,j}$. The share of each conditional group at formation of a modified group is taken into account. The aim is to obtain, for any fuel assembly rearrangement, a constant number of fuel elements ingressed in any group not depending on the cell number, as well as to take into account the most conservative scenario of fuel loading.

6. For any modified (conservative) group, using the CET-method, calculation of $\omega(t)$ in the most stressed axial segment, and checking for all fuel assembly rearrangements ingressed in any considered (alternative) fuel rearrangement algorithm, if the limiting value $\omega^{\lim}$ is exceeded.

7. If $\omega^{\lim}$ is exceeded, a conclusion about the predicted total number of failed claddings and the permissibility of this algorithm is made.

It should be added that, in order to obtain an appropriate description of the local power heterogeneity in a fuel assembly, the number of distinguished fuel element groups must be chosen using a special optimization procedure. Hereafter the number of fuel element groups in a fuel assembly is supposed to be 4, for illustrative purposes only.

2. 1. The initial data of the calculation model

The following assumptions were applicable to this study:

— VVER-1000 fuel element, fuel assembly and core operation conditions, design parameters are set according to the design objectives (Shmelev et al., 2004), with the following exceptions: 1) The cladding material is supposed to be Zircaloy-4. 2) The corrosion model of MATPRO-A (SCDAP/RELAP5/MOD2, 1990) has been used for cladding corrosion rate estimation (Pelykh and Maksimov, 2011);

— values of $\omega(t)$ are calculated for a given fuel rearrangement algorithm considering fuel assembly rearrangements within the core segment (1/6 core) – see Fig. 1;

— the layout of regulating units corresponds to the Advanced power control algorithm characterized by the most stable axial offset, as well as by use of the 10th group of control elements only (Pelykh et al., 2014);

— time dependences of the core power N and the axial coordinate H of the bottom edge of control elements are set according to Fig. 2 and 3, respectively;

— the core coolant inlet temperature stays constant (287 ºC) by means of change of pressure in the main steam collector during power maneuvering;

— the daily loading cycle is considered, where N changes in compliance with the schedule: N = 100 % for 15 h → N lowering to 90 % during 0.5 h by means of boric acid injection → N lowering to 80 % during 2.5 h at the expense of reactor poisoning → N = 80 % for 4 h → N increasing to 100 % during 2 h;

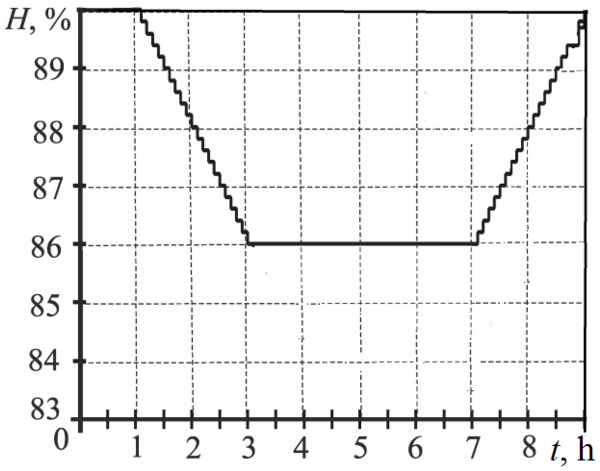

Fig. 3. Dependence of the control element edge coordinate on time

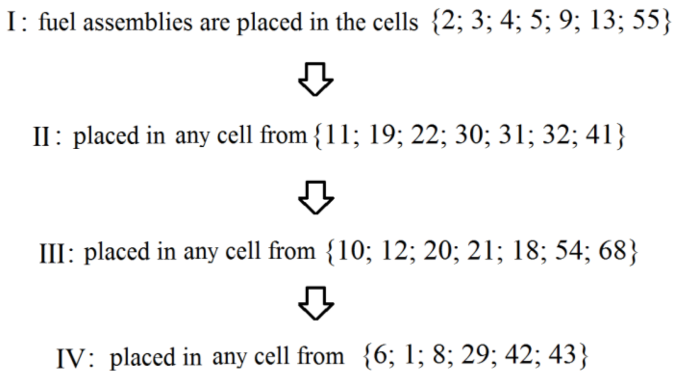

Fig. 4. Distribution of fuel assemblies in core cells by campaign year: (Arabic numeral) cell number; (Roman numeral) year

— the total isotopic composition of the fuel including the distribution of long-lived and stable fission products causing reactor slagging was specified for the start of the fifth four-year campaign of Khmelnitskiy NPP Unit 2;

— the distribution of fuel assemblies within the 1/6 core segment is set according to Fig. 4 (Vorobyev, 2011);

— the model for calculation of the power density distribution in fuel elements is based on a two-group neutron diffusion model (Pelykh and Maksimov, 2011).

2.2. The matrix of coefficients and calculation codes

The fuel element length was conditionally divided into eight equal axial segments enumerated from the core bottom, and axial power-density profiles were found by calculation of volume power-density irregularity coefficients $k_{v,i,j}$ in all axial segments, for all of the 27 core cells shown in Fig. 4.

For any fuel assembly, the power-density distribution among fuel elements was considered by distinguishing of four groups of fuel elements, each group is characterized by group-averaged

coefficients $k_{v,i,j}$. Choice of the optimal number of such groups is not discussed here because it requires a special optimization procedure. So the $k_{v,i,j}$ matrix dimension was $8\times 27\times 4$.

The following certified programs were used:

— "Reactor Simulator" code (Philimonov et al., 1998), it was applied to calculate the coefficients $k_{v,i,j}$ for fuel assembly-averaged fuel elements;

— "Femaxi" code (Suzuki, 2000), it was used to determine the evolution of stresses and strains in claddings made of Zircaloy-4;

— ANC-H code (Chao and Shatilla, 1995), this three-dimensional, two-group neutron diffusion code was applied to calculate the coefficients $k_{v,i,j}$ at 100 and 80 % of the nominal VVER-1000 power N_{nom} considering the power-density distribution among fuel elements. The power flux in a fuel element was restored using correction coefficients for homogenized cross sections. According to the decomposition method, each fuel assembly included one radial node as well as 24 axial nodes which were averaged to obtain eight axial segments.

2.3. Division of fuel elements into groups

Division of fuel elements into groups I…IV was made depending on the value of $k_{v,i,j}$ in the most high-powered axial segment (i = 4 or 5), based on the following conditions:

Group I: $k_{v,4\text{-}5,j} \in [0{,}4...1]$; II: $k_{v,4\text{-}5,j} \in [1...1{,}2]$; III: $k_{v,4\text{-}5,j} \in [1{,}2...1{,}4]$; IV: $k_{v,4\text{–}5,j} \in [1{,}4...1{,}7]$.

For estimation of the mistake following from the abstraction of four groups, coefficients $k_{v,i,j}$ obtained at N = 80 и 100 % N_{nom} using ANC-H, for fuel assemblies placed in cells 2…5, 9, 13, 55, were then averaged over four groups:

$$k_{v,6,j}(\text{ANC-H}) = \sum_{m=1}^{4} k_{v,6,j,m} \frac{n_{j,m}}{312}, \tag{9}$$

where $n_{j,m}$ is the number of fuel elements ingressed in group m, for a fuel assembly placed in the jth cell.

The values of $k_{v,6,j}(\text{ANC-H})$ obtained using Eq. (9) were compared with the corresponding values of $k_{v,6,j}(\text{RS})$ obtained using the Reactor Simulator code. Averaged among seven fuel assemblies at N=100 and 80 % N_{nom}, $k_{v,6,j}(\text{ANC-H})/k_{v,6,j}(\text{RS}) \approx 1.07$. The difference between these two results given by different codes lies within the interval 5-10 % which is typical for experimental and calculation errors when estimating linear heat rate (LHR) in a fuel assembly (Pelykh et al, 2013).

2.4. The method for obtaining conservative groups

Let's consider the fuel assembly rearrangement algorithms A and B (Table 2).

Table 2.
Algorithms A and B

Algorithm	Rearrangement	A, MJ/m^3	$\omega(t)$, % (for an assembly-averaged fuel element)
A	5-30-10-43	1.838	3.342
	9-11-20-1	1.443	2.624
	3-22-54-29	1.843	3.351
	13-19-21-42	2.652	4.822
	2-31-18	1.209	2.198
	55-41-12-6	1.955	3.555
	4-32-68-8	1.368	2.487
B	55-11-18-43	1.568	2.851
	13-32-20	2.019	3.671
	3-31-10-8	1.816	3.302
	9-19-68-42	2.054	3.735
	4-41-12-29	1.935	3.518
	2-30-21-6	1.522	2.767
	5-22-54-1	1.238	2.251

According to the fuel rearrangement model shown in Fig.4, the fuel assembly rearrangements are considered within the 1/6 core segment only (Fig. 1). Each of these two algorithms includes 7 fuel assembly rearrangements which were randomly chosen. For these 14 fuel rearrangements, using the "Reactor Simulator" code and considering assembly-averaged fuel elements, according to the adopted daily loading cycle, the relative power coefficients $k_{v,i,j}$ were calculated in all cells

included in the core segment, for all axial segments, at 80 and 100 % load levels.

Using the "Femaxi" code, the CET-criterion (7) at A_0 = 55 MJ/m3 and the MATPRO-A model of cladding corrosion (SCDAP/RELAP5/MOD2, 1990), the cladding's most stressed axial segment was determined (the 6th segment from the core bottom). The values of specific dispersion energy $A(t)$ and cladding damage parameter $\omega(t)$, obtained for the most stressed axial segment after the 4-year fuel campaign, are listed in Table 2.

For rearrangement 5-30-10-43 (algorithm A), the decomposition in conditional groups of fuel elements in the fuel assembly is shown in Table 3.

Table 3.
Distribution of fuel elements for rearrangement 5-30-10-43

Group	Cell 5	Cell 30	Cell 10	Cell 43
I	108	0	0	226
II	54	2	17	86
III	75	61	295	0
IV	75	249	0	0

It can be seen that the number of fuel elements included in each group changes when making fuel rearrangements, so in the general case:

$$\text{if } j \text{ changes, then } n_{k,j} \text{ changes}. \quad (10)$$

where $n_{k,j}$ is the number of fuel elements included in group k for a fuel assembly placed in core cell j.

To solve the problem of $n_{k,j}$ uncertainty illustrated by Eq. (10), let's introduce the conception of conservative groups formed under the following conditions:

1) The number of fuel elements included in conservative groups I*…IV* does not change when making fuel assembly rearrangements from one core cell to another one.

2) Volume power-density irregularity coefficients $k_{v,i,j}^{\mathrm{I*}} ... k_{v,i,j}^{\mathrm{IV*}}$ for any conservative group are calculated from the share of each conditional group in the core cell, taking into account the conservative principle: vacancies in each group I*…IV* are filled in the first place by fuel

elements from the conditional group with a higher number, that is with a higher power-density. For example, the distribution of fuel elements included in groups I…IV among conservative groups, considering a fuel assembly placed in core cell 5, 30, 10 and 43 for fuel campaign year 1, 2, 3 and 4, respectively, is found (Fig. 5).

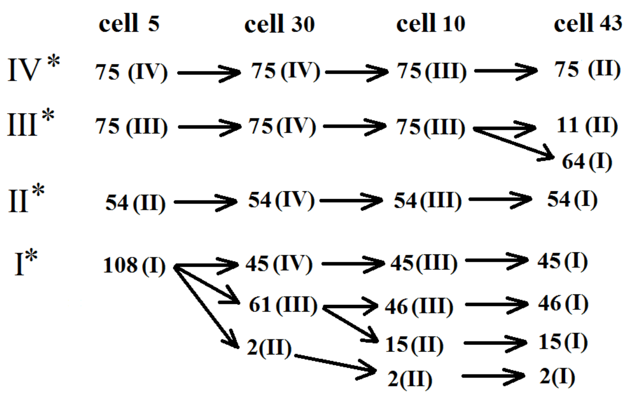

Fig. 5. Distribution of fuel elements among conservative groups for rearrangement 5-30-10-43

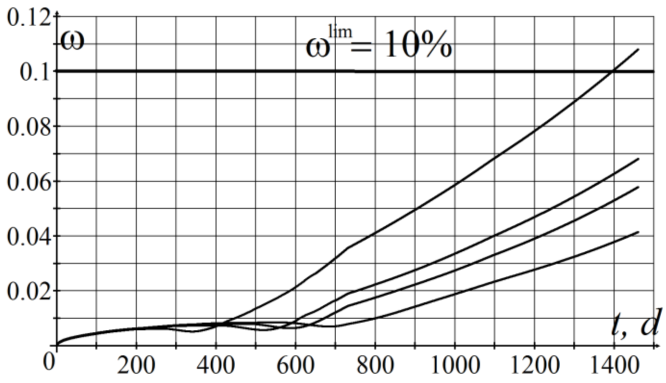

Fig. 6. Dependence of damage parameter on time for rearrangement 3-22-54-29 (four conservative groups)

Therefore, such conditions are satisfied:

$$n_j^{\mathrm{I}*} = \mathrm{const} = 108,\ n_j^{\mathrm{II}*} = \mathrm{const} = 54,\ n_j^{\mathrm{III}*} = \mathrm{const} = 75,\ n_j^{\mathrm{IV}*} = \mathrm{const} = 75 \text{ at } j = 5, 30, 10, 43.$$

Based on the distribution shown in Fig. 5, coefficients $k_{v,i,j}^{\mathrm{I}*} ... k_{v,i,j}^{\mathrm{IV}*}$ for conservative groups of rearrangement 5-30-10-43 are obtained (Table 4).

Table 4.
Coefficients $k_{v,i,j}^{\mathrm{I}*} ... k_{v,i,j}^{\mathrm{IV}*}$

j = 5	j = 30	j = 10	j = 43
	Conservative group I*, $n^{\mathrm{I}*} = 108$		
$k_{v,i,5}^{\mathrm{I}}$	$\dfrac{k_{v,i,30}^{\mathrm{II}} \cdot 2 + k_{v,i,30}^{\mathrm{III}} \cdot 61 + k_{v,i,30}^{\mathrm{IV}} \cdot 45}{n^{\mathrm{I}*}}$	$\dfrac{k_{v,i,10}^{\mathrm{II}} \cdot 17 + k_{v,i,10}^{\mathrm{III}} \cdot 91}{n^{\mathrm{I}*}}$	$k_{v,i,43}^{\mathrm{I}}$
	Conservative group II*, $n^{\mathrm{II}*} = 54$		
$k_{v,i,5}^{\mathrm{II}}$	$k_{v,i,30}^{\mathrm{IV}}$	$k_{v,i,10}^{\mathrm{III}}$	$k_{v,i,43}^{\mathrm{I}}$
	Conservative group III*, $n^{\mathrm{III}*} = 75$		
$k_{v,i,5}^{\mathrm{III}}$	$k_{v,i,30}^{\mathrm{IV}}$	$k_{v,i,10}^{\mathrm{III}}$	$\dfrac{k_{v,i,43}^{\mathrm{II}} \cdot 11 + k_{v,i,43}^{\mathrm{I}} \cdot 64}{n^{\mathrm{III}*}}$
	Conservative group IV*, $n^{\mathrm{IV}*} = 75$		
$k_{v,i,5}^{\mathrm{IV}}$	$k_{v,i,30}^{\mathrm{IV}}$	$k_{v,i,10}^{\mathrm{III}}$	$k_{v,i,43}^{\mathrm{II}}$

Having obtained $k_{v,i,j}^{\mathrm{I}^*} ... k_{v,i,j}^{\mathrm{IV}^*}$, the values of maximum LHR $q_{l,j,\max}$ for any conservative group, as well as the axial profiles of $k_{i,j}$ are found, where $k_{i,j} = \langle q_{l,i,j} \rangle / q_{l,j,\max}$ is the relative power coefficient for axial segment i and core cell j (Tables 5 and 6).

Table 5.
Values of $q_{l,j,\max}$ for groups I*…IV* of rearrangement 5-30-10-43

Group	N, %	$q_{l,j,\max}$, W/cm			
		j =5	j =30	j =10	j =43
I*	100 %	120.3	240.8	208.9	159.9
	80 %	97.73	193.6	169.7	127.9
II*	100 %	184.3	259.3	211.3	159.9
	80 %	147.5	209.6	172.8	127.9
III*	100 %	221.4	259.3	211.3	172.0
	80 %	176.0	209.6	172.8	137.8
IV*	100 %	249.7	259.3	211.3	174.1
	80 %	201.8	209.6	172.8	139.4

Table 6.
Axial profiles of $k_{i,j}$ for group IV* of rearrangement 5-30-10-43

N, %	i	$k_{i,j}$			
		j=5	j=30	j=10	j=43
100	1	0.555	0.619	0.610	0.626
	2	0.873	0.867	0.866	0.843
	3	0.966	0.944	0.952	0.925
	4	1.000	0.988	0.993	0.978
	5	0.999	1.000	1.000	1.000
	6	0.955	0.968	0.966	0.975
	7	0.840	0.853	0.864	0.845
	8	0.516	0.558	0.587	0.554
80	1	0.531	0.597	0.584	0.609
	2	0.848	0.845	0.840	0.830
	3	0.951	0.933	0.936	0.922
	4	0.996	0.987	0.988	0.981
	5	1.000	1.000	1.000	1.000
	6	0.954	0.940	0.959	0.928
	7	0.841	0.807	0.858	0.751
	8	0.522	0.558	0.594	0.546

Considering a four-year fuel campaign, the values of cladding damage parameter ω(1460 days) calculated at A_0=55 MJ/m^3 in the most stressed axial segment (6th), for conservative groups of rearrangement 5-30-10-43, are listed in Table 7.

Table 7.
$\omega(1460\text{ d})$ for rearrangement 5-30-10-43

Group	The number of fuel elements	$\omega(t)$, %	$\omega(t)$, % for one-group model
I*	108	2.154	3.342
II*	54	3.599	
III*	75	4.613	
IV*	75	5.889	

The calculated damage parameter for group IV* is 5.889 % and therefore it considerably exceeds the appropriate one-group value (3.342 %) obtained when considering an assembly-averaged fuel element. Implementing the described method, the distribution of fuel elements into conservative groups for all rearrangements included in algorithms A and B has been obtained, and corresponding values of cladding damage parameter have been determined.

2.5. The method of accounting for input parameter uncertainty

It is reasonable to define the method of cladding failure forecasting more exactly by means of considering the uncertainty of input parameters, when using the damage parameter calculation model. The main factors determining damage parameter $\omega(t)$ were found for a combined cycle of VVER-1000 variable loading by definition of the averaged relative difference $\delta A_{i,\pm}(t)$ between the specific dispersion energy $A_{i,\pm}(t)$ for the set of parameters $\{X_{1,0}, X_{2,0}, \ldots, X_{i,0} \pm \Delta X_i, \ldots, X_{k,0}\}$ and the specific dispersion energy $A_{\text{B}}(t)$ for the basic set $\{X_{1,0}, X_{2,0}, \ldots, X_{i,0}, \ldots, X_{k,0}\}$ (Pelykh and Maksimov, 2014):

$$\delta A_{i,\pm}(t) = \frac{\left|A_{i,+}(t) - A_{\text{B}}(t)\right| + \left|A_{i,-}(t) - A_{\text{B}}(t)\right|}{2 \cdot A_{\text{B}}(t) \cdot \Delta X_i}, \tag{11}$$

where t is time (eff. days); ΔX_i is deviation of the ith variable parameter, %.

Having calculated $\delta A_{i,\pm}(t = 5.48\text{ eff. years})$ for the central axial segment of a VVER-1000 core-averaged fuel element, the factors characterized by $\delta A_{i,\pm} > 2$ and thus determining $\omega(t)$ were found (Table 8).

Table 8.
Factors determining $\omega(t)$

No	Factor	Symbol	$\delta A_{i,\pm}$	The direction of influence
1	Fuel element maximum LHR	$q_{l,\max}$	18.7	$\omega(t)\uparrow$ when $q_{l,\max}\uparrow$
2	Core coolant inlet temperature	$T_{\rm in}$	5.6	$\omega(t)\uparrow$ when $T_{\rm in}\uparrow$
3	Cladding outer diameter	$d_{\rm clad}^{\rm out}$	4.19	$\omega(t)\downarrow$ when $d_{\rm clad}^{\rm out}\uparrow$
4	Fuel pellet diameter	$d_{\rm p}$	2.15	$\omega(t)\uparrow$ when $d_{\rm p}\uparrow$

As maximum LHR $q_{l,\max}$ is the chief factor determining $\omega(t)$, hence the value of $\omega(t)$ should be controlled first of all by optimizing fuel rearrangements (Pelykh, 2013).

Setting the uncertainty range for $q_{l,\max}$ as $\Delta q_{l,\max} = \pm 10\,\%$ (Pelykh et al., 2013), then having obtained the appropriate range of uncertainty for $\omega(t)$, using the three-sigma rule of the Gaussian distribution and the Bernoulli equation, the cladding failure probability can be predicted developing the technique proposed in (Pelykh et al., 2014):

1) For the *j*th rearrangement algorithm, the *m*th conservative group-averaged $\omega(t)$ is considered as a random variable $\omega_m^{\rm rand}$ distributed according to the normal law in the range $[\omega_m^{\min};\omega_m^{\max}]$, where $\omega_m^{\min} = <\omega_m^{\rm rand}> - \Delta\omega_m^{\rm rand}$; $\omega_m^{\max} = <\omega_m^{\rm rand}> + \Delta\omega_m^{\rm rand}$; $\Delta\omega_m^{\rm rand}$ is the uncertainty range for $\omega(t)$ when considering fuel elements included in group *m*.

2) Taking into account the three-sigma rule, the standard deviation $\sigma(\omega_m^{\rm rand})$ of the random variable $\omega_m^{\rm rand}$ is found for group *m*.

3) If $\omega_m^{\max} > \omega^{\lim}$, then the *m*th group-averaged cladding failure probability P_m, considering fuel assemblies operated during a four-year campaign, for each of six assemblies located in the core segment (see Fig. 1 and 4) is calculated using the well-known equation:

$$P_m = \int_{\omega^{\lim}}^{\omega_m^{\max}} \frac{\exp\left[-\dfrac{(\omega_m^{\rm rand} - <\omega_m^{\rm rand}>)^2}{2[\sigma(\omega_m^{\rm rand})]^2}\right]\cdot d\omega_m^{\rm rand}}{\sigma(\omega_m^{\rm rand})\sqrt{2\pi}}, \qquad (12)$$

where $\omega^{\lim} = 10\,\%$ according to the normative safety coefficient for $\omega(\tau)$.

For simplicity of presentation, let’s suppose for any fuel assembly that the condition $\omega^{\max} > \omega^{\lim}$ is satisfied for fuel elements included in group IV* only, so that such fuel elements will be only discussed in what follows and, therefore, the index “*m*” can be omitted.

4) Supposing that the reactor core consists of six identical segments, as well as that each core segment contains six fuel assemblies operated during a four-year campaign, the admissibility condition for any rearrangement algorithm is:

$$6 \cdot \sum_{i=1}^{6} n_{0,\,i} < n^{\lim}, \tag{13}$$

where $n_{0,\,i}$ is the predicted number of failed fuel elements within the *i*th fuel assembly, $i = \overline{1,6}$; $n^{\lim}$ is the limit total number of failed claddings according to the Nuclear Safety Regulations, $n^{\lim} = 508$ (SECNRS, 2008).

5) Aiming to determine $n_{0,\,i}$, the failure probability for k out of n_i fuel elements is found using the Bernoulli equation:

$$P_{n_i}(k) = \frac{n_i!}{(k)! \cdot (n_i - k)!} \cdot (P)^k \cdot (1 - P)^{n_i - k}. \tag{14}$$

Then the predicted number of failed fuel elements within the *i*th FA is found as

$$n_{0,\,i} = \sum_{k=1}^{n_i} P_{n_i}(k) \cdot k\,. \tag{15}$$

6) Taking into account Eq. (13)–(15), the necessary condition of rearrangement algorithm admissibility is derived:

$$\sum_{i=1}^{6} \sum_{k=1}^{n_i} \frac{n_i!}{(k)! \cdot (n_i - k)!} \cdot (P)^k \cdot (1 - P)^{n_i - k} \cdot k < \frac{n^{\lim}}{6}\,. \tag{16}$$

7) If several rearrangement algorithms satisfy Eq. (16), in order to minimize the probability of cladding failure due to accumulation of damage parameter, the best algorithm is chosen by using the criterion:

$$\begin{cases} \min\left[\sum_{i=1}^{6}\sum_{k=1}^{n_i}\frac{n_i!}{(k)!\cdot(n_i-k)!}\cdot(P)^k\cdot(1-P)^{n_i-k}\cdot k\right], \\ P = \int_{\omega^{\lim}}^{\omega^{\max}} \frac{\exp\left[-\frac{(\omega-<\omega>)^2}{2[\sigma(\omega)]^2}\right]\cdot d\omega}{\sigma(\omega)\sqrt{2\pi}}. \end{cases} \quad (17)$$

Aiming to simplify the method description, the model input parameter uncertainty will not be taken into account hereafter. While the influence of the uncertainty range $\Delta q_{l,\max} = \pm 10\ \%$ for fuel element maximum LHR $q_{l,\max}$ on the value of cladding damage parameter was studied in (Pelykh et al, 2013), the impact of this uncertainty on the number of failed fuel elements can be taken into account using the technique proposed in this paragraph.

3. Results and discussion

Having calculated cladding damage parameter $\omega(t)$ in axial segment 6 for all 14 rearrangements, the obtained spread of $\omega(t)$ for algorithms A and B was:

— one-group model, [2.2…4.82 %] and [2.25…3,74 %], respectively;

— four-group model, [0.72…10,8 %] and [0,75…6,16 %], respectively.

Hence, when using the four-group model, the maximum cladding damage parameter $\omega^{\max}$ for algorithms A and B, in comparison with the one-group model, has increased 2.2 and 1.6 times, respectively.

For example, the values of $\omega(1460\,\mathrm{d})$ calculated for fuel element conservative groups of rearrangements 3-22-54-29 and 13-19-21-42 (algorithm A) are given in Tables 9 and 10, respectively.

The dependences of damage parameter on time for conservative groups of rearrangements 3-22-54-29 and 13-19-21-42 are shown in Fig. 6 and 7, respectively.

Table 9.
$\omega(1460\text{ d})$ for rearrangement 3-22-54-29

Group	The number of fuel elements	$\omega(t)$, %	$\omega(t)$, % for one-group model
I*	67	4.147	3.351
II*	28	5.785	
III*	45	6.812	
IV*	172	10.8	

Table 10.
$\omega(1460\text{ d})$ for rearrangement 13-19-21-42

Group	The number of fuel elements	$\omega(t)$, %	$\omega(t)$, % for one-group model
I*	8	1.397	4.822
II*	39	4.013	
III*	55	4.713	
IV*	210	7.75	

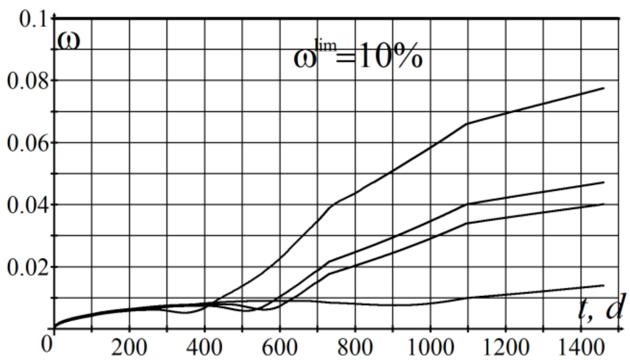

Fig. 7. Dependence of damage parameter on time for rearrangement 13-19-21-42 (four conservative groups)

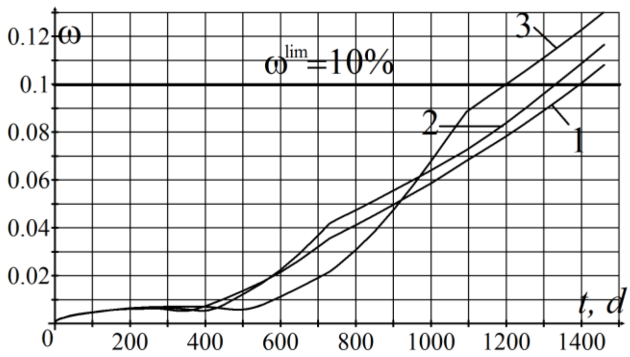

Fig. 8. Influence of load history on $\omega(\tau)$ for rearrangements 3-22-54-29 (1), 22-3-29-54 (2), 54-22-3-29 (3); Group IV*

It can be seen, that for rearrangement 3-22-54-29:

$$\omega^{\max} > \omega^{\lim}, \tag{18}$$

where $\omega^{\lim} = 10\,\%$ based on the normative safety coefficient $K_{SC4} = 10$ (NEA, 2012).

At the same time, for rearrangement 13-19-21-42:

$$\omega^{\max} < \omega^{\lim}. \tag{19}$$

In the case of algorithm A, the number of fuel elements included in conservative group IV* for

rearrangement 3-22-54-29 is 172 (see Table 9). As condition (18) is satisfied for all other rearrangements included in algorithm A, then, for the specified core segment (1/6 core), the predicted number of failed claddings is 172. Provided that the core consists of six identical segments, the predicted total number of failed claddings $n_{0,\Sigma}$ is

$$n_{0,\Sigma} = 1032\,. \tag{20}$$

But the permissibility condition for any rearrangement algorithm is:

$$n_{0,\Sigma} < n^{\mathrm{lim}}\,, \tag{21}$$

where $n^{\mathrm{lim}} = 508$ (SECNRS, 2008).

It can be seen that the necessary condition defined by Eq. (21) is not satisfied for algorithm A, hence algorithm A is not permissible.

As to algorithm B, it was found that the safety condition defined by Eq. (18) is satisfied for all rearrangements of this alternative algorithm, then Eq. (21) is satisfied also, hence algorithm B is permissible.

3.1. Influence of fuel loading history

One of the main sources of the SC4 criterion uncertainty is neglect of the real fuel loading history which is the exact sequence of sets of fuel assembly operating parameters influencing cladding damage parameter $\omega(t)$ (Pelykh, 2013). To illustrate this statement, a comparison of $\omega(t)$ for fuel elements included in conservative group IV*, for rearrangements 3-22-54-29, 22-3-29-54 and 54-22-3-29 having the same set of coefficients $k_{v,i,j}^{\mathrm{IV*}}$ for the same 4-year interval, while the fuel assembly loading history varies, has been made. The loading history, that is the sequence of core cells assigned to a fuel assembly, influences considerably on $\omega(t)$: $\omega(1460\,\mathrm{d})$ for rearrangements 3-22-54-29, 22-3-29-54 and 54-22-3-29 was 10.8, 11.7 and 13 %, respectively (Fig. 8).

3.2. The limiting role of cladding damage parameter

When designing a VVER nuclear fuel and making its safety validation, the normative strength criteria SC1 limiting circumferential stresses $\sigma_\theta(t)$ and SC2 limiting equivalent stresses $\sigma_e(t)$ are supposed to play a much more significant role in comparison with the SC4 criterion limiting the value of cladding damage parameter (Novikov et al., 2005).

In order to check this thesis, the change of $\sigma_\theta(t)$ and $\sigma_e(t)$ for fuel elements included in conservative group IV* was calculated, considering the following three rearrangements characterized by maximum values of $\omega(t)$: 3-22-54-29, 13-19-21-42 and 9-11-20-1 (algorithm A)

Denoting the yield strength of the cladding material (Zircaloy-4) by $\sigma_0(t)$, it was obtained that the ratio $\sigma_e/\sigma_0(t)$ for rearrangements 3-22-54-29 and 13-19-21-42 does not exceed 48 and 38 %, respectively (Fig. 9 and 10).

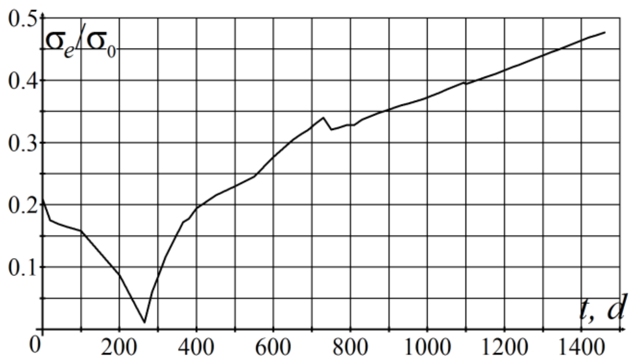

Fig. 9. Dependence $\sigma_e/\sigma_0(t)$ on time for rearrangement 3-22-54-29

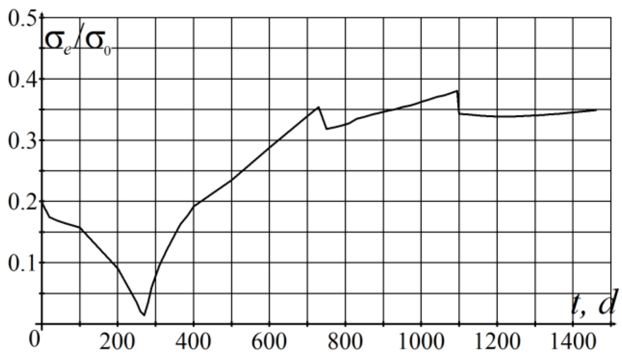

Fig. 10. Dependence $\sigma_e/\sigma_0(t)$ on time for rearrangement 13-19-21-42

For fuel elements included in group IV*, the ratio $\sigma_\theta(t)/250\,\mathrm{MPa}$ for rearrangements 3-22-54-29 and 13-19-21-42 does not exceed 15 and 10 %, respectively (Fig. 11 and 12).

As to rearrangement 9-11-20-1, the values of $\sigma_e/\sigma_0(t)$ and $\sigma_\theta(t)/250\,\mathrm{MPa}$ do not exceed the level of 41 and 11 %, respectively.

Based on the normative strength criteria SC1 and SC2 (Alexeyev, 2008), the limiting values for $\sigma_\theta(t)$ and $\sigma_e(t)$ are established as

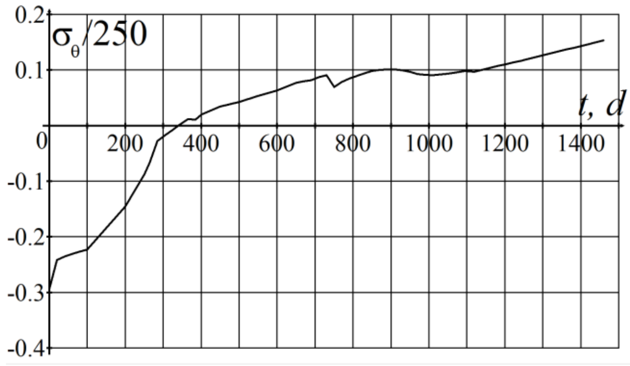

Fig. 11. Dependence $\sigma_\theta(t)/250\,\mathrm{MPa}$ on time for rearrangement 3-22-54-29

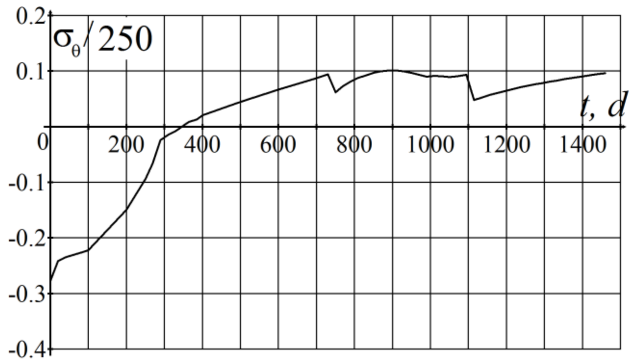

Fig. 12. Dependence $\sigma_\theta(t)/250\,\mathrm{MPa}$ on time for rearrangement 13-19-21-42

$$\sigma_\theta^{\lim}(t) = \frac{250\,\mathrm{MPa}}{K_{\mathrm{SC1}}} = 83\%\ \text{of}\ 250\,\mathrm{MPa};\ \sigma_e^{\lim}(t) = \frac{\sigma_0(t)}{K_{\mathrm{SC2}}} = \sigma_0(t)\,, \tag{22}$$

where $K_{\mathrm{SC1}} = 1.2$ and $K_{\mathrm{SC2}} = 1$ are the safety factor for SC1 and SC2, accordingly.

So, considering the most unfavorable case of fuel elements belonging to conservative group IV*, for rearrangement 3-22-54-29 the safety limit for cladding damage parameter $\omega^{\lim} = 10\,\%$ is exceeded, while the limits for $\sigma_\theta(t)$ and $\sigma_e(t)$ are not reached (Fig. 6, 9 and 11). This new result following from the concept of conservative groups, contradicts the widespread idea (Novikov et al., 2005) that, in comparison with circumferential and equivalent stresses, damage parameter plays a minor role when estimating the cladding durability.

4. Conclusions

The presented methodology is intended to estimate the failure probability due to cladding deformation damage including the damage originated from pellet to cladding interaction. There are plenty of well-known and widely used methods for elimination of fuel element cladding failures due to grid/rod fretting, debris fretting, manufacturing flaws, etc. in VVERs, and there is still a great uncertainty in knowing the true cause of cladding failure, while the generally accepted goal of achieving a zero failure rate requires detailed knowledge of existing failure mechanisms, their root causes and remedies. The presented method has been developed for predicting and limiting cladding

failures due to damage parameter increase only, and, contrary to popular opinion, it has been made clear that damage parameter plays a significant role when predicting cladding failures.

When using a cladding failure criterion for control of the cladding hermeticity, meeting the requirement that limiting components in the criterion must be independent of the fuel loading history is a significant problem. Therefore, taking into account the variability of limiting components in the SC4 criterion which is an intrinsic shortcoming of the approach based on SC4, the CET-method has been developed. Based on the CET-method, taking into account for each fuel assembly its loading history and the distribution of cladding damage parameter $\omega(t)$ among the fuel elements included in this assembly, a new method for forecasting of cladding failure due to increase of $\omega(t)$ has been developed.

Using the model of four conservative fuel element groups and considering algorithms A and B, the maximum value of $\omega(t)$ for testing fuel assembly rearrangement algorithms A and B, in comparison with the one-group model, increased 2.2 and 1.6 times, respectively. Considering the most unfavorable case of fuel elements belonging to conservative group IV*, the safety limit for cladding damage parameter $\omega^{\lim} = 10\,\%$ was exceeded for rearrangement 3-22-54-29 included in algorithm A, though the limits for circumferential stress $\sigma_\theta(t)$ and equivalent stress $\sigma_e(t)$ were not reached. This new result following from the concept of conservative groups, contradicts the commonly accepted interpretation that damage parameter, in comparison with circumferential and equivalent stresses, plays a minor role when estimating the limiting state of cladding.

The necessary condition of rearrangement algorithm admissibility and the criterion for minimization of the probability of cladding failure due to accumulation of cladding damage, permitting to select optimal algorithms, have been derived.

Provided that the core consists of six identical segments, in the case of algorithm A, the predicted total number of failed claddings is 1032, so the safety limit is exceeded twice and the condition of permissibility is not satisfied. On the contrary, the necessary condition is satisfied for all rearrangements of algorithm B, hence algorithm B is permissible.

There are still a number of shortcomings in the proposed theory. For example, though the normative safety coefficient such as 10 on the failure criterion is built in the method, and consequently the limit value of cladding damage parameter ω^{lim} is supposed to be 10 %, there is no clear understanding on the kind of cladding failure this ω^{lim} corresponds to (e.g. is it a gas leak or a direct fuel-coolant contact ?).

It should be expected that if we use a multigroup model with a higher number of fuel element groups (e.g., 10 instead of 4), then the maximum cladding damage parameter for algorithms A and B, in comparison with the one-group model, will increase greater than for the studied case of 4 groups. As this will increase the predicted number of failed fuel elements, a special optimization procedure should be implemented when choosing the number of fuel element groups in the fuel assembly.

It should be noted that while this is a "bulk" model, anisotropy of the cladding for temperature and stress due to stochastic phenomena, e.g. "hard contact" of the fuel, power excursions, etc., can not only cause failures, but significantly change the local microstructure of the cladding leading to a shortened lifetime.

Nevertheless, for different sets of fuel design and operating parameters, the proposed method allows to make comparisons on the basis of the predicted number of failures due to cladding damage accumulation.

It should be underlined that, though the proposed method for limiting cladding failures due to damage accumulation means that the known methods for preventing failure due to stress corrosion cracking (SCC) will be used also, .the dependence of cladding creep strain rate on corrosion rate is taken into account in the calculation model (Suzuki, 2010), and the influence of corrosion rate on cladding damage parameter was studied in (Pelykh and Maksimov, 2011).

In order the model could take into account the influence of corrosion on cladding damage parameter correctly, the exact data on cladding corrosion rate for the exact VVER fuel design and for the exact operation mode must necessarily be used, as the contribution of oxide thinning

accelerates significantly cladding failure. This problem could be solved by taking into account an exact cycle of coolant composition regulation and considering some limit and intermediate states of the coolant.

The developed approach to limiting of VVER fuel element cladding failures based on the CET-method is universal, as it allows us to make optimization of fuel design and operation parameters simultaneously with optimization of reactor parameters (Pelykh et al., 2014). The value of this analytical approach consists of its eligibility for different core materials and designs. This universality could be useful aiming to decrease the VVER fuel design cost and to increase the fuel operation safety. Practically the prediction of cladding failure is made on the basis of an adopted limit damage parameter $\omega^{\lim}$, as well as knowing the limit value A_0 for specific dispersion energy which is constant for a given material, and A_0 can be uniquely determined from Eq. (7) using a verified calculation tool or from experiment.

In this paper we used the model that represents a fuel element cladding made of Zircaloy-4, while all other design and operation parameters (fuel element, fuel assembly and core parameters) were adopted as those for VVER-1000. As fuel element claddings in VVER-1000 are really made of the E-110 alloy, in industrial implementations we should use a verified code developed for VVER-1000 fuel behaviour analysis instead of the FEMAXI code.

This new theory developed for prediction of cladding failures due to cladding damage accumulation needs to be verified by means of application to a real case in which cladding failures and power cycles are known, for the purpose of using it in automated systems controlling the tightness of claddings in VVERs.

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Figure captions

Fig. 1. Core segment: (numeral) cell number. The 10th regulating group cells and the segment are in bold

Fig. 2. Dependence of the core power on time

Fig. 3. Dependence of the control element edge coordinate on time

Fig. 4. Distribution of fuel assemblies in core cells by campaign year: (Arabic numeral) cell number; (Roman numeral) year

Fig. 5. Distribution of fuel elements among conservative groups for rearrangement 5-30-10-43

Fig. 6. Dependence of damage parameter on time for rearrangement 3-22-54-29 (four conservative groups)

Fig. 7. Dependence of damage parameter on time for rearrangement 13-19-21-42 (four conservative groups)

Fig. 8. Influence of load history on $\omega(\tau)$ for rearrangements 3-22-54-29 (1), 22-3-29-54 (2), 54-22-3-29 (3); Group IV*

Fig. 9. Dependence $\sigma_e / \sigma_0(t)$ on time for rearrangement 3-22-54-29

Fig. 10. Dependence $\sigma_e / \sigma_0(t)$ on time for rearrangement 13-19-21-42

Fig. 11. Dependence $\sigma_\theta(t) / 250\,\mathrm{MPa}$ on time for rearrangement 3-22-54-29

Fig. 12. Dependence $\sigma_{\theta}(t)/250\,\mathrm{MPa}$ on time for rearrangement 13-19-21-42