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Calculational basis for WWER fuel rods safety

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ABSTRACT

The topic of this paper is calculation results of thermal-physical characteristics and safety of WWER fuel elements. We consider high heat power, which amounts up to 320 W/sm and average burnup in the interval of 40-60 MW.day/kg. The calculations have been carried out in the framework of "PULSAR-2" program. The results of the program have been proved by experimental data for different parameters of WWER rods. These experimental data have been obtained at "LOVIISA-2" and Novovoronezh NPP. For the conditions of high burnup under peak mode of NPP operation we have fuel rods safety analysis. Power limits for these peaks have been also obtained.

1. INTRODUCTION.

The experience of WWER-440 and WWER-1000 reactors operation has indicated that the fuel elements of these reactors are very reliable. The leakiness of the fuel elements doesn't exceed 0,01-0,02 %, if design-operation parameters [1] are as follows:

WWER-440 - maximum thermal load on a fuel element Q_l^{max}= 325 W/sm; maximum fuel burnup B^{max} = 40 MWday/kg;

WWER-1000 - Q_l^{max}=490 W/sm; B^{max}= 59 MW day/kg. To study the potential of WWER fuel elements, the latter have been tested in the materials technology reactor (MR) to burnup B^{max} = 108 MWday/kg and under thermal loads up to 560 and 670 W/sm [2]. Positive results of operation and experimental studies prove that WWER fuel elements have considerable reserve of reliability, which can be used, for example, for fuel lifetime extension. The latter has become a reason for experimental-industrial operation of a WWER-440 fuel assembly with extended lifetime - 4 and 5 years. 78 fuel assemblies have been tested successfully at Kola NPP Unit 3. The results are as follows: maximum power production B_{max}=58,1 MWday/kg (for assemblie N66) and B^{max} = 62,6 MWday/kg (for assemblie N12) at maximal thermal load on a fuel element during the lifetime Q_l^{max} = 192 W/sm [3, 4].

Calculated studies of thermal and strength characteristics of fuel elements, performed with the use of applicable computer codes, occupy an important place in verification of fuel element reliability in different conditions. For thermal-physical calculations of fuel elements such codes as RET(TR), PIN-micro (PIN-04M), PIN-mode [5] are currently used in Russia. Complex calculated analysis of thermal-physical, strength and reliability characteristics is performed by the *PULSAR-2* code [6,7]. Computer codes may be used for verification of fuel element reliability in perspective or updated fuel cycles provided the results of verification on the basis of postreactor studies of license fuel elements, having passed experimental operation, are positive. This report gives examples of verification of the *PULSAR-2* code and the results of calculated analysis of operational reliability of the fuel elements, operating in the peak modes.

2. VERIFICATION OF THE CODE

Verification of computer programs is based on correlation of calculated and experimental data on fuel element parameters, characteristic of particular loading history and which can be checked due to in- and post-reactor studies of fuel elements.

Among these parameters are: fuel element elongation, cladding diameter change along the length of a fuel element, gas pressure under the cladding, gas emission from fuel and a number of other physical and material characteristics. These parameters represent a part of output calculated data, given by the computer code *PULSAR-2* as a result of self-coordinated solution of thermal-physical and strength problems as applied to a fuel element.

The computer code has passed multiple testing on the basis of the results of post-reactor studies of WWER and RBMK fuel elements, having been in steady-state and transient operation conditions. Below are presented examples of the code verification on the basis of the results of research of the license WWER-440 fuel elements irradiated in LOVIISA-2 RPV. It should be noted that the code verification was performed under conditions of a "blind" experiment, that is thermal and strength parameters of the fuel elements were calculated by given power history, after that the results of the calculation were compared with corresponding data of post-reactor research of the irradiated fuel elements. Table 1 presents main initial parameters of the fuel elements and also the results of calculations and post-reactor measurements performed on the fuel elements.

TABLE 1. PULLSAR-2 CODE VERIFICATION RESULTS (WWER-440, LOVIISA-2).

assembly	fuel elem.	Q_l^{max},	mean burn up,	clad diametr change,mkm		rod elongation, mm	
number	numer	W/sm	MWday/kg	exper	calc.	exper	calc.
37	001	262	48,7	-46,1	-43,9	8	9
	007	264	49,0	-48,0	-43,7	8	9
	069	260	48,7	-54,0	-43,5	8	9
38	001	202	45,9	-51,0	-44,5	8	8
	007	230	45,7	-47,5	-42,9	8	8
	069	229	46,1	-55,0	-46,0	9	9

Figures 1 and 2 give calculated and experimental distributions of fuel element cladding diameter changes (fuel elements N7 of fuel assemblies N37 and N38).

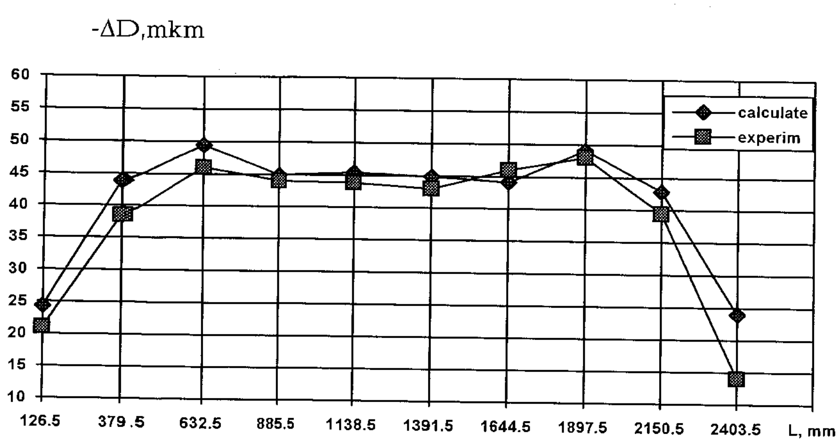

Fig. 1. Calculated and experimental residual change of diameter of the fuel element 007 of the fuel assembly N 37.

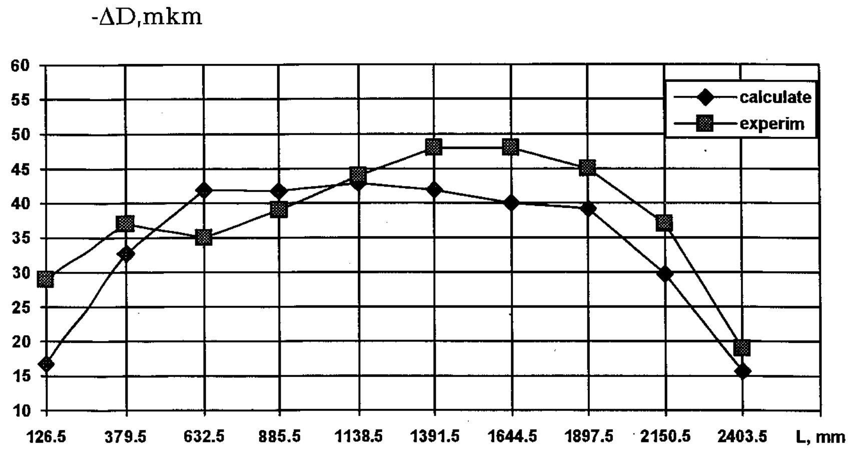

Fig.2. Calculated and experimental residual change of diameter of the fuel element 007 of the fuel assembly N 38.

Experimental operation of the fuel assemblies with 6 license fuel elements has been conducted at Novovoronezh NPP Unit-5 (WWER-1000). Main initial, calculated and experimental data for each fuel element of the fuel assembly are presented in Table 2.

Table 2. PULSAR-2 CODE VERIFICATION RESULTS (WWER-1000, NVNPP).

element	Q_l^{max},	<B>,	ΔD^{max},mkm		ΔL, mm		FGR, %	
number	W/sm	MWday/kg	exper	calc.	exper	calc.	exper	calc.
177	216	45,2	-65,0	-65,1	15	18	1,0	0,7
195	208	44,4	-69,0	-65,1	16	17	0,6	0,7
211	118	44,0	-68,0	-64,5	17	17	1,1	0,8
242	232	43,4	-58,2	-64,6	13	15	1,0	0,8
271	267	43,6	-69,0	-66,4	14	16	1,5	1,2
284	290	44,8	-68,5	-68,8	14	17	1,8	1,3

Figures 3 and 4 demonstrate the history of variation of mean thermal load Q_l(W/sm) on the fuel element N177 and cladding diameter change distribution along the length of the fuel element.

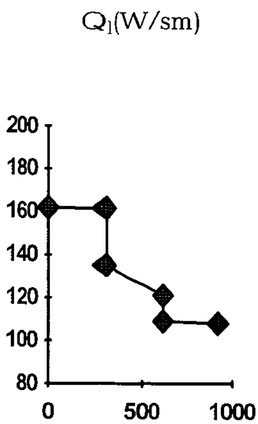

Fig.3.

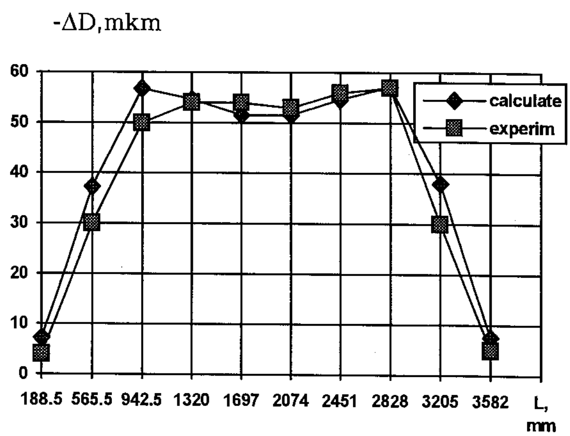

Fig.4

3. CALCULATED ANALYSIS OF WWER-440 FUEL ELEMENT OPERATIONAL RELIABILITY AT INCREASED BURNUP.

As an object for calculation the WWER-440 fuel element is taken, which must be in operation for 5 fuel cycles (1743 effective days) to burnup B_{max}=65 MWday/kg (mean fuel burn-up through the fuel element is equal to 55,45 MWday/kg) at maximum thermal load Q_l^{max} = 245 W/sm. The history of mean thermal load Q_l on the fuel element in conditions of steady-state operation is given in Fig. 5. Operational reliability of the fuel element is studied not only in conditions of steady-state operation, but in peak conditions as well, when peak power increase takes place in different instants of the fuel element lifetime, for example, at fuel burnup B_{max} = 30, 35, 50, 60 and 65 MWday/kg. Moreover, the problem of extreme character is raised - to determine maximum-permissible thermal loads Q_{lim} during peak power increase, lasting approximately 15 days, on condition that in the course of subsequent normal operation the leak-proofness would be provided only till the end of the lifetime without any strength margin. From the above purposes of the calculated analysis, as a conservative variant combinations of geometric and technological parameters have been taken, which may be considered the worst within permissible limits, a priori leading to decrease of fuel element operational reliability, in particular, minimum diameter gap between fuel pellets and cladding Δ_{min}=0,13 mm; maximum initial density

UO_2: ρ_0^{max} = 10,86 g/sm^3; initial depth of a microcrack in cladding a_0 = 50 mkm [1].

Fuel element operational reliability is evaluated by a number of thermal-physical and strength criteria, for example, such as: fuel melting point margin, short-time strength of cladding under corrosion cracking, long-time plasticity (vulnerability to damage) margin of cladding, cracking resistance of cladding in conditions of stress corrosion etc. Within the framework of this report only one criterion is considered - corrosion cracking under stress, which is described by the following equation [1]:

$$\frac{da}{d\tau} = A_0 \exp(-E^*/RT)\exp(B_0 K_I/T), \qquad (1)$$

where: a - crack depth, ; τ - time; E^* - corrosion activation energy; R - universal gas constant; T - temperature; K_I - crack intensity coefficient; A_0, B_0 - material constants.

Evaluation of fuel element operational reliability for given history of loading is conducted according to the following simplified scheme (direct solution of the problem): initial data - calculation of kinetics of the variation of thermal-physical characteristics and stress and strain state (SSS) of a fuel element during the life time - calculation of cracking resistance of cladding. In our case (Q_{lim} determination) the reverse problem must be solved - on the basis of limiting prerequisites on cracking resistance of cladding the permissible history of loading should be determined. It is obvious that this problem could not be solved directly. Therefore, iteration method of Q_{lim} selection is used for its realization. At every step of iteration the direct problem is solved: initial data - SSS calculation - calculation of corrosion cracking of cladding. Table 3 presents main calculated results, obtained to substantiate WWER-440 fuel element operational reliability in steady-state and peak conditions of operation.

Table 3. Calculation Results.

Calculated characteristics of fuel element	calcul. modes of reactor operation					
	St	P1	P2	P3	P4	P5
1.Thermal load on fuel						
Q_l^{max}, W/sm	245	245	245	245	245	245
Q_{lim}, W/sm	-	360	303	216	207	97
2. Gas pressure, Mpa	1,9	2,0	2,0	2,0	2,0	2,0

3.Fission gas release, %	1,81	1,83	1,81	1,80	1,82	1,82
4. Max. change in clad diameter, mkm	-30,1	-39,5	-31,6	-30,2	-29,8	-30,2
5. Residual elongation of a fuel element, mm	9,3	10,2	9,6	9,3	9,3	9,5
6. Corrosion crack depth, mkm	67,0	90,3	112,4	86,0	80,0	through crack

Notes: St - steady-state operation;

P1, P2, ...P5 - peak conditions, at which power peak is realized at burn-ups of 30, 35, 50, 60 and 65 MWday/kg accordingly.

Fig. 5 presents history of fuel element load Q_l (W/sm).

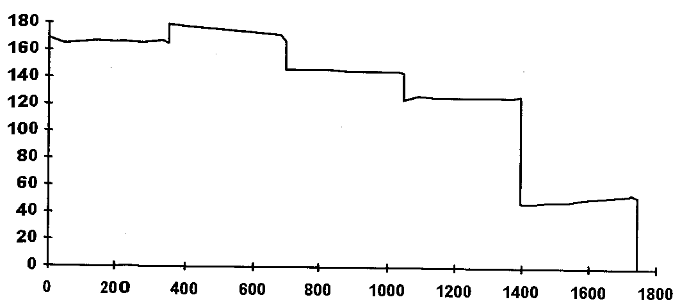

Fig. 5. History of mean thermal load Q_l of WWER-440 fuel element in steady-state reactor operation.

In the course of calculation of SSS of the fuel elements with extended lifetime it was noted that at deep burnup (>40 MWday/kg) "bamboo effect", as it is called, appear on the cladding. This is circumferential ridges, the height of which reaches 45 mkm by the end of the fuel element lifetime. For correct calculation of SSS in local areas of the fuel element the program, realizing the procedure of local interaction of fuel with cladding in two-dimensional statement, has been used as an element of PULSAR-2 code.

At fuel burn-ups close to 65 MWday/kg activation of RIM-effect takes place, leading to additional gas release. However the contribution of RIM-effect to overall gas release in a fuel element is insignificant - up to 2 %

(the maximum thickness of RIM-layer on pellets reaches 45 mkm at the maximum burn-up on the pellet surface of 83 Mwday/kg).

CONCLUSION.

On the basis of the data presented it can be closed that the computer code PULSAR-2 has got high verification properties as regards simulation of WWER-440 and WWER-1000 fuel element behavior in reactor conditions. Calculated analysis of operational reliability of WWER-440 fuel elements with extended lifetime (up to 65 MWday/kg) has determined the reserves of reliability of these fuel elements in peak conditions of NPP operation.

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