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USE OF LOW NEUTRON LEAKAGE FUEL LOADS TO DECREASE THE RADIATION LOAD ON A VVÉR-1000 VESSEL

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It is shown on the basis of data obtained at Ukrainian nuclear power plants that fuel loads with low neutron leakage can be used effectively to decrease the radiation load on the reactor vessel.

The characteristics of 104 fuel loads and the results of a determination of the radiation load on the vessel are analyzed to develop a criterion according to which a VVÉR-1000 fuel load can be classified as a load with low neutron leakage. It is shown that the following condition can be chosen as such a criterion: the run-averaged relative power release in all protruding fuel assemblies must be less than 0.57.

Different variants of the arrangement of the VVÉR-1000 core are examined and analyzed. It is shown that placing burned-out fuel assemblies along the periphery of the core and decreasing the number of neutrons leaving the core do not always result in a lower neutron load on the reactor vessel.

The control of the operational lifetime of a nuclear power plant should include a system of measures for decreasing the influence of factors which damage the equipment in a power-generating unit that is technically impossible or not cost-effective to replace. The reactor vessel is one such piece of equipment. One of the harmful factors that influence its operability is the neutron radiation. The irradiation of the vessel depends, mainly, on the arrangement of the fuel assemblies in the reactor. Therefore, the operation of fuel loads which give the lowest possible neutron flux from the core is an important measure that decreases the damaging effect of neutron radiation on the vessel. It is obvious that such an effect can be attained by placing along the periphery of the core the fuel assemblies whose fuel has burned out.

The idea of using fuel loads with fresh fuel at the center of the core and burned-out fuel at the periphery to decrease neutron leakage arose almost simultaneously with the first power reactors [1]. The main goal of such an arrangement of the core was initially considered to be to increase as much as possible the duration of a fuel run and/or the burnup of the spent nuclear fuel. Subsequently, the fuel loads charcterized by the presence of burned-out fuel along the periphery of the reactor core were used to weaken the damaging effect of the neutron radiation on the vessel. We note at the outset that the present work is devoted to decreasing the radiation load on the VVÉR-1000 vessel; economic questions concerning fuel use are not examined here.

For many reactor designs, such VVÉR-440, it is technically not difficult to place fuel asemblies with deeply burned up fuel into almost all peripheral cells. However, in VVÉR-1000 it is impossible to combine an acceptable load with peripheral cells which are completely filled with burned-up fuel. The main difficulty is due to the relatively large transverse cross section of a fuel assembly and, as a consequence, the small number of degrees of freedom in placing assemblies in cells, the high nonuniformity of the energy distribution, and other factors. Of 42 peripheral cells, ordinarily, no more than 24 and usu-

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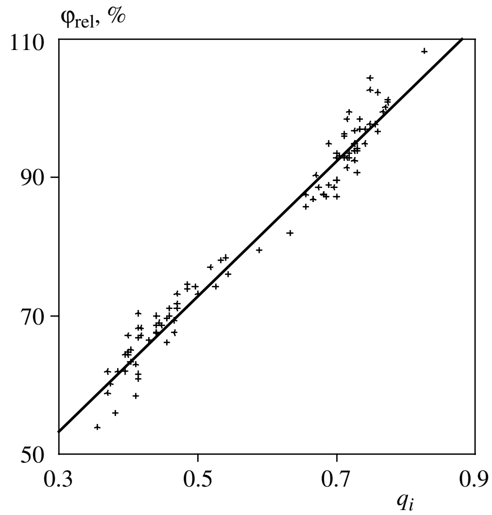

Fig. 1. The relative maximum flux density of neutrons with $E_n > 0.5$ MeV on the inner surface of a reactor vessel versus the run-averaged relative energy release of the protruding fuel assembly for 104 fuel loads of a nuclear power plant in Ukraine.

ally only 12–18 are filled with burned-out fuel assemblies. In addition, formally, any fuel assembly with nonzero burnup in the reactor can be considered as being burned up. These facts make it necessary to search for answers to the questions of the degree to which an assembly must be burned up so that when it is placed in a peripheral cell the neutron leakage would decrease, which peripheral cells should be used for burned-up fuel assemblies, and does decreasing the number of leakage neutrons always permit attaining both goals with which a decrease of the leakage is associated, i.e., an increase in the cost-effectiveness of fuel utilization and a decrease of the radiation load on the vessel.

It should be noted that the relation between placing fuel assemblies with burned up fuel into peripheral cells, decreasing the number of neutrons which irreversibly escape from the core, and decreasing the radiation load on the reactor vessel is not unique. Although from general considerations a low-leakage load can be taken as any load where the number of neutrons absorbed outside the reactor core is lower by any amount, however small, it is more accurate to take such a load as one that permits achieving only two of the goals mentioned above.

Criteria for Classifying a Fuel Load as a Load with Low Neutron Leakage. A comprehensive analysis of the characteristics of 104 VVÉR-1000 fuel loads for the power-generating units of nuclear power plants in Ukraine and of the results of a determination of the radiation load on the vessel was made to work out these criteria.

It is obvious that the run-averaged maximum total flux density of neutrons with energy $E_n > 0.5$ MeV on the inner surface of the reactor vessel can be used as an estimate of the effectiveness of the measures taken to decrease the radiation load. For clarity, it is best to use in the analysis the ratio φ_{rel} of the indicated flux density to the design density. According to the design documentation, the maximum admissible neutron fluence on VVÉR-1000 at any point on the inner surface of the vessel $5.7 \cdot 10^{19}$ cm^{-2} must be chosen over 40 fuel runs each with duration 7000 eff. h. Then, the design neutron flux density on the vessel is $5.65 \cdot 10^{10}$ sec$^{-1}\cdot$cm^{-2} [2].

Analysis showed that the run-averaged relative energy release of a protruding fuel assembly, located opposite the zone of maximum neutron flux density on the vessel q_i, can be taken as the quantity characterizing the fuel load from the standpoint of the effect of the irradiation of the vessel. Figure 1 shows that the fuel loads which were analyzed fall into two large groups: 1) $\varphi_{rel} \sim 100\%$, $q_i \sim 0.7$–0.8, 2) $\varphi_{rel} \sim 70\%$, $q_i \sim 0.4$–0.5. This gives a basis for calling fuel loads in the first group ordinary and fuel loads in the second group loads with low leakage and the inequality $q_i < 0.57$ can be used as a criterion for the latter loads. The maximum relative neutron flux density for low-leakage loads is 80%.

18	19
4.23	4.40
2.00	1.00
1.13	0.88
1.13	0.97

14	15	16	17
4.40	4.23	4.23	4.40
2.00	3.00	1.00	1.00
1.14	0.92	1.23	0.82
1.08	0.92	1.24	0.93

8	9	10	11	12	**13**
4.40	4.40	4.40	4.40	4.23	**4.40**
2.00	3.00	3.00	2.00	2.00	**1.00**
1.16	0.94	0.98	1.24	1.04	**0.63**
1.09	0.90	0.93	1.15	1.06	**0.75**

1	2	3	4	5	6	7
1.60	4.40	4.40	4.40	4.40	4.40	4.23
1.00	3.00	3.00	2.00	2.00	3.00	1.00
0.68	0.96	0.99	1.11	1.26	1.05	0.93
0.80	0.95	0.95	1.02	1.13	1.01	1.02

a

18	**19**
4.40	**4.23**
2.00	**3.00**
1.06	**0.48**
1.07	**0.57**

14	15	16	17
4.40	4.23	4.23	4.40
3.00	3.00	1.00	1.00
1.03	1.15	1.16	0.76
1.00	1.10	1.18	0.85

8	9	10	11	12	**13**
4.40	4.40	4.23	4.40	4.40	**4.40**
2.00	3.00	1.00	3.00	2.00	**1.00**
1.01	0.95	1.28	1.13	1.24	**0.67**
1.05	0.94	1.21	1.06	1.18	**0.76**

1	2	3	4	5	6	7
1.60	4.23	4.23	4.40	4.40	4.40	4.23
2.00	3.00	2.00	2.00	2.00	2.00	1.00
0.44	0.70	1.04	1.20	2.08	1.30	1.06
0.62	0.83	1.05	1.10	2.01	1.18	1.07

b

18	19
4.40	4.40
3.00	1.00
0.97	0.84
1.00	0.93

14	15	16	17
4.23	4.40	4.23	4.40
3.00	3.00	1.00	1.00
0.90	1.04	1.22	0.84
0.90	1.02	1.23	0.91

8	9	10	11	12	**13**
4.40	4.40	4.23	4.23	4.40	**4.40**
2.00	3.00	1.00	2.00	2.00	**2.00**
1.09	0.96	1.24	1.14	1.15	**0.64**
1.05	0.93	1.19	1.09	1.12	**0.70**

1	2	3	4	5	6	7
1.60	4.23	4.23	4.40	4.23	4.40	4.23
2.00	3.00	2.00	2.00	3.00	3.00	1.00
0.51	0.78	1.11	1.19	0.96	0.98	0.96
0.62	0.83	1.04	1.08	0.93	0.97	1.01

c

18	19
4.40	4.40
3.00	1.00
1.09	0.90
1.06	0.95

14	15	16	17
4.40	4.40	4.40	4.40
4.00	3.00	2.00	1.00
0.93	1.15	1.28	0.81
0.94	1.10	1.21	0.87

8	9	10	11	12	**13**
4.23	4.40	4.23	4.23	4.40	**4.23**
2.00	4.00	1.00	3.00	2.00	**4.00**
1.08	0.88	1.30	1.10	1.14	**0.33**
1.08	0.90	1.27	1.06	1.12	**0.40**

1	2	3	4	5	6	7
1.60	4.40	4.23	4.23	4.23	4.23	4.40
2.00	3.00	2.00	2.00	3.00	1.00	4.00
0.65	0.97	1.11	1.15	1.10	1.28	0.60
0.74	1.00	1.10	1.11	1.07	1.26	0.67

d

Fig. 2. Cartogram of the fuel loads of a VVÉR-1000 reactor, 30° sector: 1 – number of the core cell; 1.60 – fuel enrichment, %; 1.00 – year of operation; 0.68 – relative power of fuel assemblies at the start of a run; 0.80 – relative power of a fuel assembly at the end of a run.

Analysis shows that low-leakage loads obtain when the protruding fuel assembly with fuel enrichment >4% operates during the third or fourth year and with enrichment from 2 to 4% during the second or third year. At the same time, the practice of placing fuel asemblies with enrichment >4% in the third year of operation into corner cells in an alternating cycle cannot be recommended for decreasing the radiation load on the vessel, since this is incorrect from the standpoint of the cost-effectiveness of fuel utilization.

Analysis of Fig. 1 permits drawing several additional conclusions:

- the dependence of the neutron flux density on the run-averaged relative energy release of a protruding fuel assembly can be fit to a good approximation by the expression

$$\tilde{\varphi}_{\mathrm{rel}} = \varphi_0 + bq_i; \tag{1}$$

- the deviations of the neutron flux density from the rectilinear fit are pseudorandom, since the distribution of the quantity $x = (\varphi_{\mathrm{rel}} - \tilde{\varphi}_{\mathrm{rel}})/\sigma$, where $\sigma = 0.026$ is the standard deviation of φ_{rel}, is close to the normal distribution;
- the use of Eq. (1) in choosing a variant of the core arrangement which minimizes the radiation load on the vessel, makes it possible to estimate the maximum neutron flux density to within 10%; at the same time, there is no justification for comparing fuel loads which are close according to the run-averaged relative energy release of the protruding fuel assembly, i.e., when this parameter differs by 10%;

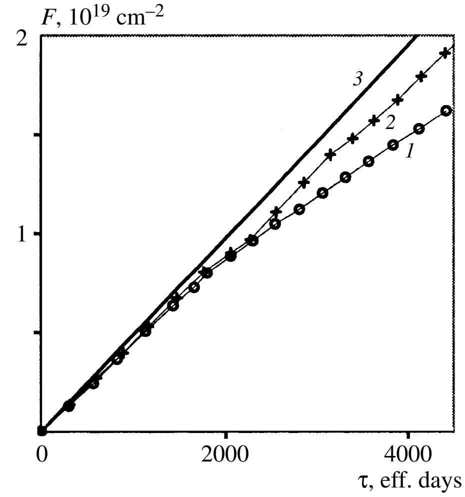

Fig. 3. Accumulation of neutron fluence by the inner surface of the vessel at the level of seam No. 3 over 17 fuel runs of the No. 1 unit at the Khmel’nitskii (*1*) and No. 3 unit at the Rovno (*2*) nuclear power plants; *3*) design fluence.

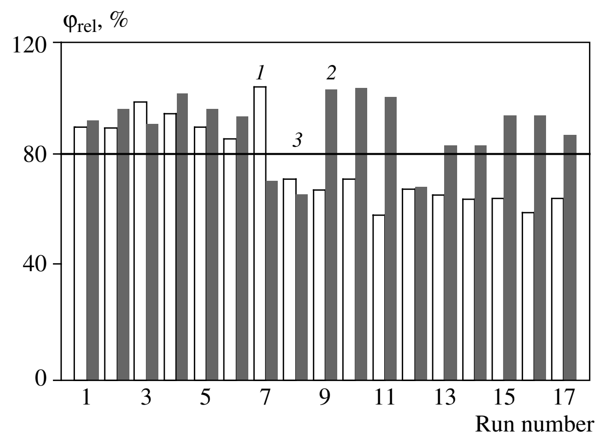

Fig. 4. Relative maximum neutron flux density on the inner surface of the reactor vessel in the No. 1 unit of the Khmel’nitskii (*1*) and No. 3 unit of the Rovno (*2*) nuclear power plants; *3*) maximum value of the relative flux density for low-leakage loads.

• the free coefficient φ_0 in Eq. (1) can be interpreted as the average contribution of the nonprotruding fuel assemblies to the relative maximum neutron flux density; it is about 1/4 of the maximum flux density with the standard load and about 1/3 for a low-leakage load.

It is obvious that the spectral characteritics of the neutron flux acting on the metal of the reactor vessel depends on the parameters of the fuel loads. The neutron spectrum on the inner surface of the vessel is characterized, to some degree, by the spectral index, which is defined as the ratio of the fluence of neutrons with energy $E_n > 0.5$ MeV and $E_n > 3$ MeV. Consequently, the dependence of the spectral index on the run-averaged relative energy release of a protruding fuel assembly can give an idea of the general characteristics of the spectrum for different fuel loads. Analysis shows that the spectral index for a load with low neutron leakage is on average 2% lower than for a standard load, i.e., in the first case more neutrons with energy $E_n > 3$ MeV are present in the neutron flux on the reactor vessel.

In [2], it was suggested that the indicators of the degree of damage to the vessel material be used as one of the functionals of the neutron flux that characterize the irradiation of the vessel. These indicators take account of the fluence and flux density of neutrons and the neutron spectrum: the number of displacements per atom (dis./at.) and the rate of accumulation of dis./at. Analysis of the dependence of the rate of accumulation of dis./at. on the run-averaged relative energy release of a protruding fuel assembly shows that it is qualitatively identical to that presented in Fig. 1 and the proposed criterion for determining the load with low neutron leakage $q_i < 0.57$ is applicable in this case also.

Variants of the Use of Fuel Assemblies with Burned-Up Fuel at the Periphery of the Core. Knowing that the fuel assemblies located in the core cells closest to the inner surface of the vessel – cell 13 of the 30° symmetry sector – have the greatest effect on the radiation load on a reactor vessel, we shall examine several arrangements of a VVÉR-1000 core.

Figures 2*a* and 2*b* show cartograms of a stationary load in a three-year fuel cycle with fresh fuel installed at the periphery of the core and loading of fuel assemblies in the third year of operation into cell 19, respectively. Comparing shows that in the second case the power of a fuel assembly in cell 13 increases. Although the average power of the peripheral fuel asemblies decreases, i.e., the number of neutrons absorbed outside the core decreases, the radiation load on the vessel increases.

There will be no positive effect, i.e., when neither the radiation load on the vessel nor the neutron leakage decreases, if a fuel assembly with fuel enrichment >4% in the second year of operation is placed in the protruding cell, as shown in Fig. 2*c*.

Figure 2*d* shows a cartogram of a load for a four-year cycle with a fuel assembly at the fourth year of operation placed into cells 7 and 13. The power of a fuel assembly placed in cell 13 is approximately half the power of a fuel assembly placed in the same cell for the loads shown in Figs. 2*a–c*.

It is evident that from the standpoint of fuel utilization it is irrelevant how the neutron flux density is distributed along the periphery of the core [1]. Moreover, from the standpoint of convenience of load arrangement and meeting the normative restrictions on the neutron-physical characteristics of the core it is much easier to place the burned-out fuel assemblies into cell 19 (symmetry 30°). However, not just any placement of burned-out fuel on the periphery of the core decreases the neutron leakage and/or decreases the radiation load on the vessel.

Effectiveness of Using Low-Neutron-Leakage Fuel Loads for Decreasing the Radiation Load on the Reactor Vessel. We shall show this for the example of the operation of the No. 1 unit of the Khmel'nitskii and No. 3 unit of the Rovno nuclear power plants. Figure 3 shows that over the same period of operation the reactor vessel of the No.1 unit of the Khmel'nitskii nuclear power plant accumulates a lower fluence than the vessel of the No. 3 unit of the Rovno nuclear power plant. This is because at the Khmel'nitskii nuclear power plant the principle of forming loads with low neutron leakage was started with the eighth fuel run. The results of a determination of the maximum flux density of neutrons with energy $E_n > 0.5$ MeV on the vessel confirm this; these results are presented in Fig. 4. At the same time, analysis of similar data obtained on the No. 3 unit of the Rovno nuclear power plant shows that only the seventh, eighth, and twelfth fuel runs are characterized by low neutron flux density on the reactor vessel, while values above the design values are obtained for some runs.

In summary, adoption in the practice of operating nuclear power plants fuel loads with low neutron leakage makes it possible to decrease the radiation load on the reactor vessel and thereby decrease the influence of one of the harmful factors on the operability of the vessel. Such loads are obtained by satisfying a criterion according to which the run-averaged relative energy release of the protruding fuel assembly, located opposite the zone of maximum neutron flux density on the vessel, must be less than 0.57.

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