control rods at a height of 284, 248.5, 177.5, 142, 106.5, and 71 cm from the reactor-zone bottom. The steady-state coefficients were compared with the corresponding values for states with transient xenon poisoning (for states with the position of the working group of control rods at a height of 248.5-71 cm we calculated the critical states of the reactor with xenon poisoning equal to that in the steady critical state with the position of the working group of control rods at 284 cm). The maximum discrepancy of the coefficients $C_k$ was 1% at a rms deviation of $0.49 \times 10^{-10}$ and that of $B_k$ was 1.6% at $1.61 \times 10^{-5}$, respectively. This discrepancy, therefore, need not be taken into account.

In summary, the a priori coefficients $C_k$ and $B_k$, which are used to find the energy distribution characteristics from the readings of extrareactor detectors, can be determined directly from the results of physical calculation of steady states of the reactor. The calculations and the files of a priori coefficients can be reduced substantially by using the above method of approximating the desired coefficients.

LITERATURE CITED


STATISTICAL PROCESSING OF DESIGN AND OPERATIONAL PARAMETERS OF THE VVÈR-1000 FUEL ELEMENT

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The choice of design and operational parameters has a large effect on the final results of calculations to validate the operational capability of fuel elements. The use of actual parameters in thermal physics and strength calculations increases the reliability of the results, including the actual safety factor of the fuel elements.

Below we present results of a statistical analysis of measurements of fuel pellets, columns, and cladding of fuel elements from a three-year run of a VVÈR-1000. Measurements were made in 1989 (94 tubes and 5000 pellets) and 1990 (160 tubes and 1500 pellets) from arbitrarily chosen tubes and fuel pellets which passed industrial receiving inspection.

Tubes for Fuel Element Cladding. The outside diameter and wall thickness of the tubes were measured with an error of 3 $\mu$m by an ultrasonic monitor with a step of 10 or 20 mm along the length of the tube on a section of 3.53 m, starting a distance of 10 mm from one of the ends. The values of the outer and inner tube diameters and the thickness of one of the tube walls were derived from the measurements. The tubes were chosen from 18 lots made in December 1988 and June 1989.

For 25 tubes, the measurements were conducted sequentially on three passes after rotating the tubes by 120° for each pass. The start of the measurement was the same for each pass. On the other tubes the measurements were conducted in one pass. The following conclusions were made from the measurements [1].

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TABLE 1. Measurements of Fuel Column Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Average</th>
<th>Root mean square deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$, g</td>
<td>1438**(1438)</td>
<td>1481 (1482)</td>
<td>1464.1 (1460)</td>
<td>7.41</td>
</tr>
<tr>
<td>$H$, mm</td>
<td>3518 (3518)</td>
<td>3530 (3530)</td>
<td>3524.5 (3524)</td>
<td>3.51</td>
</tr>
<tr>
<td>$N$</td>
<td>283</td>
<td>317</td>
<td>295.5</td>
<td>4.20</td>
</tr>
</tbody>
</table>

*Values from technical specifications in parentheses.

**If one fuel column with $M = 1438$ g is neglected, $M_{\text{min}} = 1448$ g from 199 measurements.

Comparison between measured parameters and the established technical specifications of the minimum and maximum parameter values showed that the industrially produced cladding tubes for VVER-1000 fuel elements is within the tolerance zone of the technical specifications for the inner and outer diameters with a definite safety margin. The [measured] tolerances for the outer diameter are $9.13^{+0.06}_{-0.01}$ as compared to $9.13^{+0.06}_{-0.05}$ in the technical specifications; the average value is $9.160$ mm. Here the range of measured values is $9.125-9.173$ mm ($48 \mu$m spread and $9.152$ mm average) for tubes made from December 1988 to February 1989 (measured in 1989) and $9.141-9.183$ mm ($42 \mu$m spread and an average of $9.165$ mm) for tubes made from March to June 1989 (1990 data).

The [measured] tolerance zone for the inner diameter is $7.73^{+0.05}_{-0.05}$ mm (specifications: $7.72^{+0.07}_{-0.08}$ mm, average $7.756$ mm). Here the range of measurements is $7.735-7.773$ mm ($38 \mu$m spread, $7.752$ mm average) for 1989 data and $7.740-7.778$ mm ($38 \mu$m spread, $7.759$ mm average) for 1990 data. The tube wall thickness is $0.68-0.72$ mm (average $0.702$ mm). Here the range of measured values is $0.680-0.718$ ($38 \mu$m spread, $0.701$ mm average) for 1989 data and $0.692-0.719$ mm ($27 \mu$m spread, $0.703$ mm average) for 1990 data. The spread in internal diameters for specific tubes was $2-21 \mu$m ($10-14 \mu$m averages), for tube lots $14-32 \mu$m ($20-30 \mu$m average), and for all tubes $43 \mu$m. As a result of small actual tolerances for specific tubes, quantitative probability calculations for a specific fuel element should be done with a spread of inner clad diameters of $0-20 \mu$m.

Analysis of the three-pass measurements of 25 tubes shows that the initial half spread between the minimum and maximum inner diameter in a given tube section does not exceed $12 \mu$m; for the outer diameter it is $15 \mu$m. After the tubes are assembled and chemically processed, their outer diameter is reduced by $20-30 \mu$m; the inner diameter is unchanged.

**Fuel Pellets.** The pellets for the measurements (6500) were chosen from 13 lots made from April 1988 through January 1990. Ten packaging locations were chosen arbitrarily from each lot, and 50 pellets were chosen from each packaging location. The following parameters were measured for each pellet: outer diameter (error $\leq 2 \mu$m in two or three locations along the thickness of the pellet), the diameter of the inner hole (error $\leq 50 \mu$m), and thickness (error $\leq 80 \mu$m). The density was measured for all tablets in 1989 (error $\leq 0.1$ g/cm$^3$) and weight (error $\leq 0.02$ g).

The results of the measurements showed that the actual values were within all the tolerances, established by the standards: outer diameter $7.53-7.57$ mm (average $7.551$ mm), thickness $9-13$ mm (11.881 mm), density $10.4-10.8$ g/cm$^3$ (average $10.579$ g/cm$^3$), and weight $3.9-5.9$ g (4.799 g).

The bevel on the fuel pellets was also measured: the length of the bevel slope was $1.2-1.6$ mm (average $1.3$ mm); the average angle was $23^\circ$; the pellet volume removed to form the bevel from the two ends was roughly $3.6$ mm$^3$ for an average pellet volume of $480$ mm$^3$.

An interesting criterion is the ratio of the pellet weight to its thickness. In analyzing data from 1989 for 1000 pellets this ratio was $0.353-0.465$ g/mm (average $0.41$ g/mm); in 1990 for 1500 pellets it was $0.323-0.453$ g/mm (average $0.403$ g/mm). The ratio of the pellet weight to its thickness determines the number of pellets per unit length of the fuel element and is required to examine high burnup.

**Fuel Columns.** The weight ($M$), height ($H$), and total number of pellets ($N$) were measured in 1989 for 200 assembled columns of assembled pellets using factory technology (see Table 1). We now compare the results. If it is assumed that 1) all pellets have the average parameters (from 1989 data), 2) the bevel volume is $0.75\%$ of the pellet volume, and 3) there are no gaps between the pellets in the column, then the calculated ratio of the weight of the average fuel column to its length is $4.2565$ g/cm. Analysis of the measurements for 200 columns showed that this ratio was $4.0806-4.2014$ g/cm (average $4.1542$ g/cm).