FUEL PERFORMANCE AND OPERATION EXPERIENCE OF VVER-440 FUEL IN IMPROVED FUEL CYCLE

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ABSTRACT

The paper summarizes VVER-440 second-generation fuel operation experience in improved fuel cycles using the example of Kola NPP units 3 and 4. Basic parameters of fuel assemblies, fuel rods and uranium-gadolinium fuel rods, as well as the principal neutronic parameters and burn-up achieved in fuel assemblies are presented. The paper also contains some data concerning the activity of coolant during operation.

Since September 2002, Kola NPP performs works introducing second-generation fuel in VVER-440 reactors. Currently this second-generation fuel is in trial operation at unit 3 (fuel cycles No 18-21, 2002-2007) and unit 4 (fuel cycles No 18-19, 2005-2007).

The first 2nd-generation fuel for VVER-440 was loaded in Kola-3 reactor during its 18th refueling cycle (September 2002-July 2003). The fresh fuel of this 18th fuel load pattern included the following new second-generation assemblies:

- 54 fuel assemblies with average U-235 enrichment of 4.25%, and with Gd_2O_3 burnable absorber (6 gadolinium fuel elements) integrated into the fuel;
- 6 CR fuel followers with average fuel part enrichment of 3.82% of U-235.

The fresh fuel of the next, 19th fuel load pattern (performed during the scheduled preventive maintenance (SPM) in 2003) also consisted of second-generation assemblies only:

- 54 fuel assemblies with average U-235 enrichment of 4.25%, and with Gd_2O_3 burnable absorber (6 gadolinium fuel elements) integrated into the fuel;
- 12 CR fuel followers with average fuel part enrichment of 3.82% of U-235.

The 20th fuel load pattern (SPM-2004) consisted of 60 working assemblies and 6 second-generation assemblies.

The 21st fuel load pattern (SPM-2006) consisted of 54 working assemblies and 12 second-generation assemblies.

Since April 2005, an improved fuel cycle similar to that of unit 3 using the 2nd-generation fuel for VVER-440 reactors is being introduced at Kola-4 unit.

VVER-440 fuel assembly parameters

Today, the reserves of fuel cycle improvement on the basis of traditionally structured assemblies are almost completely exhausted. Existing fuel cycles reach ultimate parameters from their economic expediency viewpoint.

Introduction of new assemblies of improved configuration would allow a next step towards enhancing nuclear fuel's cost-effectiveness and operating safety. The related reserves consist of further fuel cycle modifications based on the use of the new fuel configuration advantages, and on the design limits' updating (conservatism reduction).

Second-generation fuel assemblies differ from the regular first-generation assemblies by the following improvements:

- increased pitch between fuel elements in fuel clusters (from 12.2 to 12.3 mm for fuel assemblies and for CR fuel followers);
- increased fuel column length in fuel elements (for TVS538 type – from 2320 to 2360 mm; for RK5342 type – from 2424 to 2480 mm);
- reduced central hole diameter in fuel pellets (from 1.6 to 1.35 mm);
- increased external diameter of fuel pellets (from 7.57 to 7.60 mm);
- reduced external diameter of fuel elements (from 9.1 to 9.07 mm);
- Gd_2O_3 burnable absorber (3.35%) integrated into the fuel;
- use of hafnium plates in CR fuel followers coupler part;
- turnkey housing size for RK5342 and TVS538 fuel assembly types (145 mm);
- fuel element coating made of zirconium-niobium (1%) alloy with reduced hafnium content (to 0.01%);
- stronger fixation of fuel elements into assemblies.

These changes increase the amount of fuel loaded and reduce the neutron poison absorption.

Power density limits for second-generation assemblies with 4.25% enrichment

q_l^{MAX}= 325 W/cm

q_l^{add} in accordance with the admissible local linear load curve depending on the burnup.

Trial operation data for second-generation fuel assemblies

Complete 5-year fuel cycles using second-generation fuel have been developed and are now introduced, including a fraction of assemblies left for the 6th year of operation, with various fuel lifetimes and, correspondingly, with different numbers of loaded "fresh" fuel assemblies, depending on the specific power system requirements and economic expediency.

After two fuel lifetime cycles, the following maximum average assembly burnup was achieved in second-generation assemblies of unit 4 by the end of its 19th fuel load cycle:

- 24.13 MW·day/kg for fuel assemblies.

After three fuel lifetime cycles, the following maximum average assembly burnup was achieved in second-generation assemblies of unit 3 by the end of its 20th fuel load cycle (Fig.1):

- 35.7 MW·day/kg for fuel assemblies.

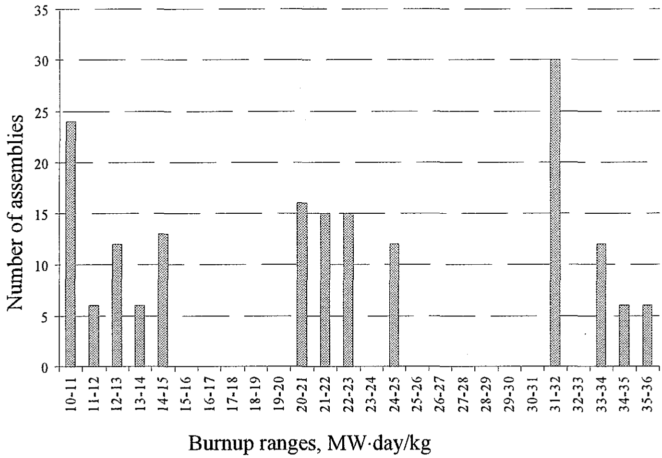


Fig. 1. Burnup distribution in second-generation working assemblies based on the results of 3 years of 2nd-generation assemblies' operation at unit 3

In course of trial industrial operation of new nuclear fuel types, calculated and experimental data are compared in view of checking and correcting the respective software and constants. Calculated and experimental concentrations of the liquid absorber (boric acid) are compared during fuel operation cycles (Figs. 2-4, 8). It can be seen that the calculated values of critical boric acid concentrations correspond to the results of measurements.

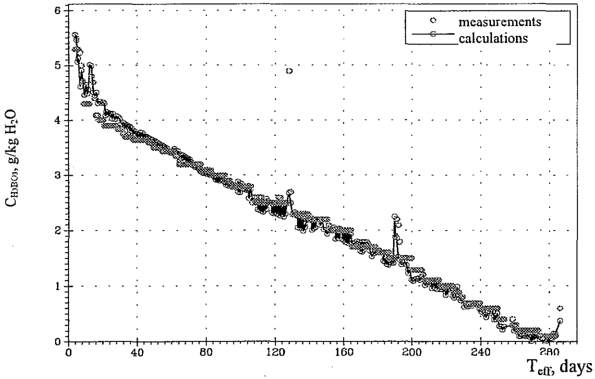


Fig. 2. Critical boric acid concentration changing in the process of burnup, 18th fuel load pattern of Kola NPP unit 3

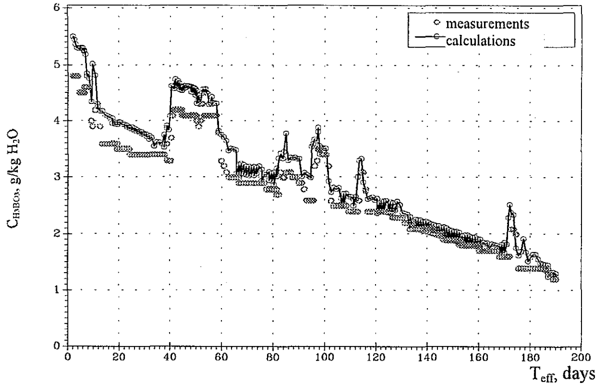


Fig. 3. Critical boric acid concentration changing in the process of burnup, 19^{th} fuel load pattern of Kola NPP unit 3

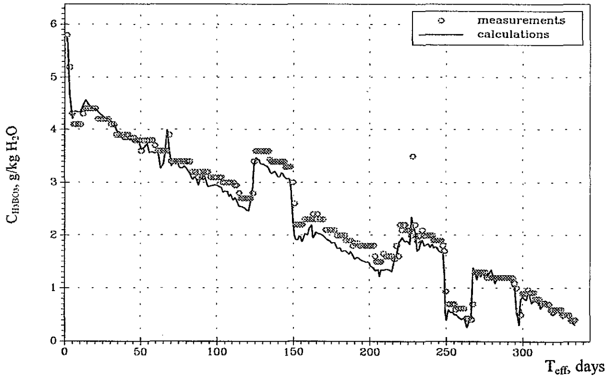


Fig. 4. Critical boric acid concentration changing in the process of burnup, 20^{th} fuel load pattern of Kola NPP unit 3

Specific conditions of Kola NPP operation in an isolated energy system resulting in an insufficient demand for its electricity compels one of its units to operate at only 50% of its design capacity. Figures 5 and 7 show the changes of: thermal power, positions of CPS control rods, and coolant temperature at the core inlet, in the processes of operation of the 20th fuel load pattern at unit 3 and the of 19th fuel load pattern at unit 4.

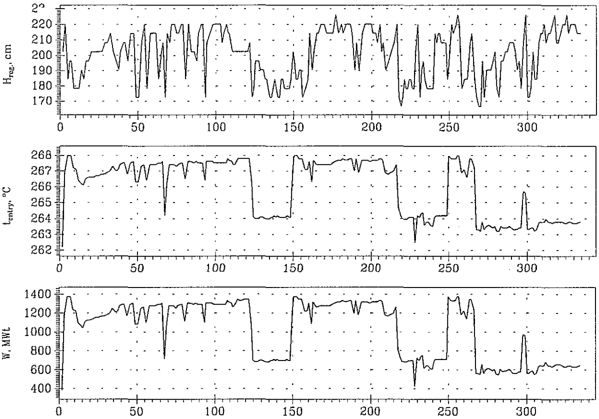


Fig. 5. Changes of: CPS control rod group position; coolant temperature at the core inlet; and thermal power in the process of burnup for the 20th fuel load pattern of Kola NPP unit 3

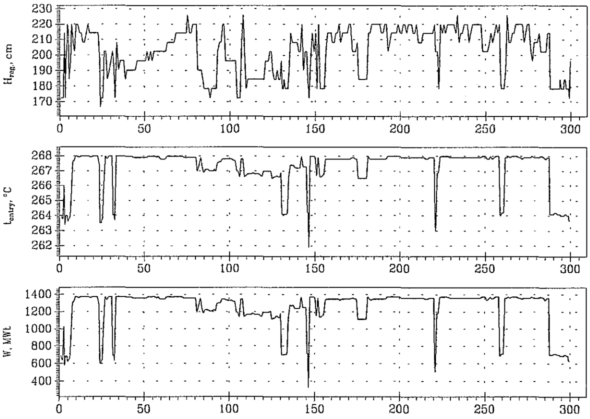


Fig. 6. Changes of: CPS control rod group position; coolant temperature at the core inlet; and thermal power in the process of burnup for the 19th fuel load pattern of Kola NPP unit 4

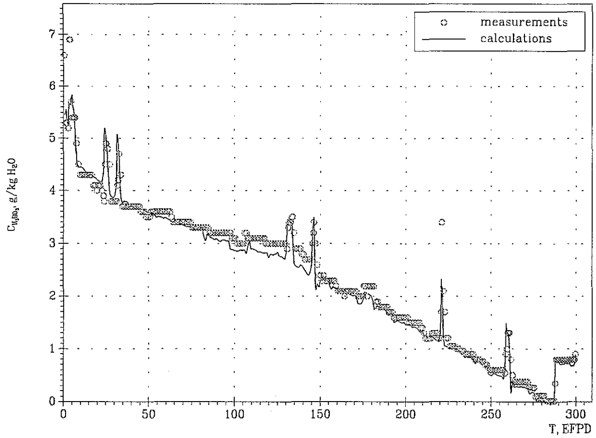
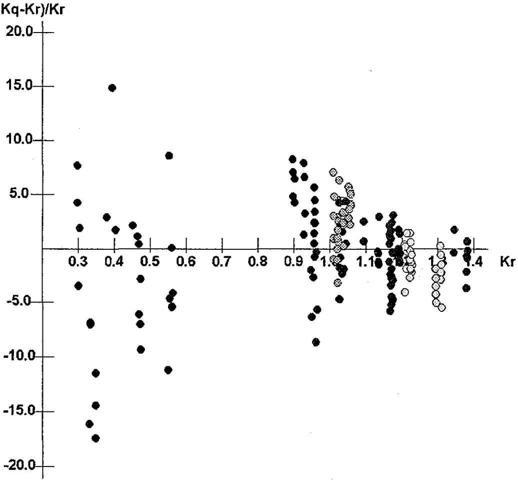


Fig. 7. Critical boric acid concentration changing in the process of burnup, 19^{th} fuel load pattern of Kola NPP unit 4



Deviation statistics
(Experiment-Calculation)
/Calculation,
in % for assemblies having
different operation periods

red	- 1 cycle;
yellow	- 2 cycles;
green	- 3 cycles;
turquoise	- 4 cycles;
blue	- 5 cycles;
violet	- 6 cycles.

Measuring date: 18.03.2005
Effective days: 150.6
Power: 1354 MW

Fig. 8. Results of comparison of power density fields for the 20^{th} fuel load cycle of Kola NPP unit 3

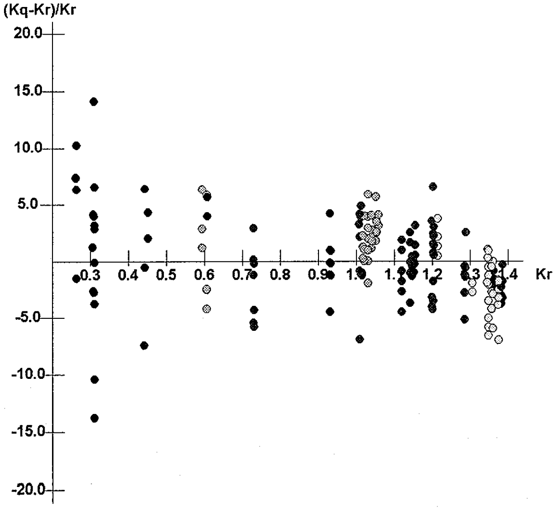
Figures 8 and 9 show the typical results of comparison of Kq (relative assembly power) measured by thermocouples and calculated for selected moments of unit 3 and unit 4 fuel loads' operation.

Relative divergence between measured and calculated values was determined using the following formula:

$$\delta = (Q_{calc}/Q_{exp} - 1) \cdot 100\%.$$

In contrast to edge assemblies, which can have a considerable divergence between calculation and measurement (here it should be remembered that relative powers Kq for these assemblies are small, so the absolute difference between calculation and measurement is also small), relative power of other assemblies (measured by thermocouples), on the whole, shows a good correspondence with the results of neutronic calculations and with the parameters specified in the qualification certificate of BIPR-7A code /5/:

- fuel assembly power non-uniformity:
  - power calculation error for most stressed assemblies ±5%
  - relative power calculation error for edge assemblies with burnups exceeding 30 MW·day/kg:
    - for reduced neutron leakage refueling scheme ±15%
    - for other assemblies (average) ±10%.



Deviation statistics
(Experiment-Calculation)
/Calculation,
in % for assemblies having
different operation periods
red - 1 cycle;
yellow - 2 cycles;
green - 3 cycles;
turquoise - 4 cycles;
blue - 5 cycles;
violet - 6 cycles.

Measuring date:04.10.2006
Effective days: 107.8
Power: 1354 MW

Fig. 9. Results of comparison of power density fields for the 19th fuel load pattern of Kola NPP unit 4

Primary circuit water chemistry data

The primary circuit of Kola-3 operated in a reducing, faintly alkaline, ammonium-potassium water chemistry mode using boric acid, in accordance with existing requirements. In order to meet the water chemistry standards by ammonium and hydrogen, hydrazine hydrate was supplied to the intake header of makeup pumps. In steady-state operation conditions, the contents of alkaline metals, chlorides and corrosion products, pH, and hydrogen concentration in the primary coolant were within the standard limits throughout the reported year.

Ammonium content in the primary coolant varied between 15-50.5 mg/dm^3; alkaline metals' content – between 0.04-0.49 mmole/dm^3; and hydrogen concentration in the coolant – between 2.7-4.8 mg/dm^3. The content of fluorides after the unit's startup was stable below 20 20 µg/dm^3. Kola NPP operates a special water treatment system (SWT-1) consisting of two independent technological groups.

Primary coolant activity and special water treatment-1 coolant flow data

Specific activity of the primary coolant determined for the sum of iodines during the operation of the 18th and 19th load patterns of unit 3 stayed at a low level of 3×10^{-5} Ci/kg. The growth of coolant activity up to 3×10^{-5} Ci/kg at the initial stage (15.09.02-24.12.02) of the 18th fuel load operation at unit 3 was caused by its power increase to 100%. In course of further operation, the coolant activity stayed practically unchanged.

The absence of coolant activity excursion in the moment of actuation of emergency protection system-1 (18th fuel load pattern) shows that no fuel elements having significant cladding defects are present in the core.

The operation of the 19th fuel loading of unit 3 showed minor fluctuations of the coolant activity by the sum of iodines, with reduced SWT-1 coolant flow rate and changed reactor power (Figs. 12-13). However, the activity practically has not exceeded the value of 3×10^{-5} Ci/kg.

Coolant activity by the sum of iodines throughout the 18th and the 19th fuel load cycles of unit 3 stayed at a low level. This fact indicated that no fuel elements having considerable defects were present in the core.

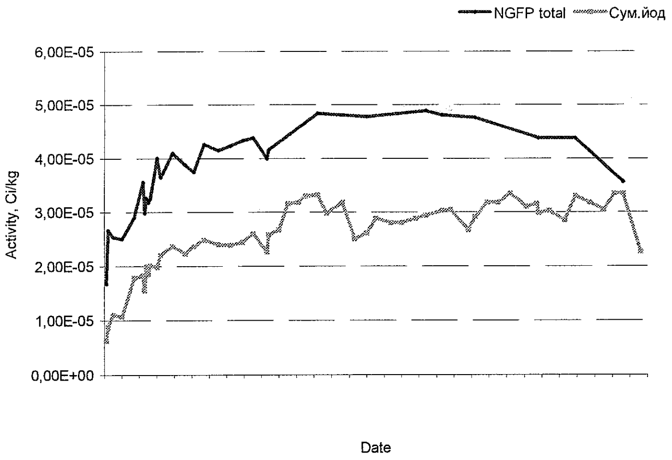


Fig. 10. Specific activity of iodines and non-gaseous fission products in the primary coolant; 18th fuel load pattern, Kola NPP unit 3

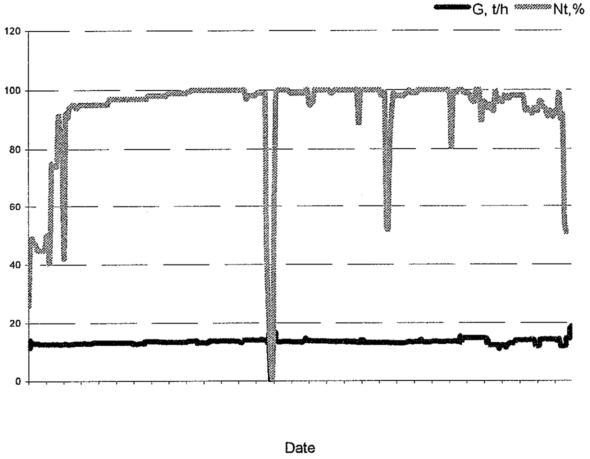


Fig. 11. Thermal power (%) and SWT-1 coolant flow rate (t/h); 18th fuel load pattern, Kola NPP unit 3

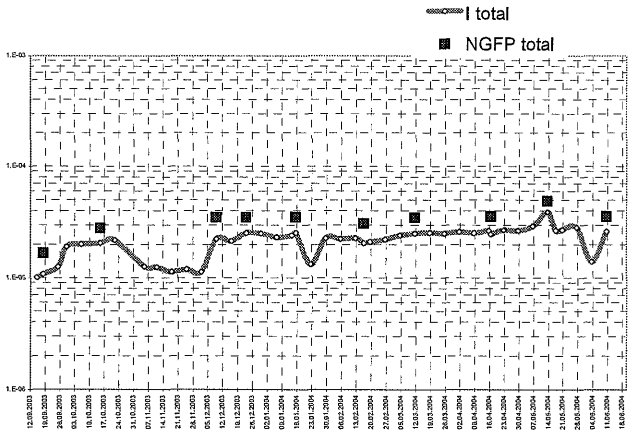


Fig. 12. Specific activity of iodines and non-gaseous fission products in the primary coolant; 19th fuel load pattern, Kola NPP unit 3 (2 hours after sampling), Ci/kg

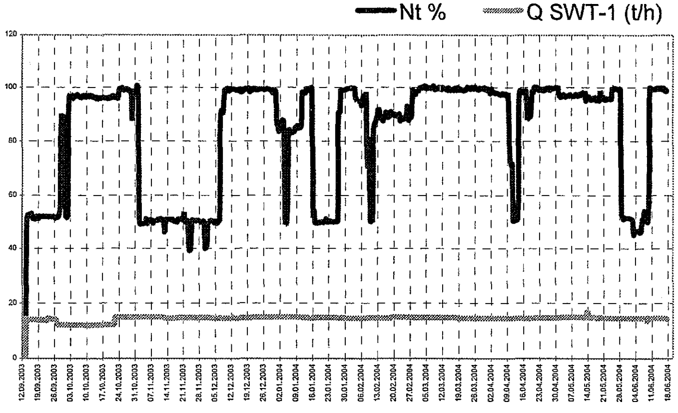


Fig. 13. Thermal power (%) and SWT-1 coolant flow rate (t/h); 19th fuel load pattern, Kola NPP unit 3

Primary coolant activity by the sum of iodines was low throughout the 18th, the 19th and the 20th fuel load cycles. This is a sign that the core contains no fuel elements with considerable defects.

The results of analysis of second-generation fuel assemblies' operation data (168 working assemblies 4.25% and 24 CR fuel followers 3.82%) coupled with the calculated projections allow continued operation of Kola-3 unit at its nominal power level.

Conclusion

The specific geographical position of Kola NPP and the state of the surrounding region's economy determine the strategy of power units' operation in the area of fuel use. Isolated energy system and, as a consequence, excessive generating capacities compel Kola NPP to operate at low power, though its units' operation at their maximum power may be needed in some unplanned situations. In the same time, the results of trial industrial operation of second-generation fuel at Kola NPP units 3 and 4 demonstrate a high reliability of new fuel types, which is confirmed by low primary coolant activity levels and by the cladding leakage monitoring data.

The process of trial industrial operation of second-generation assemblies includes the comparison of calculated and experimental data performed in order to check the compliance of fuel's neutronic parameters with the theoretical physical project of fuel cycle implementation, as well as to update the related software and the database of constants.

Obvious divergence between calculated and experimental data often cannot be discovered during the first two transient loads. This fact is explained by a relatively small fraction of the fresh second-generation fuel with burnable absorber in the active cores of Kola NPP units 3 and 4. Nevertheless, starting from the third refueling, the divergences of fuel load operating cycle and of the liquid absorber concentration in power operation mode were discovered, which required the works on identifying the reasons of these divergences and on correcting the constants to be organized. Regulatory documents provide for the updating of neutronic constants on the basis of operating data.

Technical solutions laid in the design of second-generation fuel assemblies, were proven and confirmed by the results of trial and commercial operation.

References

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