10 Symposium of AER
Moscow, Russia, 18 – 20 September 2000

DEVELOPMENT OF FOUR-YEAR FUEL CYCLE BASED ON THE ADVANCED FUEL ASSEMBLY WITH URANIUM-GADOLINIUM FUEL AND ITS IMPLEMENTATION TO THE OPERATING VVER-1000 UNITS

Lunin G., Novikov A., Pavlov V., Pavlovichev A., Filimonov P.
Russian Research Centre "Kurchatov Institute"

ABSTRACT

Over the past few years in Russia the investigations aimed at the increase of the reliability, safety and efficiency of operation of the VVER-1000 reactors as well as of its competitiveness in the world market were carried out.

In the frame of these investigations the four-year fuel cycle, based on advanced FA with zirconium alloy spacer grids and guide tubes and with fuel pellet having a reduced diameter of the central hole (1.5 mm), has been developed. For the compensation of a part of excess reactivity, Gd_2O_3 integrated burnable absorbers are used. CPS absorbing rods contain a combine absorber (B_4C + Dy_2O_3*TiO_2). A part of depleted fuel is located on the core periphery. The algorithms controlling the reactor power and power distribution have been updated.

For checking of the solutions adopted and for verification of code package developed at the RRC "Kurchatov Institute" the wide-scale experimental operation of advanced FA and its individual components is carried out.

The two-stage implementation of the four-year fuel cycle to practice of the VVER-1000 reactor operation is considered expedient. At the first stage (till 2001) it is planned to transfer the VVER-1000 reactors to the regime of fuel utilization when only a part of FAs will be operated in four fuel cycles. At the next stage, upon the confirmation of advanced FA serviceability, the NPP with the VVER-1000 will be transferred to four-year operation of all advanced FAs.

1. INTRODUCTION

Over the past few years in Russia the investigations aimed at the increase of the reliability, safety and efficiency of operation of the VVER-1000 reactors as well as of its competitiveness in the world market were carried out.

In the frame of these investigations the four-year fuel cycle, based on advanced FA with zirconium spacer grids and guide tubes and with fuel pellet having a reduced diameter of the central hole (1.5 mm), has been developed. For the compensation of a part of excess reactivity, a Gd_2O_3 integrated burnable absorber is used. CPS absorbing rods contain a combine absorber (B_4C + Dy_2O_3*TiO_2). A part of depleted fuel is located on the core periphery. The algorithms controlling the reactor power and power distribution have been updated.

The implementation of the advanced four-year fuel cycle was preceded by tests of some of its elements at the operating NPP: FA with zirconium guide tubes and spacer grids, fuel rods with the increased fuel load, uranium-gadolinium fuel elements (U-Gd rods), combined absorbers of CPS. By the present a considerable amount of operation information has been accumulated, both on individual elements of the advanced fuel cycle and on the whole cycle. Beginning from the year 2000 the Balakovo NPP power units have been loaded only by the advanced fuel. Basing on the experience gained in the designing of the advance cycle and on the results of its operation, the VVER-1000 core designs are being developed for foreign customers (China and India).

At the RRC "Kurchatov Institute" the package of new generation codes has been worked out for calculating the neutronic characteristics of the VVER-1000 core with the advanced fuel. The code package is used for the choice and substantiation of the neutronic characteristics of the advanced cycle, performance of neutronic calculations, substantiation and calculation support of the pilot operation of the advanced FA.

Below the main phases of the development and pilot operation of advanced fuel cycle are briefly described, and the main neutronic characteristics of this cycle are presented.

2. DESCRIPTION OF ADVANCED FUEL CYCLE COMPONENTS

Zirconium spacer grids and guide tubes

The replacement of steel structural elements of FA by zirconium ones makes it possible to reduce the parasitic capture of neutrons and to improve the neutron balance in the fuel lattice. As a result, the opportunity is created to decrease the enrichment of fuel (saving its multiplying properties, Fig.1) and, thus, reduce the cost of fuel.

The first six FAs with zirconium spacer grids (ZSG) and zirconium guide tubes (ZGT) were loaded in 1993 the 6-th cycle of Balakovo NPP-1. These were the FAs with the standard fuel rods, standard geometrical dimensions of the central and guide tubes provided with removable boric burnable absorbers (BA). The average fuel enrichment in the FAs was 4.23%. After the 8-th cycle all the FAs were removed from the core, the average fuel discharge burnup reached almost 43 MW*day/kg. The similar FAs were installed in the Rovno NPP-3 and in the 7-th cycle of the Balakovo NPP-1.

In the 8-th cycle of Balakovo NPP-1 24 fresh FAs with the ZSG and ZGT were used, the fuel enrichment was 4%. In six FAs the advanced fuel pellets with the central hole diameter 1.5 mm were set instead of the standard fuel pellets. As the water-uranium ratio of the fuel lattice reduced, the negative coolant temperature feed-back increased, and the increase in the mass of fuel loaded into the FA comparing with the standard one (by about 7%) made it possible to enhance the energy content of the fuel loading.

The subsequent implementation of FA with the ZSG and ZGT was accomplished on the basis of the advanced FA (see Fig.2), whose fuel enrichment spectrum (3.3, 3.6 and 4%) and geometry of guide and central tubes were unified, and the fuel rod mass was increased. As the burnable absorber the removable boric BPs (Zaporozhie NPP) and the U-Gd rods (Balakovo and Zaporozhie NPPs) were used.

In 2000 all Balakovo NPP units were loaded by FAs with U-Gd rods. By the present the core of Balakovo NPP-1 contains 131 "zirconium" FAs (including 96 FAs with U-Gd rods), the Balakovo NPP-2 core - 55 FAs (all with U-Gd rods), the Balakovo NPP-3 - 91 FAs (all with U-Gd rods), and Balakovo NPP-4 - 49 FAs (all with U-Gd rods).

From the comparison of the calculation results and experimental data (the critical parameters of the core, reactivity coefficients, worth of some CPS groups at zero and nominal power levels, power distribution) the conclusion was made that the characteristics of the core with advanced fuel are calculated within the certificates accuracy.

Uranium-gadolinium rods

The pilot operation of FAs with U-Gd rods in Russia was preceded by research works on the development of technology for manufacturing the domestic U-Gd fuel and on the analysis of its characteristics, which had been carried for some years [1]. In the RRC "Kurchatov Institute" the calculation methods and codes for calculation of the neutronic characteristics of fuel lattices containing fuel rods with gadolinium were developed, and the libraries of gadolinium isotope constants were prepared. The RRC "Kurchatov Institute" specialists participated in the measurements of the parameters of uranium-gadolinium lattices, carried out on the ZR-6 and LR-0 assemblies and on the RRC "Kurchatov Institute" critical test facility "П" with the purpose of verification of calculation procedures and codes [2].

The investigations made it possible to make a conclusion on the possibility of using the RRC "Kurchatov Institute" code package for the calculation of the neutronic characteristics of FAs with the U-Gd rods for the substantiation of their pilot operation.

In March, 1994 12 FAs with the U-Gd rods (Fig.3) were installed in the core of the Balakovo NPP-3 (5-th cycle). These were the standard FAs, in each of which 18 U-Gd rods with the 8% mass content of gadolinium oxide (Gd_2O_3) were located. The number of U-Gd rods in each FA, their arrangement in the bundle and Gd_2O_3 content in the fuel were chosen basing on variant calculations. As the heat conductivity of UO_2 in the presence of Gd_2O_3 reduces, at the equal linear heat generation rates of fuel rod and U-Gd rod the fuel temperature in the latter is higher. In order to limit the U-Gd rod power (by the time of absorber depletion) the fuel enrichment in the U-Gd rods was reduced to 3.6% (in the fuel rods it was 4.4%). In the 6-th cycle of Balakovo NPP-3 the number of fresh pilot FAs with U-Gd rods was increased to 24. The same FAs were used but in them the first periphery row was graded with the 3.6% enriched fuel rods.

The comparison of the measured and calculated core parameters during the operation of the 5-th and 6-th cycles revealed that the U-Gd rod efficiency was underestimated in the calculation and that the U-Gd rod characteristics had to be changed. Therefore the number of U-Gd rods in the FA was reduced to 12, Gd_2O_3 content was decreased to 5%, and the U-Gd rod fuel enrichment was 3.3% (see Fig.4). It was these FAs with U-Gd that were loaded to the 7-th cycle of Balakovo NPP-3 and to the 8-th cycle of Zaporozhie NPP-3.

The pilot operation of FAs with U-Gd rods permitted to prove the U-Gd rods operability and reliability, to determine the U-Gd rods parameters (U-Gd rod fuel enrichment - 3.3%, gadolinium oxide content in the fuel - 5%) and to estimate the accuracy of the calculation of the cores with U-Gd rods.

It is evident that the gadolinium efficiency as an absorber increases when it is used in the FA where steel is replaced by zirconium and the fuel enrichment is reduced by about 10% comparing with the "steel" FA. Therefore the advanced FA implemented now contain six U-Gd rods each (Fig.5). These are the FAs which are being operated at the Balakovo NPP unit 1 (96), unit 2 (55), unit 3 (91) and unit 4 (49). The number of U-Gd rods in the advanced FA can be increased up to 9-12, when the fuel loadings for the operation longer than 7000 EFPH are formed.

Combined control rods

By its functional purpose the VVER-1000 control and protection system is divided into two parts. During the normal operation the major part of CPS AR is withdrawn from the core and is designed for rapid termination of the chain reaction (group of protection) and the other part, consisting of 1-3 groups, serves for control of power and power distribution. The lower parts of absorbing rods, both of protection and control groups, are the most exposed to neutron irradiation. This essentially affects the in-use life of the CPS absorber rods.

In 1995 the pilot operation of combined CPS absorber rods began. The upper part of these rods contains boron carbide (B_4C), the absorbing material traditionally used for the VVER-1000 reactors, and the lower part (about 300 mm in length) is made of dysprosium titanate ($Dy_2O_3{*}TiO_2$). The use of dysprosium as an absorber, makes it possible to solve a number of operational problems. In particular, dysprosium is a (n,γ) absorber and, hence, it is less subjected to radiation damage than a boron-containing absorber which interacts with neutrons in (n,α) reaction. The heat release in a rod also decreases because the absorption of γ-quanta in it is low. Finally, the reduction in the physical efficiency of the dysprosium-based absorber in depletion goes slower than in the case of boron absorbers as in the successive capture of neutrons, the absorbing isotopes of dysprosium are again formed.

For substantiating the industrial operation of combined absorbers and their implementation to the VVER-1000 reactors, a series of calculation and experimental studies were carried out at the RRC "Kurchatov Institute". It was shown the efficiency of dysprosium titanate comparing with that of boron carbide is about 70%, and the reduction in the efficiency will not exceed 0.5% of the full " worth" of the standard CPS AR in the case of using dysprosium titanate in the lower part of absorbing rod (~10% of its full length). This estimate agrees with the measured values of the worth of CPS AR with combined absorbers which were first installed in the VVER-1000 of Kalinin NPP-1. Here the attempts to state the difference in the integral worth of symmetrical groups with the standard and combined absorbers (taking into account the measurement error and the asymmetry of the multiplying properties of the core) ended in failure.

The difference worth of the working group with the combined absorbers differs from the standard ones (Fig.6), its change (reduction or increase) being 40-100% at some times of group movement. At the same time the integral worth of the combined absorber does not practically differ from the standard one. At present all units of Balakovo and Kalinin NPPs are provided with the combined absorbers.

Low leakage loading patterns. FA operation in four cycles

By the present an extensive experience of VVER-1000 operation with a low leakage loading patterns, when FAs with irradiated fuel were installed on the core periphery, has been gained. In the South-Ukrainian NPP-1, having 49 CPS drives, the requirements on the scram system efficiency in the transition of the unit to the three-year fuel cycle were only met by reducing the radial neutron leakage. The consistent use of the loading patterns with partly irradiated fuel located at the core periphery takes place in the Balakovo NPP units 1-4 in the connection with the implementation of FA with U-Gd fuel there. For example, in the 6-th, 7-th and 8-th cycles of unit 3 the number of FAs with irradiated fuel at the core periphery was 18, 18 and 24, respectively, and in the 9-th cycle of unit 1 it was 29 (all 29 FAs are of the fourth year of operation).

The experience of four year operation of FAs in the VVER-1000 reactor has been only gained with the standard "steel" FAs: about 800 FAs were operated in the VVER-1000 reactors of Zaporozhie, Rovno and South-Ukrainian NPPs, with the average fuel discharge burnup exceeding 48 MW*day/kg in some FAs [3].

Distribution of CPS AR over groups, algorithms of power and power distribution control in the core

In the frame of works on improvement of the VVER-1000 fuel cycle, investigations of various control methods for power and power distribution in the core of this reactor had been performed at the RRC "Kurchatov Institute" for several years [4,6]. Basing on the data of calculation and experimental investigations the following modifications comparing the V-320 design were proposed:

- change in the CPS AR distribution over the groups, including the location of the working (No.10) CPS AR group in the core (Fig.7). As a result, the deformation of radial power distribution during a movement of the control rod groups is decreased, and the spectrum of possible loading patterns is extended;

- change in the overlapping CPS AR groups (up to 50% of the core height). As a result the efficiency of warning protection is increased and the possibility of effective control of power distribution is extended. In the manual control of power distribution the extent of overlapping can be varied;
- improvement of algorithms of power control offering the possibility of simultaneous control of reactor power and axial power distribution and decrease in the amounts of liquid wastes.

In 1998 the experiments on daily reactor power load following were carried out in the Zaporozhie NPP-5, using two group of CPS AR with variable overlapping. The tests confirmed the advantage of the proposed control procedure and also showed the expedience of change in the CPS AR distribution over the group.

3. CODE PACKAGE FOR NEUTRONIC CALCULATIONS

In the RRC "Kurchatov Institute" the code package of new generation for neutronic calculations of VVER reactors with advanced fuel has been developed. It contains the following codes [7,8[:
TVS-M code. This code is designed for calculation and approximation of few-group neutron cross-sections of cells and assemblies for the codes of BIPR and PERMAK-type and as well as for derivatives of these cross-sections as the functions of the reactor parameters and fuel burnup.
BIPR-7A code. This code is designed for performing calculations of the criticality parameters, reactivity effects and coefficients, differential and integral reactivity worth of control rods, three-dimensional power distributions in VVER reactor cores, calculational simulation of burn up processes and refuelling, xenon-135 and samarium-149 transients.
PERMAK-A code. This is used for carrying out the pin-by-pin burnup calculations of core and for obtaining information on changes in linear heat generation rates of fuel rods during the movement of the CPS control group, in load-following mode of operation and during xenon transients.
IR code. This is a specialised version of the BIPR code oriented to the simulation of nonsteady state operation regimes of the VVER-1000 reactor.

The detailed analysis of the representativeness of the calculation results of VVER-1000 neutronic characteristics by the TVS-M, BIPR7-A, PERMAK-A, IR code package was performed using:

- results of calculations by precision codes;
- measurements data obtained on the critical test facilities;
- results of measurements carried out during the startup and operation of VVER-1000 reactors.

Below the examples of comparison of calculation and experimental values of some neutronic characteristics of VVER-1000 core are given.

Differences between calculated values of critical boric acid concentration and the measured ones obtained during VVER-1000 operation at power levels are shown on Fig. 8. Fig. 9 gives distribution of differences between calculated values of critical boric acid concentration and corresponding values measured at zero power level states. Analysing these dependencies it should be taken into account the following: typical range of critical boric acid concentrations is 6-7 g/kg for the first moment of VVER-1000 fuel loading operation at power level (7-9 g/kg for zero power level) and measuring error for boric acid concentrations in this range (6-9 g/kg) is equal to about 5% (0.3-0.5 g/kg). Therefore (as it follows from the data presented) calculated and measured values of boric acid concentration are consistent within measuring error.

Fig. 10 shows the distribution of differences between calculated and measured values of the temperature reactivity coefficient (for fuel and coolant together). The characteristic range of temperature reactivity coefficients at the first moment of VVER-1000 fuel loading operation in the state at zero power level is $(5\div10)*10^{-5}$ 1/°C. It is seen that the calculated and measured values of the temperature reactivity coefficient are consistent within limits of $3*10^{-5}$ 1/°C.

Fig.11 represents the distribution of differences between calculated and measured values of FA relative power. The distributions are plotted for FAs the relative power of which is above unity for the initial period of the fuel loading operation. The data demonstrate that the calculated and measured values of the relative power for the hottest fuel assemblies of the core are consistent within the limits of 5%.

Summarising the results of verification of the TVS-M, BIPR7-A, PERMAK-A, IR code package, the following estimate of the error in the calculation of the VVER-1000 core parameters can be given:

- critical boron concentration at the beginning of cycle (nominal power).............5%
- reactivity worth of CPS..10%
- reactivity worth of individual groups of CPS...20%
- temperature coefficient of reactivity at the beginning of cycle.................$3*10^{-5}$/°C
- relative power of the hottest FAs...5%
- cycle length..3%

4. FOUR-YEAR URANIUM-GADOLINIUM FUEL CYCLE OF VVER-1000 REACTOR (FIRST STAGE)

In the advanced four-year fuel cycle (first stage) the main tendencies of development of pressure-water reactors are reflected:

- improvement of the neutron balance due to the use of structural materials slightly absorbing neutrons;
- application of burnable absorber integrated with the fuel;
- use of loading patterns with a reduced radial neutron leakage;
- increase in the burnup of discharged fuel;
- improvement of CPS groups arrangement and updated power control algorithms.

The two-stage implementation of the four-year fuel cycle to practice of the VVER-1000 reactor operation was considered expedient. At the first stage it is planned to transfer the VVER-1000 reactors to the regime when only a part of FAs is operated for four years. At the next stage, if the FAs availability is confirmed, the VVER-1000 reactors will be brought to the four-year fuel operation regime.

First fuel cycle

The first fuel loading is formed of 54 FAs with 1.6% enriched fuel, 67 FAs with 2.4% enriched fuel and 42 FAs with the average fuel enrichment 3.53% (fuel rods with enrichment 3.3% and 3.6%). The conventional loading pattern is used - the FAs with maximum enriched fuel are installed on the periphery, the FAs with minimum and intermediate enrichments - in the centre of the core. The average fuel enrichment is 2.45%. For the compensation of a part of excess reactivity and for formation of power distribution in the core, in 42 FAs the U-Gd rods with the gadolinium content 8% are used. The simplified maps of FAs used in advanced fuel cycle are shown in Fig. 12. The map of first fuel cycle is presented in Fig.13.

Main first cycle characteristics:

- time of operation at the nominal parameters - 300 EFPD;
- at the zero power level at any time of fuel cycle with all the AR withdrawn from the core the density (temperature) coefficient of reactivity is positive (negative);
- maximum relative power of fuel rod is observed in the beginning of cycle and does not exceed 1.50;
- maximum relative power of U-Gd rod is observed at the end of cycle and is 1.20;
- maximum linear thermal power of fuel rod is observed in the beginning of cycle and does not exceed 350 W/cm (without allowance for the engineering safety factor);
- maximum linear thermal power of U-Gd rod is observed at the end of cycle and does not exceed 230 W/cm (without allowance for the engineering safety factor).

Transient and equilibrium fuel cycles

During the transient cycles the transfer to the equilibrium cycle is accomplished and the loading pattern is completely changed (in comparison with the first loading pattern): a considerable part of fresh FAs (30 or 31) is located in the central part of the core, the rest 18 FAs - on the core periphery (Fig.14).

In the transient and equilibrium cycles the fuel rods with 3.3%, 3.6% and 4% enriched fuel are used. They form two types of FAs with the average fuel enrichment 3.53% and 3.90% (Fig. 12). The rods with the fuel of lower enrichment (3.3% or 3.6%) are located on the periphery part of these FAs. The FAs of this types contain U-Gd rods, six in each one. The fuel enrichment of U-Gd rods and the content of gadolinium in them are 3.3% and 5% respectively. The major number of FAs (30 or 31) is operated in the reactor during three fuel cycles in the central part, and the rest ones - during four fuel cycles, and in the course of two or three fuel cycles they are on the core periphery. This regime of fuel irradiation permits the difference between the medium and maximum fuel burnup of discharged FA to be minimized. The location of 18 FAs of the final (fourth) year of operation on the periphery core creates the conditions for reducing fast neutron fluence on reactor vessel and favours the increase in the efficiency of the CPS.

The equilibrium composition of fresh fuel is established beginning from the second refueling: the total number of loaded fresh FAs with the U-Gd rods is 48(49), including 30 FAs with the fuel of average enrichment 3.9% and 18 (19) FAs with the fuel of average enrichment 3.53%.

Main characteristics of equilibrium cycle:

- time of operation at the nominal parameters - about 290 EFPD;
- average enrichment of fresh fuel - lower than 3.8%;
- at the zero power level at any time of fuel cycle with all AR withdrawn from the core the density (temperature) coefficient of reactivity is positive (negative);
- maximum linear thermal power of fuel rods (U-Gd rods) does not exceed 300 W/cm (250 W/cm) (without allowance for the engineering factor);
- average burnup of discharged FAs is about 42 MW*day/kg, and the maximum one does not exceed 44 MW*day/kg.

The change in the maximum linear thermal power of fuel rods during the cycles (from the first to the seventh) is shown in Figs. 15 and 16. Table lists the main characteristics of advanced fuel cycle.

5. CONCLUSION

In Russia the main prerequisites to the implementation of advanced fuel cycle to the NPP with the VVER-1000 reactors have been created. For the past few years the works aimed at the increase in the reliability, safety and efficiency of the VVER-1000 operation and in its competitiveness in the world market were accomplished.

- Beginning from 1993 the FAS with the zirconium guide tubes and spacer grids have been operated at the Balakovo NPR-1. By the present the core of this unit contains 131 "zirconium" FAs (including 96 FAs with U-Gd rods), the cores of Balakovo NPP units 2,3 and 4 contain 55, 91 and 49 FAs (all with U-Gd rods) respectively.
- Pilot operation of U-Gd rods which had been carried out on the Balakovo NPP-3 beginning from 1995 made it possible (along with the U-Gd rod life tests and check of the U-Gd rod serviceability and reliability) to unify the parameters of the U-Gd rods and substantiate the representativeness of the calculation of core with U-Gd rods.
- Beginning from 1995 the replacement of standard carbide absorbers of CPS AR by the combined ones was carried out and at present the combined absorbers are used in all the CPS AR of the Balakovo and Kalinin NPP.
- In the VVER-1000 reactors the low leakage loading patterns with a part of irradiated FAs located on the core periphery are systematically used.
- The updated algorithms of control of the power distribution in the core have been developed and checked.
- A code package of new generation for the neutronic calculations of VVER, consisting of the TVS-M, BIPR-A, PERMAK-A and IR codes, has been developed and verified on the data of pilot FA operation.
- The four-year fuel cycle designed for the implementation to both the new and operating NPPs with the commercial VVER-1000 have been developed. The fuel cycle is formed on the basis of advanced FA with U-Gd. As the absorber rods of CPS AR the combined absorbers (B_4C + $Dy_2O_3*TiO_2$) are used. The low leakage loading patterns designed for reducing of radial neutron leakage and improvement of the operation conditions of reactor vessel are employed.
- The two-stage implementation of the four-year fuel cycle to practice of the commercial VVER-1000 reactor operation is considered expedient. At the first stage (till 2001) it is

planned to transfer the VVER-1000 reactors to the regime of fuel utilization when only a part of FAs will be operated in four fuel cycles. At the next stage, upon the confirmation of advanced FAs serviceability, the VVER-1000 reactors will be transferred to the four-year regime of fuel operation.

LIST OF ABBREVIATIONS

NPP	nuclear power plant
CPS AR	Control and protection system absorbing rod
BA	Burnable absorber
FA	Fuel assembly
ZSG	Zirconium spacer grid
ZGT	Zirconium guide tube
U-Gd rod	Fuel rod with gadolinium

REFERENCES

1. *O.Milovanov, V.Proselkov, A.Kuleshov* et al. Development of uranium-gadolinium fuel for the VVER reactors, Preprint IAE-5744/4, M., 1994.
2. Proceedings of VMK, vol.1 and 3. Experimental studies on physics of VVER-type uranium-water grids, 1984.
3. *A.Afanasyev.* The summary of VVER-1000 fuel and control rod utilization in Ukraine. Proceedings of the 2000 International Topical Meetings on LWR Fuel Performance. Park City, Utah, April 10-13 2000.
4. *P.Filimonov, S.Averyiyanova.* Development of methods for the control of xenon oscillations of power distribution in the VVER-1000 reactors. Atomnaya Energiya, 1996, v.81, No.1.
5. *P.Filimonov, S.Averyiyanova, S.Oleinik, S.Klimov, A.Depenmchuk.* Tests of maneuverability of the VVER-1000 out the Zaporozhie NPP-5. Atomnaya Energiya, 1998, v. 85, No.5.
6. P.Filimonov, S.Averiyanova, M.Filimonova. Control of the CPS working groups in the load following regime of VVER-1000 reactor operation. Atomnaya Energiya, 1998, v. 84, No.5.
7. *A.Novikov., V.Pshenin ,.M.Lizorkin. et al.* Problems of VVER in-core fuel management. In-core fuel management practices. Proceedings of two technical committee meetings and workshops organized by the IAEA. Madrid, 12-15 July 1988 and Vienna, 4-7 December 1989, p.325.
8. P.Filimonov, V.Mamichev, S.Averiyanova. Code " Reactor Simulator" for modeling the load-following regimes of VVER-1000 reactor operation. Atomnaya Energiya, 1998, v. 84, No. 6, p. 560-563.

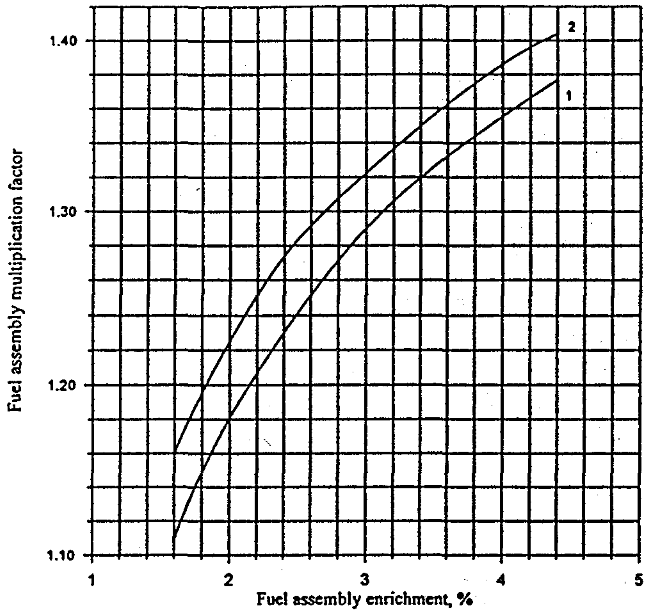


Fig.1. Dependence of the FA multiplication factor (1,2 - guide tubes and spacer grids are made of stainless steel and zirconium respectively)

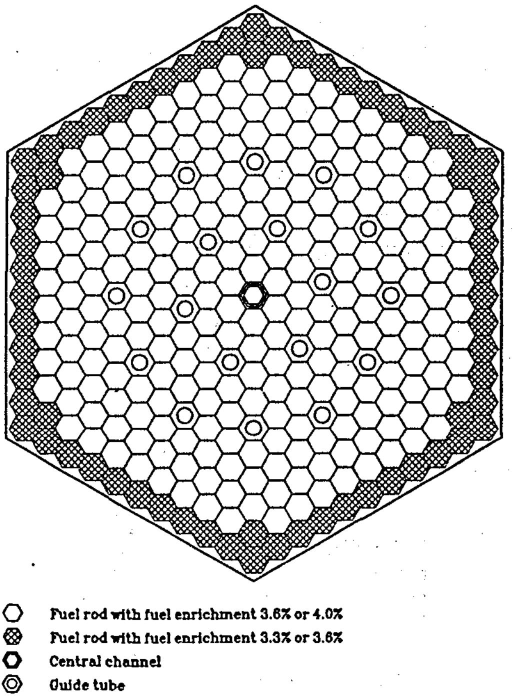


Fig.2. Zirconium fuel assembly map

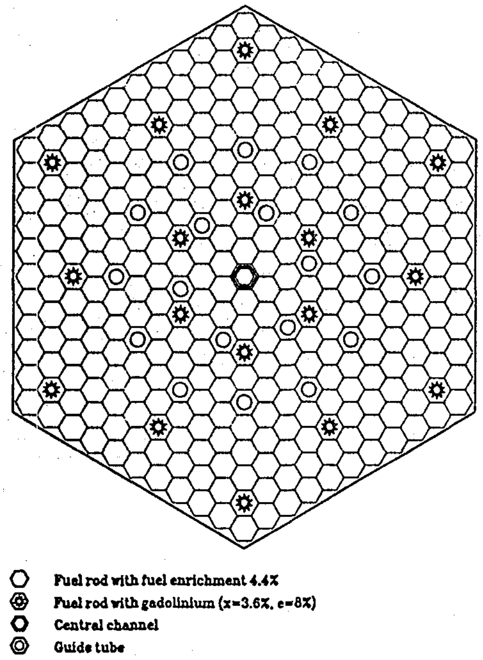


Fig.3. Pilot fuel assembly map (18 U-Gd rods)
(x - fuel enrichment, e – mass content of gadolinium oxide)

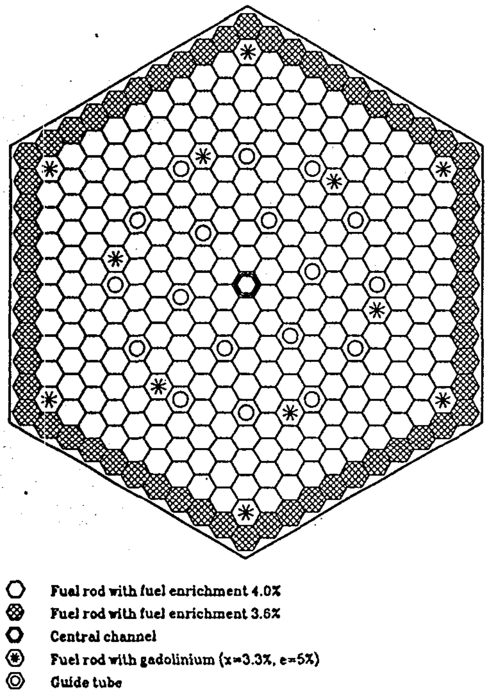


Fig.4. Pilot fuel assembly map (12 U-Gd rods)
(x - fuel enrichment, e – mass content of gadolinium oxide)

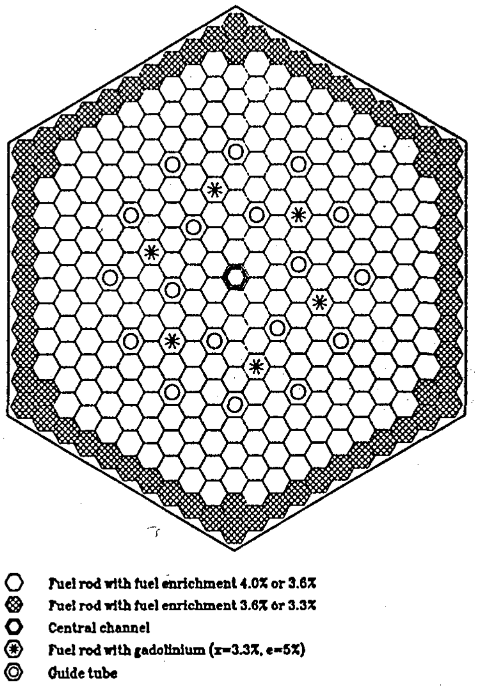


Fig.5. Advanced fuel assembly map (6 U-Gd rods)
(x - fuel enrichment, e – mass content of gadolinium oxide)

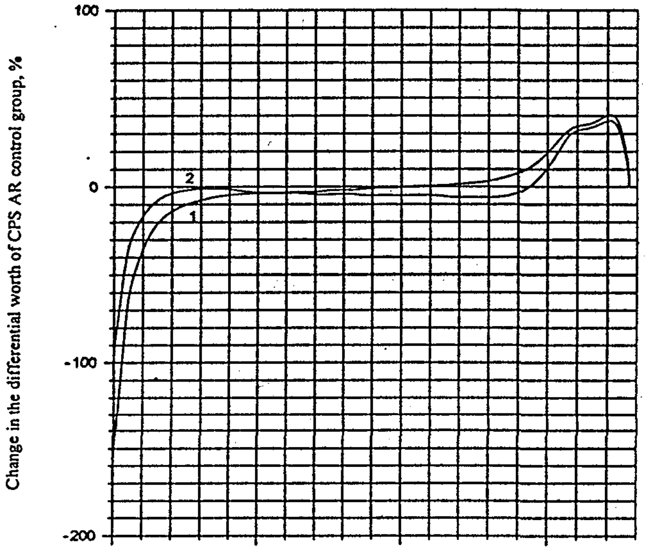
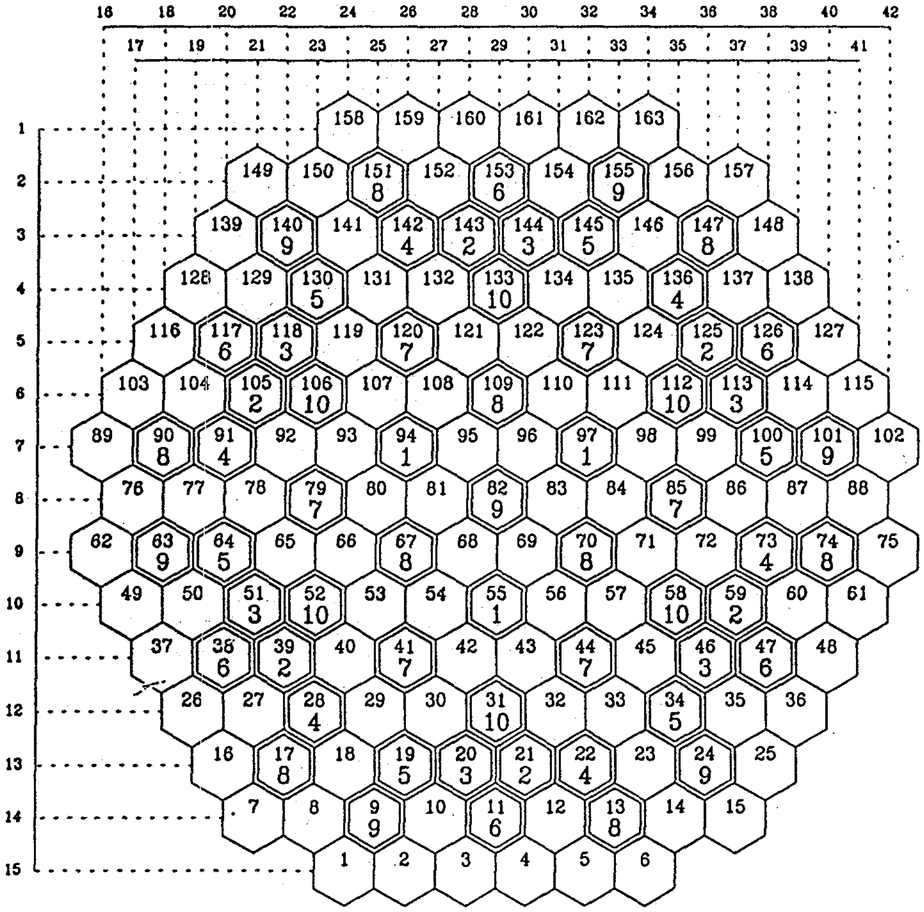


Fig.6. Change $(\{(\partial\rho/\partial h)_{carb.} - (\partial\rho/\partial h)_{comb.}\}/ (\partial\rho/\partial h)_{carb.})*100\%$ in the differential worth of CPS AR control group in the replacement of the carbide absorber rod by the combined one (1-BOC, 2 – EOC; nominal power)



** - Number of fuel assembly

** - Number of CPS group

Fig.7. Distribution of CPS AR by groups in the VVER-1000 core (advanced fuel cycle)

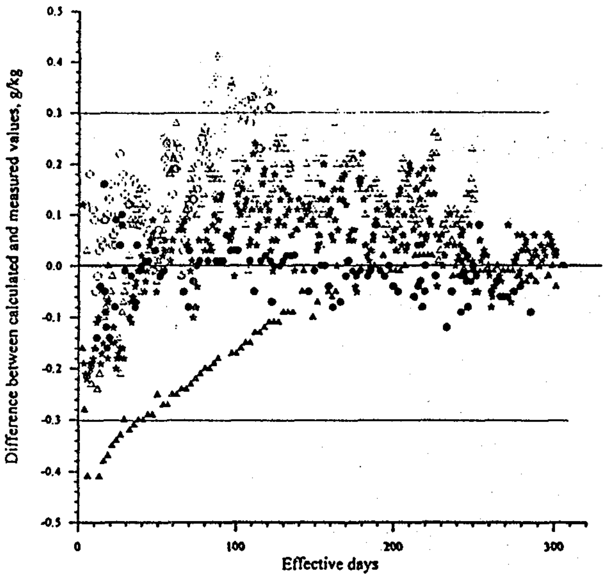


Fig.8. Difference (value_{mes}-value_{calc}) between calculated values of critical boric acid concentration and the measured ones obtained in the course of fuel loading operation with FAs with U-Gd rods. Balakovo NPP, Units 1 and 3

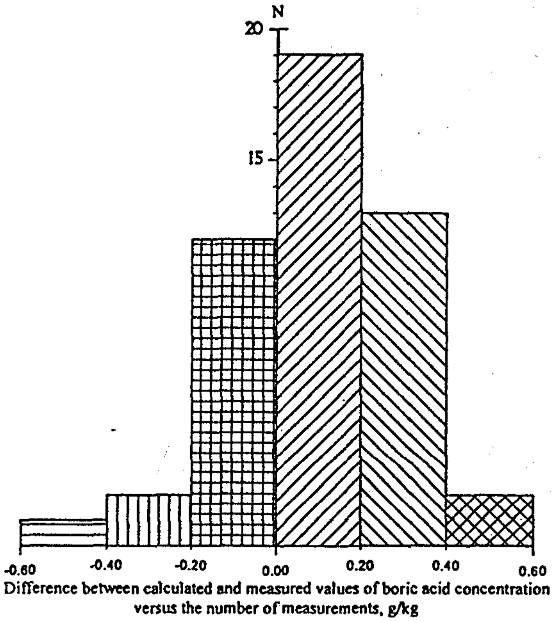


Fig.9. Distribution of differences between calculated and measured values (value_{mes}-value_{calc}) of critical boric acid concentration. Balakovo NPP, Units 1, 3 and 4. Beginning of cycle, zero power

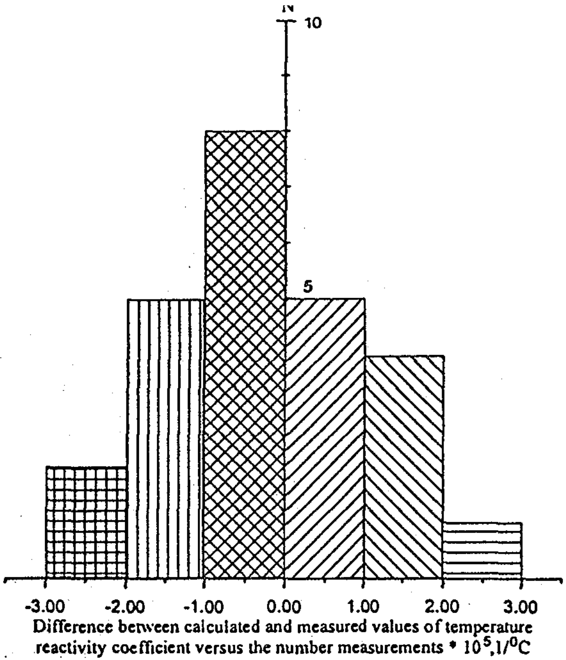


Fig.10. Distribution of differences (value$_{mes}$-value$_{calc}$) between calculated and measured values of temperature reactivity coefficient. Balakovo NPP, Units 1, 3 and 4. Beginning of cycle, zero power

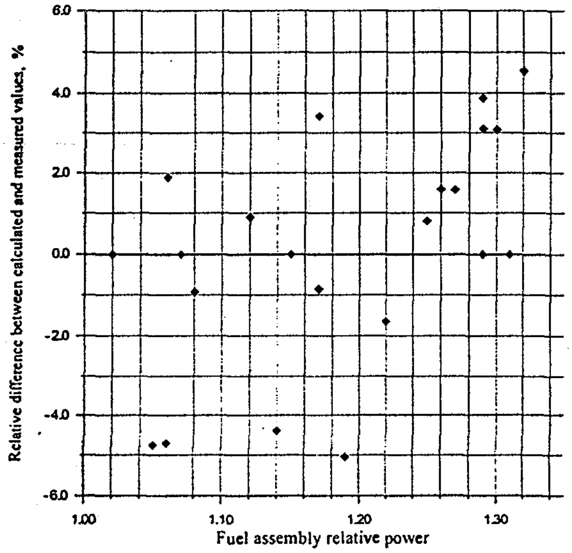


Fig.11. Distribution of relative differences $\left(\frac{value_{mes} - value_{calc}}{value_{mes}} \times 100\ \%\right)$ between calculated and measured values of fuel assembly relative power. Balakovo NPP, beginning of cycle, nominal power

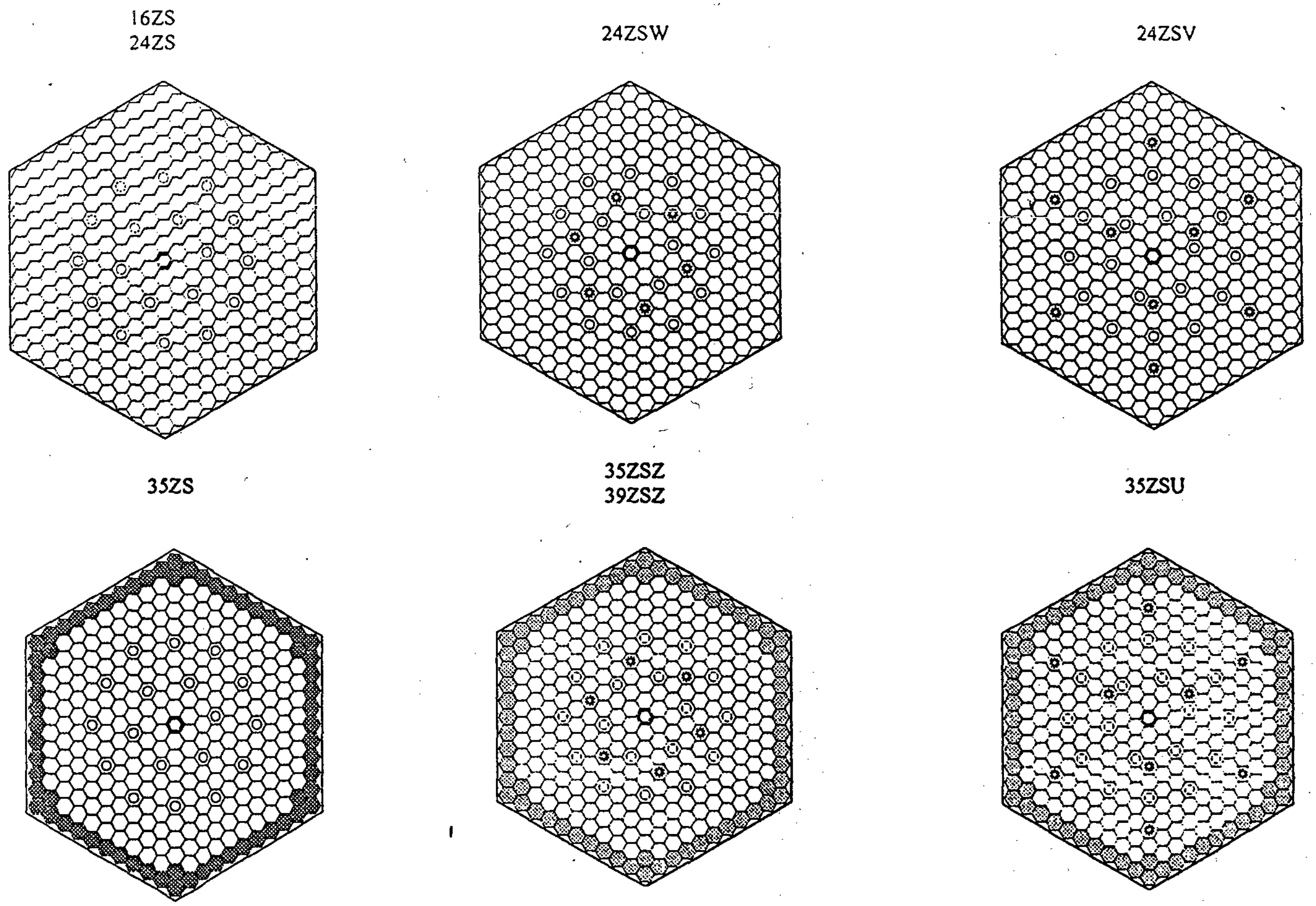


Fig. 12. Fuel assemblies map (advanced fuel cycle)

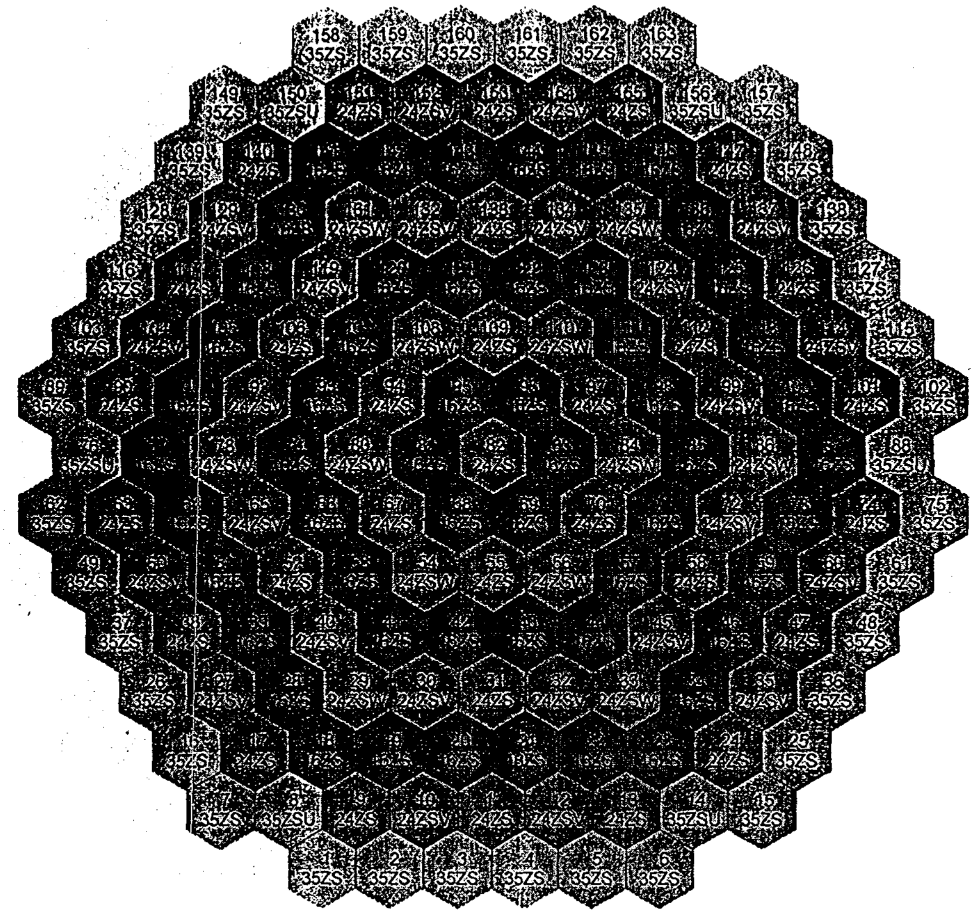


Fig.13. Map of the first fuel loading (advanced fuel cycle)

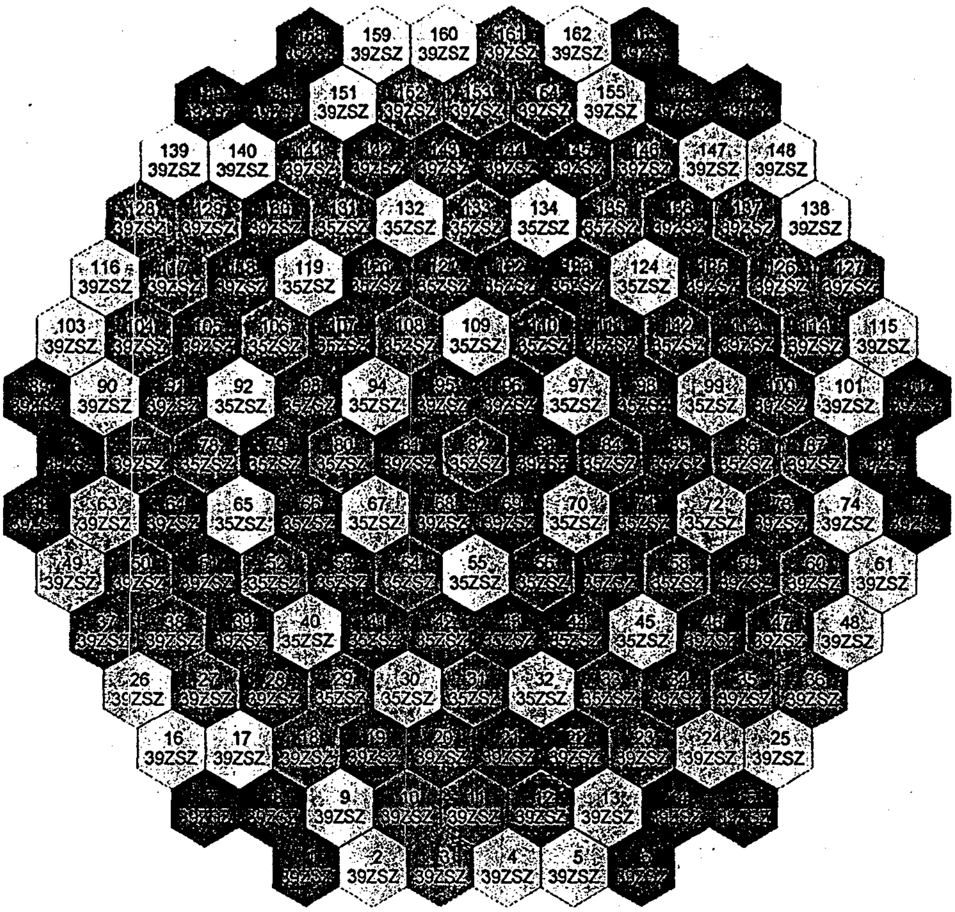


Fig.14. Map of the equilibrium fuel loading (advanced fuel cycle)

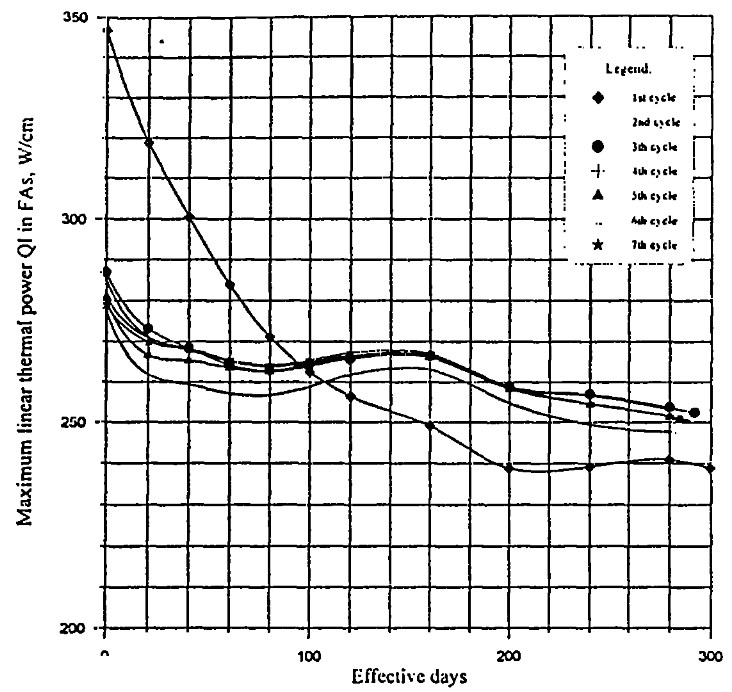


Fig.15. Maximum linear thermal power of fuel rods versus burnup

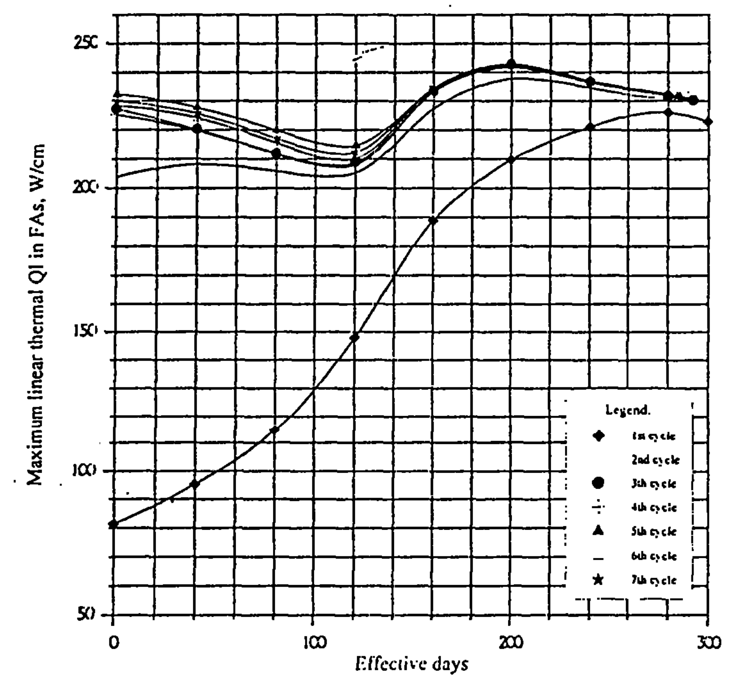


Fig.16. Maximum linear thermal power of U-Gd rods versus burn up

Table. Neutron characteristics of advanced fuel cycle

Name of characteristic				Value						
Cycle Number				1	2	3	4	5	6	7
Number of fresh FA loaded during refueling, pcs	Total			163	54	49	48	48	49	48
	with average enrichment, %	1.60		54	-	-	-	-	-	-
		2.40		67	-	-	-	-	-	-
		3.53		42	30	19	18	18	19	18
		3.90		-	24	30	30	30	30	30
Average enrichment of make up fuel in ^{235}U, wt %.				2.45	3.70	3.8	3.8	3.8	3.8	3.8
Duration of the reactor operation between refuelings, EFPD	working group position - 90% from the core bottom			300	280	292	281	286	289	284
Burn-up of unloaded fuel, MW*day/kgU	average over all FAs			12.0	25.2	33.6	39.5	41.4	41.2	41.3
	maximum over all FAs			12.4	25.5	39.1	41.0	43.6	43.3	43.4
Critical boric acid concentration ensuring subcriticality 5%, g/kg	cold, non-poisoned state, BOC, all CPS AR are out of the core			9.4	10.4	11.2	11.1	11.3	11.3	11.2
Critical concentration of boric acid in the coolant, g/kg	BOC, nominal power, xenon poisoned state			5.1	5.4	6.0	5.7	5.8	5.9	5.8
Coefficients of reactivity reactivity	coolant temperature, (1/ °C) * 10^{-5}	zero power level, BOC, all CPS AR withdrawn		-3.0	-1.0	-0.3	-2.0	-2.0	-2.0	-2.0
	coolant temperature, (1/ °C) * 10^{-5}	Nominal power	BOC	-13	-23	-24	-27	-27	-27	-27
			EOC	-50	-60	-64	-64	-65	-65	-65
	fuel temperature, (1/ °C)* 10^{-5}		BOC	-2.6	-2.7	-2.8	-2.8	-2.8	-2.8	-2.8
			EOC	-2.8	-2.9	-3.0	-3.0	-3.0	-3.0	-3.0
	boric acid concentration, 1/(g/kg) *10^{-2}		BOC	-2.2	-1.7	-1.6	-1.6	-1.6	-1.5	-1.6
			EOC	-2.2	-1.9	-1.8	-1.7	-1.7	-1.7	-1.7
Fuel rod power peaking factor, (Kr)				1.48	1.39	1.42	1.39	1.40	1.42	1.40
Maximum linear thermal power of fuel rods, W/cm				350	280	290	280	280	285	285
Repeat Criticality Temperature, °C	EOC, xenon poisoned state, no boron, direct calculation			155	175	165	170	170	170	170