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Fuel Cycle of VVER-1000: technical and economic aspects

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ABSTRACT

The paper contains estimations of dependences of technical and economic characteristics of VVER-1000 fuel cycle on number of charged FAs and their enrichment. In the study following restrictions were used:

- minimum quantity of loaded fresh FAs is equal 36 FAs, a maximum one - 78 (79) FAs,
- fuel enrichment is limited by value 4,95 %.

The following technical and economic characteristics are discussed:

- cycle length,
- average burnup of spent fuel,
- specific consumption of natural uranium,
- specific quantity of separative work,
- annual production of thermal energy,
- fuel component of electrical energy cost,
- electricity generation cost.

Results of estimations are presented as dependences of researched characteristics on cycle length, quantity of loaded FAs and their enrichments. The presented information allows show tendencies and ranges of technical and economic characteristics at change of fuel cycle parameters.

This information can be useful at definition of the fuel cycle parameters which satisfy the requirements of power system and exploiting organizations.

Introduction

An increasing interest to nuclear power stations energy production is observed today over the world. In these conditions it is necessary to draw attention not only to safety performance, but also to technical and economic parameters of operating reactors.

From the moment when the first VVER-1000 has been set in operation, the nuclerar fuel management in the reactor has changed. At power units with VVER-1000 the considerable quantity of innovations, influencing a fuel cycle, is introduced. The construction and materials of FAs, mass of fuel in FAs, burnable poison, etc. have been changed. As a result of evolution were designed new FA constructions.

In the paper the basic technical and economic characteristics of the fuel cycle, designed on basis of modern FA constructions, are analysed. Modern 12-month and 18-month fuel cycles are compared with previous fuel cycles.

1. Development of VVER-1000 Fuel Cycles

At NPPs with VVER-1000 the wide operating experience is accumulated, the considerable quantity of modifications is proved, checked and applied. This development allowed to improve parameters of fuel cycles. At start-up of the first unit with VVER-1000 in 1980 the fuel management supposed that the reactor would operate with two-year fuel cycle (Fig.

1a) of length about 300 EFPD and average burnup of spent fuel about 30 MW*day/kgU. However at the second half of 80th almost all of VVER-1000 reactors have been already operated at three-year fuel cycle. Average enrichment of fresh fuel was about 4.3 %, cycle length constituted about 300 EFPD, and average burnup of spent fuel – 40 MW*day/kgU. These fuel cycles were based on a FA with steel constructional elements.

Sufficient experience for transition to advanced FA (UTVS) with zirconium spacer grids and guiding tubes had been accumulated by the second half of 90th. For the fuel cycle, based on UTVS, annually were loaded 48 fresh FAs, average enrichment of fresh fuel constituted 3.8 % [1]. Cycle length constituted about 290 EFPD and average burnup of spent fuel – about 41 MW*day/kgUs. A load pattern (fig. 1c) with reduced leakage of neutrons was used. The fuel mass in a FA is increased by reduction to 1.5 mm of central hole diameter of fuel pellet.

In initial fuel loading the removable boric rods were applied. In the following transient and equilibrium loadings the uranium-gadolinium fuel was used. It allowed to reduce the losses of energy generation caused by incomplete burnup of absorber in removable boric rods. This fuel cycle was applied at the Rostov NPP and is being realised now at the Tianwan NPP in China.

The first zirconium constructions of FAs did not possess sufficient geometrical stability. Therefore the FAs with strengthened skeleton have been developed: TVSA by OKBM and TVS-2 by Gidropress [4]. Those FAs have different stabilization solutions, but almost identical relating neutronic characteristics.

The four-year fuel cycle, feeding 42 FAs [5], with strengthened skeleton has been developed in 2001. The interval of reactor operation between reloadings constituted approximately 290 EFPD. Loading pattern with the reduced leakage of neutrons was applied (Fig. 1d), average enrichment fuel is constituted about 4.3 %, and average burnup of spent fuel was increased to 49 MW*day/kgU [2,3]. In all cycles the burnable poison (Gd_2O_3) [6, 7] was integrated with fuel. The equilibrium fuel cycle was applied at Kalinin NPP unit1. In 2004 at Khmelnin NPP Unit 2 and at Kalinin NPP Unit 3 the operation of the first load has begun. Different options of this fuel cycle, are being realised now at operating NPPs of Ukraine and Bulgaria.

In the following analyses this fuel cycle will be accepted as the reference fuel cycle marked as «42 FA». Characteristics of this cycle will be flagged by star on the pictures, illustrating the characteristics of modern fuel cycle. Comparison of fuel cycle characteristics will give an estimate of VVER-1000 fuel cycle development trends.

Operating experience has confirmed reliability of TVSA and TVS-2 constructions. It stimulated the further modifications of FAs and improvements of fuel cycle of VVER-1000. Since 2003 various modifications of FAs are under test-industrial operation at Balakovo [8] and Kalinin NPPs: with fuel enrichment up to 4.95 %, with the increased mass and increased length of fuel rods (by 150 mm).

At the same time actions for shoter duration of reloading and servicing were applied at the Russian NPPs. These actions made possible to decrease duration of outage and to increase cycle length up to 320 EFPD.

Also possibility of unit operation with cycle length more than one year has been proved. In the actual fuel cycles at the Balakovo NPP the reactor operates between reloadings during 420-460 EFPD. In further cycles the length will be increased up to 500 EFPD.

Thus, modern requirements to VVER-1000 fuel cycle qualitatively differ from previous requirements. Today the fuel cycle should provide possibility of the reactor operation both at 12-month, and at longer interval between reloadings.

Potential of VVER-1000 fuel cycle, dependencies of fuel cycle technical and economic characteristics towards cycle length, number of charged FAs and their enrichment will be shown below. An attempt of comparison of modern 12-month and 18-month fuel cycles will be made.

The analyses are based on the strengthened construction of FAs which has experimental-industrial experience at the Russian NPPs. In such FAs length of fuel rods is equal

368 cm, fuel pellet diameter is equal 7.6 mm, central hole diameter of fuel pellet is equal 1.2 mm. FAs with described fuel parameters are being charged now on the Russian NPPs.

2. Natural Characteristics of Fuel Cycle

For demonstration of possible diapasons of VVER-1000 technical and economic characteristics the set of fuel cycles have been considered. This set includes equilibrium fuel cycles differing by quantity of charged FAs (from 36 to 78 pieces) and enrichment of loaded fuel (from 4.2 to 4.95 %). Load patterns for the set of equilibrium fuel cycles are shown in Fig. 2.

Load patterns with reduced leakage of neutrons were applied in these equilibrium fuel cycles. At core periphery are located 12 fresh FAs, other peripheral cells are occupied by FAs with maximum burnup.

Now it is possible to compare various equilibrium fuel cycles by cycle length and average burnup of spent fuel (Fig. 3). Maximum average burnup is achieved at feeding of 36 FAs with cycle length of about 320 EFPD. If a FA is located in the core not less two cycles then the maximum cycle length is about 590 EFPD.

The specific consumption of natural uranium (fig. 4) and specific quantity of separative work unit (Fig. 5) is observed for the same set of equilibrium fuel cycles. In calculation the concentration of ^{235}U in a depleted uranium is accepted according to Table 1. It is shown that the modern construction of FAs makes possible to implement 12-month fuel cycles were the parameters of fuel utilization are improved at comparison with a reference fuel cycle «42 FA». The specific consumption of natural uranium and specific quantity of separative work units increase when the cycle length grows. As a result, the fuel component of cost for long-duration cycles is more than for 12-month cycles.

It is interesting to observe the dependence of reactor annual power generation on cycle length. Annual reactor power generation depends on operating interval at nominal power and on average duration of outages. Outages differ by periodicity and duration of outage. The following variants of planned outages have been considered [16]:

- refuelling and regular maintenance outage - once by year,
- outage for refueling, maintenance work and main turbine-generator overhaul - once by four years,
- outage for refueling, maintenance work and reactor overhaul - once by eight years.

In Table 2 for 12-month, 18-month and 24-month fuel cycles the information about structure of outages during representative period is presented. The representative period is the minimum time interval during which all planned operations of reloading and inspections can be performed. For 12-month and 24-month cycles the representative period is equal to 8 years. For 18-month cycle the representative period is equal to 7.5 years (five cycles).

In Table 3 are presented duration of operations on reloading and overhaul which were used at calculation of average duration of outage for cycles length of 12, 18 and 24 months. Here are observed "Perspective " and "Realistic" duration of operations.

The «Perspective» durations conform to requirements of EUR [16] and are target for NPPs with reactors VVER-1000. In 12-month fuel cycle such duration of outages corresponds to the power load factor about 92 %. The "Realistic" duration of outages is less than «Perspective» duration in 2.5 times and corresponds to power load factor about 80 %.

From Tables 2 and 3 it is easy to calculate "Realistic" and "Perspective" average duration of planned outage. For "Realistic" regime of reloading the average annual duration of outage will constitute 68, 59 and 48 days in 12-month, 18-month and 24-month fuel cycles correspondingly. In case of a "Perspective" regime of reloading the average annual duration of outage will decrease to values 27, 24 and 19 days.

It is show, that in the long cycles annual duration of outage decreases. At "Realistic" durations of outages the annual power production in 18-month fuel cycle is by 4 % greater than in 12-month cycle. At achievement of "Perspective" parameters of outage duration the annual power production in a 12-month cycle will increase by 12%. However the transition from 12-month to 18-month fuel cycle has twice smaller effect – 2 %.

At calculation of annual power production, the duration of outage for intermediate fuel cycles (for example, a 15-month cycle) was determined by quadratic interpolation of average duration of planned outage in 12-month, 18-month and 24-month fuel cycles.

3. Cost Indexes of Fuel Cycle

It is difficult to estimate only by natural characteristics, what fuel cycle will be preferable - a traditional 12-month or a fuel cycle with the increased duration. The answer to this question can give the analysis of profit on electricity sales or the cost of electricity generating. Here an estimated cost of electricity generation is considered.

For calculations the following simple model is used

$$C(N_{FA}, E_{FA}, T_{rel}, P) = C_{op}(N_{FA}, E_{FA}, T_{rel}, P) + C_F(N_{FA}, E_{FA})$$

$$C_{op}(N_{FA}, E_{FA}, T_{rel}, P) = \frac{P}{T_{cycle} \cdot W} \cdot \frac{(T_{cycle}/\varphi + T_{rel})}{365} \qquad (1)$$

$$C_F(N_{FA}, E_{FA}) = N_{FA} * S_{FA} / (W * T_{cycle}),$$

where

$C_{op}(N_{FA}, E_{FA}, T_{rel}, P)$- operation component of cost,

$C_F(N_{FA}, E_{FA})$ - fuel component of cost,

N_{FA} - number of fresh FAs charged at reloading,

E_{FA} - averaged enrichment of charged FAs,

$S_{FA}(E_{FA})$ - cost of FA with enrichment E_{FA} [11-12]. Cost of the base stages of fuel cycle is contained in Table 1.

$T_{cycle}(N_{FA}, E_{FA})$ - length of equilibrium cycle in EFPD,

$T_{rel}(N_{FA}, E_{FA})$ - duration of reloading in days,

P - annual operation cost i.e. annual expenses for power generation without fuel expenses,

W =1000 MBт - electric output of NPP unit,

φ =0.99 - unit power load factor during cycle,

$T_{cycle}(N_{FA}, E_{FA})/\varphi$ - cycle length in days.

Annual operation cost independence on duration of fuel cycle was supposed. The operation cost (P) is determined from the relation:

$$\frac{C_F^{ref}(42, 4.3\%)}{C^{ref}(42, 4.3\%, 68, P_X)} = \frac{X}{100}, \qquad (2)$$

were

C_F^{ref} - fuel component of cost in a reference cycle “42 FAs”,

C^{ref} - cost of electricity generation in a reference cycle “42 FAs”,

X - ratio between fuel expenses (C_F^{ref}) and cost of electricity generation (C^{ref}) in a reference fuel cycle “42 FAs”

Annual operation cost (P_{10} , P_{20} and P_{30}) is determined for three ratios between fuel expenses and the cost of electricity generation ($X = 10\%$, $X = 20\%$ and $X = 30\%$). Values are determined under condition of "Realistic" duration of outages.

In Fig. 7 the dependencies are presented for relative electricity generation cost $c_{10}^{relative}(N_{FA}, E_{FA}, T_{rel}^{"real"})$ and cycle length T_{cycle} towards number of charged FAs and their enrichment

$$c_{10}^{relative}\left(N_{FA}, E_{FA}, T_{rel}^{"real"}\right) = \frac{C\left(N_{FA}, E_{FA}, T_{rel}^{"real"}, P_{10}\right)}{C^{ref}\left(42, 4.3\%, 68, P_{10}\right)}. \quad (3)$$

Here the accepted operation cost is such that in the reference four-year cycle “42 FAs” the fuel expenses are equal 10 % from the cost of electricity generating. Duration of reloading $T_{rel}^{"real"}$ was determined for each fuel cycle under condition of the "Realistic" dependence of an average duration of outages towards of the cycle length.

In Fig. 7 it is shown that at the accepted assumptions the minimum cost of electricity generation is achieved at the maximum enrichment and cycle length about 590 EFPD. The minimum cost of the electricity generation is approximately by 2 % less, than the same cost in 12-month cycle.

In Figs. 8 and 9 the same dependencies are presented for $P = P_{20}$ (Fig. 8) and $P = P_{30}$ (Fig. 9). It follows from the presented information that increasing of fuel component cost causes a change of the ratio between the cost of the electricity generation in 12-month and in 18-month fuel cycles.

When the fuel expenses are 20 % of the full expenses, the cost (Fig. 8) practically does not change at cycle length variation. In 18-month fuel cycle the annual electricity generation is more than in 12-month fuel cycle. Therefore in 18-month fuel cycle an annual profit on sales of electricity will be greater than in 12-month fuel cycle.

When fuel expenses increase up to 30 % (Fig.9), the cost of electricity generation in long-duration cycles increases too. In this case the minimum cost is achieved at the maximum fuel enrichment and at cycle length about 320 EFPD. The cost of electricity generation in fuel cycle with the largest cycle length exceeds by 3 % the minimum cost.

Figures 7-9 illustrate a trend of reduction of electricity generation cost in modern 12-month and 18-month cycles in comparison with the reference fuel cycle «42 FA». The cost of electricity generation can be reduced by 1-3 % depending on expense ratio.

It is shown that the cost of electricity generation depends on the ratio between fuel expenses and operation expenses. According to expression (1) operation expenses depend on duration of outage (T_{rel}). If the outage duration will change then the ratio between expenses will change too and therefore it can change the cost of electricity generating.

In Figures 10, 11 and 12 the dependencies are presented for relative electricity generation cost $c^{relative}\left(N_{FA}, E_{FA}, T_{rel}^{"perspective"}\right)$ and cycle length T_{cycle} towards number of charged FAs and their enrichment. Dependences are determined for the same values of annual operation costs (P_{10}, P_{20} and P_{30}). The "Perspective" average durations of outages are used.

From Fig 10-12 it is seen that the minimum of the electricity generation cost can be reduced by 8-9 % by outage duration decreasing (approximately by 2.5 times). The minimum of the electricity generation cost is achieved at fuel enrichment about 5 % and cycle length about 320 EFPD. The cost of electricity generation in 18-month fuel cycle is exceeded by 1, 2 and 3 % the minimum cost when annual operating expenses are equal P_{10}, P_{20} and P_{30} accordingly.

In the conditions of “perspective” duration of outages on the basis of the stated information it is difficulty to determinate definitively, what cycle is expedient - a 12-month or a 18-month fuel cycle. A 18-month fuel cycle can make a greater profit than 12-month's fuel cycle if the fuel expenses will be small and the price of the electricity sale will be relatively large. The analysis of profit on electricity sales is outside of this paper. Under such conditions the expediency of use of 18-month fuel cycle instead of 12-month fuel cycle is questionable.

Conclusion

In advanced fuel cycles for VVER-1000 the main tendencies of PWR evolution are presented:

- increased fuel enrichment and refueling ratio;

- increased burnup of spent fuel;
- construction elements of FA strengthened skeleton are fabricated from material with low neutron absorption;
- part of core excess reactivity is compensated by burnable poison (gadolinium) integrated with fuel;
- fuel loads are arranged with low radial neutron leakage.

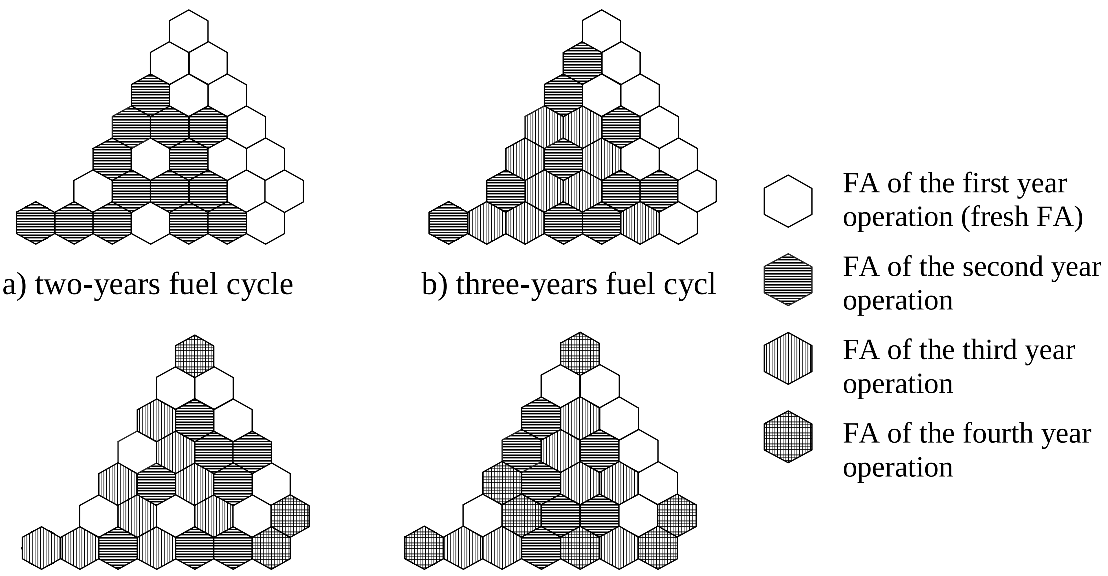
Basing on a modern construction of FAs (modifications of types TVS-2 and TVSA) it is possible to implement 12-month fuel cycles, where parameters of fuel utilization are improved in comparison with earlier applied fuel cycles.

Advanced fuel cycles for VVER-1000 ensure at satisfied safety requirements the possibility of cycle length variation in diapason from 300 to 590 EFPD and consequently possibility of NPP power production adaptation to demands of power net and to eventual changes in relations between components of electricity generation cost. At today duration of outages in modern 12-month and 18-month fuel cycles, the cost of electricity generation can be reduced by 1-3 % in comparison with the earlier implemented fuel cycles.

The comparative analysis of 12-month's and 18-month's fuel cycles has shown:

- in long-duration cycles the parameters of fuel utilization is yielded to analogous parameters of 12-month fuel cycle,
- quantity of annually electricity generation in 18-month cycles is by 2-4 % more, than in 12-month fuel cycle,
- expediency of use of 18-month fuel cycle instead of 12-month fuel cycle depends on duration of outage for a reloading and ratios between fuel and operation expenses,
- at the accepted assumption of "realistic" outages duration the 18-month's fuel cycle is expedient for using if in the today fuel cycle “42 FAs” the fuel cost is less then 20 % of the cost of electricity generating.

The cost of electricity generation can be reduced by 8-9 % by outage duration decreasing (approximately by 2.5 times). The information considered in the paper under the conditions of “perspective” duration of outages it is not sufficient to determine definitively which of the cycles is expedient - a 12-month or a 18-month fuel cycle.



c) three/four-years fuel cycle d) four-years fuel cycle

Figure 1. Patterns of equilibrium VVER-1000 core loads that are utilized in operating NPPs (symmetry sector 60^0)

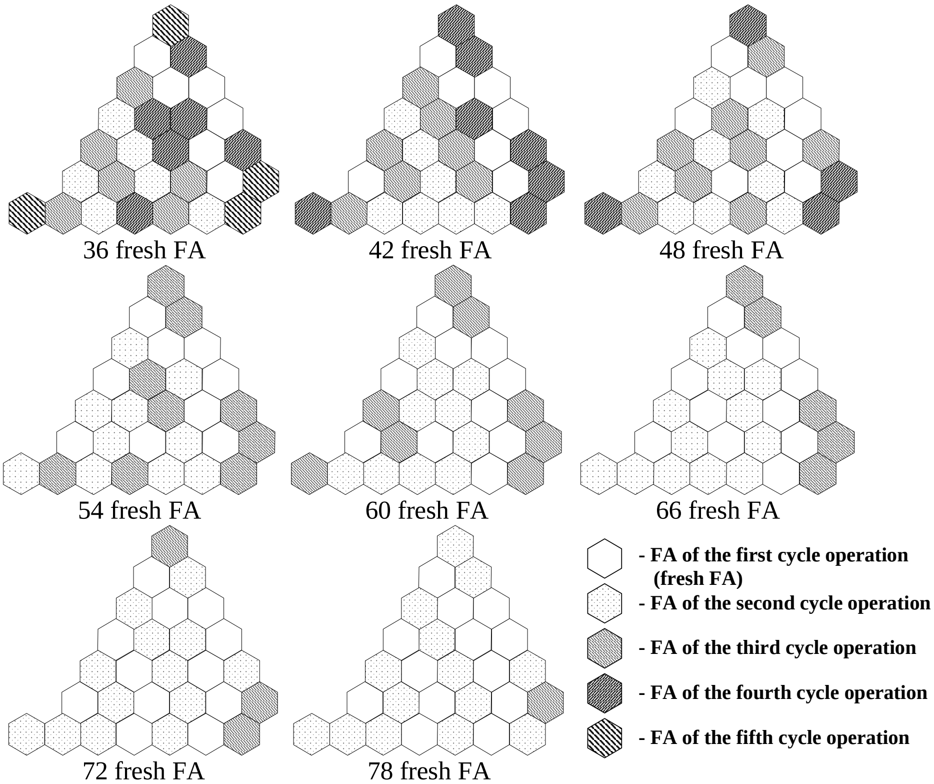


Figure 2. Patterns of equilibrium VVER-1000 core loads (symmetry sector 60^0)

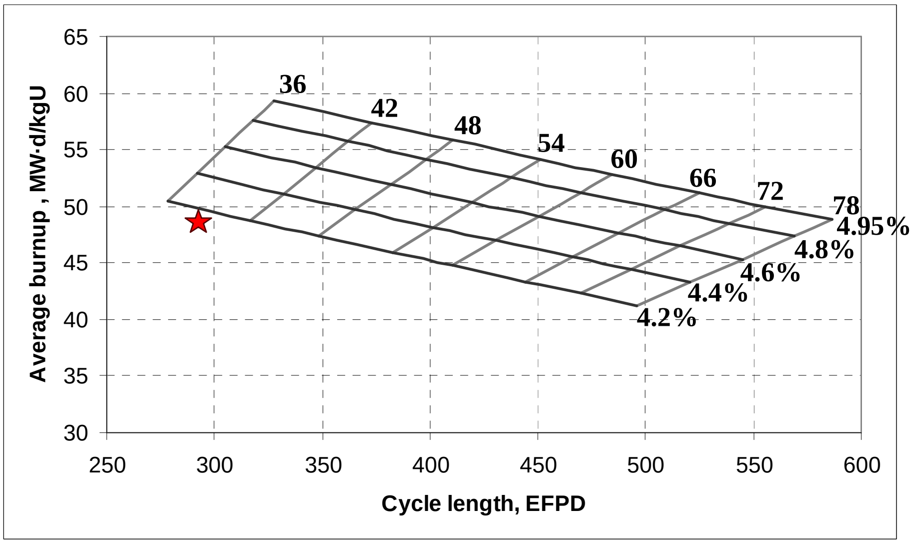


Figure 3. Average burnup versus number of loaded FAs, FA enrichment and cycle length

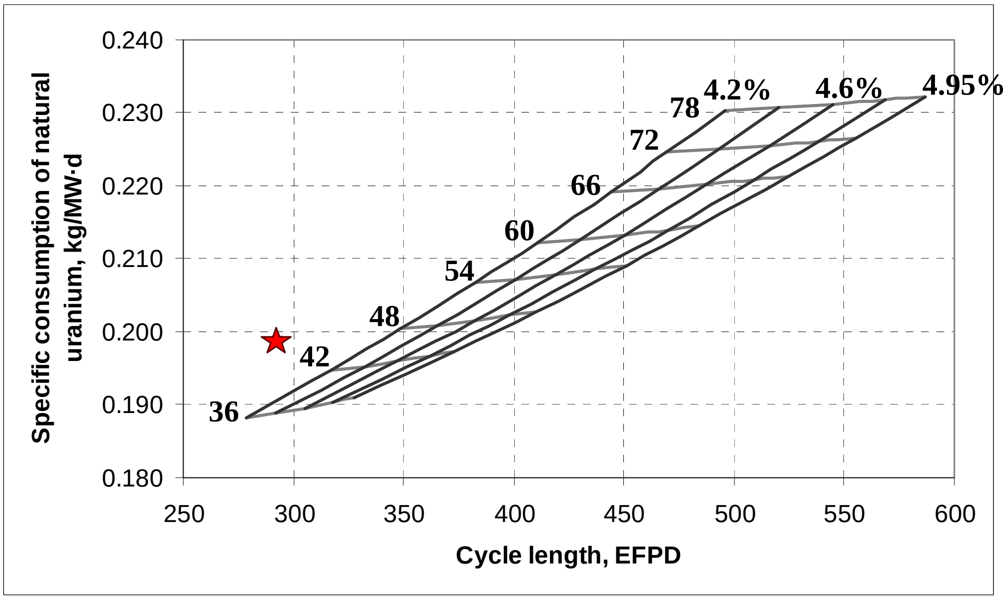


Figure 4. Specific consumption of natural uranium versus number of loaded FAs, FA enrichment and cycle length

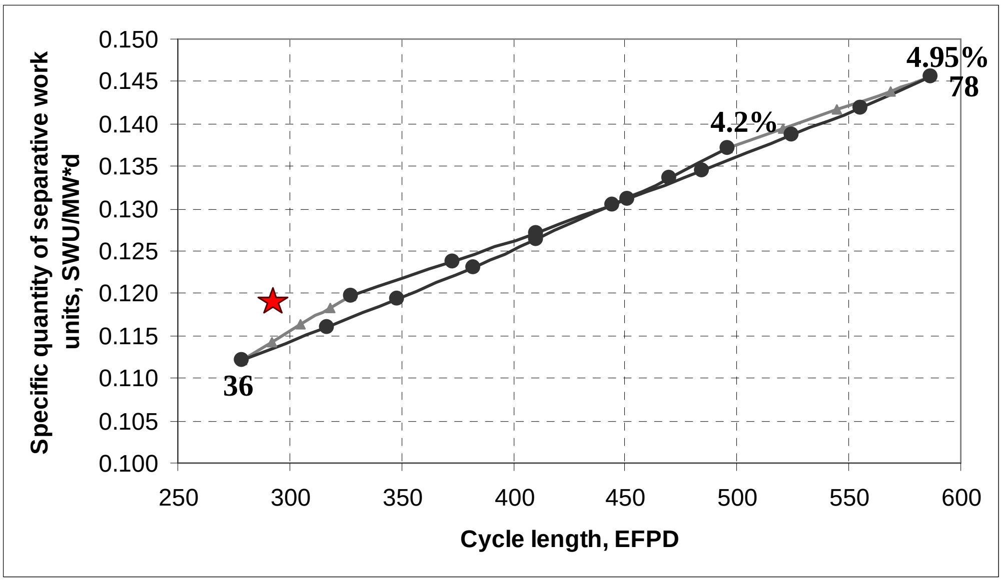


Figure 5. Specific quantity of separative work units versus number of loaded FAs, FA enrichment and cycle length

Table 1. Base cost data

Parameter	Value
The content ^{235}U in natural uranium, %	0.711
The content ^{235}U in depleted uranium, %	0.3
Cost of natural uranium and expense for conversion, \$/кгU_{nat}	131
Cost of enrichment, \$/SWU	160
Cost of fabrication FAs, \$ / kgU	320
Cost of transportation and storage of spent fuel, \$/kgU	800

Table 2. Number of planned outages during representative period

Characteristic	Fuel Cycle Length		
	12 months	18 months	24 months
Interval between initial moments of two sequential planned outages, month.	12	18	24
Duration of representative period, year	8	7,5	8
Number of planned outages during representative period	8	5	4
Number of outages for refueling and regular maintenance outage	5	2	1
Number of outages for refueling, maintenance work and turbine generator overhaul	2	2	2
Number of outages for refueling, maintenance work and reactor overhaul	1	1	1

Table 3. Duration of planned outages

Outages	Duration of planned outages	
	"Perspective"	"Realistic"
Outage for refueling and regular maintenance outage, day	20	50
Outage for refueling, maintenance work and turbine generator overhaul, day	30	75
Outage for refueling, maintenance work and reactor overhaul, day	40	100
Duration of long outage for major repairs or replacements of large components, days for all exploitation time of reactor	150	375

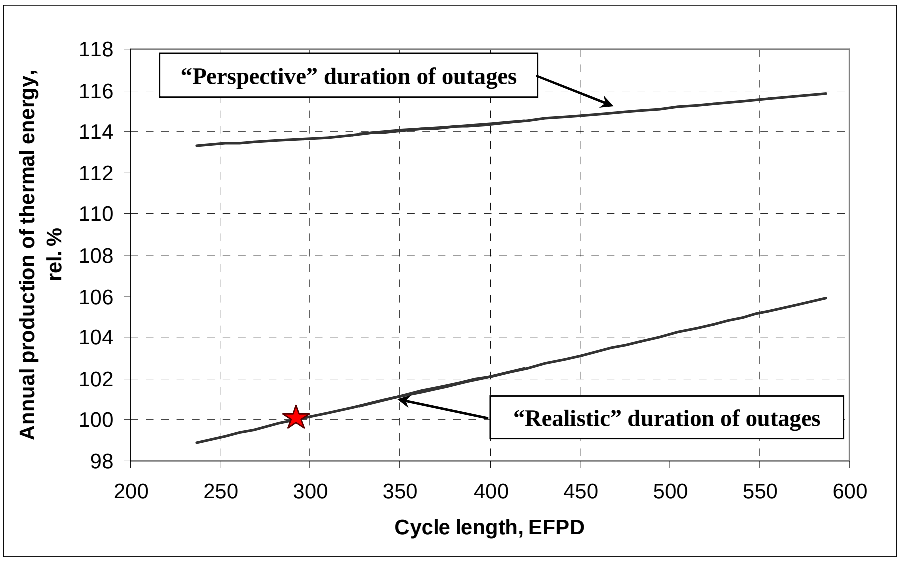


Figure 6. Annual thermal energy production versus cycle length

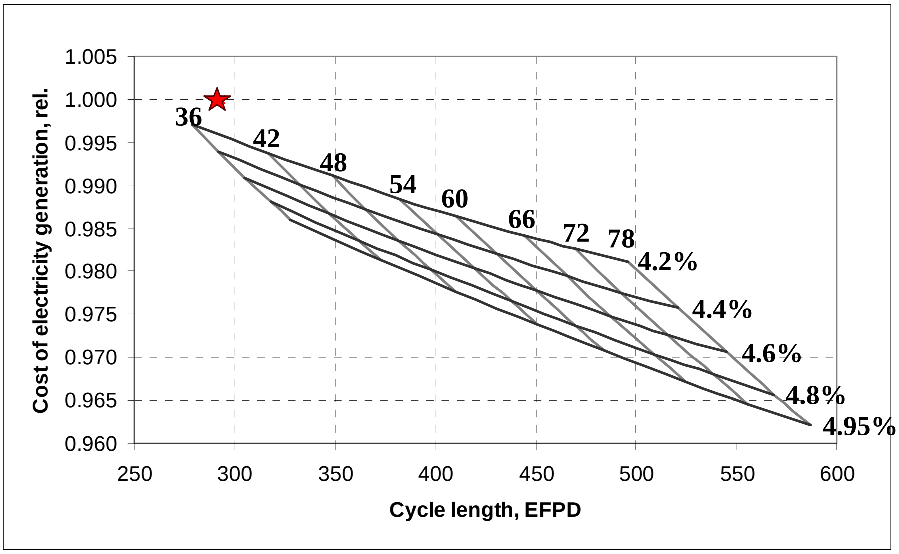


Figure 7. Cost of electricity generation versus number of loaded FAs, FA enrichment and cycle length (cost of fuel - 10%, “realistic” reloading)

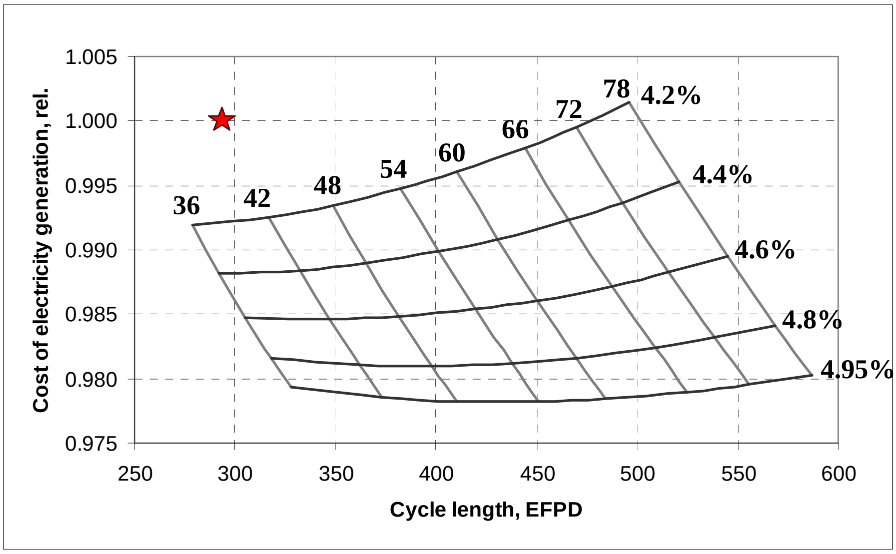


Figure 8. Cost of electricity generation versus number of loaded FAs, FA enrichment and cycle length (cost of fuel - 20%, “realistic” reloading)

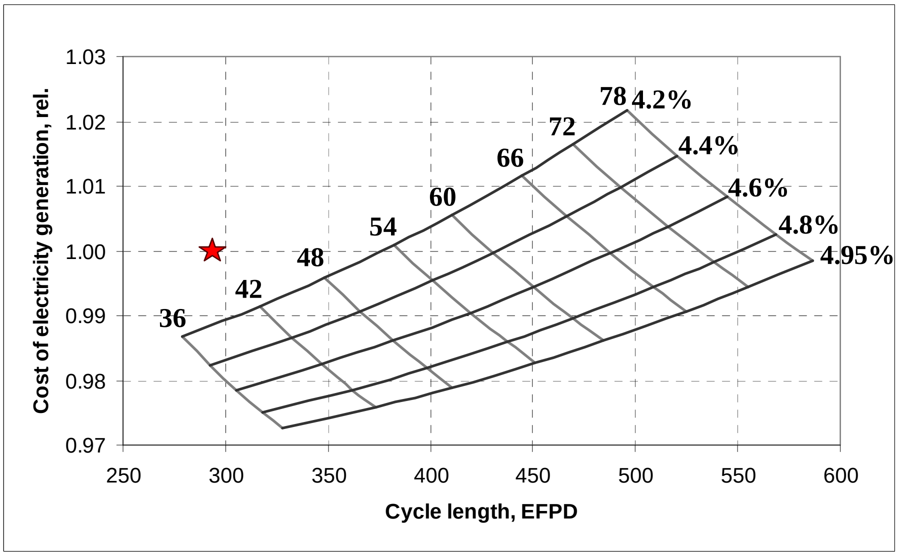


Figure 9. Cost of electricity generation versus number of loaded FAs, FA enrichment and cycle length (cost of fuel - 30%, “realistic” reloading)

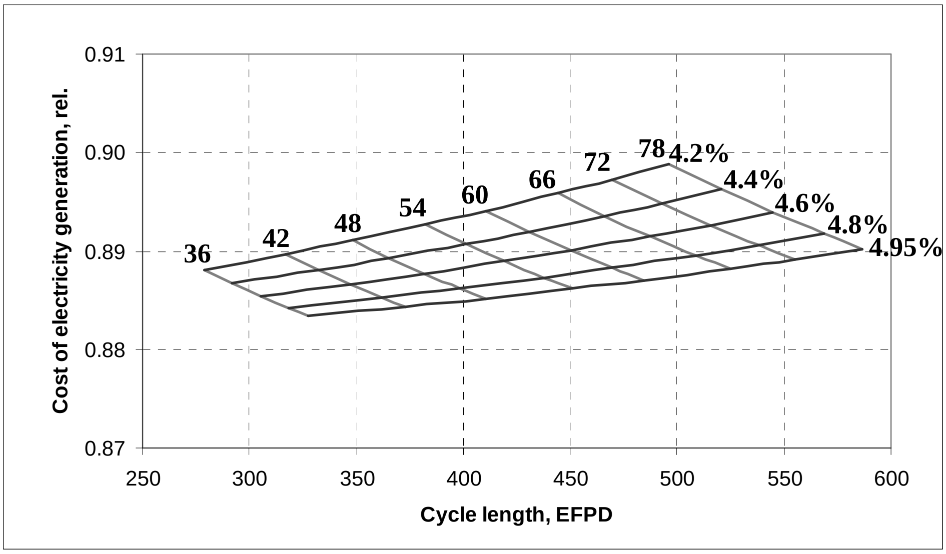


Figure 10. Cost of electricity generation versus number of loaded FAs,
FA enrichment and cycle length (cost of fuel - 10%, “perspective” reloading)

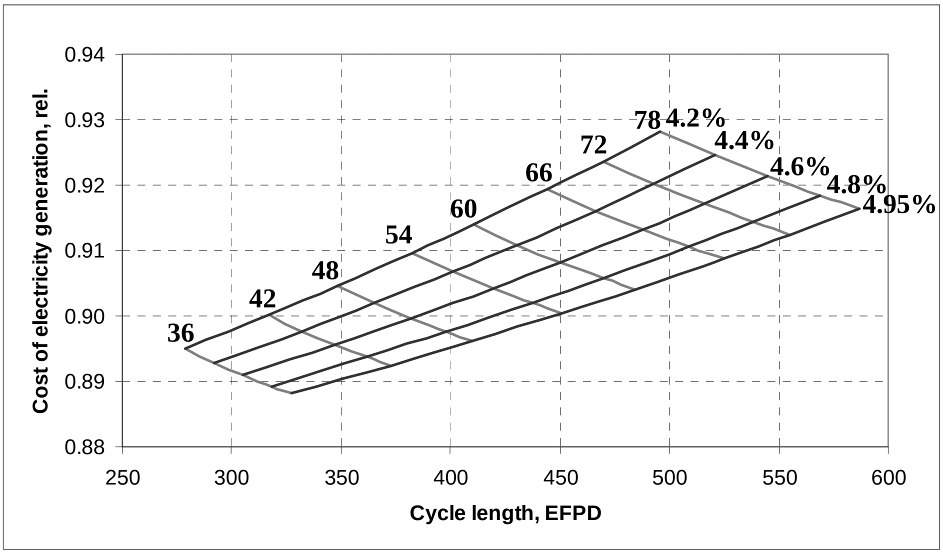


Figure 11. Cost of electricity generation versus number of loaded FAs,
FA enrichment and cycle length (cost of fuel - 20%, “perspective” reloading)

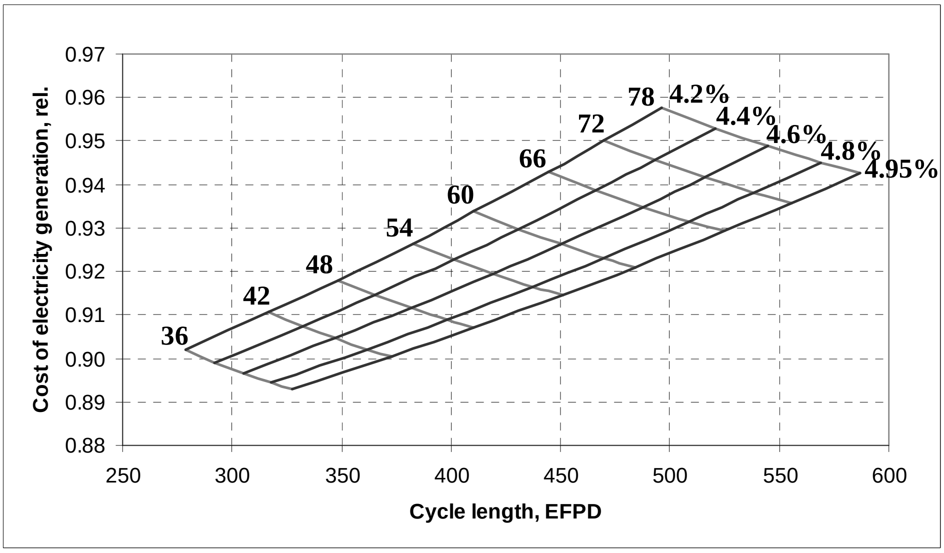


Figure 12. Cost of electricity generation versus number of loaded FAs,
FA enrichment and cycle length (cost of fuel - 30%, “perspective” reloading)

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