Fuel and fuel cycles with high burnup for WWER reactors

V. Chernushev, F. Sokolov
Joint Stock Company TVE,
Moscow, Russian Federation

XA0202222

Abstract. The paper discusses the status and trends in development of nuclear fuel and fuel cycles for WWER reactors. Parameters and main stages of implementation of new fuel cycles will be presented. At present, these new fuel cycles are offered to NPPs. Development of new fuel and fuel cycles based on the following principles: profiling fuel enrichment in a cross section of fuel assemblies; increase of average fuel enrichment in fuel assemblies; use of refuelling schemes with lower neutron leakage ("in-in-out"); use of integrated fuel gadolinium-based burnable absorber (for a five-year fuel cycle); increase of fuel burnup in fuel assemblies; improving the neutron balance by using structural materials with low neutron absorption; use of zirconium alloy claddings which are highly resistant to irradiation and corrosion. The paper also presents the results of fuel operation.

1. INTRODUCTION

The ways of increasing the technical and economic characteristics of the nuclear fuel for NPPs with WWER-440 and WWER-1000 reactors are rather traditional. First of all, they include the further improvement of the operational reliability and fuel burnup, and the increase of the fuel cycle length. These directions are actively dictated by NPP's operators.

However, the strict conditions of the nuclear fuel operation result in the reduction of its operational reliability.

The following problems can be mentioned during the NPPs operation with WWER reactors:

- time extension for inserting absorber rods of WWER-1000 control and protection system (CPS) (and sometimes, sticking) because of fuel assembly guide tubes bowing. Besides, fuel assembly bowing might lead to the creation of water gaps beyond the design ones, that in its turn may result in the local growth of power rating;
- the fuel rods failure caused by fretting wear of a cladding due to more intensive conditions of hydrodynamic effect of the coolant flow in previous WWER-440 designs.

The above mentioned as well as other problems under the conditions of the current strategy for reactors operation raise serious questions on the nuclear fuel reliability, the volume of the required R&D activities, and the accumulation of the sufficient operational experience. Also, a substantial scope of the activities in licensing the nuclear fuel with higher burnup and lifetime in normal and emergency modes.

All the abovementioned has required from the Russian nuclear fuel supplier JSC TVEL to make a comprehensive critical analysis of the design, production and operation of the nuclear fuel for NPPs with WWER reactors. As a result, under Minatom of Russia a special complex programme on the nuclear fuel and nuclear cycles improvement with a participation of the leading nuclear scientific centeres of Russia was developed. This programme includes a stage-by-stage introduction of the advanced nuclear fuel and fuel cycles with overall calculated experimental and operational testing of reliability and safety.

Table 1. Characteristics of WWER-440 Fuel Cycles

Fuel cycle	Average FA enrichment, %	Core lifetime, effective days	Average burnup, MWxd/kg U	Natural uranium consumption, kg/MW(heat)·day
Three-year fuel cycle (design)	3.28 (3.6; 2.4; 2.4)	292	28.9	0.247
Four-year fuel cycle, zirconium spacer grids, 3.82 %	3.62 (3.8; 2.4)	325	41.0	0.207
Five-year fuel cycle, zirconium spacer grids, 3.82 %	4.12 (4.21; 3.6)	337	45.0	0.198
Five (Gd)-year fuel cycle, 4.4 %, U Gd fuel assembly	4.28 (4.4; 3.6)	337	49.0	0.198

Table 2. Modernization of WWER-440 Fuel Cycles

Fuel cycle	Implementation	
	Implemented at	Introduction Stage
Four-year fuel cycle with fuel 4.4 % (non-profiled)	3^{rd} unit at Kola NPP	Experimental use at Rovno NPP
Zirconium spacer grids	3^{rd} unit at Novovoronezhsk NPP	At the rest of NPPs including experimental use at Loviisa NPP
Five-year fuel cycle with fuel 4.4 % (non-profiled)	3^{rd} unit at Kola NPP	
Modernized four-year fuel cycle with fuel 3.82 % (enrichment profiling, zirconium spacer grids, in-in-out)	4^{th} unit at Novovoronezhsk NPP (from 1995)	Czech NPPs (from 1998), Slovakian NPPs (from 1999)
Modernized four-year fuel cycle with fuel 4.21 % (enrichment profiling, zirconium spacer grids, in-in-out)		1^{st} unit at Rovno NPP (313 fuel assemblies in the core) from 1999
Modernized five-year fuel cycle with fuel 4.21 % (enrichment profiling, zirconium spacer grids, in-in-out)		2^{nd} unit at Rovno NPP (349 fuel assemblies in the core) from 1998
Experimental use of fuel assemblies 4.41 %, zirconium spacer grids, uranium-gadolinium fuel		4^{th} unit at Kola NPP from 1998

2. WWER-440

The characteristics of fuel cycles that have been developed for WWER-440 NPPs, as well as main stages in their current implementation are shown in Tables 1 and 2. As seen from Tables 1 and 2, the characteristics of nuclear fuel and fuel cycles stipulate the use of the principles in modern nuclear power engineering:

- profiling fuel enrichment in a cross section of fuel assemblies;
- increase of average fuel enrichment in fuel assemblies;
- use of refuelling schemes with lower neutron leakage ("in-in-out");
- use of integrated fuel gadolinium-based burnable absorber (for a five-year fuel cycle);
- Increase of fuel burnup in fuel assemblies.

By now, more than 56 000 fuel assemblies (7,000,000 fuel rods) have operated used at 28 NPP units with WWER-440. High operational reliability of WWER-440 nuclear fuel is characterized by the average number of leaking fuel rods about ~$3x10^{-5}$ 1/year.

It should be noted that the operational reliability of the previous WWER-440 designs is somewhat lower, and in recent years several cases of leaking fuel rods have been reported. The reason is that the fuel assemblies of the previous designs (of the W-*179/230* type) are subjected to a more intense hydrodynamic impact of coolant flow.

The design of such fuel assemblies has been improved based on the results of numerous design and experimental work aimed at increasing the vibration strength of a fuel rod cluster. At present, it is under commercial production.

3. WWER-1000

WWER-1000 was developed based on successful operational experience of NPPs with WWER-440 reactors. At present, WWER-1000 is the main nuclear reactor in the Russian nuclear industry. Naturally, the development and production of WWER-1000 nuclear fuel proceeded from the experience with WWER-440.

Nuclear fuel and fuel cycles were updated continually from the beginning of operation of NPPs with WWER-1000 (the first unit with WWER-1000 was started up 1980). Below follow the world wide trends in upgrading nuclear fuel and fuel cycles:

- improving the neutron balance by using structural materials with low neutron absorption;
- use of a integrated fuel burnable absorber;
- use of an improved core layout with low neutron leakage;
- increase of the fuel burnup rate;
- increase of the duration of a fuel cycle;
- use of zirconium alloy claddings which are highly resistant to irradiation and corrosion;
- possible operation of the core under NPP load-follow conditions.

Table 3. Characteristics of WWER-1000 Fuel Cycles

Fuel cycle	Average FA enrichment, %	Core lifetime, effective days	Average burnup, MWxd/kg U	Natural uranium consumption, kg/MW(heat)·day
Three-year fuel cycle with a burnable absorber (design)	4.31	291	40.3	0.243
3-to-4-year fuel cycle with U Gd fuel assemblies with zirconium spacer grids and guide channels	3.86	293	42.7	0.205
Four-year fuel cycle with U Gd fuel assemblies with zirconium spacer grids and guide channels	4.17	291	47.7	0.198

includes all the stages of calculation and experimental validation and studies; industrial operation of the experimental batches of fuel assemblies in commercial WWER-1000 reactors at NPPs; as well as detailed post-irradiation examination of spent fuel assemblies at a specialized research institute.

Therefore, a multistage and lengthy procedure for developing and licensing nuclear fuel conducted by JSC "TVEL" ensures a high level of reliability, cost-efficiency and safety of fuel.

The main characteristics of WWER-1000 fuel cycles (including design ones) for steady state refuelling are shown in Table 3. The design fuel cycles shown there differ in terms of progress made in development, licensing and approbation procedures.

It should be noted that experimental and industrial operation of WWER-1000 advanced fuel assemblies with zirconium spacer grids and zirconium guide tubes, and uranium-gadolinium fuel at commercial NPPs in Russia (*Balakovo* and *Novovoronezh* NPPs) and Ukraine (Zaporozhskaya and Rovno NPPs) has been under way for more than six years. There was not a single case of a leaking fuel rod over four fuel campaigns with a design time of three years (average burnup in a fuel assembly was ~49 MWd/ kgU). The successful use of fuel assemblies (totalling 312,000 fuel rods) may give grounds for licensing a project of a four-year fuel cycle based on the advanced fuel assemblies with uranium-gadolinium fuel to start its full-scale introduction at WWER-1000 NPPs somewhere between 2001 and 2002.

In 1997, the development was completed of fuel assemblies with a constantly functioning reinforced skeleton supported by spacer grids and special angels that were not loaded by external forces. This design solution does not allow fuel assemblies to bow in the course of operation and increases the stability of fuel assemblies thermo-mechanical behaviour. In 1998 12 fuel assemblies were loaded at Unit I of Kalinin NPP for experimental and industrial operation.

By now, about 20,000 fuel assemblies ($6x10^6$ fuel rods) have been irradiated at 20 WWER-1000 reactors. According to the results of fuel assemblies operation, the average number of leaking fuel rods amounts to $\sim 1.8x10^{-5}$ per a spent fuel cycle (in recent years), which testifies to a rather high operational reliability of the fuel.

Therefore, the characteristics of the updated fuel cycles for NPPs with WWER-440 and WWER-1000 have the following advantages over the design ones:

- decrease in consumption of natural uranium by 12 – 19 %;
- reduction in the total number of fuel assemblies used by 25-30 % (as a result, costs incurred at transportation and storage of spent fuel will be cut, too);
- decrease by 20-25 % in neutron flux per reactor vessel;
- increase in fuel burn-up in fuel assemblies.

Major guidelines for further improvements in WWER nuclear fuel and fuel cycles based on the successful R&D results, that are now under way, are aimed at:

- development of nuclear fuel with a burnup rate of up to 60 MW·day/ kg U;
- creating a five-year WWER-1000 fuel cycle;
- development of fuel cycles with campaign duration ranging from 18 to 24 months;
- development of nuclear fuel and algorithms for reactor management, which ensure NPP's operation under load-follow condition;
- involving reprocessed uranium in the fuel cycle.