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Physical and Power Start-up of WWR-K Research Reactor with LEU Fuel

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ABSTRACT

The paper presents the main results of the physical and power start-up of the WWR-K research reactor with low-enriched uranium fuel. Physical startup was carried out in March and April 2016, and power startup in May-June 2016.

The first criticality was achieved upon loading the core with 11 fuel assemblies of the 1st type (8-tube assemblies) and 10 fuel assemblies of the 2nd type (5-tube assemblies). Working load of the core was composed of 17 fuel assemblies of the 1st type and 10 fuel assemblies of the 2nd type. The reactivity margin was 7.2 % Δk/k, the total efficiency of compensation and automatic regulation rods was 9.9 % Δk/k, the efficiency of safety rods was 2.9 % Δk/k, the subcriticality of the core was 2.7 % Δk/k.

The absolute values of thermal (E_n<0.625 eV) and fast (E_n>1.15 MeV) neutron flux densities have been measured by activation detectors. Results of measurements showed double increase of the thermal neutron flux density in the center of the core.

Rise of the power up to the nominal level was carried out in steps accompanied with the experimental studies. The temperature feedback at temperature above ~25ºC was negative, making the reactor stable, while the absolute magnitude of this effect is negligible, that provides a good controllability of the reactor.

Results of the physical and power startup demonstrated that VVR-KN LEU fuel designed for WWR-K reactor conversion made it possible to improve the reactor performance.

1. Introduction

Following trend in Kazakhstan policy on support of nuclear weapons nonproliferation and minimization of high-enriched uranium in research nuclear installations, the Kazakhstan Institute of Nuclear Physics (INP) implements activities on conversion of the WWR-K research reactor. In a period from 2003 to 2006, the calculation studies were performed to choose designs of LEU fuel element, LEU fuel assembly and fuel composition in view of WWR-K reactor conversion [1-4]. After consideration of wide versions of the FA designs, the design of the FA composed of eight tubes of hexagonal cross-section was chosen as optimum for WWR-K reactor. It is named as VVR-KN FA, The FA outer dimension, 66.3 mm, allows usage of old support grid of the core. The FA fuel elements are thin-walled (1.6 mm). Fuel composition is uranium dioxide, dispersed in aluminum matrix, with uranium density 2.8 g/cm^3, enriched to 19.7% in uranium-235. Parameters of the new LEU FA and old HEU FA are presented in table 1.

Table 1. Parameters of the VVR-C FA and VVR-KN FA

Parameter	VVR-C FA	VVR-KN FA
Enrichment in U-235, %	36	19.7
Fuel composition	UO_2-Al	UO_2-Al
Uranium density, g·cm^{-3}	~0.8	2.8
Mass of U-235, g		
FA-1	111	245
FA-2	83	198
Amount of fuel tubes		
FA-1	5	8
FA-2	3	5
Fuel tube thickness, mm	2.3	1.6
Meat thickness, mm	0.9	0.7
Clad thickness, mm	0.7	0.45
Heat-transfer surface area, m^2	0.88	1.34

Following requirements of regulatory documents, life test of a batch of lead test assemblies (LTA) is to be performed prior to starting FA industrial production. Life test of three VVR-KN-type LTAs was carried out in the WWR-K reactor core in a period from 2011 to 2013. The life test lasted 480 effective days [5-14]. The average burnup ~50% in uranium-235 was reached in all three FAs.

Experimental studies of neutron-physical characteristics of the WWR-K reactor LEU core were carried out in the critical facility in a period from 2012 to 2015. The WWR-K physical startup core was modelled to full scale. Results of the studies confirm the results of calculations in support of opportunity for creation of compact core configuration with three high-flux irradiation channels (maximum thermal neutron flux density ~$2 \cdot 10^{14}$ neutrons/(cm^2·s), with safe building-up of critical load and work one, as well as the calculated first criticality load (11 FA-1 and 10 FA-2 [15, 16].

In an end of 2015 reactor was shut down in order to upgrade elements of the core, reactor control and protection system (CPS), actuators of CPS work elements, emergency electric system and emergency aftercooling system. In August 2015 HEU FAs were unloaded from the core. In March-April 2016 physical startup of the WWR-K RR with LEU fuel was held, and in May-June - power startup.

2. Physical startup

The WWR-K research reactor, which worked from 1967 with the fuel enriched in uranium-235 to 36%, is converted to a fuel enriched to 19.7%. Reactor conversion implies changing the reactor certified characteristics. Then, following the Kazakhstan regulatory requirements, the Reactor Safety Analysis Report (SAR) was revised. Prior the physical startup of the reactor, Safety analysis report of the WWR-K reactor with LEU was developed. SAR includes such main chapters as principles of safety assurance, analysis of potential accidents, operational limits and safe operation limits, nuclear safety, etc. [17].

The developed plan of WWR-K reactor physical startup with LEU fuel was coordinated with the Kazakhstan Committee of atomic and power supervision and control (regulatory body). The plan covers the following procedures:

- Critical mass building up – FA loading to the core to reach and fix reactor first criticality;
- Reaching core interim load; determination of efficiencies of the reactivity compensating WEs (KO), WEs of automate regulation (AR) and emergency protection (AZ);
- Reaching core work load, composed of 17 FA-1 and 10 FA-2; determination of efficiencies of the reactivity compensating WEs (KO), WEs of automate regulator (AR) and emergency protection (AZ);
- Determination of efficiencies of the most typical FA-1;
- Preliminary estimate of thermal power, with graduation of ACNP channels;
- Determination of the temperature reactivity effect;
- Determination of radiation state in reactor central hall;
- Measurement of spatial-energy distribution of neutrons in irradiation channels of the core.

Before reactor physical startup enormous work on upgrading reactor systems was implemented, namely: full replacement of reactor control and protection system, replacement of the reactor emergency aftercooling system (EAS), installing a new automatic radiation control system. The reactor new CPS (ASUZ-18R) meets IAEA requirements. Two pumps of EAS, each of the capacity 10 m^3/h, were replaced by two pumps of the capacity 45 m^3/h.

Physical startup of the WWR-K reactor with LEU fuel was imitated at the critical facility (CF). Results of experimental studies are in good agreement of the results of calculations described in reactor SAR.

Results

Critical mass building-up in course of physical startup was carried out in strict compliance with rules of nuclear safety at research reactors. There were no any FAs in the initial configuration of the core, aluminum displacers were installed in all cells of the core in order to eliminate FA loading to wrong cell.

When K_{eff}~0.98 (M~50) was reached, efficiencies of CPS WE were estimated in units of reverse multiplication thousands (RMT). The core load included 8 FA-1 and 10 FA-2.

On reaching multiplication factor ~50, in view of safety assurance, a subsequent FA was loaded with inserted several WE KO of the double net efficiency (in RMT) of the previous loaded FA. First criticality was reached with the core configuration depicted in figure 1.

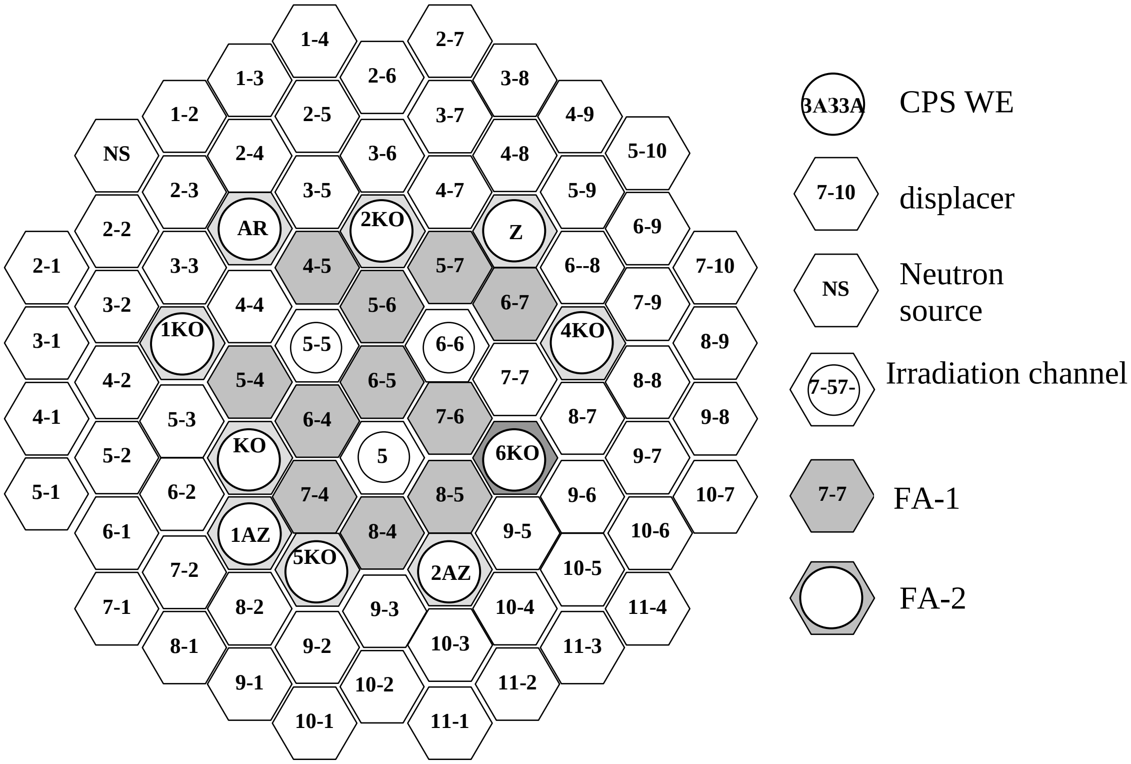

Fig. 1 Reactor first criticality load. 11 FA-1 and 10 FA-2

When the first criticality was reached and fixed, loading of the core with FAs was continued to obtain an interim load composed of 13 FA-1 and 10 FA-2 with the excess reactivity 3.4 %Δk/k. In this core configuration, graduation of CPS WE was carried out by a technique of reactivity compensation by two control rods (one rod is inserted to the core from its highest, whereas the second one is withdrawn from its lowest position in the core). Results of experimental data obtained at critical facility and at reactor are presented in table 2.

Table 2. Efficiency of CPS for the reactor core interim load (13 FA-1 and 10 FA-2)

CPS WE	**Efficiency, %Δk/k**	
	Reactor	**CF**
AR	0.23	0.21
1KO	0.72	0.74
2KO	1.84	1.95
3KO	2.32	1.75
4KO	1.03	1.08
5KO	1.08	1.32
6KO	2.01	1.76
∑KO and AR	9.23	8.81
1AZ	1.39	1.05
2AZ	1.07	1.02
3AZ	1.26	1.18
∑AZ	3.72	3.25

Next stage was building up of the core work load. Four FAs were loaded, one by one, to the core, forming work load composed of 17 FA-1 and 10 FA-2. Relevant core map is shown in figure 2.

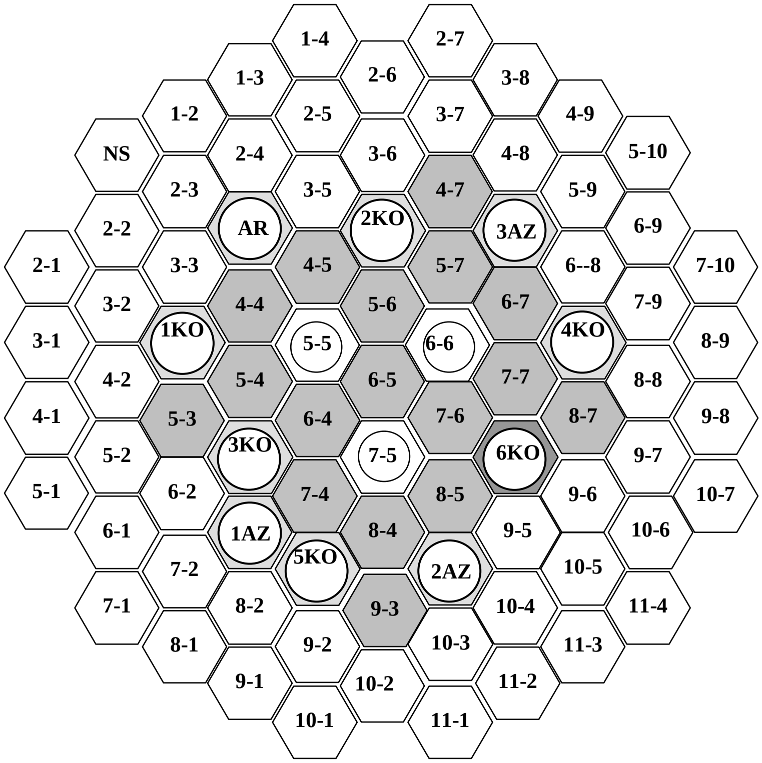

Fig. 2. Core map of the core work load: 17 FA-1 and 10 FA-2

Graduation of CPS WE for reactor core work load was carried out. Relevant results of experimental data obtained at critical facility and at reactor, as well as those presented in SAR, are given in table 3.

Table 3. CPS WE efficiencies for reactor work load (17 FA-1 and 10 FA-2)

CPS WE	**CF**	**Reactor**		
	Measured values	Measured values	**MCU**	**MCNP5**
AR	0.24	0.27	0.24	0.27
1KO	1.06	0.89	1.05	1.06
2KO	1.97	1.94	1.87	1.98
3KO	2.41	2.28	2.10	2.05
4KO	1.07	1.04	1.16	1.10
5KO	1.22	1.39	1.39	1.37
6KO	2.24	2.10	2.08	1.89
∑AR and KO	10.21	9.91	9.82	9.73
1AZ	0.93	0.93	0.81	0.90
2AZ	0.98	1.00	1.03	1.01
3AZ	0.93	0.94	1.01	0.94
∑AZ	2.84	2.87	2.85	2.84

The core excess reactivity comprises 7.2 % Δk/k; subcriticality is 2.7 % Δk/k.

With the core work load, measurements of spatial-energy distribution of neutrons were carried out in reactor central and peripheral irradiation channels of the core.

Absolute values of the thermal neutron flux density (E_n<0.625 eV) were measured by golden activation detectors by reaction ^{197}Au (n, γ) ^{198}Au. Detectors were irradiated both with and without cadmium filters.

Absolute values of the fast neutron flux density (E_n>1.15 MeV) were measured by indium activation detectors by reaction ^{115}In (n, n’) ^{115m}In. Detectors were irradiated in cadmium filters.

The results of measurement normed to reactor power 6 MW are given in table 4.

Table 4. Measured values of the thermal and fast neutron flux density for reactor work load

Cell ID	Neutron flux density, cm^{-2}·s^{-1}	
	E_n<0.625 eV	E_n >1.15 MeV
5-5 (center)	(2.0±0.2) • 10^{14}	(7.2±0.7) • 10^{13}
10-2 (periphery)	(6.8±0.7) • 10^{13}	(1.1±0.1) • 10^{13}

‘

Calculation results obtained with computer codes MCU-REA and MCNP are given in table 5 [18, 19].

Table 5. Calculated values of the thermal and fast neutron flux density for the core work load

Cell ID	Neutron flux density, x10^{14} cm^{-2}·s^{-1}			
	E<0.4 eV	E>1.15 MeV	E<0.4 eV	E>1.15 MeV
	MCU-REA		**MCNP**	
5-5	1.96	0.40	1.90	0.42
6-6	2.06	0.45	1.80	0.43
7-5	2.12	0.40	1.80	0.44
2-2	0.44	0.03	0.54	0.05
2-6	0.43	0.03	-	-
10-2	0.60	0.07	0.55	0.05
10-6	0.44	0.03	-	-
8-9	0.35	0.03	-	-

Axial distribution of the thermal neutron flux density was measured with dysprosium detectors by activation reaction ^{164}Dy (n, γ) ^{165}Dy. Axial distribution of the fast neutron flux density by detectors made of sulphur-32 in cadmium filters by activation reaction ^{32}S (n, p) ^{32}P.

Results of measurement of axial distribution of the axial distribution of neutron flux density n cell 5-5 for reactor power 6 MW are given in figure 3.

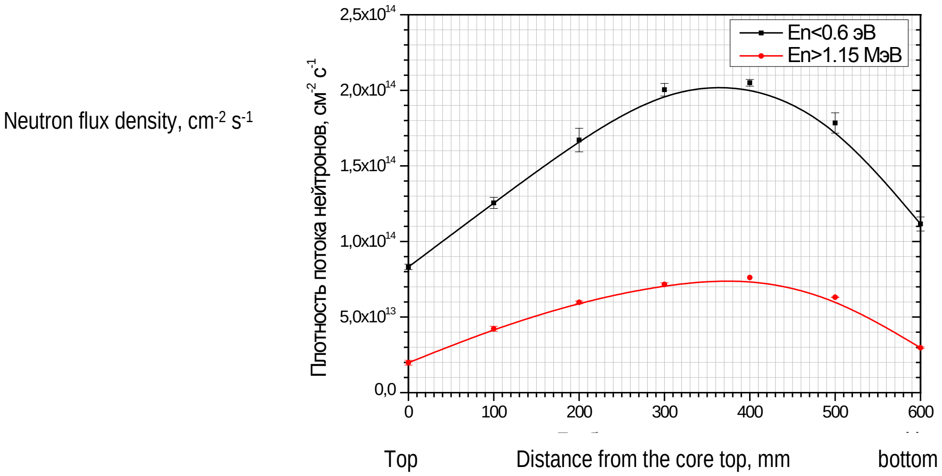

Fig. 3. Axial distribution of neutron flux density

3. Power startup

In May-June 2016, power startup of the WWR-K reactor with LEU fuel was carried out with the following main stages:

- step-wise rise of reactor power up to nominal level;
- measurement of reactivity temperature feedback at various power levels;
- check of CPS instrumentation functioning at various power level;
- determination of the reactivity effects related to power generation and poisoning;
- determination of characteristics of gamma and neutron fields in operators’ places .

Results

Step-wise rise of power up to 100%·N_{nom} (6000 kW) was done by means of automate regulator. The power was increase by steps of 5%·N_{nom} (300 kW) with one-hour staying at each step. Work of all technological systems and radiation background in reactor central hall were verified at each step. On 23 May 2016 the reactor power rating 6MW was reached.

Experiments on determination of the reactivity temperature coefficient were carried out at several power levels. An increase in the primary circuit coolant temperature was achieved at the expense of heat transfer from three working MCP to coolant. Position of the AR WE and coolant temperature in the core were recorded for every one-degree increase in coolant temperature. The reactivity temperature coefficient was determined by variation in position of the AR WE. As a result of measurement series, negative reactivity temperature coefficient, equal to -0.0016 % Δk/k/°C, was obtained.

The reactivity effects related to fuel poisoning and burning were determined in course of reactor work at nominal power during 10 days. Measurement technique was as follows:

- reactor nominal power (100% N_{nom} = 6000 kW) is reached;
- positions of the KO WEs, the AP WE are recorded, and excess reactivity are determined every two hours for 10 days;
- the reactivity effects related to uranium burnup and fuel posisoning are determined;

The final burnup comprised 3.7 % Δk/k. After going to reactor stationary poisoning (~72 h) the reactivity effect related to fuel burnup was determined. Reactivity loss at the expense of fuel burnup comprises 0.10% Δk/k per day of reactor operation at 6MW.

4. Conclusions

Results of the physical and power startups of the WWR-K reactor with LEU fuel are as follows:

1. First criticality is reached with 11 FA-1 and 10 FA-2 in the core. The same result is obtained at critical facility and via Monte Carlo calculations.

2. For the core interim configuration with 13 FA-1 and 10 FA-2, the efficiencies of the excess reactivity compensation work elements (KO WE), the automate regulator work element (AR WE) and emergency protection work elements (AZ WE) have been determined. The core excess reactivity is 3.4% Δk/k. Relevant calculated value of the excess reactivity given in SAR is 3.45% Δk/k.

3. The excess reactivity of the core work load (17 FA-1 and 10 FA-2) has comprised 7.2 % Δk/k, with subcriticality provided by CPS WEs equal to 2.7% Δk/k. At the critical facility the excess reactivity and subcriticality are, respectively, 7.6% Δk/k and 2.6% Δk/k. Relevant calculated values presented in SAR are ~7.0% Δk/k and 3.0 % Δk/k.

4. The determined efficiencies of KO WEs, AP WE and AZ WEs for the core work load meet NSR requirement, being in good agreement with relevant empirical estimates obtained at critical facility and with the calculated estimates presented in SAR as well.

5. Spatial-energy distributions of neutrons in reactor irradiation channels located in the core cells 5-5 and 10-2 have been studied. Results of measurement have shown that thermal neutron flux density in the core center has doubled.

6. The reactivity temperature feedbacks are negative, ensuring reactor intrinsic safety, stability and good control. The reactor reactivity temperature feedback equal to 0.0016 % Δk/k/°C is negative.

7. Levels of reduction of excess reactivity at the expense of stationary poisoning and fuel burnup have been found. Loss of excess reactivity at the expense of stationary poisoning has comprised 3.7% Δk/k. Loss of excess reactivity at the expense of fuel burnup has comprised 0.10% Δk/k per day at 6MW.

8. In course of reactor power startup, reactor and its technological systems demonstrated reliable functioning. The reactor new control and protection system ASUZ-18R meets all design requirements, assuring reactor safe operation.

9. The chosen work load of the core with VVR-KN FAs, developed specially for WWR-K reactor, have improved reactor work characteristics.

5. Acknowledgements

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