Calculation Studies To Substantiate Trial of Pilot Low-Enriched FAs * in the WWR-K Reactor

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ABSTRACT

Calculation studies are carried out to substantiate the WWR-K reactor conversion to low-enriched fuel (≤20%). Calculations support possibility to create in the WWR-K reactor core the conditions required for testing pilot FAs. Appropriate heat-hydraulic calculations are performed. Real operation cycles needed to achieve the average 60-% burnup are found with the computer code MCU-REA [1]. The determined reactor core characteristics show that the fuel test won't be an obstacle for other irradiation activities.

As is known, an in-reactor trial of a batch of new pilot FAs is the last and the most important pre-fabrication stage. As a rule, such trials are carried out in loop reactors, where close-to-natural FA operational conditions can be created. However, this way is too expensive; so possibility to carry out the trial in the pool-type reactor is evaluated.

Main requirements imposed on in-reactor trial of pilot FAs are as follows:

- the number of tested FAs is to be not less than three;
- the trial parameters (the FA power, the peak thermal flux, burnup, etc.) must be close, to the highest extent, to those related to the FA operation conditions;
- control of specified parameters of the trial is to be provided.

The WWR-K reactor is assumed to be converted to low-enriched fuel in the eight-tube thin-walled FAs with the 2.8-g·cm^{-3} uranium density in UO_2-Al fuel composition. The thickness of the mea and the FE are 0.7 and 1.6 mm respectively.

The main problem of the forthcoming trial in the WWR-K core is insufficient power of pilot FAs (although it's almost twice higher than that of the old one). That's why, in order to enhance the power of the pilot FAs in course of the trial, configuration and composition of the WWR-K core are assumed to be changed

To achieve working parameters of pilot FAs, beryllium displacer is installed in the core. The displacer has a through hole of the 140.5-mm diameter, forming neutron trap, where the thermal neutron flux density comprises $\approx 2.0 \cdot 10^{14}$ cm^{-2}s^{-1}. Three pilot FAs are fixed in the displacer by means of an auxiliary grid and side beryllium insertions, providing a gap of ~2 mm – to provide coolant flow.

Twenty standard FAs are removed from the WWR-K core periphery – to enhance specific generated power in the core and in pilot FAs at the 6-MW power rating. In order to compensate the reactivity loss, 23 beryllium hexagonal blocks of the 65.3-mm face-to-face size are installed in peripheral cells. The core cartogram and layout of pilot FAs in the core are shown in fig.1.

* Work was carried out with financial support from NTI.

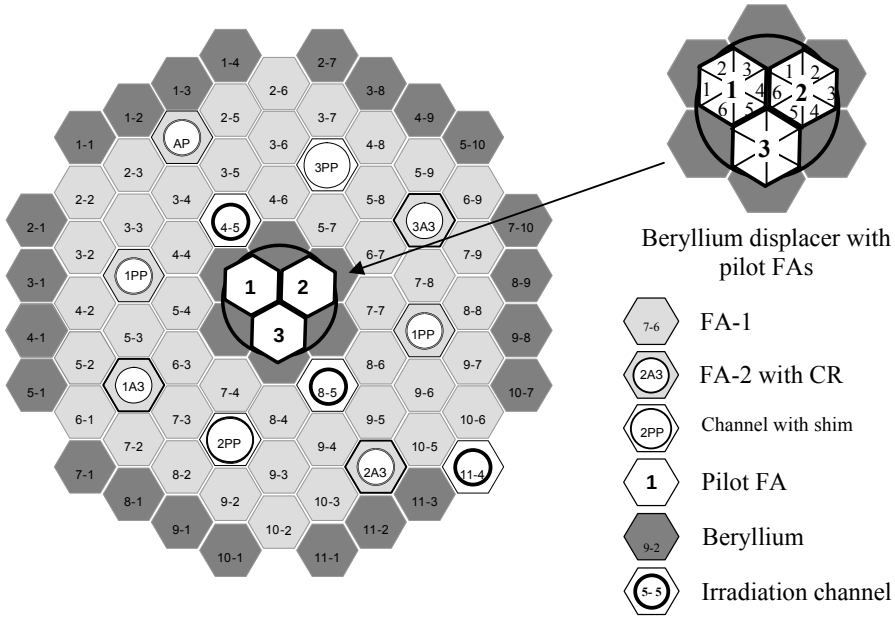

Figure 1. Cartogram of the WWR-K reactor core

Reactivity balance has been calculated for core rearrangement prior to trial:

- without 20 FAs removed from the core periphery, reactor is sub critical (-0.4%Δk/k);
- with 23 beryllium blocks, reactivity increases up to 4.2%Δk/k;
- without 6 FAs extracted from the core center and with beryllium displacer installed instead, reactivity margin decreases to 0.3%Δk/k;
- with installed three pilot VVR-KN-type FAs, reactivity margin increases to 8.1%Δk/k.

As beryllium displacer installed in the core center changes a pattern of the power distribution over the core, values of the power generated in all standard and pilot FAs have been calculated (see Table 1).

Table 1 - Power generated in FAs

Cell	Power per FA, kW	Cell	Power per FA, kW	Cell	Power per FA, kW
2-4 AP	53.3	**7-7**	**145.4**	7-3	113.5
4-3 1PP	68.7	8-6	143.3	7-8	118.9
8-7 1PP	68.2	10-2	74.8	7-9	102.6
6-2 1AZ	70.6	10-6	80.0	8-2	91.6
6-8 3AZ	70.3	2-3	87.9	8-4	137.7
10-4 2AZ	62.7	2-5	83.0	8-8	100.4
2-2	82.7	3-2	95.2	9-2	85.7
2-6	71.9	3-3	103.5	9-3	94.9
4-4	141.7	3-4	118.7	9-4	119.1
4-8	90.6	3-5	111.7	9-5	120.7
5-4	144.2	3-6	92.0	9-6	100.6
5-7	139.7	3-7	81.6	9-7	92.2
5-9	93.6	4-2	104.7	10-3	91.8
6-1	88.8	4-6	135.2	10-5	97.2
6-3	140.8	5-2	103.1	TBC 1	312.0
6-7	136.8	5-8	111.4	TBC 2	283.0
7-4	144.0	7-2	95.4	TBC 3	294.5

The hottest FA (145 kW) is found to be located in cell 7-7. It is assumed that the core worked for 380 days prior to installation of pilot FAs (charges and discharges of all FAs and the irradiation device are taken into account).

The calculated values of the power generated in pilot FAs comprise 312kW (FA 1), 283 kW (FA 2) and 294 kW (FA 3). Due to complicated geometry of the irradiation assembly, in the computational model the hottest fuel assembles – FA 1 and the FA 2, located in cell 7-7 – have been divided into six sectors. Values of the power generated in the sectors [in kW per 1 cm^3 of meat], calculated for FA 1 and FA 2, are presented in Tables 2 and 3. The azimuth irregularity factor comprises 1.32 - for the FA1 outer FE, and 1.17 - averaged over all FEs of the FA.

Table 2 - Average specific generated power in fuel elements of the FA 1

FE #	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6
1	0.966	0.891	0.617	0.617	0.805	1.094
2	0.855	0.826	0.644	0.633	0.756	0.891
3	0.769	0.773	0.633	0.617	0.697	0.724
4	0.724	0.719	0.633	0.633	0.671	0.730
5	0.673	0.655	0.590	0.585	0.622	0.655
6	0.662	0.633	0.596	0.585	0.622	0.644
7	0.652	0.665	0.628	0.612	0.622	0.665
8	0.684	0.708	0.676	0.687	0.687	0.708

Table 3 - Average specific generated power in fuel elements of the FA 2

FE #	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6
1	0.668	0.811	0.798	0.818	0.821	0.837
2	0.630	0.755	0.756	0.763	0.763	0.737
3	0.622	0.709	0.709	0.725	0.705	0.627
4	0.625	0.680	0.684	0.682	0.671	0.629
5	0.597	0.621	0.625	0.638	0.636	0.598
6	0.605	0.629	0.624	0.621	0.630	0.605
7	0.641	0.634	0.640	0.646	0.645	0.630
8	0.680	0.687	0.686	0.692	0.694	0.710

In order to take into account the generated power axial irregularity, all fuel elements of FA 1 are divided over the height into 12 sections. Results of calculation are shown in fig. 2. The irregularity factor has comprised 1.37.

Following data presented in table 2 and fig.2, the peak specific power generated in fuel meat of a pilot FA is found to be equal to1.368 $kW \cdot cm^{-3}$. This value is used when calculating the trial thermal modes.

Hydraulic calculation has been performed for a modified open flow area (with 23 cells occupied by beryllium). Results of calculation for four values of the pressure fall across the core are presented in Table 4.

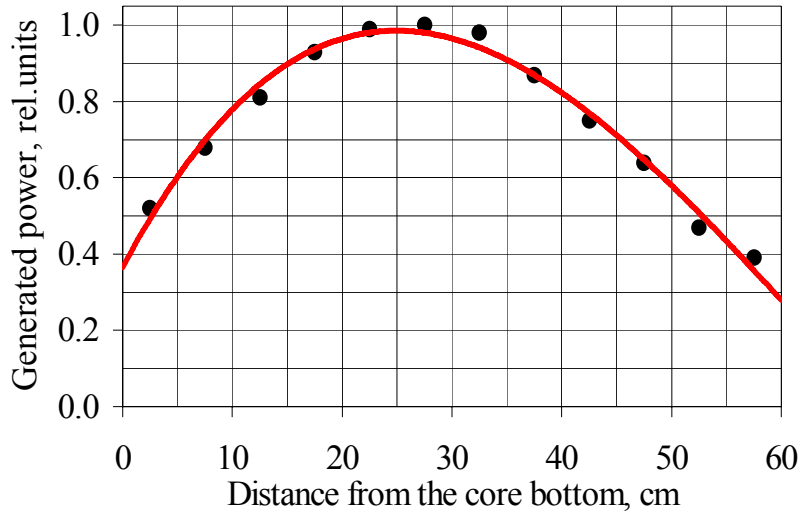

Figure 2. Power generated in the hottest sector (№ 6) of the pilot fuel assembly (FA 1) versus the height

Table 4 – The coolant flow rate and velocity in the eight-tube FA 1 versus pressure fall

Pressure fall, cm of water column	105	150	200	300
Flow rate (G), $kg \cdot s^{-1}$	3.50	4.18	4.83	5.92
Flow rate (G), $m^3 \cdot h^{-1}$	12.6	15.1	17.4	21.3
Velocity (w), $m \cdot s^{-1}$	1.56	1.86	2.15	2.64

And, at last, the maximum temperature of the FE wall has been determined for FA 1 on a base of the calculated generated power and the performed hydraulic calculation (see Table 5).

Table 5 – Results of thermal calculation for the hottest pilot fuel assembly (FA 1)

Coolant inlet temperature, °C	35			45		
FA power, kW	312			312		
Peak power density generated in FE meat*, kW/cm^3	1368			1368		
Pressure fall across the core, bar	0.15	0.20	0.30	0.15	0.20	0.30
Coolant velocity in gaps between FEs, m/s	1.86	2.15	2.64	1.86	2.15	2.64
Peak thermal flux, kW/m^2	510	508	509	512	513	508
Maximum temperature on FE surface, °C	83	78	72	91	86	80
ONB temperature (by Forster-Greif), °C	123	122	121	123	122	121
ONB temperature margin factor	1.84	2.03	2.34	1.69	1.87	2.16

* A fraction of the power generated in a FE meat is assumed to be equal to 0.94.

Table 5 demonstrates that even for the 45°C inlet coolant temperature, the limit value of the FE wall (95°C) isn't reached. The ONB margin factor on the FE wall comprises 1.69 (following the norms in effect, it must be not less than 1.40). The height distribution of the FE wall temperature and the coolant temperature in a gap between fuel elements are shown in figures 4 and 5.

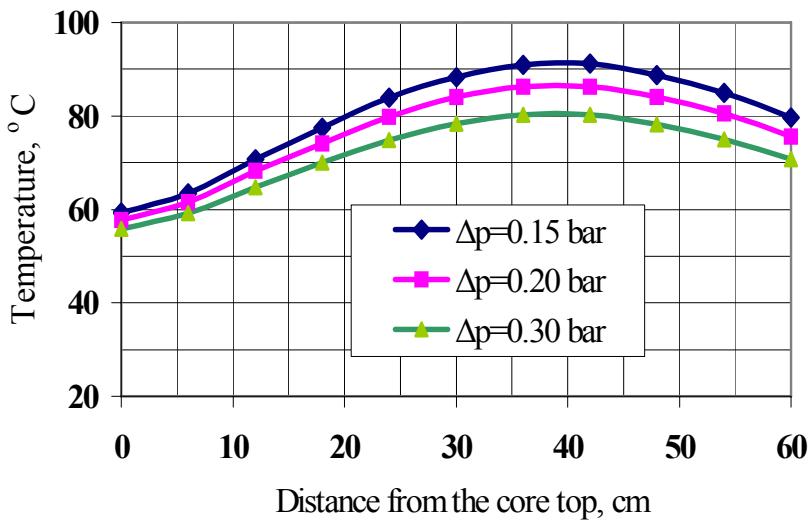

Figure 4. Temperature of the inner surface of the first FE of the pilot FA 1

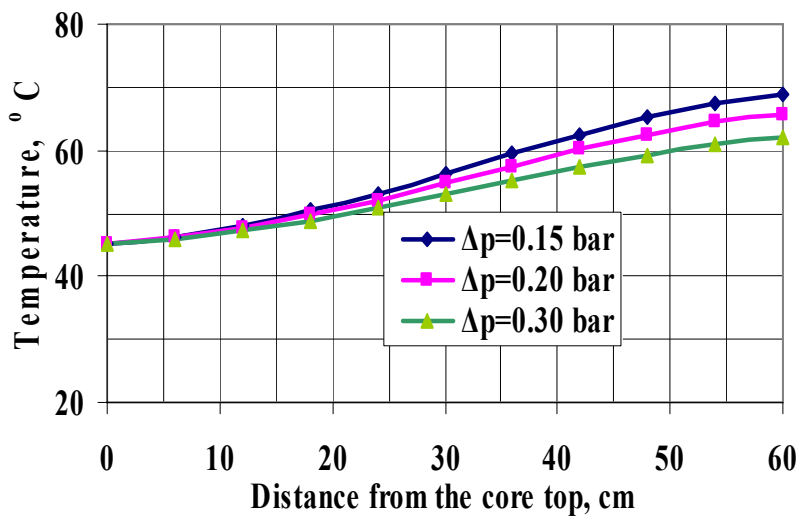

Figure 5. Coolant temperature between the first and second FEs of the pilot FA 1.

The coolant maximum temperature at the outlet from pilot FA (the worst case) comprises 70°C, being by 5 °C higher than the limiting value (65 °C). And one should take in mind that conservative approach was used in thermal calculation, in view of safety enhancement.

As is said earlier, the central beryllium displacer and the beryllium reflector have introduced substantial changes in the generated power distribution. Besides, the net number of standard FAs has decreased by 20 pieces. So, thermal modes of the core are to be evaluated.

A section of the face of the FA in cell 7-7, adjacent to beryllium displacer, with the specific power generated in the FE meat, equal to 0.807 kW/cm^3 and obtained with the irregularity factors taken into account, is taken as the hottest section in the core. Results of thermal calculation are presented in Table 6.

Table 6. Results of thermal calculation for the hottest standard FA

The coolant core inlet temperature, °C	35			45		
FA power, kWт	145.4			145.4		
Peak power generated in the FE meat*, kW/cm^3	0.807			0.807		
Pressure fall across the core, bar	0.15	0.20	0.30	0.15	0.20	0.30
Coolant velocity in gaps between FEs, m/s	2.14	2.47	3.03	2.14	2.47	3.03
Peak thermal flux, kW/m^2	251	251	250	252	252	251
Max temperature of the FE surface, °C	58	57	53	67	65	62
ONB temperature (by Forster-Greif),°C	120	120	119	120	120	119
ONB temperature margin factor	3.72	4.12	4.75	3.46	3.84	4.44

* A fraction of the power generated in FE meat is assumed to be equal to 0.94.

Table demonstrates that thermotechnical reliability of the core is assured, in spite of changes in core configuration and composition. Variation in the temperature on the FE surface at the coolant core inlet temperature 45 °C is shown in Fig.6. The coolant maximum core outlet temperature doesn't exceed 54 °C.

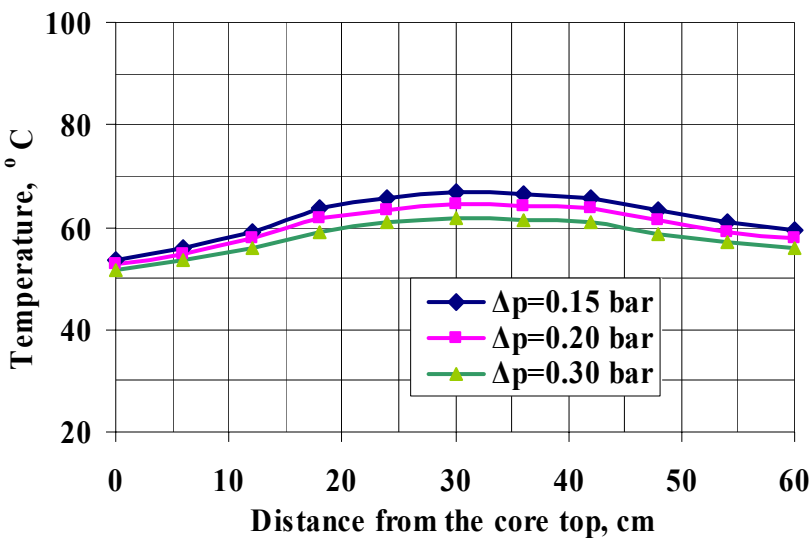

Figure 6. Temperature of the inner surface of the VVR-V-type FA first FE (cell 7-7, sector № 6) versus the core height

Reactor operation time and the number of operation cycles needed to achieve the 60-% maximum average burnup in pilot FA have been calculated

Results of calculations are presented in Table 7 and in figures 7 and 8. After each operation cycle, the reactor was shutdown for six days for staying, reloading and experimental work.

Table 7 – The generated power density averaged over a volume of the computational FA cell

	kW/cm^3	Burnup, %	kW/cm^3	Burnup, %	kW/cm^3	Burnup, %	kW/cm^3	Burnup, %
FA #	50 FAs		46 FAs		43 FAs		43 FAs	
FA 1	0.1275	4.1	0.1175	17.2	0.1033	33.8	0.0860	59.4
FA 2	0.1228	3.9	0.1146	16.6	0.0992	32.4	0.0835	57.3
FA 3	0.1263	4.0	0.1207	17.1	0.1018	33.9	0.0872	59.6
No. of cycles	1		4		6		15	
Op.time, d	30		84		126		315	

Note: Reduction of the core load in course of reactor operation is to increase the power generated in pilot FA.

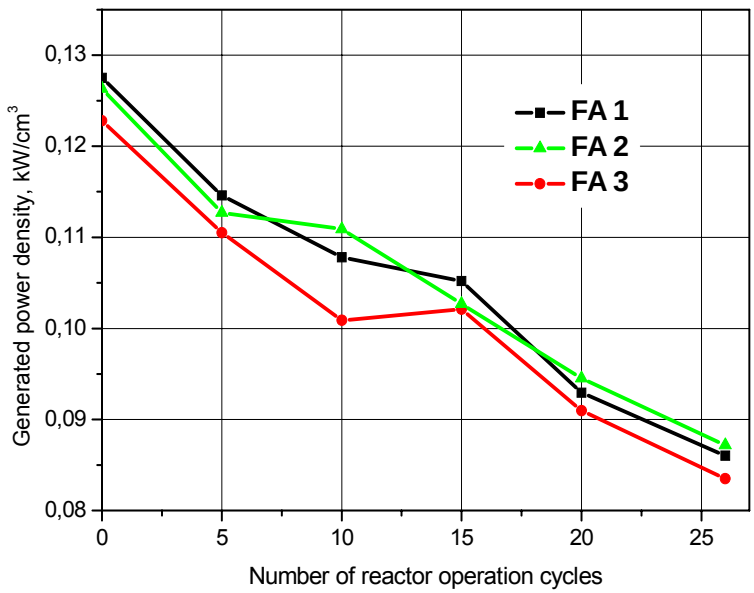

Figure 7. The power density generated in tested fuel assembles versus time of trial

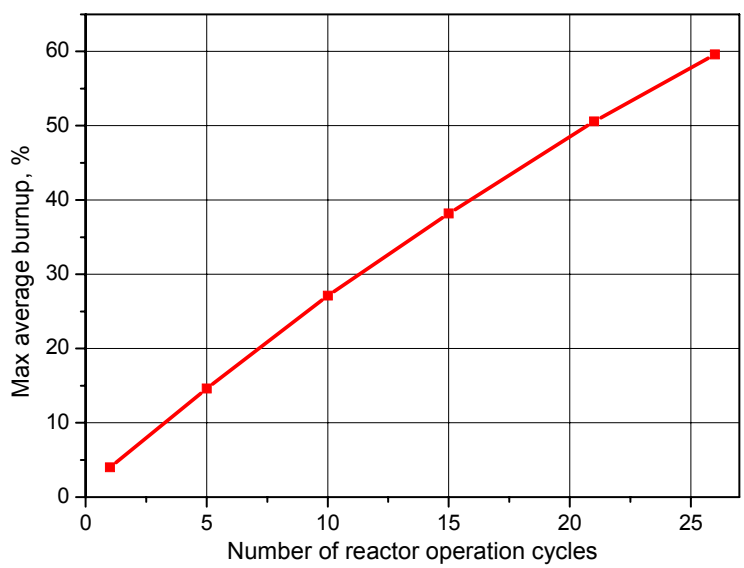

Figure 8. Max average burnup in tested FAs versus reactor operation time

To determine effect of irradiation device on characteristics of neutron fields, flux density of thermal and fast neutrons were calculated in irradiation channels of the core and reactor vessel (see Table 8).

Table 8. Thermal/fast neutron flux density in irradiation channels

Irradiation channel	Current core		Core under trials	
	Thermal	Fast	Thermal	Fast
cell 4–5	9.8E+13	1.7E+13	1.3E+14	1.6E+13
cell 8-5	1.0E+14	1.7E+13	1.3E+14	1.6E+13
cell 11-4	3.6E+13	5.0E+12	3.8E+13	4.4E+12
tank (Ø 100 mm)	8.7E+12	3.0E+11	7.3E+12	5.2E+11

Following analysis of the results obtained, the thermal neutron flux density in central channels has increased by на 30 %; as for the rest channels, its characteristics are left, practically, the same.

CONCLUSIONS

1. A version of arrangement of pilot FAs in the existing WWR-K reactor core has been substantiated. Beryllium displacer installed in the core center (instead of removed six FAs and the central irradiation channel) will make it possible to test three pilot FAs at the same time. In order to increase the power per FA, the core size is assumed to be reduced via removal of 20 FAs and installation of beryllium blocks instead.
2. The calculated values of the power generated in three pilot FAs comprise 312.0, 283.0 and 294.5 kW respectively. These values are close to those related to FA operational modes of the core.
3. Thermal-hydraulic calculation of the WWR-K reactor core with pilot FAs has shown that at the 6 MW power rating the pilot FA fuel element wall maximum temperature doesn't exceed 91 °C even at the coolant core inlet temperature comprising 45 °C.
4. Arrangement of the side beryllium reflector in the existing WWR-K reactor core is shown to improve to some extent its neutron-physical characteristics (the thermal neutron flux density in the irradiation channels inside the core, fuel burnup level, etc).
5. The evaluated reactor operation time needed to achieve 60-% burnup in pilot FAs comprises 560 days. The appropriate quantities of fresh FA needed are: 60 FA-1 and 6 FA-2.

Authors express their gratitude to workers of the Institute of Nuclear Reactors of the Russian Scientific Center "Kurchatov Institute" Kukharkin N., Gomin E., Gurevich M., Marin S. and Yudkevich M. for provision of the computer code set MCU-REA and assistance in its use.

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