FULL-CORE CONVERSION OF THE WWR-M RESEARCH REACTOR IN UKRAINE TO THE USE OF LEU FUEL

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Abstract

Full-core conversion of the WWR-M research reactor in Ukraine with simultaneous replacement of all remaining HEU fuel by fresh LEU fuel requires the new safety analysis of the reactor because of great decrease of the number of fuel assemblies in the core. Because of considerable increase of reactivity due to loading a fuel assembly into the core and reactivity worth of control rods, the following potential accidents are analysed for the new LEU core: incidental falling of a fuel assembly in a cell of the core and spontaneous withdrawal of a control rod group because of malfunction of electronic equipment. To provide the safety of the reactor, some limiting conditions for operation are revised. In particular, maximum allowed effective multiplication factor when all control rods are fully in and all safety rods are fully out is decreased from 0.988 to 0.977, and maximum allowed power of the reactor is decreased from 10 MW to 7 MW. The safety analysis shows that with the revised limiting conditions for operation, such the events with accompanying one additional equipment malfunction and one error of personnel do not lead to damage of fuel elements and release of radioactivity exceeding allowed level. For neutronics calculations, the MCNP code based on the Monte Carlo method is applied. Thermal-hydraulics is calculated with the PLTEMP code.

1. INTRODUCTION

The WWR-M reactor in Ukraine is a tank type light-water cooled and moderated research reactor with beryllium reflector. Replaced HEU fuel assemblies are WWR-M2 (36%). LEU replacement fuel assemblies are WWR-M2 (19.75%), which have been tested successfully in the similar WWR-M research reactor in Gatchina (Russia) by irradiation to over 75% burnup [1]. HEU and LEU fuel assembly parameters are shown in Table I [1-3].

TABLE I: FUEL ASSEMBLY PARAMETERS

	HEU WWR-M2	LEU WWR-M2
Enrichment, %	36	19.75
Number of fuel elements	3	3
Mass of ^{235}U, g	37	41.7
Fuel meat composition	UO_2-Al 1.1 gU/cm^3	UO_2-Al 2.5 gU/cm^3
Length of fuelled region, cm	50	50
Pitch/flat-to-flat, mm	35/32	35/32
Element/clad/meat, mm	2.5/0.76/0.98	2.5/0.78/0.94
Hydraulic resistance coefficient	4.35	4.35
Relative coolant velocities between fuel elements (starting from the centre)	1.18; 0.89; 1.05; 0.86	1.18; 0.89; 1.05; 0.86

In accordance with the program of pilot usage of LEU fuel approved by the Ukrainian Regulatory Committee, most burned HEU fuel assemblies were successively replaced by fresh LEU fuel assemblies. By using this way, safety parameters and performance of the reactor remained almost the same as with HEU fuel but such the conversion progressed very slowly. Thus, the new full-core conversion program with simultaneous replacement of all remaining HEU fuel by fresh LEU fuel was developed [4].

2. NEW LEU CORE

In order to maintain sufficient production of medical and industrial isotopes, the new LEU core pattern was optimized [4], as shown in *FIG.1*. Because of the safety and control rods peculiarity, their location in the WWR-M reactor core cannot be changed. Thus, the centre of the core had to be shifted toward the irradiation channels.

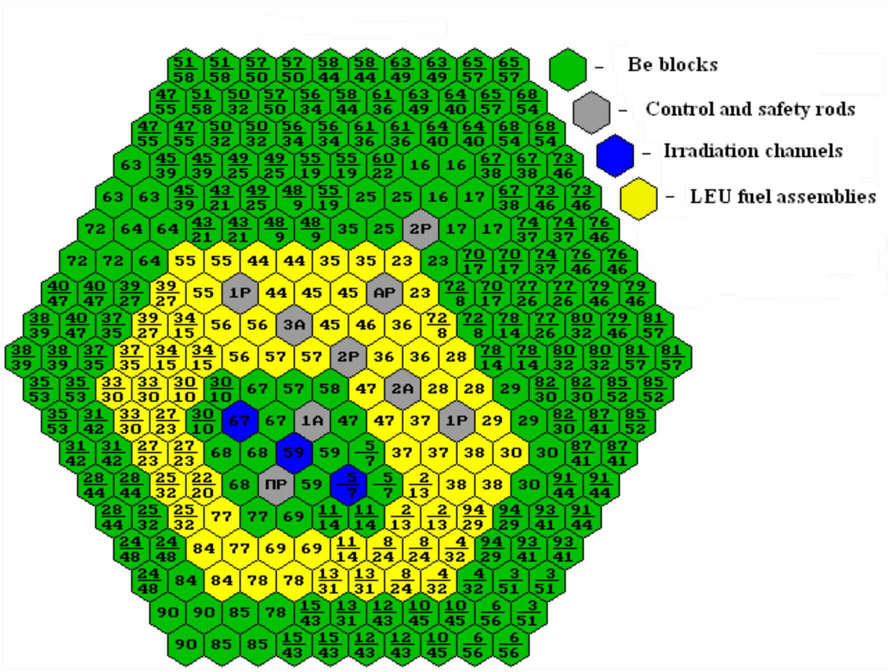

FIG. 1. LEU core layout.

Main calculated parameters of the old mixed and new LEU cores are shown in Table II. Total and specific activities of ^{99}Mo after 5 days of irradiation are depicted in *FIG.2*. For natural molybdenum, activities are less than for ^{98}Mo because of higher self-shielding, as shown in *FIG.3*. Calculated distributions of ^{98}Mo(n,γ) reaction rate are in good agreement with measurement, as shown in *FIG.4,5*.

For neutronics calculation, the MCNP code based on the Monte Carlo method is applied [5]. Continuous-energy cross-sections for use with the MCNP are calculated with the NJOY code [6] using ENDF/B-VII data [7]. Thermal-hydraulics is calculated with the PLTEMP code [8].

The codes were validated against measured data for critical experiments and previous mixed cores of the WWR-M reactor. For the new LEU core, reactivity worth of the control and safety rods is measured again and compared to the correspondent calculated values. As shown in Table III and *FIG. 6-8*, the measurement is in good agreement with calculation.

TABLE II: MAIN PARAMETERS OF THE OLD MIXED AND NEW LEU CORES

		Mixed Core	LEU Core
Number of Fuel Assemblies		207	72
Nominal Power, MW		10.0	7.0
Average Fuel Burnup, %		30	0.5
Maximal Excess Reactivity, $		7.0	7.0
Reactivity Worth of Control Rods, $	1P	4.2	7.6
	2P	3.8	6.0
	ΠP	2.6	3.9
	AP	0.5	0.7
Reactivity Worth of Safety Rods, $	1A	2.5	4.6
	2A	2.0	4.3
	3A	2.5	4.6
Minimal Sub-Criticality when 2P, AP, 2A and 3A are fully in and 1P, ΠP and 1A are fully out, %		0.9	3.6
Minimal Sub-Criticality when all control rods are fully in and all safety rods are fully out, %		2.5	7.3
Maximal Reactivity due to Loading a Fuel Assembly in a cell of the core, %		1.1	2.2
Power Peaking Factor		2.0	1.6
Maximal Thermal Flux, 10^{14} n/cm^2/s		1.2	1.3
Maximal Specific Activity of ^{99}Mo, Ci/g ^{98}Mo		17.0	19.1

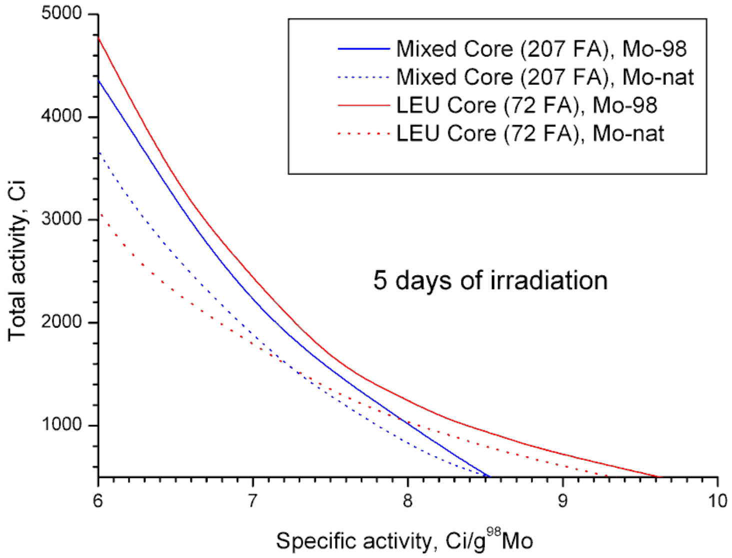

FIG. 2. Potential to produce ^{99}Mo for the mixed and LEU cores.

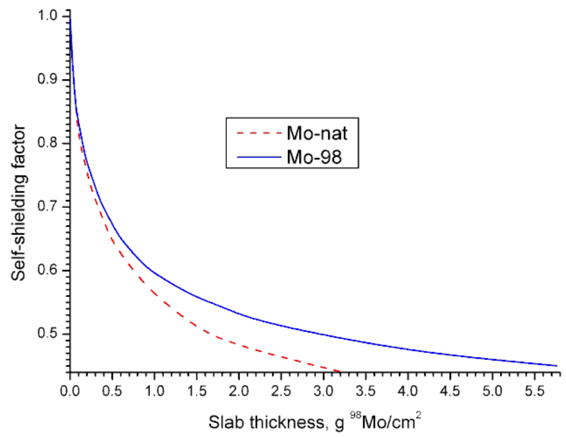

FIG. 3. ^{98}Mo(n,γ) self-shielding factor for infinite slab.

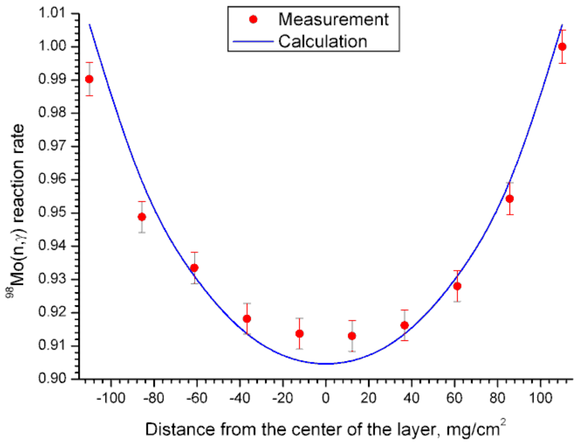

FIG. 4. Distribution of ^{98}Mo(n,γ) reaction rate through the natural molybdenum layer.

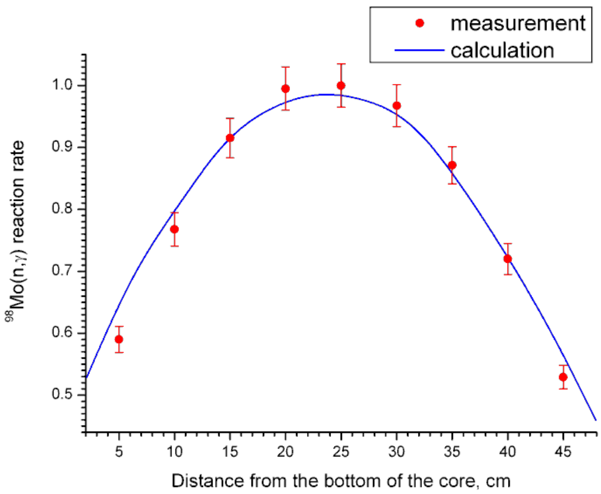

FIG. 5. Axial distribution of ^{98}Mo(n,γ) reaction rate.

TABLE III: REACTIVITY WORTH OF THE CONTROL AND SAFETY RODS, $

	Calculation	Measurement
1P	7.55	7.71
2P	5.95	6.15
ПР	3.88	3.97
AP	0.70	0.73
1A	4.61	4.9
2A	4.26	4.0
3A	4.57	4.9

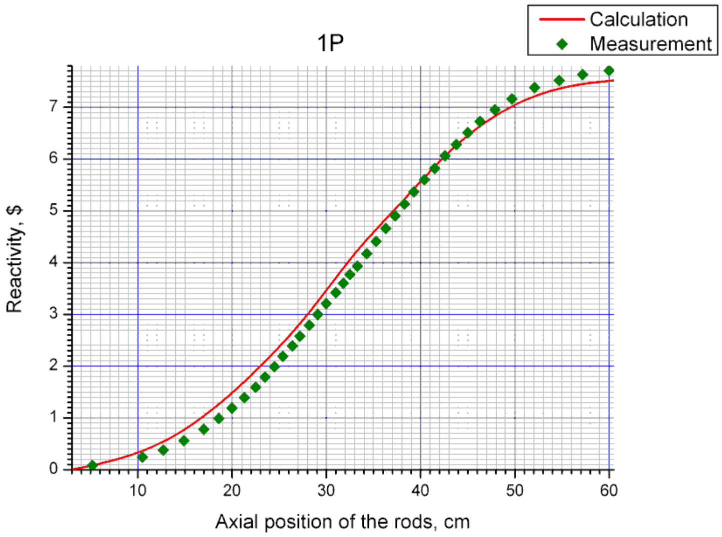

FIG. 6. Reactivity worth of the 1P rods.

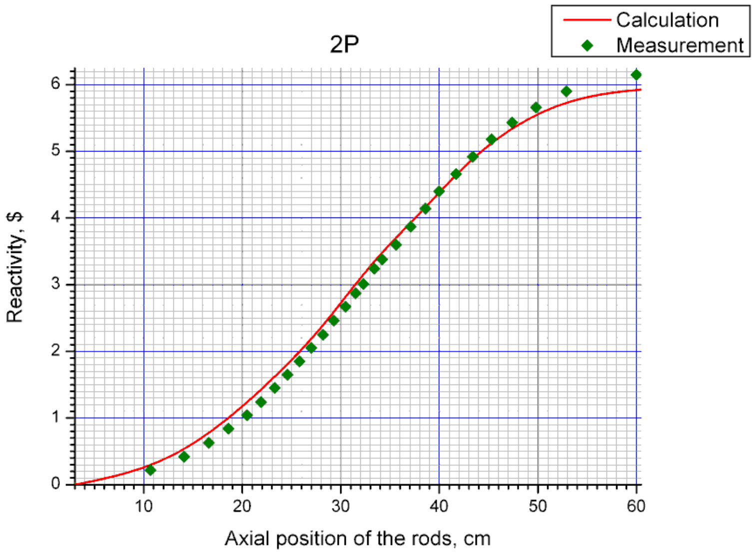

FIG. 7. Reactivity worth of the 2P rods.

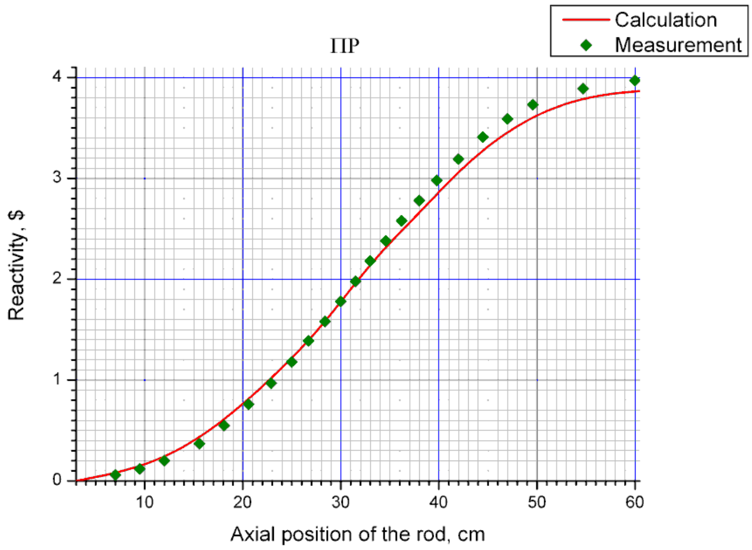

FIG. 8. Reactivity worth of the ПР rod.

3. ACCIDENTS ANALYSIS

All the accident analyses required by the Ukrainian regulation to use LEU fuel for the WWR-M research reactor in Kiev have been performed for equilibrium core and included in the Safety Analysis Report [9]. However, because of great decrease of the number of fuel assemblies in the new LEU core with accompanying increase of reactivity due to loading a fuel assembly into the core and reactivity worth of control rods, the following potential accidents are analyzed again: incidental falling of a fuel assembly in a cell of the core and spontaneous withdrawal of a control rod group. To provide the safety of the reactor, some limiting conditions for operation are revised. In particular, maximum allowed effective multiplication factor when all control rods are fully in and all safety rods are fully out is decreased from 0.988 to 0.977, and maximum allowed power of the reactor is decreased from 10 MW to 7 MW.

3.1. Spontaneous withdrawal of a control rod group

The following worst scenario is considered:

The reactor has maximal excess reactivity. The reactor power is 2.5 MW. The slowest control rod (ПР) is fully out of the core. Automatic regulating system is not in operation. Because of malfunction of electronic equipment, the most efficient group of control rods (1P) starts to move spontaneously with maximum speed from the lowest to highest position. Reactor operating personnel does not switch off electric power supply of this bank drive because of misunderstanding the situation.

When reactor power reaches 8.4 MW, the accident signals “Exceeding nominal reactor power on 20%” and “Power increase period is less than 10 seconds” are automatically generated by the instrumentation and control system. After 0.31 sec from this moment (including also delay of the signal), safety rods except the most effective of them (1A) are fully in the core. The rods 2P, ПР and AP move down until reach the lowest position.

Calculated reactivity and neutron power as functions of time are shown in *FIG. 9,10*. Peak reactor power is 8.7 MW, power peaking factor is 1.72, peak power density in the fuel meat is 1.4 kW/cm^3, peak fuel temperature is 105 ^{0}C, peak clad temperature is 102 ^{0}C, minimum margin to ONB is 1.2. Thermal-hydraulics was calculated with the PLTEMP code using conservative approach, thus the temperatures calculated can be considered only as upper estimation of real temperatures.

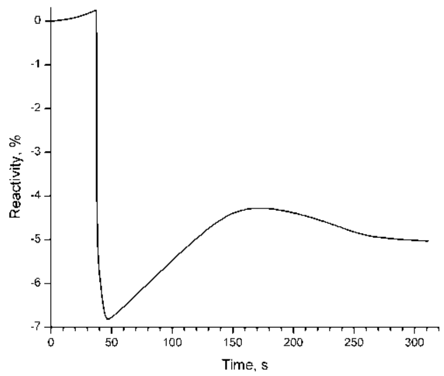

FIG. 9. Reactivity for spontaneous withdrawal of a control rod group.

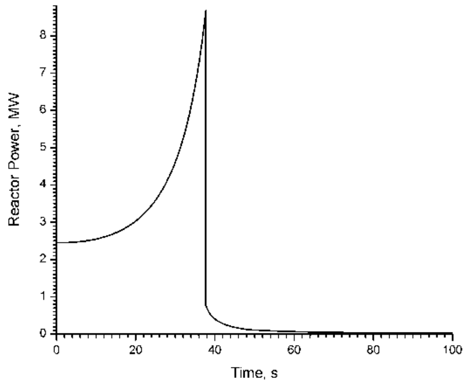

FIG. 10. Reactor power for spontaneous withdrawal of a control rod group

Thus, the analysis shows that such the event with accompanying one additional equipment malfunction and one error of personnel does not lead to damage of fuel elements and release of radioactivity exceeding allowed level.

3.2. Incidental falling of a fuel assembly in a cell of the core

When reactor is on operation, falling of a fuel assembly in a cell of the core is impossible because of steel cover over the core. This incident is possible only during reload of the core when all control rods are fully in and safety rods are fully out.

Maximum allowed effective multiplication factor when all control rods are fully in and safety rods are fully out is 0.977. Hence, effective multiplication factor after falling of any fuel assembly in any cell during reload of the core is not more than 0.977. For the new LEU core, increasing of effective multiplication factor because of loading a fuel assembly in a cell of the core is not more than 2.2%. Hence, even if one excess loading operation is done because of error of personnel, effective multiplication factor after falling of a fuel assembly in a cell of the core is less than 1. Thus, the analysis shows that such the event with accompanying one additional error of personnel does not lead to damage of fuel elements and release of radioactivity exceeding allowed level.

4. CONCLUSIONS

Full-core conversion of the WWR-M research reactor in Ukraine deteriorates performance of the reactor because of considerable decrease of the number of fuel assemblies in the core with accompanying rise of fuel expenditures and reduction of total reactor power. However, due to optimization of the new LEU core pattern, its maximal thermal neutrons flux and potential to produce ^{99}Mo are higher than for the old mixed core.

Because of considerable increase of reactivity due to loading a fuel assembly into the core and reactivity worth of control rods, the following potential accidents are analysed for the new LEU core: incidental falling of a fuel assembly in a cell of the core and spontaneous withdrawal of a control rod group because of malfunction of electronic equipment. To provide the safety of the reactor, some limiting conditions for operation are revised. In particular, maximum allowed effective multiplication factor when all control rods are fully in and all safety rods are fully out is decreased from 0.988 to 0.977, and maximum allowed power of the reactor is decreased from 10 MW to 7 MW. The safety analysis shows that with the revised limiting conditions for operation, such the events with accompanying one additional equipment malfunction and one error of personnel do not lead to damage of fuel elements and release of radioactivity exceeding allowed level.

REFERENCES

[1] KONOPLEV, K. A. et al., “LEU WWR-M2 Fuel Qualification”, The 24-th Intl. Meeting on the Reduced Enrichment for Research and Test Reactors (RERTR 2002), Bariloche, Argentina, November 3-8, 2002.

[2] KIRSANOV, G. A. et al., “Hydraulics of the WWR-M Reactor Core”, Atomn. Energ., **39**, 5 (1975) 320 (in Russian).

[3] ISAKAS, I. E., KIRSANOV, G. A., KONOPLEV, K. A., “Thermal Calculation of the WWR-M Reactor Core”, Preprint No. 859, Petersburg Nuclear Physics Institute, Gatchina (1983) (in Russian).

[4] MAHLERS, Y. P. et al., “Feasibility of converting the WWR-M research reactor in Ukraine from HEU to LEU fuel by the end of 2010”, The 32d Intl. Meeting on Reduced Enrichment for Research and Test Reactors, Lisbon, Portugal, October 10 - 14, 2010.

[5] BRIESMEISTER, J. F., Ed., “MCNP - A General Monte Carlo N-Particle Transport Code, Version 4C”, LA-13709-M, Los Alamos National Laboratory (April 2000).

[6] CHADWICK, M.B. et al., “ENDF/B-VII.0: Next generation evaluated nuclear data library for nuclear science and technology”, Nucl. Data Sheets **107** (2006) 2931.

[7] MACFARLANE, R. E., MUIR, D. W., BOICOURT, R. M., “The NJOY nuclear data processing system, version 91”, LA-12740-M, Los Alamos National Laboratory (1994).

[8] OLSON, A. P., “A Users Guide to the PLTEMP/ANL v2.1 Code”. ANL/RERTR/TM-32, Argonne National Laboratory (October 2003).