SAFETY ANALYSIS OF THE WWR-M REACTOR IN UKRAINE TO ALLOW OPERATION USING LEU FUEL

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ABSTRACT

The WWR-M research reactor in Ukraine is jointly studied by the Argonne National Laboratory and the Kiev Institute for Nuclear Research for conversion to LEU (19.75%) fuel. Candidate LEU replacement fuel assemblies are LEU WWR-M2 (3 tubes, UO_2-Al fuel meat with 2.5 gU/cm^3 and 41.7 g ^{235}U), which have been tested successfully in the WWR-M reactor in Gatchina by irradiation to over 75% burnup. To qualify this LEU fuel for conversion of the WWR-M reactor in Ukraine, the safety analysis is performed. Neutronic and thermal-hydraulic characteristics of LEU fuel equilibrium core and transition mixed core containing both LEU and HEU fuel are calculated. The following accidents are analyzed: spontaneous withdrawal of a control rod bank and incidental falling of a fuel assembly in a cell of the core. The models applied for calculations are validated against measured data, which include critical experiment results for fresh fuel assemblies and measured neutronic distributions in a real WWR-M reactor core.

INTRODUCTION

The WWR-M research reactor with light-water coolant and beryllium reflector in Kiev (Ukraine) is being jointly studied by the Argonne National Laboratory and the Kiev Institute for Nuclear Research for conversion to LEU (19.75%) fuel. Nominal power of the reactor is 10 MW. Available fuel assemblies are WWR-M2 (36%) and WWR-M5 (90%). Candidate LEU replacement fuel assemblies are LEU WWR-M2 (19.75%), which have been tested successfully in the WWR-M reactor in Gatchina by irradiation to over 75% burnup.[1] The fuel assembly parameters and designs are shown in Table 1 and Fig.1.[1, 2, 3]

A study confirming the feasibility of converting the WWR-M research reactor in Ukraine from HEU to LEU fuel has been already completed.[4] With LEU WWR-M2 fuel assemblies, the reactor would require about 10% fewer fuel assemblies per year than with the current WWR-M2 (36%) fuel assemblies. Fast and thermal neutron fluxes in key experiment positions would decrease by only 1 - 2%.[4]

To qualify this LEU fuel for conversion of the WWR-M reactor in Kiev and to get the appropriate license of the Ukrainian Nuclear Regulatory Committee, the safety analysis should be performed.

Table 1. Fuel Assembly Parameters

	WWR-M5	WWR-M2	LEU WWR-M2
Enrichment, %	90	36	19.75
Number of fuel elements	6	3	3
Mass of ^{235}U, g	66	37	41.7
Fuel meat composition	UO_2-Al 1.2 gU/cm^3	UO_2-Al 1.1 gU/cm^3	UO_2-Al 2.5 gU/cm^3
Length of fueled region, cm	50	50	50
Pitch/flat-to-flat, mm	35/33.5	35/32	35/32
Element/clad/meat, mm	1.25/0.43/0.39	2.5/0.76/0.98	2.5/0.78/0.94
Specific heat transfer surface, cm^2/cm^3	6.6	3.67	3.67
Hydraulic resistance coefficient	6.5	4.35	4.35
Relative coolant velocities between fuel elements (starting from the center)	0.90; 1.01; 1.08; 0.98; 1.06; 0.88	1.18; 0.89; 1.05; 0.86	1.18; 0.89; 1.05; 0.86

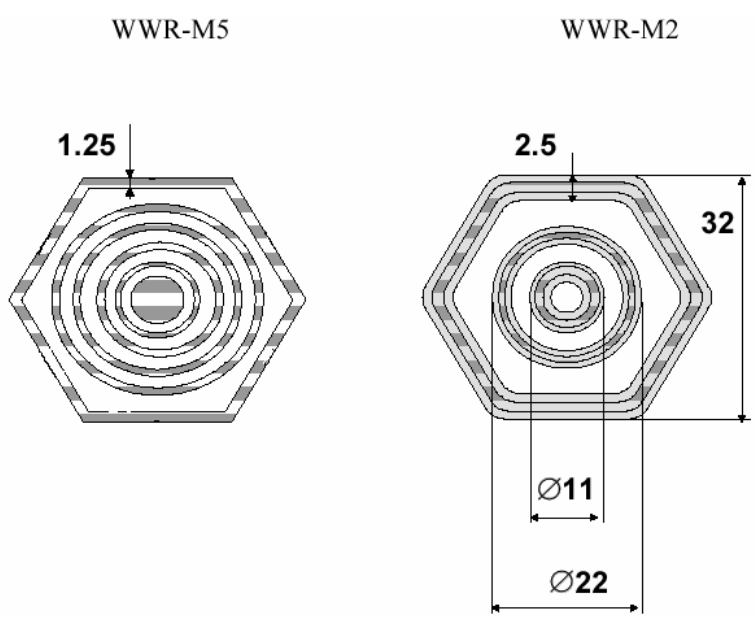

Fig.1. Fuel Assembly Designs

LEU FUEL EQUILIBRIUM CORE

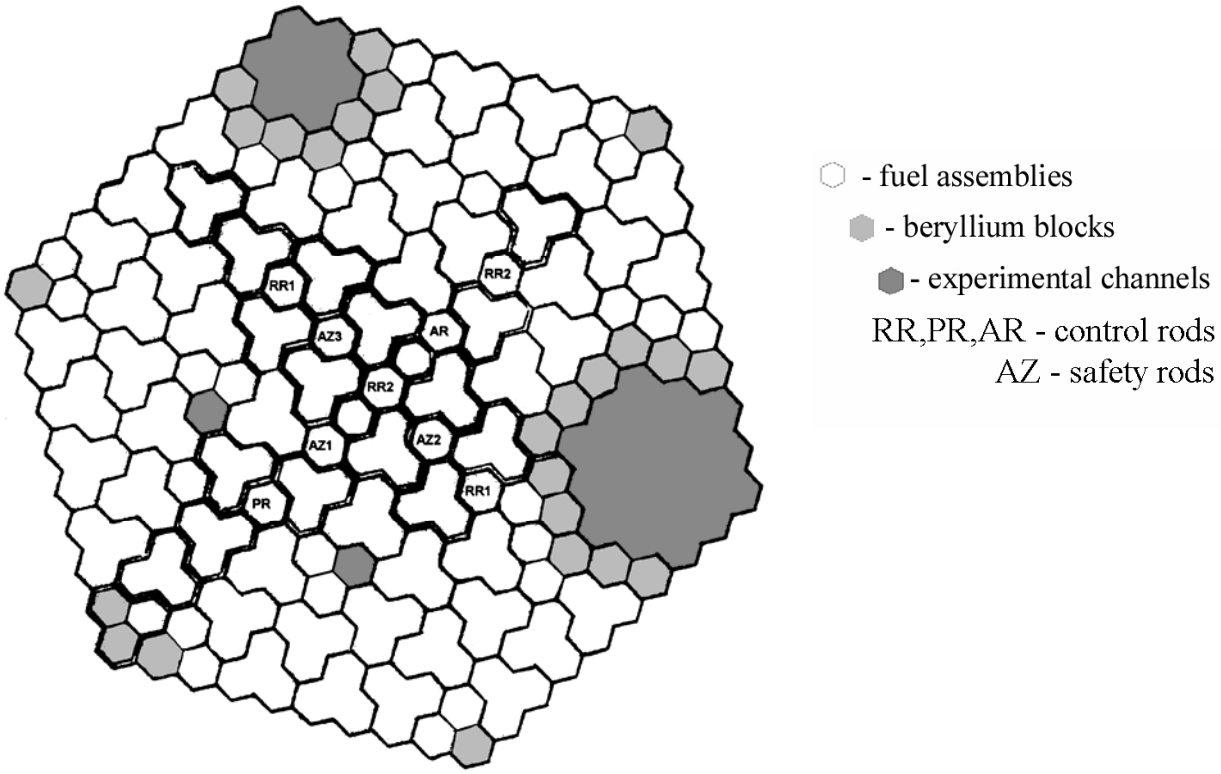

Fig. 2. Equilibrium core configuration

Equilibrium LEU core parameters are the following:

Number of fuel assemblies in the core: 210 Cycle length: 24.1 EFPD (effective full-power days)

Maximum excess reactivity: 5.29%

Reactivity worth of control and safety rods.

RR1: 3.09%	RR2: 3.02%	PR: 1.62%
AR: 0.39%		
AZ1: 1.96%	AZ2: 1.63%	AZ3: 2.03%

Minimum sub-criticality when RR1, RR2, PR and AR are fully in and AZ1, AZ2 and AZ3 are fully out: 2.56% (sub-criticality is defined here as 1-k_{eff}, where k_{eff} is the effective multiplication factor)

Minimum sub-criticality when RR2, AR, AZ1 and AZ2 are fully in and RR1, PR and AZ3 are fully out: 0.70%

Power peaking factor: 2.23 Maximum power density: 200 W/cm^3

Maximum fuel element surface temperature: <94C

Minimum DNBR: 5.6 Minimum margin to ONB: 1.37

MIXED FUEL CORE

The mixed HEU-LEU core parameters are the following:

Number of fuel assemblies in the core: 210 Cycle length: 20.4 EFPD

Maximum excess reactivity: 5.29%

Reactivity worth of control and safety rods.

RR1: 3.27% RR2: 3.03% PR: 1.87%

AR: 0.41%

AZ1: 2.13% AZ2: 1.87% AZ3: 2.16%

Minimum sub-criticality when RR1, RR2, PR and AR are fully in and AZ1, AZ2 and AZ3 are fully out: 2.89%

Minimum sub-criticality when RR2, AR, AZ1 and AZ2 are fully in and RR1, PR and AZ3 are fully out: 0.93%

Power peaking factor: 2.29 Maximum power density: 206 W/cm^3

Maximum fuel element surface temperature: <95C

For neutronic and thermal-hydraulic calculation, the codes REBUS-PC [5], MCNP-4C [6] and PLTEMP 2.1[7] were used.

CRITICAL EXPERIMENTS

Criticality calculations were validated using the measurements carried out by the Petersburg Institute of Nuclear Physics.[8] The results of the measurement and calculation are presented in Table 2.

Table 2. Results of criticality measurement and calculation

Layout	Type of fuel assemblies	Experimental critical number of fuel assemblies	Calculated effective multiplication factor	Deviation from the measurement, %
1	WWR-M2	94.1	0.9984	-0.16
2	WWR-M2	93.5	0.9979	-0.21
3	WWR-M2	108.8	0.9962	-0.38
4	WWR-M2	146.1	0.9945	-0.55
5	WWR-M2	147.8	0.9952	-0.48
6	WWR-M2	187.4	0.9949	-0.51
7	WWR-M2	225.1	0.9944	-0.56
8	WWR-M5	56.2	1.0039	0.39
9	WWR-M5	55.1	1.0037	0.37
10	WWR-M5	63.3	1.0064	0.64

Average deviation of calculations from the measurements is -0.14%. Maximum deviation is 0.64%. Root-mean-square deviation is 0.45%.

NEUTRONIC DISTRIBUTIONS IN A REAL WWR-M REACTOR CORE

Neutronic calculations were validated using the measurements carried out by the Kiev Institute for Nuclear Research.[9] Core layout and locations of the measurements are shown in Fig.3. Some results of the measurement and calculation are presented in Fig. 4-6. Maximum relative deviation of the calculation data from the measurements is 15%. Root-mean-square deviation is 7.7%.

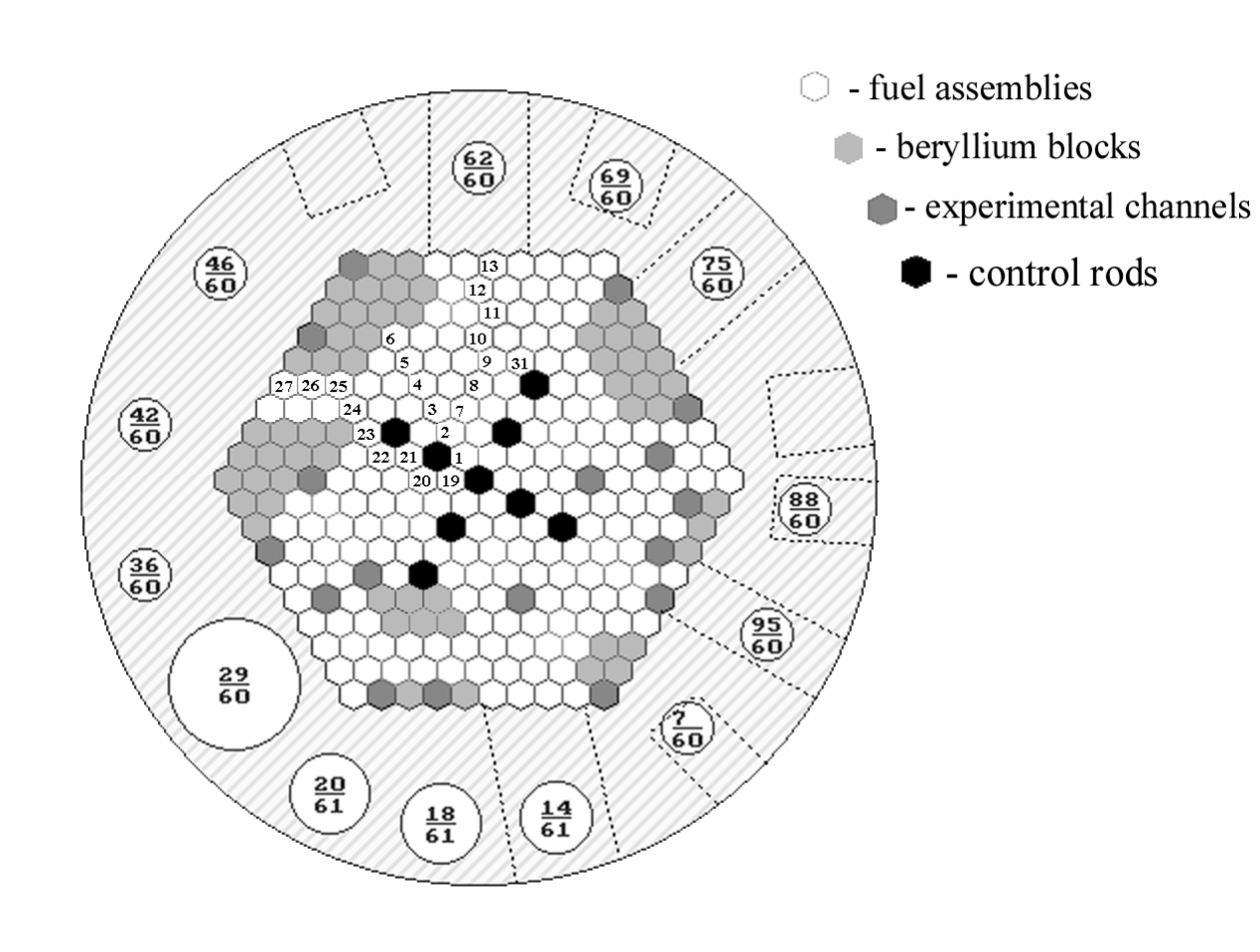

Fig. 3. Core layout and location of the measurements

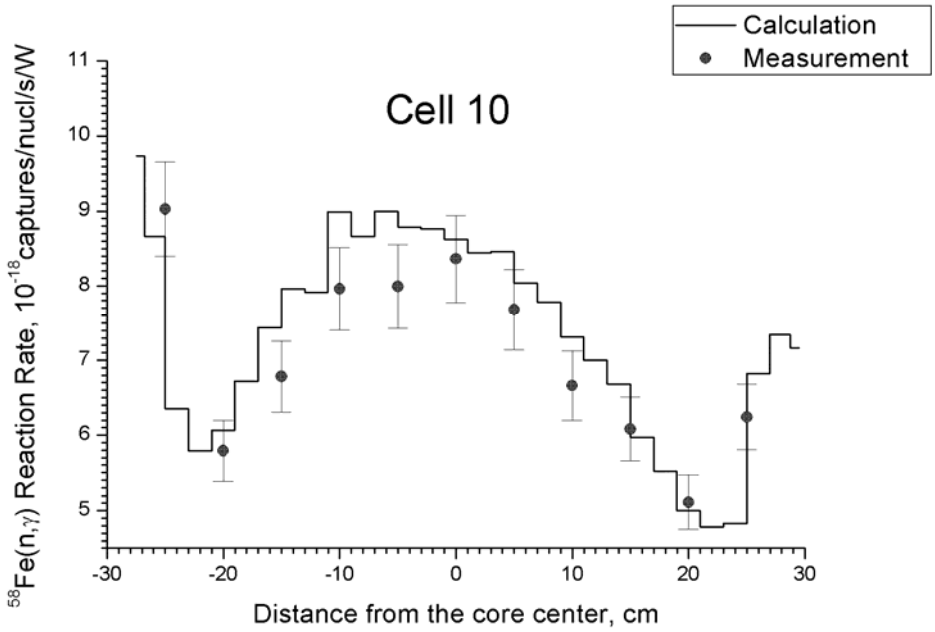

Fig. 4. Axial distribution of ^{58}Fe(n,γ) reaction rate in cell 10

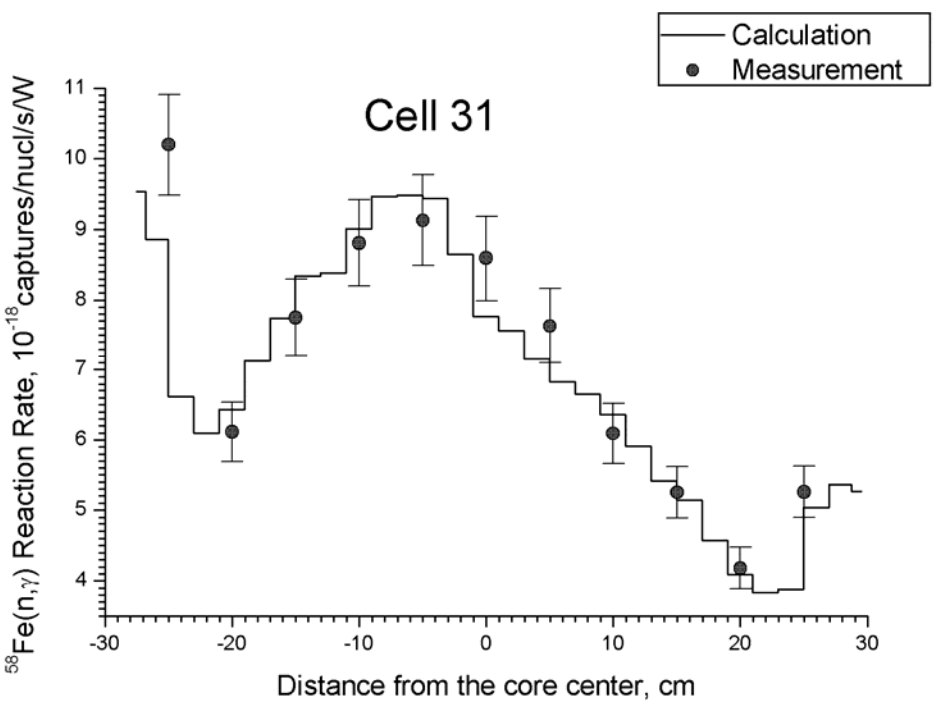

Fig. 5. Axial distribution of ^{58}Fe(n,γ) reaction rate in cell 31

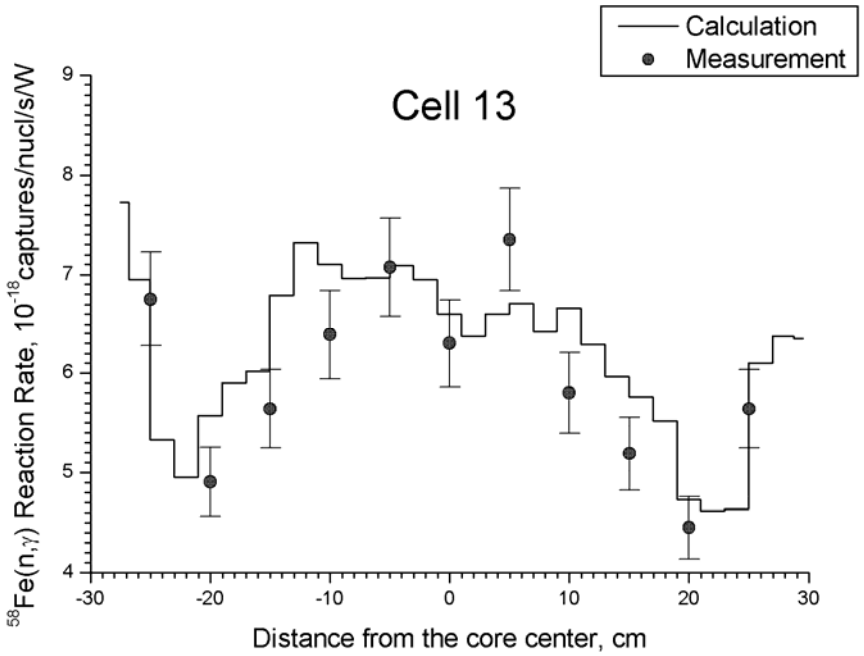

Fig. 6. Axial distribution of ^{58}Fe(n,γ) reaction rate in cell 13

ACCIDENTS ANALYSIS

1. Break of the supporting grid

As determined by materials study, supporting grid will keep its reliability at least up to $F(E \geq 0.8$ MeV)=2.09 10^{21} n/cm^2, where $F(E \geq 0.8$ MeV) is the integral flux of fast neutrons. At this moment $F(E \geq 0.8$ MeV)=1.63 10^{21} n/cm^2. As calculated for equilibrium LEU core, maximum flux of fast neutrons ($E \geq 0.8$ MeV) on supporting grid is 5.8 10^{12} n/cm^2/sec for nominal reactor power (10 MW). Thus, this limit can be reached only after 918 EFPD.

2. Spontaneous withdrawal of a control rod group.

The following worst scenario is considered.

A. The reactor has maximum excess reactivity. The reactor power is 3.1 MW. The slowest control rod (PR) is fully out the core. Automatic regulating system is not in operation. Because of malfunction of electronic equipment, the most efficient bank of control rods (RR1) 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.

B. When reactor power reaches 12 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 (AZ3) are fully in the core. The rods RR2, PR and AR move down the core until reach the lowest position.

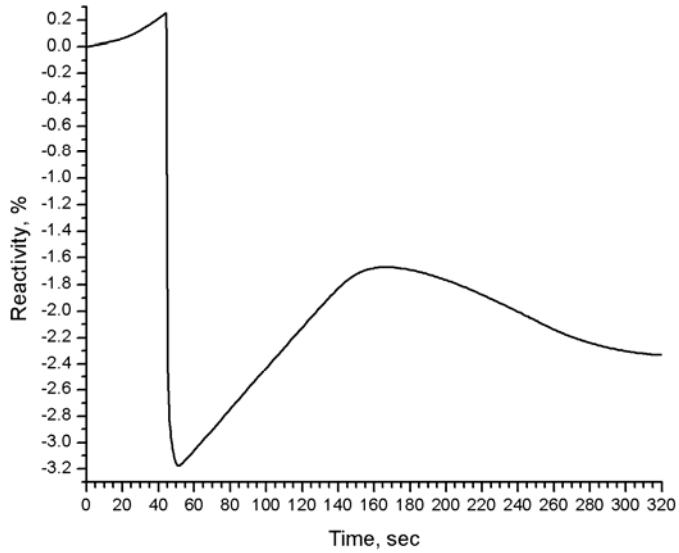

Fig. 7. Reactivity for spontaneous withdrawal of a control rod group

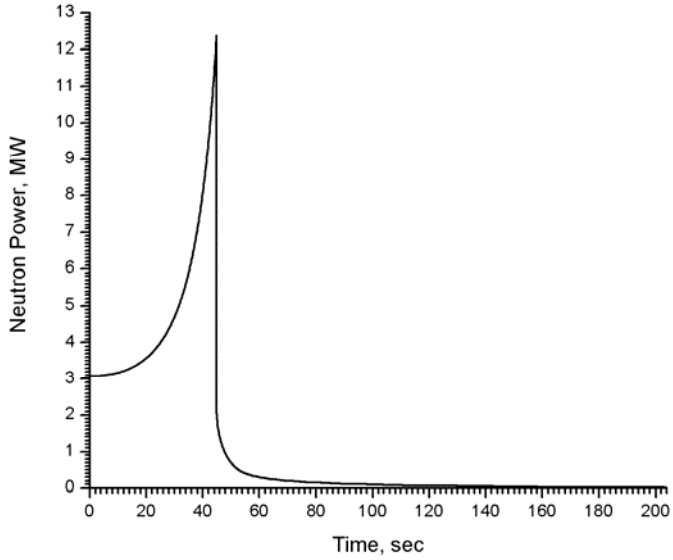

Fig. 8. Neutron power for spontaneous withdrawal of a control rod group

Calculated reactivity and neutron power as functions of time are shown in Fig.7 and 8. Peak reactor power is 12.4 MW, power peaking factor is 2.12, peak power density in the core is 236 W/cm^3, peak fuel temperature is less than 105 C, peak surface temperature is less than 102 C, minimum DNBR is 4.6, minimum margin to ONB is 1.2. Thermal-hydraulics was calculated using conservative approach, thus the temperatures calculated can be considered only as upper estimation of real temperatures.

Thus, the analysis shows that if the critical reactor power is more than 12.4 MW and maximum effective multiplication factor when RR2, AR, AZ1 and AZ2 are fully in and RR1, PR and AZ3 are fully out is less than unity, then such initial 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. 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.

Minimum sub-criticality when RR1, RR2, PR and AR are fully in and AZ1, AZ2 and AZ3 are fully out is 2.56%. Hence, effective multiplication factor after falling of any fuel assembly in any cell during reload of the core is less than 0.9744. If RR1, RR2, PR and AR are fully in and AZ1, AZ2 and AZ3 are fully out then increasing of effective multiplication factor because of loading a triple fresh fuel assembly in a cell of the core is less than 1.03%. 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 0.9847.

Thus, the analysis shows that if the minimum sub-criticality when RR1, RR2, PR and AR are fully in and AZ1, AZ2 and AZ3 are fully out is more than 1.03%, then such initial event with accompanying one additional error of personnel does not lead to damage of fuel elements and release of radioactivity exceeding allowed level.

CONCLUSIONS

The WWR-M research reactor in Kiev (Ukraine) is being jointly studied by the Argonne National Laboratory and the Kiev Institute for Nuclear Research for conversion from HEU to LEU fuel. Candidate LEU replacement fuel assemblies are LEU WWR-M2 (19.75%), which have been tested successfully in the WWR-M reactor in Gatchina by irradiation to over 75% burnup. A study confirming the feasibility of converting the WWR-M research reactor in Ukraine from HEU to LEU fuel has been already completed. To qualify this LEU fuel for conversion of the WWR-M reactor in Kiev and to get the appropriate license of the Ukrainian Nuclear Regulatory Committee, the safety analysis is being performed now.

Neutronic and thermal-hydraulic characteristics of LEU fuel equilibrium core and transition mixed core containing both LEU and HEU fuel have been calculated. The models applied for calculations have been validated against measured data, which include critical experiment results for fresh fuel assemblies and measured neutronic distributions in a real WWR-M reactor core. Some accidents have been analyzed: spontaneous withdrawal of a control rod bank and incidental falling

of a fuel assembly in a cell of the core. Severe accidents with accompanying melting of the core have not been analyzed yet. Moreover, the safety analyses of fresh and depleted LEU fuel storage has not been completed yet. This work is planned to be finished by the end of 2004.

ACNOWLEDGEMENTS

The work was supported by a contract with the Argonne National Laboratory. We would like to thank James E. Matos, Nelson A. Hanan and Ray B. Pond (RERTR Program) for their assistance and very useful criticism.

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