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ABSTRACT

The 10 MW, WWR-M research reactor of the Kiev Institute for Nuclear Research is jointly studied with the Argonne National Laboratory to examine the feasibility of conversion from HEU (36%) to LEU (19.75%) fuel. A potential core configuration was chosen for comparison of analytical results with HEU fuel and candidate replacement LEU fuels. Core reactivity, fuel assembly power, experiment flux, fuel-cycle length, the number of fuel assemblies consumed per year, and shutdown margins are compared using HEU and LEU fuels.

The reactor currently uses HEU (36%) WWR-M2 fuel assemblies (3 tubes, UO_2-Al fuel meat with 1.1 gU/cm^3 and 37.0 g ^{235}U). Candidate LEU replacement fuel assemblies, which would result in the same fuel cycle length and the same annual fuel consumption as the HEU (36%) fuel are: LEU WWR-M2 (3 tubes, UO_2-Al fuel meat with 2.3 gU/cm^3 and 38.3 g ^{235}U) and LEU WWR-MR (37 pins, U9Mo-Al fuel meat with 2.4 gU/cm^3 and 38.1 g ^{235}U).

Five LEU WWR-M2 fuel assemblies with 41.7 g ^{235}U per assembly, UO_2-Al fuel meat with 2.5 gU/cm^3, and a fueled height of 50 cm have completed irradiation testing in the WWR-M reactor at the Petersburg Nuclear Physics Institute in Gatchina to an average ^{235}U burnup of over 70%. This LEU fuel is considered to be qualified for conversion of the WWR-M reactor in Kiev and other research reactors using HEU (36%) WWR-M2 fuel assemblies. For reactors using assemblies with a fueled height of 60 cm, the ^{235}U content per assembly would be 50 g with the same fuel meat composition as the fuel assemblies that were tested in Gatchina.

Two 37-pin LEU test assemblies – one with UO_2-Al fuel meat and about 48 g ^{235}U and the other with U9Mo-Al fuel meat and about 96 g ^{235}U are scheduled to begin irradiation testing in the WWR-M reactor in Gatchina before the end of 2002. If these tests (lasting about two years) are successful, LEU pin-type fuel assemblies with up to 96 g ^{235}U would be candidate fuels for LEU conversion of the WWR-M reactor in Kiev and other research reactors using WWR-M2 fuel assemblies.

INTRODUCTION

The WWR-M is a 10 MW research reactor in Ukraine that is being jointly studied by the Argonne National Laboratory and the Kiev Institute for Nuclear Research to examine the feasibility for conversion from HEU to LEU fuel. Both diffusion theory and Monte Carlo methods have been used to study the reactor performance with the current HEU (36%) WWR-M2 fuel assemblies and two proposed LEU (19.75%) fuel assembly designs.

REACTOR MODEL

The reactor model shown in Figure 1 contains 210 WWR-M2 fuel assemblies, two thermal- and two fast-flux experiments, eight control- and safety-rods, a regulating rod, nine horizontal beam tubes, fifteen vertical irradiation channels, six peripheral beryllium assemblies, an inner beryllium reflector, an outer water reflector, and a graphite thermal column. This model represents a possible WWR-M core configuration that could be built; it serves here only as the basis to compare results with the HEU and LEU fuels.

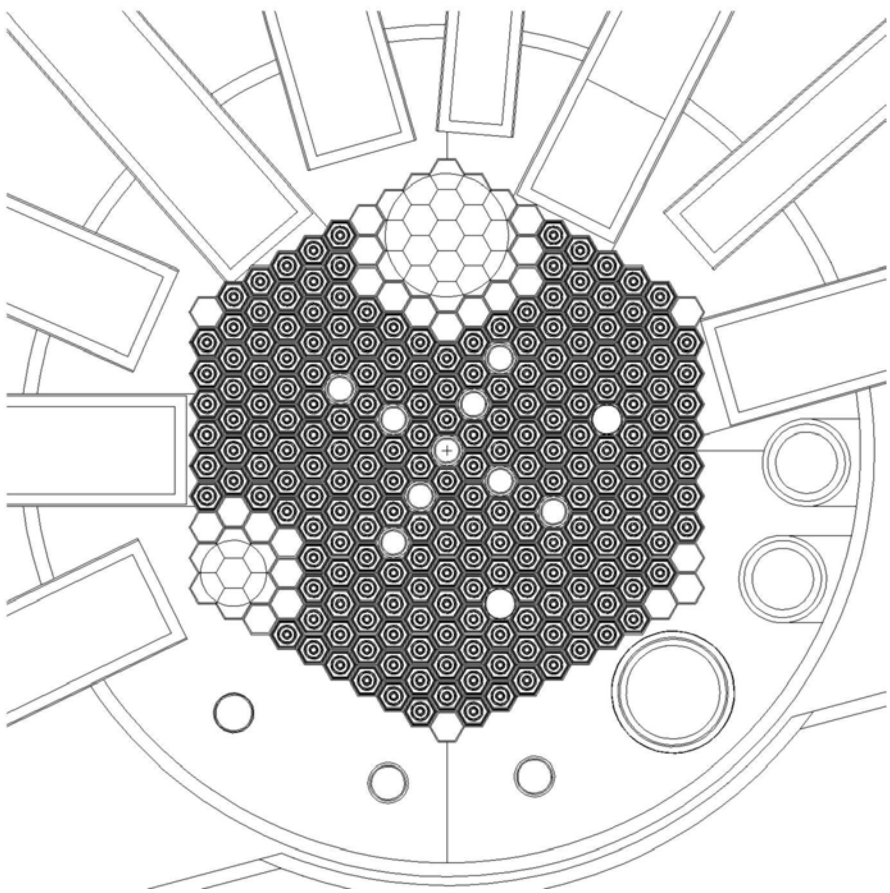

Figure 1. The MCNP Model for a Possible Core of the WWR-M Research Reactor at the Kiev Institute for Nuclear Research

In the burnup model for the equilibrium fuel cycle, 10 fuel assemblies follow separate paths through the reactor core. Fresh fuel is introduced in ten core locations, then moved to ten other locations at the end of each fuel burn, and finally discharged after 21 cycles. Performance of the thermal- and fast-flux experiments are calculated at the beginning-of-equilibrium cycle (BOEC).

The Monte Carlo model of the reactor shown in Figure 1 includes all of the reactor details including the reactor tank, the tube and channel pipes, the thermal column, the hexagonal core geometry, and the cylindrical beam tubes, irradiation channels, reflectors, etc. In diffusion theory, much of this detail had to be eliminated because of the necessity of using only one finite-size hexagon to makeup each reactor region. In most cases, the region size is based upon area. The diffusion theory reactor model also did not include the beam tubes because they cause severe power distortions in the fuel assemblies nearby. Without the beam tubes, the reactor power distribution with diffusion theory and Monte Carlo are in good (< 3%) agreement.

FUEL ASSEMBLY DESIGNS

Cross sections of the two fuel assembly designs that were studied are shown in Figure 2. Key fuel assembly design parameters are shown in Table 1. The HEU (36%) WWR-M2 fuel assembly consists of an outer hexagonal tube and two inner cylindrical tubes. Each fuel assembly contains a total of 37 g ^{235}U. The meat consists of UO_2-Al dispersion fuel with a uranium density of about 1.1 g/cm^3.

The first candidate LEU WWR-M2 tubular design has the same geometry as the HEU design, but contains 38.3 g ^{235}U with UO_2-Al dispersion and a uranium density of about 2.3 g/cm^3 in the fuel meat. A second case with this geometry had an increased ^{235}U loading of 41.7 g. The second candidate LEU fuel assembly is the WWR-MR design with 37 fuel pins that contain U9Mo-Al dispersion fuel meat, a uranium density of about 2.4 g/cm^3, and a total of 38.1 g ^{235}U. The 37 pins are distributed in a hexagonal array within a 0.8 mm-thick aluminum shroud that has the same hexagonal shape and the same outer dimensions as the WWR-M2 tubular design.

Figure 2. HEU and LEU Fuel Assembly Designs that Were Studied

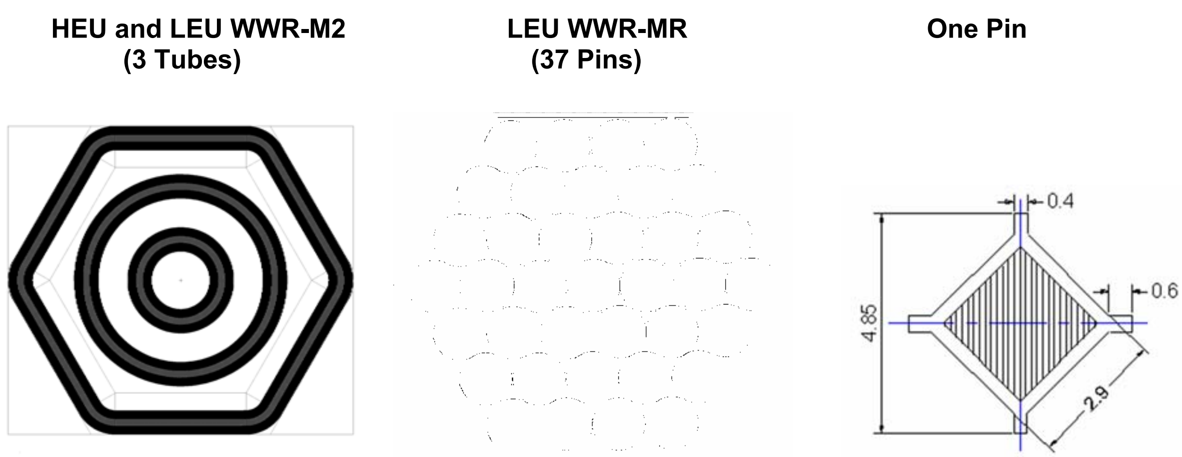

Table 1. Fuel Assembly Design Parameters

	WWR-M2 HEU (36%)	WWR-M2 LEU (19.75%)	WWR-M2 LEU (19.75%)	WWR-MR LEU (19.75%)
^{235}U/FA	37.0	38.3	41.7	38.1
U Density, g/cm^3	1.1	2.3	2.5	2.4
FA Pitch/Flat-to-Flat, mm	35/32	35/32	35/32	35/32*
Element/Clad/Meat, mm	2.5/0.76/0.98	2.5/0.78/0.94	2.5/0.78/0.94	2.9/0.4/2.1

* The thickness of the aluminum shroud of the WWR-MR pin-type fuel assembly is 0.8 mm.

COMPUTER CODES

The Monte Carlo calculations were performed using the MCNP code[1], and the coupled diffusion and burnup calculations used the DIF3D codes[2,3] and the REBUS-3 / REBUS-PC codes.[4,5] Seven-group cross sections for use with diffusion theory were calculated using the WIMS-ANL code[6] with ENDF/B-VI nuclear cross section data. Continuous-energy cross-sections for use with MCNP were calculated with the NJOY code[7], also using ENDF/B-VI data.

FUEL CYCLE RESULTS

HEU (36%) WWR-M2 Tubular Fuel

Fuel cycle results for the current HEU (36%) fuel and the proposed LEU (19.75%) fuels are shown in Table 2. A core such as the one shown in Figure 1 with 210 fuel assemblies in which 10 fresh assemblies are introduced at the beginning of each operating cycle would have a fuel cycle length of about 20.9 days. The reactor would consume 100 fuel assemblies per year, assuming that it operates for 5,000 full-power hours annually.

The next step was to determine the ^{235}U loading of LEU WWR-M2 tube-type fuel assemblies and LEU WWR-MR pin-type fuel assemblies that would provide the same fuel cycle length and the same number of fuel assemblies used per year as the current HEU (36%) fuel.

Table 2. Fuel Cycle Length and Fuel Assemblies User per Year for the HEU and Candidate LEU Fuels.

Fuel Assembly Type	Geometry	Enrichment, %	Fuel Meat Comp.	^{235}U Mass, g	Equilibrium Fuel Cycle Length, days	Average ^{235}U Discharge Burnup, %	Used Fuel Assemblies Per Year[a]
WWR-M2	3 Tubes	36	UO_2-Al 1.1 gU/cm^3	37.0	20.87	67.6	100
WWR-M2	3 Tubes	19.75	UO_2-Al 2.3 gU/cm^3	38.3	20.9	63.7	100
WWR-M2	3 Tubes	19.75	UO_2-Al 2.5 gU/cm^3	41.7	24.4	67.7	90
WWR-MR	37 Pins	19.75	U9Mo-Al 2.4 gU/cm^3	38.1	20.9	64.4	100

[a] Assumes 5,000 full-power-hours or 208.3 full-power-days of operation per year at 10 MW with 210 fuel assemblies; 10 fuel assemblies are discharged and 10 fresh fuel assemblies are inserted at the beginning of each operating cycle.

LEU WWR-M2 Tubular Fuel

With LEU UO_2-Al fuel meat, a ^{235}U loading of 38.3 g would result in discharge of 100 spent fuel assemblies per year, the same as with the current HEU (36%) fuel assuming 5,000 hours of operation per year at a power of 10 MW. With a ^{235}U loading of 41.7 g in the same fuel assembly geometry, only 90 fuel assemblies would be required per year for the same operating conditions.

This latter case with a loading of 41.7 g ^{235}U and UO_2-Al fuel meat with a uranium density of 2.5 g/cm^3 is important because five of the these fuel assemblies were successfully irradiation tested[8] in the WWR-M reactor at the Petersburg Nuclear Physics Institute (PNPI) in Gatchina to average ^{235}U burnups of over 70%. The fuel assemblies were manufactured by the Novosibirsk Chemical Concentrates Plant around 1996. The irradiation tests at PNPI were completed in 2001. These LEU fuel assemblies are considered to be qualified for use in conversion of the WWR-M reactor in Kiev and other research reactors that currently use HEU (36%) WWR-M2 type fuel assemblies. The loading of 41.7 g ^{235}U corresponds to a fuel meat height of 50 cm. For reactors using WWR-M2 fuel assemblies with a fueled height of 60 cm, the equivalent ^{235}U content would be 50 grams per assembly with the same fuel meat composition.

LEU WWR-MR Pin-Type Fuel

With the LEU WWR-MR pin-type fuel design, a ^{235}U loading of 38.1 g was calculated to have the same 20.9-day fuel cycle length as the current HEU (36%) tubular fuel. About 100 fuel assemblies would be consumed per year for 5,000 hours of operation at 10 MW.

The ^{235}U loading that is required to match the 20.9 day cycle length of the HEU (36%) fuel is slightly smaller with the LEU pin-type design (38.1 g ^{235}U) than with the LEU tube-type design (38.3 g ^{235}U) because the volume fraction of water in the pin-type design (0.60) is larger than in the tube-type design (0.55). The larger water volume fraction in the pin-type design leads to a more thermal neutron spectrum that more than compensates for the increased neutron absorption in its LEU U9Mo-Al fuel meat, as compared with the LEU UO_2-Al fuel meat in the tubular design.

Two LEU test fuel assemblies with 37 fuel pins have been manufactured[9] by the A.A. Bochvar All Russian Research Institute for Inorganic Materials (VNIINM) and are currently scheduled to begin irradiation testing in the WWR-M research reactor at PNPI in Gatchina before the end of 2002. One test assembly has 37 pins with UO_2-Al fuel meat and a total ^{235}U loading of about 48 grams. The second test assembly has 37 pins with U9Mo-Al fuel meat and a total ^{235}U loading of about 96 grams. The irradiation tests are expected to be completed in two years.

If these irradiation tests are successful, loadings of up to about 48 g ^{235}U per fuel assembly with UO_2-Al fuel meat and up to 96 g ^{235}U per fuel assembly with U9Mo-Al fuel meat could be considered as candidate LEU fuels in order to reduce the number of fuel assemblies that would be consumed per year or to produce desired flux-tilting to enhance the performance of selected experiments.

FLUX PERFORMANCE RESULTS

The flux performance of the reactor with the different HEU and LEU fuels is shown in Table 3. This table shows the neutron flux in the two thermal-flux and the two fast-flux experiment locations that were calculated using the MCNP Monte Carlo model of the reactor at BOEC for the current HEU fuel and the candidate LEU fuels. The DIF3D diffusion theory model of the reactor gave very nearly the same results. These data show that the ratio of both the fast and the thermal fluxes in these experiment positions would be smaller by only 1 - 2% in the LEU tubular designs in comparison with the current HEU tubular design. However, in the LEU pin-type design, the fast and thermal fluxes in the experiment positions would be reduced by 5 - 6% in comparison with the current HEU (36%) fuel.

Table 3. Thermal and Fast Fluxes x 10^{-14} and LEU/HEU Flux Ratios in Selected Experiment Positions.

Experiment Matrix Position[a]	**HEU (36%) WWR-M2** 3 Tubes UO_2-Al 1.1 g U/cm^3 37 g ^{235}U 20.87days	**LEU (19.75%) WWR-M2** 3 Tubes UO_2-Al 2.3 g U/cm^3 38.3 g ^{235}U 20.9 days	**LEU (19.75%) WWR-M2** 3 Tubes UO_2-Al 2.5 g U/cm^3 41.7 g ^{235}U 24.4 days	**LEU (19.75%) WWR-MR** 37 Pins U9Mo-Al 2.4 g U/cm^3 38.1 g ^{235}U 20.9 days
Thermal:				
0917	1.30[b]	1.28	1.27	1.22
	-	0.98	0.98	0.94
0801	0.88	0.87	0.88	0.82
	-	0.99	1.00	0.94
Fast:				
0721	0.66	0.65	0.65	0.62
	-	0.99	0.99	0.95
0729	0.59	0.58	0.59	0.55
	-	0.98	0.99	0.94

[a] Matrix position in the experiment location xxyy where xx is the hex-ring and yy is the hex-number in the ring. The thermal flux is < 0.625 eV and the fast flux is > 0.821 MeV. The flux (n/cm^2-s) is multiplied by 10^{-14} and by the BOEC eigenvalue in order to normalize the flux for each fuel type.
[b] Table format for each experiment matrix position: The upper number is the MCNP calculated fluxes with beam tubes and all other reactor details. The lower number is the LEU/HEU flux ratio calculated using MCNP. The flux values and LEU/HEU flux ratios calculated using the diffusion theory model are nearly the same as those that were calculated using MCNP.

REACTIVITY BALANCE TABLES

Fuel cycle lengths and ^{235}U masses for each case are based upon satisfying an operational requirement that the BOEC excess reactivity be less than 5.67% Δk/k ($7). The reactivity balance table data shown in Table 4 indicate that these conditions are met. At BOEC, all Xe is assumed to have decayed and the Sm concentration is at its equilibrium value. All control rods are fully-withdrawn. The reactivity worth of the experiments is - 0.5% Δk/k. At EOEC, all rods are fully-withdrawn except for the partially-inserted regulating rod, which has a reactivity worth of – 0.15 % Δk/k. The cold-to-hot reactivity change was calculated to be - 0.37% Δk/k for the reference case with HEU (36%) fuel. The worth of the experiments is - 0.5% Δk/k.

Table 4. Reactivity Balance Tables

Balance Table Reactivity Component % Δk/k ($)*	**HEU (36%)** **WWR-M2** 3 Tubes UO_2-Al 1.1 g U/cm^3 37 g ^{235}U 20.87days	**LEU (19.75%)** **WWR-M2** 3 Tubes UO_2-Al 2.3 g U/cm^3 38.3 g ^{235}U 20.9 days	**LEU (19.75%)** **WWR-M2** 3 Tubes UO_2-Al 2.5 g U/cm^3 41.7 g ^{235}U 24.4 days	**LEU (19.75%)** **WWR-MR** 37 Pins U9Mo-Al 2.4 g U/cm^3 38.1 g ^{235}U 20.9 days
BOEC Cold, All Control Rods Out				
No Xe; Equilibrium Sm	6.16	6.06	6.07	6.07
Experiments	- 0.50	- 0.50	- 0.50	- 0.50
Net Excess Reactivity	5.66 ($6.99)	5.56 ($6.86)	5.57 ($6.88)	6.57 ($6.88)
EOEC All Control Rods Out				
MCNP Cold Excess	1.06	1.25	1.07	1.18
Cold to Hot Change	- 0.37	- 0.32	- 0.32	- 0.31
Experiments	- 0.50	- 0.50	- 0.50	- 0.50
Regulating Rod	-0.15	- 0.15	- 0.15	- 0.15
Net Excess Reactivity	0.04 ($0.05)	0.28 ($0.35)	0.10 ($0.12)	0.22 ($0.27)

* Based on β_{eff} = 0.0081 (Ref. 10)

SHUTDOWN MARGINS

Table 5 shows shutdown margins at the beginning of the equilibrium cycle (BOEC) for each of the HEU and LEU cores that were studied. Each core at BOEC had no Xenon and equilibrium concentrations of Samarium. All of the control rods were fully-inserted, the regulating rod was fully-withdrawn, and all safety rods were fully-withdrawn. The data show that all of the cores would be subcritical by at least 1% Δk/k under the specified conditions and satisfy the reactor's shutdown margin requirements.

Table 5. Shutdown Margins at BOEC

No Xe; Equilibrium Sm; All Control Rods IN; Regulating Rod OUT; All Safety Rods OUT

State of Core	**HEU (36%)** **WWR-M2** 3 Tubes UO_2-Al 1.1 g U/cm^3 37 g ^{235}U 20.87days	**LEU (19.75%)** **WWR-M2** 3 Tubes UO_2-Al 2.3 g U/cm^3 38.3 g ^{235}U 20.9 days	**LEU (19.75%)** **WWR-M2** 3 Tubes UO_2-Al 2.5 g U/cm^3 41.7 g ^{235}U 24.4 days	**LEU (19.75%)** **WWR-MR** 37 Pins U9Mo-Al 2.4 g U/cm^3 38.1 g ^{235}U 20.9 days
BOEC				
K_{eff} at BOEC	0.9796	0.9824	0.9827	0.9848
% Δk/k	- 2.08	- 1.79	- 2.26	- 1.53

CONCLUSIONS

A study has been completed to determine the feasibility of converting the WWR-M research reactor at the Kiev Institute for Nuclear Research in Ukraine from HEU to LEU fuel. With the same ^{235}U loading of 41.7 g as in five LEU WWR-M2 tube-type fuel assemblies that have been successfully irradiation tested to an average ^{235}U burnup of over 70% at the Petersburg Nuclear Physics Institute in Russia, the reactor would require about 10% fewer fuel assemblies per year than with the current HEU (36%) fuel. Fast and thermal neutron fluxes in key experiment positions would decrease by only 1 - 2%. Thus, it is feasible to convert the WWR-M reactor in Kiev to LEU fuel using a qualified LEU fuel that is currently available for this purpose.

Two LEU test assemblies based a new pin-type design developed and manufactured by the A.A. Bochvar All-Russian Research Institute of Inorganic Materials are scheduled to begin irradiation testing in the WWR-M reactor at PNPI before the end of 2002. The pins of one test assembly contain UO_2-Al fuel meat and a total ^{235}U content of about 48 g. The pins of the second test assembly contain U9Mo-Al fuel meat and a total ^{235}U content of about 96 g. The irradiation tests are expected to last about two years. If the tests are successful, LEU fuel assemblies containing pins with either UO_2-Al or U9Mo-Al dispersion fuel meat could be used for LEU conversion of the WWR-M reactor in Kiev. However, the pins with U9Mo-Al fuel meat have the potential of providing ^{235}U loadings that are high enough to satisfy flux-tilting requirements to enhance neutron fluxes in selected experiment positions in the core.

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