Feasibility Studies for LEU Conversion of the WWR-SM Reactor in Uzbekistan Using Pin-Type and Tubular Fuels

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ABSTRACT

The 10 MW WWR-SM research reactor in Uzbekistan currently uses HEU (36%) IRT-3M 6-tube fuel assemblies manufactured by the Novosibirsk Chemical Concentrates Plant in Russia. This study compares the neutronic performance and preliminary thermal-hydraulic performance of the reactor and its experiments for several core sizes using various LEU pin-type and LEU tube-type fuel assembly designs with the performance of the current HEU (36%) reference fuel assembly and core. Several LEU fuel assembly designs are identified which would be suitable for conversion of the WWR-SM reactor if they are manufactured, successfully irradiation tested, and made commercially available in Russia.

INTRODUCTION

The WWR-SM research reactor in Uzbekistan currently uses IRT-3M HEU (36%) 6-tube fuel assemblies fabricated by the Novosibirsk Chemical Concentrates Plant in Russia. The Institute of Nuclear Physics (Tashkent) plans to convert the WWR-SM reactor soon after a suitable LEU (19.7%) fuel assembly is manufactured, successfully irradiation tested, and made commercially available in Russia. A paper (Ref. 1) presented at the 2002 RERTR meeting provided results of analyses performed for several types of fuel assemblies using the core configuration and reactor power being used around that time (a 16-FA core operated at 8 MW). Presently, the reactor core is configured with 18 fuel assemblies and operates at 10 MW. The objective of this study is to define and optimize the geometry and loading specifications of LEU fuel assemblies that could be used for conversion of the WWR-SM reactor from HEU to LEU fuel. Several core configurations (18, 20 and 24-FA cores) with three different types of LEU FA were analyzed: IRT-3M tube-type FA with U9Mo-Al fuel, IRT-4M FA with UO_2-Al fuel, and IRT-MR pin-type FA with U9Mo-Al and “monolithic” U9Mo fuel. Both neutronics results (annual fuel consumption, experiment performance, shutdown margin) and thermal-hydraulics results (maximum power levels) are presented.

THE WWR-SM RESEARCH REACTOR

Reactor Description

The WWR-SM reactor is located at the Institute of Nuclear Physics in Ulugbek, 30 km NE of Tashkent, Uzbekistan. The reactor first reached criticality in September 1959 and was upgraded from 2 to 10 MW in the 1970s. Presently the reactor operates at 10 MW using a beryllium-reflected compact core of 18 Russian-supplied 6-tube IRT-3M (36%) fuel assemblies. The control system consists of 6 shim rods, 3 safety rods and one automatic regulating rod (AR). All control rods are 23 mm in diameter and consist of a 600 mm column of B_4C absorbers inside a 1-mm-thick stainless steel tube. An aluminum alloy follower rod, 23 mm in diameter and 518 mm long, is located below each control rod except for the AR rod. The active core height is 600 mm.

The reactor is used for radioisotope production, neutron activation analyses, and experiments in nuclear physics, solid-state physics, and nuclear engineering. To carry out these measurements the reactor has nine horizontal beam tubes, a graphite thermal column, and numerous vertical irradiation channels in both core and reflector regions. Ref. 2 gives a description of the WWR-SM research reactor.

REACTOR CORES AND FUEL ASSEMBLIES

Presently, the reactor operates with a core consisting of 18 IRT-3M (36%) 6-tube fuel assemblies. However, in the past, it has operated with cores composed of 24 fuel assemblies. In this study core configurations with 18, 20, and 24 FA have been analyzed.

Figure 1 shows horizontal cross-sections of the fuel assemblies used in this study. Table 1 summarizes the major characteristics of these assemblies:

1) 6-Tube IRT-3M FA consist of six concentric square tubes with cylindrical corners containing either UO_2-Al (HEU) or U9Mo-Al (LEU) fuel meat. IRT-3M HEU (36%) fuel is presently used in the WWR-SM reactor.
2) 6-Tube IRT-4M LEU FA consist of six concentric square tubes with cylindrical corners containing UO_2-Al fuel meat. Fuel tubes with UO_2-Al fuel meat and the same uranium density as IRT-4M FA have been tested in the IVV-2M reactor in Russia (Ref. 3) and IRT-4M fuel assemblies have been tested in the WWR-SM reactor in Uzbekistan (Refs. 3-6).
3) IRT-MR LEU FA consist of an array of 176 fuel elements (pins). In the results discussed in this paper, unless otherwise mentioned, the four elements located at the corners of the FA were aluminum elements with no fuel.

Figure 1. Horizontal Cross Sections of IRT-3M, IRT-4M and IRT-MR Fuel Assemblies

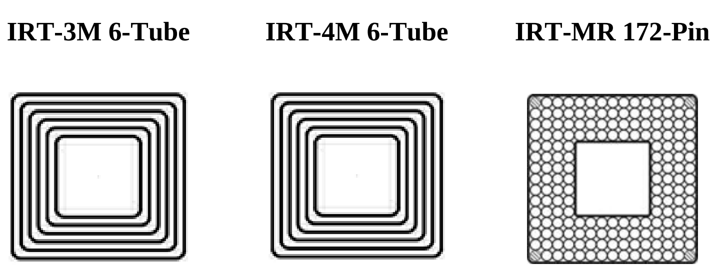

Table 1. Fuel Assembly Parameters

Parameters	6-Tube IRT-3M	6-Tube IRT-3M		6-Tube IRT-4M	172-FE IRT-MR	172-FE IRT-MR
Fuel Meat	UO_2-Al	U9Mo-Al		UO_2-Al	U9Mo-Al	U9Mo
Wt. % ^{235}U	36.0	19.7	19.7	19.7	19.7	19.7
$(g\ U/cm^3)_{meat}$	2.4	5.1	4.7	2.8	3.7 to 6.9	15.65
Dispersant VF, %	27.8	32.6	29.8	32.5	23.6 to 44.1	100
^{235}U/FA, g	300	347	317	265	285 to 450	296 and 325
$T_{meat,}$, mm	0.50	0.50	0.50	0.70	2.1 x 2.1 to 1.5 x 1.5	0.963 x 0.963 and 1.010 x 1.010
T_{clad}, mm	0.45	0.45	0.45	0.45	0.40	0.40
$H_{meat,}$, mm	600	600	600	600	600	600

METHODS, CODES, AND MODELS

Neutron Cross Sections

Neutron cross sections for both diffusion theory and Monte Carlo calculations are based on ENDF/B-VI data (Ref. 7). Multi-group cross sections for use in the diffusion theory burnup calculations were generated with the WIMS-ANL code (Ref. 8) and its 69-group library. These cross sections were collapsed into 7 broad groups with energy boundaries (eV) of 1.0E+7, 8.21E+5, 5.53E+3, 4.0, 6.25E-1, 2.50E-1, 5.8E-2, and 1.0E-5.

Since WIMS-ANL is a one-dimensional code, tube-type fuel assemblies were represented by a series of concentric circular regions of coolant, clad and fuel meat materials. Region radii were chosen to preserve the area of each region (see Fig. 1). Cross sections were also generated for non-depletable regions in the reactor, including beryllium, water and graphite reflectors, control rods and control rod followers, and in-core and ex-core experiment regions.

For the pin-type fuel assemblies (IRT-MR), a unit cell containing one fuel element and its associated coolant was used to generate neutron cross-sections using the WIMS-ANL code.

Diffusion Theory Burnup Calculations

Three-dimensional XYZ models (without beam tubes) of the WWR-SM research reactor were analyzed using the diffusion theory fuel cycle analysis code REBUS-PC (Refs. 9 and 10). For the cores with tube-type fuel assemblies (IRT-3M and IRT-4M), each fuel assembly cross section was homogenized for the burnup analyses. That is, the same composition was used for all six tubes in each axial plane. For the core with the pin-type IRT-MR FA, twelve different homogenized regions were used in each axial plane. Five axial regions were used in all burnup models. For all cores analyzed in this study, two fresh FA were added at the center of the core and two spent FA were discharged from the edge of the core at the beginning of each cycle.

The first equilibrium burnup calculation was performed for the core using the existing fuel (IRT-3M, 36%). This calculation was performed with all the control rods outside the core and with an end-of-equilibrium cycle (EOC) excess reactivity of about 2% Δk/k (to account for the temperature effects, control rods insertion, and uncertainties), and it defined the reference fuel cycle length for the present core. This fuel cycle length was then used to determine the ^{235}U loading required for all other designs (IRT-3M and IRT-MR FA) using U9Mo-Al and U9Mo. The same EOC excess reactivity of about 2% Δk/k was used. For the IRT-4M fuel assembly (UO_2-Al), this procedure was not used because the fuel loading is fixed. The fuel cycle lengths were determined using the same EOC excess reactivity as for the other cores.

After definition of the fuel loadings and fuel cycle lengths, the equilibrium burnup calculations were repeated, this time with the control rods inserted at their average position during the operating cycle. The fuel compositions of the different zones were saved to be used in the Monte Carlo analyses described below.

Monte Carlo Calculations

Detailed Monte Carlo models of the reactor were developed using the MCNP code (Ref. 11). These models included the beam tubes and all the experiments, and were used to calculate the following parameters:

- Detailed power densities for use in the thermal-hydraulics analyses: beginning-of-equilibrium-cycle (BOC) compositions with no Xe present, and with the control rods inserted to obtain a critical core (two banks of two shim rods each fully-inserted and the other two shim rods partially-inserted, as used in normal operation) were used. Power densities in fifteen axial segments were obtained for each fuel pin in all of the IRT-MR fuel assemblies and for each of the four sides and four corners in every tube of all IRT-3M and IRT-4M fuel assemblies.
- Experiment performance: BOC compositions with equilibrium Xe and the control rods at their average position during an operating cycle were used.
- Shutdown Margin: BOC compositions with no Xe present were used.

Thermal-Hydraulics Calculations

The maximum power level at which the reactor could operate was calculated for a margin of 1.4 to onset of nucleate boiling (ONB) based on the temperature ratio $(T_{ONB} - T_{IN})/(T_{WALL} - T_{IN})$ using the Forster-Grief correlation (Refs. 12, 13) without engineering ("hot channel") uncertainty factors for a coolant inlet temperature of 45ºC. The limiting fuel assembly was identified by examining the detailed power density data from the Monte Carlo calculations described above. Additional analyses are planned to address engineering ("hot channel") uncertainty factors and differences there may be in these factors between HEU and LEU fuels, particularly regarding ^{235}U homogeneity.

For the IRT-MR pin-type FA, detailed thermal-hydraulics analyses for an entire FA are in progress. At this time, conservative estimation of the maximum operating power using the IRT-MR fuel assemblies were performed using the power densities calculated using a single fuel element (pin). The SINDA/G code (Ref. 14) was used to model a single fuel element using the flow characteristics of an average fuel element in the fuel assembly.

The PLTEMP-ANL Version 2.1 code (Ref. 15) was used to calculate the maximum power level at which the reactor could operate using cores composed of IRT-3M HEU (36%), IRT-3M LEU, and IRT-4M LEU fuel assemblies.

RESULTS

Fuel cycle performance and key safety-related characteristics were used to compare the cores analyzed in this study. These include annual fuel consumption, experiment performance, maximum allowable operating power, and shutdown margins. Results for tubular fuels are shown in Table 2 and results for pin-type fuels are shown in Table 3. These results are discussed in the paragraphs following the tables.

Table 2. Summary of Reactor Parameters Using IRT-3M and IRT-4M Tubular Fuels

Type of Fuel Assembly	**IRT-3M**	**IRT-3M LEU**		**IRT-4M LEU**		
Enrichment	36	19.7		19.7		
Fuel Meat	UO_2-Al	U9Mo-Al		UO_2-Al		
Number of FA in Core	18	18	20	18	20	24
g ^{235}U per FA	300	347	317	265	265	265
Uranium Density, g/cm^3	2.4	5.1	4.7	2.8	2.8	2.8
Vol-% Dispersed Phase	27.8	32.6	29.8	32.5	32.5	32.5
Operational Performance						
Fuel Cycle Length, d	25.1	25.1	25.1	10.0	14.4	20.2
FA per Year (5000 h/yr)	16.6	16.6	16.6	41.7	28.9	20.6
FA/Year: LEU/HEU	-	1.0	1.0	2.5	1.7	1.2
Experiment Performance[1,2]						
^{33}S Experiments	1.0	0.97	0.93	1.00	0.96	0.87
^{32}S Experiments	1.0	0.99	0.95	1.02	0.98	0.91
Thermal Flux Experiments	1.0	0.96	0.93	1.04	0.99	0.96
Key Safety Margins						
Power (MW) at ONB Temperature Ratio of 1.4[3], (T_{IN} = 45ºC)	11.6	11.2	12.2	11.1	-	15.7
Power at ONB, MW	17.1	16.5	17.9	16.3	-	23.2
Shutdown Margin[4], % Δk/k	- 3.47	- 3.30	- 3.14	- 5.22	- 4.54	- 3.80

[1] Experiment performance data are based on a power level of 10 MW. Values shown are the ratio of the performance index with LEU fuel to that with the present IRT-3M HEU (36%) fuel.
[2] Uncertainty: σ < 0.5%
[3] Onset of Nucleate Boiling Temperature Ratio = $(T_{ONB} – T_{IN})/(T_{WALL} – T_{IN})$
[4] Uncertainty: σ < 0.3%

Table 3. Summary of Reactor Parameters Using IRT-MR Pin-Type Fuels.

All IRT-MR Cases Have a Cycle Length of 25.1 Days and Use 16.6 FA/Year, the same as for the Current IRT-3M HEU (36%) Tubular Fuel

No. FA In Core	Type of Fuel Meat	Fuel Meat Cross Section mm	^{235}U/ FA, g	U Dens., g/cm^3	Vol-% Disper-sant	^{33}S/^{32}S/ Thermal Flux Experiment Perf. Ratio[1,2]	Shut-down Margin[3] % Δk/k	**Conservative Estimate** of Maximum Power[4], MW	**Work is in Progress to Obtain Realistic Estimates of Maximum Power Levels**
18	U9Mo-Al	2.1 x 2.1	450	5.0	31.9	1.00/0.99/0.99	- 2.69	6.9	
18	U9Mo-Al	1.9 x 1.9	405	5.5	35.1	0.99/0.99/0.98	- 2.67	7.6	
18	U9Mo-Al	1.6 x 1.6	355	6.8	43.5	0.98/0.99/0.97	- 2.60	8.6	
18	U9Mo	1.01x1.01	325	15.6	--	0.95/0.98/0.95	- 2.33	9.6	
20	U9Mo-Al	2.1 x 2.1	400	4.5	28.8	0.95/0.96/0.95	- 2.73	7.9	
20	U9Mo-Al	1.9 x 1.9	360	4.9	31.3	0.94/0.96/0.95	- 2.71	8.8	
20	U9Mo-Al	1.6 x 1.6	324	6.2	39.6	0.93/0.96/0.94	- 2.73	9.8	
20	U9Mo-Al	1.5 x 1.5	315	6.9	44.1	0.92/0.95/0.94	- 2.75	10.2	
20	U9Mo	.963x.963	296	15.6	--	0.92/0.94/0.92	- 2.55	11.0	
24	U9Mo-Al	2.1 x 2.1	335	3.7	23.6	0.87/0.90/0.96	- 3.04	10.9	
24	U9Mo-Al	1.9 x 1.9	310	4.2	26.8	0.86/0.90/0.95	- 2.84	12.1	
24	U9Mo-Al	1.6 x 1.6	285	5.5	35.1	0.85/0.90/0.93	- 2.84	12.6	

[1] Experiment performance data are based on a power level of 10 MW. Values shown are the ratio of the performance index with LEU fuel to the performance index with the present IRT-3M HEU (36%) fuel.
[2] Uncertainty: $\sigma < 0.5\%$
[3] Uncertainty: $\sigma < 0.3\%$
[4] At Onset of Nucleate Boiling Temperature Ratio = $(T_{ONB} - T_{IN})/(T_{WALL} - T_{IN}) = 1.4$

Annual Fuel Consumption

One of the basic principles for LEU conversion in the RERTR program has always been that operation of the LEU core should result in the use of the same number or fewer fuel assemblies per year than in the HEU core, for economic reasons.

Use of IRT-4M LEU FA in the WWR-SM core with 18 FA would result in consumption of 2.5 times more fuel assemblies per year than with the HEU (36%) fuel. Even if the core size were increased to 24 FA, the annual fuel consumption would still be 1.2 times that of the HEU core. The basic reason for this poor performance is the smaller mass of ^{235}U present in the LEU IRT-4M FA (265 g) as compared with the IRT-3M HEU (36%) FA (300 g). As a result, IRT-4M LEU fuel assemblies are not suitable for conversion of the WWR-SM reactor, even though these FA may be commercially available.

All LEU FA containing either U9Mo-Al (IRT-3M and IRT-MR) or U9Mo (IRT-MR) were designed to maintain the same annual fuel consumption as the IRT-3M HEU (36%) FA. In all FA with U9Mo-Al fuel, the volume fraction of the dispersant is smaller than 33% for the IRT-3M FA and smaller than 45% for the IRT-MR FA. These volume fractions of the dispersed phase are believed to be within the range of manufacturing possibilities for tubular and pin-type geometries.

Experiment Performance

As in the majority of research reactors the experiments loaded in a core change very often. The experiments loaded in the July 2003 core at the WWR-SM were used for the comparison of experiment performance in this study. A summary of these experiments follows:

- Three ^{33}S experiments located inside fuel assemblies were explicitly modeled. The performance index is the average of the (n, p) reaction rate in ^{33}S for all three experiments. Note that this reaction that requires mostly fast neutron flux.
- Three ^{32}S experiments, two located inside fuel assemblies and one located inside a beryllium reflector assembly, were explicitly modeled. The performance index is the average of the (n, p) reaction rate in ^{32}S for all three experiments. Note that this is a threshold reaction that requires fast neutron flux.
- Six experiments requiring thermal neutron flux are located inside beryllium reflector assemblies. The performance index for these experiments is based on the average thermal flux (< 0.625 eV) in a water region (cylindrical with diameter equal to 1.5 cm) in the center of the beryllium reflector assemblies.

The performance for these experiments in all the core configurations studied is presented in Tables 2 and 3. The following is a summary of the results:

- For all the cores with 18 FA, the experiment performance for all LEU core configurations decreases by 5% or less when compared with the present HEU (36%) core. The performance for the configuration with the IRT-4M LEU FA is higher than for the other FA because of its relatively low ^{235}U loading. This is the same reason that would result in a high annual fuel consumption with the IRT-4M FA (see above).
- For all the cores with 20 FA, the experiment performance for all the LEU core configurations decreases by less than 8% when compared with the HEU core with 18 FA.
- For all the cores with 24 FA, the experiment performance decreases by less than 15% for the ^{33}S experiments, less than 10% for the ^{32}S experiments, and less than 7% for the experiments in the reflector.
- The larger the core size, the larger the decrease in performance when compared with the HEU core with 18 FA.

Maximum Power Levels

The maximum power levels calculated using IRT-3M LEU FA with U9Mo-Al fuel in an 18 FA core are slightly smaller than for the present IRT-3M HEU (36%) fuel, but are adequate for operation at a power level of 10 MW. As expected, the maximum power level would increase if the core were enlarged to 20 FA because the peak power density at 10 MW would be reduced. As stated previously, additional analyses are planned to address engineering ("hot channel") uncertainty factors and differences there may be in these factors between HEU and LEU fuels, particularly regarding ^{235}U homogeneity.

Cores with 18 – 24 IRT-4M FA could also be operated at a power level of 10 MW, but IRT-4M FA are not suitable for converting this reactor because they would result in a significant increase in fuel consumption.

For IRT-MR pin-type fuel, conservative initial estimates by ANL are based on analyses for a single fuel pin. The conservative power levels in Table 3 show that the maximum power level increases as the cross section of the fuel meat is decreased, and more water is available for cooling inside the assembly. Some of the fuel pin designs, for example, the original pin design with 2.1 x 2.1 mm fuel meat, could not be operated at a power level of 10 MW in cores with 18 or 20 FA. For the other pin designs, thermal-hydraulic calculations using the entire limiting fuel assembly or at least key sections of the limiting fuel assembly are in progress at ANL using pin-by-pin power density data from the Monte Carlo calculations to obtain a more realistic estimate of the maximum power level at which the different cores could be operated.

Shutdown Margins

Reference 16 states that the reactor must be subcritical by not less than 2% Δk/k with all shim rods and the automatic rod fully-inserted and with all safety rods fully-withdrawn. Tables 2 and 3 show that all of the core configurations analyzed in this study satisfy this criterion. For the core configurations with IRT-4M FA, these margins are larger than for the core configurations with the other FA because IRT-4M FA have a relatively low ^{235}U content, which results in a small excess reactivity at the beginning of the operating cycle and a short fuel cycle length.

Additional Analyses for IRT-MR Pin-Type FA

All of the IRT-MR fuel assemblies discussed above contained 172 fueled FE and four unfueled FE located in the corners of the fuel assembly. Other fuel assembly configurations were also studied, but were discarded because they did not add any benefit to the present design. These configurations included:

- FA with 176 fueled FE presented worse thermal hydraulics characteristics than those with the four unfueled corner FE. This configuration was the original design.
- FA with the four corner fuel elements replaced by either B_4C absorber mixed with aluminum (10 and 25% of B_4C) or by depleted uranium were suggested by our Russian colleagues, but were discarded because detailed calculations showed that they did not provide any benefit. The suggestion to place absorbers in the corner FE was made to decrease the peak power density that occurs (in almost all the core configurations analyzed here) in the outside pins which face the beryllium reflector. However, the analyses showed that even with the absorbers, the peak power pin only moves to a pin located farther from the corner (still facing the beryllium reflector). The peak power density actually increases with the use of absorbers in the corners because of the power depression in the pin(s) close to the absorber.

CONCLUSIONS

The objective of this study was to optimize the geometry and loading specifications of LEU fuel assemblies that could be used for conversion of the WWR-SM reactor from HEU to LEU fuel. Several performance indices were used to compare the different designs: annual fuel consumption, shutdown margin, experiment performance, and maximum power levels. For the maximum power levels, the same criterion presently being used for the HEU fuel (ONB temperature ratio of 1.4 without hot channel factors, and as-designed dimensions) was used for all the fuel assemblies considered in this study. The conclusions for each type of FA are presented below:

IRT-3M FA with U9Mo-Al Fuel: Two core sizes and two uranium loadings were defined: an 18 FA core with 5.1 gU/cm^3 and a 20 FA core with 4.7 gU/cm^3. Both designs provide the same annual fuel consumption as the HEU fuel, satisfy the shutdown margin criterion, and can operate at a power level of 10 MW. Experiment performance is lower by 4% or less for the 18 FA core, and by 7% or less for the 20 FA core. These FA would be suitable for use in LEU conversion of the WWR-SM reactor if they are manufactured, successfully irradiation tested, and made commercially available in Russia.

IRT-4M FA with UO_2-Al Fuel: IRT-4M fuel with a defined loading (2.8 g U/cm^3) has been irradiation tested in research reactors in Russia and Uzbekistan and work is in progress to commercialize this fuel by the end of 2003. For the three core sizes used in this study, this FA would allow operation at the maximum design power level of 10 MW. Shutdown margin requirements would be satisfied. Experiment performance, compared with the HEU core, is the same or slightly better for the 18 FA core, decreases by 4% or less for the 20 FA core, and by 13% or less for the 24 FA core. However, the annual fuel consumption increases by more than 20% for the 24 FA core, by 70% for the 20 FA core and by 150% for the 18 FA core. Because of the significant increase in annual fuel consumption, IRT-4M FA are not suitable for LEU conversion of the WWR-SM reactor.

IRT-MR FA with U9Mo-Al and U9Mo: Three core sizes, several geometries and uranium loadings were analyzed for this FA type. For all the geometries analyzed, the uranium loading was designed to provide the same annual fuel consumption as the HEU core. A conservative estimate of the maximum power level was calculated in this paper. More realistic estimations will be performed in the future. The conclusions for the different core sizes are:

- **18 FA cores:** All designs analyzed meet the shutdown margin criterion. Experiment performance decreases by 5% or less when compared with the HEU fuel. However, based on a conservative estimate of the maximum allowable operating power (using the same criterion as that for the HEU core with tubular fuel), none of the designs using IRT-MR fuel can be used at the WWR-SM reactor design operating power of 10 MW. However, it is anticipated that more realistic thermal-hydraulic calculations will show that the design using monolithic U9Mo fuel (1.01x1.01 mm fuel meat) could be used at the 10 MW power level if this fuel is manufactured, successfully irradiation tested, and made commercially available in Russia.

- **20 FA cores:** All designs analyzed meet the shutdown margin criterion. Experiment performance decreases by 8% or less when compared with the HEU fuel. Using the same criterion as for the HEU tubular fuel, the design with U9Mo fuel (0.963x0.963 mm fuel meat), and the 1.5x1.5 mm fuel meat design with U9Mo-Al fuel could be operated at a power level of 10 MW. It is anticipated that more realistic thermal-hydraulic calculations will show that the design using U9Mo-Al fuel (1.6x1.6 mm fuel meat) could also be operated at 10 MW. These FA could be used for LEU conversion of the WWR-SM reactor if they are manufactured, successfully irradiation tested, and made commercially available in Russia.

- 24 FA cores: All designs analyzed (2.1x2.1 mm, 1.9x1.9 mm, and 1.6x1.6 mm fuel meat, U9Mo-Al) meet the shutdown margin criterion. Experiment performance decreases by 7% or less for the experiments in the reflector, by 10% for the ^{32}S experiments, and by 15% or less for the ^{33}S experiments. All designs could be operated at the 10 MW reactor design power and could be used for LEU conversion of the WWR-SM reactor if they are manufactured, successfully irradiation tested, and made commercially available in Russia.

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