Accelerating the Design and Testing of LEU Fuel Assemblies for Conversion of Russian-Designed Research Reactors Outside Russia

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ABSTRACT

This paper identifies proposed geometries and loading specifications of LEU tube-type and pin-type test assemblies that would be suitable for accelerating the conversion of Russian-designed research reactors outside of Russia if these fuels are manufactured, qualified by irradiation testing, and made commercially available in Russia.

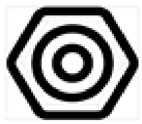
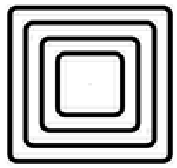
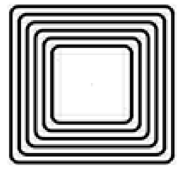
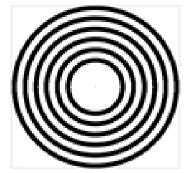
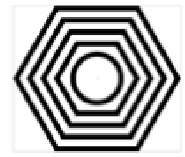
Introduction

The 13 Russian-designed research reactors outside Russia that use HEU fuel and are candidates for LEU conversion are shown in Table 1. Horizontal cross sections of the different HEU fuel types in current use are shown in Table 2.

Table 1. Research Reactors Outside Russia That Are Candidates for LEU Conversion

	Reactor	Country	City	Power Level	HEU Fuel-Type and Enrichment
Reactors Using WWR-M2 Type Fuel Assemblies					
1.	WWR-M	Ukraine	Kiev	10 MW	WWR-M2 (36%)
2.	BRR	Hungary	Budapest	10 MW	WWR-M2 (36%)
3.	ZLFR	Germany	Zittau	10 W	WWR-M2 (36%)
4.	DRR	Vietnam	Dalat	500 kW	WWR-M2 (36%)
Reactors Using MR-6 and WWR-TS Type Fuel Assemblies					
5.	MARIA	Poland	Swierk	16-30 MW	MR-6 (36%)
6.	WWR-K	Kazakhstan	Almaty	6 MW	WWR-TS (36%)
Reactors Using IRT-3M Type Fuel Assemblies					
7.	WWR-SM	Uzbekistan	Tashkent	10 MW	IRT-3M (36%)
8.	VR-1	Czech Republic	Prague	5 kW	IRT-3M (36%)
Reactors Using IRT-2M Type Fuel Assemblies					
9.	LWR-15	Czech Republic	Rez	10 MW	IRT-2M (36%)
10.	New IRT	Bulgaria	Sofia	200 kW	IRT-2M (36%)
11.	IRT-DPRK	N. Korea	Pyongyang	8 MW	IRT-2M (36%)
12.	IRT-1	Libya	Tajoura	10 MW	IRT-2M (80%)
13.	Critical Fac.	Libya	Tajoura	~ 0	IRT-2M (80%)

Table 2. Horizontal Cross Sections and Key Data for HEU Fuel Types Currently-Used in Russian-Designed Research Reactors in Countries Outside Russia

WWR-M2	IRT-2M	IRT-3M	MR-6	WWR-TS
				
HEU (36%) UO_2-Al HEU (36%) U-Al 37 - 44 g ^{235}U per FA 32 mm Flat-to-Flat	HEU(36%) UO_2-Al 230/198 g ^{235}U HEU (80%) U-Al 171/147 g ^{235}U per 4/3-Tube FA 67 mm Flat-to-Flat	HEU (36%) UO_2-Al 342/300 g ^{235}U per 8/6-Tube FA 69.2 mm Flat-to-Flat	HEU (36%) UO_2-Al 430 g ^{235}U per 6-Tube FA 70 mm OD	HEU (36%) UO_2-Al 109/83 g ^{235}U per 5/3-Tube FA 65.3 mm Flat-to-Flat
Ukraine, Hungary, Vietnam, Germany	Czech Republic, Libya, Bulgaria, N. Korea	Uzbekistan, Czech Republic	Poland	Kazakhstan

Definitions of LEU Fuel Status

The following definitions are used to describe the status of LEU fuel assemblies:

1. Qualified Fuel Assemblies are FA that have been successfully irradiation tested and are licensable from the point of view of fuel irradiation behavior.
2. Available Fuel Assemblies are FA that are available from a commercial manufacturer.
3. Suitable Fuel Assemblies are FA that are qualified and commercially available and satisfy RERTR program criteria for conversion of specific reactors:
    a. The number of FA used per year is about the same or less than with HEU fuel.
    b. The performance of experiments is not significantly lower than with HEU fuel.
    c. Safety criteria for use in a specific reactor are satisfied.
4. To be Acceptable for use in a specific reactor, a fuel assembly must be qualified, commercially available, suitable for use in that reactor, and the reactor owner and operating organization must agree to accept this fuel assembly for conversion.

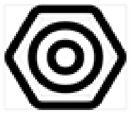
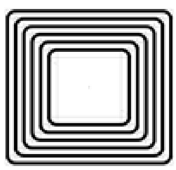
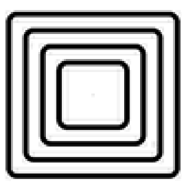
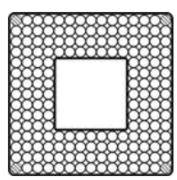
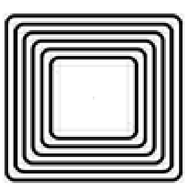
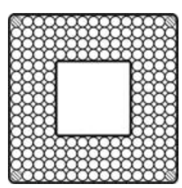
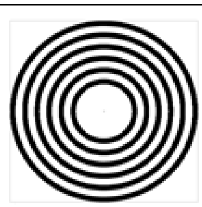
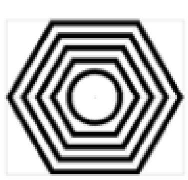
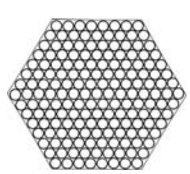
Some observations regarding these definitions are:

- After a fuel assembly is qualified, documentation needs to be prepared and approved, capital equipment may need to be procured, and production problems may need to be resolved before a fuel assembly is commercially available.
- A fuel assembly can be commercially available, but not qualified because manufacturers are generally willing to supply fuels that customers are willing to purchase.
- A suitable fuel assembly must be both qualified and commercially available. For a specific reactor, a fuel assembly may be suitable for use with a large core but not suitable for use with a small core.
- A suitable fuel must be acceptable to the owner and operating organization of each specific reactor before it can be used for LEU conversion.

Status of LEU Fuel Assemblies

Table 3 shows the status of LEU fuel assemblies as of October 2003.

Table 3. Status of LEU Fuels Assembles (October 2003)

LEU Fuel that is Qualified and Commercially Available		
	**WWR-M2** LEU UO_2-Al 41.7 g ^{235}U (50 cm) 50 g ^{235}U (60 cm) per FA 32 mm Flat-to-Flat	**WWR-M2** FA with LEU UO_2-Al fuel meat and 2.5 g U/cm^3 are qualified in accord with Minatom requirements and have been commercially available since 2001. These FA were qualified by irradiation testing (Refs. 1-3) in the WWR-M reactor at the Petersburg Nuclear Physics Institute to ~75-80% average ^{235}U burnup.
LEU Fuel in the Process of Being Qualified and Made Commercially Available		
	**IRT-4M** LEU UO_2-Al 300/265 g ^{235}U per 8/6-Tube FA 69.4 mm Flat-to-Flat	Four **IRT-4M** FA with LEU UO_2-Al fuel meat and ~3 g U/cm^3 were irradiation tested (Refs. 4 - 7) in the WWR-SM reactor in Uzbekistan to average ^{235}U burnups of ~60% between November 2000 and March 2002. Two combined IVV-2M FA, each with two fuel elements containing UO_2-Al with ~3 g U/cm^3, were irradiated in the IVV-2M reactor in Sverdlovsk during 2001 to average ^{235}U burnups of 50-60%. Post-irradiation materials studies demonstrated their functionality to burnups not less than 60%. IRT-4M FA are expected to be commercially available by the end of 2003 (Ref. 3).
LEU Fuels That Need to Be Qualified and Commercialized Before They Are Suitable for Conversions		
		**IRT-2M** tubular FA with LEU U9Mo-Al fuel meat and 4.7 g U/cm^3 (30 vol-% U9Mo) need to be manufactured, irradiation tested, and commercialized before they are suitable for use in conversion of reactors using IRT-2M FA. **IRT-MR** pin-type FA with LEU U9Mo-Al or U9Mo fuel meat need to be designed, manufactured, irradiation tested and commercialized before they are suitable for conversion of reactors using IRT-2M FA.
		**IRT-3M** tubular FA with LEU U9Mo-Al fuel meat and 4.7 g U/cm^3 (30 vol-% U9Mo) need to be manufactured, irradiation tested, and commercialized before they are suitable for use in conversion of reactor using IRT-3M FA. **IRT-MR** pin-type FA with LEU U9Mo-Al dispersion fuel and U9Mo monolithic fuel have been designed for possible use in the WWR-SM reactor in Uzbekistan and need to be manufactured, irradiation tested, and commercialized before they are suitable for conversion use. Feasibility studies need to be performed for possible use of LEU IRT-MR pin-type FA in other reactors that use HEU IRT-3M FA.
		**MR-6** FA with LEU U9Mo-Al tubular fuel and 4.7 g U/cm^3 (30 vol-% U9Mo) need to be manufactured, irradiation tested, and commercialized before they are suitable for use in conversion of the MARIA reactor in Poland. **MR-R** FA with LEU pin-type fuel need to be designed, manufactured, tested, and commercialized before they are suitable for use in conversion of the MARIA reactor in Poland.
		**WWR-TS** FA with LEU UO_2-Al fuel and 2.5 g U/cm^3 need to be fabricated to determine whether they meet manufacturing specifications. **WWR-TS** FA with LEU pin-type fuel need to be designed, manufactured, tested, and commercialized before they are suitable for use in conversion of the WWR-K reactor in Kazakhstan.

LEU Conversion Feasibility Studies

Analytical feasibility studies are normally performed to determine the fuel-type, fuel element and fuel assembly geometry and loading specifications, reactor core size, and reactor performance for fuel options that would be suitable for LEU conversion if the candidate fuels are qualified, commercially available, and acceptable to reactor owners and operating organizations. In this regard, the feasibility studies provide guidance to fuel development efforts by defining the requirements for suitable fuels.

ANL has completed neutronics feasibility studies for reactors outside Russia that are shown in Table 4. This work has produced an excellent overview of the design specifications of candidate LEU fuel assemblies that could be used for conversion of most of the reactors in Table 1.

Table 4. Neutronics Feasibility Studies Completed and Planned by ANL

Country	Reactor	Power Level	HEU Fuel-Type	LEU Fuel-Types	Ref.
Ukraine	WWR-M	10 MW	WWR-M2 (36%)	WWR-M2 (19.7%)	8
Hungary	BRR	10 MW	WWR-M2 (36%)	WWR-M2 (19.7%)	9, 10
Uzbekistan	WWR-SM	10 MW	IRT-3M (36%)	IRT-3M (19.7%) IRT-MR (19.7%)	11 – 15
Czech Republic	LWR-15(1)	10 MW	IRT-2M (36%)	IRT-2M (19.7%) IRT-3M (19.7%) IRT-4M (19.7%) IRT-MR (19.7%)(2)	16, 17
Bulgaria	New IRT	200 kW	IRT-2M (36%)	IRT-2M (19.7%) IRT-3M (19.7%) IRT-4M (19.7%) IRT-MR (19.7%)(2)	18
Poland	MARIA	16-30 MW	MR-6 (36%)	MR-6 (19.7%) MR-R (19.7%)(2)	14, 19-21

(1) Preliminary feasibility study. (2) Feasibility study planned.

For reactors that use WWR-M2 fuel assemblies with HEU (36%) UO_2-Al fuel meat, substitution of LEU UO_2-Al fuel meat with 2.5 g U/cm^3 has resulted in an LEU fuel element that is qualified, commercially available, and suitable for use in core conversions.

For LEU tubular fuel assemblies that require U9Mo-Al dispersion fuel meat to achieve the required ^{235}U loading, an attempt was made in the feasibility studies discussed in this paper to utilize existing fuel element and fuel assembly dimensions to the maximum extent possible and to substitute LEU U9Mo-Al fuel meat containing about 30 vol-% (4.7 g U/cm^3 in fuel meat) for HEU UO_2-Al fuel meat. A loading of 30 vol-% U9Mo in the dispersed phase of is nearly the same as the volume loading of UO_2 (29 vol-%) in UO_2-Al dispersion fuel with 2.5 g U/cm^3 and 36% enrichment that was developed, qualified, and commercialized by Russian institutes in the 1980s and put into routine use in a number of reactors. This design combination of LEU fuel elements and fuel assemblies with the same geometry and fuel meat volume loading of the dispersed phase was chosen to increase the probability that these fuels will be successfully manufactured, qualified, commercialized, and accepted by reactor operating organizations.

For LEU pin-type fuel assemblies, fuel element and fuel assembly design studies for the WWR-SM reactor in Uzbekistan are nearly complete using both U9Mo-Al dispersion fuel and U9Mo monolithic fuel. Feasibility studies using LEU pin-type fuel assemblies are planned for several other reactors.

Table 5 summarizes the results of the ANL neutronics feasibility studies. A “check mark” in the table means that the fuel assembly would be suitable for use in core conversion if it is qualified and made commercially available. An X means that the fuel assembly is NOT suitable for use in conversion of that reactor, even though the fuel may be qualified and commercially available.

Table 5. LEU Fuels That Would Be Suitable if They Are Qualified and Commercially Available

Country	Reactor	HEU Fuel	Candidate LEU Fuel Assemblies			
Ukraine	WWR-M	WWR-M2 (36%)	√ WWR-M2 (19.7%)			
Hungary	BRR	WWR-M2 (36%)	√ WWR-M2 (19.7%)			
Poland	MARIA	MR-6 (36%)	√ MR-6 (19.7%)	MR-R (19.7%)(1)		
Reactors Using IRT-Type Fuels			**IRT-2M**	**IRT-3M**	**IRT-4M**	**IRT-MR**
Uzbekistan	WWR-CM	IRT-3M (36%)	**X**	√	**X**	√
Czech Republic	LWR-15	IRT-2M (36%)	√	√	√	**(1)**
Bulgaria	New IRT	IRT-2M (36%)	√	√	√ **X (2)**	**(1)**

(1) A feasibility study is planned to determine fuel element and fuel assembly specifications.
(2) Suitable for use in a large core, but not suitable for use in a small core.

Proposed LEU Fuel Assemblies for Testing

Table 6 shows the detailed geometry and specifications for the LEU fuel assemblies that are proposed for irradiation testing in the WWR-SM reactor in Uzbekistan, the LWR-15 reactor in the Czech Republic, the MARIA reactor in Poland, and the BRR reactor in Hungary. These fuel assemblies would be suitable for use in accelerating reactor conversions if they are qualified and made commercially available.

Table 6. Proposed Geometry and Specifications for LEU Fuel Assemblies for Irradiation Testing

Country/Reactor	FA-Type	Fuel Meat	FE/FA	Thickness, mm FE	Clad	Meat	Vol-% Disp. Phase	g ^{235}U per FA	Uran. Density g/cm^3
Uzbekistan	IRT-3M (19.7%)(1)	U9Mo-Al	6	1.4	0.45	0.5	30.0	317	4.7
WWR-SM	IRT-3M (19.7%)(2)	U9Mo-Al	6	1.4	0.45	0.5	32.4	347	5.1
	IRT-MR (19.7%)(1)	U9Mo-Al	172	4.5	0.4	1.6 x 1.6	39.6	324	6.2
	IRT-MR (19.7%)(1)	U9Mo	172	4.5	0.4	~1.0 x 1.0	100	~ 296	15.7
Czech Rep.	IRT-2M (19.7%)	U9Mo-Al	4/3	2.0	0.65	0.70	30.2	265/228	4.7
LWR-15	IRT-3M (19.7%)	U9Mo-Al	8/6	1.4	0.45	0.50	30.0	362/317	4.7
	IRT-MR (19.7%)(3)		172	4.5	0.4				
Poland, MARIA	MR-6 (19.7%)	U9Mo-Al	6	2.0	0.7	0.6	29.9	475	4.7
	MR-R (19.7%)(3)								
Hungary, BRR	WWR-M2 (19.7%)	UO_2-Al	3	2.5	0.75	1.0	29.0	50	2.5

(1) For core with 20 fuel assemblies. (2) For core with 18 fuel assemblies. (3) A feasibility study is planned to determine specifications.

Conclusions

Extensive neutronics feasibility studies using tube-type and pin-type LEU fuels have been completed or are planned by the RERTR Program at ANL to identify fuel element and fuel assembly design options that would be suitable for LEU conversion of most Russian-designed research reactors outside of Russia, if these fuels are manufactured, qualified by successful irradiation testing, and made commercially available.

WWR-M2 tubular fuel assemblies containing LEU UO_2-Al fuel meat are suitable for use in LEU conversion of several reactors outside Russia. However, there are a number of reactors for which the uranium densities that can be achieved on a commercial basis with LEU UO_2-Al fuel are simply too low, and result in fuel assemblies that are not suitable and probably not acceptable for LEU conversions by reactor owners and operating organizations.

For LEU tubular fuel assemblies that require U9Mo-Al dispersion fuel meat to achieve required ^{235}U loadings, an attempt was made in the feasibility studies discussed in this paper to utilize existing fuel element and fuel assembly dimensions to the maximum extent possible and to substitute LEU U9Mo-Al fuel meat containing about 30 vol-% (4.7 g U/cm^3 in fuel meat) for HEU UO_2-Al fuel meat. This design combination of fuel elements and fuel assemblies with the same geometry, the same dimensions, and a very similar volume loading of the dispersed phase in the fuel meat was chosen to increase the probability that these fuel will be successfully manufactured, qualified, commercialized, and accepted by reactor owners and operating organizations.

After good experience has been obtained in manufacturing fuel tubes containing 30 vol-% U9Mo, the volumetric loading could be increased toward ~35 vol-% (5.4 g U/cm^3), the probable fabrication limit for extruded fuel tubes.

For LEU pin-type fuel assemblies, fuel element and fuel assembly design studies for the WWR-SM reactor in Uzbekistan are nearly complete using both U9Mo-Al dispersion fuel and U9Mo monolithic fuel. Feasibility studies using LEU pin-type fuel assemblies are planned for several other reactors.

The geometry and specifications are provided for the LEU fuel assemblies that are proposed for irradiation testing in the WWR-SM reactor in Uzbekistan, the LWR-15 reactor in the Czech Republic, the MARIA reactor in Poland, and the BRR reactor in Hungary. These fuel assemblies would be suitable for use in accelerating research reactor conversions if they are qualified by successful irradiation testing and made commercially available in Russia.

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