Feasibility Study of Potential LEU Fuels for a Generic MNSR Reactor

J.E. Matos and R.M. Lell

RERTR Program
Argonne National Laboratory
Argonne, Illinois, USA 60439

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ABSTRACT

A feasibility study was performed for a generic Miniature Source Reactor (MNSR) reactor to identify potential LEU fuels that could be used for conversion of these reactors. The model that was used and analysis results obtained with the current HEU fuel are first described. Potential LEU fuels are then listed. The study results were used to identify fuels that may be suitable for use in MNSR conversions, the qualification status of these fuels, and potential manufacturers. Five LEU fuels and core designs were identified that match the excess reactivity of the HEU core. Conversion of MNSR reactors to these fuels would be technically feasible if all safety requirements are shown to be satisfied, the fuels are qualified and licensed, and manufacturers are available to fabricate the fuels at a reasonable price.

INTRODUCTION

A generic MNSR reactor model was constructed using the MCNP Monte Carlo code, data from two published MNSR papers[1,2], additional information[3] on the dimensions and composition of the beryllium reflectors in the GHARR-1 MNSR-type reactor, and two papers[4,5] on the LEU conversion of the Slowpoke-2 reactor of the Ecole Polytechnique in Montreal, Canada. Radial and axial models for the HEU core are shown in Figure 1.

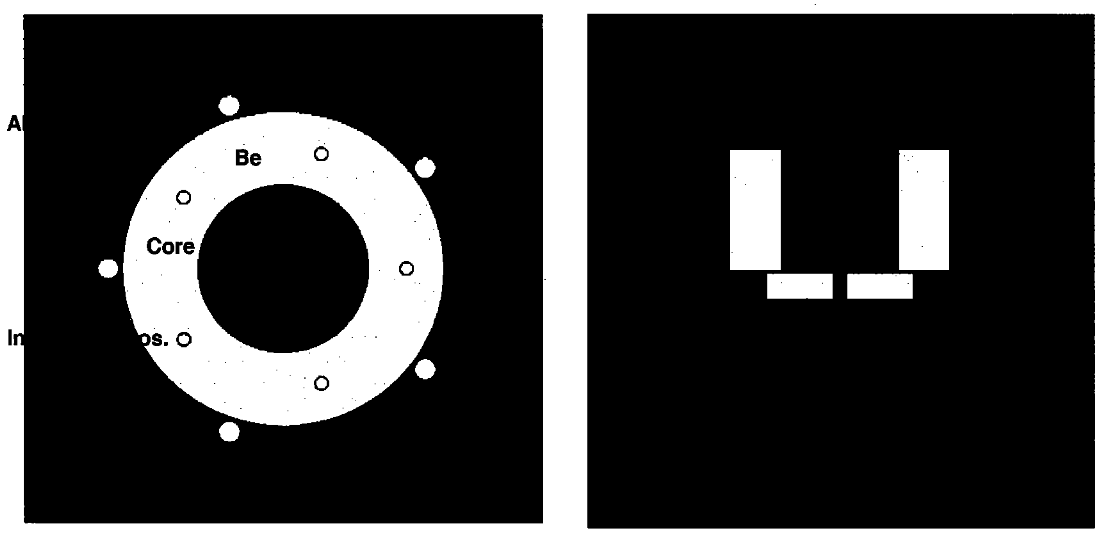


Figure 1. Radial and Axial Models for the HEU Generic MNSR Reactor (Yellow, beryllium; Green, water; Blue, aluminum structures

General characteristics of the core and fuel pins are shown in Table 1. Dimensions of the beryllium reflectors and their elemental composition are shown in Tables 2 and 3, respectively.

Table 1. Overall Characteristics of the HEU Generic MNSR Core

Core	**Fuel Pins**
347 Fuel Pins	Fuel Meat OD: 4.3 mm
3 Dummy Aluminum Pins	Clad OD: 0.6 mm
4 Aluminum Posts	Clad Thickness: 0.6 mm
981 g ^{235}U	Fuel Height: 230 mm
90% Enriched Uranium	^{235}U per Pin: 2.83 g
U Density in Alloy Fuel Meat	0.94 g/cm^3 (~27 Wt-% U)

Table 2. Dimensions of the Beryllium Reflectors

Dimensions of the Beryllium Reflectors[3]			
Beryllium Reflectors	**Outer Diameter, mm**	**Inner Diameter, mm**	**Height, mm**
Annular Radial Reflector	435.0	231.0	238.5
Bottom Plate Reflector	290.0	*	50.0

* The inner diameter of the bottom Be reflector plate was assumed by ANL to be 25.4 mm because that was the assumed outer diameter of the control rod guide tube.

Table 3. Elemental Composition of Beryllium Reflector[3]

Material	**ppm**	**Material**	**ppm**	**Material**	**ppm**
Be		N	200	Li	1.0
BeO	25,000	Cr	200	Dy	1.0
Fe	4,000	Zn	150	Cd	0.5
Pb	3,000	Ni	100	Sm	0.5
Al	3,000	Mn	20	Eu	0.1
Mg	1,000	Ag	15	C	0.1
Si	800	Co	10		
Cu	200	B	2.0		

ANALYSIS RESULTS FOR HEU GENERIC CORE

The excess reactivity of the HEU-fueled generic core with 347 fuel pins with a total ^{235}U loading of 981 grams was calculated to be 0.87% Δk/k (8.7 milli-k, or 870 pcm). These reactors are designed to have an as-built excess reactivity of 0.4% Δk/k (4 mk or 400 pcm).

Reactivity adjustments are made in MNSR reactors by inserting small cadmium sleeves in the water pool outside the beryllium reflector. Since the model did not include these cadmium sleeves, part of the difference between the calculated and design excess reactivity could be accounted for by the worth of these sleeves. Also, ANL did not have all of the as-built data needed for the model. An example is the as-built density of the beryllium. The model can be refined when these data are available. However, because the results are fairly good already, the conclusions of this study for potential LEU fuels will be approximately correct.

POTENTIAL LEU FUELS CONSIDERED HERE

A list of the fuels that are used in the vast majority of research reactors worldwide are shown in Table 4, along with UMo fuels that are still under development. The list includes U-Al alloy fuel, six dispersion fuels, and two non-dispersion fuels. A maximum volumetric loading of 38 vol-% was used as a realistic production value for extruded pins with dispersion fuel.

Table 4. Potential LEU Fuels That Are Considered Here.

	Fuel Type	Density of Dispersed Phase	Wt-% U in Dispersed Phase	Uranium Density in Disp. Phase	Max LEU Density in Fuel Meat, g U/cm^3
1	U-Al Alloy Fuel	5.7[1]	64	3.7	1.0[2]
2.	UAl_x-Al Dispersion Fuel	6.4	70	4.5	1.7[3]
3.	U_3O_8 –Al Dispersion Fuel	8.2	85	7.0	2.6
4.	UO_2-Al Dispersion Fuel	~ 9.5	88	8.4	3.2
5.	U_3Si_2-Al Dispersion Fuel	12.2	92.5	11.3	4.3
6.	U_3Si-Al Dispersion Fuel	15.2	96	14.6	5.5
7.	U9Mo-Al Dispersion Fuel	17.3	91	15.7	6.0
8.	UO_2 Pellets in Zircaloy Clad	10.6	88	9.3	9.3[4]
9.	U9Mo Monolithic Wires Clad in Al	17.3	91	15.7	15.7[4]

[1] Density of UAl_4
[2] Corresponds to 28 wt-% U in U-Al alloy fuel.
[3] For 38 volume-% of the dispersed phase for extruded pins for all six of the dispersion fuels listed.
[4] For 100 volume-% of monolithic fuel.

ANALYSIS RESULTS FOR LEU CORES

MNSR reactors currently use extruded pins containing U-Al alloy fuel meat with a uranium density of ~ 0.94 g/cm^3 and a uranium enrichment of 90%. Thus, candidate LEU fuels need to be capable of uranium densities greater than 5 g/cm^3 if no changes are made in the fuel pin or core design. In this context, the uranium densities of alloy fuel and oxide dispersion fuels shown in Table 4 are clearly too low to be considered as candidate fuels for conversions.

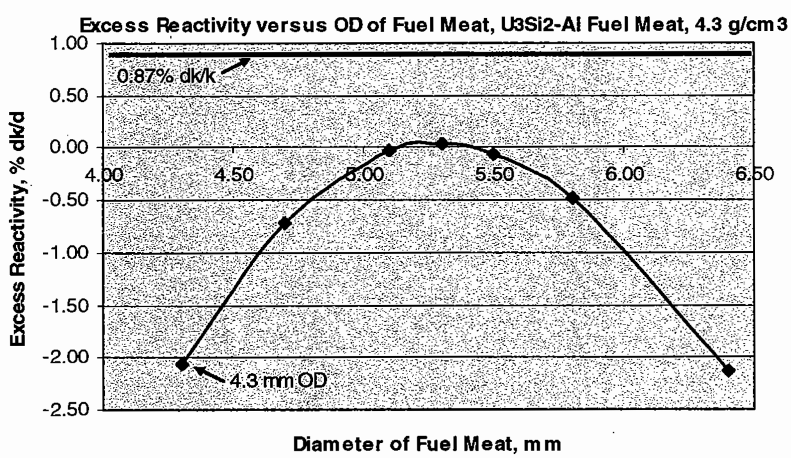
U_3Si_2-Al Fuel

LEU U_3Si_2-Al dispersion fuel is considered here in more detail because it is highly qualified[6] and is currently used in many research reactors worldwide. If U_3Si_2-Al dispersion fuel is simply substituted for the HEU alloy fuel with no dimensional changes and the same number of fuel pins, a uranium density of about 5.4 g/cm^3 is required to match the excess reactivity. For extruded fuel pins, 38 vol-% U_3Si_2 corresponds to a uranium density in the fuel meat of about 4.3 g/cm^3. Thus, modifications to the fuel pin design are needed for U_3Si_2-Al fuel to be a viable fuel candidate for conversion of MNSR reactors.

Two modifications of the fuel pin design were considered using cores that have the same 347 fuel pins as the HEU design and LEU U_3Si_2-Al fuel with 4.3 g/cm^3.

In the first modification, the outer diameter (OD) of the fuel meat was increased, starting from the current value of 4.3 mm and keeping fixed the 0.6 mm thickness of the cladding. The results of calculations of excess reactivity versus the OD of the fuel meat shown in Figure 3 indicate that the reactivity never reaches the required value of 0.87% $\Delta k/k$. The trade-off between increasing the ^{235}U loading and decreasing the neutron moderation is clearly shown.

Figure 3. Excess Reactivity Versus OD of Fuel Meat, U_3Si_2-Al Fuel Meat, 4.3 g/cm^3.



In the second modification, the OD of the fuel pin (and hence the water volume fraction in the core) was maintained. The cladding thickness was reduced from 0.6 mm to the standard value of 0.38 mm and the OD of the fuel meat was increased from 4.3 mm to 4.74 mm. The resulting excess reactivity was nearly identical with that of the HEU core.

Thus, this modification is the <u>first</u> potential LEU fuel option if fuel pins with 4.3 g U/cm^3 can be extruded reliably with a cladding thickness of 0.38 mm. The ^{235}U loading of each pin would be 3.44 g and the 347 pins in the core would contain 1197 g ^{235}U.

U_3Si-Al and U9Mo-Al Dispersion Fuels

With no changes in the number of pins in the core (347) and no changes in the fuel pin, fuel meat, or cladding dimensions of the current HEU fuel, direct substitution of fuel meat consisting of either U_3Si-Al dispersion fuel with 5.37 g U/cm^3 (38 vol-% U_3Si) or U9Mo-Al dispersion fuel with 5.76 g/cm^3 (38 vol-% U9Mo) would have about the same excess reactivity as the HEU core. The U9Mo fuel requires a higher uranium density than the U_3Si fuel because molybdenum has a higher neutron absorption cross section than silicon.

Thus, U_3Si-Al and U9Mo-Al dispersion fuels are the <u>second</u> and <u>third</u> potential LEU fuel candidates if a fuel manufacturer is available and if all safety criteria are shown to be satisfied.

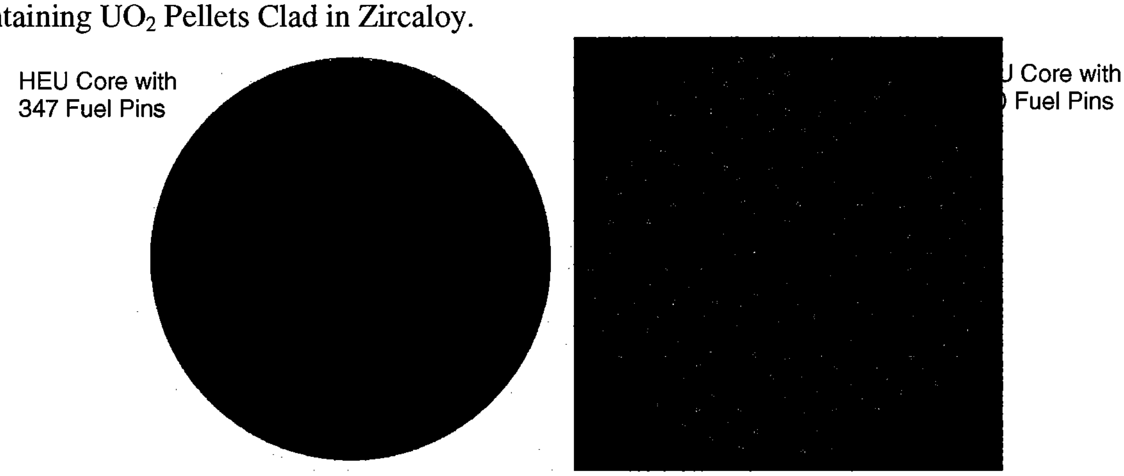
UO_2 Pellets Clad in Zircaloy

Because the uranium density in UO_2 pellets is larger than required, the number of fuel pins and their spacing in the core need to be modified. Utilizing data[4,5] used in conversion of Slowpoke-2 reactors, a core with 210 fuel pins with an OD of 5.25 mm was found to have nearly the same excess reactivity as the current HEU core.

The LEU core model with 210 fuel pins is shown in Figure 4. The spacing of the fuel pins that is shown is one example that was used for purposes of these calculations. Other fuel pin spacings are possible. The spacing of the pins is not the same as used in Slowpoke-2 reactors.

Fuel consisting of UO_2 pellets clad in zircaloy was used successfully in 1997 to convert the Slowpoke-2 reactor of Ecole Polytechnique in Montreal, Canada. This same LEU fuel was used in 1984 to start-up the Slowpoke-2 reactor at the Royal Military College in Ontario, Canada.

Figure 4. Reference HEU Core Model with 347 Pins and LEU Core Model with 210 Fuel Pins Containing UO_2 Pellets Clad in Zircaloy.



U9Mo Wires Clad in Aluminum

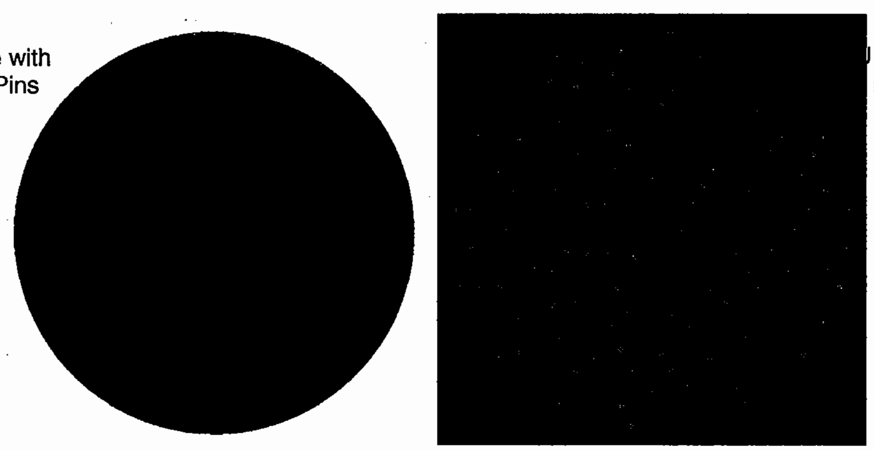
As for UO_2 pellets, the uranium density of monolithic U9Mo is much larger than is required. Thus, the number of fuel pins and their spacing in the core need to be modified if this fuel is to be used. Two fuel pin and core designs were studied.

In the first case, the number of pins in the core was fixed at about 210 and the OD of the UMo wires was varied. A core with 208 pins, 3.5 mm OD U9Mo wires, and 0.6 mm cladding was found to have the same excess reactivity as the HEU core. The radial model of the core is the same as shown in Figure 4, except that two of the fuel pins were replaced with dummy aluminum pins.

In the second case, the OD of the U9Mo wires was fixed and the number of pins in the core was varied. A core with 167 pins with 4.16 mm OD U9Mo wires and 0.6 mm cladding was found to have the same excess reactivity as the HEU core. The radial model of the core that was used in the calculations is shown in Figure 5. Clearly, other choices of variables are also possible.

Thus, U9Mo wires clad in aluminum are the fifth potential fuel that could be used for conversion of MNSR reactors when this fuel is qualified, a manufacturer is available, and if all safety requirements of the reactor are satisfied.

Figure 5. Reference HEU Core Model with 347 Pins and LEU Core Model with 167 Fuel Pins Containing U9Mo Wires Clad in Aluminum.



Summary of LEU Fuels That Provide Sufficient Excess Reactivity

The five potential LEU fuels that can provide sufficient excess reactivity for conversion of MNSR reactors are summarized in Table 5, along with the current HEU (90%) fuel for reference purposes.

Table 5. LEU Fuels That Provide Sufficient Reactivity

Fuel Type	U Dens., g/cm^3	OD meat, mm	Clad Mat./ Thick., mm	No. of Pins	g ^{235}U Per Pin	g ^{235}U in Core	Excess React., % Δk/k
Reference HEU (90%) Fuel							
UAl Alloy	0.94	4.3	Al/0.6	347	2.83	981	0.87
LEU (19.75%) Dispersion Fuels							
U_3Si_2-Al	4.29	4.74	Al/0.38	347	3.44	1194	0.83
U_3Si-Al	5.37	4.3	Al/0.6	347	3.54	1229	0.90
U9Mo-Al	5.76	4.3	Al/0.6	347	3.80	1319	0.87
LEU (19.75%) Monolithic Fuels							
UO_2 Pellets	9.34	4.16	Zr/0.546	210	5.78	1215	0.83
U9Mo Wires[1]	15.72	3.50	Al/0.6	208	6.87	1429	0.87
U9Mo Wires[2]	15.72	4.16	Al/0.6	167	9.73	1625	0.90

[1] Number of pins fixed; vary OD of U9Mo wire. [2] OD of U9Mo wire fixed; vary number of pins.

Changes in the thermal neutron (<0.625 eV) fluxes in the inner and the outer irradiation positions are shown in Table 6. The flux losses that are shown are first-approximation results with no optimization attempted. Some of the flux losses can be recovered by careful optimization of the fuel locations in the smaller cores or by making other adjustments.

Table 6. Thermal Neutron Fluxes in Irradiation Positions

LEU Fuel Type	U Dens., g/cm^3	No. Pins	g ^{235}U in Core	Relative[1] Thermal Flux, % Inner Pos.	Outer Pos.
U_3Si_2-Al	4.29	347	1194	- 8.2	- 4.7
U_3Si-Al	5.37	347	1229	- 7.9	- 5.0
U9Mo-Al	5.76	347	1319	- 10.4	- 6.1
UO_2 Pellets, Zr Clad	9.34	210	1215	- 3.8	- 5.9
U9Mo Wires, Al Clad[2]	15.72	208	1429	- 5.1	- 7.1
U9Mo Wires, Al Clad[3]	15.72	167	1625	- 5.7	- 7.8

[1] Relative to thermal fluxes in the HEU core.
[2] Number of pins fixed; vary OD of U9Mo wires. [3] OD of U9Mo wire fixed; vary number of pins.

LEU FUEL QUALIFICATION STATUS AND POTENTIAL MANUFACTURERS

The qualification status of the five potential LEU fuels is shown in Table 7 along with the current fuel manufacturers.

Table 7. Qualification Status and Current Manufacturers of LEU Fuels for MNSRs.

	Fuel Type	Max. LEU Density, g/cm^3	Will it Work?	Qualif-ication Status	Current Fuel Manuf-acturer
1	U_3Si_2-Al Dispersion	4.3	Yes[1,2]	Qualified (?)	-
2	U_3Si-Al Dispersion	5.5	Yes[1]	Qualified (?)	-
3	U9Mo-Al Dispersion	6.0	Yes[1]	Qualified (?)	-
4	UO_2 Pellets, Zr Clad	9.3	Yes[1]	Qualified	Zircatec, Canada
5	U9Mo Monolithic, Al Clad	15.7	Yes[1]	Planned	-

[1] Provided that shutdown margins, thermal-hydraulic safety margins, and all safety requirements are satisfied.
[2] The cladding thickness needs to be reduced from 0.6 mm to 0.38 mm.

Issues that need to be addressed in assessing qualification of potential LEU fuels:

- Fuel meats for the dispersion and UO_2 fuels have been irradiated to burnups far beyond the very low burnups that are achievable in MNSR reactors. These fuel meats are therefore qualified without further irradiation testing.
- Fabrication qualification will be required for extruded pins.
- Pins consisting of U9Mo monolithic wires clad in aluminum are at the beginning stage of fuel development.
- All of the potential fuels except for UO_2 pellets in zircaloy tubes will require funds for final qualification and licensing.

Potential manufacturers of extruded fuel pins include:
- Chalk River Laboratories in Canada,
- Korea Atomic Energy Research Institute in South Korea,
- manufacturing plant in China, and
- Novosibirsk Chemical Concentrates Plant in Russia.

These potential manufacturers are not now ready to supply extruded dispersion or U9Mo monolithic fuels on a commercial basis. The only LEU fuel that is currently qualified, licensed, and has a manufacturer available is UO_2 pellets clad in zircaloy tubes manufactured by Zircatech Precision Industries in Canada. Other manufacturers of UO_2 pellets in zircaloy tubes may be interested in entering this market.

CONCLUSIONS

Five potential LEU fuels have been identified that would provide sufficient excess reactivity in the generic MNSR:

- U_3Si_2, U_3Si, and U9Mo dispersion fuels clad in aluminum
- UO_2 pellets clad in zircaloy
- U9Mo monolithic wires clad in aluminum

Thermal neutron fluxes would be reduced by 4-10% in the inner irradiation channel and by 5-8% in the outer irradiation channel, depending on the type of fuel utilized.

- Flux reductions are smallest (4-6%) with fuel consisting of UO_2 pellets in zircaloy tubes.

It would be feasible to use these fuels for LEU conversions if:

- All safety requirements are shown to be satisfied
- The fuels are qualified and can be licensed
- Manufacturers are available to fabricate the fuel at a reasonable price.

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