COMPARISON OF NEUTRONIC PERFORMANCE CHARACTERISTICS OF THE PROPOSED NIST REACTOR WITH DIFFERENT LEU FUELS

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ABSTRACT

As a potential replacement for the NBSR at NIST, a concept reactor with a horizontally-split core using low-enriched uranium (LEU) silicide dispersion (U_3Si_2-Al) fuel has recently been studied. In this paper, the neutronic calculations with low-enriched U-Mo fuels (U-10Mo monolithic and U-7Mo/Al dispersion) and U_3Si_2-Al fuel are compared with the objective of identifying the best fuel candidate for the reactor for practical operations and maximum cold neutron production. For the comparisons, a multi-cycle equilibrium core was calculated for each fuel based on a 30 day reactor cycle at 20 MW power. With its very high U density, the potential to load more U in the core with U-10Mo monolithic fuel is explored with using alternate fuel management schemes, high power level (30 MW), or longer cycle (45 days) to achieve higher burnups.

KEYWORDS: Low-Enriched Uranium, Research Reactor, Neutronic Performance Characteristics

1. INTRODUCTION

A conceptual design of a reactor, referred to as the NBSR-2 in this paper, is being studied as a potential replacement for the NBSR [1], the reactor that has operated for over 50 years at the National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR). Feasibility studies have demonstrated the potential for the NBSR-2 design to provide bright cold neutron beams for scientific experiments [2, 3]. The proposed design, with 20 MW thermal power and a 30-day operating cycle, is selected to be on a similar scale as the NBSR. For improved neutron flux performance, the design consists of a horizontally-split compact core that is cooled and moderated by light water while reflected by heavy water [4]. The fuel elements (FEs) in the design are conventional plate type for material testing reactors using low-enriched uranium (LEU), with ^{235}U enrichments less than 20 % by weight to comply with nuclear non-proliferation requirements. U_3Si_2-Al dispersion fuel was chosen for initial studies to investigate and verify the viability of the novel design in terms of neutronics and safety performance characteristics [3].

U_3Si_2-Al dispersion fuel was prioritized for the NBSR-2 because it is the only LEU fuel certified by the US Nuclear Regulatory Commission that is currently available for research reactors. For the fuel conversion of five high performance research reactors (HPRRs) – reactors with peak thermal neutron flux greater than 10^{14} cm^{-2}s^{-1}, including the NBSR – in the United States from high-enriched uranium (HEU) to LEU, the relatively-low U density of U_3Si_2-Al dispersion fuel makes it difficult to achieve high power densities after conversion. Furthermore, the power density with U_3Si_2-Al dispersion fuel in HPRRs must be limited to comply with the current regulatory limit that the peak heat flux be less than 140 W/cm^2 [5].

For these reasons, other LEU fuels containing high-density uranium molybdenum (U-Mo) alloys are being explored for use in HPRRs [6]. While the fuel conversion program in the United States is focused on U-10Mo monolithic fuel [7], U-Mo dispersion fuels are being pursued in other countries [8, 9]. In this paper, these advanced LEU fuels, the U-Mo monolithic and dispersion fuels, are modeled in the current NBSR-2 design with the resulting neutronics performance characteristics compared with the U_3Si_2-Al dispersion fuel as a reference base for their performances. Thermal hydraulics, safety analyses, and engineering constraints were not evaluated in this study.

2. LEU FUELS FOR HIGH PERFORMANCE RESEARCH REACTORS

The NBSR-2 is a "tank-in-pool" design with an Al tank (2 m height and 2 m diameter) that is filled with heavy water and is placed in a pool of light water. The heavy water in the tank is the reflector for the core, while the core itself is moderated and cooled by light water. The core is split horizontally – with each half containing nine fuel elements in a Zr box to separate heavy water from light water – to maximize the useful flux trap volume between the two halves. Two cold neutron sources (CNSs), not yet optimized in design, are placed 40 cm from the reactor on the north and south sides of the flux trap. The positions of the CNSs balance a tradeoff between cold neutron performance and estimated heat load for the CNSs. Four '#' shaped hafnium control blades provide criticality and safety control. Schematics of the NBSR-2 are shown in Figure 1. A complete description of the NBSR-2 design can be found in Ref [3].

The NBSR-2 was fueled in previous studies with 18 fuel elements each containing 17 plates of U_3Si_2-Al dispersion fuel. U_3Si_2-Al dispersion fuel can be fabricated with U densities up to 4.8 g/cm^3. There are two advanced U-Mo alloy fuels with high-uranium densities that have recently drawn interest from the nuclear fuel conversion community. The two fuels, U-7Mo/Al dispersion fuel and U-10Mo monolithic foil, have Mo mass fractions of 7 % and 10 %, respectively. The U-10Mo monolithic foil is a pure metallic alloy that has a very high uranium density of 15.5 g/cm^3. Table I summarizes the three LEU fuels investigated in this paper.

Table I: Comparison of the three LEU fuels.

Fuel	**U_3Si_2-Al**	**U-7Mo/Al**	**U-10Mo**
Type	Dispersion	Dispersion	Monolithic
Compositions	U, Si, Al	U, Mo, Al	U, Mo
Enrichment (%)	19.75	19.75	19.75
Density (g/cm^3)	6.52	9.97	17.22
Uranium density (g/cm^3)	4.80	7.98	15.50
U-235 density (g/cm^3)	0.95	1.58	3.06

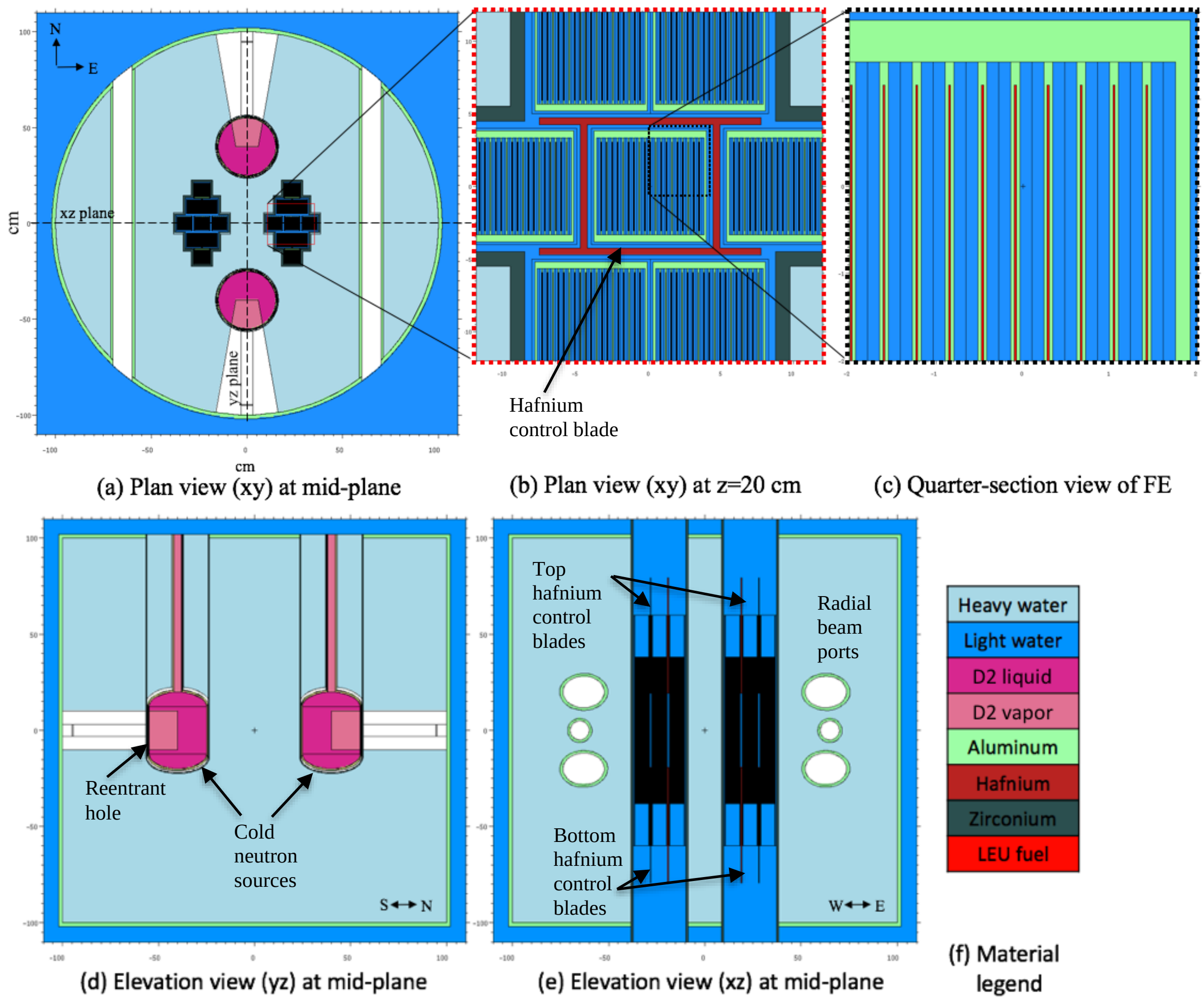


Figure 1. Schematics of the NBSR-2.

Reactions of U-Mo alloy with Al powder in the dispersion fuel and cladding form interaction layers that, along with other effects such as recrystallization [10], lead to fuel swelling at high burnups. To mitigate these adverse effects and prevent delamination in the case of U-10Mo monolithic fuel, a protective interlayer of Zr is added between the U-10Mo foil and the Al cladding [11]. The reference U-10Mo fuel system uses a 25.4 µm thick (1 mil) layer of Zr. For U-Mo dispersion fuel, the addition of Si to the dispersion has been found to reduce the interaction layers [12] and mitigate fuel swelling for fission densities > 3.0×10^{21} f/cm^3 [13], but is neglected in this study.

The dimensions of the fuel meat can be adjusted to some extent by the designer in the model to achieve specific goals. For example, reducing the fuel volume fraction can decrease the power peaking factor at the expense of cycle length. In this study, an initial point for the LEU fuel designs was to vary the fuel meat thickness to achieve a similar mass of ^{235}U in each fuel plate. The three LEU fuels were modeled with 17-plate fuel elements having a constant fuel plate thickness (50 mil), as shown in Figure 2, to keep the water channel thickness constant for the purpose of comparison. The parameters of the U-Mo fuels in this study are similar to those used in the preliminary analyses for the conversion of NBSR from HEU to LEU [14, 15].

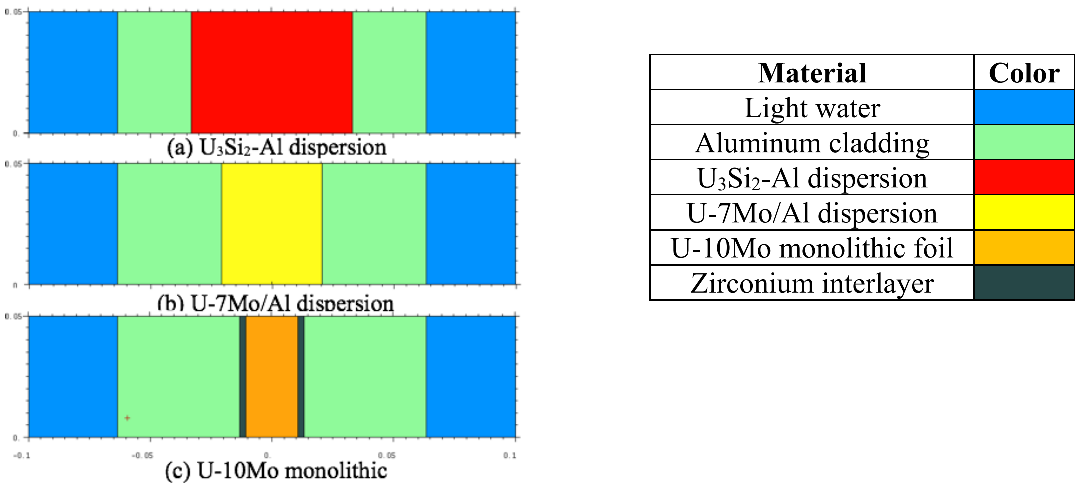


Figure 2. The cross-sectional views of the three LEU fuels being investigated.

For the U-10Mo fuel, the cladding thickness can be substantially reduced since the fuel meat is very thin, opening the possibility for 19 fuel plates in each element. The higher U loading with 19-plate fuel elements in the core presents the opportunity 1) to extend the reactor cycle beyond 30 days, 2) to extend burnup of fuel elements by burning them for more than three cycles, and/or 3) to operate at higher thermal power. Thus, a model with 19-plate fuel elements was created for the U-10Mo case to explore these options. The parameters for three LEU fuels studied in this paper are summarized in Table II.

Table II: Fuel parameters of the LEU Fuels.

Fuel plate parameter	**U3Si2/Al**	**U-7Mo/Al**	**U-10Mo (17[a])**	**U-10Mo (19[a])**
Number of plates per FE	17	17	17	19
Length (cm)	60	60	60	60
Width (cm)	6.134	6.134	6.134	6.134
Fuel meat thickness (mil)	26.0	16.2	8.5 (10.5[b])	8.5 (10.5[b])
Fuel plate thickness (mil)	50	50	50	42.5
Cladding thickness (mil)	12	17	19.75	16
Volume (cm^3)	24.31	15.14	7.95	7.95
Fuel meat mass (g)	158.48	151.22	136.83	136.83
Total U-235 mass in FE (g)	392.5	406.7	413.6	462.2

[a] The number in parenthesis refers to the number of plates in each FE
[b] Including the 1 mil Zirconium interlayer on both sides of the foil

3. RESEARCH METHODOLOGIES

The neutronics calculations were performed using MCNP6, a generalized Monte Carlo code for radiation transport. Key performance characteristics of the core, such as neutron flux and fission rate, can be calculated by MCNP6 with a multi-cycle equilibrium core. To consistently obtain a multi-cycle equilibrium core for the three LEU fuels, a process was developed based on an iterative equilibrium core search procedure [16]. Starting from an initial estimate of the equilibrium core [17], the criticality calculation (KCODE) and depletion/burnup (BURN) features of MCNP6 were employed to simulate six reactor cycles in an iterative process. Each 30-day cycle was split into four stages: startup (SU) for 1.5 days, beginning of cycle (BOC) for 13.5 days, middle of cycle (MOC) for 15 days, and end of cycle (EOC) for 0.01 days.

The BURN feature was used to simulate the decaying of the fuel for 7 days in the EOC stage. For the next cycle, the fuel elements were shuffled according to one of the fuel management schemes shown in Figure 3. In Scheme A and Scheme B, the first number in the pair denotes the fuel batch number and the second number is unique identifier for the FE in the batch. In Scheme C, black and white font color distinguish FEs in the two halves, while the first number denotes the batch number and the second number denotes the number of cycles that the element will go through.

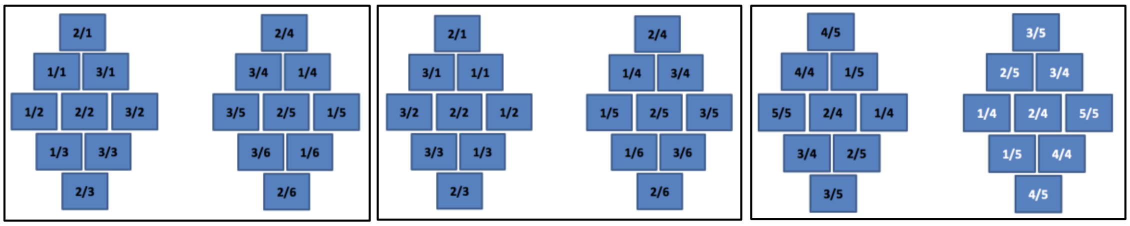


Figure 3. The fuel management schemes used in this study.

In Scheme A and Scheme B, the six third-cycle fuel elements are discarded and six fresh fuel elements are added – with the difference being that the fresh elements are loaded nearest the flux trap in Scheme B instead of the outside of core like in Scheme A. Scheme A is used for the 17-plate models of the three LEU fuels at 20 MW reactor power. Scheme B and Scheme C were used with the 19-plate model with U-10Mo fuel. The purpose of Scheme B was to increase coupling of the two core halves with fresh fuel loaded near the flux trap, while the purpose of Scheme C was to reach higher burnups by having only four fresh elements added each cycle and burning each for either four or five cycles at 20 MW power.

To accurately model the fuel burnup in the BURN step, the control blades positions were first estimated for each stage (except EOC) using the estimated control blade worth shown in Figure 4 along with the excess reactivity of the core determined by KCODE with control blades fully withdrawn to 20 cm away from the core. The control blade insertion, defined as the total length of control blade inserted into each core half, was estimated in order to achieve k_{eff} of 1.03 for SU (to compensate for ^{135}Xe poisoning) and 1.01 for BOC and MOC. For EOC, the control blades were withdrawn away from the core, as they would be at the end of a cycle. Following the adjustment of control blades for each stage, an updated input with the BURN card was run for the designated length to calculate the fuel burn up and fission product inventories. The iterative process was fully automated for consistent replication for each of the LEU fuel cases being investigated.

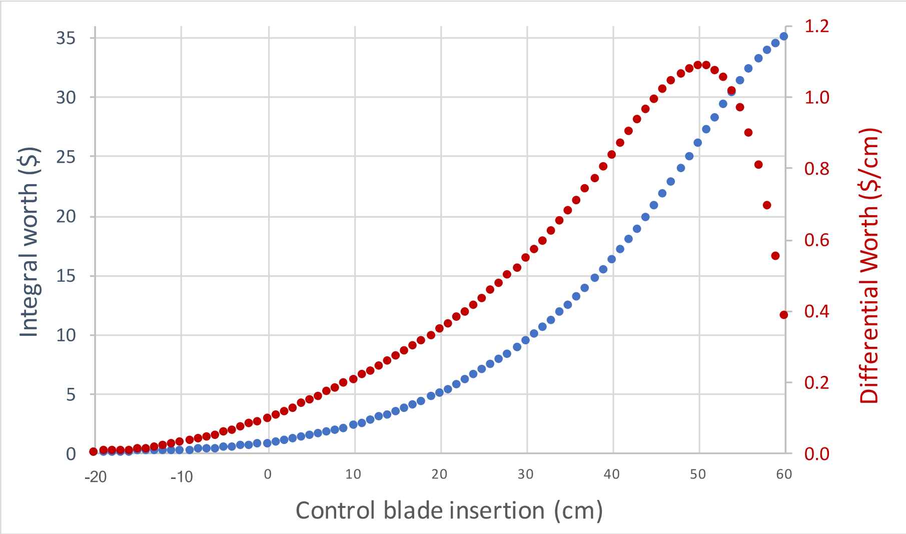


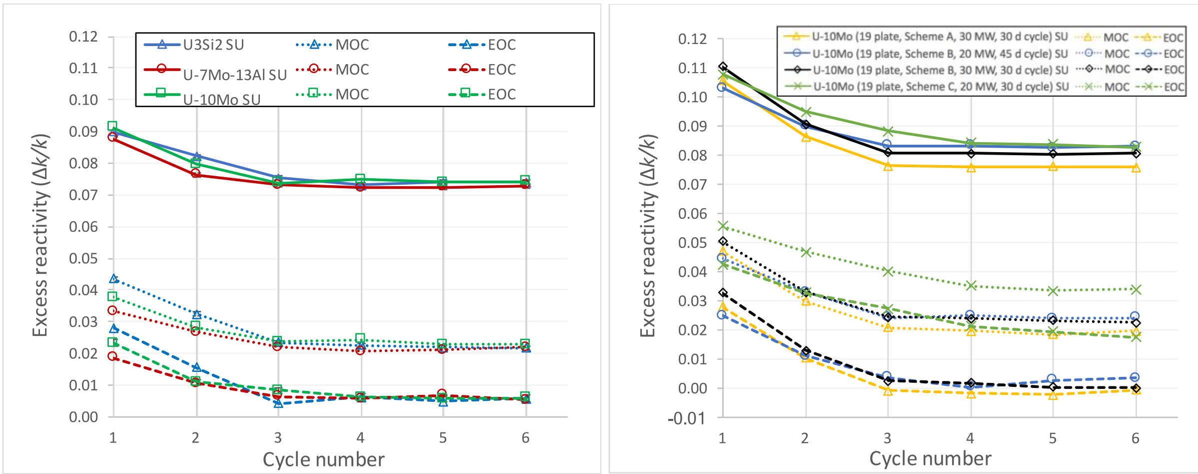
Figure 4. The integral and differential control blade worth determined using KCODE in the SU stage of Cycle 1 for the U_3Si_2-Al case.

4. RESULTS

After estimating the equilibrium cores for each LEU fuel, the reactor physics parameters and fuel inventories were compared.

4.1. Excess reactivity

Although the different LEU FEs contain similar ^{235}U masses in the 17-plate model, slight differences in the power distribution and neutron economy can affect the fuel burnup, and, therefore, the maximum cycle length at a given power. Analyzing the results from the equilibrium core search, the excess reactivities ($\Delta\rho = \frac{k_{eff}-1}{k_{eff}}$) at the beginning of the SU, MOC and EOC stages, shown in Figure 5(a), indicate that the LEU fuels in the 17-plate model perform similarly with the given power level, fuel management scheme and cycle length. Figure 5(b) shows the results for excess reactivity for 19-plate model with U-10Mo fuel using (Case 1) Scheme A at 30 MW, (Case 2) Scheme B with a 45 day cycle length at 20 MW, (Case 3) Scheme B at 30 MW and (Case 4) and Scheme C at 20 MW power. Based on these results for U-10Mo fuel, the fuel loading in the 19-plate model is sufficient for 900 MW-days (MWD) of operation in Case 2 and Case 3 as well as with Case 4 with the hybrid 4/5 batch fuel management scheme (Scheme C). For Case 4, the cycle can be extended past 600 MWD since excess reactivity remains at EOC. For Case 1, the reactivity was negative by EOC, indicating that the cycle would have to be less than 900 MWD.



(a) 17-plate model (b) 19-plate model

Figure 5. Excess reactivities at SU, MOC and EOC with control blades fully withdrawn (a) for the three LEU fuels using Scheme A and (b) for the 19-plate model of U-10Mo with Scheme B and Scheme C.

The fissile content of the discharged FEs at EOC of Cycle 6 in terms of ^{235}U burnup and ^{239}Pu mass for the different fuels and cycle parameters were compared, as shown in Table III. The fissile inventories of the three LEU fuels in the 17-model were similar, with small differences owing to the initial loading of ^{235}U. For the 19-plate model of the U-10Mo fuel, the fissile inventories were similar despite differences in power, cycle length since the amount of MWD was constant. Scheme C, with only four fresh elements at SU instead of six, had discharged elements with similar burnups despite only operating for 600 MWD.

Table III: Fuel burnup and ^{239}Pu mass for the discharged elements in the west core half from Cycle 6.

						Burnup (%)			^{239}Pu-239 (g)		
Fuel	**# of fuel plates**	**Fuel manage-ment**	**Power (MW)**	**Cycle length (days)**	**MWD**	**FE 3/1**	**FE 3/2**	**FE 3/3**	**FE 3/1**	**FE 3/2**	**FE 3/3**
U_3Si_2-Al	17	Scheme A	20	30	600	30.0	30.7	29.8	6.5	6.8	6.6
U-7Mo/Al	17	Scheme A	20	30	600	28.7	31.7	28.9	6.7	7.0	6.7
U-10Mo	17	Scheme A	20	30	600	28.4	31.2	28.3	6.8	7.0	6.7
	19	Scheme A	30	30	900	37.4	41.5	37.7	9.5	9.6	9.4
	19	Scheme B	20	45	900	37.8	41.4	37.8	9.5	9.8	9.5
	19	Scheme B	30	30	900	37.8	41.1	37.6	9.7	9.8	9.7
						FE 4/4	**FE 5/5**		**FE 4/4**	**FE 5/5**	
	19	Scheme C	20	30	600	36.6	42.2		9.4	9.8	

4.2 Cold neutron performance

Since the primary purpose of the NBSR-2 is the production of high-quality cold neutron beams, mesh tallies (FMESH) in MCNP6 were used to compare flux distributions in the MOC equilibrium core models for each of the LEU cases. The three LEU fuels performed very similarly in terms of flux distribution with

Scheme A. Thus, the interesting comparison was the U-10Mo fuel with the 17-plate model using Scheme A and the 19-plate models using Scheme B and Scheme C at 30 MW and 20 MW, respectively. Figure 6 shows the flux distributions from the reactor center toward the north CNS for these cases for fast neutrons, slow neutrons (<0.4 eV), and cold neutrons (<10 meV). Owing to difference in reactor power, 19-plate model with Scheme B had approximately 50 % more flux than 17-plate model with Scheme A. The 19-plate model with Scheme C slightly outperformed the 17-plate model as well, likely due to the fresh fuel being loaded nearest the flux trap.

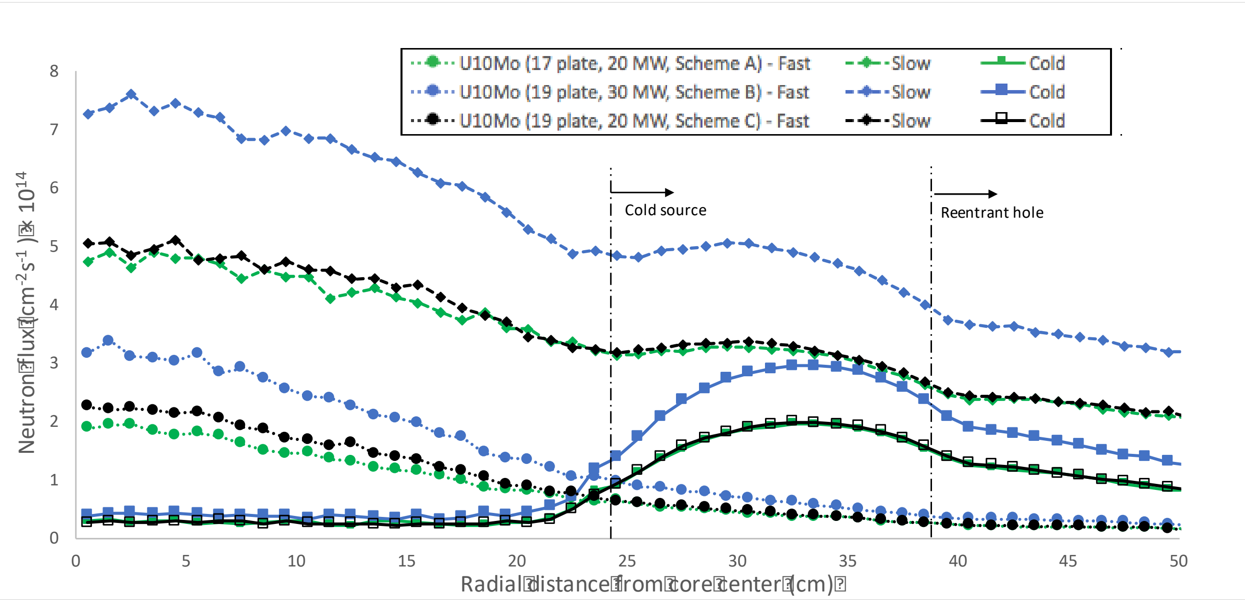


Figure 6. The flux distribution from the reactor center toward the north CNS for three U-10Mo cases

5. SUMMARY

Three LEU fuel options – U_3Si_2-Al dispersion, U-10Mo monolithic and U-7Mo/Al dispersion – performed similarly in a 17-plate FE model that kept plate thickness constant. The U-10Mo has a very thin fuel meat (10.5 mil) that could enable more plates in a FE of fixed size. We explored this possibility with a 19-plate FE with combinations of three fuel management schemes, power levels (20 MW or 30 MW) and cycle lengths (30 days or 45 days) to demonstrate that the reactor design could potentially reach 900 MWD of operation with six fresh FEs each cycle. A fuel management scheme with only four fresh FEs, potentially improving the economic viability of operating a reactor of this design, reached 600 MWD of operation of this reactor design. However, increasing the neutron flux by 50 % for cold neutron instruments – if allowed by fuel qualification and engineering constraints that have not been explored – or extending reactor cycle to 45 days with the 19-plate U-10Mo FEs also improve the economics of this reactor design. In comparing the three LEU fuels, the ability to load more fuel in the NBSR-2 design with U-10Mo allows more flexibility in the fuel management scheme and could lead to other optimizations that maximize cold neutron production for scientific research at the NCNR.

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