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COMPARISON OF U_3Si_2 AND U-10Mo LEU-FUELED REACTOR CORES FOR THE PRECONCEPTUAL NIST NEUTRON SOURCE DESIGN

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ABSTRACT

The National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR) is one of the primary U.S. national research facilities that hosts thousands of visiting domestic and international scientists/researchers for various research projects. The National Bureau of Standards Reactor (NBSR) has been operational more than 50 years, but due to increasing outage times and costly maintenance, a new replacement reactor, namely the NIST Neutron Source (NNS), is being planned by the NCNR to replace the aging NBSR. The preliminary conceptual design of the NNS core was based on Material Test Reactor (MTR) plate type U-10Mo fuel; however, due to recent difficulties and unknown timeline for the certification of U-10Mo fuel in the U.S., NCNR is investigating the possibility of using low-enriched uranium silicide dispersion (U_3Si_2/Al) *as alternative fuel material. In this paper, the neutronics performance of low-enriched* U_3Si_2/Al *fuel and U-10Mo fuel are compared with the objective of identifying the dimensions of* U_3Si_2/Al *fuel plates that can yield similar neutronics behavior to the current U-10Mo fuel plates without modifying overall assembly size. Hence, the main objective of the NNS is to provide neutrons for the two cold sources located around the core, and the current compact core design delivers more neutron intensity and brightness for the cold neutron sources. Neutron transport analyses follow an optimization process for minimizing the difference between the* k_∞ *of the silicide plates to the U-10Mo, maximizing the coolant channel thickness and* ^{235}U *content inside the assembly. Results show correlations between the fuel-to-coolant area ratio and the reactivity worth characteristics of the U-10Mo and* U_3Si_2/Al *plates in the NNS.*

Keywords: Material Test Reactor, NBSR, NNS; LEU; Neutronics; U_3Si_2; U-10Mo

NOMENCLATURE

A_f	Fuel meat area (mm^2)
A_r	Area ratio, A_f/A_∞
A_∞	Coolant channel area (mm^2)
F_i	1st order Fourier series fit for i-th data set
k_∞	Infinite multiplication factor
P_i	2nd order polynomial fit for i-th data set
ρ	Mass density (g/cm^3)
ρ_U	Uranium density (g/cm^3)
t_c	Cladding thickness (mm)
t_f	Fuel meat thickness (mm)
t_∞	Coolant channel thickness (mm)
w_f	Fuel meat width (mm)
w_p	plate width (clad and coolant, mm)

1. INTRODUCTION

The National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR) hosts the National Bureau of Standards Reactor (NBSR). The NBSR is a 20 MW_{th} research reactor that supports an oversubscribed demand for cold and thermal neutron scattering research, and it has been in operation since 1967. Its ageing status has made it prone to extended outage times and costly maintenance, which prompted efforts for designing a replacement reactor, namely, the NIST Neutron Source (NNS).

The NNS is planned to be a 20 MW_{th} reactor with a compact core design using 3x3 fuel assemblies, each containing 21 high assay low-enriched U-10Mo, Material Test Reactor (MTR) type fuel plates at 19.75% U-235 enrichment. The pre-conceptual core design is shown in Figure 1, which has been investigated in prior works [1–3].

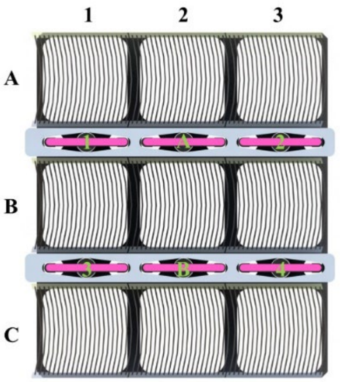

FIGURE 1: THE NNS PRE-CONCEPTUAL CORE LAYOUT.

Although U-10Mo is planned, the ever-evolving state of the low enriched U-10Mo fuel certification efforts in the U.S. prompts worries about whether the fuel would be ready in time for fueling the NNS. This prompted the NCNR to investigate other high assay low-enriched alternatives, namely uranium silicide-aluminum dispersion (U_3Si_2/Al) fuel. The U_3Si_2/Al fuel has been extensively investigated in the past, and it is deemed acceptable for fueling research reactors like the NNS [4,5]. This is based on a safety evaluation report issued by the U.S. nuclear regulatory commission (NRC), specifically NUREG-1313 [6]. The U_3Si_2/Al fuel cited in NUREG-1313 is one with 4.8 gU/cm^3 (uranium density, ρ_U), which is lower than the 5.2 gU/cm^3 proposed in more recent studies [7].

This work seeks to understand the feasibility of using U_3Si_2/Al fuels in the NNS using simplified unit-cell models. The results compare the U-10Mo plates with the silicide plates in terms of dimensions and infinite multiplication factor k_∞ to understand the reactivity cost of switching from U-10Mo to U_3Si_2/Al fuel plates within the constraints of the compact NNS concept, keeping overall fuel assembly dimensions constant. A correlation between the U_3Si_2/Al fuel plate dimensions and the reactivity tradeoff (relative to U-10Mo) is investigated as well.

2. METHODOLOGY

2.1 Unit-cell Model

This work utilizes a unit-cell model with reflective boundaries along the length and width of the fuel plate, as shown in Figure 2. All simulations are performed with Monte Carlo N-Particle (MCNP) code, version 6.2 [8]. Per Figure 2, the thickness and width of the fuel meat is set to t_f and w_f, respectively. The water (H_2O) gap and the cladding have the same width in the unit cell model, namely w_p, however they have different half-thicknesses where the water channel half-thickness is t_∞ and the cladding thickness is t_c.

The unit-cell approach is well-known and well-utilized for sensitivity analyses to reduce computational cost [9]. This study is no different, where a variety of dimensions are adopted for the fuel plate in the model to optimize the infinite multiplication factor (k_∞). Considering the variability in the uranium density (ρ_U) of the U_3Si_2/Al fuel, and optimization analysis is performed to find a fuel plate that offers a k_∞ that is closest to the U-10Mo fuel plate with the minimal reduction in the water channel thickness. This is done to ensure suitable thermal-hydraulics cooling conditions.

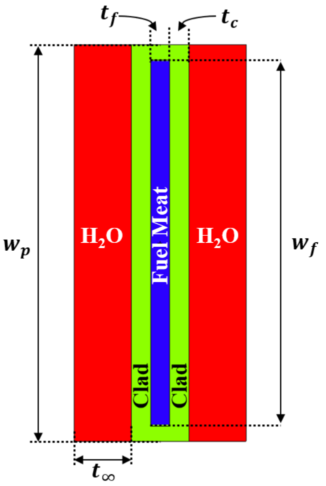

FIGURE 2: A TOP VIEW OF THE UNIT CELL MODEL.

To prepare the models for the optimization analysis, it is important to consider the composition of each U_3Si_2/Al fuel, both of which are presented in Table 1. Note the presence of parasitic uranium isotopes like ^{236}U in both compositions. This is because it is assumed that this fuel by down-blending highly enriched uranium to the high assay low-enriched uranium (HALEU) in the U.S. [10]. Previous studies by the NCNR revealed that accounting for the impurities from down-blending yields considerable variations in the neutronics results and cycle length [11], and so it is deemed necessary to account for the impurities here as well. U_3Si_2/Al compositions are assumed to have the same ^{235}U enrichment as the planned U-10Mo fuel plates, which retain the HALEU enrichment level of 19.75%.

TABLE 1: THE COMPOSITIONS OF EACH U_3Si_2/Al MATERIAL USED IN THIS STUDY. NOTE THAT THE MASS FRACTIONS ARE PROVIDED FOR EACH ISOTOPE.

Nuclide	**U_3Si_2/Al $\rho_U =$ 4.8 gU/cm^3**	**U_3Si_2/Al $\rho_U =$ 5.2 gU/cm^3**
^{232}U	1.48E-09	1.53E-09
^{234}U	1.93E-03	1.99E-03
^{235}U	1.47E-01	1.51E-01
^{236}U	3.41E-03	3.52E-03
^{238}U	5.90E-01	6.08E-01
^{28}Si	5.40E-02	5.56E-02
^{29}Si	2.74E-03	2.82E-03
^{30}Si	1.81E-03	1.86E-03
^{27}Al	1.99E-01	1.76E-01
^{14}N	1.79E-05	1.70E-05
^{15}N	6.53E-08	6.21E-08
ρ [g/cm^3]	6.4687	6.8043

2.2 Optimization Approach

The dimensions of the plate are varied by modifying the thicknesses of the fuel plate from its U-10Mo nominal geometry, which is shown in Figure 2. The dimensions were varied iteratively, resulting 12 total cases that will be further discussed in the results section. For references, the nominal composition and dimensions of the fuel plate are provided in Table 2, and they correspond to the currently selected characteristics of fuel plates in the pre-conceptual NNS design.

TABLE 3: THE NOMINAL GEOMTRY & COMPOSITION OF THE U-10Mo FUEL PLATE.

Material	t_f, w_f [mm]	t_c, w_p [mm]	t_∞, w_p [mm]
U-10Mo (ρ=17.14 g/cm^3)	0.250, 65	0.44, 70.5	1.352, 70.5

Nuclide	Mass Frac.	Nuclide	Mass Frac.
^{232}U	1.80E-09	^{94}Mo	9.15E-03
^{234}U	2.34E-03	^{95}Mo	1.58E-02
^{235}U	1.78E-01	^{96}Mo	1.67E-02
^{236}U	4.14E-03	^{97}Mo	9.60E-03
^{238}U	7.16E-01	^{98}Mo	2.44E-02
^{92}Mo	1.45E-02	^{100}Mo	9.82E-03

3. RESULTS AND DISCUSSION

The silicide compositions were simulated with the nominal dimensions as listed in Table 3. The initial results given in Table 5 shows that all cases could be a good candidate for the NNS as silicide fuel. However, equivalent core excess reactivity does not guarantee comparable cycle length. Core cycle length could be matched with more or less same amount of ^{235}U mass inside the reactor core, hence consumption of U-235 per MW-day of operation is more or less constant [12]. Keeping same amount of ^{235}U inside the core is possible by approximately tripling (2.97) fuel thickness for 5.2 g/cm^3 silicide fuel and more for the 4.8 g/cm^3 silicide fuel. Table 4 shows the dimensions of each case, alongside the percent change in each of the thicknesses from the nominal dimensions in Table 3. For all simulations, the results converged to within ±5% relative error.

TABLE 4: A LIST OF ALL CASES INVESTIGATED IN THIS WORK.

ρ_U	Case	Dimensions t_f×t_c×t_∞	Plate Number in Assembly	% Change from Nominal Assembly $\Delta\%t_f\times\Delta\%t_c\times\Delta\%t_\infty$
	Ref	**0.250×0.44×1.3517**	**21**	**0×0×0 %**
4.8 g/cm^3	1	0.750×0.44×1.1017	21	300.00×0.00×-18.50%
	2	0.650×0.44×1.4711	18	222.86×0.00× -6.71%
	3	1.000×0.44×1.7433	15	285.71×0.00× -7.87%
	4	0.800×0.44×1.2784	19	289.52×0.00×-14.43%
	5	0.750×0.44×1.1975	20	285.71×0.00×-15.62%
	6	0.750×0.44×1.8683	15	214.29×0.00×-1.27%
5.2 g/cm^3	7	0.750×0.44×1.1017	21	300.00×0.00×-18.50%
	8	0.650×0.44×1.4711	18	222.86×0.00× -6.71%
	9	1.000×0.44×1.7433	15	285.71×0.00× -7.87%
	10	0.800×0.44×1.2784	19	289.52×0.00×-14.43%
	11	0.750×0.44×1.1975	20	285.71×0.00×-15.62%
	12	0.750×0.44×1.8683	15	214.29×0.00×-1.27%

Note how the optimization process only varies t_f and t_∞, where the t_∞ variations are kept to a minimum. The results of the optimization analysis are presented in Table 5, where the nominal case (U-10Mo) is put against each of the U$_3$Si$_2$/Al cases described in Table 4. Starting with case 1, the nominal dimension of an assembly is kept the same, but the fuel meat composition is changed from U-10Mo to 4.8 gU/cm^3 and 5.2 gU/cm^3 U$_3$Si$_2$/Al.

It was found that the Case 2 and Case 3 of 4.8 g/cm^3 silicide fuel gives higher multiplication factor than that have same dimension of 7 and 8. It cannot be possible in a state of over-moderation region of a system without any changes in the geometry. These cases are eliminated for reactor safety. In terms of the cooling/moderating area, Case 6 and Case 12 employ a cooling area very close the original cooling area and, nearly the same amount of coolant is able to flow inside the fuel assembly. Unfortunately, in terms of amount of total fuel content inside the assembly, is just about 2/3 of expected amount of fuel content, so it is not to a conceivable candidate for the NNS assembly. Although, Case 5 and Case 11 are given similar results with respect to the Case 4 and Case 10, and, nearly similar flow area reductions are observed in all above mentioned cases, Case 10 has the maximum uranium content (1.33% higher volume than Case 11) and the minimum flow area blockage (1.19% lower than Case 5 & 11) in the other remaining cases by considering fuel density, fuel loading volume in an assembly.

TABLE 5: A SUMMARY OF ALL CASES INVESTIGATED IN THIS WORK.

ρ_U	Case	k_∞	$\left(\frac{k_\infty - k_{\infty,ref}}{k_{\infty,ref}}\right)$%
4.8g/cm^3	**Ref**†	**1.57464**	-3.83%
	1	1.65588	0.05%
	2	1.67052	0.94%
	3	1.67885	1.44%
	4	1.66476	0.59%
	5	1.66105	0.37%
	6	1.65588	0.05%
5.2 g/cm^3	**Ref**†	**1.59154**	-4.85%
	7	1.65712	0.13%
	8	1.66762	0.76%
	9	1.67847	1.42%
	10	1.66509	0.61%
	11	1.66351	0.52%
	12	1.67613	1.28%

† The dimensions kept constant, and density and fuel compositions are changed. U-10Mo k_∞value is calculated as 1.65498 at reference dimensions.

4. CONCLUSION

A feasibility and optimization study was conducted to demonstrate the performance of 4.8 gU/cm^3 and 5.2 gU/cm^3 U$_3$Si$_2$/Al fuel plates for the NNS pre-conceptual core. The performance was compared to the nominal U-10Mo plates while maintaining flow area and maximizing fuel loading in an assembly, all the while constraining the overall fuel assembly dimensions.

A model, specifically Case 10, that contains 19 fuel plates with 0.8 mm fuel thickness has minimum coolant gap reduction with 14.4%. Case 10 delivers k_∞ comparable to that of an assembly which uses U-10Mo nominal plate dimensions in the current NNS design. Future studies will seek to perform more thorough comparisons between the fuel plates, namely power and safety margins comparisons, as well as full-core, burnup, reactivity feedback, and cycle length analyses.

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