RERTR 2022 – 42ND INTERNATIONAL MEETING ON
REDUCED ENRICHMENT FOR RESEARCH AND TEST REACTORS

OCTOBER 3-5, 2022
VIENNA INTERNATIONAL CENTRE
VIENNA, AUSTRIA

Neutronic Simulation of Curved Fuel Plate with Flat Plate Geometry

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ABSTRACT

This study examined the validity of using flat fuel plates to model an MTR-type curved-plate fuel assembly in neutronic calculations. Neutronics analysis of the MTR-type fuel assembly often utilizes equivalent flat-fuel-plate models to simplify input preparation, such as employing repeated structures in the lattice geometry, and to accelerate the numerical computation. In this study, we demonstrated the validity of this approach for the NBSR low-enriched uranium (LEU) fuel design as a case study. By leveraging the stochastic neutronic tool, Serpent 2, we built a single assembly model based on the curved plate geometry and demonstrated that the k_{eff} of an NBSR curved-fuel-plate model agreed with that of an equivalent flat-fuel-plate model within 20 pcm. All the Serpent 2 calculations were verified by replicating the same models in MCNP6.2. We also showed that this equivalence becomes less valid, i.e., the deviation in k_{eff} increases when the fuel plate curvature increases.

1 Introduction

The Material Testing Reactor (MTR) was a light-water (H_2O)-cooled-and-moderated reactor specifically designed to facilitate the conception and design of future reactors [1], which operated at the National Reactor Testing Station from 1952 to 1970. The MTR-plate-type fuel sets the standard for fuel geometry for subsequent Research and Test Reactors (RTRs) both within the U.S. and worldwide. For example, all the five U.S. High-Performance Research Reactors (USHPRR) and the McMaster Nuclear reactor (MNR) [2] of McMaster University in Canada are operating with the MTR-plate-type fuel, as shown in Figure 1. The MTR-plate-type fuel usually employs curved fuel plates to mitigate the vibration caused by the coolant flowing between the fuel plates and to minimize the heating effect on the mechanical joints [4]. The curved fuel plates are commonly approximated by equivalent flat fuel plates for neutronics analysis [5] to alleviate modeling efforts. For example, the NBSR neutronics model has historically been built with equivalent flat-fuel-plate elements using MCNP [6], a U. S. NRC-recognized neutronics tool for reactor safety analysis and core design. The "Lattice" feature of MCNP can build geometries by repeating rectangular or hexagonal cells [6], which simplifies input preparation and might accelerate the numerical computation. Because of the small curvatures of the current MTR-plate-type fuels, the equivalence between the curved fuel plates and the equivalent flat fuel plates had until recently been assumed valid based on engineering judgment and some benchmark against reactor data.

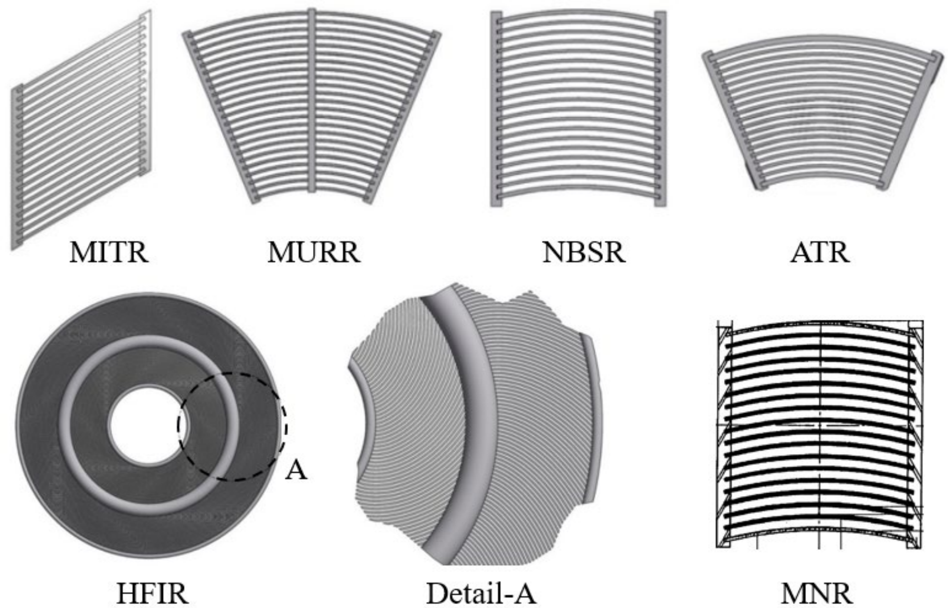

Figure 1. Comparison of the fuel elements of the RTRs (modified from [2-3]).

In this study, we demonstrated the validity of this approach for the NBSR LEU fuel design as a case study with stochastic neutronics calculations. We also extended our investigation to cover MTR-type curved fuel plates with larger curvatures. The paper is organized as follows: Section 2 briefly introduces the NBSR design. Section 3 presents the construction of the NBSR single-element curved-fuel-plate model. Section 4 illustrates the process of building the NBSR single-element equivalent flat-fuel-plate model. Section 5 demonstrates the equivalence of these two models for neutronics analysis. Section 6 extends the discussion to cover curved fuel plates with larger curvatures. Section 7 concludes this paper by summarizing the findings.

2 The NBSR Design

The NBSR is a heavy-water (D_2O)-moderated-and-cooled tank-type reactor operating at the National Institute of Standards and Technology (NIST) with a nominal thermal power level of 20 MW [4]. The NBSR employs the MTR plate-type fuel elements, the fuel meats of which consist of U_3O_8 in aluminum powder dispersion fuel. The NBSR is currently fueled by Highly Enriched Uranium (HEU) [7] with ^{235}U enrichment of 93±1 wt.%. Figure 2a illustrates the cutaway isometric drawing of a typical NBSR fuel element [8] with an overall length of 1.75 m, which contains an upper and a lower fuel section separated by a 17.78 cm gap. This "split-core" design maximizes the thermal neutron flux in the center of the gap for neutron scattering experiments [4]. Seventeen (17) fuel plates are placed between two unfueled end plates in each fuel section, bounded by two side plates, as illustrated in Figure 2 (b).

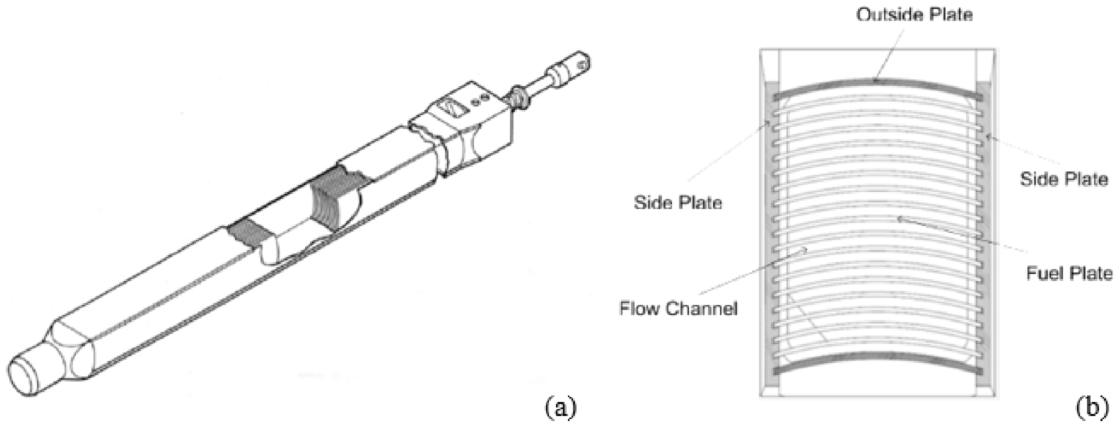

Figure 2. (a) Cutaway isometric drawing [8] and (b) cross-sectional view of a typical NBSR fuel element (dimensions are shown in inches) [9].

The NBSR core consists of thirty (30) fuel elements arranged in a hexagonal array with the position designation shown in Figure 3a. The space denoted with <R> represents the position of the regulating rod, and the six positions indicated with <> represent the in-core irradiation thimbles. Figure 3b shows the fuel shuffling scheme of the 30 NBSR fuel elements, among which sixteen (16) stay in the core for eight 38.5-day cycles, and fourteen (14) remain in the core for seven 38.5-day cycles. Each fuel element is marked with two numbers and one letter. The first number (7 or 8) denotes the total number of cycles that the fuel element will stay in the core, and the second number (1 - 8) represents the cycle in which the fuel element currently resides. The letter can be either W or E, indicating whether the fuel element is in the west or the east part of the core.

N

	D1	F1	H1	J1		
	C2	E2	<>	I2	K2	
	B3	<>	F3	H3	<>	L3
A4	C4	E4	<>	I4	K4	M4
	B5	<>	F5	H5	<>	L5
	C6	E6	<R>	I6	K6	
	D7	F7	H7	J7		

(a)

N

	8-1W	7-2W	7-2E	8-1E		
	8-3W	7-5W	<>	7-5E	8-3E	
	7-3W	<>	8-7W	8-7E	<>	7-3E
7-1W	8-6W	7-7W	<>	7-7E	8-6E	7-1E
	8-4W	<>	8-8W	8-8E	<>	8-4E
	7-4W	7-6W	<R>	7-6E	7-4E	
	8-2W	8-5W	8-5E	8-2E		

(b)

Figure 3. (a) Fuel position map and (b) fuel shuffling scheme in the NBSR.

The NBSR is under conversion from HEU to Low Enriched Uranium (LEU) using a high-density alloy of U-10Mo (uranium-10 wt.% molybdenum). Only the fuel composition, fuel meat thickness, and aluminum cladding thickness will be changed during the conversion. In contrast, the overall geometry of the fuel plates and the fuel elements will remain the same as that in the present HEU NBSR [9]. Preliminary MCNP6.2 calculations of the LEU NBSR have been conducted [10] and the model was used as the basis of this study.

3 The NBSR Single-element Curved-fuel-plate Model

We used Serpent 2 [11], a three-dimensional continuous-energy Monte Carlo reactor physics code, to perform the neutronics calculations in this study. We employed the reflective boundary conditions at x= ± 25 cm and y= ± 25 cm, and a black boundary condition at z= ± 100 cm (any neutrons that exit get lost) for all the Serpent 2 calculations performed. The NBSR single-element curved-fuel-plate model was constructed according to the NIST LEU NBSR design drawings [12-15]. Figure 4 shows the cross-sectional views of the NBSR single-element curved-fuel-plate model. Table 1 summarizes the dimensions of the NBSR fuel element geometries and their references.

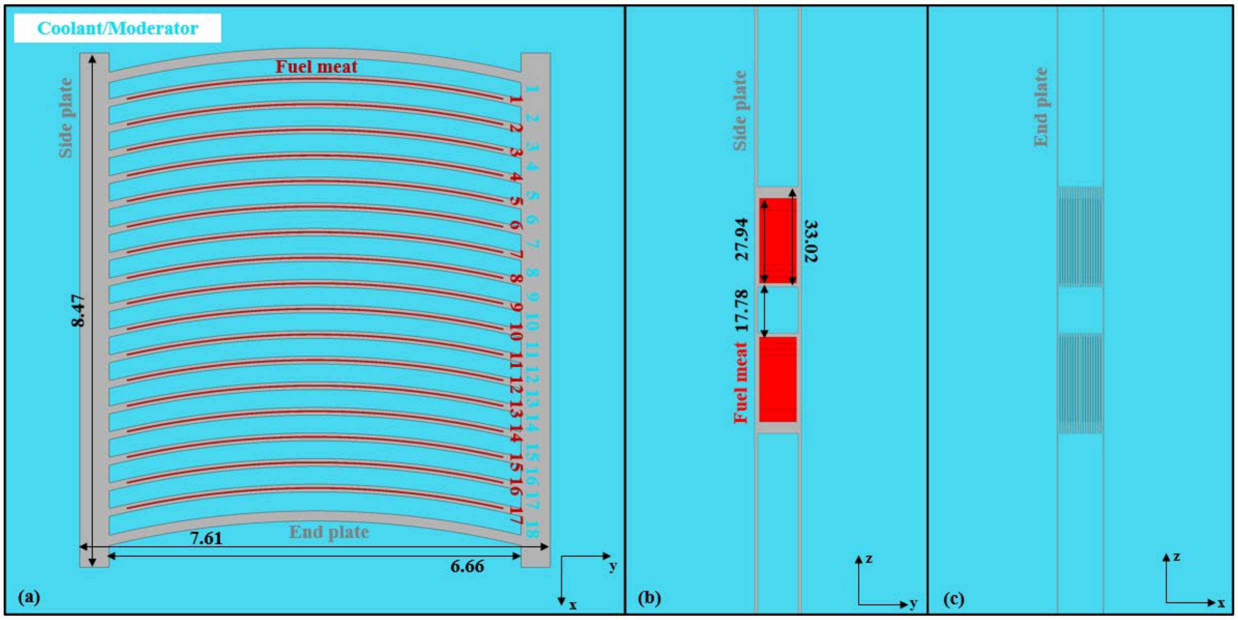

Figure 4. The (a) x-y, (b) y-z, and (c) x-z cross-sectional views of the Serpent 2 model of the reference NBSR fuel element (dimensions are shown in cm).

Table 1. Dimensions of the NBSR fuel element geometries and the references

Geometry	Parameter	Dimension	Reference
Fuel assembly	Length	3.335 inch (8.4709 cm)	[12]
	Width	2.996 inch (7.60984 cm)	[12]
Side plate	Length	3.335 inch (8.4709 cm)	[12]
	Thickness	0.187 inch (0.47498 cm)	[13]
End plate	Thickness	0.065 inch (0.1651 cm)	[14]
	Concave radius	5.5 inch (13.97 cm)	[12]
Fuel plate	Thickness	0.05 inch (0.127 cm)	[15]
	Concave radius	5.5 inch (13.97 cm)	[12]
Fuel meat	Thickness	0.0085 inch (0.02159 cm)	[15]
	Unbent width	2.415 inch (6.134 cm)	[15]
Coolant channel	Maximum thickness	0.116 inch (0.29464 cm)	[12]

The curved-fuel-plate model was symmetric with respect to the x-axis. All the curved plates, including the fuel plates, the fuel meats, and the end plates, were modeled with individual curved surfaces, since repeated structures could not be employed. Because the NBSR fuel plates have a thickness of 0.127 cm and a curvature radius of 13.97 cm, we modeled each of them using a concave surface with a curvature radius ($R_{fp,concave}$) of 13.97 cm and a convex surface with a curvature radius ($R_{fp,convex}$) of 14.097 cm. Because the fuel meats are located at the center of the fuel plates, they shared the same centerline curvature and the same curvature center, as depicted in Figure 5. With a thickness of 0.02159 cm, the fuel meats' concave ($R_{fm,concave}$) and convex ($R_{fm,convex}$) curvature radii were 14.02271 cm and 14.04430 cm, respectively.

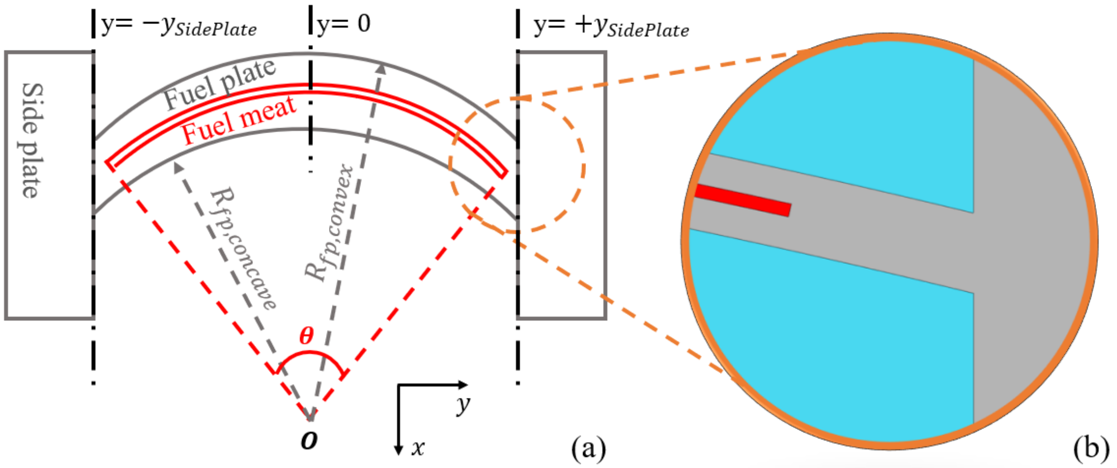

Figure 5. (a) A schematic of a unit cell (not to scale) and (b) a zoomed view of the intersection of the fuel plate with the side plate (to scale).

The fuel meat's degree of curvature (θ) was determined as 0.43527 rad (25°) from the specified fuel meat x-y cross-sectional area (A_{fm}) by solving

$$\theta/2 \times \left(R_{fm,convex}^2 - R_{fm,concave}^2\right) = A_{fm}. \quad (1)$$

The fuel plate x-y cross-sectional area (A_{fp}) was calculated by analytically integrating

$$\int_{-y_{SidePlate}}^{+y_{SidePlate}} \left(\sqrt{R_{fp,convex}^2 - y^2} - \sqrt{R_{fp,concave}^2 - y^2}\right) dy = A_{fp}, \quad (2)$$

noting that

$$\int \sqrt{a^2 - x^2} dx = \frac{x}{2}\sqrt{a^2 - x^2} + \frac{a^2}{2} arcsin\left(\frac{x}{a}\right) + C. \quad (3)$$

4 The NBSR Single-element Equivalent Flat-fuel-plate Model

We constructed the NBSR single-element equivalent flat-fuel-plate model from the NBSR single-element curved-fuel-plate model by following the process summarized in Figure 6. The parameters explicitly conserved are shown below.

- The thickness of the fuel meat.
- The volume of the fuel meat in each fuel plate.
- The thickness of the fuel plate.
- The volume of each fuel plate.
- The volume of each coolant channel.
- The volume of each end plate.
- The volume of the side plate in each unit cell.
- The volume of the side plate in each fuel element.

The geometry modifications were made on the x-y plane only, while all the z locations remained unchanged. In Figure 6, the parameters in *Italic* font are those of the curved-fuel-plate model, and the parameters in the boxes are those calculated for the equivalent flat-fuel-plate model.

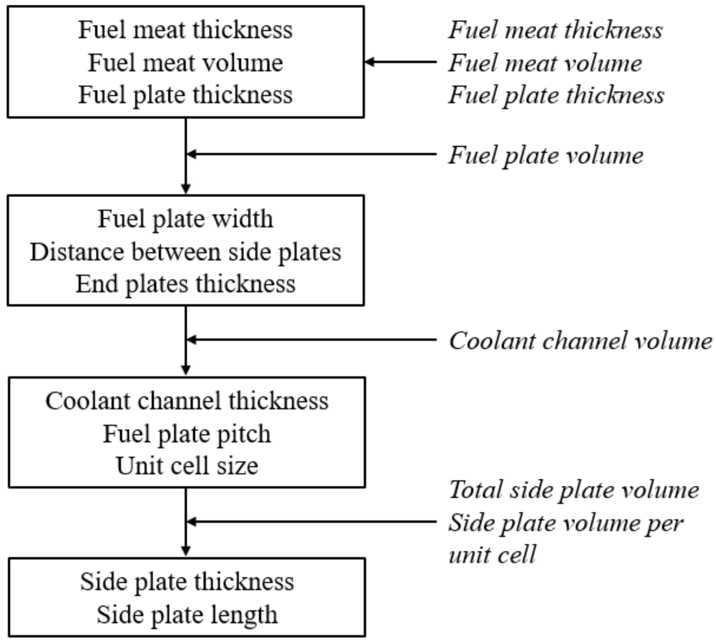

Figure 6. The process of developing the equivalent flat-fuel-plate model.

5 Demonstration of the Equivalence Between the NBSR Single-element Curved-fuel-plate and Equivalent Flat-fuel-plate Models

This section demonstrates the equivalence between the NBSR single-element equivalent flat-fuel-plate model and the curved-fuel-plate model. All the Serpent 2 calculations conducted in this study employed 100,000 neutron histories per cycle, 200 active cycles, and 50 inactive cycles. The uncertainties associated with the effective neutron multiplication factors (k_{eff}) were around 20 pcm (per cent mille). The general nuclear cross section and fission yield libraries employed were from ENDF/B-VII.1, whereas the thermal neutron scattering, S (α, β), cross section library used was from ENDF/B-VII.0.

5.1 MCNP models

As noted in Section 2, initial modeling of the LEU NBSR had been performed with MCNP6.2, a tool that has been amply validated for this application, and the reference neutronics code under the RERTR program. A single-element model was extracted from this legacy MCNP LEU NBSR model and was updated to reflect the changes described above for the Serpent 2 equivalent flat-plate model. The MCNP6.2 curved-plate model, was converted surface-by-surface and cell-by-cell from the Serpent 2 model, while retaining the alphanumerical labels Serpent employed as comments in the MCNP input for ease of comparison and future reference. Because repeated structures could not be used for the curved-plate model, it was significantly more laborious in input files preparation than the flat-plate model. As a rough order-of magnitude guide to the difference, the geometry specification was about 500 lines in the flat-plate model, and about 1000 lines in the curved-plate model. The MCNP models were exercised to verify the validity of the conclusions presented below in this section.

5.2 Equivalence at the equilibrium state

We calculated the k_{eff} for the startup (SU) state of the equilibrium LEU NBSR. The fuel compositions used for the neutronics calculations were taken from fuel element D7 calculated in ref. [10]. Table 2 summarizes the k_{eff} of the NBSR single-element curved-fuel-plate and equivalent flat-fuel-plate models calculated with Serpent 2 and MCNP6.2. The keff of the NBSR single-element equivalent flat-fuel-plate models agreed with those of the NBSR single-element curved-fuel-plate models within statistical uncertainties (20 pcm). This demonstrates the equivalence between the two models at the equilibrium state.

Table 2. k_{eff} of the SU equilibrium curved-fuel-plate and equivalent flat-fuel-plate models.

Model	k_{eff}	k_{eff} uncertainty	Δk_{eff}
Serpent curved	1.22473	0.00019	0.00020
Serpent equivalent flat	1.22453	0.00019	
MCNP curved	1.22465	0.00019	0.00015
MCNP equivalent flat	1.22450	0.00018	

5.3 Equivalence through a fuel cycle

We calculated the k_{eff} through a postulated 30-day cycle of the LEU NBSR. Table 3 summarizes the fresh fuel isotopic composition that we employed at the beginning of the cycle.

Table 3. Fresh fuel isotopic composition (LEU).

	^{235}U	^{238}U	Mo	Total
Mass in the element (g)	383	1556	215	2154
Mass density (g/cm^3)	3.06	12.42	1.72	17.19
Weight fraction (%)	17.78	72.24	9.98	100

The fuel was depleted with a whole-element fission power of 0.6667 MW (20 MW / 30 elements) for 30 days to reach a burnup of 10.32 MWdays/KgHM. The calculations were performed at the specific depletion steps of 0, 0.1, 0.2, 0.5, 1, 1.5, 2, 5, 10, 15, 20, 25, and 30 days. We employed the more frequent depletion steps at the beginning of the cycle to capture the impact of the accumulation of the fission-product neutron poisons, such as ^{135}Xe. Figure 7 compares the k_{eff} of the NBSR single-element curved-fuel-plate and equivalent flat-fuel-plate models through the postulated 30-day cycle.

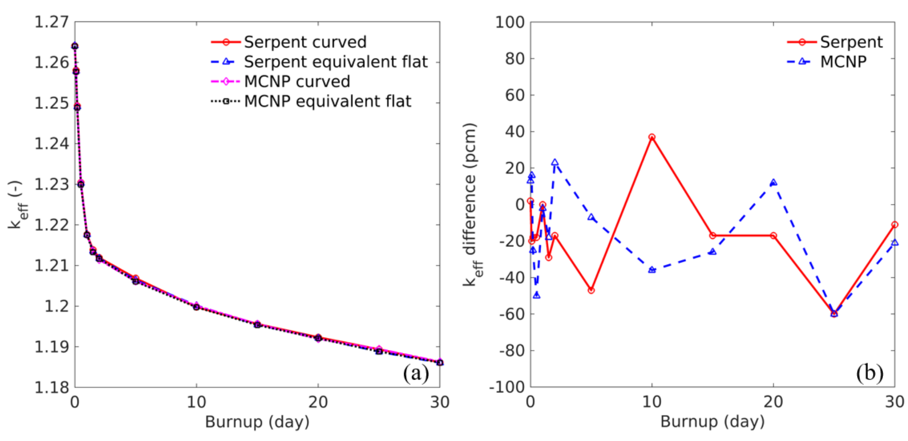

Figure 7. (a) k_{eff} and (b) difference in k_{eff} of the NBSR single-element models through a postulated 30-day fuel cycle (equivalent flat-fuel-plate model - curved-fuel-plate model).

Calculated with both Serpent 2 and MCNP6.2, the absolute differences in k_{eff} oscillated around zero through the fuel cycle, with a maximum of around 60 pcm, and arrived at around 20 pcm at the end of the cycle. This demonstrates that, similarly to the equilibrium state, the NBSR single-element equivalent flat-fuel-plate model is equivalent to the NBSR single-element curved-fuel-plate model through a fuel cycle.

6 Impact of the Fuel Plate Curvature on the Equivalence Between the Curved-fuel-plate and Equivalent Flat-fuel-plate Models

This section discusses the validity of approaching the curved fuel plates with equivalent flat-fuel-plate models when larger plate curvatures are considered to support power upgrades of the currently operating RTRs or for future reactor designs. In addition to the NBSR fuel element with a fuel meat curvature of 25°, we investigated five more fuel element designs with the fuel meat curvatures of 45°, 55°, 68°, 80°, and 90°. We assumed that the increase in the fuel plate curvature was realized by shortening the distance between the side plates. This means although the coolant channel volumes decreased with the increasing fuel element curvature, the volumes of the other components of the fuel elements remained unchanged. In the Serpent 2 models, we varied the curvature radii of the fuel meats, fuel plates, and end plates to conserve their thicknesses and volumes. Figure 8 compares the x-y cross-sectional view of these fuel element designs.

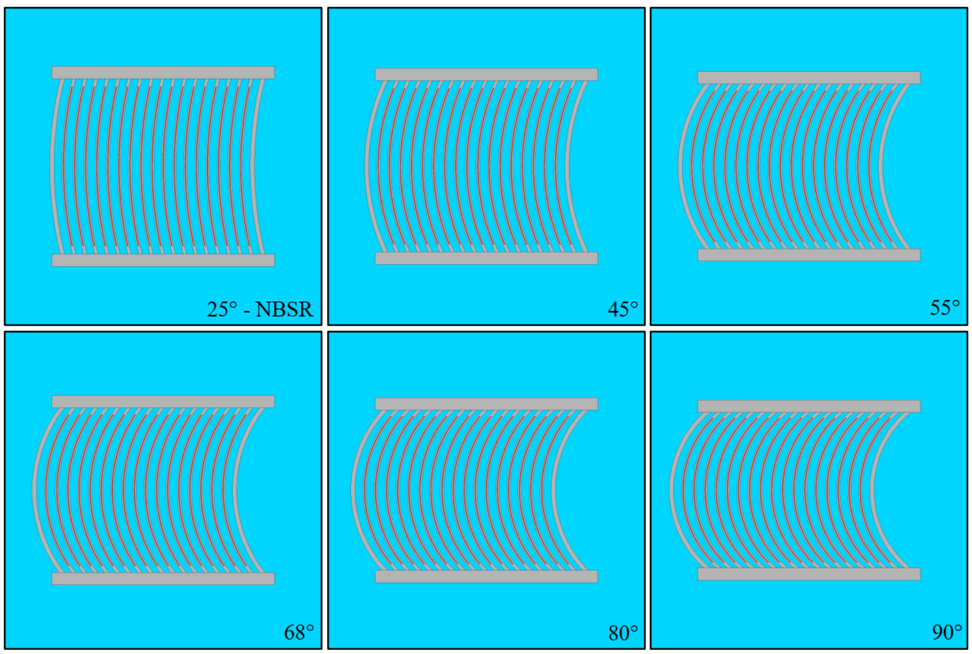

Figure 8. The x-y cross-sectional views of the Serpent 2 models of the six fuel elements with different curvatures.

We built the equivalent flat-fuel-plate models of the fuel element designs shown above by using the methodology introduced in Section 4. Figure 9a compares the k_{eff} of the equivalent flat-fuel-plate models with those of their curved counterparts using fuel isotopic compositions described in Section 5.1. While the k_{eff} of the 25° fuel element design employed in the NBSR could be approximated with the equivalent flat-fuel-plate model within the 20-pcm statistical uncertainty, the equivalent flat-fuel-plate model underpredicted the k_{eff} when the fuel meat curvature became larger. The underprediction reached 0.737% for the 90° cases, which would be 737 pcm if the 90° curved-fuel-plate model were critical.

Table 4 summarizes the relative differences between the six-factor-formula factors of the equivalent flat-fuel-plate models and those of their curved counterparts (equivalent flat-fuel-plate model – curved-fuel-plate model). The two dominant contributors to the k_{eff} underprediction were the underestimated thermal neutron non-leakage probability (L_T) and the underestimated neutron absorption rate in the fuel meat (f). Both fuel element models had the same volume because the volumes of all the components were conserved when converting the curved-fuel-plate model to the equivalent flat-fuel-plate model. The higher neutron non-leakage probabilities in the curved-fuel-plate models indicate that the curved surfaces promoted the confinement of the neutrons within the fuel elements. The equivalent flat-fuel-plate models could not correctly account for this effect. The absorption of neutrons by the side plates was impeded in the curved-fuel-plate models because the fission neutrons needed to pass through several layers of the fuel plates to reach the side plates, as illustrated in Figure 9b. The equivalent flat-fuel-plate models could not correctly account for this effect either. The above two effects caused the overestimation of neutron absorption in both the side plates and the coolant outside of the fuel element in the equivalent flat-fuel plate models, which led to underestimating the neutron absorption in the fuel meat, as shown in Figure 9c.

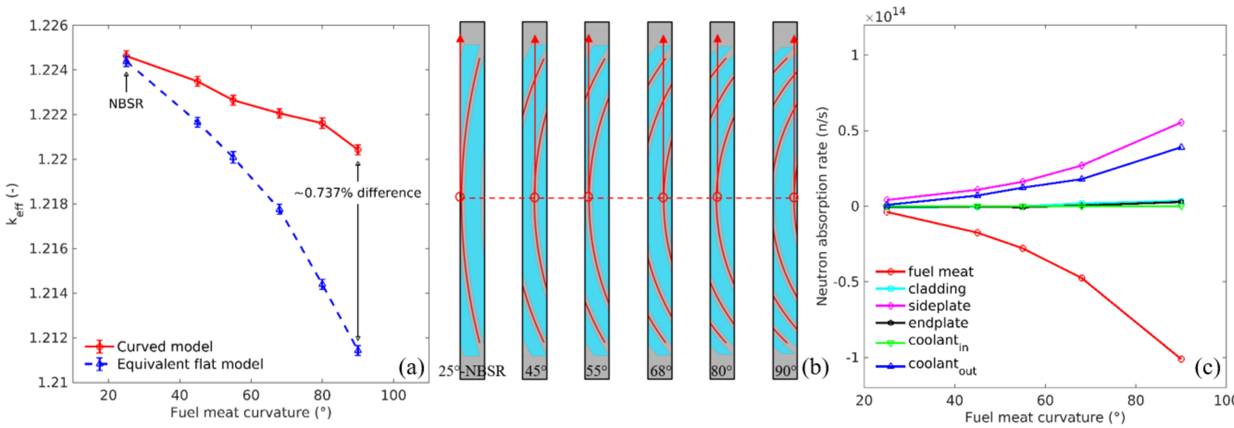

Figure 9. Comparison of the k_{eff} of the curved-fuel-plate models with those of the equivalent flat-fuel-plate models, (b) comparison of the unit cells of the fuel elements with different curvatures. (the arrows mark one possible path for the fission neutrons to reach the side plates), and (c) differences in neutron absorption rate in different fuel element components (equivalent flat-fuel-plate model – curved-fuel-plate model).

Table 4. The relative differences of the six-factor-formula factors for different curvatures (equivalent flat-fuel-plate model – curved-fuel-plate model).

	25°	45°	55°	68°	80°	90°
η	5.03E-05	9.57E-05	1.86E-04	7.05E-05	-4.18E-04	-1.71E-04
f	-2.05E-04	-1.11E-03	-1.20E-03	-2.09E-03	-2.97E-03	-3.99E-03
p	-1.68E-05	-2.45E-04	-6.31E-05	-6.83E-05	-1.33E-04	-2.04E-04
ϵ	5.79E-05	2.61E-04	2.51E-04	2.90E-04	4.63E-04	6.18E-04
L_F	6.00E-06	0.00E+00	-4.00E-06	-1.00E-06	-3.00E-06	-5.00E-06
L_T	-9.45E-05	-4.87E-04	-1.25E-03	-1.72E-03	-2.85E-03	-3.62E-03

7 Summary and conclusions

In this study, we examined the validity of using flat fuel plates to model an MTR-type curved-plate fuel assembly in neutronic calculations. By leveraging the stochastic neutronics code Serpent 2, we demonstrated the equivalence between an NBSR LEU single-element equivalent flat-fuel-plate model and an NBSR LEU single-element curved-fuel-plate model. This finding was verified by replicating the same models in MCNP6.2.

We extended our study to cover larger plate curvatures to support potential power upgrades of the currently operating RTRs or for future reactor designs. We found that while the k_{eff} of the NBSR fuel element design could be approximated with the equivalent flat-fuel-plate model within the 20-pcm statistical uncertainty, the equivalent flat-fuel-plate models will underpredict the k_{eff} when the fuel meat curvature becomes larger. The underprediction will reach 0.737% for fuel elements with 90° fuel plates. This emphasizes the importance of understanding the uncertainties caused by approaching curved fuel plates with flat-fuel plate models for neutronics calculations.

We will build an NBSR LEU whole-core curved-fuel-plate model for future LEU NBSR analysis to reduce the uncertainties in k_{eff} calculations.

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