Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Neutronic Simulation of Curved Fuel Plate with Flat Plate Geometry

C. Lu, A. Cuadra, P. Kohut, and L.-Y. Cheng
Nuclear Science and Technology Department

RERTR 2022 – 42nd International Meeting on
Reduced Enrichment for Research and Test Reactors
Vienna, Austria October 3-5, 2022

@BrookhavenLab

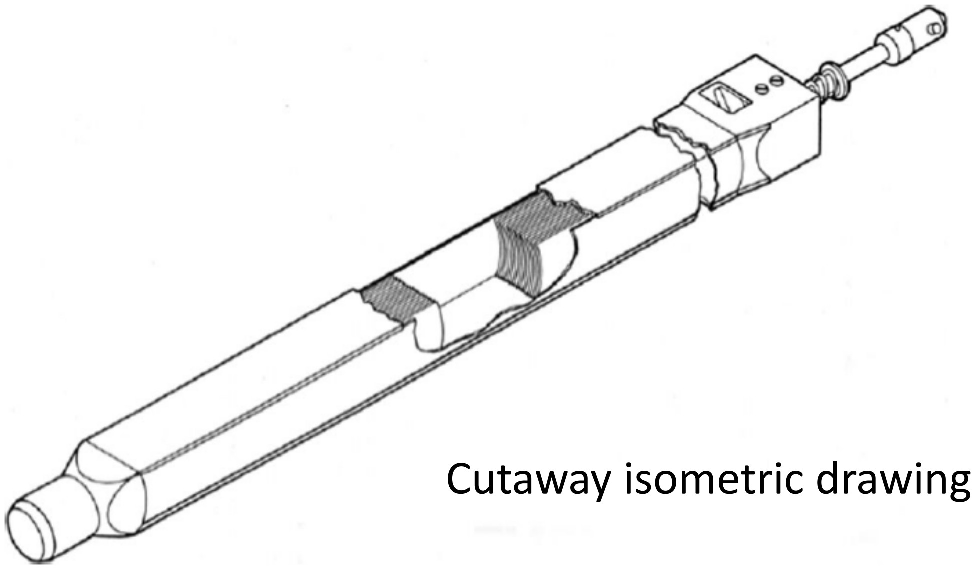
Outline of Presentation

- Objective – demonstrate equivalence of curved-plate and flat-plate model
- NBSR fuel element – geometry and neutronic model
- Single element curved fuel plate model
- Equivalent flat fuel plate model
- Comparison of results – Keff at start up and through a fuel cycle
- Impact of increased fuel plate curvature
- Summary and conclusion

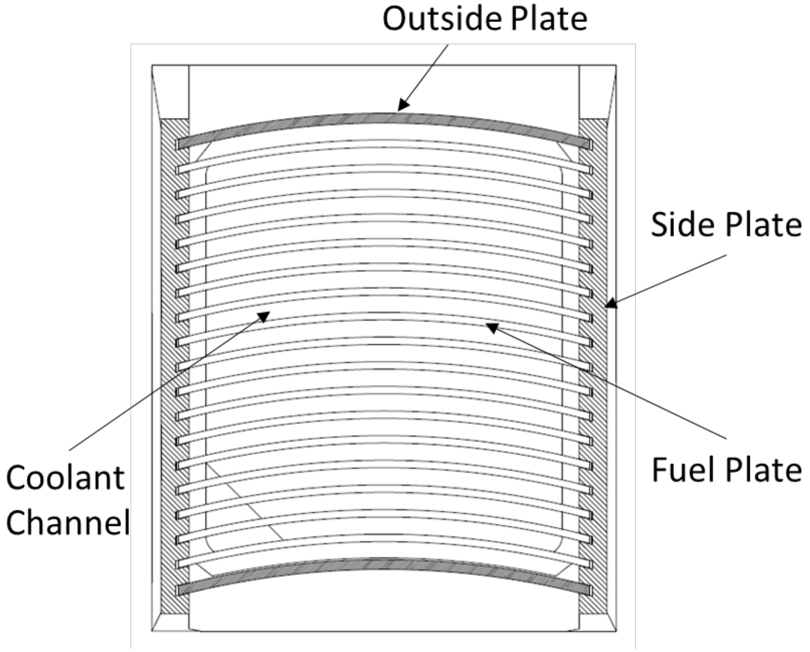
The NBSR (1)

❖ The NBSR

- Is a heavy-water (D_2O)-moderated-and-cooled tank-type reactor operating at the NIST
- Uses 30 MTR plate-type fuel elements in the core
- Operates at a nominal thermal power level of 20 MW
- Has elements with an overall length of 1.75 m. Upper and lower fuel sections are separated by a 17.78 cm gap to maximize the thermal neutron flux
- Has 17 fuel plates in each fuel section

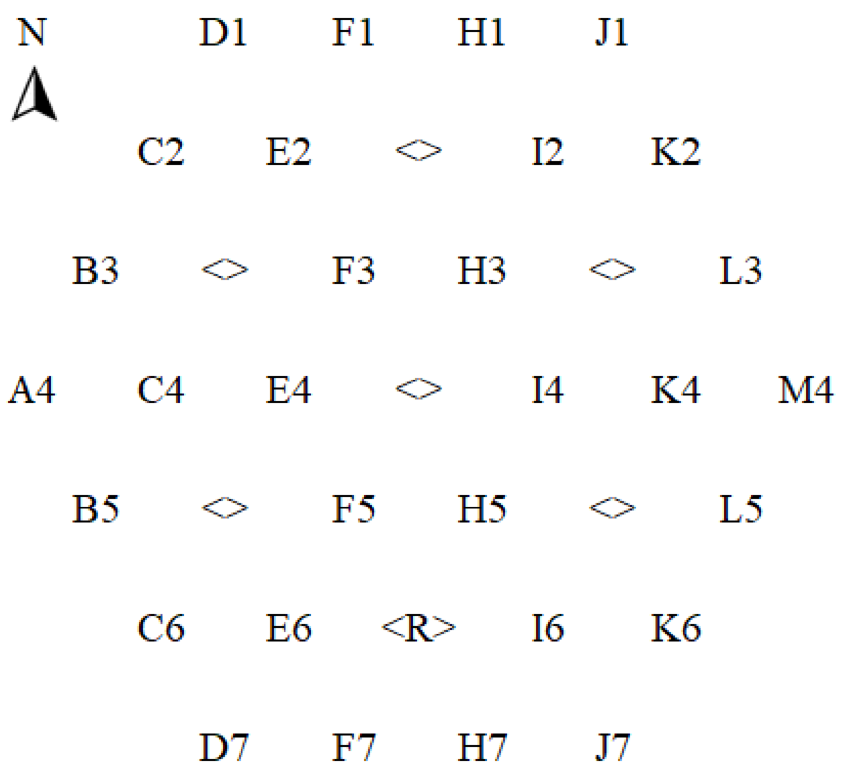


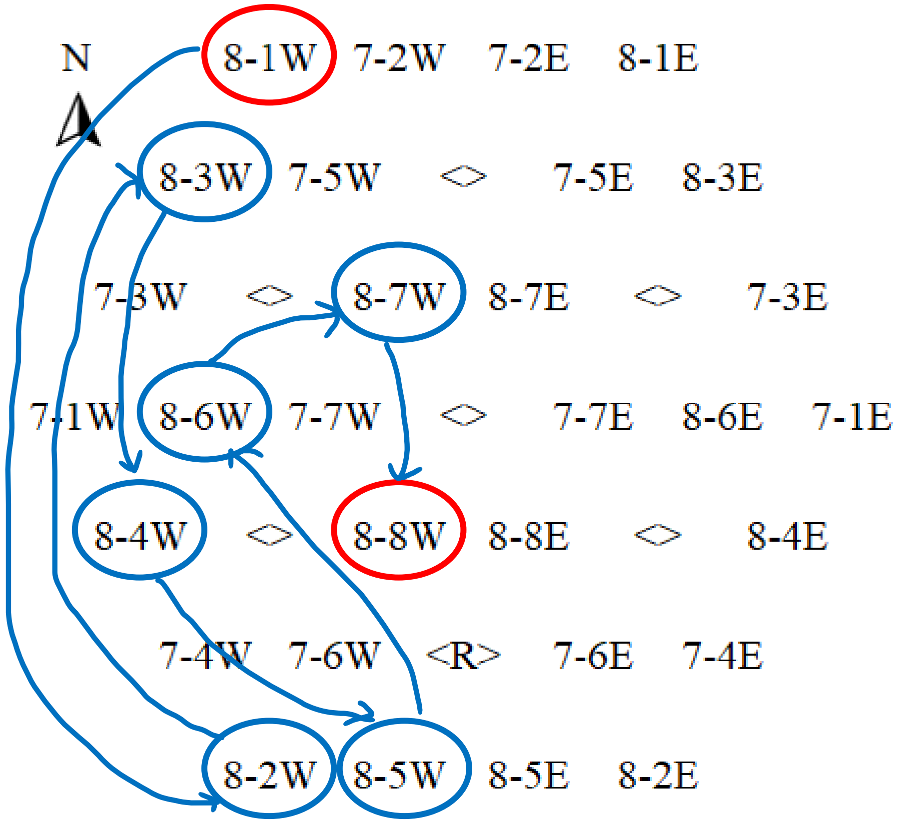
Cutaway isometric drawing



Cross-sectional view

The NBSR (2)





- ❖ Positions of the 30 fuel elements
  - ➢ <R> represents the regulating rod
  - ➢ <> represents the in-core irradiation thimbles (6 in total).

- ❖ Fuel shuffling scheme
  - ➢ The first number (7 or 8) -> total number of cycles
  - ➢ The second number (1 to 8)-> current cycle
  - ➢ W (west) and E (east)

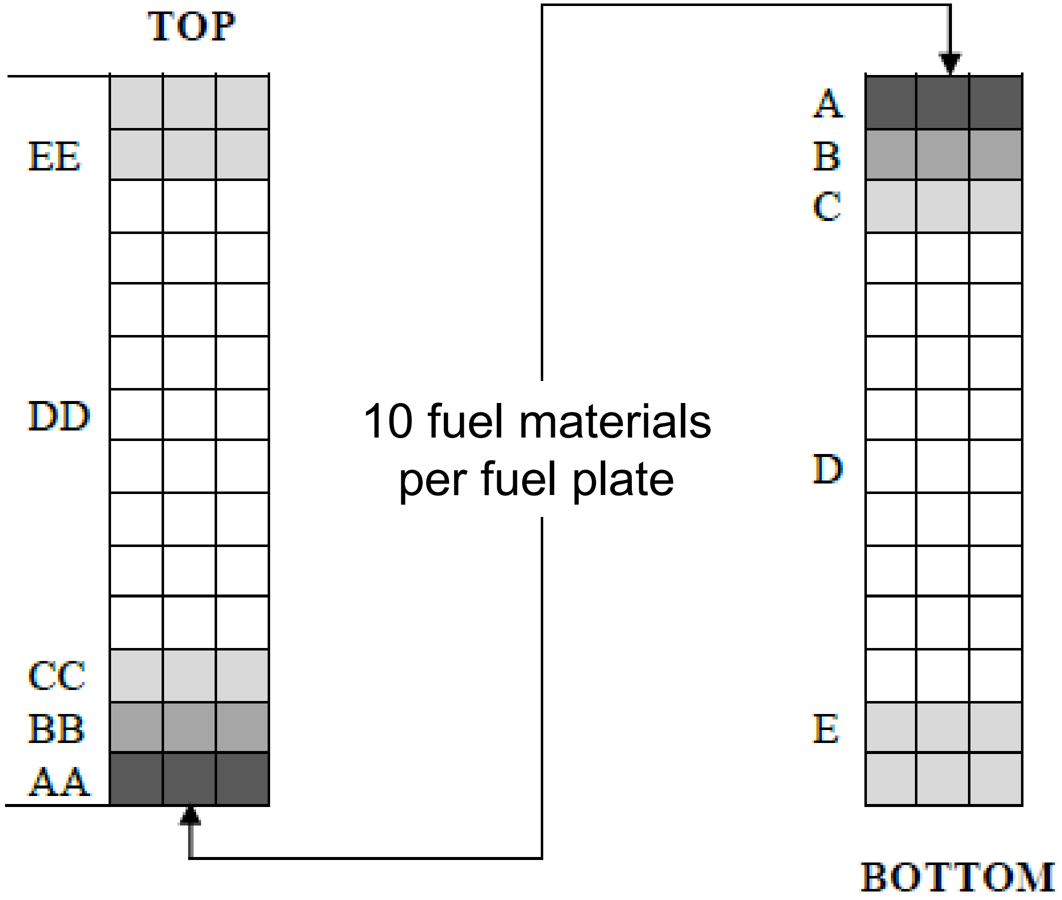
The NBSR Neutronics Model Fuel Compositions

❖ Axial and transverse zones

- Each fuel plate is broken into 14 axial meshes
- And 3 transverse meshes for calculating power distribution
- ~2x2 cm mesh

❖ Plate-by-plate material zones

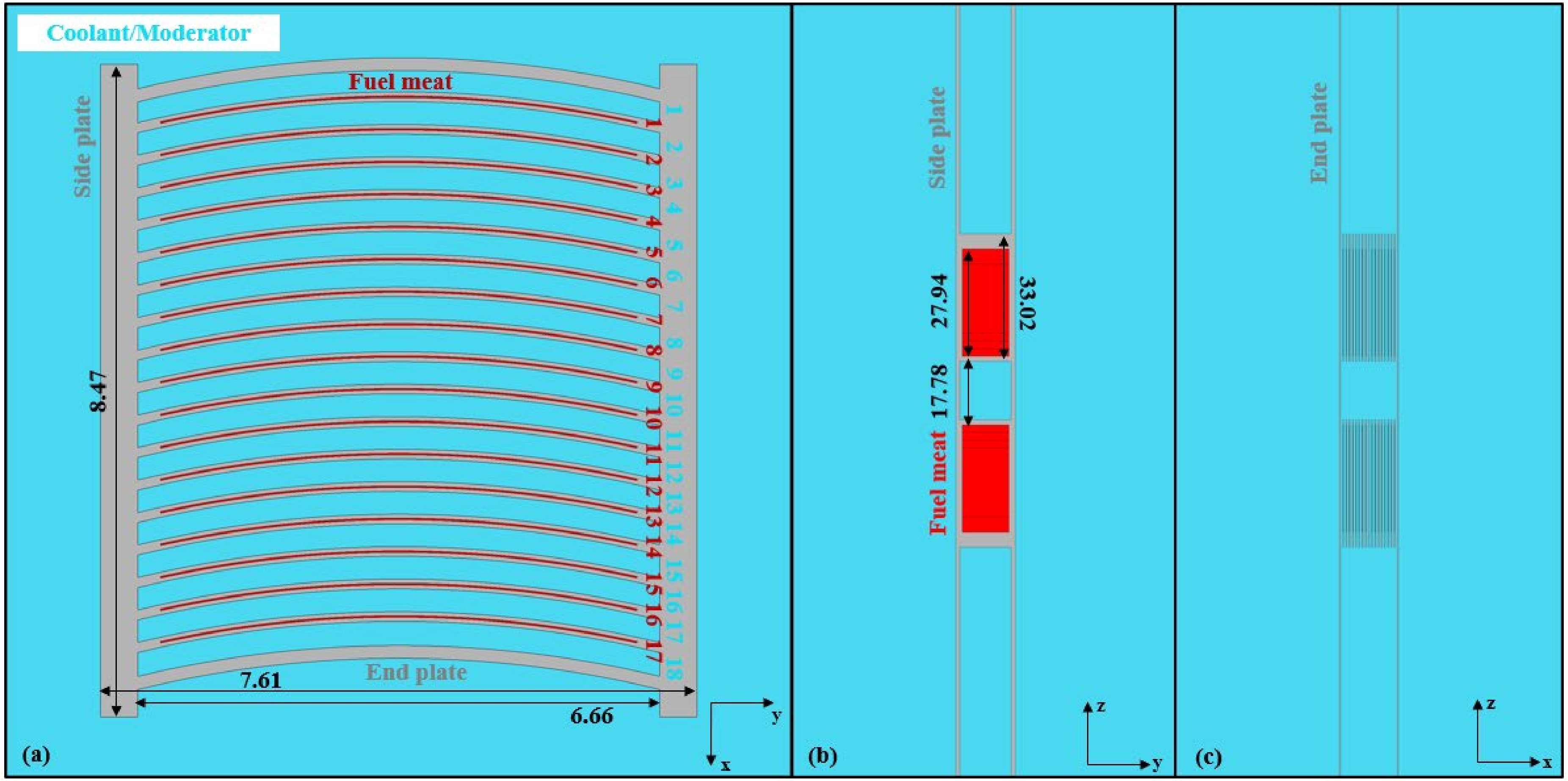
- 180° symmetry
- Plates 1 and 17 -> same compositions
- Plates 2 and 16 -> same compositions
- Plates 3 - 15 -> same compositions
- 10 fuel materials per fuel plate
- In total: 10 × 3 × 30 = 900 fuel materials



Axial composition zones and power meshes in a fuel plate

The Single-element Curved-fuel-plate Model (1)

- ❖ Model constructed according to the NIST LEU NBSR design drawings
- ❖ Two neutronics codes were used, Serpent 2 and MCNP 6.2



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)

The Single-element Curved-fuel-plate Model (2)

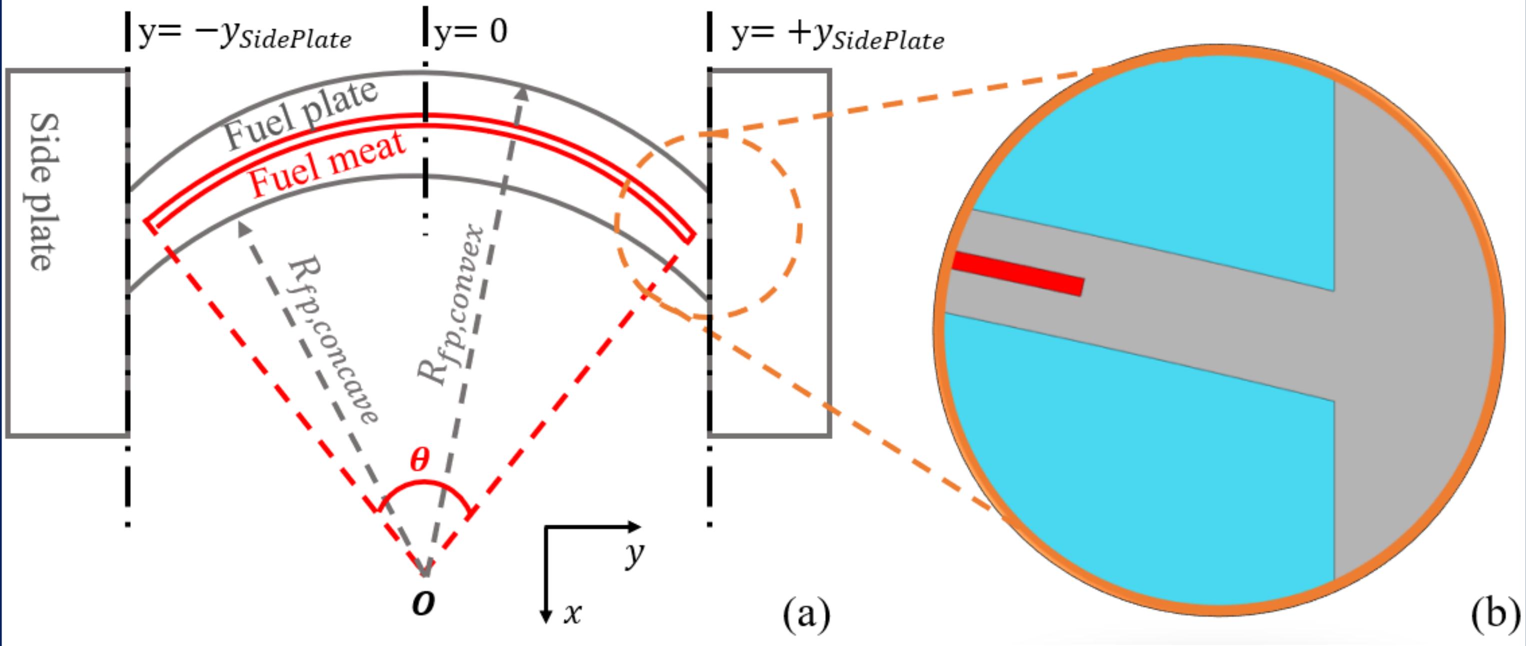
❖ Calculations of the fuel meat and fuel plate cross-sectional areas

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

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

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

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



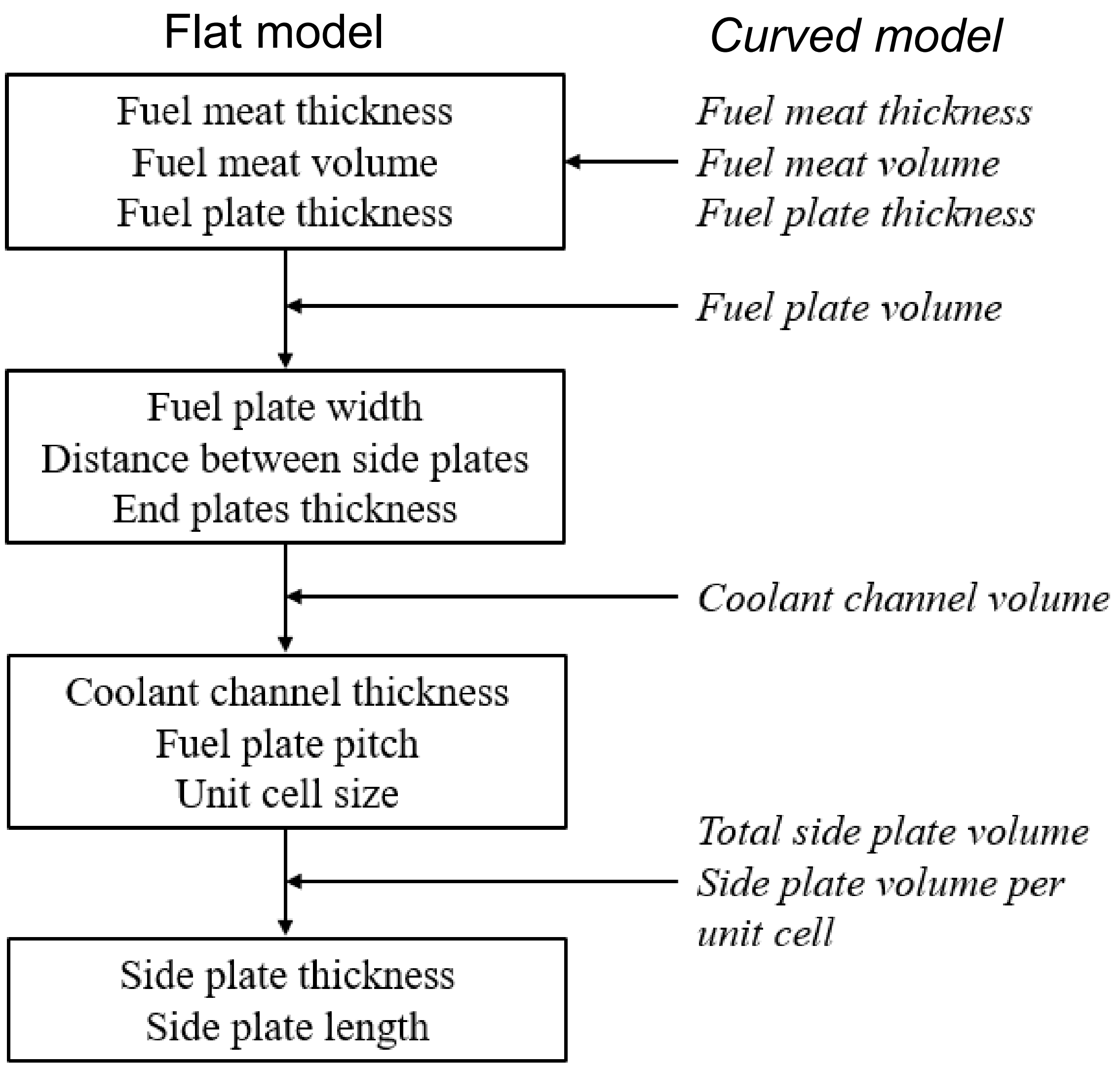
(a) A schematic of a unit cell (not to scale) and (b) a zoomed view of the intersection of the fuel plate with the side plate (to scale).

The Single-element Equivalent Flat-fuel-plate Model

❖ To construct the NBSR single-element equivalent flat-fuel-plate model from the curved-fuel-plate model, the following parameters were explicitly conserved

- Fuel meat thickness
- Fuel meat volume per fuel plate
- Fuel plate thickness
- Fuel plate volume per fuel plate
- Coolant channel volume
- End plate volume
- Side plate volume per unit cell
- Side plate volume per fuel element

❖ The geometry modifications were made on the x-y plane only, while all the z locations remained unchanged



The process of developing the equivalent flat-fuel-plate model

Equivalence Between the NBSR Single-element Curved-fuel-plate and Equivalent Flat-fuel-plate Models (1)

❖ MCNP model for verification

- Version MCNP6.2
- Converted surface-by-surface and cell-by-cell from the Serpent 2 model
- ~500 lines in the flat-plate model
- ~1000 lines in the curved-plate model

❖ Agreement within statistical uncertainties (20 pcm), which demonstrates the equivalence between the two models at the equilibrium state.

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

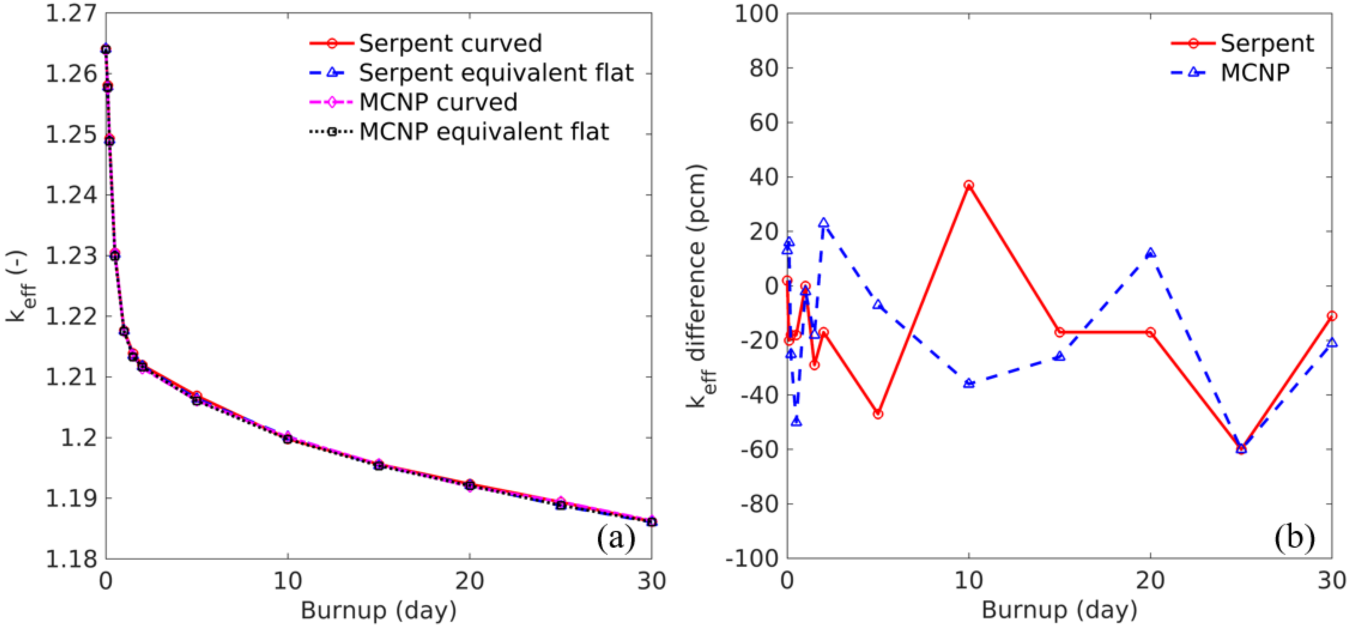
Model	k_{eff}	k_{eff} uncertainty	Δk_{eff}
Serpent curved	1.22473	0.00019	**0.00020**
Serpent equivalent flat	1.22453	0.00019	
MCNP curved	1.22465	0.00019	**0.00015**
MCNP equivalent flat	1.22450	0.00018	

Equivalence Between the NBSR Single-element Curved-fuel-plate and Equivalent Flat-fuel-plate Models (2)

- ❖ k_{eff} investigated through a postulated 30-day cycle
  - ➢ With a whole-element fission power of 0.6667 MW (20 MW / 30 elements)
  - ➢ With finer steps at the BOL
- ❖ The absolute differences in Serpent and MCNP k_{eff}
  - ➢ Oscillated around zero
  - ➢ Maximum ~60 pcm
  - ➢ Arrived at around 20 pcm at the EOC
- ❖ Demonstrates the equivalence between the two models through a fuel cycle

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

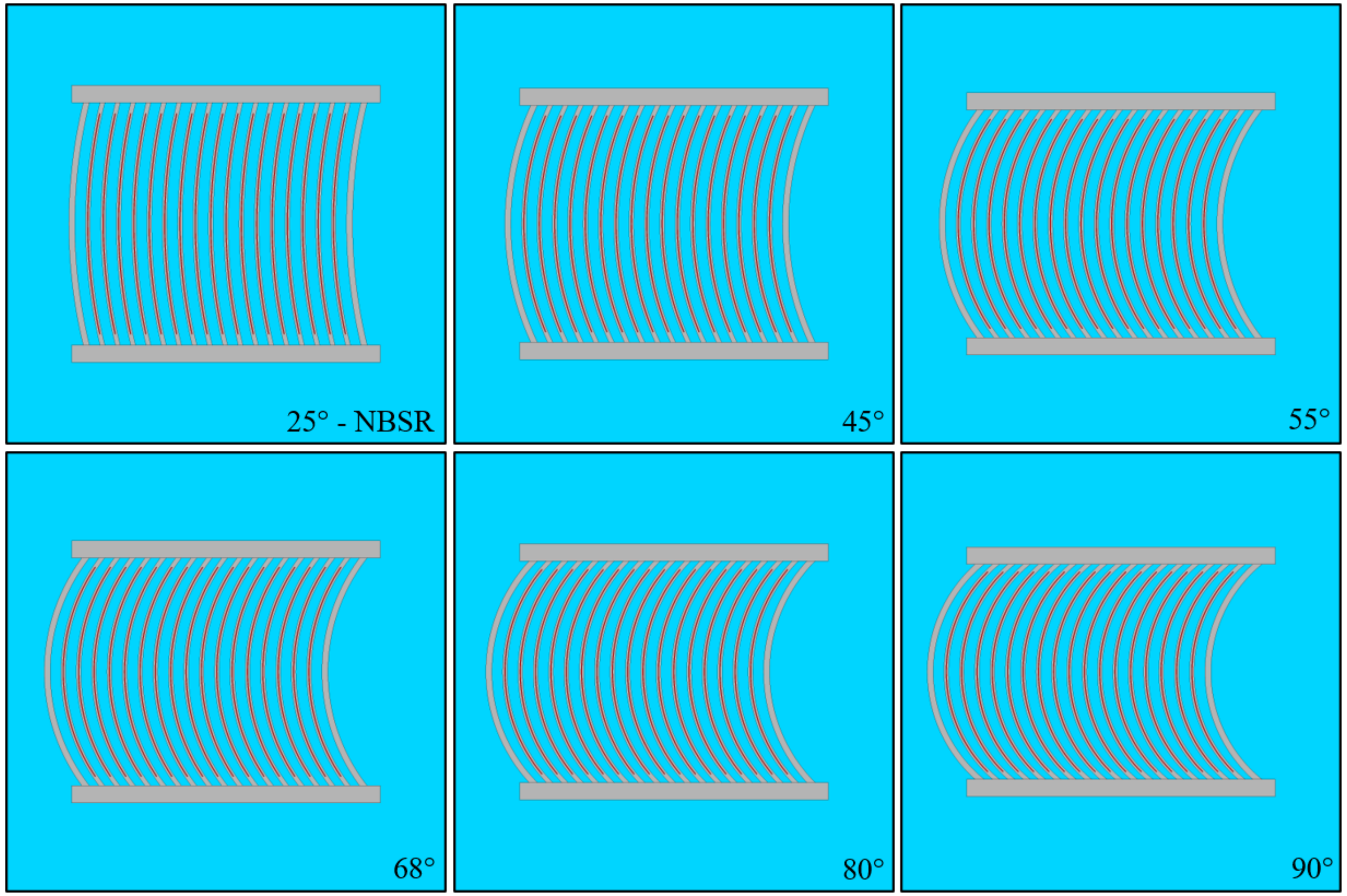


(a) k_{eff} and (b) difference in k_{eff} of the NBSR single-element models through a postulated 30-day fuel cycle (equivalent flat-fuel-plate model - curved-fuel-plate model)

Impact of the Fuel Plate Curvature on the Equivalence Between the Curved-fuel-plate and Equivalent Flat-fuel-plate Models (1)

- To discusses the validity of approaching the equivalence when larger plate curvatures are considered for
  - Current RTR power upgrades
  - Future RTR designs

- Increase in plate curvature realized by shortening the distance between the side plates
  - Coolant channel volumes decreased
  - Volumes of the other components of the fuel elements remained unchanged

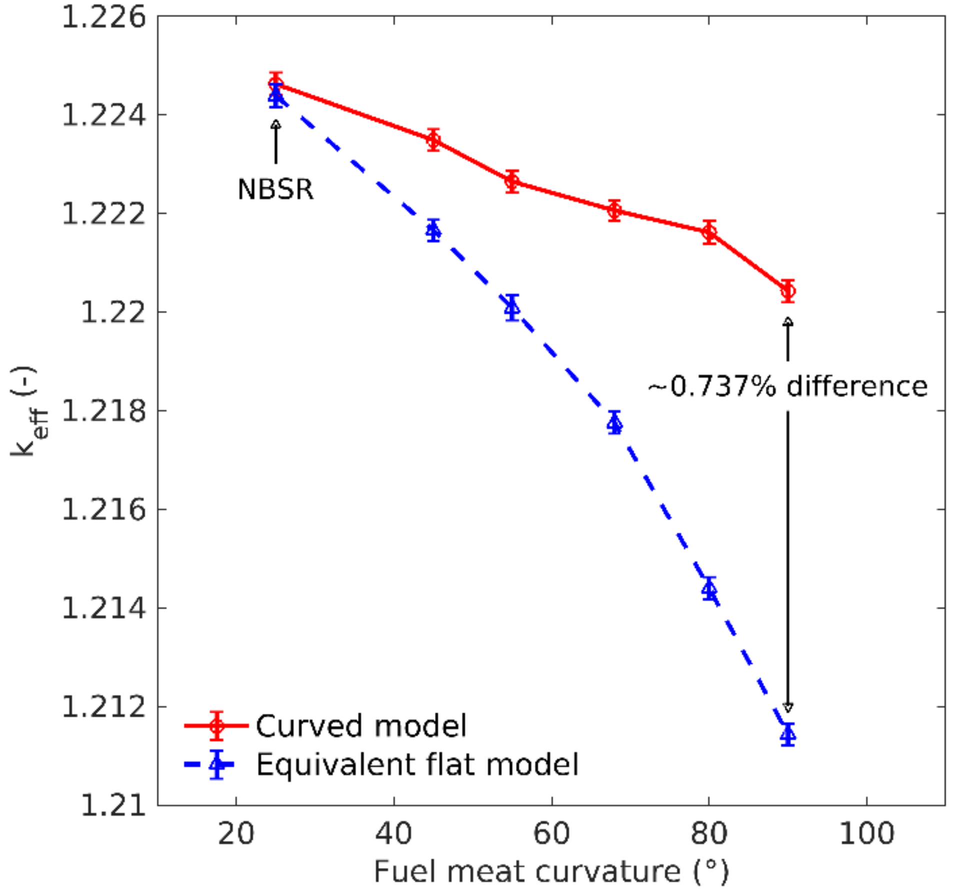


The x-y cross-sectional views of the Serpent 2 models of the six fuel elements with different curvatures

Impact of the Fuel Plate Curvature on the Equivalence Between the Curved-fuel-plate and Equivalent Flat-fuel-plate Models (2)

❖ Findings

- k_{eff} of the 25° fuel element design was approximated within 20 pcm
- 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
- This would be 737 pcm if the 90° curved-fuel-plate model were critical



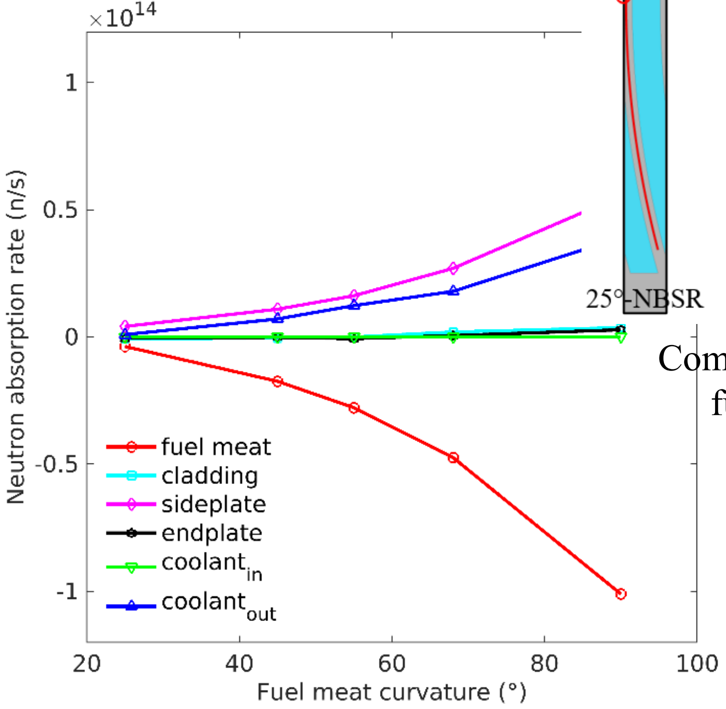
Comparison of the k_{eff} of the curved-fuel-plate models with those of the equivalent flat-fuel-plate models

Impact of the Fuel Plate Curvature on the Equivalence Between the Curved-fuel-plate and Equivalent Flat-fuel-plate Models (3)

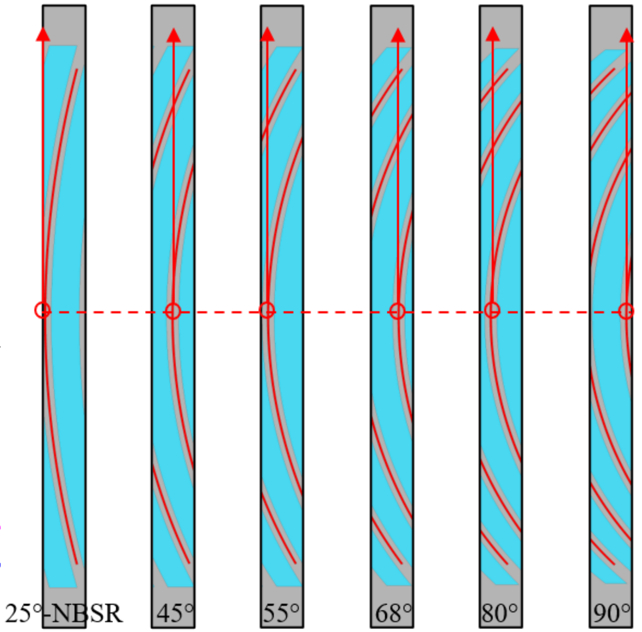
What caused the underprediction??

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



Differences in neutron absorption rate (equivalent flat-fuel-plate model – curved-fuel-plate model)



Comparison of the unit cells of the fuel elements with different curvatures

Summary

- ❖ The equivalence between an NBSR LEU single-element equivalent flat-fuel-plate model and an NBSR LEU single-element curved-fuel-plate model was demonstrated with Serpent 2 and MCNP6.2.
- ❖ Study was extended to cover larger plate curvatures. Findings included
  - ➢ k_{eff} of the 25° fuel element design was approximated within 20 pcm
  - ➢ 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 emphasized the importance of understanding the uncertainties caused by modeling curved fuel plates with equivalent flat fuel plates for neutronic calculations.
- ❖ Plan to build an NBSR LEU whole-core curved-fuel-plate model for future LEU NBSR analysis to reduce the uncertainties in k_{eff} calculations.