Preliminary Modeling and Analysis of Helical Cruciform Fuel in PWRs using RELAP5-3D

INL/MIS-26-92406

05/18/2026 – IRUG 2026, Idaho Falls, Idaho

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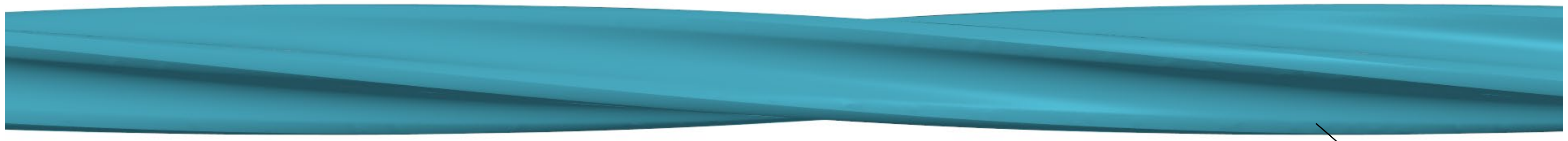
1. Introduction



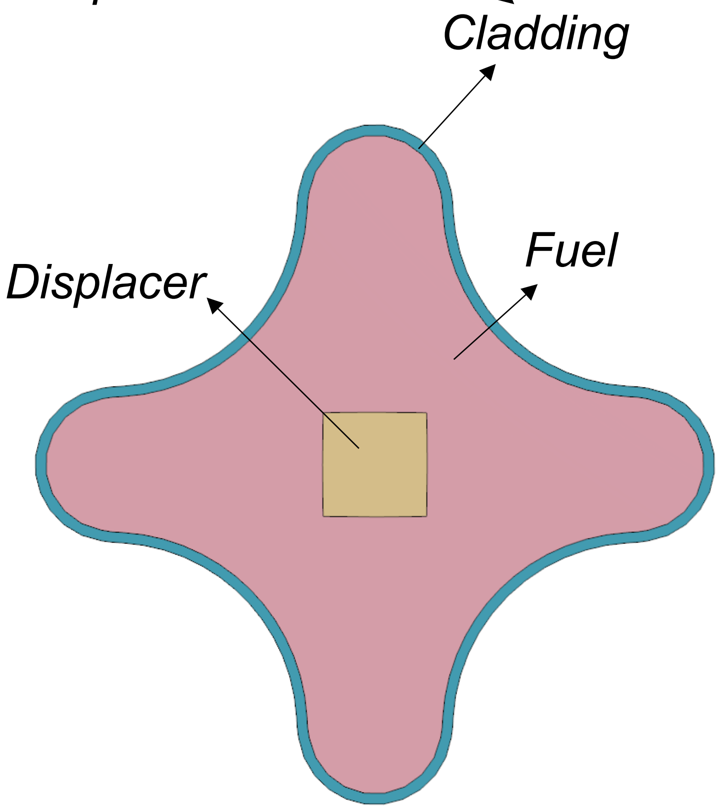
Axial view of a HCF pin

- Helical cruciform fuel (HCF) is being evaluated as an advanced fuel geometry for potential light water reactor (LWR) applications

- Adoption of HCF requires understanding the thermal-hydraulic behavior of the fuel under representative reactor conditions, including DBAs

- The developed surrogate model may support an ongoing Phenomena Identification and Ranking Table (PIRT) activities

- **Objective: develop and assess an equivalent RELAP5-3D HCF model for preliminary PWR analysis**



HCF cross section

2. Development of RELAP5-3D Surrogate for HCF

- RELAP5-3D cannot directly resolve the detailed 3D HCF geometry
- A surrogate representation is developed using equivalent hydraulic and thermal parameters
- The surrogate must preserve the dominant system-level effects relevant to PWR operation, e.g., stored energy, thermal conduction time scales, etc.
- Key modeling aspects:
  - Friction factor / pressure-drop closures
  - Thermal-response representation
- The surrogate is intended for system-level analysis, *not a detailed description*

2.1 Friction Factor Closure

- RELAP5-3D compute pressure drops based on the Darcy-Weisbach equation:

(Vol 1 – 3.3.8)

$$\left(\frac{dP}{dx}\right)_f = \frac{\lambda_f(Re_f)M_f^2}{2D\rho_f A^2}$$

$$Re_f = \frac{\rho_f D v_f}{\mu_f}$$

- The Blasius correlation proves adequate for turbulent regime in HCF

(Vol 4 – 6.1.1)

$$\lambda_f = \frac{0.316}{Re_f^{0.25}}$$

$\frac{dP}{dx}$	Pressure gradient
λ_f	Fluid Friction factor
M_f	Fluid mass transfer rate
D	Hydraulic diameter
ρ_f	Fluid density
A	Cross-sectional area
Re_f	Fluid Reynolds number
v_f	Fluid velocity
μ_f	Dynamic viscosity

2.1 Friction Factor Closure

- Comparison for friction factors (or pressure gradients)

$$\mathrm{MRE} = \frac{1}{\mathrm{N}} \sum \left| \frac{\lambda_{\mathrm{Blasius}} - \lambda_{\mathrm{ref}}}{\lambda_{\mathrm{ref}}} \right|$$

$$\mathrm{MaxRE} = \max \left| \frac{\lambda_{\mathrm{Blasius}} - \lambda_{\mathrm{ref}}}{\lambda_{\mathrm{ref}}} \right|$$

Definitions:

$\lambda_{\mathrm{Blasius}}$ Blasius friction factor

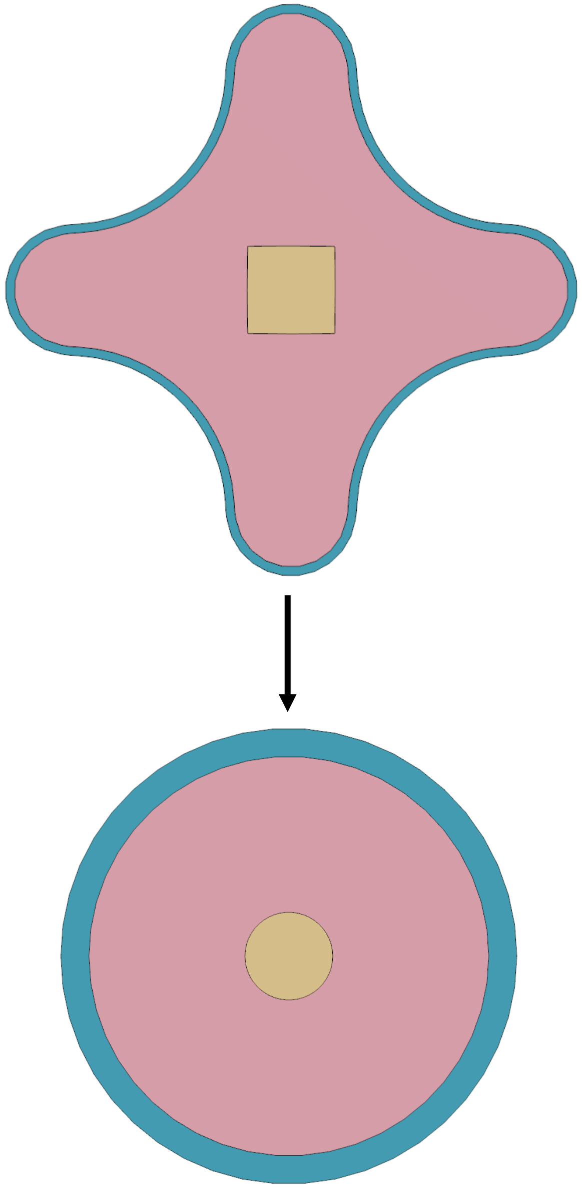
λ_{ref} Friction factor from different references in the literature

Reference	Bundle configuration	MRE (%)	MaxRE (%)
Kinsky et al. (2025)	Square 9x9	7.1	7.3
Zhang et al. (2025)	Square 4x4	0.2	0.5
Conboy et al. (2013)	Square 4x4	2.7	2.7
Tang et al. (2023)	Square 3x3	0.3	0.7

Results consider the range of $16{,}210 \leq \mathrm{Re} \leq 50{,}000$

2.2 Heat Transfer Modeling

- An equivalent pin model preserve key HCF thermal characteristics
- The surrogate model maintains consistency in both heat **structure volume** and **heat transfer area**
- Cards **1CCCG101** through **1CCCG199** ensures **consistent volumes** through radial discretization
- Cards **1CCCG601** through **1CCCG699** ensure consistent **heat transfer area**
- The surrogate thermal response is evaluated against a full 3D heat-conduction model of the HCF geometry



3. Test Case and Simulation Details

PWR Steady-State Operation at Full Power

Parameter	Value/Note	Unit
Power	2,300	MWth
Core mass flow rate	12,586	kg/s
Active fuel length	3.86	m
Fuel lattice	Square	-
# Subchannels	32,000	-

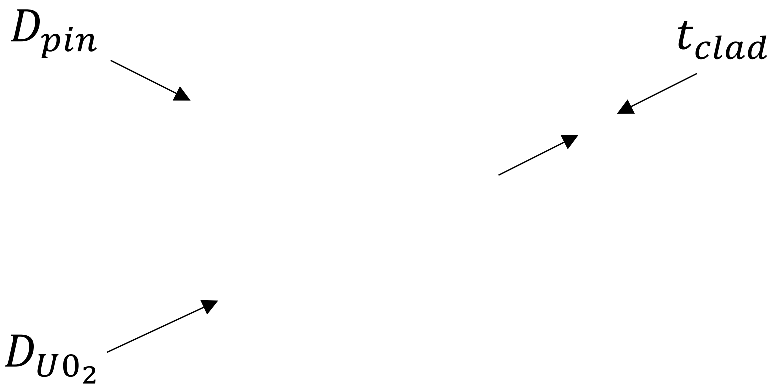
3. Test Case and Simulation Details

Simulated cases

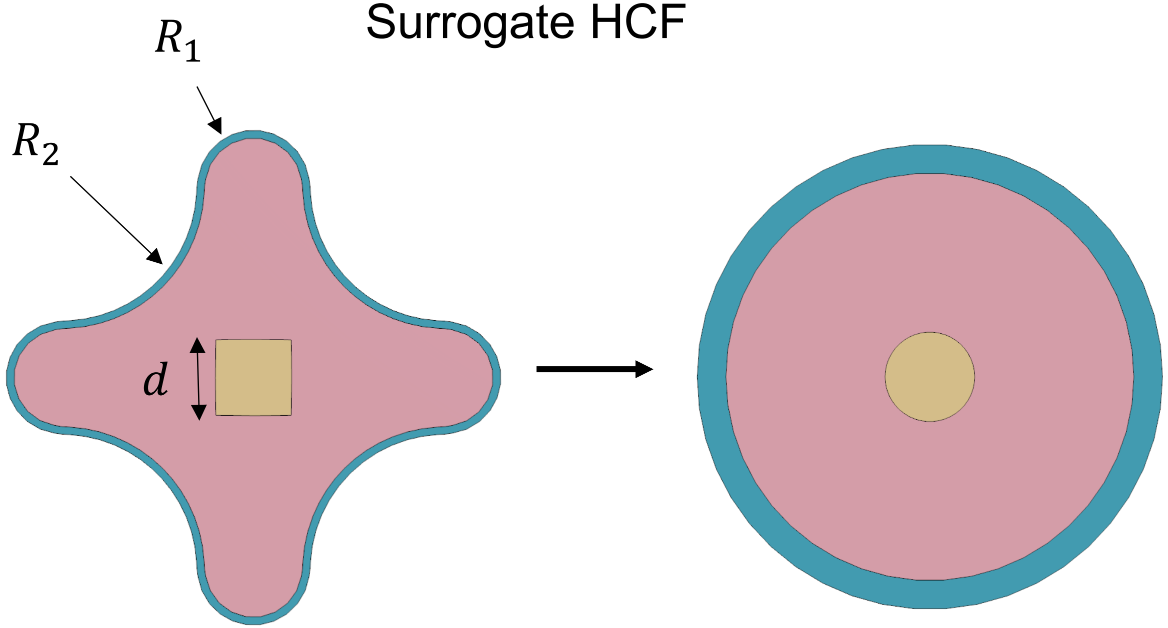
Case	Analysis tool	Description	Goal
Baseline pin fuel	RELAP5-3D	Reference PWR core with conventional UO_2 fuel	Compare the conventional pin fuel with the HCF in a full power PWR operation
Surrogate HCF	RELAP5-3D	Reference PWR core with the HCF surrogate fuel model	
Full 3D HCF	STAR-CCM+	Full 3D HCF using boundary conditions from the Surrogate HCF case for surrogate assessment	Validation – check the adequacy of the HCF surrogate approach

3. Test Case and Simulation Details

Baseline pin fuel



Surrogate HCF



D_{pin}	Pin diameter	$10.8\ mm$
D_{UO_2}	Fuel diameter	$9.0\ mm$
t_{clad}	Cladding thickness	$0.8\ mm$
k_{UO_2}	UO_2 thermal conductivity	MATPRO

R_1	Lobe radius	$1.5\ mm$
R_2	Valley radius	$3.6\ mm$
d	Displacer side	$2.0\ mm$
k_{U-Zr}	U-Zr thermal conductivity	$= 3 \times k_{UO_2}$ Chen & Bai (2018)

* *The HCF geometry may include other geometric parameters not consider in this work.*

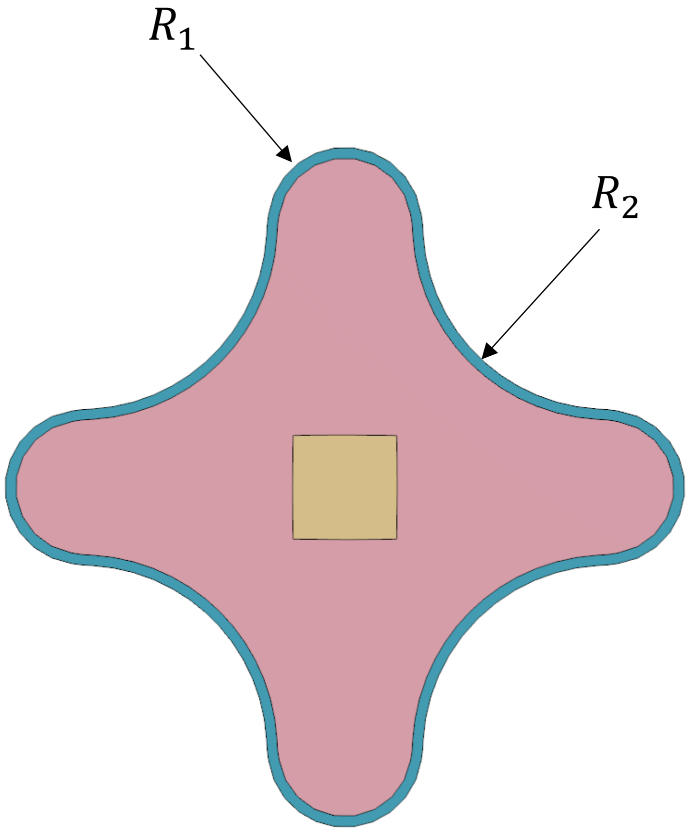
3. Test Case and Simulation Details

- Lobe and valley radii were conveniently selected
- HCF cross-sectional area matches the reference UO_2 pin:

$$4\frac{4\pi R_1^2 + 4(R_1+R_2)^2 - \pi R_2^2}{\pi D^2} \approx 1.0$$

- Subchannel areas are also the same
- HCF wetted perimeter increases:

$$\frac{4\pi R_1 + 2\pi R_2}{\pi D} \approx 1.22$$

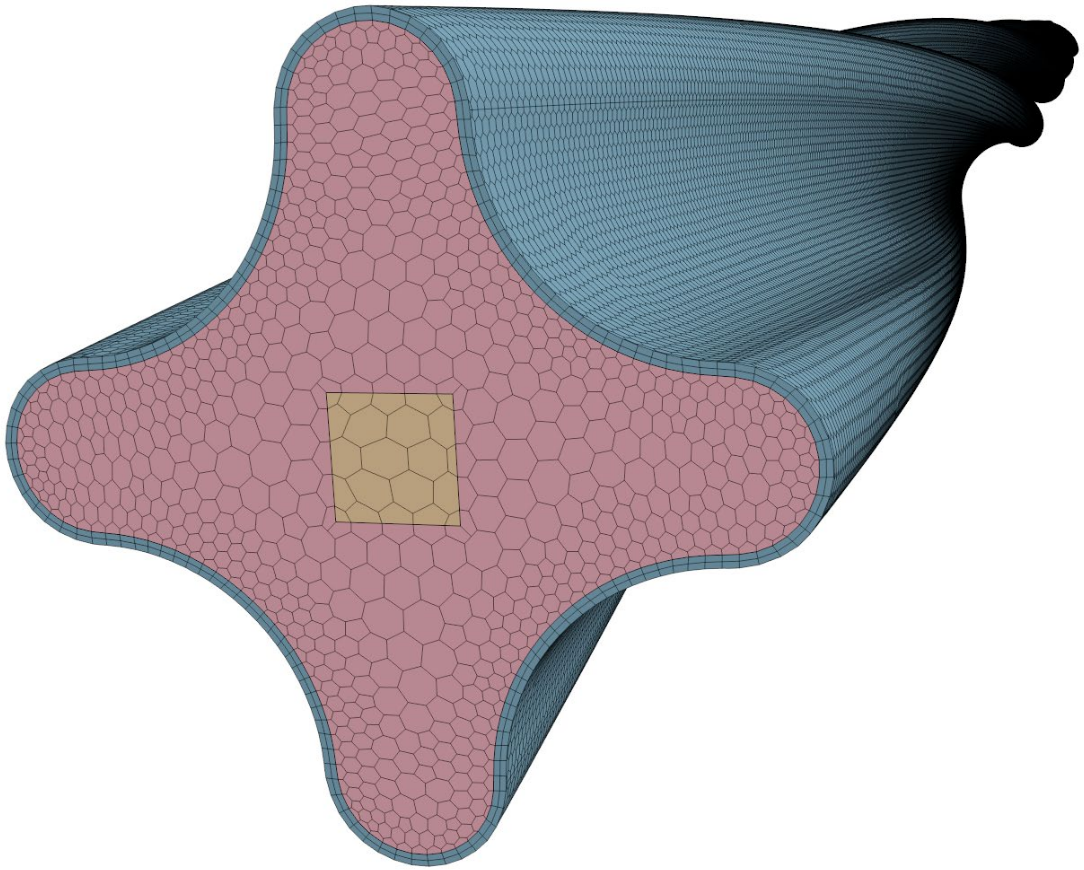


R_1 lobe radius

R_2 valley radius

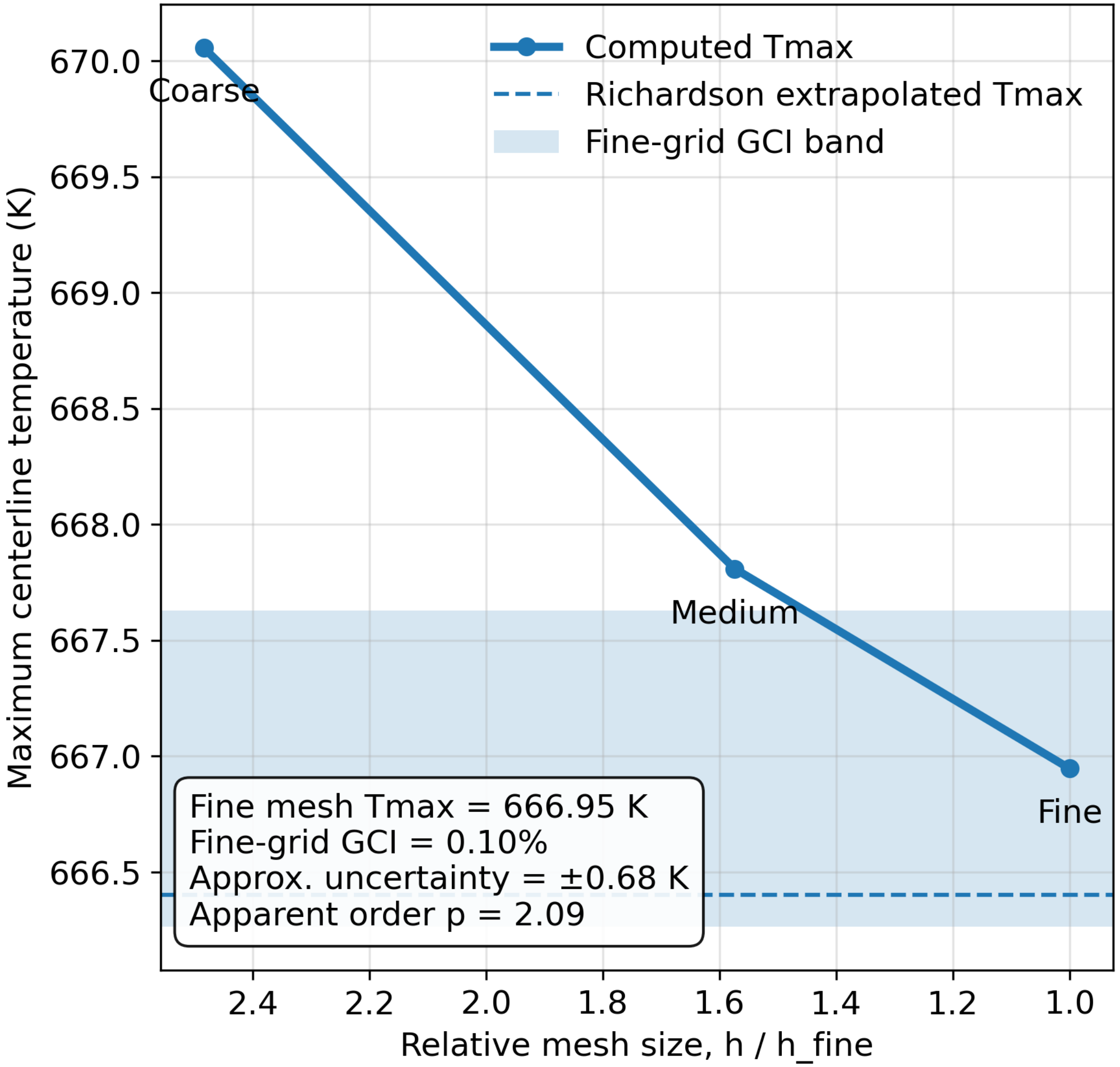
3. Test Case and Simulation Details

- A full 3D HCF model was developed in STAR-CCM+ to validate the surrogate model temperature solution
- Surrogate-model surface temperatures were imposed on the 3D HCF model (only within the fuel domain)
- The 3D HCF model uses the same total power as the surrogate model
- Mesh convergence points to negligible result changes beyond ~13 million elements



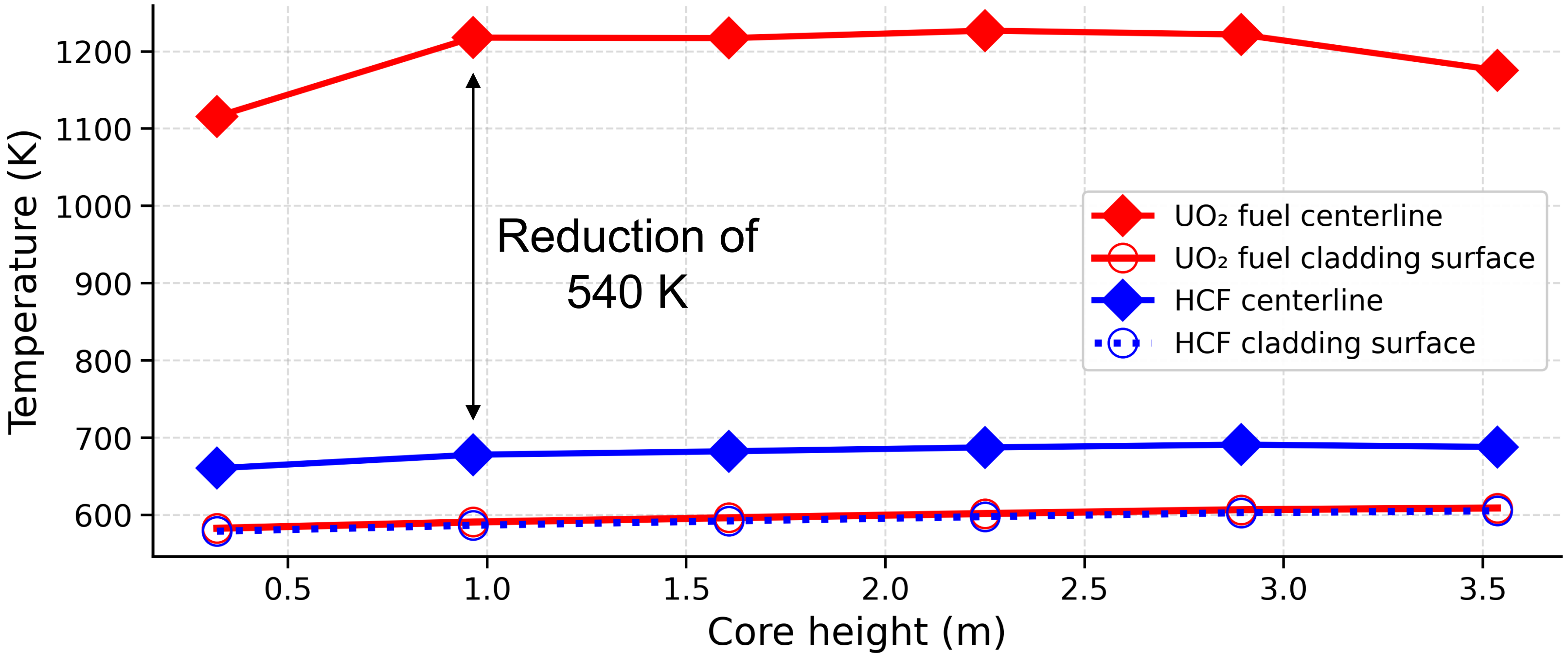
3. Test Case and Simulation Details

- The mesh refinement study confirms the solution is in the asymptotic range, with a marginal discrepancy from the Richardson-extrapolated value
- The fine mesh provides sufficient accuracy for this work while avoiding the added cost of tens-of-millions-cell meshes
- Mesh sizes:
  - Coarse: 0.88M elements
  - Medium: 3.44M elements
  - Fine: 13.4M elements

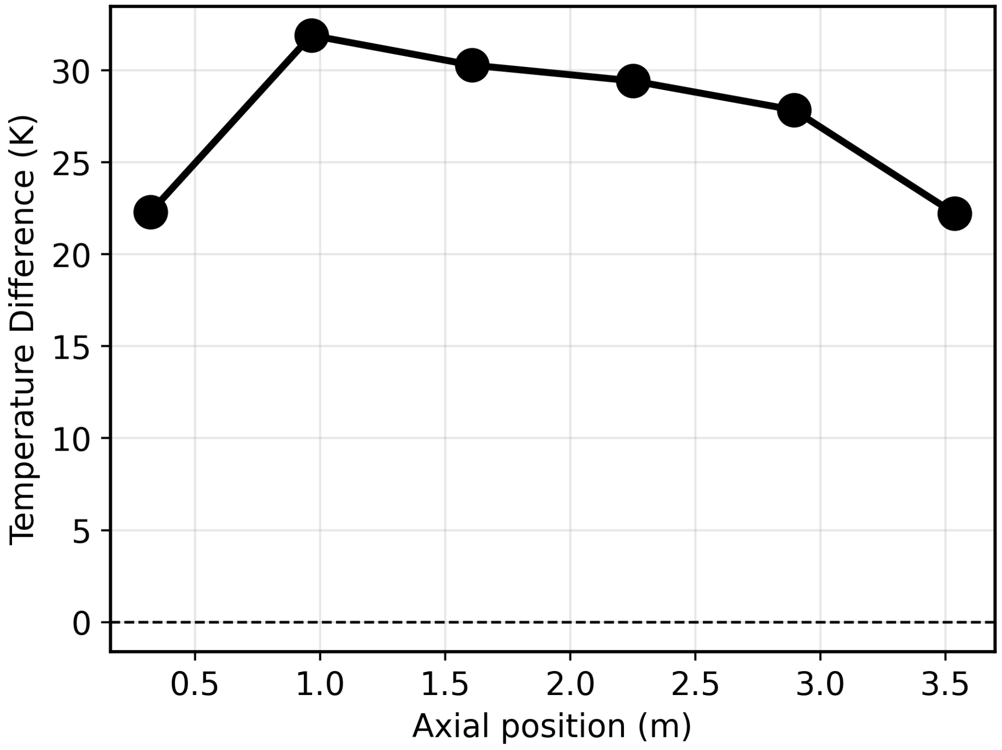


4. Results: Baseline pin fuel vs. Surrogate HCF

- Centerline axial temperature compared under reference normal-operation conditions
- Evaluation focuses on replacing cylindrical UO_2 fuel with the HCF surrogate
- Results showcase the thermal impact of the HCF surrogate replacement



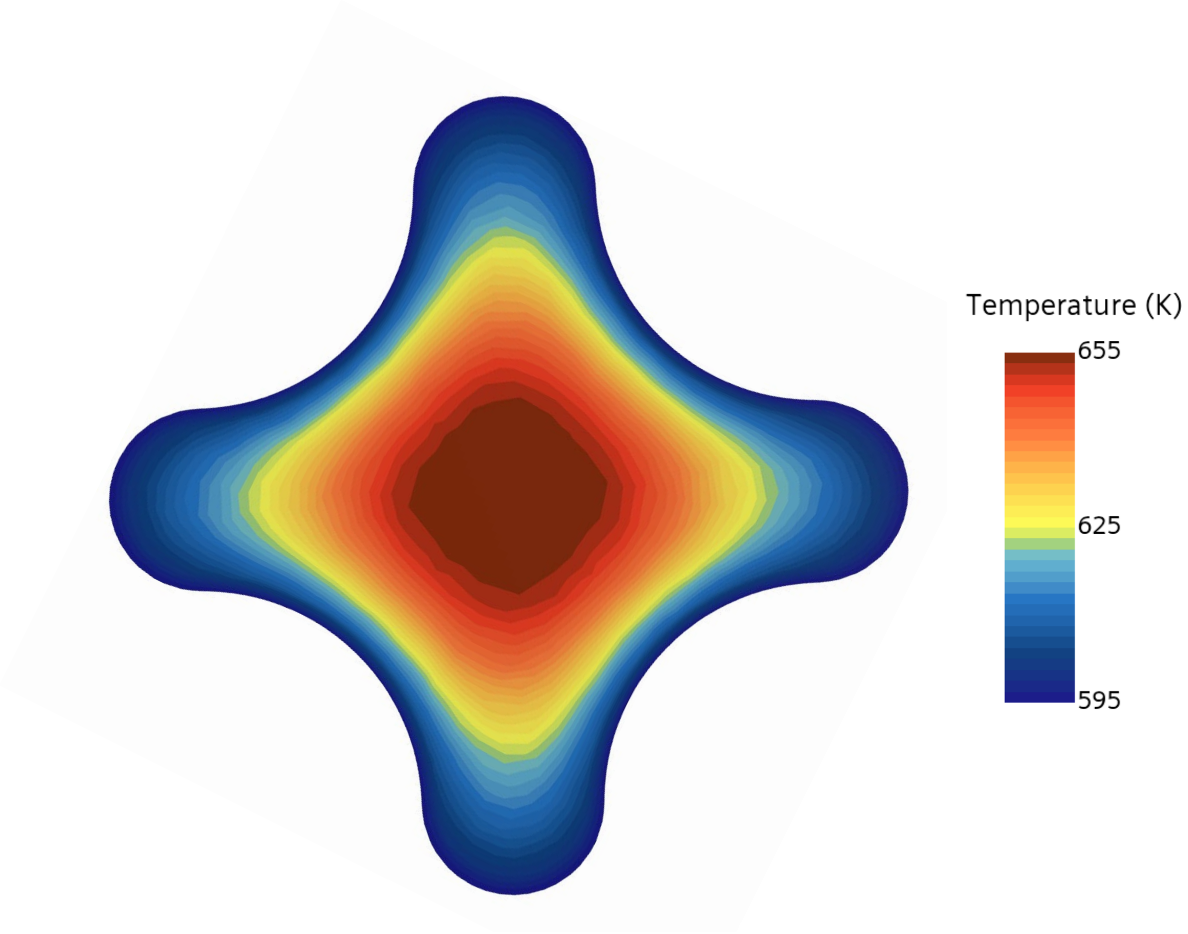
4. Results: Validation Against Full 3D HCF



Temperature difference:
Surrogate – 3D HCF

Maximum absolute error: 31.9 K

Mean absolute error: 27.3 K



Temperature contour on mid section of the HCF

Conclusion and Ongoing Work

Conclusions:

- HCF fuel reduces peak centerline temperature by 540 K compared with conventional UO_2 fuel
- HCF surrogate agrees well with the full 3D heat conduction model, with a difference of ~30 K
- The Blasius correlation proves to adequately capture pressure drops in HCF geometries
- Current results support the surrogate approach for efficient HCF thermal-hydraulic analysis

Ongoing Work:

- Perform sensitivity analysis on key thermal, geometric, and material parameters
- Extend the work to LOCA conditions
- Assess surrogate accuracy and HCF performance under transient accident scenarios

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