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3D Finite Element Analysis of Thermal-Mechanical Behavior in Helical Cruciform Fuel

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1. Introduction

The Helical Cruciform Fuel (HCF) is emerging topic in next-generation metallic fuels due to its superior thermal-hydraulic performance and self-supporting structure. With the increasing demand for Small Modular Reactors (SMRs) requiring high power density, the Lightbridge-type HCF concept has been revisited as a proven technological benchmark. Previous studies on these HCF designs highlight their ability to accommodate significant volumetric swelling while maintaining flow area stability.

In this study, 3D finite element analysis (FEA) was conducted to investigate the burnup-dependent thermo-mechanical behavior of HCF fabricated from U-10Mo, U-10Zr, and U-50Zr alloys. A merged fuel–cladding model was developed to capture coupled thermo-mechanical responses and irradiation-induced deformation. The numerical framework was validated against the BISON fuel performance code under representative operating conditions.

Among the candidate alloys, U-50Zr received particular focus due to its enhanced phase stability and irradiation tolerance at high temperature and burnup. U-50Zr exhibited the most stable mechanical response under high-burnup conditions, suggesting its superior suitability for long-cycle SMR operations. Its performance was evaluated in comparison with U-10Mo and U-10Zr to assess its suitability for high–power-density HCF applications. The results demonstrate the feasibility of HCF for advanced reactor systems.

2. Methods and Results

2.1 FEA Model Setup and ABAQUS Input Generation

This study aims to evaluate 3D HCF Modeling performance analysis using different metallic fuel alloys based on the ABAQUS^{TM} framework .

The material properties used in the simulation—including Young's modulus, Poisson's ratio, thermal conductivity, specific heat capacity, swelling behavior, and thermal expansion coefficient—were adopted from the models described in the BISON Theory Manual and supplemented by experimental measurement data from Idaho National Laboratory [1].

2.2 Modeling and Constructing Boundary Conditions

HCF 3D model's geometry and mesh structure are shown in Fig.1. The geometrical parameters of HCF follow the methodology established in previous research [2]. In this model, perfect contact between the fuel and cladding was assumed without considering the initial gap.The HCF model was constructed with a rod length of 0.5 m and twisted pitch (H) of 0.56 m .

Periodic behavior between adjacent fuel was assumed by constraining selected 4 nodes at 0.25H and 0.5H intervals in the x,y directions [3]. At the bottom, displacements in the x,y,z directions were fixed to zero, while at the top, displacements in the x, y directions were fixed to zero. On the outer surface of the cladding, a convective boundary condition and an external pressure boundary condition were applied. The convective condition used a heat transfer coefficient to account for coolant heat removal based on the previous research [2]. The linear power profile was obtained from previous research, starting at an initial 20 kW/m and decreasing to 14 kW/m at the end of life [4].

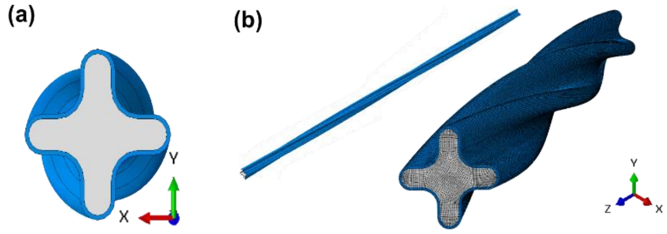

Figure 1 HCF 3D model (a) x-y cross-section area, and (b) 3D mesh structure

2.3 Calculation results

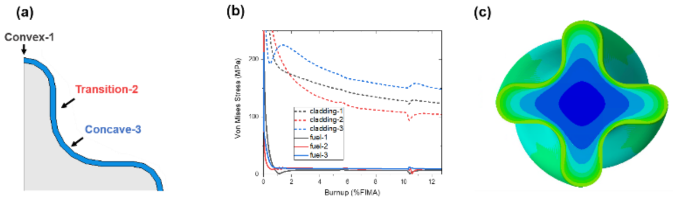

Figure 2 HCF fuel and cladding (a) geometry positions, (b) Von Mises Stress history depending on the position, and (c) Von Mises stress distribution at the bottom surface.

Fig. 2 (a) shows the geometric positions of the HCF fuel. As shown in Fig. 2 (b), the high initial stress generated during the early stages of irradiation were found to undergo significant relaxation over FIMA (Fissions per Initial Metal Atom), primarily driven by the irradiation-induced creep of both the fuel and cladding. In terms of stress magnitude, the cladding exhibits a range of 100–200 MPa, whereas the fuel remains at a significantly lower level of 0–15 MPa. As fuel swelling progresses, mechanical interaction transfers stress from the fuel to the cladding, leading to a localized concentration in the concave region. Consequently, as shown in Fig. 2 (c), the cladding stress increases, forming a characteristic diamond-shaped distribution.

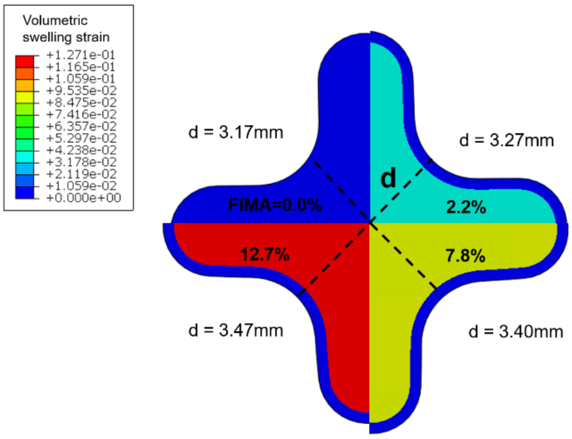

Figure 3 Volumetric swelling strain and distance from center to concave profile depending on the burnup

The morphologic evolution of the HCF cross-section at the axial position of Z = 0.25 as a function of burnup is illustrated in Fig. 4. To quantify the geometric stability of the HCF design, the radial distance from the fuel center to the concave region was monitored across increasing FIMA levels. As burnup increases, the concave regions move outward, demonstrating the self-swelling accommodating shape of the HCF. Unlike conventional cylindrical pins that exert direct radial expansion from isotropic swelling, the HCF's multi-lobed shape acts as an internal buffer for volumetric expansion. This allows the fuel to reach 13% FIMA with minimal external deformation, ensuring structural stability at high burnup.

3. Conclusion

The 3D computational analysis confirms that the enhanced surface-to-volume ratio of the HCF significantly mitigates the fuel centerline temperature. Specifically, the results demonstrate that the fuel temperature remains well below the solidus line of the U-50Zr alloy even under high-burnup conditions (~13% FIMA). Furthermore, the HCF exhibits excellent geometric stability because its unique shape acts as a buffer for swelling, allowing the HCF to maintain geometric stability without significant deformation. This combined thermal and structural performance provides a substantial safety margin against fuel melting and mechanical degradation, validating the HCF design as a future fuel candidate.

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REFERENCES

[1] Beausoleil, G. L., Cinbiz, M. N., Yao, T., Wang, Y., Di Lemma, F. G., Adkins, C. A., Pavlov, T. R., Song, R., Capriotti, L., & Williams, W. J. (2021). *U-50Zr Microstructure and Property Assessment for LWR Applications*. https://doi.org/10.2172/1825221.

[2] Hou, Y., Dong, Y., Gao, C., Chen, B., Zhang, C., Li, W., & Xiang, Y. (2024). U-50Zr helical cruciform fuel performance analysis based on MOOSE framework. *Annals of Nuclear Energy*, *204*, 110529. https://doi.org/10.1016/j.anucene.2024.110529

[3] Cai, M., Cong, T., Xiao, Y., & Gu, H. (2023). Preliminary Thermal-Mechanical coupled modeling of U-10Mo helical cruciform fuel rods under the unirradiated and irradiated conditions. *Annals of NuclearEnergy*,*181*,109532.https://doi.org/10.1016/j.anucene.2022.109532

[4] Deng, Y., Shirvan, K., Wu, Y., & Su, G. (2019). Utilization of 3D fuel modeling capability of BISON to derive new insights in performance of advanced PWR fuel concepts. *Journal of Nuclear Materials, 516*,271–288. https://doi.org/10.1016/j.jnucmat.2019,01,032,