SAFETY AND THERMO-MECHANICAL PERFORMANCE OF METALLIC HELICAL CRUCIFORM FUEL IN LIGHT-WATER COOLED SMALL MODULAR REACTORS

Y. CHOI, K. SHIRVAN

Department of Nuclear Science and Engineering, Massachusetts Institute of Technology

77 Massachusetts Ave, 02139 Cambridge MA – United States of America

Summary

This study explores the safety and thermo-mechanical performance of metallic helical cruciform fuel (HCF), a.k.a. Lightbridge Fuel, for the NuScale VOYGR SMR. Key points include:

1. **Safety Performance**:
    - **CFD Simulations**: HCF channels show lower critical heat flux (CHF) and wall temperatures, indicating better heat removal and potential for power uprate.
    - **DNB Assessment**: HCF channels have a higher minimum departure from nucleate boiling ratio (MDNBR), suggesting improved safety margins.
2. **Thermo-Mechanical Performance**:
    - **Finite Element Analysis**: HCF exhibits lower operating temperatures but higher cladding stress due to the high thermal conductivity and volumetric swelling of metallic fuel.
    - **Model Sensitivity**: The study highlights the need for accurate models for Zr-rich fuels, particularly for plasticity, creep, and swelling.
3. **Comparative Analysis**: HCF shows significantly lower peak fuel temperatures but higher cladding stress compared to conventional UO2 cylindrical fuel.
4. **Future Work**: Further studies will focus on contact mechanics, multi-rod modeling, and coupling CFD with fuel performance codes to address structural integrity and coolant blockage due to fuel swelling.

The study is supported by the U.S. Department of Energy and utilizes advanced simulation tools like STAR-CCM+ and BISON.

What are the key findings from the safety performance study?

The key findings from the safety performance study are:

1. **Heat Removal Capability**: HCF channels demonstrate better heat removal capability, evidenced by lower exit void fractions and lower wall temperatures compared to cylindrical fuel channels.
2. **Critical Heat Flux (CHF)**: HCF channels show a lower CHF, indicating a higher margin for power uprate under the same power and flow conditions.
3. **Departure from Nucleate Boiling Ratio (DNBR)**: HCF channels have a higher minimum DNBR (MDNBR) compared to cylindrical fuel channels, suggesting improved safety margins. Specifically, HCF channels achieved an MDNBR of 1.60, while cylindrical channels had an MDNBR of 1.34.
4. **Flow Mixing**: The twisted geometry of HCF enhances flow mixing, which improves heat transfer from the fuel surface.

These findings suggest that HCF geometry can potentially allow for power uprate while maintaining or improving safety performance compared to conventional cylindrical fuel geometry.

What are the main advantages of HCF over cylindrical fuel?

The main advantages of Helical Cruciform Fuel (HCF) over cylindrical fuel are:

1. **Increased Heat Transfer Area**: HCF has a 35% larger heat transfer area, which enhances heat removal efficiency.
2. **Lower Operating Temperature**: Due to the high thermal conductivity of the U-50Zr alloy, HCF operates at a lower temperature, reducing the mobility of fission gases and improving fuel performance.
3. **Higher Critical Heat Flux (CHF) Margin**: The larger heat transfer area and improved flow mixing in HCF channels result in a higher CHF margin, allowing for potential power uprate.
4. **Self-spacing Design**: HCF rods support each other at every twist pitch, eliminating the need for spacer grids and reducing pressure drop.
5. **Reduced Irradiation-induced Swelling**: The higher zirconium content in HCF reduces swelling and the likelihood of fission gas release compared to U-rich U-Zr alloys.
6. **Lower CRUD Formation**: Lower wall temperatures and void fractions in HCF channels imply less CRUD (Chalk River Unidentified Deposits) formation.

These advantages make HCF a promising option for improving the performance and safety of small modular reactors (SMRs).

What are the safety benefits of HCF's lower operating temperature?

The safety benefits of HCF's lower operating temperature include:

1. **Reduced Fission Gas Release**: At lower operating temperatures, fission gases behave more like solid fission products, significantly reducing their mobility and the likelihood of gas release, which can improve fuel integrity and performance.
2. **Lower Cladding Stress**: Lower temperatures reduce thermal expansion and associated stresses on the cladding, enhancing the structural integrity of the fuel rod.
3. **Decreased CRUD Formation**: Lower wall temperatures result in less formation of CRUD (Chalk River Unidentified Deposits), which can improve heat transfer efficiency and reduce the risk of localized corrosion and other operational issues.
4. **Enhanced Safety Margins**: Lower operating temperatures contribute to higher critical heat flux (CHF) margins, allowing for safer operation under higher power conditions and reducing the risk of boiling crises.
5. **Improved Fuel Longevity**: Reduced thermal stresses and lower fission gas release rates can extend the operational life of the fuel, contributing to overall reactor safety and efficiency.

These benefits collectively enhance the safety and reliability of reactors using HCF, making it a favorable option for small modular reactors (SMRs).