Thermal-Structural Analysis of a Heat Pipe Reactor Core Monolith: A 2D Finite Element Study

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1. Introduction

Heatpipe Reactors (HPRs) utilize a solid monolithic core where heat from fuel pins is conducted through thin metallic webs to adjacent liquid-metal heat pipes, and severe thermal gradients at high operating temperatures induce significant thermal stresses in these thin webs.

As HPRs gain renewed interest for remote, off-grid, and space power applications, licensing-ready structural verification methodologies are increasingly needed; however, the thermo-structural behavior of the sub-millimeter-scale webs separating fuel and heat pipe channels remains insufficiently characterized in the open literature, particularly under postulated heat pipe failure conditions where localized loss of cooling can substantially redistribute the stress field. To help close this gap and establish a regulatory verification database for liquid-metal HPRs, this study evaluates the temperature distribution, thermal expansion, and thermo-structural integrity of an HPR core monolith under nominal operating conditions using a 2D ABAQUS finite element model, with a full-height 3D sector geometry currently under development to extend this evaluation to axial and multi-axial effects.

2. Description of the Numerical Work

2.1 Core Geometry and 2D FEA Modeling

Based on the Megapower-type fast reactor, a 60° rotational symmetry sector containing 352 fuel channels and 204 potassium heat pipe channels within an SS 316 monolith was modeled. The pitch is 1.6 cm between heat pipes and fuel channels, and 2.7713 cm between adjacent fuel channels. A 2D planar model, representing a radial cross-section of the active monolith region, was established to evaluate radial temperature gradients and in-plane stress concentrations across the webbing.

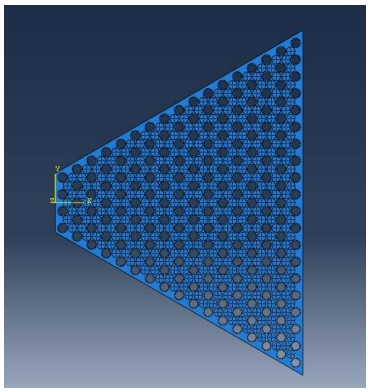


Fig 1. 2D planar model

A full-height 3D sector geometry - stacking the bottom plate (0.5 cm), gas plenum (20 cm), lower reflector (15 cm), active monolith (150 cm), and upper reflector (15 cm) – has been constructed to support future evaluation of axial elongation and 3D heat redistribution. Structural and thermal analysis using this 3D model has not yet been performed and is planned as a subsequent phase of this work.

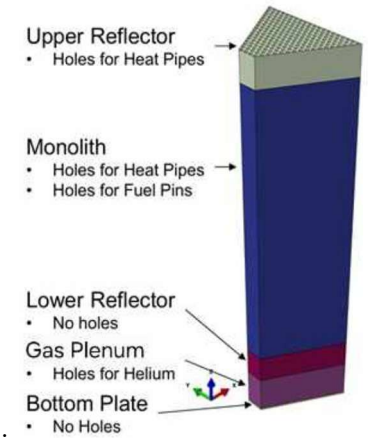


Fig 2. 3Dfull-height sector model schematic

2.2 Material Properties and Boundary Conditions

Temperature-dependent properties for SS 316 and UO_2 (19.75 wt% U-235) were applied based on ASME BPVC Section II, Part D. For steady-state thermal analysis, an isothermal condition of 677°C was prescribed at the heat pipe inner surfaces and core boundary, while volumetric fission heat rates were mapped onto the fuel mesh with adiabatic external

boundaries. Mechanical boundary conditions allowed free thermal expansion.

The finite element analysis was performed using ABAQUS/Standard (2025). For the steady-state thermal analysis, the 2D sector model was discretized using DC2D4 (4-node linear heat transfer quadrilateral) elements, comprising 156,914 elements (131,634 user-defined and tied elements plus 25,280 internally generated contact elements) and 187,792 nodes. The same mesh was subsequently converted to the corresponding structural element type for the thermal-stress analysis.

3. Results

3.1 Thermal Analysis

The 2D steady-state thermal analysis yielded a peak fuel centerline temperature of 753°C and a maximum monolith temperature of 696°C under the 677°C heat pipe boundary.

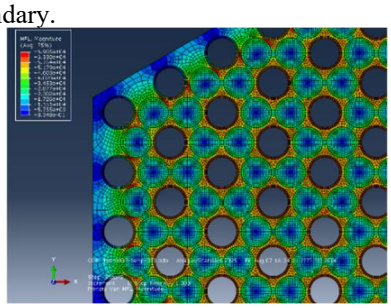


Fig. 3 – Steady-state temperature distribution, NT11

The heat flux distribution peaked at 6.905×10^4 W/m^2, showing symmetric radial heat removal from fuel pins through the thin monolith webbing to the heat pipes.

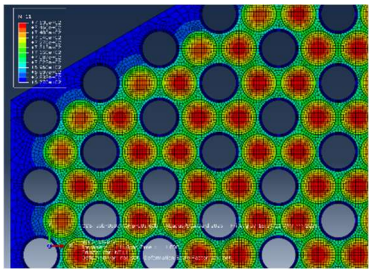


Fig. 4 – Heat flux magnitude distribution, HFL

3.2 Structural Analysis

The 2D structural analysis revealed that maximum von Mises stresses (110–210 MPa) concentrated at the narrow web ligaments between fuel and heat pipe channels. This stress range is higher than the reference level (37.1 MPa)[1] due to the over-constraint of the 2D planar setup, which restricts axial strain relaxation and overestimates contact pressures at the helium gaps. To resolve these planar constraints and capture multi-axial stress redistribution, the full-height 3D sector model is currently being developed.

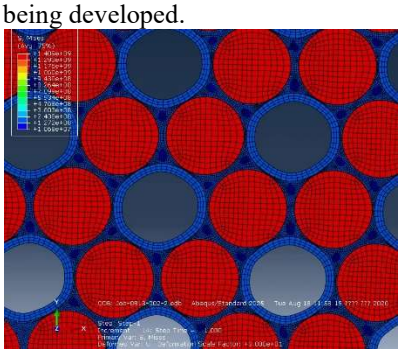


Fig. 5 – Von Mises stress distribution (S, Mises)

4. Conclusions

This study established an ABAQUS FEA framework for the thermal and structural assessment of an HPR monolithic core. The 2D thermal analysis derived a peak fuel temperature of 753°C and heat flux of 6.905×10^4 W/m^2. The 2D structural analysis identified stress concentration zones across the thin webbing (110–210 MPa) and clarified planar over-constraint mechanisms. A full-height 3D sector model is being constructed to resolve these constraints and provide realistic multi-axial stress fields for future failure evaluations.

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