DETERMINATION OF CARBIDE FUEL MAXIMAL BURNUP FOR ALLEGRO GAS COOLED FAST REACTOR

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The presented work focuses on determination of the maximum allowable burn-up of mixed uranium-plutonium carbide fuel (U,Pu)C in a SiC/SiC_f cladding used in Gas-Cooled Fast Reactors (GFRs), a promising concept among the Generation IV nuclear reactor designs. GFRs, characterized by their use of fast neutron spectrum and helium as a gaseous coolant, offer potential advantages in terms of sustainability, safety, and the efficient use of nuclear fuel resources. Their development, however, is challenged by the immense demands placed on fuel and structural materials, particularly due to high operation temperature and irradiation conditions.

1. METHODOLOGY

To assess the maximum acceptable burn-up, a simulation-based approach was employed. The TRANSURANUS fuel performance code, widely utilized for modelling the thermo-mechanical behaviour of nuclear fuel, was used to analyse a representative fuel rod, with its parameters detailed in Table 1. The fuel rod was discretized into 20 axial nodes, 19 of which had the same height. The irradiation conditions, outlined in Table 2, were chosen to ensure that the coolant outlet temperature reached the nominal 850 °C at the start of the simulation. The corresponding LHR and fast neutron flux distributions along the rod are illustrated in Fig 1.

TABLE 1. MODEL FUEL ROD PARAMETERS

Parameter	Value	Parameter	Value
Pellet radius [mm]	3,57	Fuel stack height [mm]	860
Inner cladding radius [mm]	3,7	Fuel rod plenum height	50
Outer cladding radius [mm]	4,5	Initial fuel porosity [%]	5
Pellet surface roughness [mm]	10^{-3}	Fuel rod filling gas pressure [MPa]	1
Inner cladding surface roughness [mm]	$3 \cdot 10^{-3}$	Gas temperature at filling [°C]	20
Pellet dishing volume fraction [% vol.]	1	Fuel ^{235}U enrichment [% w]	0,7
Fuel mean grain size [mm]	0,01	Fuel ^{235}Pu enrichment [% w]	25

TABLE 2. SIMULATED IRRADIATION CONDITIONS

Parameter	Value
Coolant pressure [MPa]	7
Linear heat rate [kW/m]	10,8
Fast (>1 MeV) neutron flux [$cm^{-2}s^{-1}$]	$1{,}03 \cdot 10^{15}$
Channel mass flow rate [g/h]	13760
Inlet coolant temperature [°C]	400
Fuel rod pitch [mm]	11

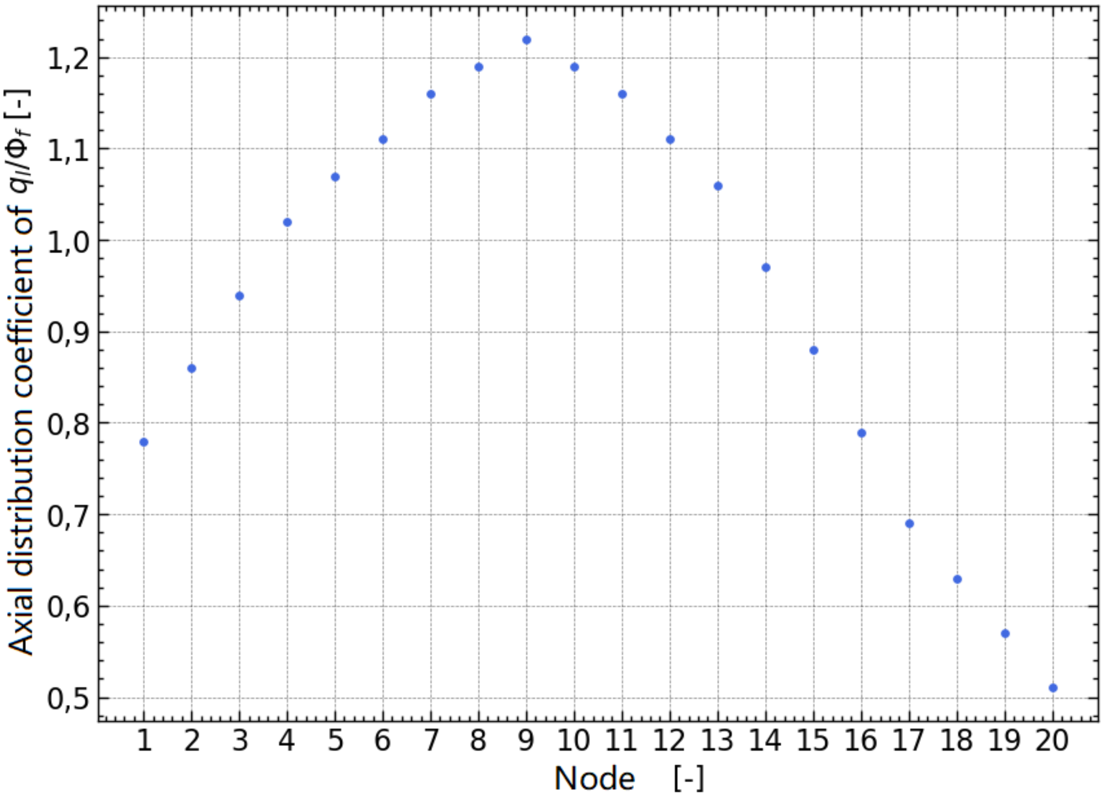

FIG. 1. Axial distribution of LHR/Fast neutron flux in the model fuel rod during irradiation

The evaluation of the simulation results focused on four key limiting parameters, derived from fuel safety guidelines summarized by the OECD [1] and the design criteria for EM^2 reactor fuel based on NRC recommendations [2]. These four limiting parameters are as follows:

- Fuel melting temperature
- Maximum allowable operation cladding temperature
- Internal fill gas pressure
- Cladding stress (axial/hoop stress)

Whereas in the case of the fill gas pressure, the limiting value was determined by the pressure of the coolant, based on [1], exact values for other limiting parameters were found in the open literature. The fuel melting temperature was found in [3]. The maximum allowable operation cladding temperature was, in accordance with [2], considered equal to the temperature of thermal dissociation of SiC, as provided by [2]. In total, four experimental values of hoop tensile strength and two values of axial tensile strength for SiC/SiC$_f$ cladding samples were selected based on [2], [4], [5], and [6]. For the analysis, sources reporting the highest measured values and those providing both hoop and axial strengths were preferred. Based on [2], the limiting value was set to one third of the hoop or axial tensile strength. Exact limiting values are summarized in Table 3. In addition to the four selected limiting parameters, a fifth criterion—the closure of the fuel-cladding gap—was also imposed and evaluated. This criterion was introduced due to the lack of experimental data on pellet-cladding mechanical interaction (PCMI) for the specific cladding material and fuel under consideration.

Total of 70 000 hours of irradiation was simulated. Whenever any of the limiting parameters was reached, the corresponding values of average fuel rod burn-up and fission gas release (FGR) were recorded, along with the burn-up, FGR, volumetric, and areal fuel swelling at each node. These results, were then compared with experimental data available in the open literature based on the burn-up and temperature of selected nodes in the time of the criterion fulfilment. The most significant source of areal swelling values was [7], while volumetric swelling values were primarily taken from [8]. FGR values were obtained from [8] and [9]. These sources were selected based on their similarity in material composition and parameters to the analysed representative fuel rod.

TABLE 3. EXACT VALUES OF LIMITNING PARAMETERS

Parameter	Value
Fuel melting temperature [K]	2750
Maximum allowable operation cladding temperature [K]	2818
Limiting cladding hoop stress [MPa]	104,5 [4], 115,3 [2], 116,7 [5], 126,7 [6]
Limiting cladding axial stress [MPa]	74,7 [2], 81,7 [6]

2. FINDINGS AND CONCLUSSIONS

Two of the four limiting parameters were reached during the simulation, along with meeting the closure of the fuel-cladding gap criterion. The corresponding average burn-up values for each limiting criterion are presented in Table 4. Among the evaluated criteria, the most restrictive one was found to be the internal fill gas pressure. A comparison between available experimental data and simulation results revealed that the calculated values of FGR were overestimated. This discrepancy is likely due to the FGR models implemented in the TRANSURANUS code, which are primarily based on oxide fuels rather than carbide fuels. Since oxide fuels exhibit a higher capacity to release fission gases, applying these models to mixed carbide fuel results in an overprediction of FGR. If models better suited to the characteristics of mixed carbide fuel were employed, the maximum permissible burn-up would likely be higher and constrained by a different factor—most probably the closure of the fuel-cladding gap, as suggested by the simulation results.

TABLE 4. ROD AVERAGE BURN-UP EVALUATED FOR EXCEEDED CRITERIA

Criterion	Rod average burn-up [MWd/kg UO_2]
Fill gas pressure	42,32
Fuel gap closure	50,90
Cladding stress (tangential)	55,04

3. REFERENCES

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