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# Comparison Between Zirconium-Based and Iron-Based Alloys in the Thermomechanical Performance of Nuclear Fuel in Small Modular Reactors

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## 1. Introduction

After the Fukushima Daiichi accident, different concepts of accident-tolerant fuels (ATF) began to be investigated as alternatives to the conventional zirconium alloys used as fuel cladding in light-water reactors. Among the candidate materials, iron-based alloys, such as FeCrAl alloys and stainless steels, have received attention due to their thermal and mechanical properties, which differ from those of traditional zirconium alloys [1]. The introduction of these materials can affect important fuel-performance parameters, including fuel temperature, cladding deformation, and fission gas release (FGR) in the fuel rod during irradiation [2].

In small modular reactors (SMR) based on pressurized light water reactors (PWR), fuels with high burnup can produce more energy due to the longer utilization period of the fuel pellets require a detailed assessment of the thermal and mechanical behavior of fuel rods [3]. Therefore, it is necessary to evaluate the effects of different cladding materials on parameters associated with the thermomechanical performance of irradiated fuel, since differences in the mechanical properties of cladding materials, such as mechanical strength and creep deformation at high temperature, can result in significant differences in the thermomechanical behavior of the fuel rod, including pellet-cladding mechanical interaction (PCMI) and cladding deformation [4].

This work compares the thermomechanical behavior of zirconium-based and iron-based alloys used as fuel-rod cladding materials under operational conditions representative of PWR-type SMR.

## 2. Methodology

The fuel rods and operating parameters used in this work were based on the British Rolls-Royce SMR design [2]. Fuel behavior calculations were performed using the TRANSURANUS code [5], to comparatively evaluate the different fuel rod coating materials under the same operating conditions.

Table I: Operational conditions adopted in the simulations [2].

| Parameter | Value |
|---|---|
| Thermal power | 1358 MW(th) |
| Coolant pressure | 15.5 MPa |
| Core inlet temperature | 295 °C |
| Core outlet temperature | 325 °C |
| Coolant mass flow rate | 7992 kg/s |

The thermo-hydraulic parameters of the core were used as boundary conditions in the thermomechanical calculations, including coolant pressure, inlet and outlet temperatures, and thermal power. The same operating conditions were maintained for all cases analyzed, allowing direct comparison between the different coating materials.

Zircaloy-4, M5, FeCrAl alloys and AISI-316 stainless steel claddings were evaluated. For cases with iron-based alloys, different cladding thicknesses and increased fuel enrichment were considered as a strategy to mitigate the neutronic penalty associated with these materials, which have larger neutron absorption cross sections than zirconium alloys [1, 2].

Table II: Geometric parameters of the evaluated fuel rods.

| Parameter | Zircaloy-4 / M5 | AISI-316 / FeCrAl |
|---|---|---|
| Cladding outer diameter (mm) | 9.502 | 9.502 |
| Cladding thickness (mm) | 0.572 | 0.572 / 0.429 / 0.286 |
| Pellet diameter (mm) | 8.192 | 8.192 / 8.478 / 8.764 |
| Enrichment (wt% U-235) | 4.95 | 6.0 |

## 3. Results and Discussion

The results indicate significant differences between Outerthe cladding materials evaluated, especially in relation to the core temperature of the fuel, release of fission gases, and cladding deformation during irradiation. The cases with iron-based alloys presented higher core temperatures than those observed for zirconium-based coatings from the initial stages of irradiation, a behavior associated with differences in the thermal and mechanical properties of the cladding materials, which influence radial heat transfer and gap closure between fuel and cladding during irradiation [6,7].

The combination of greater thermal expansion and lower creep deformation in iron-based coatings contributed to delaying the closure of the pellet-cladding gap. Reducing the cladding thickness decreased the radial thermal resistance, partially mitigating the temperature increase observed in the cases with FeCrAl and AISI-316.

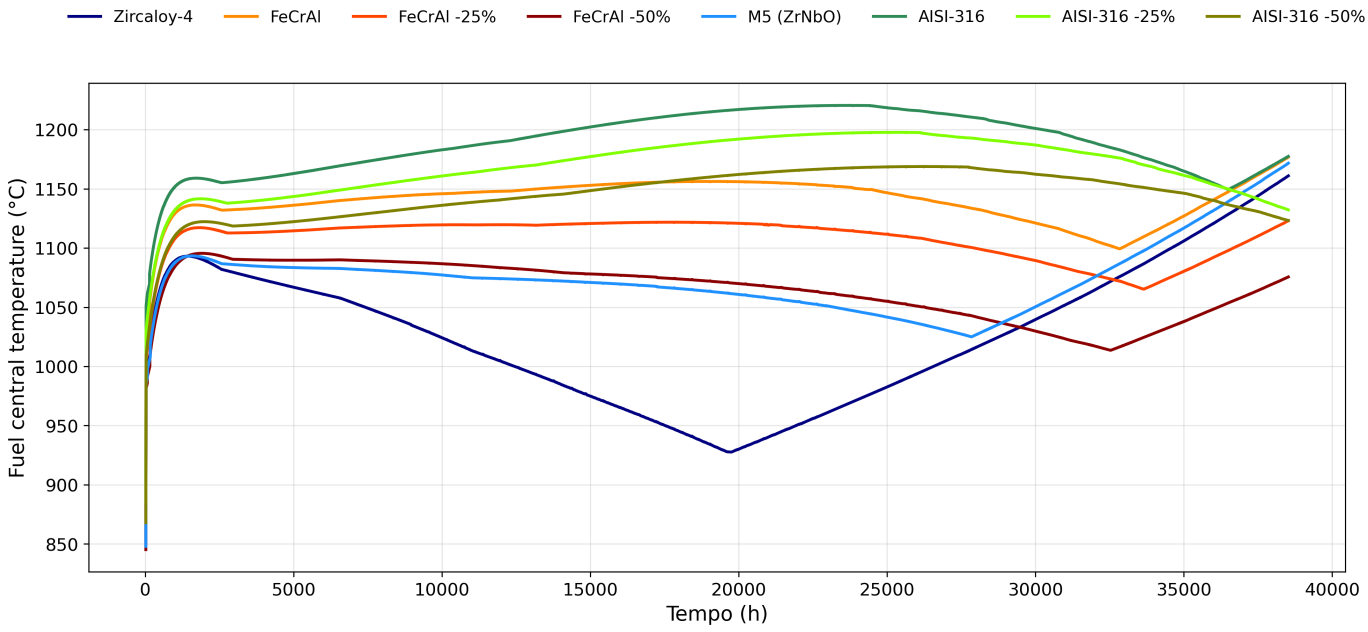


Figure 1: Core fuel temperature as a function of time.

The contact pressure results indicate earlier gap closure in the Zircaloy-4 and M5 cases. This closure increases the mechanical interaction between the fuel and the cladding and raises the thermal conductivity after contact. In contrast, iron-based liners maintained lower contact pressures and creep deformations throughout the irradiation, indicating a lower tendency for gap closure between the pellet and the cladding. In the thinned AISI-316 cases, the absence of contact between the pellet and the cladding suggests that heat transfer remained dominated by conduction in the gas gap between the pellet and the cladding.

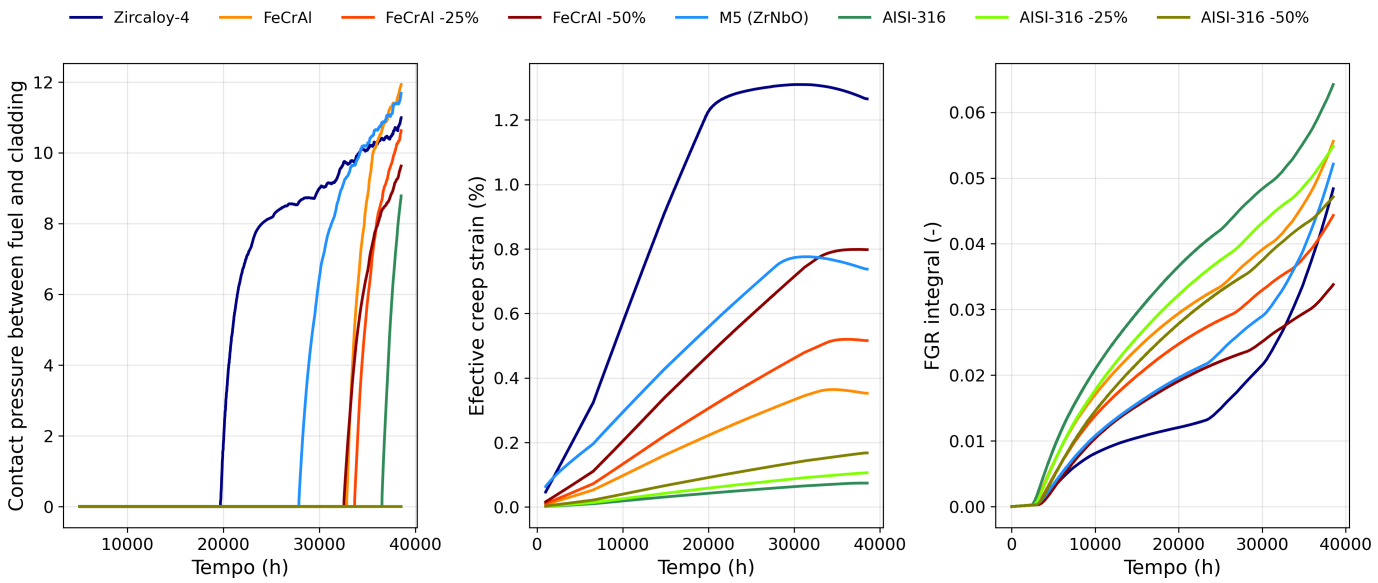


Figure 2: (a) Contact pressure between fuel and cladding: (b) Effective creep deformation, and (c) Release of fission gases in the fuel rod.

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Cases with iron-based alloys showed higher values of fission gas release compared to zirconium-based claddings, a behavior associated with the higher core temperatures observed in these cases. The increase in temperature favors the diffusion and migration mechanisms of fission gases in the fuel, intensifying their release into the pellet-cladding gap during irradiation [6].

## 4. Conclusions

The results obtained indicate that coating materials significantly influence the thermomechanical behavior of the fuel rod under operating conditions representative of a PWR-type SMR. Cases with iron-based alloys showed higher fuel core temperatures and fission gas release values than those observed for zirconium-based coatings, in addition to lower creep deformations along the irradiation path.

Reducing the coating thickness partially mitigated the thermal effects observed in the cases with FeCrAl and AISI-316, resulting in lower core temperatures and lower fission gas release values. The results suggest that geometric modifications may represent a relevant strategy for applying iron-based alloys in fault-tolerant fuels for PWR-based SMRs.

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