Implementation of Cr-Coated ATF Cladding Models in the Steady-State Fuel Performance Code FRAPCON

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1. Introduction

Cr-coated zirconium alloy cladding is a leading accident-tolerant fuel (ATF) concept because it can reduce normal-operation corrosion and high-temperature steam oxidation [1,4]. Fuel-rod analysis therefore needs to represent both the coating geometry and its material response.

FRAPCON-4.0 assumes a single-material cladding and cannot directly represent a thin coating [2]. This study implemented effective-property models for Cr-coated Zircaloy and Cr-coated HANA and verified them for steady-state operation. Explicit multilayer mechanics and transient conditions were excluded.

2. Methods and Results

2.1 Effective Geometry and Volume Fractions

For ATF materials, the cladding diameter was defined at the substrate-coating interface; the coolant-facing diameter was obtained by adding twice the coating thickness. After the axial geometry was read, radii and material fractions were calculated once and stored for subsequent property calls.

At each axial location, annular areas give the coating volume fraction, and the substrate and Cr densities (7.19 g/cm³ for Cr) give the mass fraction:

$$V_{coat} = A_{coat} / (A_{base} + A_{coat}) \quad (1)$$

$$\rho_{eq} = \rho_{base} V_{base} + \rho_{Cr} V_{coat}\ , \quad f_{m,coat} = \rho_{Cr} V_{coat} / \rho_{eq} \quad (2)$$

For the reference geometry, a 20 μm coating gives a volume fraction of 0.0361.

2.2 Property Mixing Rules

Thermal conductivity, specific heat and thermal expansion use the existing mass-fraction linear mixture. The axial elastic modulus uses a volume-fraction Voigt mixture, assuming that the perfectly bonded layers undergo the same strain:

$$k_{eff} = f_{m,base}\, k_{base} + f_{m,coat}\, k_{Cr} \quad (3)$$

$$E_{eff} = V_{base}\, E_{base} + V_{coat}\, E_{Cr} \quad (4)$$

Yield stress and thermal creep are not obtained by directly mixing material properties. Empirical factors B and C, representing the effect of the Cr coating on cladding response, multiply the substrate values:

$$B = 1 + V_c\,(0.35 - 5.5\times10^{-4}\, T_C) \quad (5)$$

$$C = 0.0349\, \exp(1816.2/T_K)\, \sigma_{MPa}^{-0.09} \quad (6)$$

The creep factor was derived from internal-pressure tests of coated and uncoated Zry-4 [3] and is applicable at 330-400 °C and 90-150 MPa hoop stress; outside this range the substrate correlation is used. Normal corrosion was set to 10% of the substrate oxide growth. The external oxide was treated as Cr_2O_3 with k=(3300/TK+1.2)·2TD/(3-TD).

Table I summarizes the implemented models. Properties without sufficient evidence retain the substrate correlations.

Table I. Property models applied to Cr-coated cladding

Property	Cr-Zry	Cr-HANA	Model
k, cp and thermal expansion	Yes	Yes	Mass fraction
Elastic modulus	Yes	Yes	Voigt volume fraction
Yield stress	Yes	Base	B(T,Vc)
Thermal creep	Yes	Base	C(T,σ)
Normal corrosion	Yes	Yes	0.10 × substrate
Oxide conductivity	Yes	Yes	Cr_2O_3

2.3 Linear-Power Conversion Error and Correction

FRAPCON converted the input linear power to coated-surface heat flux but later recovered linear power using the interface diameter. The two diameters are identical for a single layer; with a 20 μm coating, however, only 99.58% of the input power was recovered, causing burnup to decrease artificially with coating thickness.

The correction retains the input rod-average linear power for burnup, axial power, fission-gas generation and decay heat, while the coated-diameter surface heat flux is used only at the coolant boundary. Total power is therefore conserved and the larger external area affects only heat transfer.

2.4 Verification

Property-level tests linked a small Fortran driver directly to the compiled property module and called each

function independently. The Voigt modulus was checked at coating volume fractions of 0, 0.2 and 1. Yield, creep, corrosion and Cr_2O_3 conductivity were compared with analytical values; valid-range gates and out-of-range fallback were checked with a scaled numerical tolerance of 10^{-12}. A source-level check also verified that the creep factor acts only on thermal creep, not irradiation creep. Full-rod verification used an APR1400 reference case over 1254.5 days.

From 0 to 20 μm, effective thermal conductivity, specific heat and elastic modulus increased by 14.4%, 2.3% and 8.4%, respectively (Fig. 1).

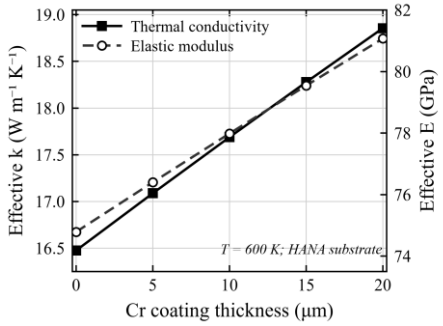

Fig. 1. Effective thermal conductivity and elastic modulus at 600 K

At zero coating thickness, uncoated Zircaloy matched Cr-coated Zircaloy and uncoated HANA matched Cr-coated HANA for all major outputs, including burnup, fuel temperature and rod internal pressure.

After the correction, rod-average burnup remained 59.96 GWd/MTU at every thickness (Fig. 2). Peak fuel centerline temperature decreased from 2546.33 to 2536.83 °F because of the higher conductivity and larger heat-transfer area. Peak internal pressure decreased overall from 1212.71 to 1199.03 psi, and all cases completed normally.

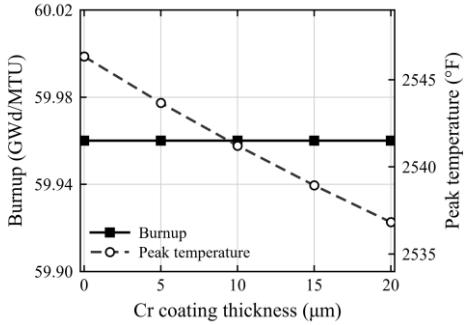

Fig. 2. Burnup and peak centerline temperature after the power-conversion correction

The creep correlation remains narrower than the reference operating range.

3. Conclusions

FRAPCON-4.0 was extended with Cr-coated cladding geometry, material routing and eight property models. Existing results were reproduced at zero coating thickness, and separating linear power from surface heat flux preserved burnup while retaining the thermal effects of the coating.

Further work should compare the mass-fraction mixture with cylindrical series resistance, extend the creep model to coating thickness and wider conditions, assess corrosion-factor and Cr_2O_3-density assumptions, obtain HANA-Cr data, and develop multilayer interfacial mechanics.

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