Verification of Aluminum Cladding Oxide Growth Models in the PROPER Fuel Performance Code

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1. Introduction

Research and test reactors widely use plate-type fuel elements consisting of U_3Si_2-Al dispersion fuel meat enclosed in aluminum alloy cladding (e.g., Al6061, AG3NE). The U_3Si_2-Al fuel was qualified by the U.S. NRC (NUREG-1313) [1] as a low-enriched uranium fuel for use in non-power reactors, replacing the previously used high-enriched uranium fuels.

During irradiation, the aluminum cladding undergoes waterside corrosion, forming an oxide layer (boehmite) on the outer surface. Since the oxide has significantly lower thermal conductivity than the aluminum substrate, the growing oxide layer increases the cladding temperature and can limit fuel performance and safety margins. Kim et al. developed oxide growth models for aluminum cladding in 2008 [2] and a revised version in 2020 [3].

PROPER (Performance and Reliability of Plate-type Element for Reactor) is a Python-based fuel performance analysis code developed for research reactor plate-type fuel. The code consists of multiple coupled analysis modules. Both oxide growth models have been implemented in the corrosion module.

This paper verifies the oxide growth module of the PROPER code by comparing the predictions with the results published by Kim et al. [2] for five irradiation test cases. Additionally, the two models [2,3] are compared under identical conditions to quantify the effect of model differences.

2. Oxide Growth Models

Both models use a rate-law approach for oxide growth:

$$\frac{\mathrm{dx}}{\mathrm{dt}} = kx^{-p} \tag{1}$$

$$\mathrm{x} = \left[\mathrm{x}_0^{p+1} + (p+1)kt\right]^{\frac{1}{p+1}} \tag{2}$$

where x is the oxide thickness, p is the rate-law exponent determined by the oxide solubility, k is the rate constant, and t is the irradiation time. The key difference lies in the rate constant k.

$$\text{Kim et al. [2]: } \mathrm{k} = 3.9 \times 10^5 \exp\left(-\frac{6071}{T_{wx} + \frac{ABq"x}{k_T}}\right) \tag{3}$$

$$\text{Kim et al. [3]: } \mathrm{k} = 4.5 \times 10^3 \exp\left(-\frac{4340}{T_{wx} + \frac{Aq"}{k_T}}\right) \tag{4}$$

where T_{wx} is the oxide–water interface temperature (K), A is the coolant velocity enhancement factor, B = 0.37 is an in-pile correction factor, q" is the surface heat flux (MW/m^2), x is the oxide thickness (μm), and kT is the oxide thermal conductivity (W/m·K). The model by Kim et al. [2] includes the oxide thickness x in the rate constant, creating a positive feedback mechanism. The revised model [3] removes both x and B, and uses recalibrated constants.

3. PROPER Code

PROPER is a fuel performance analysis code for research reactor plate-type fuel. The code employs a modular architecture with coupled calculations as summarized in Table I.

Table I: PROPER code module structure

Module	Description
Input	Input data preprocessing
Preprocessing	Mesh generation, initial geometry setup
Irradiation	Power density, burnup, neutron fluence
Material	Fuel (U_3Si_2-Al), cladding (Al6061, AG3NE), coolant (H_2O) properties
Thermal	Heat conduction temperature distribution
Corrosion	Al cladding oxide growth
Swelling	Fission gas bubble swelling
Coupling	Iterative convergence

4. Verification and Results

The PROPER code was configured to use the oxide–water interface temperature as a direct input, bypassing the thermal analysis to isolate the corrosion module. The time step was set to 0.1 days. Five cases from Kim et al. [2] were selected: two FUTURE plates (BR-2, high heat flux) and three RERTR plates (ATR, low heat flux). Table II summarizes the irradiation histories.

Table II: Irradiation histories

Case	Reactor	Period (EFPD)	T_{wx} (°C)	q" (MW/m^2)	pH	Ref.
FUTURE Right	BR-2	40	122→109	3.2→2.7	5.9→6.2	[2, 4]
FUTURE Left	BR-2	40	128→116	3.4→2.9	5.9→6.2	[2, 4]
RERTR-6 B5	ATR	135	120→100	1.1→0.77	5.2	[2, 5]
RERTR-6 B7	ATR	135	107→93	0.82→0.73	5.2	[2, 5]
RERTR-7A B7	ATR	90	106→101	2.3→2.1	5.2	[2, 5]

Fig. 1 shows the oxide thickness growth history for all five cases. The PROPER code predictions using the model by Kim et al. [2] show good agreement with the original paper results, confirming the correct implementation of the corrosion module. When comparing the two models [2,3] under identical input conditions, they produce nearly identical results at low heat flux conditions (RERTR cases). However, at high heat flux conditions (FUTURE cases), the model by Kim et al. [2] tends to predict higher oxide thickness than the revised model [3], which is attributed to the positive feedback from the oxide thickness self-referencing term in Eq. (3).

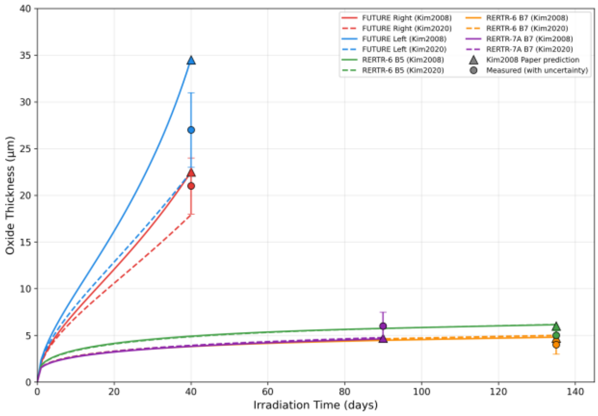

Fig. 1. Predicted oxide thickness compared with PIE measurements and predictions by Kim et al. [2].

5. Conclusion

The oxide growth module of the PROPER code was verified against five irradiation test cases covering a wide range of heat flux conditions. The predictions using the model by Kim et al. [2] showed good agreement with the original paper results, confirming the correct implementation of the corrosion module. Under identical input conditions, the two models [2,3] produced similar results at low heat flux, while the model by Kim et al. [2] predicted higher oxide thickness at high heat flux due to the positive feedback from the oxide thickness self-referencing term in the rate constant.

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