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Composition Evolution Modeling and Property Evaluation Framework for Ag–In–Cd Control Rod Materials

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1. Introduction

Ag–In–Cd (AIC) alloys have been widely used as absorber materials in pressurized water reactor (PWR) control rods due to their chemical stability and favorable irradiation performance. However, long-term neutron irradiation induces transmutation reactions (Ag→Cd, In→Sn), resulting in compositional evolution and phase transformation from a single fcc phase to a mixed or hcp-dominant structure. These microstructural changes are known to cause irradiation swelling and mechanical degradation, which ultimately limit control rod lifetime [1–3].

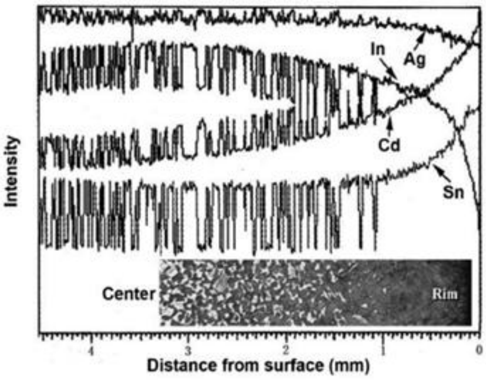

Figure 1. Composition evolution observed in PIE of an irradiated AIC control rod material [1]

Although several studies have investigated the irradiation behavior and swelling mechanisms of AIC absorbers [4,5], a systematic framework linking composition evolution modeling with experimentally verifiable out-of-pile property evaluation remains limited. The objective of this study is to establish an integrated methodology that (1) predicts the composition evolution of AIC alloys as a function of neutron fluence and radial position and (2) connects the predicted composition to out-of-pile property evaluation as a basis for subsequent in-reactor behavior assessment.

2. Methods and Results

A First-order differential equations was formulated to describe irradiation-induced compositional evolution based on isotope-specific neutron absorption cross sections and transmutation chains. Under a thermal neutron assumption (0.025 eV), the governing equation for nuclide inventory evolution was expressed in fluence-dependent form and numerically integrated using a Python-based computational module.

Table I: Governing equation of the number of each nuclide

Ag	$dN_{Ag,107} = -\Phi \cdot \sigma_{Ag,107} N_{Ag,107} dt$ $dN_{Ag,109} = -\Phi \cdot \sigma_{Ag,109} N_{Ag,109} dt$
Cd	$dN_{Cd,106} = -\Phi \cdot \sigma_{Cd,106} N_{Cd,106} dt$ $dN_{Cd,108} = -\Phi \cdot \sigma_{Cd,108} N_{Cd,108} dt + \Phi \cdot \sigma_{Ag,107} N_{Ag,107} dt$ $dN_{Cd,110} = -\Phi \cdot \sigma_{Cd,110} N_{Cd,110} dt + \Phi \cdot \sigma_{Ag,109} N_{Ag,109} dt$ $dN_{Cd,111} = -\Phi \cdot \sigma_{Cd,111} N_{Cd,111} dt + \Phi \cdot \sigma_{Cd,110} N_{Cd,110} dt$ $dN_{Cd,112} = -\Phi \cdot \sigma_{Cd,112} N_{Cd,112} dt + \Phi \cdot \sigma_{Cd,111} N_{Cd,111} dt$ $dN_{Cd,113} = -\Phi \cdot \sigma_{Cd,113} N_{Cd,113} dt + \Phi \cdot \sigma_{Cd,112} N_{Cd,112} dt$ $dN_{Cd,114} = -\Phi \cdot \sigma_{Cd,114} N_{Cd,114} dt + \Phi \cdot \sigma_{Cd,113} N_{Cd,113} dt$ $dN_{Cd,116} = -\Phi \cdot \sigma_{Cd,116} N_{Cd,116} dt$
In	$dN_{In,113} = -\Phi \cdot \sigma_{In,113} N_{In,113} dt$ $dN_{In,115} = -\Phi \cdot \sigma_{In,115} N_{In,115} dt$
Sn	$dN_{Sn,114} = -\Phi \cdot \sigma_{Sn,114} N_{Sn,114} dt + \Phi \cdot \sigma_{In,113} N_{In,113} dt$ $dN_{Sn,116} = -\Phi \cdot \sigma_{Sn,116} N_{Sn,116} dt + \Phi \cdot \sigma_{In,115} N_{In,115} dt$

To account for spatial effects, a one-dimensional radial neutron flux attenuation model was coupled with the depletion equations. The macroscopic absorption cross section, updated at each time step, was used to evaluate local neutron flux reduction within the absorber radius. This coupled (r,t)-dependent framework enabled the prediction of nuclide inventories as functions of both accumulated fluence and radial position.

The calculated results show that Ag and In contents decrease progressively with increasing neutron fluence, while Cd and Sn accumulate due to transmutation reactions. Significant radial compositional gradients were observed, with surface regions experiencing more pronounced Ag depletion and Sn formation than the center. At high fluence conditions (~1.5×10^{22} n/cm^2), the outer region composition approached the reported hcp single-phase formation region [5], indicating the potential onset of accelerated local swelling.

For experimental validation, alloy specimens were fabricated for both the initial (pure) AIC composition and selected evolution-predicted compositions. Material property comparison was performed between the fabricated specimen with unirradiated composition and a commercially manufactured reference AIC material. The measured properties showed acceptable agreement, confirming the reliability of the fabrication and evaluation methodology.

Based on this validation, the same approach is expected to provide consistent property assessment for the evolution-predicted compositions.

3. Conclusions

An integrated framework for composition evolution modeling and property evaluation of Ag–In–Cd control rod materials was developed. The proposed methodology combines transmutation-based depletion analysis with radial neutron flux attenuation modeling, enabling quantitative prediction of nuclide distribution under irradiation conditions.

The results demonstrate that compositional evolution is strongly dependent on accumulated neutron fluence and radial position, and that high-fluence surface regions may reach hcp-dominant compositions associated with increased swelling potential.

By linking calculated compositions with experimentally fabricated simulated alloys, this study provides a practical pathway for out-of-pile property evaluation as a surrogate approach for predicting in-reactor material behavior. The developed framework can serve as a foundational methodology for long-term irradiation performance assessment and structural integrity evaluation of AIC absorber materials in flexible operation environments.

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