

Prediction of Composition Evolution and Material Properties of Ag-In-Cd Absorbers for Flexible Operation of PWRs

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1. Introduction

To achieve the net-zero emissions, flexibility of power-system has become increasingly important to accommodate the inherent fluctuation of renewable energy sources, such as solar power. Consequently, nuclear power plants, which have traditionally operated as baseload generators, are increasingly required to provide flexible operation. Such load-following imposes higher loads on control rods, requiring assurance of their structural integrity.

The Ag-In-Cd (AIC) alloy was introduced into CE-type control element assemblies to resolve cracking of B₄C-bearing finger tips [1,2], and has an extensive service history in PWR control rods, exhibits smaller irradiation-induced dimensional change than B₄C.

The composition of AIC control rod materials evolves through irradiation-induced transmutation [3]. This study establishes a framework that predicts continuous compositional evolution through 1) neutron depletion and transmutation calculations, 2) fabrication of compositionally varying specimens, and 3) evaluation through out-of-pile testing. By comparing the measured data with literature-based predictions, this study aims to establish a material property database including high-temperature, irradiation, and flexible operating conditions, supporting control rod integrity assessments and related computational codes.

2. Methods and Results

2.1 Composition Evolution Calculation

Under PWR neutron spectra, the constituent elements of the nominal 80Ag-15In-5Cd (wt.%) alloy transmute along well-known chains: neutron capture on silver isotopes followed by beta decay produces cadmium, capture on In-115 produces Sn-116, and Cd-113 burns out to Cd-114 without a change of element. The alloy therefore evolves from a ternary fcc solid solution toward a quaternary Ag-In-Cd-Sn system with steadily increasing Cd and Sn contents. A depletion model was constructed that solves these coupled capture and decay chains for a cylindrical absorber, with one-dimensional radial attenuation of the incident flux representing the strong self-shielding of the alloy. The model is

parameterized by surface fluence, and its single-group thermal-spectrum treatment neglects resonance self-shielding and in-life spectrum hardening, so the calculated composition change is interpreted as a conservative upper bound. The calculated tendencies were checked against published post-irradiation compositions and independent calculations reported for irradiated AIC rods [4,5].

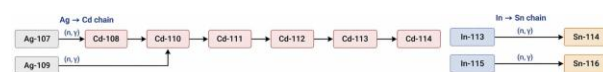


Fig. 1. Neutron capture chain of Ag, In, Cd isotopes [3]

Three robust trends emerge from the calculation. First, silver and indium deplete monotonically while cadmium and tin accumulate, so the property-relevant composition departs progressively from the as-fabricated ternary. Second, the change is strongly surface-weighted: because the alloy is nearly black to thermal neutrons, the outer region transmutes roughly twice as fast as the interior, in qualitative agreement with radial composition gradients observed in post-irradiation examinations [4]. Third, as Cd-113 in the outer shell is consumed, the reaction front penetrates inward, so the transmuted layer thickens with fluence. At high fluence the outermost region approaches compositions for which transformation of the fcc matrix into a lower-density hcp phase has been reported [4,5]. As a composition criterion, examination of irradiated AIC showed a two-phase fcc + hcp structure at about 77.5 wt.% Ag and a single hcp phase at 55–61 wt.% Ag [6], and simulated Ag-In-Cd-Sn alloys followed the same fcc → fcc + hcp → hcp sequence with increasing Cd and Sn contents [5]. The associated changes in atomic volume and lattice parameter are the accepted origin of AIC swelling.

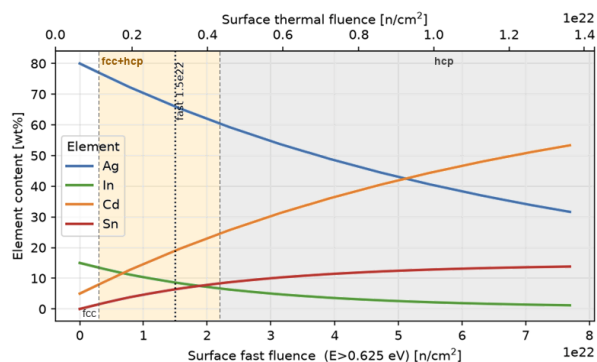


Fig. 2. Composition evolution calculation results at peak-change location, under full time 25% CR insertion scenario

2.2 Irradiation effect on AIC material properties

Irradiation affects AIC properties through two distinct channels: displacement damage and transmutation-induced composition change. The historical database indicates that hardening produced by displacement damage at low irradiation temperature is annealed out at temperatures at and above the alloy recrystallization temperature, which lies below the PWR operating range; specimens irradiated at operating temperature showed essentially unchanged hardness and tensile behavior, whereas composition change is permanent and cumulative [7,8]. This ordering justifies the surrogate approach adopted here: unirradiated alloys fabricated to the calculated transmuted compositions capture the dominant and persistent part of in-reactor property evolution, and the residual displacement-damage contribution is bounded separately by literature-based correction factors. The same reasoning implies that the correction factors themselves must be applied with care for properties, such as creep rupture, for which irradiation effects reported in the literature act in the direction of reduced margin [7].

2.3 Literature-Based Prediction of In-Reactor Behavior of AIC: Life-limiting property and variable

A synthesis of post-irradiation examinations and vendor evaluations from the US, Europe, and Japan yields a consistent two-step evolution of AIC rod degradation [1,9-11]. In the first stage, the absorber-cladding gap narrows, a process governed mainly by thermal creep of the low-strength absorber under self-weight and spring loads together with cladding creep-down; absorber creep shows a strong grain-size dependence, and the static stresses in service are low.

In the second stage, after contact (gap closure), transmutation-driven swelling continues essentially unaffected by cladding restraint, increases linearly with fluence, and accelerates once the hcp phase appears; the cladding is thereby strained at quasi-static rates toward its irradiation-reduced ductility limit, producing axial cracks of intergranular, irradiation-assisted character near the rod tip [10-12].

Vendor stress evaluations concluded that swelling forces, rather than compressive creep, control the absorber-cladding interaction [11], and hot-cell examination of part-length absorber rods that reside in the core found no absorber slumping [8]. Cladding wear against guide structures, with fatigue added under frequent maneuvering, constitutes a parallel degradation path that has proven controllable by surface treatment and management criteria [1,13]. The life-limiting variable is therefore the epithermal fluence accumulated at the rod tip.

3. Conclusions

A linked evaluation scheme connecting composition-evolution calculation, surrogate-alloy specimen definition, and property measurement has been established for AIC part-strength control rod development under flexible operation. The calculation provides burnup-dependent compositions. The literature survey indicates that transmutation-driven swelling governs the ultimate lifetime, and the epithermal fluence is therefore the life-limiting variable. Property measurements on the fabricated specimen matrix and formulation of fluence-dependent property models are expected to contribute to the performance evaluation and safety assessment of the part-strength control element assembly.

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