Assessment of CRUD deposition on Fuel Cladding in a Boron-Free Coolant Environment

Junhyuk Jeong[a], Yunju Lee[b] and Ji Hyun Kim[a]*
[a]*Department of Nuclear Engineering, Ulsan National Institute of Science and Technology (UNIST), 50 UNIST-gil, Eonyang-eup, Ulju-gun, Ulsan, 44919, Republic of Korea*
[b]*Korea Institute of Materials Science(KIMS), 797 Changwon-daero, Seongsan-gu, Changwon-si, Gyeongsangnam-do, 51508, Republic of Korea*
**Corresponding author: kimjh@unist.ac.kr*

Keywords : boron-free water chemistry, CRUD deposition, boiling-induced deposition, zirconium oxide

1. Introduction

Boron-free primary coolant systems are being considered for advanced reactor concepts, including small modular reactors (SMR) in order to simplify water chemistry control and mitigate boron-related operational issues such as crud-induced power shift (CIPS).[1,2] However, the deposition behavior and chemical characteristics of corrosion-related unidentified deposits (CRUD) under boron-free conditions remain insufficiently understood.[3]

In this study, CRUD deposition on zirconium-alloy fuel cladding was investigated under boron-free, KOH pH controlled high-temperature and high-pressure loop conditions simulating subcooled nucleate boiling (SNB) and bulk coolant environments representative of advanced reactor operation.

2. Experimental

To evaluate the optimal pH range under boron-free water chemistry conditions, CRUD deposition experiments were conducted at pH_T303.5 °C values of 6.9, 7.2, and 7.4. For all test conditions, the dissolved hydrogen (DH) concentration was maintained at 25 cc/kg·H_2O, and KOH was employed as the sole alkali additive for pH control.

Surface heat flux conditions representative of fuel cladding were simulated using an indirect heating method with cartridge heaters. Zirconium alloy cladding specimens were mounted onto the heater assembly after sequential cleaning. Prior to each experiment, the loop system was chemically cleaned using KOH and deionized water circulation to remove residual metallic ions. Dissolved hydrogen was controlled by injecting high-purity hydrogen gas, while conductivity, pH, and dissolved oxygen were continuously monitored in situ.

The experiments were performed under stepwise heat flux escalation. After achieving steady-state thermal-hydraulic conditions, Ni and Fe-based metal ion solutions were continuously injected to induce CRUD formation. The metal ion concentration was maintained constant throughout the experimental period.

Table I: Experimental conditions for CRUD deposition tests under boron-free environment Parameter

	Condition
pH Conditions	6.9 / 7.2 / 7.4
Dissolved Hydrogen	25 cc/kg·H_2O
Alkaline Additive	KOH

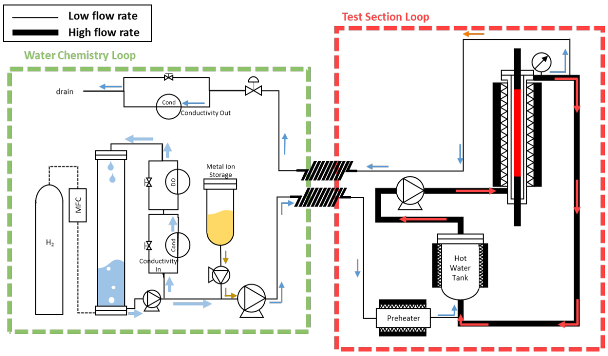

Fig. 1. Schematic of the experimental setup for fuel cladding CRUD deposition

3. Results and Discussion

CRUD deposition experiments under boron-free KOH-controlled conditions (pH 6.9, 7.2, and 7.4 at DH 25) were performed to assess the influence of water chemistry on deposit formation.

Under the KOH-pH6.9-DH25 condition, the highest chimney number density (4.97×10^9 m^{-2}) and the smallest inter-chimney spacing were observed, indicating relatively active subcooled nucleate boiling and enhanced corrosion product precipitation. Consequently, both the CRUD layer and oxide film thicknesses were significantly greater than those observed under pH 7.2 and 7.4 conditions.

In contrast, at pH 7.2 and 7.4, chimney structures were less developed and cross-sectional porosity was minimal, suggesting limited CRUD growth. These differences are attributed to variations in surface temperature and boiling behavior during the experiments.

Compositional analysis revealed that the Ni/Fe atomic ratio ranged from 0.78 to 0.81 across all conditions, indicating a limited dependence on pH within the tested range and suggesting a dominant influence of coolant temperature. Powder XRD analysis consistently identified nickel ferrite ($NiFe_2O_4$) as the primary crystalline phase under all conditions, confirming compositional uniformity at the crystallographic level.

4. Conclusions

Microstructural and compositional analyses using SEM–EDS and XRD demonstrated that CRUD formed under boron-free conditions exhibits a porous and chimney-like morphology similar to that observed in operating pressurized water reactors. The deposits were predominantly composed of Fe–Ni spinel oxides, with nickel ferrite identified as the major crystalline phase.
In the absence of soluble boron and lithium, CRUD chemistry is primarily governed by pH- and temperature-dependent Fe–Ni spinel formation. Despite the elimination of boron-related hideout mechanisms, the characteristic morphological features of CRUD were preserved. These results indicate that the fundamental mechanisms of CRUD formation remain operative under boron-free conditions and support the applicability of the developed experimental framework to future boron-free advanced reactor systems.

REFERENCES

[1] International Atomic Energy Agency, Advances in SMR Developments, International conference on small modular reactors and their applications, 2024
[2] Li, Shengzhe et al., A combined method for predicting the boron deposited mass and the CIPS risk, Science and Technology of Nuclear Installations, 2019.
[3] Kim, Mun Hwan et al., Experimental evaluation of primary water chemistry for prevention of axial offset anomaly, Thermochimica acta, 2012