Sensitivity analysis of CRUD growth and boron hideout on fuel assemblies

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***Keywords** *: Sensitivity study, PWR, CRUD, boron hideout, AOA*

1. Introduction

Axial Offset Anomaly (AOA) has been regarded as a critical issue in the long-term, high-power operation of pressurized water reactors (PWRs), due to the abnormal shift in axial power distribution [1,2]. It has been reported that AOA is related to corrosion deposits on the surfaces of fuel assemblies, called Corrosion-Related Unidentified Deposit (CRUD) [1,3]. The CRUD is a porous structure with a thickness of a few dozen micrometers, typically, and it is composed of nickel and iron oxides.

The CRUD structure on the hot surface of fuel assemblies includes steam chimney structures, which lead to wick-boiling phenomena and highly concentrated soluble species, such as boron and lithium, within the deposit structure [4–5]. Several studies have been conducted and have suggested the theoretical relationship between CRUD growth and boron hideout to predict the occurrence of AOA during PWR operation [6–9]. However, these models have not been quantitatively analyzed together with the operating conditions of PWRs and the characteristics of the CRUD layer. In this study, a sensitivity study was conducted on CRUD growth and boron hideout, based on our previous studies related to a numerical model [10].

2. Method

2.1. Theoretical models updated for the sensitivity study

The multiphysics model to theoretically predict CRUD growth and boron hideout under PWR operation conditions was developed through our previous studies [4–5]. The model solved coupled multiphysics processes, in terms of heat transfer and mass transfer within the wick-boiling structure, which is a combined structure of a porous domain and steam chimneys, as shown in Figure 1, by including chemical reactions of soluble species. Through the previous study, the model predicted reasonable CRUD growth and the trend of boron hideout under PWR operation conditions.

The model was updated to consider a large number of simulation conditions and to reduce errors in extreme operation conditions. By implementing the parallel computing toolbox of MATLAB using parfor functions, the structure of the previous model was revised entirely. A total of 56,320 sensitivity cases were generated, as shown in the following section, and they were simulated using this modified model over approximately two months on a desktop environment [10]. Also, to reduce numerical errors under harsh conditions, some thermal properties related to chemical reaction and CRUD growth were manually fixed to their maximum and minimum bounds when they exceeded these limits.

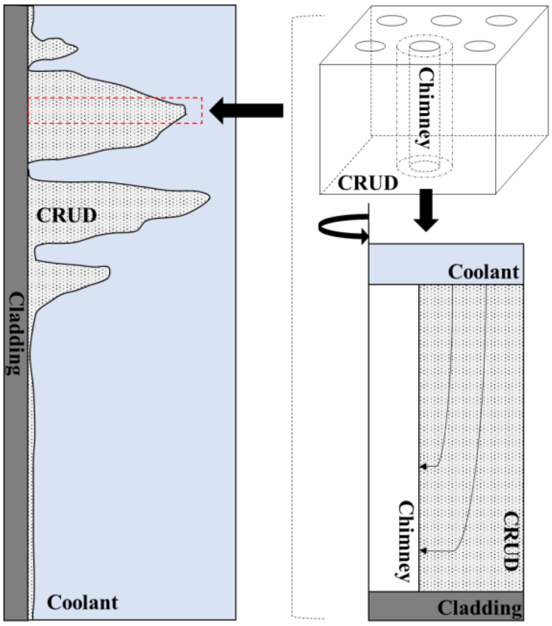

Figure 1. Macroscale geometry of the CRUD layer by volumetrically averaging the mesoscale wick-boiling structure.

2.2. Selection of the sensitivity parameters

Six parameters were selected, as shown in Table 1, including cladding heat flux, bulk coolant temperature, shutdown removal rate of the CRUD layer, particulate concentration of corrosion products, CRUD porosity, and chimney density. For the heat flux and coolant temperature, the range of these parameters in commercial PWRs was selected by adjusting the maximum bounds based on the power peaking factor of the thermo-hydraulics model [10]. Ultrasonic fuel cleaning was assumed when defining the shutdown removal rate, and the removal rate was assumed to range from 0 to 90%. The range of the particulate concentration of corrosion products was determined by modifying the range suggested by D. Walter for the Seabrook plant, by reducing its minimum bound to consider lower particulate concentrations [11]. The ranges of CRUD porosity and chimney density were selected based on several literature sources related to CRUD modeling [4–9].

Table 1. Sensitivity parameters used in this study.

Parameter (unit)	**Range (interval)**
Cladding heat flux (MW/m^2)	0.4-1.3 (0.1)
Bulk coolant temperature (K)	560-610 (5)
Shutdown removal rate (%)	0-90 (30)
Particulate concentration (ppb)	0.5-4.0 (0.5)
CRUD porosity (%)	50-80 (10)
CRUD chimney density (1/mm^2)	2000-5000 (1000)

3. Results and discussion

3.1 Sensitivity study along with cladding heat flux and bulk coolant temperature

CRUD growth and boron hideout were influenced by both cladding heat flux and bulk coolant temperature. CRUD growth was linearly proportional to cladding heat flux, whereas a threshold behavior was observed, with a dramatic increase in CRUD growth as bulk coolant temperature increased. For the boron hideout, no simple linear relationship was observed with either cladding heat flux or bulk coolant temperature. This behavior is consistent with the wick-boiling structure, in which the increase in soluble-species concentration within the structure depends on the thickness of the CRUD layer. Because precipitation of lithium metaborate occurs under high temperature and high concentrations of soluble boron and lithium, it leads to a minimum CRUD thickness required for boron hideout.

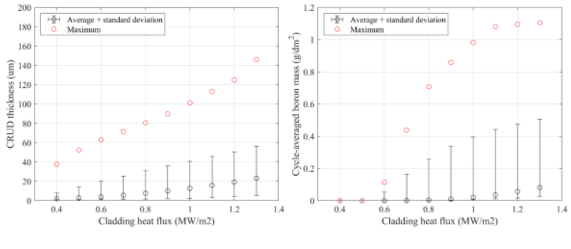

Figure 2. Sensitivity results of CRUD growth and boron hideout, along with cladding heat flux.

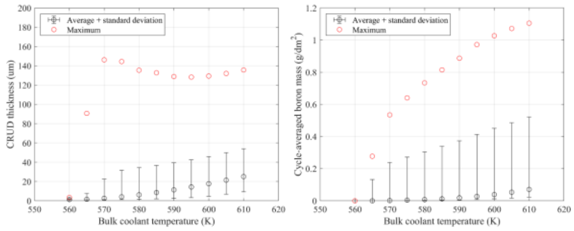

Figure 3. Sensitivity results of CRUD growth and boron hideout, along with bulk coolant temperature.

3.2 Sensitivity study along with particulate concentration of corrosion products

Both the CRUD growth and boron hideout were proportional to the particulate concentration of corrosion products. CRUD growth was linearly proportional to particulate concentration over the entire sensitivity range, while boron hideout was linearly proportional only over a limited range (0.5–3.0 ppb). In addition, the recommended level of particulate concentration was identified as 0.5–1.0 ppb to prevent significant boron hideout during long-term, high-power operation of PWRs [10].

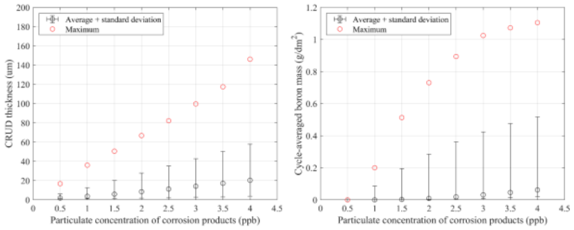

Figure 4. Sensitivity results of CRUD growth and boron hideout, along with the particulate concentration of corrosion products.

3.3 Sensitivity study along with shutdown removal rate of CRUD after ultrasonic fuel cleaning

Both CRUD growth and boron hideout decreased with increasing shutdown removal rate. The decrease in CRUD growth with shutdown removal rate was not pronounced, due to the characteristics of the growth mechanisms [4]. The decrease in boron hideout under harsh conditions (red dots in the figure) was also not significant; however, when considering the overlap between the parametric ranges and real PWR operating conditions, boron hideout showed a significant reduction with increasing shutdown removal rate [5].

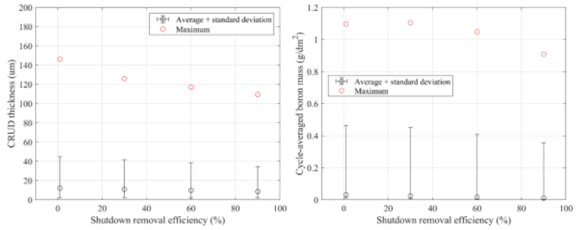

Figure 5. Sensitivity results of CRUD growth and boron hideout, along with the shutdown removal rate.

3.4 Sensitivity study along with CRUD porosity and chimney density

Both the CRUD growth and the boron hideout were significantly affected by the CRUD porosity. CRUD porosity is the most important parameter for the wick-boiling structure because it affects both heat and mass transfer of coolant, soluble species, and CRUD particles. CRUD growth is also influenced by the heat transfer rate (subcooled nucleate boiling); therefore, the growth amount of the CRUD layer is strongly affected by the CRUD porosity. In addition, boron hideout depends on CRUD thickness as well as CRUD porosity (through mass transfer of soluble species and heat transfer); thus, boron hideout is also significantly affected by CRUD porosity.

For chimney density, the sensitivity of CRUD growth and boron hideout to this parameter was not significant compared with the effect of CRUD porosity. Chimney density is generally considered to depend on the boiling regime. Accordingly, an uncertainty in this sensitivity study was identified: evaluating the influence of chimney density on CRUD growth and boron hideout independently of the heat transfer regime may be inadequate.

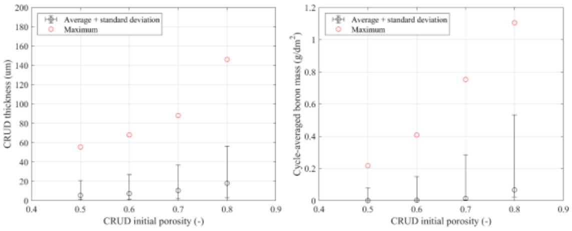

Figure 6. Sensitivity results of CRUD growth and boron hideout, along with CRUD porosity.

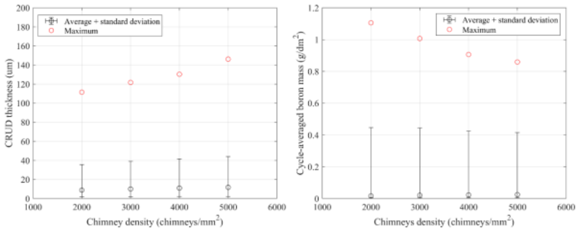

Figure 7. Sensitivity results of CRUD growth and boron hideout, along with chimney density.

4. Conclusion

A total of 56,320 sensitivity cases were simulated and analyzed using the modified multiphysics model for CRUD growth and boron hideout. Although some cases represented harsh conditions that cannot be achieved under real PWR operating conditions, the results provide a sufficient basis for quantitatively analyzing CRUD growth and boron hideout with respect to PWR operating conditions and CRUD-layer characteristics. The sensitivity results can be used as a basis for quantitatively understanding CRUD growth and boron hideout, and for further applications such as surrogate modeling.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF), grant funded by the Korea government (MSIT) (RS-2023-00259713).

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