Effect of Heat Flux on Fuel Crud Deposition in a PWR Primary Environment

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1. Introduction

One of the challenges in pressurized water reactors (PWRs) is to enhance the efficient heat transfer rate between the coolant and the fuel assembly in terms of energy efficiency. Accordingly, many PWRs uprated their power to take the heat transfer rate higher than before. However, the uprated reactor power leads to the sub-cooled nucleate boiling (SNB) on the fuel cladding tubes, and it accelerates the deposition of corrosion products on the fuel cladding tubes, called crud [1,2]. The crud on the fuel cladding tubes causes a variety of problems such as axial offset anomaly (AOA), thermal conductivity reduction, and localized corrosion of the fuel claddings, resulting in severe operational problems as well as economic penalties of nuclear power plants (NPPs) [3,4].

Laboratory studies show that the crud deposition is accelerated through the micro layer-evaporation and drying-out beneath vapor bubbles formed on the cladding surface under SNB conditions [5-8]. Furthermore, the SNB process inside thick crud forms capillary pores, called boiling chimney. Boron dissolved in a primary coolant can be easily accumulated into these pores, and the concentrated boron can act as a direct cause of the AOA phenomenon [4,9]. Therefore, many researches have been focused on the SNB behavior occurring on the fuel cladding tube to mitigate and to prevent the crud deposition and the AOA phenomenon.

The SNB behavior on the heated surface depends heavily on various factors such as heat flux, system pressure, oxide thickness, and surface characteristic [10-13]. In our previous studies, we have discussed the effects of the thickness of ZrO_2 layer and the surface characteristics regarding the SNB behavior and the crud deposition behavior [12,13]. Under simulated primary coolant conditions, these two factors affect significantly not only the SNB behavior but also the crud deposition behavior. In this paper, we evaluate the effect of the heat flux on the SNB behavior and the crud deposition behavior in a simulated primary condition. To elucidate the effect of the heat flux on the SNB behavior and the crud deposition behavior, the crud deposition tests were conducted under the two different heat flux conditions: 20 W/cm^2 and 80 W/cm^2. At each test, the SNB behavior on the fuel cladding tube was periodically monitored using an acoustic emission (AE) technique and correlated with the crud deposition behavior.

2. Experimental Methods

Crud deposition tests were performed using the KAERI crud deposition loop reported in our previous work [12,13]. This loop system consisted of three main sections: primary water circulation section, crud source injection section, and AE acquisition section.

The primary water solution was stored in the primary water solution tank with a capacity of 200 L and recirculated via the HP pump, pre-heater, test section, and heat exchanger with a flow rate of 5 m/s. Crud deposition tests were conducted in the test section. The inlet solution into the test section was preheated and the system pressure was maintained at 130 bar. To attain an SNB condition on the fuel cladding surface, an internal heater inserted into the cladding was heated to the two different heat flux conditions: 20 W/cm^2 and 80 W/cm^2. As a given heat flux condition, the water temperature of the flowing water adjacent to the fuel cladding tube was maintained at 328±5 ℃ for 20 W/cm^2 and 330±5 ℃ for 80 W/cm^2, respectively. Dissolved oxygen (DO) was controlled below 5 ppb to eliminate the effects of oxygen on the crud deposition, and dissolved hydrogen (DH) was maintained at 35 cc/kg·H_2O (STP) by controlling the hydrogen overpressure of the solution tank.

After these conditions were stabilized, we injected the mixed Fe and Ni ions (each 0.5 ppm in weight) into the test section through the crud source injection pump with a flow 1.1 mL/min from the crud source tank directly to the downstream of the preheater. During the crud deposition tests, the acoustic sounds of SNB emitted from the heated cladding surface were monitored through the AE acquisition section for 300 s every 5 day. Crud deposition tests were conducted for 30 days. Table 1 summarizes the main experimental conditions for the crud deposition tests.

Table 1. Main experimental conditions for the crud deposition tests.

Heat flux (W/cm^2)	Water temp. (°C)	Solution concentration (ppm)	Others
20	328±5	•Primary water: 1200 B + 2.2 Li •Crud source: 0.5 Fe + 0.5 Ni	P=130 bar DO<5 ppb DH=35 cc/kg Flow=5 m/s 30 day-test
80	330±5		

After the deposition tests, the cladding tube was cut into tubular segments for the measurement of crud deposition mass and microscopic analysis of the crud. The concentration of Ni and Fe was analyzed using an inductively coupled plasma-atomic emission spectroscope (ICP-AES). The morphology and composition of the crud were analyzed using a scanning electron microscope (SEM) and an energy dispersive spectroscope (EDS).

3. Results and Discussion

Fig. 1 shows the AE hit number of the SNB signals under the two different heat flux conditions during the deposition tests. The AE hit number indicates the event number of AE signals detected on a channel. Therefore, it can be effective to compare quantitatively the relative boiling phenomenon on the cladding tube under the two different heat flux conditions. The AE hit number of the boiling signals at the two heat fluxes increased gradually as the test time progressed. However, a greater number of hits were recorded at the heat flux of 80 W/cm^2 than at the heat flux of 20 W/cm^2 throughout the deposition test duration. This indicates that the SNB behavior on the cladding tube increased remarkably at the higher heat flux condition during the deposition tests.

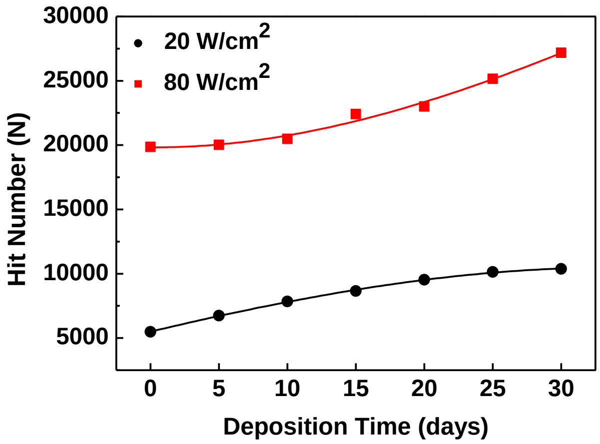
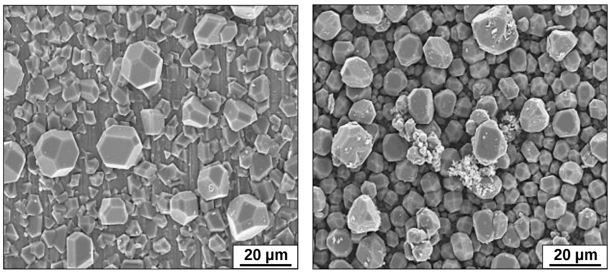


Fig. 1. Variation of the hit number of the AE signals under the two different heat flux conditions during the deposition tests.

Fig. 2 (a) and (b) show the SEM micrographs of crud deposited on the fuel cladding tubes at the two different heat flux conditions after the deposition tests. Polyhedral cruds with various sizes were uniformly deposited on both cladding tubes. However, the size and density of the crud increased evidently at 80 W/cm^2 than 20 W/cm^2. These cruds were analyzed to be a nickel ferrite ($Ni_xFe_{3-x}O_4$), where x=4-5, by SEM-EDS.

Fig. 3 shows the amount of crud deposited on the two cladding tubes after the deposition tests. The amount of crud increased by approximately 264 % at 80 W/cm^2 compared to that at 20 W/cm^2. According to the fuel inspections and the empirical studies, the crud deposition rate is accelerated through the evaporation of a micro-layer of liquid beneath a vapor bubble when SNB occurs on the fuel cladding surface [5-9,14]. In addition, our previous works demonstrated that a higher SNB on the fuel cladding surface leads to an increase in crud deposition [12,13]. Consequently, it is considered that the increased SNB behavior results in an increase in the amount of crud deposition in this work.



(a) (b)

Fig. 2. SEM micrographs of the crud formed at the two heat fluxes: (a) 20W/cm^2 and (b) 80 W/cm^2.

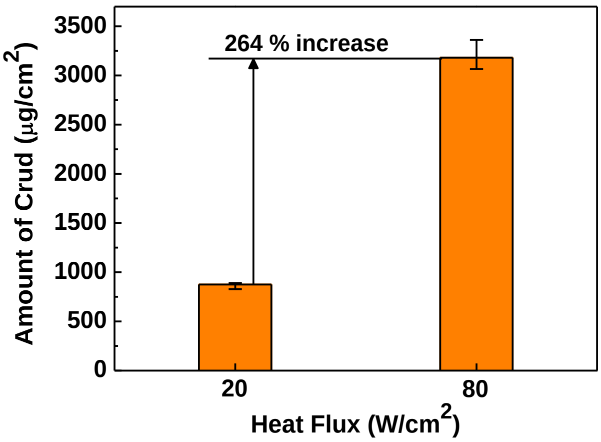


Fig. 3. Amount of crud deposited on the fuel cladding tube under the two different heat flux conditions after the deposition tests for 30 days.

4. Conclusions

This paper provides the effect of heat flux on the fuel crud deposition behavior and SNB behavior in simulated primary water of a PWR. AE monitoring results revealed that the SNB behavior increases at the high heat flux (80 W/cm^2) than the low heat flux (20 W/cm^2). Accordingly, the crud deposition mass increased by approximately 264 % at 80 W/cm^2 compared to that at 20 W/cm^2. In conclusion, the heat flux increases not only the SNB behavior, but also the crud deposition mass.

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