

Experimental Investigation of CRUD Effects on Transient Heat Transfer and Quenching Characteristics under Bottom Reflood Conditions

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1. Introduction

Chalk River Unidentified Deposits (CRUD) are porous corrosion-product deposits formed on fuel cladding surfaces during the normal operation of pressurized water reactors (PWRs) [1]. CRUD has conventionally been regarded as detrimental to fuel thermal performance because its relatively low thermal conductivity introduces additional thermal resistance between the fuel cladding and coolant. Previous studies have shown that CRUD deposition can increase the cladding temperature during normal operation and consequently reduce the thermal margin of the fuel [1]. However, the porous and hydrophilic structure of CRUD may also significantly alter boiling and rewetting phenomena during the reflood phase of a loss-of-coolant accident (LOCA). Previous studies have suggested that these competing effects can result in different thermal responses depending on the heat transfer regime [2]. Therefore, experimental characterization of the effect of an actual CRUD layer on reflood heat transfer is necessary to evaluate its influence on fuel coolability during accident conditions.

2. Experimental Methods

2.1 CRUD Deposit Experiment

In the present study, CRUD was first deposited on the surface of a test specimen under simulated PWR operating conditions utilizing DISNY facility [3]. The deposition experiment was conducted at a system pressure of 15.5 MPa, an inlet coolant temperature of 335 °C, and an applied heat flux of 600 kW/m². After 5 hr of deposition, a CRUD layer with an approximately 30 μm thickness was formed on the heated surface. A CRUD thickness of approximately 30 μm is within the range reported for PWR fuel surfaces.

2.2 Bottom Reflood Experiment

As illustrated in Fig. 1 and Table I, a bottom reflood experiment was conducted using CRUD-deposited and bare rods. The reflood test section was designed to reproduce transient cooling behavior under bottom injection of emergency coolant, where liquid coolant rises upward while counter-current vapor flow develops. The target initial surface temperature of the rod was

above 800°C. The coolant bulk temperature was maintained during reflood experiments with controlled subcooling for 6.5°C.

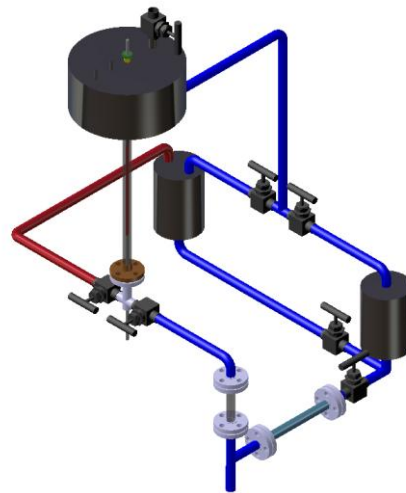


Fig. 1. Schematic of bottom reflood experiment loop.

Table I: Summary of Thermal Hydraulic Conditions

Parameter	Specimen (Rod)		Coolant	
Index	Initial T _{surf}	Surface	Sub-cooling	Velocity
Test #1	841.72 °C	CRUD	6.5 °C	25.4 mm/s
Test #2	814.88 °C	Bare	6.5 °C	25.4 mm/s

3. Results and Discussion

Fig. 2 shows that the presence of CRUD significantly modified the reflood heat transfer characteristics. Compared with the bare surface, the CRUD-deposited surface generally exhibited enhanced heat transfer during the reflood transient, except in the inverted annular flow film boiling regime. In particular, the CRUD layer resulted in an increase in the minimum film boiling temperature (MFBT), indicating an earlier destabilization of the vapor film and transition toward surface rewetting. Consequently, the CRUD-deposited specimen exhibited a shorter quenching time than the bare specimen. The heat transfer coefficient during the rapid cooling and quenching process was also increased

in the presence of CRUD. These observations indicate that the porous surface structure formed by CRUD can promote liquid-surface interaction and facilitate rewetting during the transition from film boiling to more effective cooling regimes.

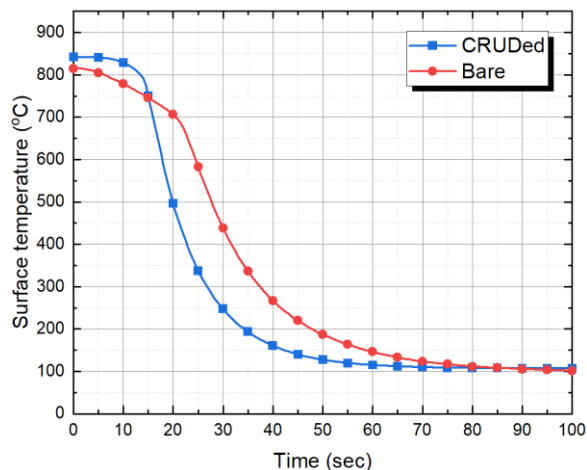


Fig. 2. Surface temperature histories.

This behavior is consistent with previous observations for porous and hydrophilic oxide-deposited surfaces. Such surfaces have been reported to enhance liquid spreading and capillary-driven liquid supply, thereby increasing the MFBT and accelerating quenching [4]. Literature data for nanoparticle-deposited porous surfaces generally show an increase in MFBT and enhanced quenching heat transfer compared with untreated surfaces [4]. CRUD formed under boiling conditions is also known to possess heterogeneous porous structures containing microscopic pores and steam chimneys, providing a physical basis for enhanced liquid transport and surface rewetting.

In contrast, a different trend was observed in the inverted annular flow film boiling regime. In this regime, the heat transfer performance of the CRUD-deposited surface was lower than that of the bare surface. Because direct liquid contact with the heated surface is strongly restricted by the intervening vapor layer, the beneficial effects associated with CRUD wettability and capillary liquid transport are expected to be limited. Under these conditions, the additional conductive resistance introduced by the low-thermal-conductivity CRUD layer becomes dominant, resulting in deterioration of the overall heat transfer performance.

These results demonstrate that the influence of CRUD on reflood heat transfer cannot be represented solely by an additional thermal resistance. Instead, two competing mechanisms govern the thermal response of a CRUD-deposited surface: deterioration caused by the thermal resistance of the deposit and enhancement associated with its porous and wettable surface characteristics. The former dominates during inverted annular flow film boiling, whereas the latter becomes increasingly important as the vapor film destabilizes and the surface approaches rewetting. Consequently, CRUD deposition

increased the MFBT, enhanced quench heat transfer, and shortened the overall quenching time. The present experimental results show the regime-dependent thermal effects of CRUD and can contribute to improved modeling of CRUD effects in safety analyses.

4. Conclusions

This study experimentally investigated the effects of CRUD layer on reflood heat transfer. The CRUD-deposited surface showed reduced heat transfer performance during inverted annular flow film boiling due to the additional thermal resistance of CRUD. In contrast, CRUD enhanced subsequent cooling, resulting in a higher minimum film boiling temperature, shorter quenching time, and higher quench heat transfer coefficient. These results demonstrate that CRUD has regime-dependent effects during reflood, governed by the competition between its thermal resistance and enhanced rewetting characteristics. In the future, bottom reflood experiments will be conducted under various CRUD thickness conditions to quantify the thermal properties and investigate the trends in the quench heat transfer performance.

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