

Assessment of Transient Reflood Cooling Performance as a Basis for Heat Transfer Evaluation of CRUD-Deposited Surfaces

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1. Introduction

CRUD on fuel cladding surfaces in pressurized water reactors (PWRs) is recognized as an important factor influencing heat transfer performance under both normal operation and accident conditions. CRUD originates from corrosion products in the primary system and deposits on the cladding surface under subcooled nucleate boiling conditions [1]. While CRUD formation during steady operation mainly introduces additional thermal resistance and elevates cladding temperature, its impact becomes more significant under design-basis accident scenarios where effective emergency cooling is required.

In PWR designs such as APR1400 and OPR1000, ECCS operation involves bottom reflood injection, where coolant rises upward against counter-current vapor flow. The thermal-hydraulic behavior during reflood is governed by complex two-phase heat transfer mechanisms, including film boiling, transition boiling, and nucleate boiling. Quench curves derived from surface temperature measurements are widely used to identify characteristic transition temperatures such as minimum film boiling temperature, rewetting temperature, and critical heat flux temperature [2].

Although bottom reflood heat transfer has been widely studied [3–4], most investigations focus on clean rod surfaces. Because CRUD alters both thermal resistance and surface wettability, it can affect rewetting dynamics, quench front propagation, and transient heat flux behavior. However, systematic evaluation of reflood heat transfer on CRUD-deposited surfaces remains limited.

Accordingly, the ultimate objective of this research is to evaluate the heat transfer performance of CRUD-deposited surfaces under bottom reflood conditions. As a foundational step, the present study establishes an experimental framework to analyze transient cooling behavior based on measured temperature histories. This methodology will be extended to CRUD-deposited specimens to develop a mechanistic quench heat transfer model incorporating both additional thermal resistance and surface condition effects.

2. Experimental Method

As illustrated in Fig. 1, a bottom reflood quenching experiment was conducted using a single cylindrical rod

to simulate reflood conditions. The test section was designed to reproduce transient cooling behavior under bottom injection, where liquid coolant rises upward while counter-current vapor flow develops. The target initial surface temperature of the rod was at least 730 °C (≈ 1000 K) prior to coolant injection. The coolant bulk temperature was maintained at saturation temperature with controlled subcooling conditions. The reflood condition corresponds to a low-pressure steam-liquid interaction environment, where quench front propagation governs the dominant heat transfer mechanism.

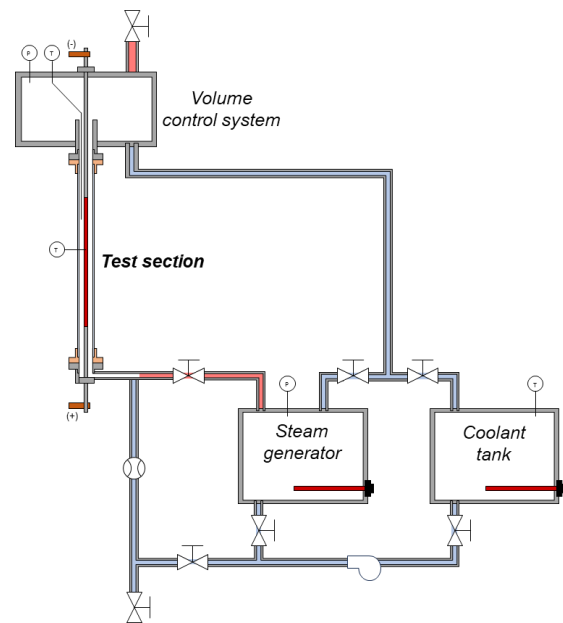


Fig. 1. Schematic of reflood test loop.

Table I: Summary of Thermal Hydraulic Conditions

Parameter	Specimen (Rod)		Coolant	
	Initial T_{surf}	Linear power	Sub-cooling	Velocity
Test #1	810.05 °C	1.85 kW/m	1.0 °C	25.4 mm/s
Test #2	747.90 °C	-	1.0 °C	25.4 mm/s

Inner wall temperature was measured continuously during the transient cooling process. The measured temperature history was used as a boundary condition for

inverse heat conduction analysis. The governing one-dimensional transient heat conduction equation in cylindrical coordinates was utilized to reconstruct heat flux and heat transfer coefficient during reflooding. The radial domain was discretized into finite control volumes, and explicit time integration was applied under stability constraints verified by Fourier number analysis. The reconstructed heat flux and heat transfer coefficient were further used to generate the boiling curve to identify transition points corresponding to film boiling collapse and nucleate boiling onset.

3. Results and Discussion

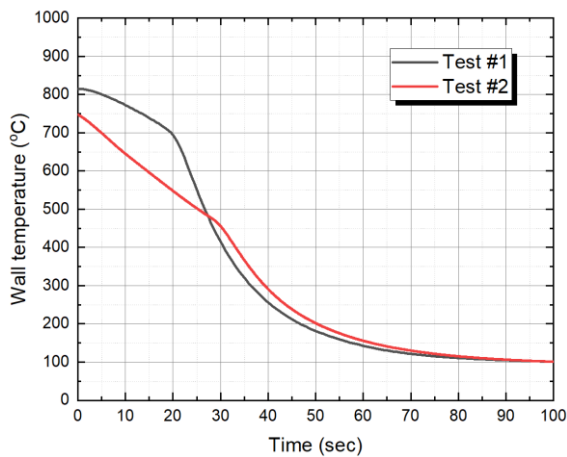


Fig. 2. Surface temperature histories.

Fig. 2 compares the transient wall temperature histories obtained from Test #1 and #2. The primary differences between the two cases are the initial surface temperature prior to quenching and the presence of continued heating during the early stage of reflood in Test #1. A notable distinction is observed during the early film boiling regime. In Test #2, the cooling rate is slightly reduced compared to Test #1 during the initial 0–25 s period. This behavior can be attributed to a relative delay in coolant supply to the heated surface due to the slower propagation of the rewetting front. The higher initial wall temperature and sustained heating in Test #2 likely intensified vapor generation, thereby strengthening the vapor layer and reducing effective liquid–solid contact. As a result, the effective film boiling heat transfer coefficient decreased, leading to a moderated temperature decay in the early stage. This trend indicates that increased vapor production can suppress early liquid access and temporarily reduce cooling efficiency under reflood conditions.

In addition, the higher initial wall temperature in Test #2 resulted in an upward shift of characteristic quench-related temperature parameters. The minimum film boiling temperature and the apparent rewetting temperature were observed at higher absolute temperature levels compared to Test #1. This behavior is consistent with the increased vapor generation intensity and thicker initial vapor layer formed at elevated surface temperatures. Consequently, the temperature at which

vapor film instability occurs increases with increasing initial wall temperature.

Overall, the results indicate that transient liquid supply, vapor film instability, and quench front propagation are the primary mechanisms governing heat removal under bottom reflood conditions. The consistency between temperature evolution, reconstructed heat flux peak, and boiling curve characteristics supports the validity of the inverse heat conduction methodology for analyzing reflood heat transfer behavior.

4. Conclusions

An experimental and inverse analysis approach was applied to characterize transient reflood heat transfer behavior. The results demonstrated that vapor film collapse and rewetting front propagation control the dominant heat removal event during bottom reflood conditions. The reconstructed peak heat flux ($\sim 90 \text{ kW/m}^2$) falls within the typical range reported for reflood experiments, supporting the physical consistency of the inverse methodology.

Future work will extend the methodology to specimens with CRUD-deposited surfaces to quantify the combined effects of thermal resistance and surface wettability. Based on these results, a mechanistic quench heat transfer model will be developed to improve predictive capability for CRUD-influenced reflood cooling.

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REFERENCES

- [1] J. Deshon, D. Hussey, B. Kendrick, J. McGurk, J. Secker, and M. Short, Pressurized Water Reactor Fuel Crud and Corrosion Modeling, *The Journal of The Minerals*, Vol. 63, No. 8, p. 64–72, 2011.
- [2] J. J. Carbajo, A study on the rewetting temperature, *Nuclear Engineering and Design*, Vol. 84, No. 1, p. 21–52, 1985.
- [3] M. Chen, D. Chen, H. Liu, H. Liu, L. Zhong, and J. Deng, Experimental Investigation of Droplet Transient Behavior during Reflood Cooling Process of Single-rod Channel,” *International Journal of Thermal Sciences*, Vol. 195, p. 108667, 2024.
- [4] Y. Sudo, Film Boiling Heat Transfer during Reflood Phase in Postulated PWR Loss-of-coolant accident,” *Journal of Nuclear Science and Technology*, Vol. 17, No. 7, p. 516–530, 1980.