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Test Requirements for Surface Characteristics of High Burnup Cladding Under LOCA and RIA Conditions

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1. Introduction

Newly proposed acceptance criteria for the Emergency Core Cooling System (ECCS) in Korea include oxidation limits reflecting the degree of burnup, assessment of the effects of breakaway oxidation, and changes in core geometry due to fuel relocation and dispersion [1, 2]. In addition, the nuclear fuel modeling requirements for safety analyses during a Loss-of-Coolant Accident (LOCA) require consideration of cladding inner surface oxidation, thermal resistance by CRUD (Chalk River Unidentified Deposit) and the oxide layer, and fuel pellet relocation and dispersion.

In preparation for the upcoming revision of the LOCA and the Reactivity Initiated Accident (RIA) licensing standards, it is necessary to establish multi-physics experimental data, validate multi-physics coupled safety analysis systems, and develop uncertainty quantification methodology. These can be used to evaluate the suitability of the analysis models for individual physical phenomena that require further evaluation under the new licensing standards, and to validate the integrated analysis system and the evaluation methodology for licensing.

One of the major phenomena related to core safety in high-burnup nuclear fuel is the increased clad oxidation due to corrosion. Under LOCA or RIA conditions, cladding properties with significant oxide film thickness contribute to significant degradation of clad strength and ductility. On the other hand, even under steady-state conditions, the additional thermal barrier provided by the clad oxide layer and the CRUD can increase the fuel temperature and hence the cladding internal pressure.

The CRUD deposition due to subcooled boiling on the cladding surface increases according to the core power increase, long cycle operation and the use of high burnup fuel. In terms of safety analysis, recent licensing analyses have required that the effects of CRUD be included in the heat transfer model when analyzing the accident behavior of fuel rods.

For these purposes, KEARI is now preparing multi-physics coupled LOCA and RIA experiments on the surface characteristics due to oxidation and CRUD in high burnup claddings. This paper briefly summarizes the current status of research on LOCA and RIA technical standards for high burnup cladding. In addition, the test requirements for the LOCA and RIA experiments related to the surface characteristics of the high burnup cladding are briefly summarized.

2. High Burnup Cladding in LOCA

The oxide and hydriding of the cladding as a function of nuclear fuel burnup are key parameters affecting corrosion and fuel performance in LOCA [3]. Thus, it is necessary to develop accurate models and correlations affected by oxide and hydriding. As fuel burnup increases, the hydrogen content in the cladding gradually increases, causing corrosion of the cladding. The degree of hydriding is affected by the cladding material properties, coolant conditions, and the clad surface oxide film thickness.

The surface of PWR high burnup cladding is characterized by oxide layer and hydriding formation, as well as CRUD due to deposition of various solid particles in the coolant. The main characteristic variables of the CRUD are the CRUD appearance (color), chemical composition, thickness, adhesive strength, areal density, particle size, porosity, and radioactivity.

According to Johnson Jr., the CRUD of spent fuel in pressurized water reactor (PWR) is mainly composed of $Ni_xFe_{3-x}O_4$, and the CRUD has been found to have a thickness of up to 85 μm. With improvements in clad material and operation, current PWR CRUDs are limited up to about 10 μm [4].

Post irradiation examination of PWR nuclear fuel has reported the formation of up to 15 μm at an average burnup of 55 GWd/tU [5]. The CRUD density has been reported to have a distribution of 48 to 65 mg/dm^2 (up to 1214 mg/dm^2) for spent fuel from PWRs and about 500 mg/dm^2 for spent fuel from boiling water reactors [6]. The porosity of the CRUD varies depending on the condition of the CRUD formation, and is generally known to be 40 - 50 % for PWRs [7].

Most of the experiments conducted on nuclear fuel under accident conditions have been aimed at investigating the nuclear fuel material behavior without considering the thermal-hydraulic conditions. Some studies have been conducted to simultaneously investigate the influence of both thermo-mechanical and thermal-hydraulic parameters on nuclear fuel material behavior. However, they are limited to measurement of fracture-related parameters such as cladding fracture pressure and fracture temperature, and post-test cladding phenomena. In the surface characterization experiment of the high-burnup cladding during the LOCA, we aim to apply real-time measurement technology to cladding tubes including oxidized cladding or simulated CRUD to perform thermo-mechanical and thermal-hydraulics coupled experiments in consideration of the high burnup. Table I shows the test conditions for the high-burnup surface characterization experiments during the LOCA.

Table I: Test Conditions for LOCA

Major test parameter	Test condition
Heater power	up to 2.5 kW/m
Ambient pressure	atmospheric
Clad internal pressure	2 ~ 7 MPa
Coolant velocity	0.2 ~ 6 cm/s
Clad initial temperature	500 ~ 600 ^{o}C
Initial oxidation thickness	up to 150 μm
Initial CRUD thickness	up to 100 μm
CRUD areal density	48 ~ 65 mg/dm^2
CRUD porosity	30 ~ 80 %

3. High Burnup Cladding in RIA

The existing RIA safety standards regulate only the maximum enthalpy that can be accumulated in the nuclear fuel cladding during an accident. The maximum enthalpy is based on experimental data for low-burnup nuclear fuel. Recent studies have shown that for high-burnup nuclear fuel, the increase in enthalpy is below the threshold, but various risks have emerged, such as nuclear fuel damage. As a result, interest in RIA in high-burnup nuclear fuel has increased, and various international joint experimental programs have been conducted in research reactors in France, Japan, and Russia.

Based on the latest research findings, the newly proposed RIA regulatory requirements are more stringent than the previous ones. In particular, the operating margin of nuclear reactors is reduced as the burnup of nuclear fuel increases. Accordingly, improvement in safety analysis code or additional in-pile experiments have been promoted overseas. It is necessary to perform uncertainty reduction of the safety analysis and additional validation experiments for the new requirements.

Various experiments have been conducted to investigate the effects of surface characteristics on the boiling heat transfer. The main parameters of these experiments especially for the critical heat flux and quenching were the material types and the surface characteristics such as oxide thickness and structure geometry. However, very few fast transient experiments for boiling heat transfer according to the surface characteristics have been performed under RIA conditions.

Traditionally, in terms of analyzing nuclear fuel behavior during RIA, the focus has been on the phenomena under conditions where the energy generated during a very short period of time accumulates in the fuel pellets. Thus the heat transfer model at the cladding surface has not been considered important and the thermal-hydraulic model used in typical accident conditions has been applied. However, it has been recognized that the post-DNB heat transfer correlations can have a significant effect on the cladding temperature. In recent years, there has been a need to develop major thermal-hydraulic models for the very fast transient conditions and to develop a multi-physics coupled system analysis code for the RIA analysis.

In general, oxide films on heating surfaces are known to affect boiling heat transfer and have been studied under various conditions. However, there is some lack of knowledge on the effects of the surface characteristics on the fast transient boiling such as RIA. Therefore, in this study, we simulate the oxide film on a high burnup cladding tube and perform fast transient boiling heat transfer experiments under RIA conditions similar to the operating conditions of a nuclear power plant. The experiments are divided into steady state and transient state, and bare and oxidized tubes made of Zircaloy-4 and Inconnel-600 will be used. The system pressure is up to about 15 MPa, the inlet subcooling is up to 300 kJ/kg, and the mass flow rate is up to 3500 kg/m^{2}s. The applied power to the cladding is a pulsed power simulating steady state or RIA. The data obtained from the experiments will be used to investigate overall boiling heat transfer phenomena from single phase to post-CHF heat transfer during the fast transient conditions.

4. Conclusions

Based on the LOCA and RIA test requirements presented in this paper, the effects of surface properties such as oxidation and CRUD on the LOCA and RIA safety in high burnup nuclear fuel will be evaluated. The results of this study can be used to secure experimental data for new domestic acceptance criteria, to develop and validate individual models for regulatory standards and safety analysis methodology.

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