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Failure behavior of Zircaloy-4 cladding after oxidation and water quench

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Abstract

Simulated LOCA (loss of coolant accident) tests and subsequent mechanical tests on Zircaloy-4 cladding were carried out to evaluate the failure behavior of the cladding. Zircaloy-4 claddings were oxidized in a steam environment from 900 to 1250 °C for a given time period followed by a flooding of cool water to simulate LOCA tests. After the simulated LOCA test, the ductility of the oxidized cladding was evaluated by mechanical tests such as ring compression test and 3-point bend test. Evaluation of the absorbed contents such as hydrogen and oxygen were also carried out. The results showed that Zircaloy-4 cladding failed during thermal shock when the ECR (equivalent cladding reacted) value exceeded 20%. Lower boundary of brittle failure at thermal shock corresponds to 20% of ECR line calculated by the Baker–Just equation regardless of test temperature. On the other hand, boundary of ductile failure by the mechanical test did not followed after the ECR line. It rapidly decreased above 1000 °C to show that all Zircaloy-4 claddings behaved brittle fracture above 1150 °C when it oxidized at 300 s. Microstructural analysis revealed that boundary of ductile failure by the mechanical test fitted well when the absorbed oxygen content inside the prior-β layer was below 0.5 wt%.

1. Introduction

Fuel cladding is a component which contains fuel pellets to prevent fission products from being released outside. Because of the advantage of a neutron economy, zirconium alloy is used for the fuel cladding. It is of importance that the fuel cladding should maintain its fuel integrity in a postulated design-based accident, as well as during a normal operation. In terms of this, a loss of coolant accident (abbreviated as LOCA) is treated as one of the most important design-basis accidents in a light water reactor (LWR). When a LOCA occurs, the temperature of the fuel system rises so that the cladding undergoes an oxidation caused by the reaction of the mixture of water and steam. After a certain time interval, the emergency core cooling system activates, and water is injected to cool down the hot core, which is inevitably accompanied by a thermal shrinkage of the cladding. When the embrittled cladding cannot stand the stress involved, the cladding fragments, which results in a release of radioactive fission product. To maintain the fuel integrity under postulated LOCA conditions, the Nuclear Regulatory Commission (NRC) established the fuel safety criteria related to a LOCA, where the peak

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fuel temperature and the total oxidation cannot exceed 1204 °C and 17% level respectively [1]. However, such criteria have been founded by applying a safety margin based on the Hobson's ring compression test [2], and it is reported that there exist differences between the existing safety criteria and the behavior of a actual cladding [3,4].

The objectives in this study are to quantitatively analyze the failure behavior of the fuel cladding and to construct a failure map of the fuel cladding under a simulated LOCA situation. Cladding was oxidized at various temperatures and times followed by an injection of cool water. Mechanical tests, such as the ring compression test and the 3-point bend test were carried out at the oxidized cladding. Finally, mechanical test result after LOCA test was incorporated into the conventional failure map and the revised failure diagram of the fuel cladding was evaluated to quantitatively evaluate the failure behavior of the oxidized cladding.

2. Experimental

2.1. Simulated LOCA test

Fig. 1(a) shows an illustration of a facility used for simulated LOCA test. A 200 mm-long Zircaloy-4 tube, which respectively has 9.5 mm outer diameter and 0.57 mm of thickness, was used in this study. Composition of Zircaloy-4 was Zr–1.3Sn–0.2Fe–0.1Cr, whose microstructure was stress-relieved. A direct heating by the ohmic resistance was applied to heat the specimen up to 1265 °C. The length of the heated section of the specimen was 160 mm. Specimen temperature was measured by a pyrometer. Before the test, a temperature calibration of the pyrometer was performed by using an attached thermocouple on the specimen at the same time. The temperature profile of the pyrometer and the thermocouple calibration revealed that the differences were no more than about 3–5 °C during the entire test period. In addition, axial temperature profile along the specimen was measured. Temperature value at the point ±80 mm from the midpoint revealed no more than ±20 °C.

To simulate a LOCA condition, the specimen was oxidized in a flowing steam at a desired temperature and time. The steam injected before turning on the power. During the initial stage of heating, an overshoot of the temperature may occur that could affect the high temperature oxidation behavior of the specimen. To minimize the overshoot, a

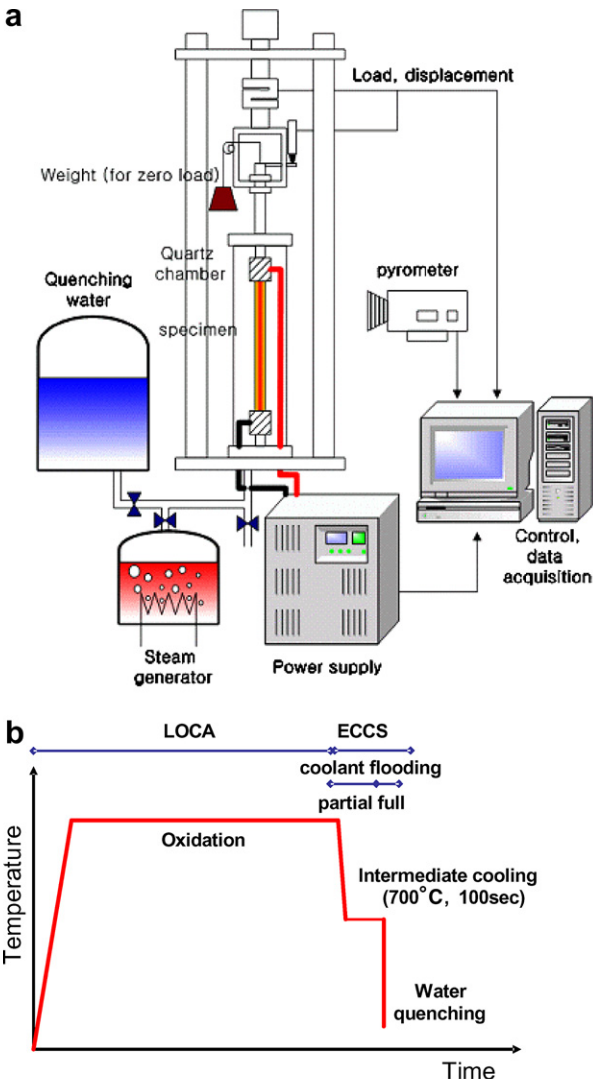

Fig. 1. Illustration of the LOCA simulation test: (a) test facility; (b) test scheme.

two-step heating was adopted. That is, a specimen was heated below the desired temperature in a short time to maintain the peak temperature below the test temperature, then it was heated to the desired temperature. When the cladding is exposed to an emergency coolant at the refill regime, a violent heat transfer between the hot cladding and cold water makes the coolant vaporize into steam, and the cladding temperatures do not abruptly drop until the sufficient coolant flooded the core. To simulate such a transient, the specimen was cooled at an intermediate temperature of 700 °C for 100 s after being oxidized, and then quenched. Such a transient is depicted in Fig. 1(b). During the test, the specimen may be subjected to unnecessary loads due to