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Crack formation in cladding under LOCA quench conditions

Hsingtzu Wu, Yutaka Udagawa, Takafumi Narukawa, Masaki Amaya*

Nuclear Safety Research Center, Japan Atomic Energy Agency, 2-4, Shirane Shirakata, Tokai-mura, Naka-gun, Ibaraki-ken 319-1195, Japan

HIGHLIGHTS

- The order of crack formation in cladding is proposed based on experimental data.
- Experimental data and RANNS computation suggest that the formation of cracks in the oxide during LOCA quench conditions could be related to the heat capacity inside cladding.
- RANNS computational results suggest off-center pellets might also affect crack formation in cladding in LOCA quench conditions.

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ABSTRACT

Loss-of-Coolant-Accident (LOCA) is a design basis accident that is considered in safety analyses for LWR. This paper discusses crack formation in one-side oxidized Zircaloy-4 cladding with LOCA oxidation quench experimental data. Two types of test pins were used in these experiments. One consisted of a Zircaloy-4 cladding tube and alumina pellets. Another comprised a Zircaloy-4 cladding tube alone. The experimental results showed that the fracture load in the latter cases was larger by about 1000 N, and cracks in the oxide layer were clearly observed in the former cases but not in the latter cases. This trend suggested that the order of cracks formed in cladding during LOCA quench conditions should be, first in the α-Zr(O) layer, and then in the oxide, finally in the prior-β layer when the fracture of cladding occurs. The formation of cracks in the oxide was considered to be related to the maximum thermal stress generated in the cladding during quench. RANNS computation suggested that the maximum radial temperature difference in the former case tended to be larger than that in the latter case, and the radial temperature difference increases considerably with off-center pellets, which might also affect crack formation.

1. Introduction

Loss-of-Coolant-Accident (LOCA) is a design basis accident that is considered in the safety analysis of a light water reactor (LWR). Generally there are three phases in a large break LOCA, *i.e.*, blowdown, refill and reflood phases. The blowdown phase occurs as a result of a break in the coolant system through which the primary coolant is rapidly expelled; the refill phase starts when the emergency core cooling system (ECCS) is activated; the reflood phase is initiated when the fuel elements in the reactor vessel begin to be flooded with the water injected by ECCS. The fuel cladding could become embrittled due to the oxidation occurred during the blowdown and refill phases. As the temperature of fuel cladding drops rapidly in the reflood phase, the thermal shock could fracture the embrittled cladding and damage the coolable geometry and structural integrity of the reactor core. Therefore it is necessary to investigate the cladding embrittlement and fracture behaviors under postulated LOCA quench conditions (WNEA, 2009). In this study, the crack formation in cladding is discussed with data of six LOCA quench experiments and simulation results using a fuel behavior analysis code.

2. Description of experiments

The experiment conditions in this study were slightly different from a design-basis LOCA: a fully restraint condition along the axial direction and excessive oxidation time were adapted in this study in order to clearly observe the crack formation in the relatively thick oxygen-stabilized alpha (α-Zr(O)) layer and oxide layer in the cladding. This section is divided into two parts. The first one specifies two types of test fuel pins used in six LOCA quench experiments, which are described in the second part, and the specification is listed in Table 1.

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* Corresponding author. Tel.: +81 29 282 5028; fax: +81 29 282 5429.
E-mail address: amaya.masaki@jaea.go.jp (M. Amaya).

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Table 1
Experimental data.

	Group 1 (20% BJ-ECR)		Group 2 (25% BJ-ECR)			
Experiment ID	Exp-1	Exp-2	Exp-3	Exp-4	Exp-5	Exp-6
Case number	1	2	1	1	2	2
Pellets inside cladding	Yes	No	Yes	Yes	No	No
Average oxidation temperature (°C)[a]	1198.5	1197.6	1198.4	1198.6	1199.2	1197.9
Oxidation time (s)[b]	1197.0	1200.5	1875.7	1881.0	1872.5	1872.5
Quench temperature (°C)[a]	694.1	686.1	699.2	694.5	681.1	693.1
Fracture time (TAQ) (s)[c]	NA	NA	7.8	4.0	55.5	50.9
Fracture temperature (°C)[a]	NA	NA	116.6	110.7	71.1	52.6
Fracture load (N)	NA	NA	1996.0	2128.0	3100.0	3146.0

[a] The control temperature.
[b] Region I in Fig. 2.
[c] Time after quench (illustrated in Fig. 2).

2.1. *Specification of test fuel pin*

Two types of test pins were used in this study. One consisted of a non-irradiated 17 × 17-type Zircaloy-4 cladding tube and 15 alumina (Al_2O_3) pellets. Another consisted of the cladding tube alone. The length, outer diameter and wall thickness of the cladding tube were 190 mm, 9.50 mm and 0.64 mm, respectively. The alumina pellet was 8.0 mm in diameter and 10.0 mm in length. Here, the alumina pellets were used to simulate the heat capacity of uranium oxide pellets (WNEA, 2009). The cases with pellets inside cladding are labeled as “case 1” and the cases without pellets inside cladding as “case 2.”

2.2. *Experimental procedure*

Fig. 1 shows a schematic of the experimental setting. The test pin—filled with about 0.1 MPa of Argon gas at room temperature before being sealed—was placed at the center of a quartz tube. Steam was introduced into the quartz tube at a rate of about 5 mg/(cm^2 s) from the bottom, flowed through the annulus and finally dispersed to the air. The temperature measured by a thermocouple welded at the axial center of cladding was defined as *the control temperature*. The effect of a spot-welded thermocouple on the cladding behavior in experiments that simulate LOCA conditions was considered negligible (Nagase et al., 2009). The test pin was heated at a rate of about 10 °C/s to 1195 °C using an infrared furnace when *the control temperature* reached about 90 °C.

Fig. 2 shows a typical history of *the control temperature* in the experiments. The isothermal oxidation phase (region I in Fig. 2) was initiated when *the control temperature* reached about 1195 °C, and it was maintained at (1198 ± 3) °C throughout the duration of oxidation time, which was controlled to be similar for group 1 (Exp-1 and Exp-2) and group 2 (Exp-3 to Exp-6) as shown in Table 1. The Equivalent Cladding Reacted (ECR) values, computed using the Baker–Just equation (Baker and Just, 1962), go to 20% and 25% for groups 1 and 2, respectively. In all experiments, the pressure difference between the inside and outside of cladding was so small that ballooning and rupture of cladding did not occur, and only the outer surfaces of the test pins were oxidized. Cladding was completely restrained along the axial direction by a grab that was connected to a load cell just after region I. Then the test pins were naturally cooled down (region II in Fig. 2) until *the control temperature* reached a quench temperature of about 700 °C, and the test pins were quenched by room-temperature water injected from the bottom of the quartz tube at a rate of 3.0–4.0 cm/s. The quench temperatures of the six experiments are also listed in Table 1. *The control temperature* was continuously measured by the spot-welded thermocouple during the experiments. The axial load generated in cladding after the isothermal oxidation phase was measured by the load cell with an uncertainty of about 1%.

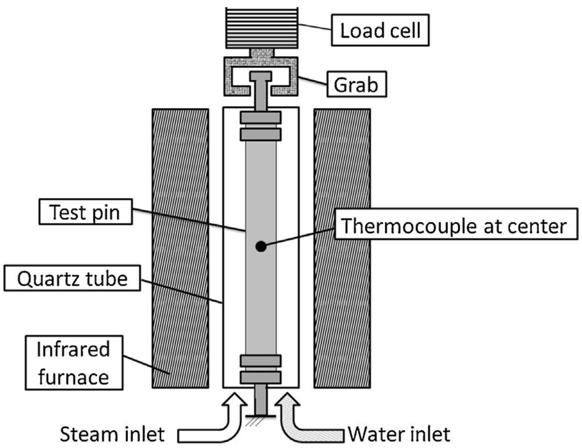

Fig. 1. Sketch of experimental setup.

3. Results and discussion

The experimental data are discussed from three perspectives in this section. The order of crack formation in cladding is discerned with experimental data. Then the effects of heat capacity inside cladding and the off-center pellets on the crack formation in the oxide layer are analyzed with RANNS computation. RANNS is a pin-scale code developed by Japan Atomic Energy Agency (JAEA) for transient analyses of fuel rods, and more information can be found in (Wu et al., 2016).

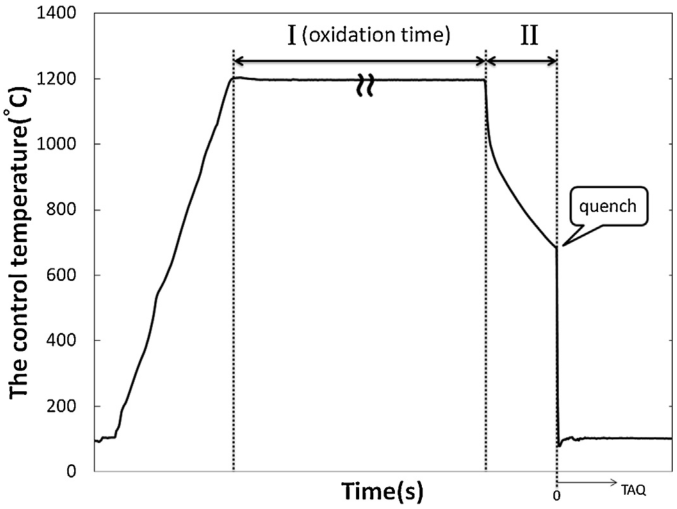

Fig. 2. A temperature history of the experiments.