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Experimental investigations on out-of-pile single rod test using fuel simulator and assessment of FRAPTRAN 2.0 ballooning model

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ABSTRACT

The extent of clad tube ballooning is important when analyzing the upper limits of coolant-channel blockage and subsequent planning of emergency core cooling system (ECCS) design strategy. As per revised ECCS acceptance criteria, the safety-analysis code system should be able to predict precisely fuel rod behavior to simulate a realistic safety analysis under off-design conditions. Considering these aspects, the present investigation was carried out to access the capability of FRAPTRAN 2.0 code to predict the ballooning behavior of cladding at various heating rates and internal pressures. Three tests at (4.5, 5.5, and 6.5) MPa and heating rates of 1.7–4 K/s were performed on a facility named 'FISRBIT' (**F**acility to **I**nvestigate **S**ingle-**R**od **B**ehavior **I**n **T**ransient) under inert gas atmosphere. Transient temperature, pressure, and deformation were recorded during the experiment at three axial positions over the internally heated Zircaloy-4 clad tube. Ballooning started at the location with the highest temperature; then propagated in the axial directions. Under fast transient heating, the balloon was confined near the highest temperature site, but at slower rates, an axially elongated balloon was observed. The test time between initiation of ballooning and rupture varied from 25 to 100 s depending on heating rate and internal pressure. The maximum hoop-strain prediction based on the hoop-stress calculation by the Rosinger model was better than the FRACAS-I and BALON-2 models. Using the Rosinger model, the hoop stress increased gradually until burst; hence, it was judged to simulate the physics of ballooning adequately. The rupture timing prediction by the FRAPTRAN 2.0 code was sooner than in the experimental results. One reason for the early rupture prediction was the time-independent behavior of the plastic model adopted by the code for modeling the ballooning phenomenon.

1. Introduction

Economic concerns are now compelling nuclear power utilities to consider the increase of average burn-up for fuel assemblies and to adopt new types of cladding materials to enhance thermal and safety margins. Sustaining such aggressive conditions for fuel and reactor cores requires new research on fuel rod behavior under reference accidental conditions to meet current safety criteria and to provide new technical bases for modeling. As per revised emergency core-cooling-system (ECCS) acceptance-criteria, the safety analysis-code system should calculate the fuel behavior models. A loss of coolant accident (LOCA) analysis requires a thorough investigation of ballooning and burst behavior of fuel cladding to identify their potential interference with emergency cooling effectiveness. This is because ballooning and rupture locations at the same axial position could result in significant flow blockage. The deformation behavior for cladding has been widely investigated in the past to validate the models in the context of LOCA assessment. Chung and Kassner (1979) investigated the effect of the internal pressure, heating rate, steam, and temperature on the ballooning behavior of Zircalloy-4 cladding. Chapman et al. (1979) reported that clad deformation is extremely sensitive to small temperature variation at the surface. Karb et al. (1982) conducted experiments to investigate the influence of the nuclear environment on the cladding failure behavior. No significant effect was observed due to irradiation exposure over the cladding failure mechanism. Erbacher and Leistikow (1987) stated that a large azimuthal temperature gradient around the periphery of a clad tube causes uneven wall thickness in the ballooned region resulting in a small burst strain. Kim et al. (2004) reported the role of phase transformation (from α to β phase) in the deformation behavior of Zircaloy-4 under transient conditions. Recent series of experiments conducted by Kekkonen (2005) at Halden Reactor provided

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Nomenclature

E	modulus of elasticity (N/m^2)
K	strength coefficient
m	strain sensitivity factor
n	strain hardening factor
P_i	instantaneous pressure inside rod (N/m^2)
P_{ini}	initial fill pressure of rod (N/m^2)
P_o	external coolant pressure (N/m^2)
r_o	outside radius of clad tube (m)
r_i	inside radius of clad tube (m)
r	instantaneous cladding radius (m)
r_{ini}	initial cladding radius (m)
r_{ave}	average cladding radius (m)
r_{cn}	inside radius of clad tube at nth node (m)
r_{fn}	pellet radius of at nth node (m)
R	specific gas constant
T	temperature (K)
t	instantaneous thickness of cladding (m)
t_{avg}	average cladding thickness (m)
T_0	reference temperature (K)
T_{Gn}	gas temperature at nth node (K)
T_p	plenum temperature (K)
V_p	plenum volume (m^3)
ΔZ_n	axial length up-to node n (m)

Greek letters

ε_b	burst strain
ε_θ	effective hoop strain
ε_z	effective axial strain
ε_r	effective radial strain
ε_i	strain at previous time step
ε_{i+1}	strain at current time step
$d\varepsilon^p$	increment in plastic strain
σ_{ini}	initial stress (N/m^2)
σ_θ	hoop stress (N/m^2)
σ_z	axial stress (N/m^2)
σ_e	effective stress (N/m^2)
α	thermal expansion coefficient
ν	Poisson's ratio

substantial data regarding fuel rod behavior under transient conditions for code validation and further improvement. Because the precise prediction of fuel rod behavior is essential for a realistic safety analysis, the FRAPTRAN 2.0 code developed by Pacific Northwest National Laboratory is widely used by many research groups to simulate reactor transients (such as a LOCA) in a Light Water Reactor. The code calculates local large plastic deformation during ballooning using the 'BALON2' model (Hagrman et al., 1981). The burst criterion for the prediction of failure is based mainly on experiments conducted by Chapman et al. (1979), Chung and Kassner (1979), and Hobson and Rittenhouse (1972).

It is apparent from a literature review that the deformation is strongly governed by the temperature distribution over the surface of the clad tube. The extent of ballooning in a biaxial direction is important for analyzing the upper limits of coolant-channel blockage. In the present investigation, an experimental facility named 'FISRBIT' (**F**acility to **I**nvestigate **S**ingle **R**od **B**ehavior **I**n **T**ransient) was designed and developed to simulate LOCA scenarios by internally heating the Zircaloy-4 clad tube using a fuel simulator. Assessment of the FRAPTRAN 2.0 code was carried out based on transient temperature and radial deformation data recorded during the experiments.

2. Experimental setup and procedure

2.1. Details of the test section

Fig. 1 shows details of the test section. The clad tube (length 340 mm, outer diameter 9.5 mm) was placed concentrically inside an enclosure of length 500 mm and the assembly was placed in a vertical position. The design characteristics of the facility are shown in Table 1. One end of the clad tube was fixed at the top flange of the enclosure and connected to a highly flexible copper clamp at the bottom end to minimize bowing of the clad tube at elevated temperatures. The clad tube was heated internally using a tungsten heater (100 mm long) that was fixed inside the clad tube (i.e., 150 mm from the top end flange) using annular alumina pellets as packing. To measure deformation during ballooning, the tungsten heater was placed so that the zone of highest temperature during transient heating would be at the linear variable differential transformer (LVDT, strain gauge based technology) sensor location. Both ends of the tungsten heater were connected to a molybdenum rod of 6 mm diameter. The molybdenum rod was also insulated from the clad tube by the annular alumina pellets. To capture the transient temperature on the exterior surface of the clad tube, four K-type thermocouples (outer diameter 0.5 mm) were spot welded using zirconium foil of 0.1 mm thickness. One thermocouple was spot welded on the clad tube over the center location of the tungsten heater and one thermocouple was spot welded on either side of the central position at 30 mm distance to measure axial temperatures during the transient. One thermocouple was spot welded on the clad tube just below the top flange to measure the temperature of the plenum.

To measure the radial deformation of the cladding, three LVDTs were mounted to the wall of the enclosure at the locations where the thermocouples were spot-welded. The cladding deformation was measured using a ceramic rod (diameter 2.5 mm) to minimize the effect of thermal expansion at elevated temperatures. A glass window was also provided on one face of the enclosure for the capture of high-speed images. Fig. 2 shows a photograph of the experimental facility. The clad tube was pressurized using helium gas to the desired pressure through a stainless steel pipeline connected to a pressure port above the top flange of the setup. The desired pressure in the clad tube was maintained using a solenoid valve in combination with a pressure switch. To create a non-oxidizing atmosphere around the clad tube, helium gas was supplied to the enclosure through the bottom end flange. The power was supplied to the tungsten heater through flexible copper cables connected to a programmable DC power supply (capacity 1000 A and 10 V). The current input to the heating element was measured using a shunt mounted in series. The data voltage drop across the tungsten heater, and the current from the shunt were recorded for the power history. The signals from the thermocouples, LVDTs, pressure transducer, and DC power supply were acquired using a data acquisition system. All the thermocouples, LVDTs, pressure transducer, and shunt were calibrated before installation.

2.2. Experimental procedure

The clad tube was pressurized with helium to the desired pressure by energizing the solenoid valve in the pressure line. The helium gas was supplied to the enclosure through the