Nuclear Engineering and Design 339 (2018) 194–201

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Optical observation of the ballooning and burst of E110 and E110G cladding tubes

Richard Nagy[a,b,*], Márton Király[a], Tamás Szepesi[c], Attila Gábor Nagy[a], Ádám Almási[a]

[a] Hungarian Academy of Sciences, Centre for Energy Research, 1121 Budapest, Konkoly-Thege Miklós út 29-33, Hungary
[b] Óbuda University, Doctoral School on Material Sciences and Technologies, 1034 Budapest, Bécsi str. 96/b, Hungary
[c] Hungarian Academy of Sciences, Wigner Research Centre for Physics, 1121 Budapest, Konkoly-Thege Miklós út 29-33, Hungary

ABSTRACT

During the last decades several experiments revealed interesting details of the ballooning and burst of nuclear cladding tubes in accident conditions involving high temperature and high pressure. To further investigate this phenomenon, a new set of experiments was conducted at MTA EK. A large tube furnace was fitted with two optical telescopes on opposite sides to observe the ballooning and burst of Russian E110 and E110G (sponge based E110) fuel cladding samples. The experiments were recorded using regular and high-speed cameras. Based on the captured images we developed a method to separate the contours of the cladding tubes during the ballooning to measure the change in diameter. Two successive modes of ballooning were observed, the uniform growth of the samples was followed by an asymmetrical, local ballooning (bulge formation) 2 s before the burst. It was found that the samples have bent by approximately 5° relative to their original axis in the latter phase and this was not caused by the jet effect of the high pressure argon gas escaping after the burst. Every sample opened up on the convex side of the bend. Axial grooves have formed on the surface of the E110G samples under tension. The high-speed camera was used to capture the cracking and the burst. Prior to the burst, a high temperature spot was observed at the position where the crack would initiate. The timescale of the crack propagation was 0.2 ms, the crack tip was estimated to be at least 100 °C hotter than the rest of the sample. The burst pressure was determined between 700 °C and 900 °C at different pressurization rates.

1. Introduction

During loss-of-coolant accidents (LOCA) the geometry of the fuel assembly may change. The high internal pressure in the fuel rods, coupled with the loss of pressure in the reactor vessel and the rise of the fuel temperature can lead to the ballooning of the fuel cladding. The size of the deformation depends on several parameters including pressure increase rate, temperature history, degree of cladding oxidation, pressure difference between the inside and the outside of the cladding, presence of spacer grids and the deformation of neighbour rods (Hózer et al., 2005; Billone et al., 2009).

The cladding materials of the fuel rods in water-cooled nuclear reactors are zirconium alloys, which have low neutron absorption, low corrosion rate and high mechanical strength under normal operation conditions. In Russian VVER type reactors the cladding alloy is usually the E110 (Zr1%Nb) or one of its newly developed versions. However, at temperatures above 700 °C the mechanical stresses can result in significant non-elastic deformation leading to the burst of the fuel element. These conditions can be expected in loss-of-coolant accidents. When the pressure and most of the coolant is lost the cooling effectiveness decreases drastically and the cladding temperature can rapidly increase up to 1000 °C because of the decay heat.

To determine the burst pressure under different circumstances, two different methods have been used: either an isobaric sample is heated, or an isothermal sample is loaded by increasing pressure. Isobaric experiments can be closer to the reality of a LOCA, however, the isothermal method yielded similar results as well.

During LOCA the pressure of the primary coolant system drops to the containment pressure, and so the internal pressure of the fuel rods becomes higher than the coolant pressure. That changes the direction of the mechanical stresses in the cladding. The high temperature coupled with the pressure difference between the inner and outer surfaces of the cladding can initiate intense cladding deformation (i.e. ballooning) at the hottest part of the fuel rod. The extent of the deformation and the failure of the rod depends mainly on the cladding temperature and the fuel rod internal pressure.

Several sets of ballooning tests with E110 single rods and bundles were carried out in the MTA EK (Hungarian Academy of Sciences Centre for Energy Research) in Hungary (Hózer et al., 2005). The main objective of the single-rod tests was to provide the necessary experimental data for model development. Recently, the comparison of E110 and E110G cladding behaviour was also the aim of the various test series (Hózer et al.,2014).

Investigations of cladding tube deformation and flow blockage phenomena in a VVER assemblies were the main objectives of the integrated bundle tests (Hózer et al., 2005). Russian and German single rod and bundle tests showed the behaviour of E110 under accident conditions (oxidization, burst, quench, effect of hydrogen content,

---

[*] Corresponding author.

https://doi.org/10.1016/j.nucengdes.2018.08.027
Received 23 May 2018; Received in revised form 22 August 2018; Accepted 27 August 2018
Available online 22 September 2018
0029-5493/ © 2018 Published by Elsevier B.V.

secondary hydriding, etc…) (Yegorova, xxxx; Steinbrück et al., 2010). These integrated tests only gave the final stage of the fuel rods, i.e. the already ballooned and burst rods, but the actual kinetics of the ballooning and burst was unknown.

A mathematical description of the ballooning was published in 1977 by Kramer and Deitrich (1977). An analytical differential equation was developed to calculate the bulge formation, which revealed that temperature perturbations as low as 10 °C at around 800 °C have an effect on the bulge formation. In a study by Chung and Kassner (1978) high-speed camera recordings of the ballooning and burst of Zircaloy-4 cladding tubes were published. In these experiments ballooning and oxidation in high temperature steam was recorded at 1000 fps around the phase transition temperature. A laser lamp illuminated a 75 mm long sample, and fiber optics was used to observe the ballooning and the diametric and axial changes in an isobaric setup. Hofmann and Raff (1981) installed the video camera axially in a similar test series to record the circumferential strain at the burst position.

A new experimental series was launched at MTA EK to investigate the dynamics of cladding ballooning of VVER fuel claddings. Our goal was to reproduce the previously measured VVER data regarding burst pressure at different pressurization rates using the isothermal method, and to observe the ballooning and burst phenomena in detail using regular and high-speed video recording in the high temperature furnace.

2. Experimental

The experimental setup consisted of four parts: a modified tube furnace, an optical system, the pressure system and the control and data acquisition unit as seen in Fig. 1.

An electrically heated, three-zone steel tube furnace was constructed and built to keep the sample at a constant high temperature. The two outer zones and the central zone were regulated by PID controllers guided by K-type thermocouples. The inside of the furnace was 520 mm long and 104 mm in diameter. Heating up to the target temperature took 3–6 h because of the large thermal inertia of the insulation of the furnace. The temperature stability was ± 2 °C measured on the sample's surface. On two opposite sides of the retort, small stubs led to the outside of the furnace, these were the entry points of the telescopes.

The high pressure argon gas was fed into the cladding samples by a needle valve, in order to maintain a certain rate of internal pressure increment. The pressure increment had to be compensated for the volume growth, the thermal expansion, and also for some possible leakage at the joins and sealing rings. It was tested between 1 kPa/s and 0.5 MPa/s and the accuracy and linearity was over 99%. In the case of very small pressure increments, a 1 dm^3 buffer was put between the needle valve and the sample via a 0.7 mm inner diameter capillary to better regulate the argon flow. This increased the free volume by up to 50 times as the sample and the tubing itself was only about 20 cm^3, and was also helpful to avoid the uneven pressurization of the samples. The pressure was measured by two Suco 0720 type, linear mechanical–inductive transducers and two MAI-250 type Bourdon-tube manometers to read the pressure of the buffer and the sample during operation.

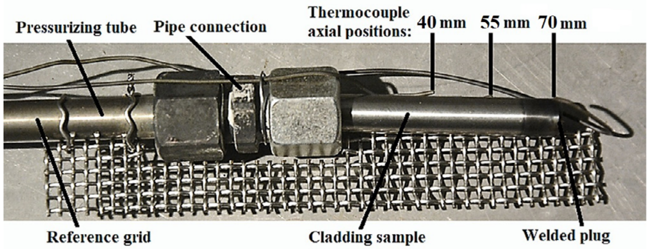

Fig. 2. An end-welded 85 mm long sample connected to the pressurizing pipes, with three thermocouples and the spatial reference grid. The axial position was measured from the connection.

For data acquisition and control, we used a Measurement Computing USB-2408 multifunction measurement device. The virtual instrument that controls the pressure increment rate and handles the data acquisition was developed in LabView 2014. Simple moving average and difference quotient was calculated from the measured pressure to regulate the stepper motor on the needle valve through a power amplifier circuit connected to the digital output of the DAQ unit.

Two identical optical telescopes have been constructed to observe and record the behaviour of the cladding samples during the tests, which were operable at 1000 °C. To avoid fatigue or stress caused by different thermal expansions, a telescopic dual tube system was used to adjust the effective focal length. At the point of burst a high pressure gas front hits the front lens, therefore thick lenses were designed. The first lens also had to resist internal stresses caused by the 10 °C/mm temperature gradient. The telescopes consisted of a flat-corrected condenser objective lens group (3 lenses, 27 mm in diameter) and an ocular or eyepiece lens (40 mm in diameter) made of high purity quartz (Heraeus). The lenses were held in place by quartz spacer rings. These

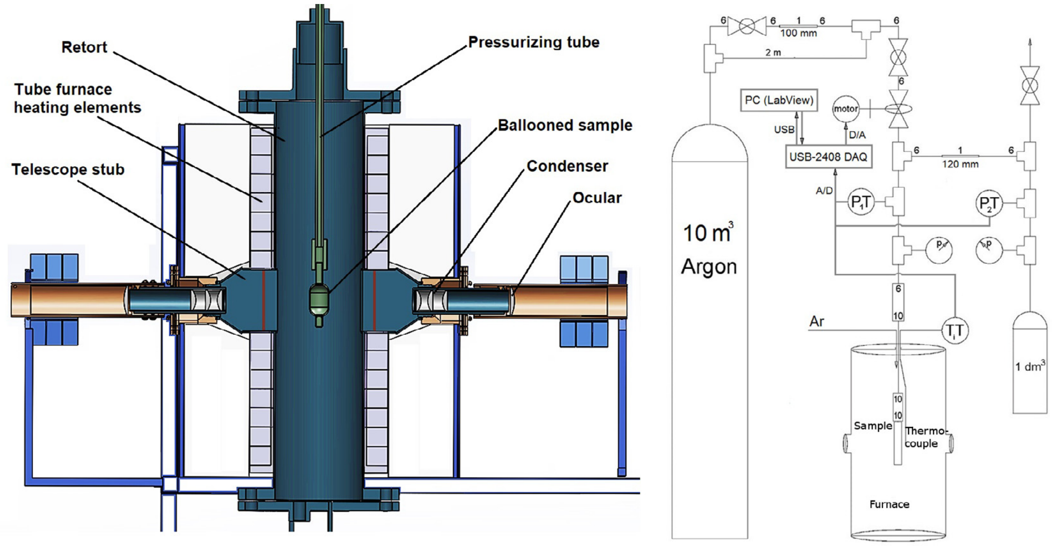

Fig. 1. The experimental setup: a schematic view of the furnace with the telescopes (left), and the pressure and control system (right).

Download English Version:

https://daneshyari.com/en/article/11031681

Download Persian Version:

https://daneshyari.com/article/11031681

Daneshyari.com