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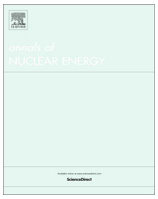

Burst investigation on zircaloy-4 claddings in inert environment

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ABSTRACT

An extensive burst investigation has been carried out on the zircaloy-4 claddings in an inert environment to simulate clad burst during a postulated loss-of-coolant-accident (LOCA) conditions. The parameters varied during the burst experiments were heating rate and internal overpressure. The temperature, internal overpressure and ballooning data were monitored online and recorded during the heating process of burst specimen. In addition, post-experiment measurements were also conducted on the burst specimen to determine various burst parameters–burst strains and burst stress. A semi-empirical correlation was developed to predict the burst stress for a given burst temperature. A reasonable agreement between the predicted and experimental data has been observed. The proposed correlation was also compared with available established correlation for steam environment.

1. Introduction

The zircaloy-4 claddings are used as container of fuel pellets in nuclear reactors. These tubes also act as a barrier between the coolant and the fuel. The heat produced due to fission gets transferred to the coolant through these tubes. During loss of coolant accident (LOCA) scenario, the coolant supply is affected and as such the clad tube surface temperature rises. The continuous rise in temperature and consequent rise in fission gas pressure can cause extensive deformation of the clad tubes. As a result, the clad ballooning is accompanied with axial contraction. Another consequence of ballooning deformation is the thinning of the tube, which makes it difficult to withstand the excessive stresses causing the tube to burst. Further, heating of zircaloy clad tube causes a change in microstructure at 1085 K temperature from α-phase (hcp) to β-phase (bcc) at 1248 K. In fact, within temperature range 1085–1248 K both α and β phases co-exist. The change in phase causes a change in material properties of clad tube.

An exhaustive review of literature by Alam et al. (2011) suggests that a lot of work has already been carried out to investigate the clad failure phenomena due to LOCA. In postulated LOCA experiments, the clad specimens are usually pressurized from inside by an inert gas either by helium or argon. The clad burst experiments are generally performed in various outside environments of air, inert gas, steam and vacuum. The operating variables are internal overpressure and heating rate or temperature. One of the ends of the clad specimen is kept unconstrained to allow the free contraction of the specimen during ballooning. Some of the important studies have been listed in Table 1. Such studies are helpful in formulating or improving the safety regulations of the nuclear reactor. The output of these studies also serves as valuable inputs for the designing of new reactors. From Table 1, it is clear that the burst studies are either conducted in constant temperature (isothermal) conditions or in constant heating rate conditions. Erbacher et al. (1982) performed an extensive experimental investigation on the bursting of zircaloy-4 cladding in steam environment. They also proposed a correlation for the burst stress as a function of burst temperature and oxygen content. Erbacher et al. (1982) and Neitzel and Rosinger (1980) developed the burst criterion of Zircaloy fuel claddings. The developed criterion was validated with the burst data of various researchers. Ferner and Rosinger (1985) found that azimuthal temperature difference played an important role in the ballooning deformation of the clad tube. Arai et al. (1987) developed the Larsen–Miller parameter (LMP) correlation for the combined data of isothermal and high thermal transient tests. They also demonstrated the suitability of LMP approach in predicting the cladding failure for wide range of time–temperature conditions. Zhou et al. (2004) performed short term rupture study on zircaloy clad tubes and they found that the burst test data followed the Larson–Miller parameter approach. Kim et al. (2004) conducted a study to see the changes in microstructure due to variation in thermal transients and temperature of the specimen. They found that the phase transformation from α-phase to β-phase played an important role in deformation of zircaloy-4. Seok et al. (2011) analyzed the creep data obtained

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Nomenclature

C	circumference, m
h	clad tube thickness, m
p	internal overpressure, Pa
R	clad tube radius, m
t	time, s
T	temperature, °C or K
TCE	total circumferential elongation
UCE	uniform circumferential elongation
Greek letters	
η	heating rate, K/s
σ	stress, MPa
ε	strain
Subscripts	
B	burst
r	radial direction
o	initial conditions
θ	circumferential direction

from the burst tests on ZIRLO claddings and ring-creep tests. The outcomes of the two tests were found to complement each other. Fewer studies are also available for zircaloy-4 clad tube bursting in outside inert atmosphere. The purpose of such studies is to set a reference for the zircaloy-4 cladding bursting in an outside oxidizing (steam) environment. One such study was conducted by Emmerich et al. (1969). They conducted experiments for very low range of internal overpressure as well as heating rate. Most recently, Khan et al. (2013) have developed a burst criterion for zircaloy-4 clad tubes in inert atmosphere.

Keeping in view the importance of clad failure under LOCA conditions, there is a need to develop burst equation for zircaloy-4 clad tubes used in Indian pressurized heavy water reactors (PHWRs) for an outside inert environment. The objective of the present work is to study the effect of internal overpressure and heating rate on the ballooning and subsequent bursting of the clad tube and to evolve a semi-empirical burst stress correlation (burst equation). It has also been observed that the transient clad ballooning data is rarely available in open literature. In the present work, an attempt has been made to capture the ballooning data in terms of tube wall displacement. The tracking data may be of use for validation of various transient numerical clad deformation models.

2. Experimental setup and procedure

The schematic diagram of the experimental setup is shown in Fig. 1. It consists of a strong mild steel enclosure to carry out the clad burst safely at a required pressure and heating rate. To pressurize test specimen (zircaloy-4 clad tube) at a given pressure, an argon gas cylinder with control valve is used. The internal overpressure has been monitored with the help of a pressure gauge and a pressure transducer. The test specimen is heated with the help of 64 kV A silicon controlled rectifier. The high magnitude direct current is transmitted to the specimen through copper bus bars and copper clamps. The magnitude of current passing through the specimen sets the desired rate of heating. Ungrounded K-type sheathed thermocouples (2 Nos.) have been spot welded on the outer surface of the clad specimen to measure the specimen temperature.

To capture the ballooning of the heated specimen at three different axial positions, a frame holding three non-contact type displacement transducers (accuracy ±10 μm) has been fabricated. The wall displacement of the tube is transmitted to the displacement sensors with the help of extremely light ceramic rod-block assembly, shown in Fig. 2. One end of each ceramic rod has been fitted to a ceramic block placed on clad specimen while the other end has been glued to a small piece of galvanized iron sheet as the displacement transducers can only detect metals. The guide mechanism, consisting of short length copper tubes, allows the ceramic rods to move vertically upward towards the transducers, as shown in Fig. 2.

An additional argon gas cylinder is used to conduct the burst experiments in inert atmosphere. The argon gas is purged through a perforated tube inside the enclosure right below the clad specimen, as shown in Fig. 1. This ensures the argon rich atmosphere near the clad specimen. Moreover, the purging is started a few

Table 1
Some important experimental studies on clad failure.

Author (s) (year)	Clad material	Inside clad fluid	Outside environment	Temperature conditions	Range of parameters
Emmerich et al. (1969)	Zircaloy-4	Helium	Argon	Constant heating rate	p = 2.5–11.9 bar η = 0.3–23.1 K/s
Erbacher et al. (1982)	Zircaloy-4	Helium	Steam	Constant heating rate	p = 10–140 bar η = 1–30 K/s
Ferner and Rosinger (1985)	Zircaloy-4	Inert gas	Steam	Constant heating rate	p = 3–29 bar η = 1–25 K/s
Arai et al. (1987)	Zircaloy-2	Argon	Atmosphere	Both constant heating rate and isothermal	p = 9.8–147.1 bar η = 5–200 K/s T = 923, 973 and 1073 K
Zhou et al. (2004)	Zircaloy-4 and Nb-modified Zircaloy-4	Argon	–	Constant temperature (isothermal)	T = 723–773 K σ_B = 40–100 MPa
Kim et al. (2004)	Zircaloy-4	Argon	Steam	Both constant heating rate and isothermal	p = 100–600 bar η = 1–100 K/s
Seok et al. (2011)	ZIRLO	Argon	Atmosphere	Constant temperature (isothermal)	T = 365–570 °C σ_B = 40–520 MPa
Khan et al. (2013)	Zircaloy-4	Argon	Argon	Constant heating rate	p = 20–80 bar η = 17.6–81.1 K/s