Nuclear Engineering and Design 313 (2017) 236–242

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Full length channel Pressure Tube sagging under completely voided full length pressure tube of an Indian PHWR

Sujay Negi [a,*], Ravi Kumar [a], P. Majumdar [b], D. Mukopadhyay [b]

[a] Indian Institute of Technology, Roorkee 247667, India
[b] Bhabha Atomic Research Centre, Mumbai 400085, India

HIGHLIGHTS

- At 16 kW/m input, thermal stability was attained at 595 °C, without PT-CT contact.
- At 20 kW/m step input, PT-CT contact occurred at 637 °C near bottom-center of the tube.
- PT integrity was maintained throughout the experiment.

ARTICLE INFO

Article history:
Received 8 July 2016
Received in revised form 28 November 2016
Accepted 19 December 2016

Keywords:
LOCA
Sagging
Pressure Tube
Calandria Tube
PHWR

ABSTRACT

An experimental investigation was conducted to simulate the sagging behavior of a full length Pressure Tube of a channel of 220 MWe Indian PHWR. The investigation aimed to recreate a condition resembling Loss of Coolant Accident (LOCA) with Emergency Core Cooling System (ECCS) failure in a nuclear power plant. A full length channel assembly immersed in moderator was subjected to electrical resistance heating of Pressure Tube (PT) to simulate the residual heat after shutting down of reactor. The temperature of PT started rising and the contact between PT and CT was established at the center of the tube where average bottom temperature was 637 °C. The integrity of PT was maintained throughout the experiment and the PT heat up was arrested on contact with the CT due to transfer of heat to the moderator.

1. Introduction

Safety considerations for a PHWR may be categorized as moderate frequency events like power distribution anomalies which cause positive reactivity insertion resulting from uncontrolled withdrawal of control rods or uneven concentration of neutron poison in the moderator. The decrease in primary heat transport (PHT) system inventory due to rupture anywhere in the coolant flow line as well as the increase in PHT system inventory due to failure in control system are moderately frequent events. Other moderate frequency failure events include malfunctioning of support and auxiliary systems leading to leak accidents and component trips. Low frequency events involve rupture or failure of components on a larger magnitude. The failure of coolant channel due to rupture in PHT piping of a size bigger than double ended largest feeder pipe lead to LOCA. Multiple failure events involve large or small LOCA events along with failure of ECCS system, failure to close isolation devices on the interconnection between PHT loops or containment impairment (AERB Safety Guide (2000)).

In a 220 MW(e) nuclear power reactor in Indian Pressurized Heavy Water Reactor (PHWR), the fuel in contained in 306 horizontal channels, each consisting of a Pressure Tube (PT) concentrically enveloped by Calandria Tube (CT) using garter springs. The pressurized heavy water coolant flows through the channels around the fuel bundles and carry the heat away for steam generation to be used in power production. These channels are completely submerged in heavy water moderator, housed in a calandria shell.

Loss of Coolant Accident (LOCA) is a mode of failure for a nuclear power plant where the coolant system removing the heat generated in the reactor channel stops working or the coolant is

Abbreviations: PT, Pressure Tube; CT, Calandria Tube; LOCA, Loss of Coolant Accident; ECCS, Emergency Core Cooling System; CANDU, CANada Deuterium Uranium; PHT, primary heat transport; PHWR, Pressurized Heavy Water Reactor.

* Corresponding author.
E-mail addresses: negi.sujay@gmail.com (S. Negi), ravikfme@gmail.com (R. Kumar), pmajum@barc.gov.in (P. Majumdar), dmukho@barc.gov.in (D. Mukopadhyay).

http://dx.doi.org/10.1016/j.nucengdes.2016.12.026
0029-5493/

somehow lost partially or completely. The reactor's emergency shutdown system stops the fission reaction, but the nuclear fuel, due to its decay heat, continues to generate significant heat. In such scenario, Emergency Core Coolant System (ECCS) serves to replenish the lost coolant in the reactor cooling system to remove the decay heat. In a postulated Loss of Coolant Accident with Emergency Core Coolant System (ECCS) Failure, the coolant replenishing system also fails, causing the temperature of the reactor core to rise uncontrollably. Under this condition of coolant starvation, the fuel bundles get heated by the stored as well as the decay heat of the fuel. This heat is transferred to the PT until it leads to its deterioration. The break size is an important parameter that determines the course of deformation of the Pressure Tube. A range of break sizes in the heat transport system and correlation between them to the maximum temperature attained by the fuel inside the PT under a LOCA with ECCS failure mode was reported by Brown et al. (1984). The Pressure Tube is seen to either balloon or sag due to its own weight and high temperature creep depending upon the internal pressure and heat up rates and eventually lead to PT-CT contact. Gillespie (1981) used a program called WALLR to predict the transient heat transfer along a radius through the PT and CT to the moderator following the contact between the tubes. Using a 1.5 m PT and 1.8 m CT immersed in water, he experimentally concluded that when the internal pressure was above 2.5 MPa, the top of the PT contacted CT first whereas when the pressure was below 1 MPa, the bottom of the tube contacted CT first.

Ballooning mode of deformation is the preferred mode over sagging because it is likely to provide more heat transfer area as per Gupta et al. (1996). Nevertheless, there always exists a possibility of rupture during ballooning. They found that the circumferential temperature variations affect not only the heat transfer but also the time which fuel rods fail and slump on to the Pressure Tube. At higher temp, fuel clad may balloon under the internal pressure of fission gases and cause flow blockage for any emergency coolant injected of may rupture leading to release of fission products. Circumferential temp gradient arise due to CT-PT contact and these gradients are smaller in case of ballooning but significant in case of sagging. The higher heater power in the experimentation resulted in a steeper circumferential temperature gradient. This was observed by Yuen et al. (1988) while studying the PT circumferential temperature distribution and found it to be directly dependent on PT deformation when surrounded by a moderator. The initial contact between the tubes leads to sudden increase in heat flux to the moderator, depending upon the PT temperature at the time of contact and contact conductance between the PT and CT.

Experimental channel heat-up for an Indian Pressure Tube was done by Nandan et al. (2010) where they inspected PT deformation at different heat up rates. The PT-CT test-section in use was 2000 mm in length, housed in a 2500 mm tank. It was found that sagging initiates at around 450 °C in each case and the contact between PT and CT occurred at around 585 °C to 625 °C. PT integrity was seen to be maintained in each case.

In the present work, a scenario involving multiple failure event of LOCA along with ECCS failure has been experimentally recreated. In the wake of Fukushima Diiachi nuclear disaster (2011), there has been an urgent need to revisit and reaffirm the safety of Indian PHWR. LOCA with ECCS studies on Indian manufactured Pressure Tube have never been conducted on their full length. Findings of a study to simulate a slow heat up scenario for simulation of sagging in the full-length Indian PT has been taken up in this paper. The test setup and all fabrication has been done at the Mechanical and Industrial Engineering Department of the Indian Institute of Technology, Roorkee, India.

2. Experimental set-up and procedure

The schematic diagram of the experimental set-up is shown in Fig. 1a. It primarily consisted of a tank of 5-m length. The tank was made of mild steel with 40 cm height and 30 cm width. It was fabricated and tested thoroughly for any leakage. The tank had glass windows at regular intervals so that physical inspection at the time of experiment could also be done. The tank was mounted on a movable stand. The actual photograph of the setup tank is shown in Fig. 1b. The Calandria Tube (CT) of Zircaloy -

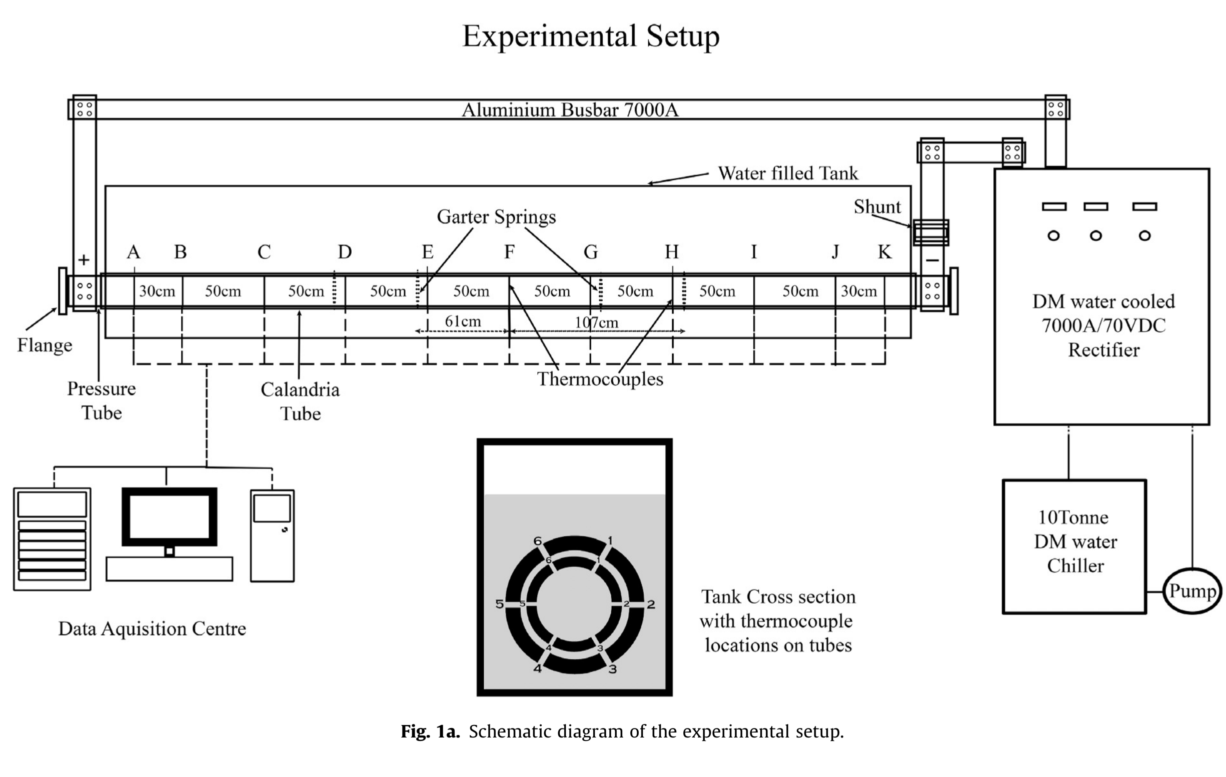

Fig. 1a. Schematic diagram of the experimental setup.