In-reactor deformation of cold-worked Zr–2.5Nb pressure tubes

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Abstract

Over forty years of in-reactor testing and over thirty years of operating experience in power reactors have provided a broad understanding of the in-reactor deformation of cold-worked Zr–2.5Nb pressure tubes, and an extensive data-base upon which to base models for managing the life of existing reactors and for designing new ones. The effects of the major operating variables and many of the metallurgical variables are broadly understood. The deformation is often considered to comprise three components: thermal creep, irradiation growth and irradiation creep. Of the three, irradiation growth is best understood – it is thought to be driven by the diffusional anisotropy difference (DAD). It is still not clear whether the enhancement of creep by irradiation is due to climb-plus-glide (CPG), stress-induced preferred absorption (SIPA) or elasto-diffusion (ED). The least understood area is the transition between thermal creep and irradiation where the fast neutron flux may either suppress or enhance the creep rate. The three components are generally treated as additive in the models, although it is recognized that this is only a crude approximation of reality. There are still significant gaps in our knowledge besides the thermal- to irradiation-creep transition, for example, the effect of Mo which is produced from Nb by transmutation in the thermal neutron flux is not known, and on-going work is required in a number of areas. This paper reviews the current state of knowledge of the in-reactor deformation of cold-worked Zr–2.5Nb pressure tubes, and highlights areas for further research.

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1. Introduction

The fuel channel of the CANDU® nuclear power plant comprises a Zr–2.5 Nb pressure tube and two steel end-fittings (in contact with the primary coolant), a Zircaloy-2 calandria tube (in contact with the moderator), and four spacers maintaining the annular gap between pressure tube and calandria tube. The pressure tubes are the primary containment of the high temperature D2O inside the core of a CANDU® reactor. They are subjected to high stresses, temperatures and fast neutron fluxes which cause changes in the dimensions and material properties. In addition, service-induced wear occurs. To ensure the safe, reliable and economic performance of the reactor, it is important that these changes are known and that the rate of change can be predicted and demonstrated to remain within the design basis. The pressure tubes are designed, specified, manufactured and operated to standards published by the Canadian Standards Association [1–6].

1.1. Fuel channel design

The core of a CANDU® reactor is a cylindrical tank (calandria) containing D2O moderator at 70 °C. It is penetrated by 380 (675 MW units) or 480 (875 MW units) horizontal fuel channels, Fig. 1.1.1. The cold-worked Zr–2.5 wt% Nb pressure tube is 6 m long, 104 mm in diameter and has a wall thickness of 4.2 mm. The chemical specification for the alloy is given in Table 1.1. The pressure tube contains the natural UO2 fuel, encased in Zircaloy-4 sheathing, and heat transport fluid, D2O, operating at temperatures from 520 to 540 K at the inlet to 565–585 K at the outlet. The inlet pressure is about 10.5 MPa and the outlet pressure is about 9.9 MPa, resulting in an initial axial stress in the pressure tube wall of about 65 MPa and an initial hoop stress that varies from about 130 MPa at the inlet to about 122 MPa at the outlet. Superposed on the axial stress from
the pressure is a relatively small axial component due to an end-load from the out of core hardware that varies with time from tensile to compressive. The peak fast flux is up to $3.5 \times 10^{17} \text{ n m}^{-2} \text{ s}^{-1}$, $E > 1$ MeV. The pressure tube and the annealed Zircaloy-2 calandria tube are separated by spacers and the annular gap is filled with flowing CO$_2$ to insulate the pressure tube from the cold moderator. The calandria tube has a wall thickness of 1.4 mm and an inside diameter of 129 mm. The pressure tubes are rolled into 403 stainless steel end-fittings at each end of the channel. The end-fittings have mechanical closures to enable on-power refueling and are connected to the heat transport system (HTS) by carbon steel 'feeders'.

The annulus gas system has been developed to detect the presence of moisture if a leak develops in the primary pressure boundary inside the reactor core. The ability to detect moisture at an early stage of the formation of a sub-critical, through-wall crack in the pressure tube is an important component in assuring leak-before-break of the tubes.

### 1.2. Aging mechanisms

Pressure tubes must accommodate the following aging mechanisms [7–9]: dimensional changes, material property changes, deuterium ingress due to corrosion and in-service damage and wear. In older CANDU$^\text{®}$ units these changes were not fully understood, and have required monitoring, and in some cases maintenance. In newer CANDU stations adequate allowances for them have been made for the design life of the reactor.

To assess their aging characteristics, pressure tubes are subject to periodic non-destructive inspection, and material surveillance, which, in Canada, requires a pressure tube to be removed every three years from the unit with the highest integrated neutron fluence (lead unit), for evaluation of fracture properties. These requirements are defined in Ref. [5]. The data that has been obtained from the periodic inspection and surveillance programs has been supplemented by in-service inspection programs, destructive examination of tubes removed as a result of in-service damage and irradiation of small specimens in test reactors [10–13].

### 2. Deformation of pressure tubes

During reactor operation, the effects of temperature, stress and neutron flux change the dimensions of the pressure tubes. Irradiation and thermally induced deformation of fuel channel components will, in the absence of other mechanisms, eventually determine fuel channel life. The dimensional changes in pressure tubes during normal reactor operation are axial elongation, diametral expansion, sag and wall thinning. One can consider that there are three mechanisms contributing to the dimensional changes: irradiation growth – the change in shape at constant volume in a fast neutron flux, thermal creep – the change in shape due to the effect of temperature and stress in the absence of a fast neutron flux, and irradiation creep, the additional change in shape due to stress and fast neutron flux [14].