INTERNATIONAL DATABASE ON HEAVY WATER REACTOR PRESSURE TUBE DIAMETRAL CREEP

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ABSTRACT

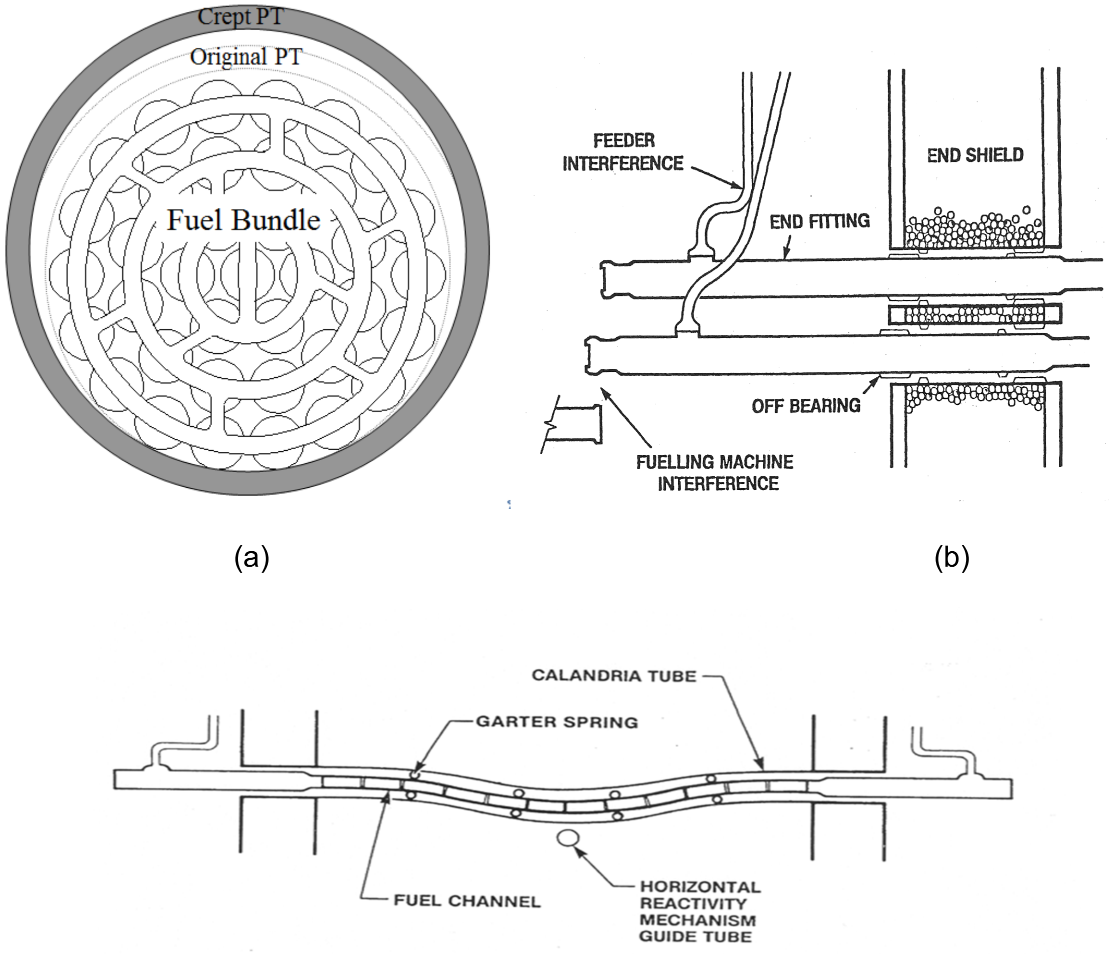
Pressure tube deformation is a critical aging issue in operating Heavy Water Reactors (HWRs). With age, horizontal pressure tubes deform under the influence of pressure, temperature and fast neutron flux in three ways: diametral (or transverse) creep - leading to flow bypass and reduced critical heat flux for fuel rods, longitudinal (or axial) creep - leading to interference between feeder pipes and/or with the fuelling machine, and sag - leading to interference with in-core components. Of these, pressure tube diametral creep is of primary interest, as it determines the end-of-life for pressure tubes in most HWRs. A Co-ordinated Research Project (CRP) has been established under the auspices of the IAEA and with participation from all HWR operating countries to address this issue with a three-pronged approach.

1. Establishment of the first all-inclusive international database of in-reactor measurements of the pressure tube diametral creep,
2. Microstructure characterization of pressure tube material coupons collected from currently operating HWRs, and
3. Development of prediction models or methods for pressure tube deformation.

This paper focusses on item (1) above. Presently, each reactor unit uses the measured creep data, which is obtained by gauging select tubes during outages, to extrapolate future pressure tube performance for the entire core and to determine reactor shutdown trip setpoints. The extrapolation is typically done by applying empirical equations that consider the pressure tube’s historical operating conditions of pressure, temperature and neutron flux or fluence, and that are optimized for each plant or unit. Application of one plant’s model to other plants, through the examination of resulting prediction biases, has revealed trends, which may point to material-intrinsic factors, i.e. microstructure characteristics that affect pressure tube creep behaviour. The extensive International Database on Heavy Water Reactor Pressure Tube Diametral Creep, presented here, includes about 600 gauged tubes and presents the possibility for the CRP participants to investigate predictive model comparisons and gain new insights, in particular because it combines CANDU 6 and Indian HWR data.

1. Introduction

Pressure tube deformation is a critical aging issue in operating Heavy Water Reactors (HWRs). According to the service year, horizontal pressure tubes have three kinds of deformation: diametral creep leading to the flow bypass and the penalty to critical heat flux for fuel rods, longitudinal creep leading to the interference of feeder pipes and/or with fuelling machine, and sagging leading to the interference with in-core components and potential contact between the pressure tube and calandria tube. These deformation modes occur over the life of the pressure tube, which is about 20-30 full-power years depending on operating conditions, and are shown in Figure 1.



(a) (b)

(c)

Fig 1. Modes of Pressure-Tube Deformation: (a) Radial Creep, (b) Axial Creep, (c) Vertical Sag

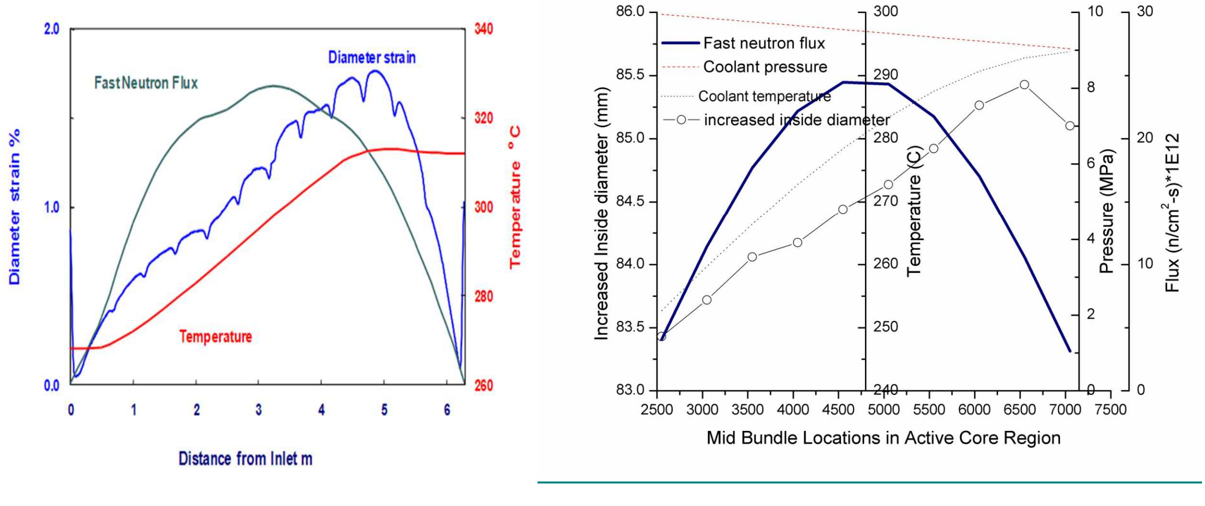
Since the first pressure tube was produced in the 1960’s, manufacturing processes have been evolving. Many of the manufacturing changes were adopted to reduce the risk of pressure tube failures resulting in loss of coolant accidents. The effects of the these changes on the longer term dimensional changes due to irradiation creep have only been realised after many years of reactor operation through various monitoring programs. Each pressure tube has unique behaviour even within a specified manufacturing envelope. The deformation behaviour of an individual pressure tube is therefore subject to so-called extrinsic effects (the operating conditions) and intrinsic effects (the material characteristics dictated by the manufacturing process).

2. In-Plant Measurements and Prediction of Pressure Tube Radial Creep

Predictive models have been developed to determine the diametral creep, elongation and sag rates of pressure tubes based on the extrinsic conditions and these are used to provide assurance at every plant that adverse conditions will not develop in the projected operating period for the fuel channel, specifically to avoid:

- Coolant flow by-pass of the fuel bundles to the extent that fuel over-heating and dry-out conditions prevail. Current creep limit is 5.1%.
- Contact between the pressure tube and calandria tube resulting in blister formation and potential failure of the pressure tube subsequent loss of coolant.
- Interference of feeders that could create adverse stresses in the feeder joints and subsequent failure leading to a loss-of-coolant accident.
- Off-bearing travel for the pressure tube that would inhibit the normal operation of the fuel channels during start-up and shut-down.

Presently, each reactor unit uses measured creep data, which is obtained by gauging select tubes during outages, to linearly extrapolate future pressure tube performance for the entire core [1]. Figure 2 schematically shows a typical radial-creep curve (blue) of a gauged pressure tube along with the axial variation of flux and temperature. Locations along the tube experience different flux and temperature, with the radial creep responding accordingly (the “dips” in the measured radial creep curve correspond to locations of fuel bundle ends, where the fast neutron flux is depressed and thus creep is lower). Figure 3 summarizes all gauged CANDU 6 pressure tubes from which detailed radial creep measurements have been collected under this CRP. Overall, 199 lattice sites (out of 380) have been gauged in eleven CANDU 6 units, for a total of 323 tubes with 534 gaugings (some tubes are gauged multiple times during their operating life).

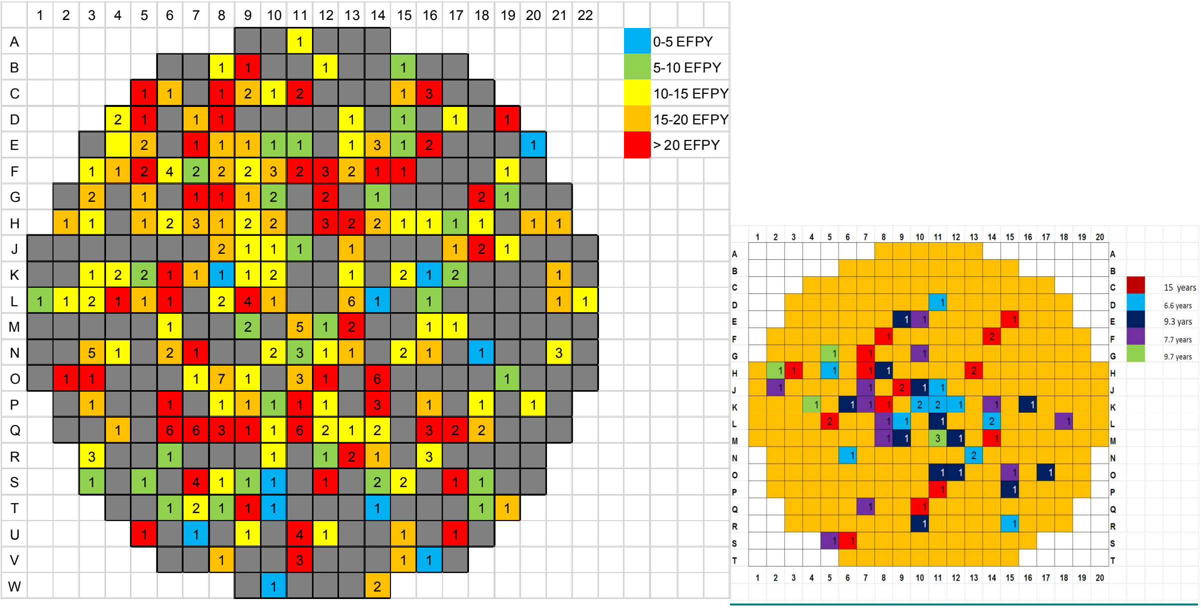


(a) Typical CANDU 6

(b) Typical Indian 220-MWe HWR

Fig 2. Axial Dependence of Radial Pressure-Tube Creep

The database presently consists of mid-bundle radial-creep measurements, i.e. 12 values along the pressure tube in operating CANDU 6 units, and 10 values along the pressure tube in seven Indian 220-MWe HWRs.



(a) Typical CANDU 6

(b) Typical Indian 220-MWe HWR

Fig 3. Core Maps Showing Lattice Sites Gauged and Included in the Database (grey or orange is unmeasured, colours reflect the latest gauging (EFPY = effective full power years) and the numbers indicate the number of different NPP units in which this site was gauged)

The extrapolation of a gauged channel creep to other non-gauged channels is typically done by applying empirical equations that consider the pressure tube's historical operating conditions of pressure, temperature and neutron flux or fluence, and that are optimized for each plant or unit [1, 2]. However, intrinsic material effects sometimes lead to large variations in the pressure tube behaviour for a given set of operating conditions. Although some recent advancement in the understanding of the important microstructure parameters has been made [3], these effects have not been studied to the same degree as the effect of the operating conditions [4]. The intrinsic variables are the result of variations in manufacturing process that have evolved over time and also of random variations in the specified manufacturing process.

Application of one plant's model to other plants, through the examination of resulting prediction biases [5], has revealed trends, which point to material-intrinsic factors, i.e. microstructure characteristics that affect pressure tube creep behaviour. For example, Figure 4 shows the deviations from predictions when a model from a station with tubes aligned with their back ends at the outlet is used on a unit with tubes aligned with back ends at the inlet. The strong tilt arises because the microstructure systematically varies from front-end to back end during extrusion (front-end comes out of the extrusion press first). The extensive International Database on Heavy Water Reactor Pressure Tube Diametral Creep, developed during this CRP and presented here, includes about 600 gauged tubes and presents the possibility for the CRP participants to investigate predictive model comparisons and gain new insights, in particular because it combines CANDU 6 and Indian HWR data.

Apart from addressing operability of existing HWR plants, designers and owners of advanced HWRs will benefit from the results of this study into the development of predictive pressure-tube creep models, based on operating conditions (extrinsic influence) and individual pressure tube manufacturing history (intrinsic influence).

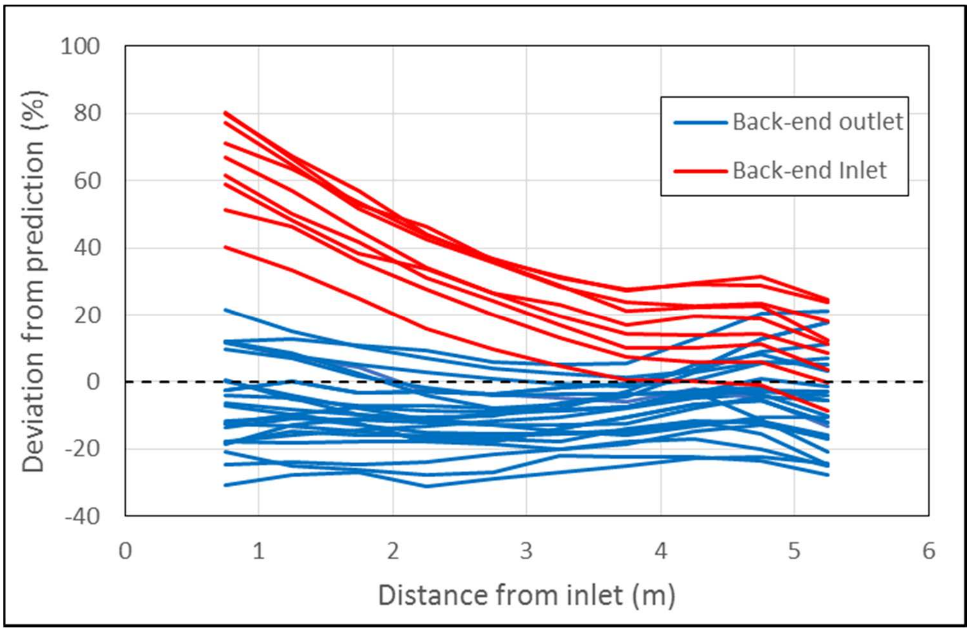


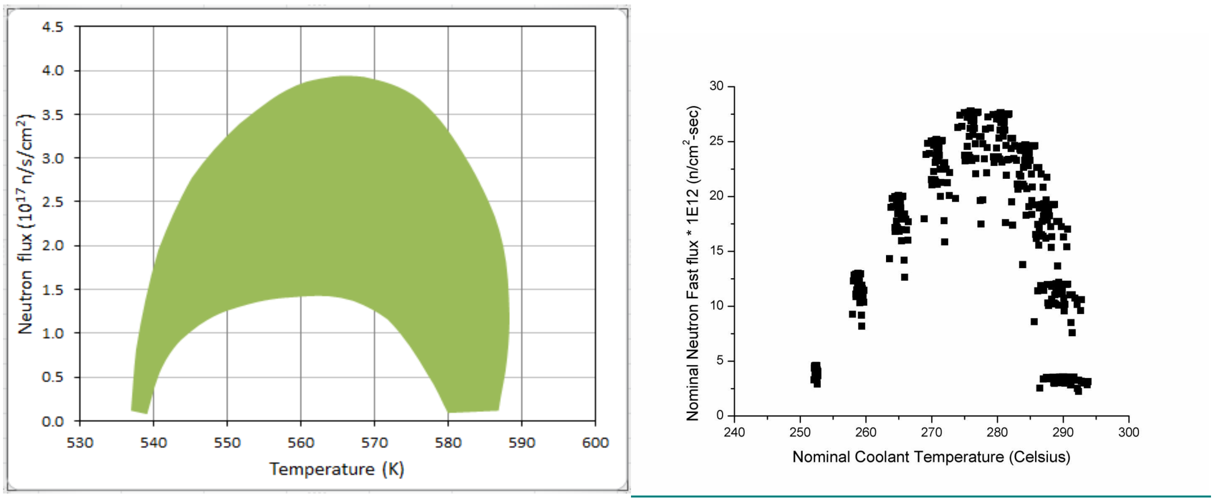
Fig 4. Residuals from model fit showing pressure tubes from two units. One unit (blue) was similar to the modelled units while the other unit (red) was configured with the tube back-end at the inlet and deviates significantly from the modelled units.

3. Manufacturing History and Operating Conditions of Pressure Tubes

The Zr-2.5Nb pressure tubes used in 700 MWe CANDU-6 reactors are manufactured from forged hollow billets that may or may not have been given a beta-quench treatment. They are nominally extruded at 815°C, cold-drawn 27%, and stress relieved in a steam autoclave at 400°C for 24 hours.

The Zr-2.5Nb pressure tubes used in 540 MWe and 220 MWe Indian HWRs are manufactured from extruded hollow billets that have been given a beta-quench treatment. They are nominally extruded at 800°C, stress-relieved at 480°C for 3 hours followed by a two-stage pilgering reduction involving an intermediate stress-relief at 550°C for 6 hours, followed by a steam autoclave at 400°C for 36 hours.

For a 700 MWe CANDU-6 reactor the pressure tubes operate at temperatures between 260°C and 310°C with coolant pressures up to about 11 MPa in fast neutron fluxes up to about 3.7 $x10^{17}$ n/m2-s. For a 540 MWe reactor the pressure tubes operate at temperatures between 260°C and 304°C with coolant pressures up to about 10.5 MPa in fast neutron fluxes up to about 2.8 $x10^{17}$ n/m2-s. For a 220 MWe reactor the pressure tubes operate at temperatures between 249°C and 293°C with coolant pressures up to about 10.5 MPa in fast neutron fluxes up to 2.5 $x10^{17}$ n/m2-s. Figure 5 shows these operating ranges graphically.



(a) Typical CANDU 6 (b) Typical Indian 220-MWe HWR

Fig 5. Comparison of Operating Conditions in CANDU (a) and Indian (b) HWRs

4. Effect of Intrinsic Parameters

Comparing actual gauging data obtained from tubes from different units but located at the same lattice site, i.e. having nominally identical operating conditions, illustrates the large variability introduced by intrinsic manufacturing-dependent parameters, i.e. microstructure characteristics.

Figure 6 shows creep in six different CANDU 6 pressure tubes, all in lattice site O14 in six different units. In particular, this is the creep at the axial midline (average of bundle 6 and 7) measured several times for each channel.

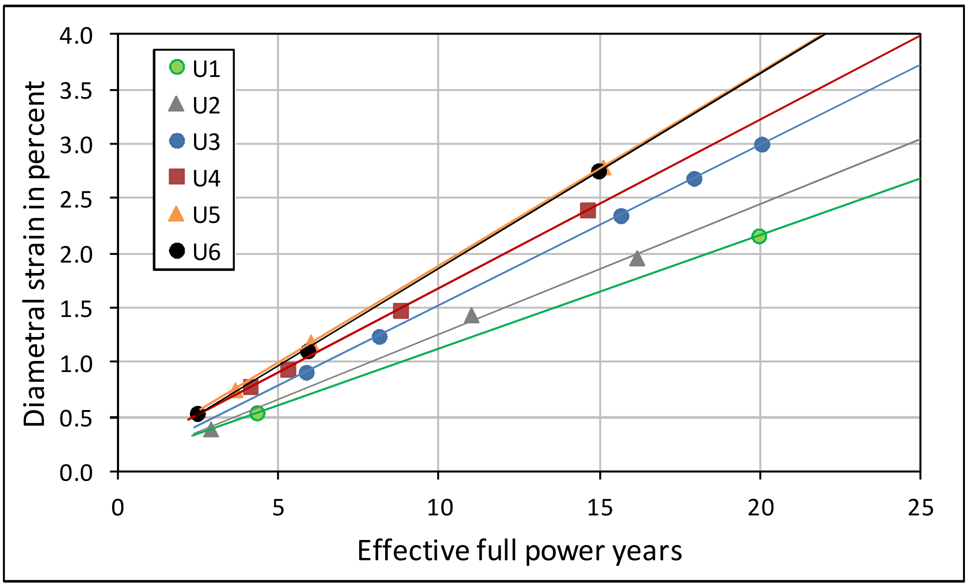


Fig 6. Measured Mid-Plane Radial Creep from Tubes at Lattice Site O14 in Six Different CANDU Units

While all tubes creep linear with time, this illustrates the variability amongst pressure tubes. For example, the tube in Unit 6 has strain rate 70% faster than tube in Unit 1 (under nominally identical operating conditions). These six tubes have significantly different manufacturing process except for the tubes in U5 and U6 which were made identically.

The pressure tubes of all the Indian reactors are manufactured by the same process except for melting of ingot (earlier double melting is replaced by quadruple melting to control impurities like hydrogen, chlorine and phosphorous). Normalised fluence (dividing the peak fluence of a given channel by the maximum amongst the channels considered) has been chosen as a primary parameter to make the gauged channel data independent of lattice location. Percentage change in inside diameter of the pressure tubes of five 220 MWe units is compared against the normalised fluence in Figure 7. Scatter at a given normalised fluence indicates the presence of similar variation in the intrinsic parameters characterising the manufacturing process.

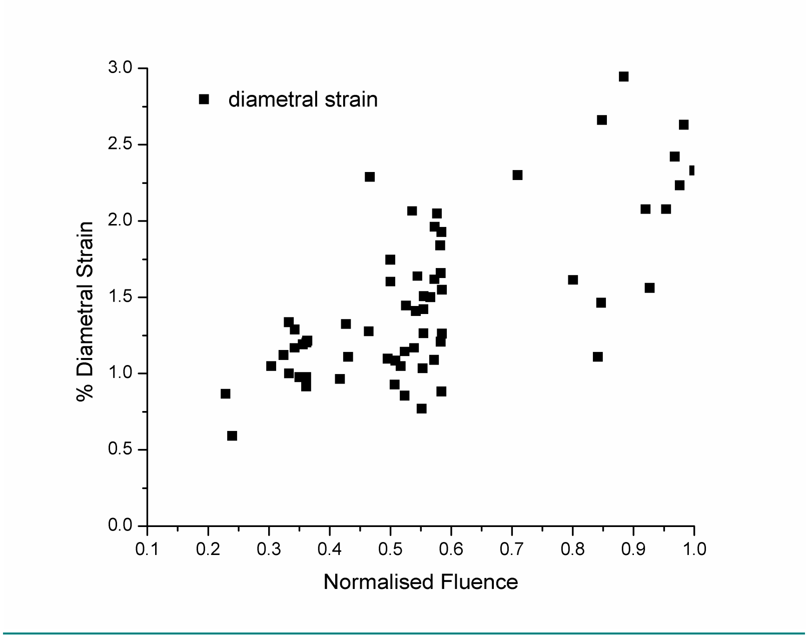


Fig 7. Measured Mid-Plane Radial Creep from Tubes in Five Different Indian HWR Units

This database from 11 CANDU and seven Indian HWRs allows for the first time such a quantitative comparison of this variable behaviour (can’t be done if studying one unit by itself).

5. Conclusions

An extensive International Database on Heavy Water Reactor Pressure Tube Diametral Creep has been assembled, including about 600 gauged tubes and presents the possibility for participants of the IAEA the CRP on *Prediction of Axial and Radial Creep in Pressure Tubes* to investigate predictive model biases when applied to different reactor units and gain new insights into effects of operating conditions and microstructure/manufacturing effects, in particular because it combines CANDU 6 and Indian HWR data. Apart from addressing operability of existing HWR plants, designers and owners of advanced HWRs will also benefit from the results of this study.

References

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