Diametral Creep Assessment of Pressure Tubes at Gentilly-2 Up Until 2003 (5900 EFPD)

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Abstract

Pressure tube (PT) diametral creep in a CANDU-6® reactor is a permanent strain due to the phenomenon of irradiation. Creep affects the coolant flow in the fuel channels and reduces, at constant channel flow, the margin to critical heat flux (CHF). As a result, creep affects the safety margins and must be compensated by reducing the station power.

AECL developed the RC-1980 correlation to predict creep strain as a function of the operating conditions (flux, temperature, and pressure), based on CANDU-6® inspection data through 1997.

Between 1987 and 2003, creep measurements were performed on 62 PTs at Gentilly-2 during outages. The results have revealed that the average creep represents only about 84% of its prediction.

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1. Introduction

For a given constant flow rate in a CANDU® fuel channel, the pressure tube (PT) diametral creep causes a reduction of the margin to the critical heat flux (CHF) because it results in flow by-pass of PHT coolant around fuel bundles. Therefore, PT diametral creep has a significant impact on the critical channel power (CCP). A reduction in ROP trip set points is needed to maintain the required trip probability. The reduction in ROP trip set points decreases the ROP margin to trip during normal operation and will have an impact on operation at full power. Therefore, it is important to characterize the distribution of creep rates within a given reactor e.g. in Gentilly-2's.

The diametral creep issue has lead to much effort in developing RC-1980 model as a function of various parameters. The RC-1980 model takes into account CIGAR (Channel Inspection and Gauging Apparatus for Reactors) data from the CANDU-6® power reactors. However, there is a large axial and channel-to-channel variation in strain rates that results in a bias on the prediction of the channel maximum deformation. Station PT deformations, measured and predicted, must be considered to provide the proper diameter ratio for the plant specific model prediction.

Comparison with RC-1980 correlation has been performed regularly for the Gentilly-2 PTs.

The present work consists of assessing the diametral creep at Gentilly-2 up until 2003 (5900 Equivalent full power days - EFPD). The assessment consists of using measurements gathered in 1987, 1990, 1993 and 1997 with CIGAR (Channel Inspection and Gauging Apparatus for Reactors), in 2002 with MED (Mesure de l'expansion diamétrale) and in 2003 with CANDE

(CIGAR/Advanced NDE – Non-Destructive Examination). In 2003, fifteen (15) PTs were inspected, including seven (7) PTs that were inspected for the first time. Therefore, a total of sixty-two (62) PTs, representing more than 16% of all PTs, were inspected. In the present work, RC-1980 is used to compare predicted and measured PT deformation rates in order to provide plant specific model predictions. Figure 1 illustrates the fuel channels that were inspected at Gentilly-2 up until 2003. The fifteen (15) measurements performed in 2003 are indicated, including the seven (7) channels inspected for the first time.

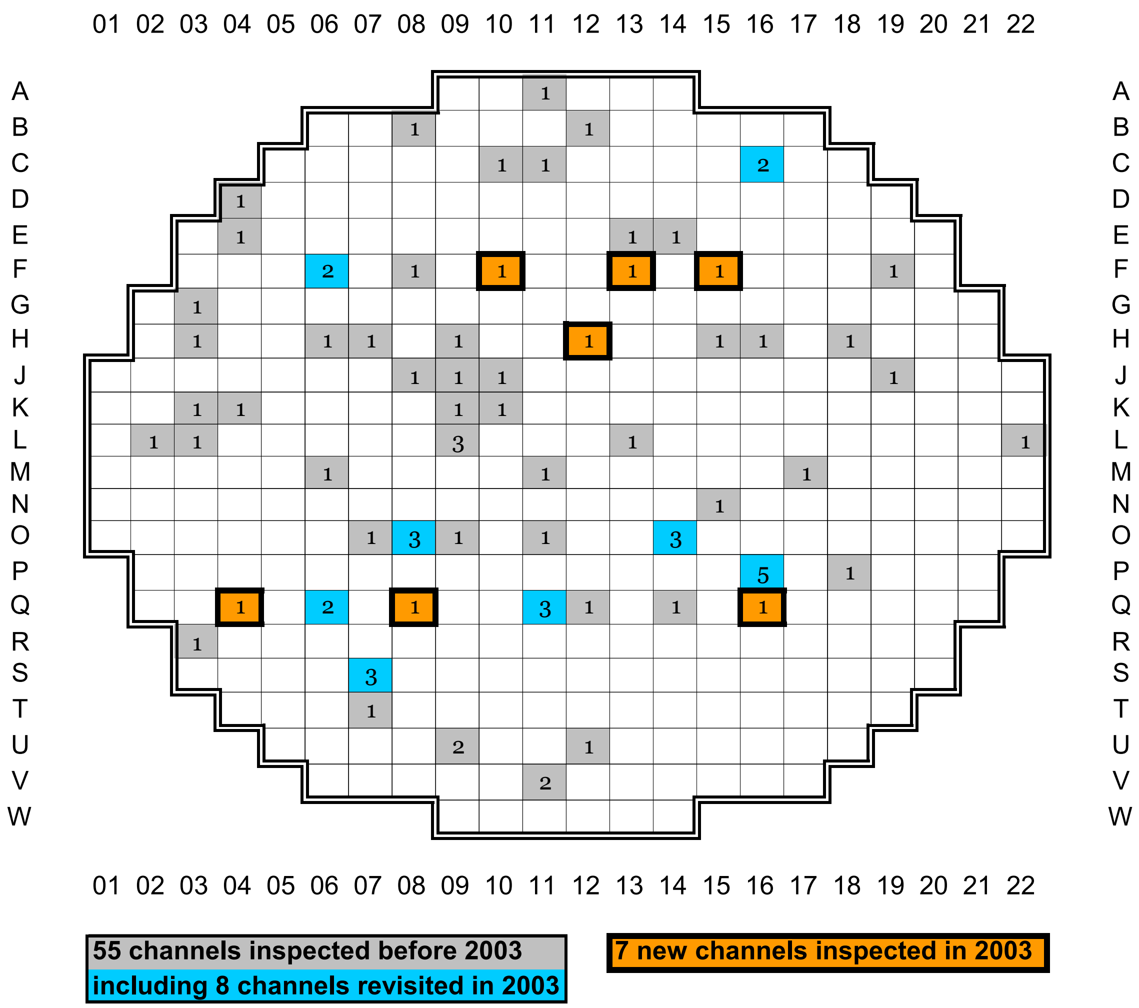

Figure 1 Channels inspected up until 2003 at Gentilly-2

2. Method

The purpose of the work is to compare the maximum measured diametral creep with the maximum calculated diametral creep using equation RC-1980.
The diametral creep is defined as follows:

$$\varepsilon = \frac{D_{final} - D_{initial}}{D_{initial}} \qquad \textbf{Equation 1}$$

Where:

- $D_{initial}$ is the internal diameter at commissioning
- D_{final} is the current (in-service) internal diameter

2.1 Diametral creep measurements

Initial diameters are obtained from final inspection before commissioning either during fabrication or after installation inside the reactor.

In service diameters are obtained from eighty-one (81) measurements in sixty-two (62) PTs between 1987 and 2003 using the following methods:

- CIGAR between 1987 and 1997;
- MED in 2002;
- CANDE in 2003.

The measurement error for all methods CIGAR, MED and CANDE is within ±100 µm.

At each axial position along the fuel channel, diametral measurements using the CIGAR, MED and CANDE methods provide three-channel data e.g. a minimum, a maximum and an average value, as illustrated in Figure 2. For the present assessment, we consider the average measurement at each axial location along the PT.

Since the calculations using correlation RC-1980 are performed only at the twelve (12) axial positions corresponding to the fuel bundle centres, for the purpose of comparison, the local average measured creep at the centre position of each fuel bundle is used. It is possible to deduce central bundle positions with the following method:

- In the region around the middle of a channel, we identify a few fuel bundles endings. (The creep is lower at the endings of a fuel bundle where the fast neutronic flux is lower due to the absence of fuel);
- We determine the average fuel bundle length for the channel;
- We deduce the centre position of all fuel bundles using the average length.

Then, we can calculate the local average creep at the centre of each fuel bundle.

Figure 2 illustrates the measured internal PT diameter along the fuel channel and the deduced fuel bundle centre locations.

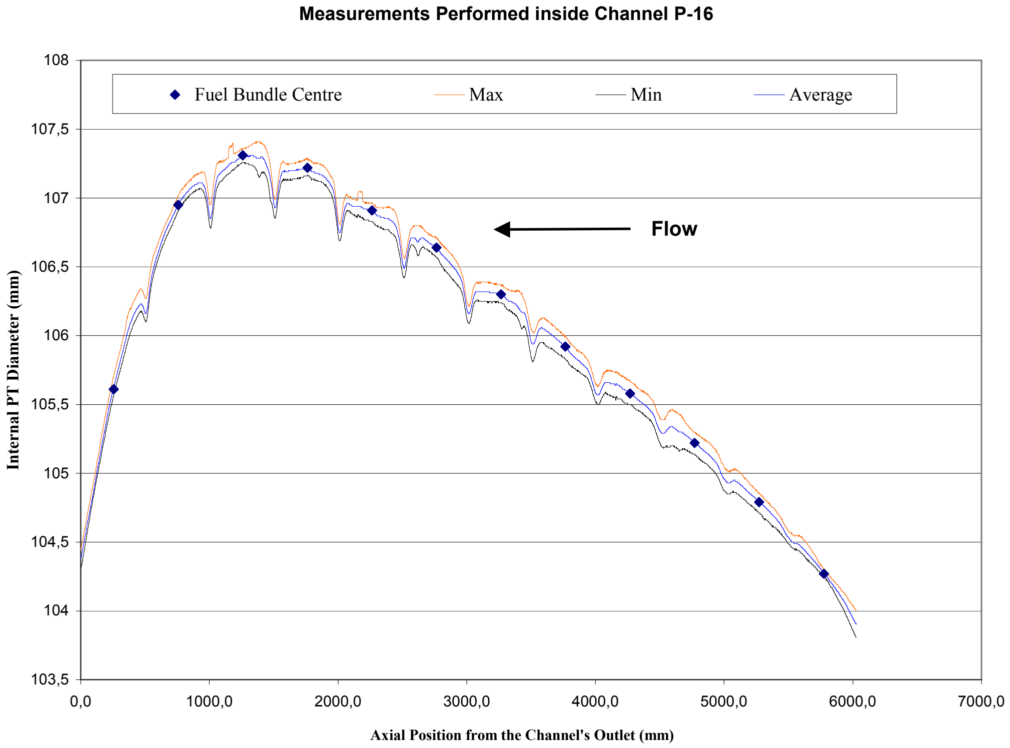

Figure 2 Fuel Bundle Centre Location

2.2 Maximum Diametral Creep Calculations

The computer programme FLUAGE, which contains equation RC-1980, is used to calculate the maximum diametral creep.
The required input data are:

- The initial diameters, the "as built" PT dimensions;
- The burnup;
- The operating parameters (fast flux, coolant temperature and pressure).

Initial PT Diameters
The initial PT diameters consist of fourteen (14) channels measured at different axial locations during the inaugural inspection of the reactor. Nine (9) of these channels appear on the list of measured channels with CIGAR, MED, or CANDE. Axial interpolation is carried out to obtain the diameter in the middle of each of the twelve (12) bundles. For the remaining fifty-three (53) channels, the manufacturer diameters are used. (A single value only is available for all axial locations.)

Fast Neutronic Flux
The average flux over the reactor life is used since a sensitivity analysis revealed that for the analysed period of time, the average flux value is applicable to consider the integrated effect of the flux.

Coolant Pressure and Temperature Distributions
The axial profiles from header-to-header calculation using NUCIRC are considered. The boundary conditions are those typical at full power, and should be representative of the time-averaged values. The fuel bundle model used is the generic CANDU-6® model for a 37-element fuel bundle.

2.3 Measurement-to-Calculation Diametral Creep Ratio

Once the measured and the calculated (predicted) diametral creep values (ε) are determined, the ratio of the maximum measured diametral creep to the maximum calculated diametral creep for a given fuel channel can be obtained:

$$R = \frac{\varepsilon_{measured,MAX}}{\varepsilon_{calculated,MAX}}$$ **Equation 2**

The ratio R enables to compare the maximum measured creep with the maximum calculated creep for a given channel. It is important to note that the two maximum creep values (measured and calculated) are not necessarily at the same axial position.

Figure 3, Figure 4 and Figure 5 respectively illustrate the measured and calculated internal diameter of channel P16 (representative of maximum creep), O08 (representative of average creep) and channel Q11 (representative of minimum creep).

For channel P16, we can observe that the maximum creep is under-predicted and that the predicted location of the maximum diametral creep is one fuel bundle away from the measured maximum. However, the method consists takes into consideration the maximum creep independent from its location. Therefore, the precise location of the maximum creep is not crucial.
For all three channels, the predicted trend is a good representation of the actual diametral creep trend.

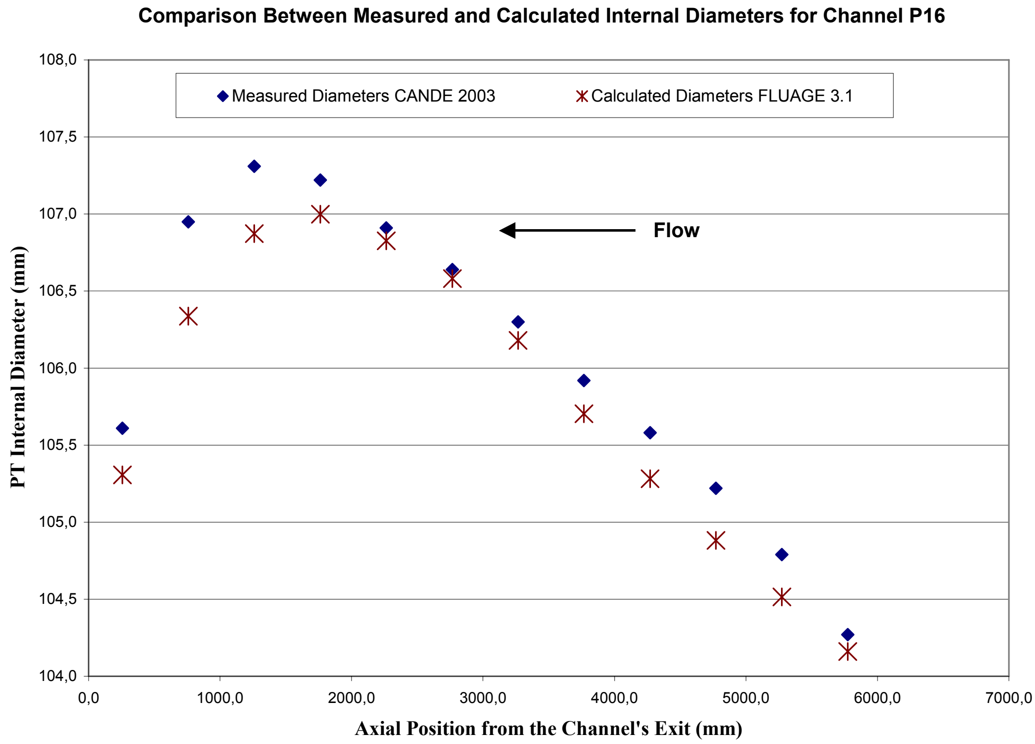

Figure 3 Measured and calculated internal diameter of channel P16 (representative of maximum creep)

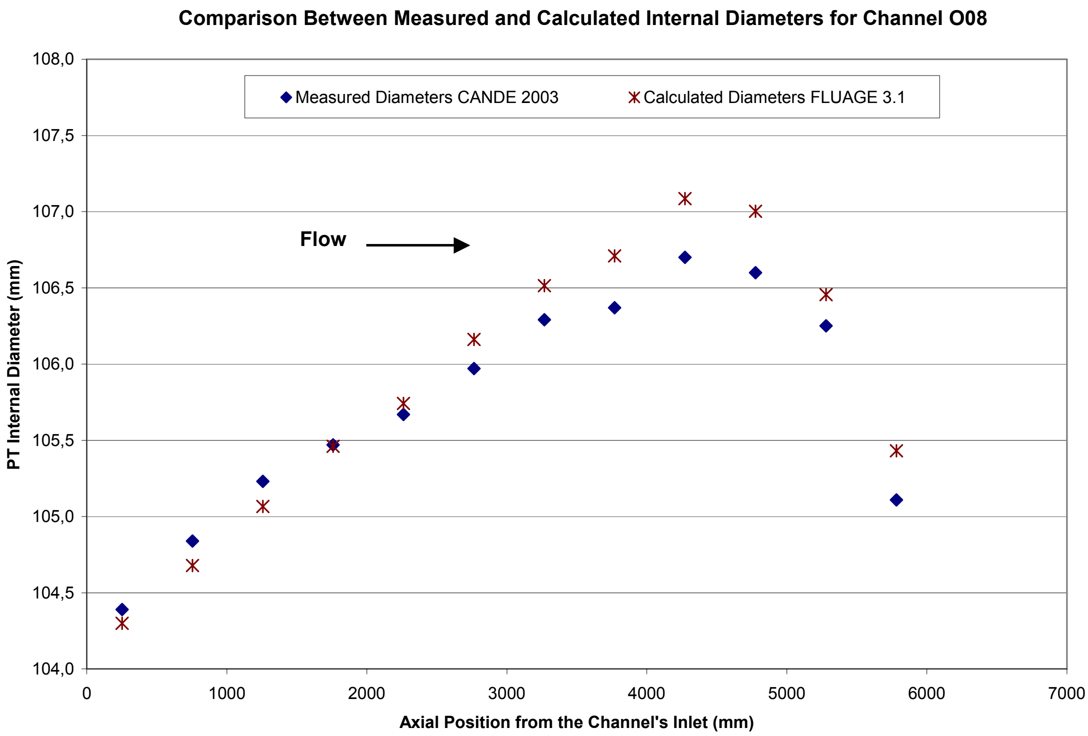

Figure 4 Measured and calculated internal diameter of channel O08 (representative of average creep)

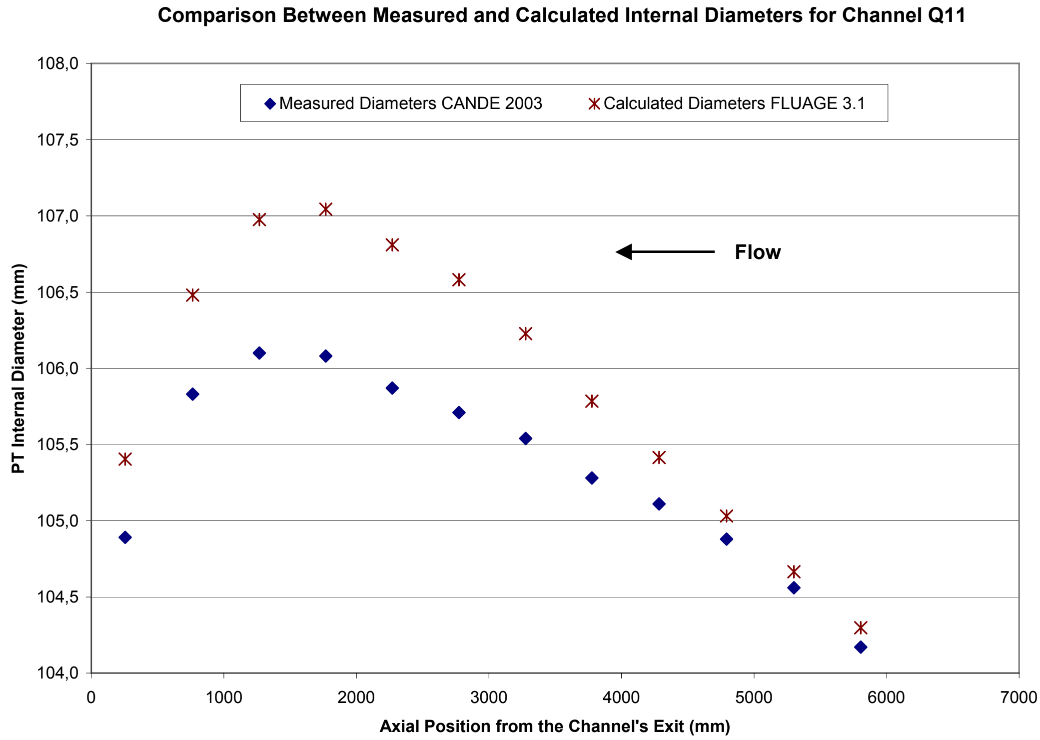

Figure 5 Measured and calculated internal diameter of channel Q11 (representative of minimum creep)

2.4 Consistency between Different Measurement Methods

Since three (3) different measurement methods (CIGAR, MED, CANDE) were used at Gentilly-2, we must verify the consistency between these results. Figure 6 illustrates the evolution of the maximum measured diametral creep as a function of operation time for channel P16, which was inspected using all three methods: CIGAR, MED and CANDE. The trend given by the three CIGAR measurements (carried out in 1990, 1993 and 1997) is consistent with more recent measurements with MED (2002) and CANDE (2003). We can conclude that the measured diametral creep with CANDE is consistent with past methods (CIGAR, MED). Therefore, data quality is assumed identical regardless of the measurement technique. The performance of the latter technique was demonstrated in the laboratory with measurement data and an independent expert.

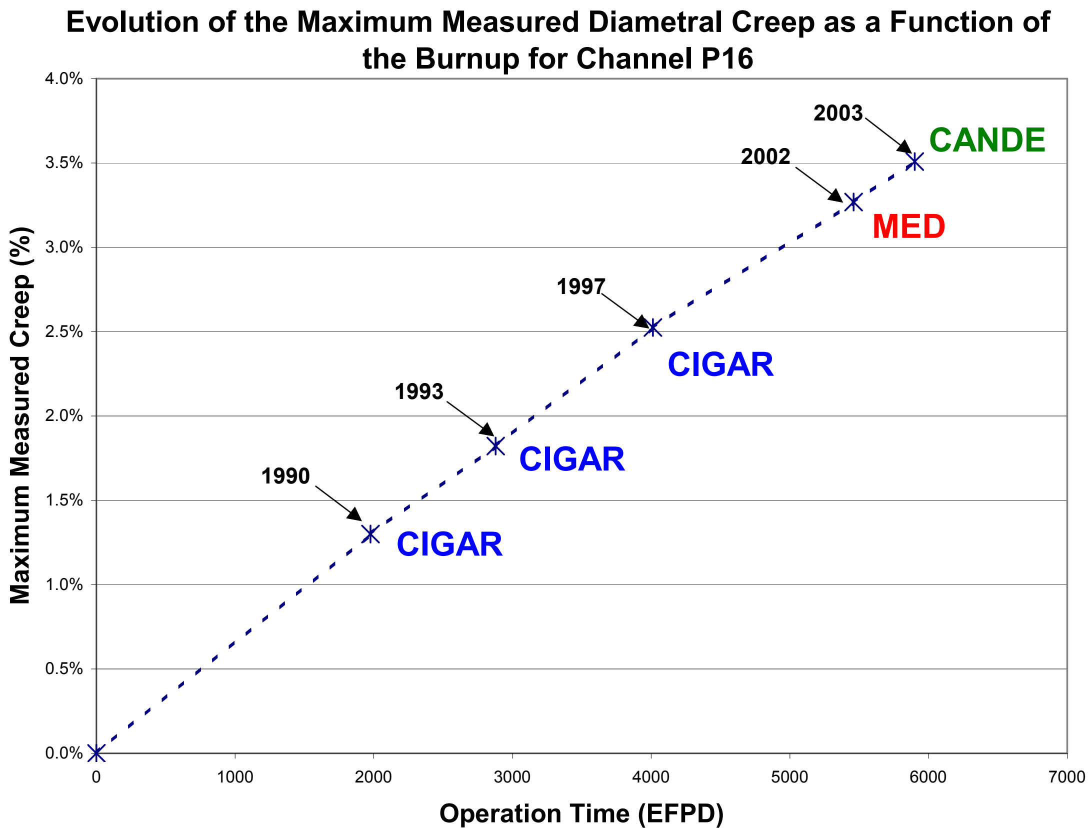

Figure 6 Evolution of the Channel P16 Maximum Measured Diametral Creep Over Operation Time

2.5 Results for Measured and Calculated Creep

Diametral creep is assessed for sixty-two (62) inspected channels. The mean of the measured maximum diametral strain is only 0.84 of that predicted, with a standard deviation of 0.096.

Figure 7 shows the maximum measured creep as a function of the maximum calculated creep for the sixty-two (62) inspected fuel channels at Gentilly-2. In general, the data are well distributed around the average value, with very few points away from the general trend. We can see that only three (3) channels (K04, K10, P16) show a greater diametral creep than predicted with correlation RC-1980. However, the diametral creep for channels K04, K10, and P16 is within the 95% confidence interval of RC-1980.
Figure 8 illustrates the frequency distribution of the measured-to-calculated creep ratios. The frequency of tubes at a given creep rate relative to the average creep rate becomes a major factor in determining the overall uncertainty of the predictions for PTs that have not actually been inspected (i.e. their creep rate trend characteristic). Figure 8 shows that data are well distributed around the average ratio of 84%.

With only three (3) channels on sixty-two (62) for which measurements are greater than the predictions, 95% of the measured channels have a diametral creep lower than calculated with RC-1980.
Therefore, on average correlation RC-1980 overestimates the maximum diametral creep.
Figure 9 illustrates the average creep rate obtained at the end of each measurement campaign. As shown, the measurements gathered in the last three campaigns made the average measured

creep rate relative to the rate calculated by RC-1980 converge between 0.80 and 0.85. This small variation of the average value with data from the last two inspections is an indication of the convergence. Moreover, the last two campaigns are the most significant in terms of number of channels gauged. This convergence gives us reasonable confidence in the mean creep ratio for Gentilly-2.

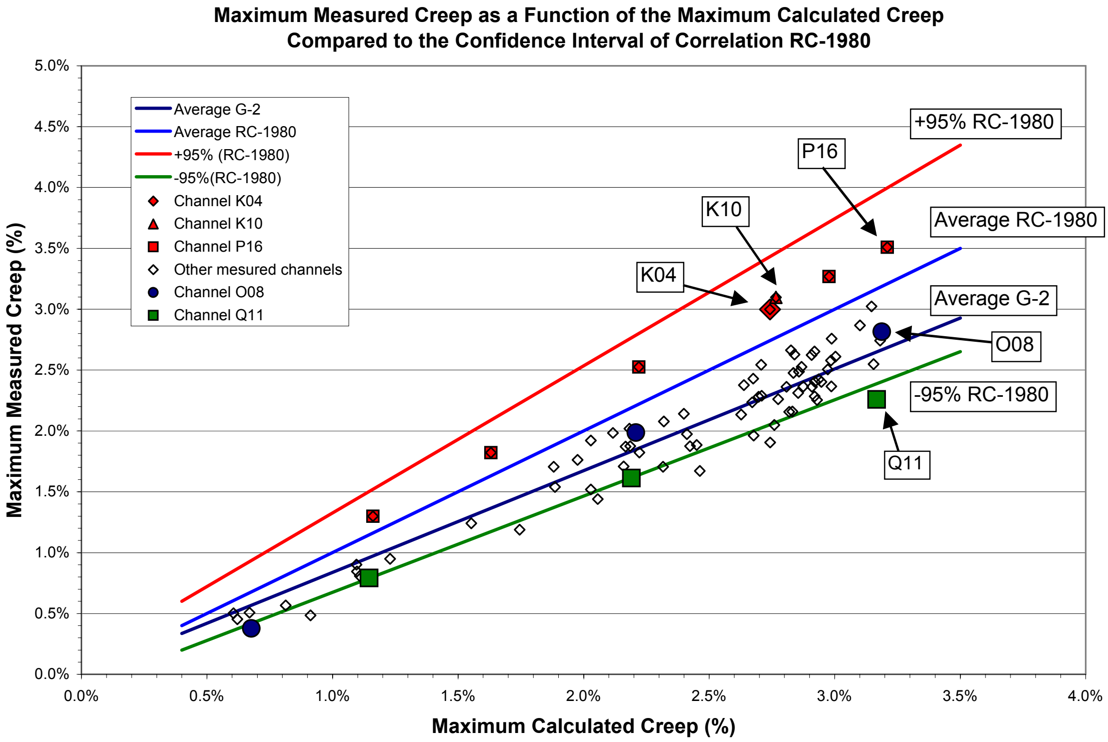

Figure 7 Maximum Measured Creep as a Function of the Maximum Calculated Creep for the 62 Inspected Fuel Channels at Gentilly-2

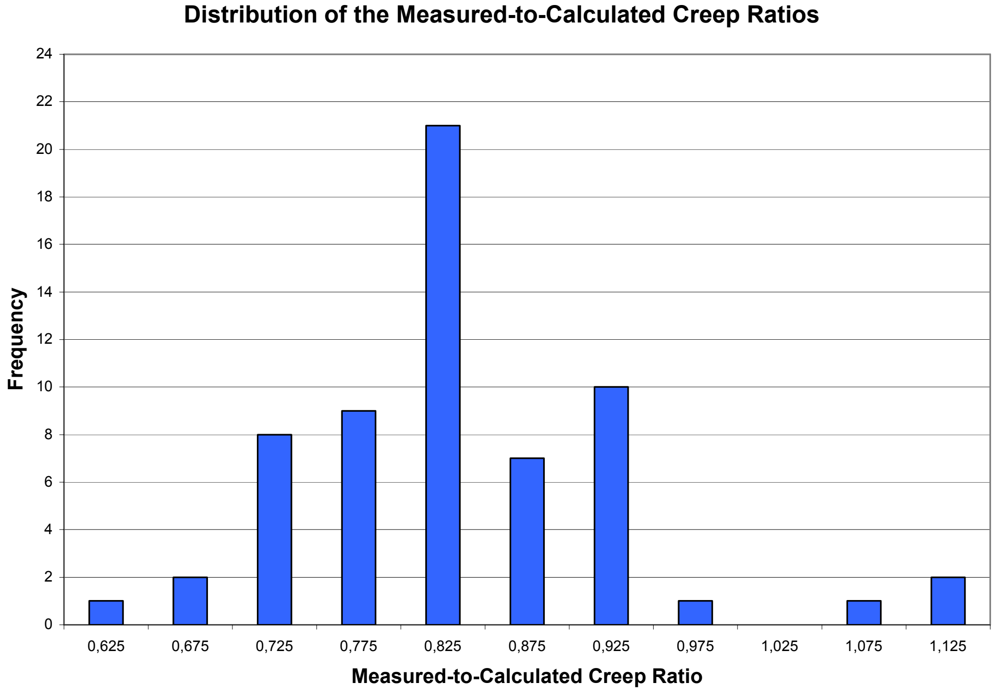

Figure 8 Frequency Distribution of the Measured-to-Calculated Creep Ratios

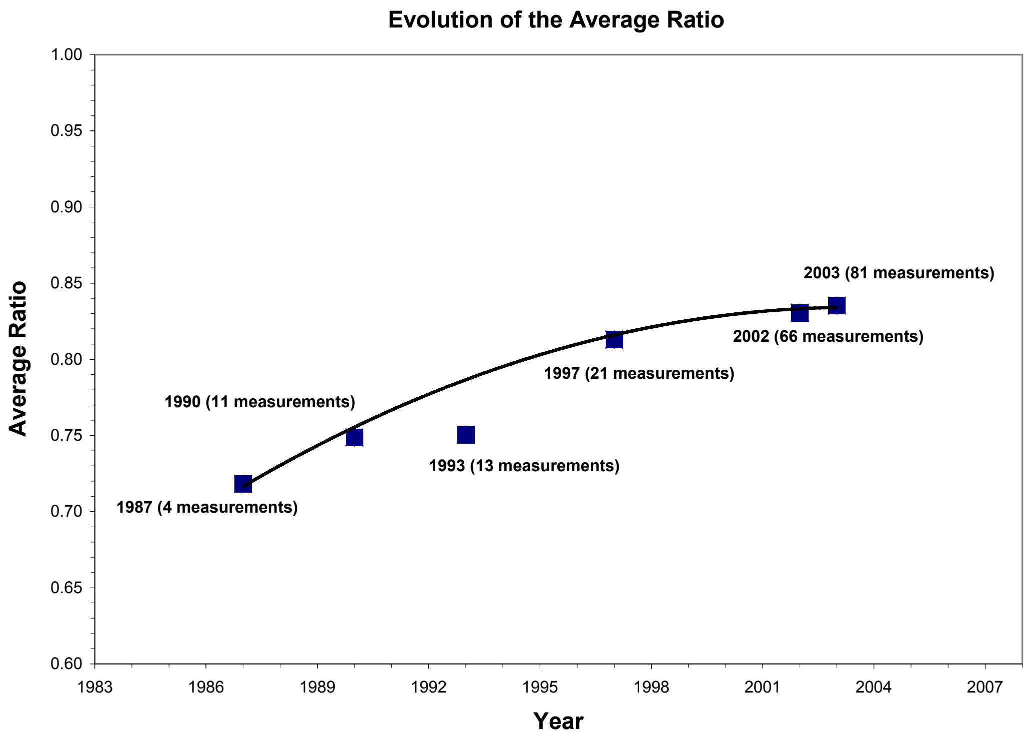

Figure 9 Evolution of the ratio as a function of the number of measurements

3. Conclusion

A total of sixty-two (62) PTs were inspected, representing around 16% of all PTs. In the present work, we compare PT deformation rate measurements with predictions using design equation RC-1980 in order to provide plant specific model prediction.

When compared to prediction of RC-1980, on average measured diametral creep represents 84% of the calculated value (with a standard deviation of 0.096). Ninety-five percent (95%) of the inspected PTs have a lower diametral creep than predicted.

In this work the measure of interest is the maximum value (axially) of the mean diametral creep known as the maximum-mean diametral creep. One key feature is that the frequency distribution of the measured-to-calculated creep ratios appears to be normally distributed as shown in Figure 8. We can conclude for Gentilly-2 that on average correlation RC-1980 overestimates the maximum diametral creep and that a bias correction needs to be applied in order to accurately predict channel maximum deformation.

Another key feature is that different CANDU® stations may have different design limits on diametral strain due to operating conditions and design differences. Therefore, careful attention should be paid on following factors:

- The creep-rate variability from one PT to another;
- Any design equation only represents an average PT;
- The average of the design equation will depend on the database of measurements used to "tune" the equation;
- The frequency of PTs with a given creep rate relative to the average creep rate is a major factor in determining the overall uncertainty of the predictions applied to unmeasured PTs.

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