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EVALUATION MODEL FOR DIAMETER CHANGE OF CANDU PRESSURE TUBE

Jong Yeob Jung

Research Scientist, Korea Atomic Energy Research Institute, Daejeon, South Korea (agahee@karei.re.kr)

ABSTRACT

Measurements of the inside diameter of the pressure tubes in CANDU reactors have shown that the diameter has been increasing over time, and this phenomena has been explained as a creep phenomenon which is a kind of aging process of the pressure tube owing to the operating conditions of irradiation by neutron flux, high pressure, and high temperature over the plant life. The diameter expansion of the pressure tube has been regarded as a principle aging mechanism governing the heat transfer and hydraulic degradation within the primary heat transport system of the CANDU reactor. Diametrical expansion results in a reduction of the fuel cooling owing to the increased bypass flow, which increases the possibility of a fuel dry-out and thus limits the operating power of the reactor. In order to explain the mechanism of the creep phenomena of the pressure tube, traditionally the creep deformation has been modeled as a combination of thermal creep, irradiation creep and irradiation growth. However, this modeling approach is too complex to determine all parameters and constants which are relevant to the equation.

In this research, we proposed a very simple approach for modelling the pressure tube diameter deformation in which the pressure tube diameter was modelled based on the measured data, flux distribution of each fuel channel and temperature variation inside the pressure tube. Rules were derived to determine the effect of flux and temperature distribution on the diameter expansion based on the measured data of pressure tube diameter. Results from applying the methodology show a dramatic improvement of the prediction accuracy of pressure tube diameter compared to the previous modelling results.

INTRODUCTION

Diametrical expansion of the pressure tube in CANDU reactors has been explained as a kind of creep phenomena owing to the operating conditions of irradiation by neutron flux (~ 3.5 x 10^{17} $nm^{-2}s^{-1}$, E>1Mev), high pressure (9.5 ~ 11 MPa), and temperature (270 ~ 310 ^{0}C) over the plant life. The diameter expansion of the pressure tube has been regarded as a principle aging mechanism governing the heat transfer and hydraulic degradation within the primary heat transport system of the CANDU reactor. Diametrical expansion results in a reduction of the fuel cooling owing to the increased bypass flow, which increases the possibility of a fuel dry-out and thus limits the operating power of the reactor.

Many studies have been doing to evaluate the expansion of the pressure tube diameter of CANDU reactor. Because an expansion of the pressure tube diameter affects critical channel power owing to the increase of by-pass coolant flow, an accurate prediction of the pressure tube diameter is very important in assessing the operational margin of CANDU reactor. Traditional studies include the understanding of the pressure tube material behavior under the irradiation condition [1], research of the manufacturing and micro-structure effect on the pressure tube deformation [2], and development of the appropriate model describing the pressure tube diametrical creep behavior [3-5].

Following equation (1) is the traditional modeling for the creep deformation of the pressure tube consisting of three parts such as thermal creep, irradiation creep, and irradiation growth.

$$
\begin{aligned}
\dot{\varepsilon} = \ \dot{\varepsilon}_{tc} + \ \dot{\varepsilon}_{ic} + \ \dot{\varepsilon}_{ig} &: \text{strain} - \text{rate for PT creep} \qquad (1) \\
\dot{\varepsilon}_{tc} = \ C_1(T,P)\exp(-Q_1/T) &: \text{ thermal creep} \\
\dot{\varepsilon}_{ic} = \ C_2(T,P,x,\emptyset)\exp(-Q_2/T) &: \text{ irradiation creep}
\end{aligned}
$$

$$\dot{\varepsilon}_{ig} = \; C_3(T,P,x,\emptyset,t)\exp(-Q_3/T): \text{ irradiation growth}$$

T: temperature, P: coolant pressure, x: axial position, Φ: fast neutron flux, t: irradiation time,
Q_1, Q_2, Q_3: activation temperatures

Here, thermal creep changes the pressure tube diameter shape owing to the effects of temperature and stress in the absence of a fast neutron flux. Irradiation creep changes the diametrical shape from irradiation, and irradiation growth is an additional change in diametrical shape owing to irradiation.

However, since the traditional ways of modeling the pressure tube diameter expansion were too complex to determine so many relevant parameters appropriately, another approaches such as data regression model [6], neural network algorithm [7] and optimized methodology based on the measured data [8-14] have been applied.

In this research, we proposed a very simple approach for modelling the pressure tube diameter in which the pressure tube diameter was modelled based on the measured data of pressure tube diameter, flux distribution of each fuel channel and temperature variation inside the pressure tube, as described in references 12 and 13, such as the following equation (2).

$$\%creep\_rate_{model} = \; A_1\%creep\_rate_{flux} + \; A_2creep\_rate_{temp} \tag{2}$$

However, former researches [12, 13] determined the parameters A_1 and A_2 by engineering judgement not by the logical algorithm and there was some discrepancy between the measured data and predicted diameter. To overcome this, in this study, new rules were derived to determine the effect of flux and temperature distribution on the diameter expansion. Results from applying the new rules show a dramatic improvement of the prediction accuracy of pressure tube diameter compared to the previous modeling results.

NEW RULES FOR PRESSURE TUBE DIAMETER MODELLING

Figure 1 shows the shape of the inner diameter of the pressure tube and the distribution of the neutron flux and temperature along the axial direction. Basic idea of this research to establish the diameter prediction model started from Figure 1, that is, the shape of diameter of the pressure tube can be expressed as a combination of the fast neutron flux and temperature distribution such as an equation (1). Figure 2 shows an example of the inner diameter change of pressure tube according to the operation period for the same pressure tube.

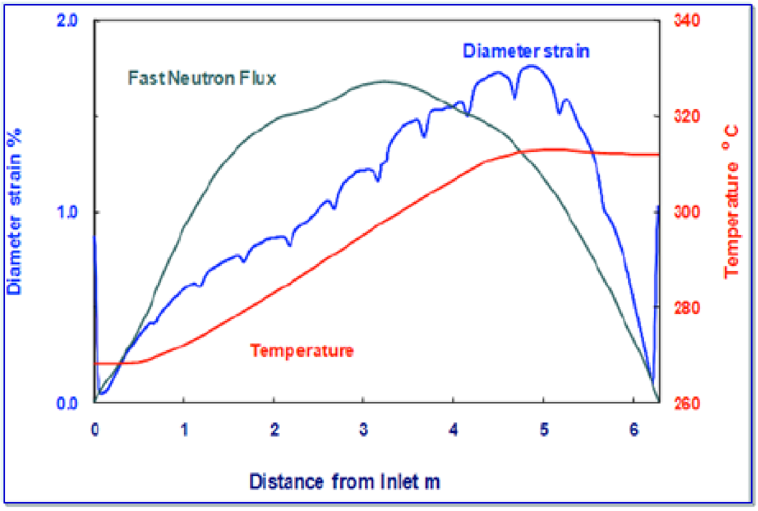

Figure 1. Distribution of diametrical deformation, neutron flux and temperature in the pressure tube.

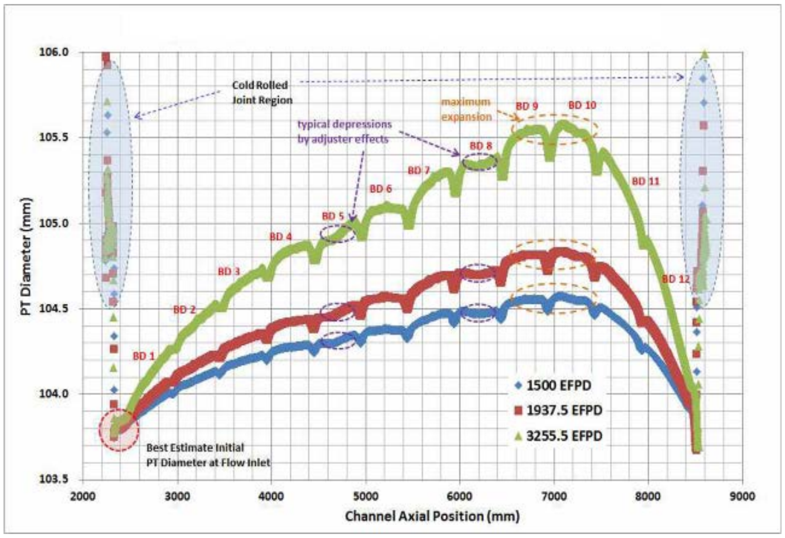

Figure 2. Example of a measured diameter for a CANDU 6 pressure tube.

In this research, we modified the equation (2) which is the initial prediction model for pressure tube diameter to the following equations (3) ~ (5).

$$\%creep\_rate_{MEA} = \%creep\_rate_{FLUX} + \%creep\_rate_{TEMP} \quad (3)$$

$\%creep\_rate_{MEA}$: strain-rate of measured diameter
$\%creep\_rate_{FLUX}$: effect of flux on diameter expansion
$\%creep\_rate_{TEMP}$: effect of temperature on diameter

$$\%creep\_rate_{FLUX} = F_1 \times \%creep\_rate_{flux} \quad (4)$$

$$\%creep\_rate_{TEMP} = T_1 \times (BD\ \ location) + T_2 \quad (5)$$

Here, F_1, T_1 and T_2 are the constant scaling factors which determine the each contribution of neutron flux and temperature on the pressure tube diameter expansion. $\%creep\_rate_{MEA}$ is the strain-rate value derived from the measurement data for each pressure tube and $\%creep\_rate_{flux}$ is the normalized neutron flux distribution for each fuel channel. Procedures for deriving both $\%creep\_rate_{MEA}$ and $\%creep\_rate_{flux}$ are explained in the references 9, 12 and 13. Following 4 rules were introduced in order to determine the scaling factors.

RULE 1: Determination of F_1

As shown in Figure 1, the neutron flux distribution inside the pressure tube has the maximum value at the middle position, where corresponding to the location of fuel bundle 6 and 7. Thus, it was assumed that the portion of diameter expansion owing to the neutron flux ($\%creep\_rate_{FLUX}$) was the half of the total expansion ($\%creep\_rate_{MEA}$) at the locations of bundle 6 and 7. Therefore, F_1 could be determined as the equation (6).

$$F_1 = 0.5 \times \frac{[(\%creep\_rate_{MEA})_{at\ \ BD6} + (\%creep\_rate_{MEA})_{at\ \ BD7}]}{\left[(\%creep\_rate_{flux})_{at\ \ BD6} + (\%creep\_rate_{flux})_{at\ \ BD7}\right]} \quad (6)$$

RULE 2: Determination of T_1

Figure 1 shows again that the temperature distribution increases linearly from the inlet to the outlet. Since the contribution of the temperature effect on the diameter expansion is same to the residual between the measured strain-rate and the expansion owing to the neutron flux ($creep\_rate_{TEMP} = T_1 \times (BD\ location) + T_2 = \%creep\_rate_{MEA}$ -$\%creep\_rate_{FLUX}$), T_1 can be determined as the following equation (7).

$$T_1=\{(\%creep\_rate_{MEA}-\%creep\_rate_{FLUX})_{atBD6}-(\%creep\_rate_{MEA}-\%creep\_rate_{FLUX})_{atBD1}\}/\{\Delta X_{BD1\text{-}BD6}\} \quad (7)$$

RULE 3: Determination of T_2

Because T_2 is an y-axis intersection of equation (5), it could be determined as a residual between the measured strain-rate and the expansion owing to the neutron flux at the location of fuel bundle 1 (x = 0) like an equation (8).

$$T_2 = (\%creep\_rate_{MEA} - \%creep\_rate_{FLUX})_{at\ BD1} \quad (8)$$

RULE 4: $\%creep\_rate_{TEMP}$ at Bundle 10, 11 and 12

Since the temperature at the outlet is almost constant as shown in Figure 1, $\%creep\_rate_{TEMP}$ at the locations of fuel bundle 10, 11 and 12 were modified as the following equation (9).

$$\begin{aligned}(\%creep\_rate_{TEMP})_{at\ BD10} &= (\%creep\_rate_{TEMP})_{at\ BD9}\\ (\%creep\_rate_{TEMP})_{at\ BD11} &= (\%creep\_rate_{TEMP})_{at\ BD8}\\ (\%creep\_rate_{TEMP})_{at\ BD12} &= (\%creep\_rate_{TEMP})_{at\ BD4}\end{aligned} \quad (9)$$

Figure 3 shows the reason clearly why the equation (9) was introduced from the residual between the measured strain-rate and the expansion owing to the neutron flux.

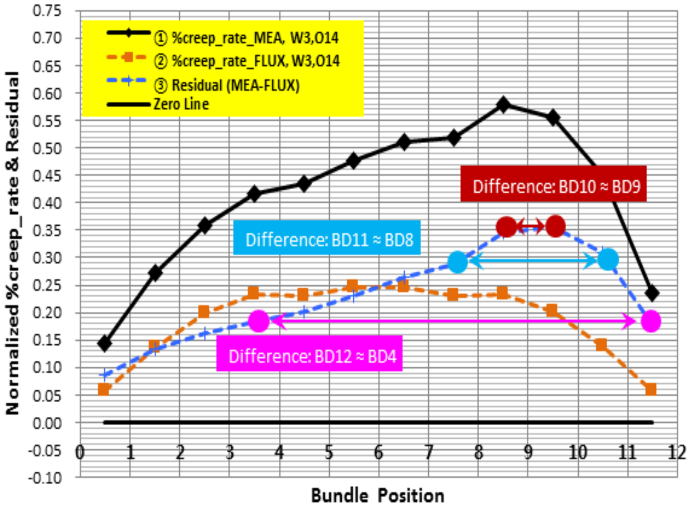

Figure 3. Determination of %creep_rateTEMP at the locations of bundle 10, 11 and 12.

EVALUATION RESULTS OF PRESSIRE TUBE DIAMETER

Former evaluation results for the pressure tube diameter before applying the new rules were reported in references 12 and 13. Results from the applying the new rules of equations (6) ~ (9) are compared to those former results regarding the same pressure tubes.

Figure 4 is the former evaluation result applying the equation (2) and Figure 5 is the new evaluation result from applying new rules of equations (6) ~ (9), respectively, regarding the same fuel channel. Black solid curve is the measured data of pressure tube diameter and blue dotted curve is the evaluation result from the developed methodology in Figures 4 and 5. As can be seen, there was much improvement in the diameter prediction result when we applied new rules for determining the scaling factors F_1, T_1 and T_2 as shown in Figure 5 compared to Figure 4.

Figures 6 and 7 show the other evaluation results for another fuel channel's pressure tube and we can also confirm the improvement of the prediction accuracy from the new methodology.

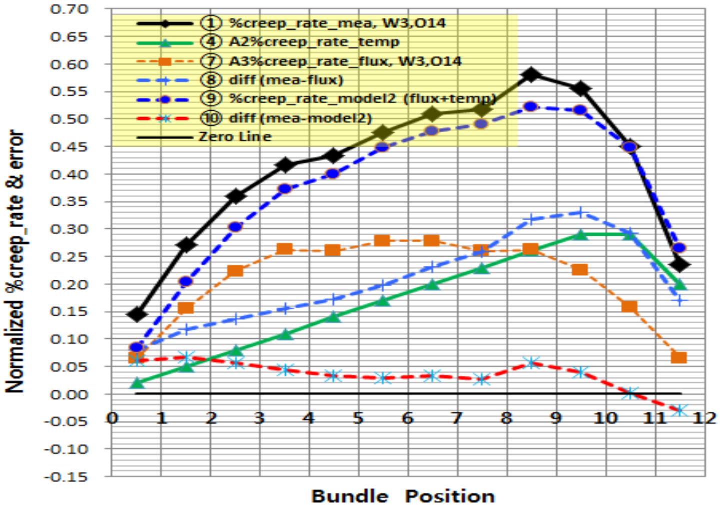

Figure 4. Diameter prediction results from the former methodology (eq. (2)).

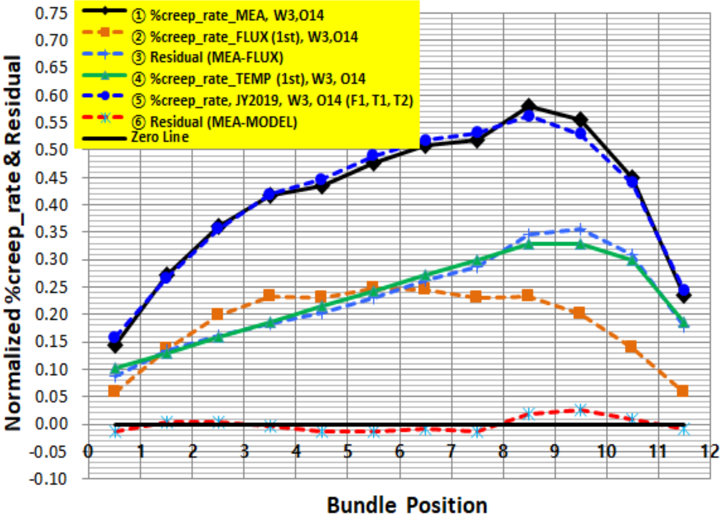

Figure 5. Diameter prediction results from the new rules (eq. (3) ~ eq. (5)).

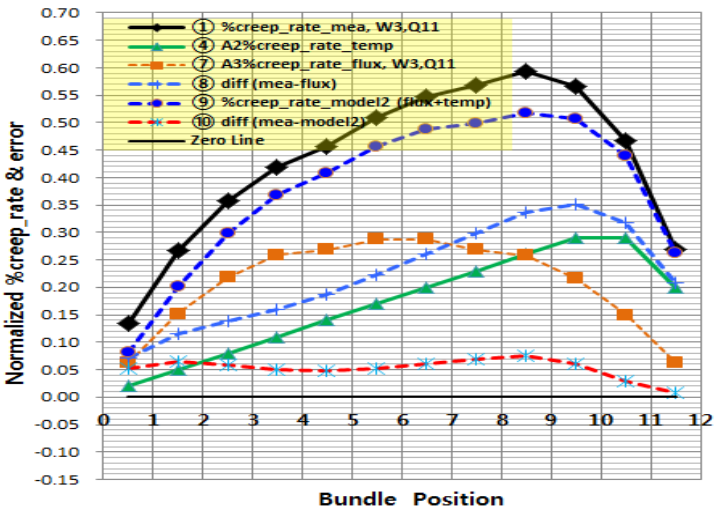

Figure 6. Diameter prediction results from the former methodology (eq. (2))

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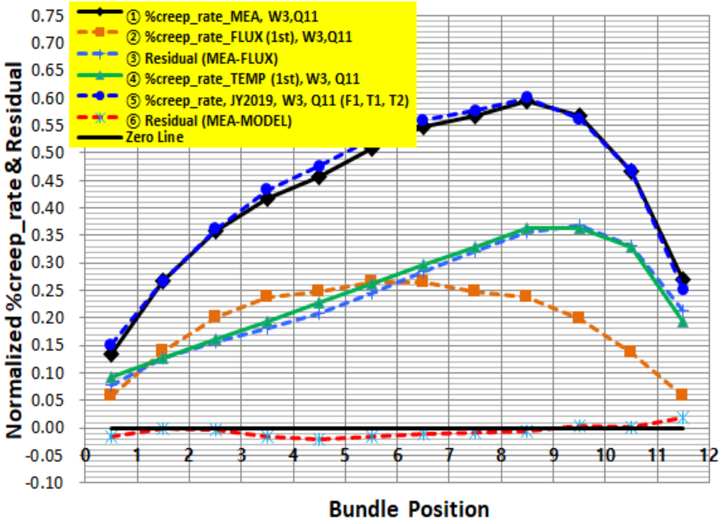

Figure 7. Diameter prediction results from the new rules (eq. (3) ~ eq. (5)).

Figures 8 and 9 shows the comparison results from the currently developed model and existing methodology for two different pressure tubes. The black curve is the measured data and the blue dotted curve is the evaluation result from the current new rules and the purple curve is the result from the existing methodology. It is clear that the currently developed methodology predicts the pressure tube diameter very close to the measured data than the existing methodology.

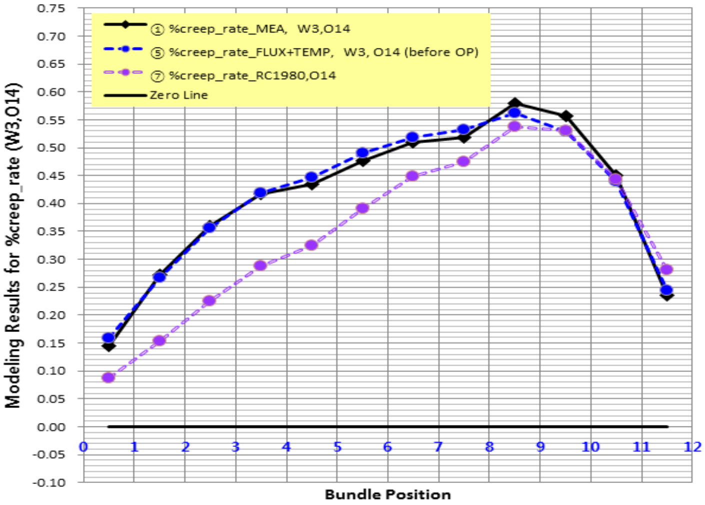

Figure 8. Comparison of pressure tube diameter prediction results.

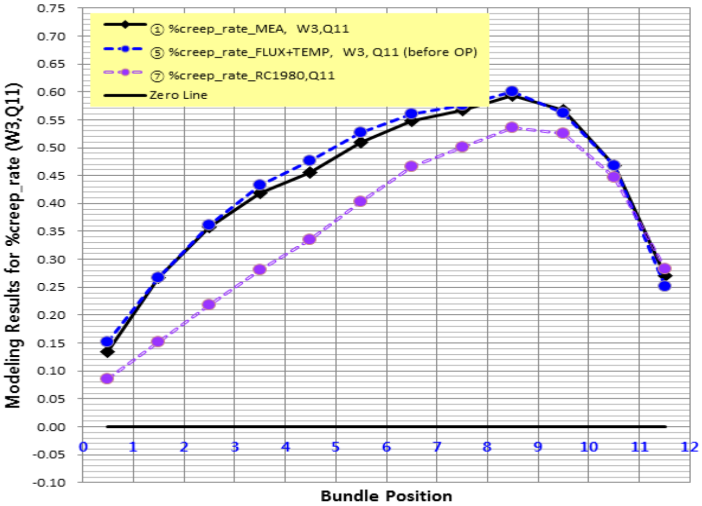

Figure 9. Comparison of pressure tube diameter prediction results for another channel.

CONCLUSION

Because an expansion of the pressure tube diameter affects critical channel power owing to the increase of by-pass coolant flow, an accurate prediction of the pressure tube diameter is very important in assessing the operational margin of CANDU reactor.

In this study, new rules were derived to determine the effect of flux and temperature distribution on the diameter expansion. Results from applying the new rules show a dramatic improvement of the prediction accuracy of pressure tube diameter compared to the previous modeling results.

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