Transactions of the Korean Nuclear Society Fall Meeting
Ilsan, Korea, October 24-25, 2019

Application of New Rules for the Prediction of CANDU Pressure Tube Diameter

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1. Introduction

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]. 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 [8-12] have been applied.

Basic approach for modeling the pressure tube diameter was described in reference 12, in which the pressure tube diameter was modeled based on the measured data of pressure tube diameter, flux distribution of each fuel channel and temperature variation inside the pressure tube such as the following equation (1).

$$\%creep\_rate_{model} = A_1\%creep\_rate_{flux} + A_2 creep\_rate_{temp} \quad (1)$$

However, a former research 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.

2. Derivation of New Rules

Basic concept of the pressure tube diameter modeling is that the diameter can be expressed as a combination of neutron flux and temperature effects such as equation (1). In this study, the equation (1) was modified to the following equations (2) ~ (4).

$$\%creep\_rate_{MEA} = \%creep\_rate_{FLUX} + creep\_rate_{TEMP} \quad (2)$$

$\%creep\_rate_{MEA}$: Measured diameter strain-rate
$\%creep\_rate_{FLUX}$: Flux effect on dia. expansion
$\%creep\_rate_{TEMP}$: Temp. effect on dia. expansion

$$\%creep\_rate_{FLUX} = F_1 \times \%creep\_rate_{flux} \quad (3)$$
$$\%creep\_rate_{TEMP} = T_1 \times (BD\ location) + T_2 \quad (4)$$

Here, F_1, T_1 and T_2 are the scaling factors and constant 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 reference 9 and 12.

2.1 Rule 1: Determination of F_1

Fig. 1 shows that the neutron flux distribution inside the pressure tube has the maximum value at the middle position, where correspond 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 (5).

$$F_1 = 0.5x\{(\%creep\_rate_{MEA})_{at\ BD6} + (\%creep\_rate_{MEA})_{at\ BD7}\} / \{(\%creep\_rate_{flux})_{at\ BD6} + (\%creep\_rate_{flux})_{at\ BD7}\} \quad (5)$$

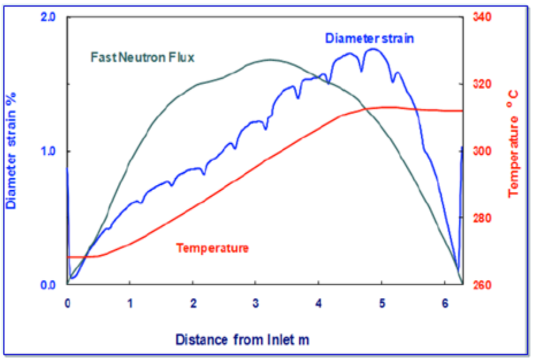


Fig. 1. Distribution of diametrical creep, neutron flux and temperature within the pressure tube

2.2 Rule 2: Determination of T_1

Fig. 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 (6).

$$T_1=\{(\%creep\_rate_{MEA}-\%creep\_rate_{FLUX})_{at\ BD6} - (\%creep\_rate_{MEA}-\%creep\_rate_{FLUX})_{at\ BD1}\}/\{\Delta X_{BD1\text{-}BD6}\} \quad (6)$$

2.3 Rule 3: Determination of T_2

Because T_2 is an y-axis intersection of equation (4), 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 (7).

$$T2 = (\%creep\_rate_{MEA} - \%creep\_rate_{FLUX})_{at\ BD1} \quad (7)$$

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

Since the temperature at the outlet is almost constant as shown in Fig. 1, $\%creep\_rate_{TEMP}$ at the locations of fuel bundle 10, 11 and 12 were modified as the following equation (8).

$$\begin{aligned}(\%creep\_rate_{TEMP})_{at\ BD10} &= (\%creep\_rate_{TEMP})_{at\ BD9}\\ (\%creep\_rate_{TEMP})_{at\ BD11} &= (\%creep\_rate_{TEMP})_{at\ BD8}\\ (\%creep\_rate_{TEMP})_{at\ BD12} &= (\%creep\_rate_{TEMP})_{at\ BD4}\end{aligned} \quad (8)$$

Fig. 2 shows the reason clearly why the equation (8) was introduced from the residual between the measured strain-rate and the expansion owing to the neutron flux.

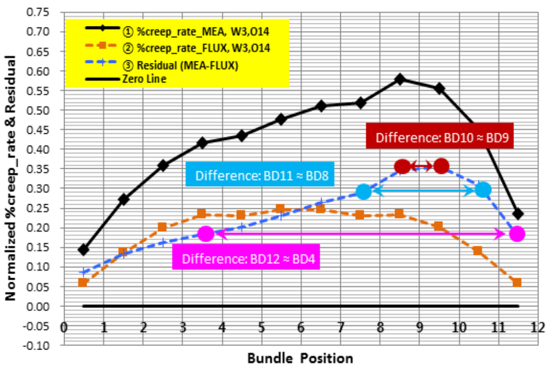


Fig. 2. Determination of $\%creep\_rate_{TEMP}$ at the locations of bundle 10, 11 and 12

3. Pressure tube Diameter Evaluation Results

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 (5) ~ (8) are compared to those former results regarding the same pressure tubes.

Fig. 3 is the former result and Fig. 4 is the new result from applying new rules, respectively, regarding the same fuel channel of O14. Much improvement in the diameter prediction results can be seen from two results after new rules were applied.

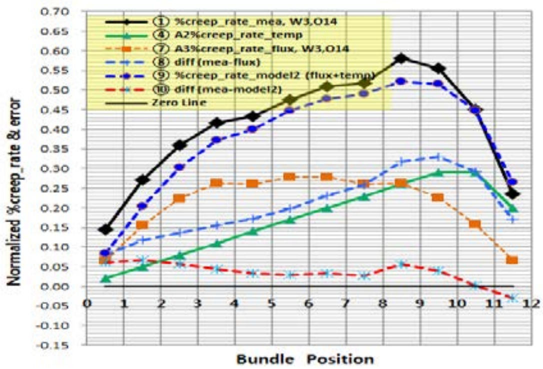
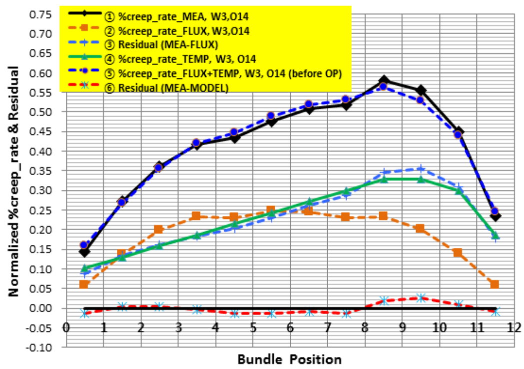


Fig. 3. Diameter prediction results from the former methodology for O14 channel



Fig, 4. Diameter prediction results from the new rules for O14 channel

Fig. 5 shows the comparison result of currently developed model and existing methodology of RC1980, which is the Canadian methodology. The black curve is the measured diameter and the blue dotted curve is the evaluation result from the current new rules and the purple curve is the result from RC1980. It is clear that the currently developed methodology predicts the pressure tube diameter very close to the measured data than RC1980.

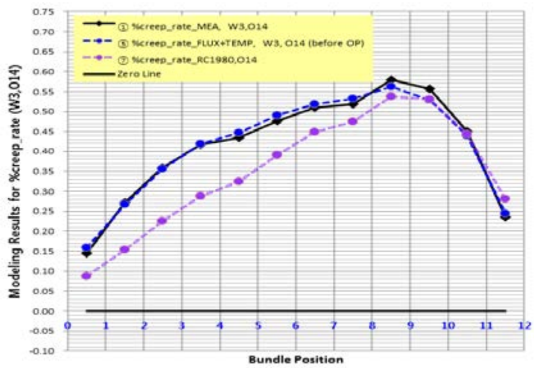


Fig. 5. Comparison of pressure tube diameter prediction results

4. Conclusions

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

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (Ministry of Science and ICT). (NRF-2017M2A8A4017282).

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