

## Comparison of Various Statistical Models for the Pressure Tube Diameter Expansion in CANDU

Gyeong-Geun Lee<sup>a\*</sup>, Hyung-Ha Jin<sup>a</sup>, Dong-Hyun Ahn<sup>a</sup>, Sang-Yeob Lim<sup>a</sup>, Iseul Ryu<sup>a</sup>  
<sup>a</sup> Materials Safety Technology Development Division, Korea Atomic Energy Research Institute,  
 111, Daedeok-daero, 989beon-gil, Yuseong-gu, Daejeon 34057, Republic of Korea  
 \*Corresponding author: [gglee@kaeri.re.kr](mailto:gglee@kaeri.re.kr)

### 1. Introduction

The pressure tube (PT) is the main components in a CANDU reactor. Neutron irradiation during operation causes a diametral expansion in PT, and the expansion increases bypass flow which affects the fuel cooling. This phenomenon reduces the operating margin of the reactor and affects plant safety. A CANDU unit measures dimensions of pressure tubes periodically by in-service inspection.

To estimate the diameter expansion of the PT, Canadian researchers developed a mechanical model [1]. This model is widely used all over the world. Recently, the in-service inspection data has been accumulated substantially, and various statistical models are developed using the data [2].

In this study, various statistical models were developed from a simple linear model based on strain rate to 3-level multilevel model based on diameter strain. The pros and cons of each method were analyzed by comparing the prediction results.

### 2. Methods and Results

The data used in this study were the in-service data collected in Wolsung units. This data includes diameter changes with bundle location measured on selected channels in the CANDU unit at various temperatures and neutron fluxes. The statistical fitting was implemented by open source R software [3].

#### 2.1 Strain rate-based models

The strain rate of PT diameter expansion can be expressed by dividing the measured diameter change by the EFPH at the time of measurement. It has only one representative value for each unit-channel-bundle position. If the diameter change is measured several times at one location, the last measured in-service inspection was used as a representative value. The amount of strain at that position can be obtained easily by multiplying EFPH. The reason that the strain rate can be defined in this way is that the diameter of the PT increases almost linearly with the EFPH by neutron irradiation during operation.

The strain rate collected at each location is put into one pool without considering channel and bundle

information and modeled for temperature and flux, it becomes a strain rate-based linear model of each unit.

$$D_{rate} \sim 1 + x + y + xy + x^2 + x^2y^2$$

x : flux  
y : temperature

It can be calculated simply and has the advantage of expressing the overall trend of the pressure tube change, but it is not possible to simulate the unique characteristics of each channel and the prediction interval is narrow compared to other models, so it is somewhat non-conservative.

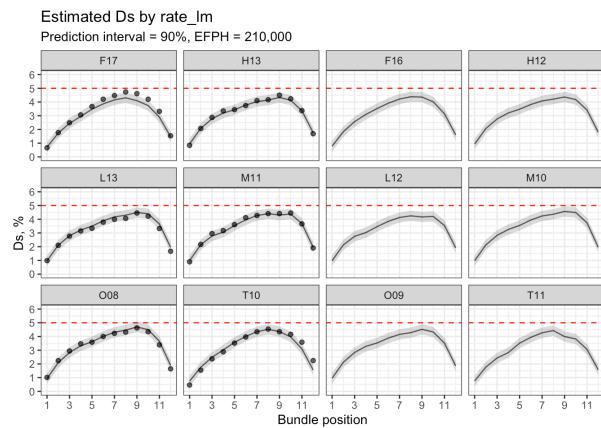


Fig. 1. Estimated diameter strains of W3 unit by linear model.

#### 2.2 Strain Rate-based Multilevel Model

Each channel is physically connected to each other and correlates with heat transfer and material deformation. In order to consider this channel-unit correlation, it is more reasonable to introduce a multi-layer model rather than a simple linear model.

$$D_{rate} \sim (1 + x + y + xy + x^2 + x^2y^2) + (1 + x + y + xy + x^2 + x^2y^2 |channel)$$

In this model equation, the first line shows the overall trend of the strain rate, and the second line means the strain rate for each channel. This model results in significantly higher prediction accuracy for channels that already have measured results.

Conversely, in the case of a channel that has never been measured, the prediction interval becomes wider.

Multilayer models are not simply calculated in close form like linear models, but model parameters are calculated using general numerical optimization techniques, or model parameters are calculated using Markov Chain Monte Carlo (MCMC) technique. Fig. 2. shows the estimated results of rate-based model.

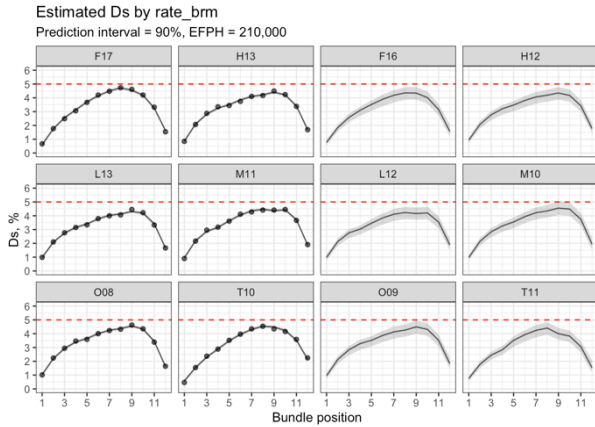


Fig. 2. Estimated diameter strains of W3 unit by strain rate-based multilevel model.

### 2.3 2-level Multilevel Model considering EFPH

In general, data measured at large EFPH are more reliable than the data measured at small EFPH is small. But after converting to rate, that information is removed. Therefore, precision can be improved if the weights of EFPH are considered directly in the model. This is a 2-level multilevel model equation considering EFPH.

$$D_s \sim (1 + (x + y + xy + x^2 + x^2y^2) \times EFPH) + (1 + (x + y + xy + x^2 + x^2y^2) \times EFPH | channel)$$

Since the EFPH term has been added, if only one measurement is performed in one channel, the effect of EFPH cannot be accurately identified, and the prediction interval may be widened. However, as the number of in-service inspection results measured twice or more increases, prediction becomes more accurate than the strain rate-based model that uses only the last in-service inspection result.

Fig. 3 shows the result of the 2-level multilevel model. It is similar to Fig.2, however, it shows more wide-range prediction intervals.

### 2.4 3-level Multilevel Model considering EFPH

The models introduced above are basically unit-based models. In other words, the prediction is made using the in-service inspection data measured by each unit. In this case, it is difficult to predict when there is insufficient data by building a new power plant.

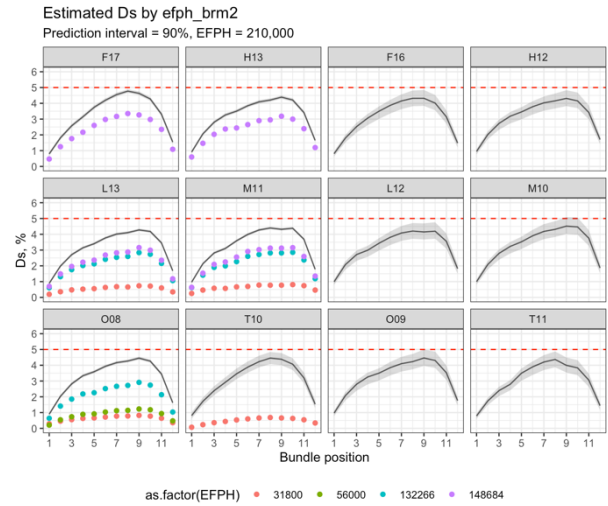


Fig. 3. Estimated diameter strains of W3 unit by 2-level multilevel model.

It is recommended to consider a 3-level multi-layer model in order to understand the overall diameter change trend by considering the trends for each power plant. The 3-level multilevel model synthesizes and predicts the overall correlation for unit-channel-bundle. The 3-level model expression is shown in the following expression.

$$D_s \sim (1 + (x + y + xy + x^2 + x^2y^2) \times EFPH) + (1 + (x + y + xy + x^2 + x^2y^2) \times EFPH | channel : unit) (1 + (x) \times EFPH | unit)$$

The 3-level multi-layer model showed high prediction accuracy for the initial in-use inspection data of individual units, but the 2-level model showed higher accurate predictions as the number of in-use inspections increases.

## 3. Conclusions

Various statistical models were compared using Wolseong diameter change data. A simple linear model showed non-conservative predictions. A multilevel model based on the strain rates showed increased accuracy compared with the linear model. When EFPH was additionally considered in the multilevel model, it showed excellent predictive power. In the case of the 3-level model, it was helpful to understand the trend of all units.

## REFERENCES

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