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# Multiple Linear Regression Analysis for Evaluating the Impact of Uncertainty Variables on LBLOCA Consequence

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## 1. Introduction

The best estimate plus uncertainty (BEPU) method has been increasingly applied for the evaluation of the loss of coolant accident (LOCA). In this methodology, an identification of uncertainty variables affecting an accident consequence is an essential task. The Pearson correlation coefficient has been usually used as a measure to identify important parameters and determine their ranking [1-2]. However, in the statistics, the correlation coefficient does not represent the influence of independent variable against dependent variable, but represents the degree of linearity between them. On the other hand, a regression analysis is a statistical method used to estimate the relationship between a dependent variable and one (simple regression) or more (multiple regression) independent variables. In this study, the multiple linear regression analysis was performed for evaluating the impact of uncertainty variables on LBLOCA consequence.

## 2. BEPU Calculations for APR-1400 LBLOCA

The LBLOCA by 100 % double-ended guillotine break at the reactor coolant pump discharge leg was considered to be analyzed, and the transient was analyzed by using MARS-KS code [3]. The 124 calculations for APR-1400 LBLOCA were conducted by applying the 3rd order Wilks' formula and with considering 18 uncertainty parameters according to KINS-REM [4-5]. Table I shows the uncertainty variables and the quantification information used in this study. The uncertainty parameters from 5 to 10 are related to core heat transfer, so that they influence the reflood phenomena. All uncertainty parameters for the reflood phenomena were not considered in this study, but the accurate uncertainty quantification of individual parameters still remains difficult and challenging due to the lack of relevant data. Therefore, KINS-REM had determined 18 uncertainty parameters and they have been applied for regulatory audit calculation and licensing.

In this study, the influence of uncertainty parameters was evaluated for each blowdown PCT and reflood PCT, since the dominant phenomena occurring at the blowdown and the reflood phase are different to each other. Fig. 1 shows the blowdown and reflood PCT distributions.

Table I: Uncertainty variables

| No | Models/Variables | Distribution | Mean | Uncertainty |
|---|---|---|---|---|
| 1 | Gap conductance | Uniform | 0.95 | 0.55 |
| 2 | Fuel conductivity | Uniform | 1.0 | 0.153 |
| 3 | Core power | Normal | 1.0 | 0.01 |
| 4 | Decay heat | Normal | 1.0 | 0.033 |
| 5 | Groeneveld CHF | Normal | 0.985 | 0.2638 |
| 6 | Chen nucleate boiling | Normal | 0.995 | 0.1505 |
| 7 | Chen transition boiling | Normal | 1.0 | 0.149 |
| 8 | Dittus-Boelter liquid convection | Normal | 0.998 | 0.127 |
| 9 | Dittus-Boelter vapor conv. | Normal | 0.998 | 0.127 |
| 10 | Bromley film boiling | Normal | 1.004 | 0.1864 |
| 11 | Break CD | Normal | 0.947 | 0.0706 |
| 12 | Pump 2-f head | Uniform | 0.5 | 0.5 |
| 13 | Pump 2-f torque | Uniform | 0.5 | 0.5 |
| 14 | SIT pressure (MPa) | Uniform | 4.245 | 0.215 |
| 15 | SIT inventory ($m^3$) | Uniform | 49.95 | 4.65 |
| 16 | SIT temperature (K) | Uniform | 308 | 14.0 |
| 17 | SIT loss coefficient | Normal | 18.0 | 2.33 |
| 18 | IRWST temperature (K) | Uniform | 302.5 | 19.5 |

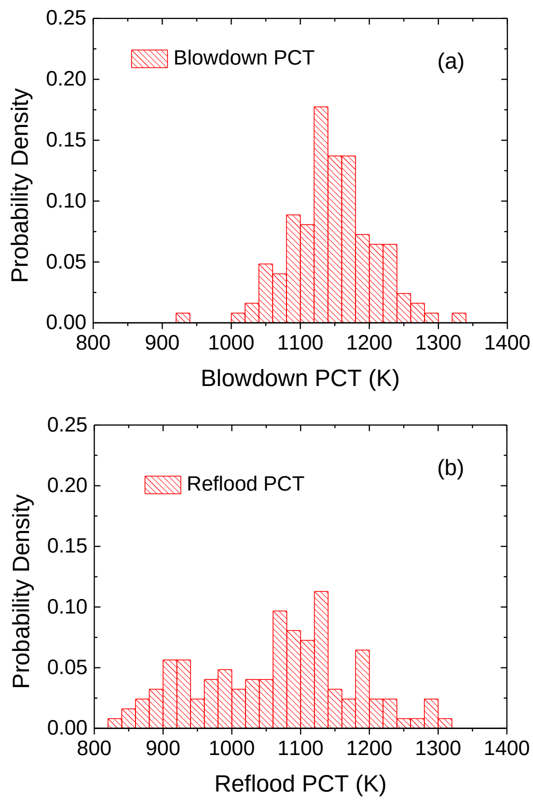


Fig. 1. PCT distributions; (a) blowdown phase (b) reflood phase

## 3. Results and Discussion

Based on these results, the multiple linear regression analysis for evaluating the impact of uncertainty variables was performed by using 'R' program [6].

For the case of k independent variables $x_1$, $x_2$, $\cdots$, $x_k$, the mean of dependent variable Y is given by the multiple linear regression model as following;

$$\mu_Y|_{x_1,x_2,\cdots,x_k} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k \quad (1)$$

and the sample regression equation is written as

$$\hat{y} = \hat{\beta}_0 + \hat{\beta}_1 x_1 + \hat{\beta}_2 x_2 + \cdots + \hat{\beta}_k x_k \quad (2)$$

where each regression coefficient $\beta_j$ is estimated by $\hat{\beta}_j$ from the sample data using the least squares method. Then, for the i$^{th}$ data point $\{x_{1,i},\ x_{2,i},\ \cdots,\ x_{k,i}, y_i\}$, the following equation can be derived.

$$y_i = \beta_0 + \beta_1 x_{1,i} + \beta_2 x_{2,i} + \cdots + \beta_k x_{k,i} + \varepsilon_i \quad (3)$$

or

$$y_i = \hat{y}_i + e_i = \hat{\beta}_0 + \hat{\beta}_1 x_{1,i} + \cdots + \hat{\beta}_k x_{k,i} + e_i \quad (4)$$

where $y_i$ is the observed response to the values $x_{1,i}$, $x_{2,i}$, $\cdots$, $x_{k,i}$, and $\varepsilon_i$ and $e_i$ are the random error and the residual, respectively. Then, the sum of squared residuals is written as

$$\sum_{i=1}^{n} e_i^2 = \sum_{i=1}^{n}\left(y_i - \hat{\beta}_0 - \hat{\beta}_1 x_{1,i} - \cdots - \hat{\beta}_k x_{k,i}\right)^2 \quad (5)$$

These equations are more conveniently formulated with matrix notation. Then, equation (5) can be written as

$$\sum_{i=1}^{n} e_i^2 = (\mathbf{y} - \mathbf{X}\hat{\boldsymbol{\beta}})'(\mathbf{y} - \mathbf{X}\hat{\boldsymbol{\beta}}) \quad (6)$$

To find the $\hat{\boldsymbol{\beta}}$ in the sense that the sum of squared residuals, equation (6), is minimized, take derivatives with respect to $\hat{\boldsymbol{\beta}}$ and set them equal to zero. Then, vector normal equations for multiple linear regression can be obtained as following;

$$\mathbf{X}'\mathbf{X}\hat{\boldsymbol{\beta}} = \mathbf{X}'\mathbf{y} \quad (7)$$

$$\hat{\boldsymbol{\beta}} = (\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\mathbf{y} \quad (8)$$

A multiple linear regression model between 18 uncertainty variables and the blowdown/reflood PCTs was obtained, and Fig. 2 shows the estimated regression coefficients ( $\hat{\beta}$ ) for each uncertainty variable. The adjusted $R^2$ illustrates the adequacy of a fitted regression model. They were calculated to be 0.932 and 0.900 for blowdown and reflood PCTs, respectively, which means that 93.2% and 90.0% of the variation in PCTs have been explained by the multiple linear regression model.

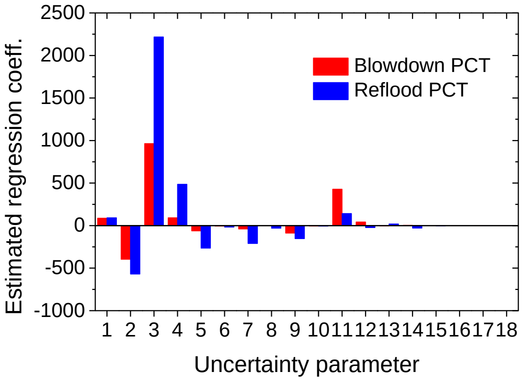


Fig. 2. Estimated regression coefficients of uncertainty parameters

The hypothesis tests for the regression coefficients of individual uncertainty variables were performed to identify the important variables as following;

1. $H_0$: $\beta_j = 0$
2. $H_1$: $\beta_j \neq 0$ (9)
3. $\alpha = 0.05$

The null hypothesis is that the regression coefficient of j$^{th}$ predictor is equal to zero, which means there is no relationship between the PCTs and the uncertainty variable. The alternative hypothesis is that j$^{th}$ predictor is different from zero, which means it has an influence to the PCT. Fig. 3 shows the P-values for individual uncertainty variables. If the P-value is less than the α, the alternative hypothesis is accepted in that the uncertainty variable can be identified as influential. Otherwise, the null hypothesis is not rejected. As shown in Fig. 3, the parameters with the P-value less than 0.05 (e.g. parameter #1~#5, etc.) follow the alternative hypothesis, so that they were identified as influential. On the other hand, the parameters with the P-value higher than 0.05 (e.g. parameter # 6, etc.) follow the null hypothesis, so that they were identified as not influential.

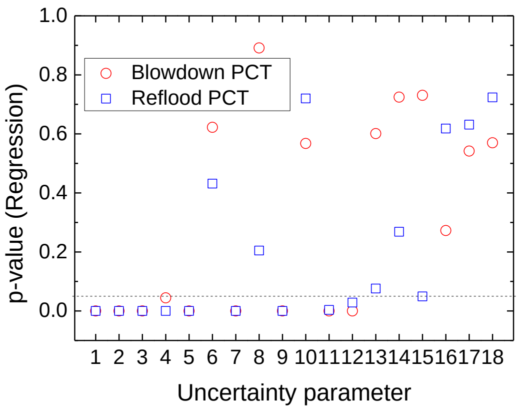


Fig. 3. P-values of uncertainty parameters

The estimated regression coefficients shown in Fig. 2 depend on the units of uncertainty parameters, so that the standardized regression coefficients were calculated as shown in Fig. 4.

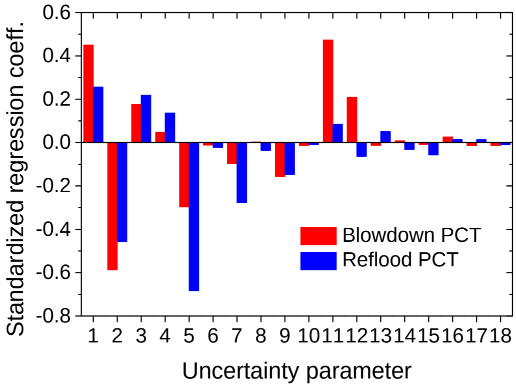


Fig. 4. Standardized regression coefficients of uncertainty parameters

Summarizing the results so far, the influential uncertainty variables on the blowdown and reflood PCTs are ranked in Table II.

Table II: Rank of influential uncertainty variables

| **Rank** | **Blowdown PCT** | **Reflood PCT** |
|---|---|---|
| 1 | Fuel conductivity | Groeneveld CHF |
| 2 | Break CD | Fuel conductivity |
| 3 | Gap conductance | Chen transition boiling |
| 4 | Groeneveld CHF | Gap conductance |
| 5 | Pump 2-f head | Core power |
| 6 | Core power | Dittus-Boelter vapor |
| 7 | Dittus-Boelter vapor | Decay heat |
| 8 | Chen transition boiling | Break CD |
| 9 | Decay heat | Pump 2-f head |
| 10 | | SIT water inventory |

## 4. Conclusions

In this study, the BEPU calculations for APR-1400 LBLOCA were conducted by applying the 3rd order Wilks' formula and with considering 18 uncertainty parameters according to KINS-REM. Based on these calculation results, the influence of uncertainty variables on the blowdown and reflood PCTs was evaluated by applying the multiple linear regression analysis. In the evaluation, the important uncertainty parameters were identified by the hypothesis test, and their ranking was determined through standardized regression coefficients.

As a result, the uncertainty parameters and their importance affecting the blowdown PCT and the reflood PCT were also shown to be different. The multiple linear regression analysis showed that 9 parameters have an influence on the blowdown PCT. For the reflood PCT, the multiple linear regression analysis identified 10 parameters to have an influence on it. However, in order to evaluate the adequacy of the multiple linear regression analysis results, additional deterministic sensitivity studies should be performed

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