Evaluation for the Impact of Uncertainty Parameters on PCT by the Linear Regression Analysis

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1. Introduction

The best-estimate methods plus uncertainty analyses (BEPU) have been widely used for the evaluation of the loss of coolant accident (LOCA) of the nuclear power plant after the amendment of the 10CFR50.46 rule in 1988. In Korea, the KREM (KHNP Realistic Evaluation Methodology) has been applied to most PWR plants [1]. The KINS (Korea Institute of Nuclear Safety) has also developed the KINS Realistic Evaluation Methodology (KINS-REM) to check the validity of the licensee's results [2].

As the regulatory demands for BE methods increase, there are still several technical issues. One of them is to determine uncertainty parameters that the technical justifications should be given for the uncertainty of an individual model, correlation, or method through the sufficient assessments for experiments. The plant performance such as power level, pump performance, and safety system can also be considered as the uncertainty parameters. 27 ~ 29 uncertainty parameters were applied to the KREM, and they were not small numbers [1]. It is very challenging to define the reliable range of uncertainty, and we must consider which parameters are more focused technically on determining the range of uncertainty. Therefore, it is necessary to evaluate which of these parameters has more effect on the acceptance criteria, the peak cladding temperature (PCT).

This study was conducted to confirm the impact of uncertainty parameters for the large break LOCA analysis using BEPU. The LOFT L2-5 test selected for the evaluation [3]. The TRACE V.5.0 patch 5 code and DAKOTA code [4,5] were utilized for uncertainty analyses. The 'R' program [6] was applied for the multiple linear regression analysis which it has implemented the many statistical techniques.

2. Uncertainty Parameters and BE calculation

The LOFT L2-5 test simulated 200% cold leg break with loss of off-site power. The TRACE input model was based on the previous study [7]. From the transient calculations, the peak cladding temperature was predicted as 1024.3 K at ~ 36 sec after breaking the pipe.

Table I and II show a list of the uncertainty parameters in this study. 36 uncertainty quantification (UQ) sensitivity coefficients for specific models can be implemented in the current TRACE code. They can be categorized into four groups: Interfacial heat transfer model, wall heat transfer model, fuel model, and drag model. 35 uncertainty values except for the film to transition boiling T_{min} criterion temperature (S10) were used for the multiplicative mode. Seven system parameters such as accumulator temperature/pressure, HPSI/LPSI water temperature, etc. were also considered for LOFT L2-5.

Table I: List of Uncertainty Parameters

Model Group	Parameters	
Interfacial heat transfer model (7)	S00) Liquid to bubbly-slug HT	S01) Liquid to annular-mist HT
	S02) Liquid to TR HT	S03) Liquid to stratified HT
	S04) Vapor to bubbly-slug HT	S05) Vapor to annular-mist HT
	S06) Vapor to TR HT	
Wall heat transfer model (10)	S08) 1-ϕ liquid to wall HT	S09) 1-ϕ vapor to wall HT
	S10) Film to transition boiling T_{min}	S11) Dispersed film boiling HT
	S12) Subcooled boiling HT	S13) Nucleate boiling HT
	S14) DNB_CHF	S15) Transition boiling HT
	S36/S37) Vapor/Liquid to wall inverted annular HT	
Interfacial drag model (8)	S24) Bubbly	S27) Droplet
	S28) Bubbly/slug rod-Bestion	S29) Bubbly/slug-Vessel
	S30) Annular/mist vessel	S31) Dispersed flow film boiling
	S32) Inverted slug flow	S33) Inverted annular flow
Drag model (2)	S22) Wall drag	S23) Form loss

Table II: Uncertainty Parameters for Fuel and System

Model Group	Parameters	Range
Fuel model (9)	S16) Gap conductance	0.2 ~ 2.0
	S17) Fuel thermal conductivity	0.78 ~ 1.22
	S18) Clad metal-water reaction	0.5 ~ 1.5
	S19) Rod internal pressure	0.986 ~ 1.014
	S20) Burst temperature	0.5 ~ 1.5
	S21) Burst strain	0.5 ~ 1.5
	S34) Clad thermal conductivity	0.877 ~ 1.123
	S35) Clad specific heat	0.44 ~ 1.56
	S38) Fuel specific heat	0.915 ~ 1.085
System Parameters (10)	S39) Accumulator Pressure (MPa)	4.00 ~ 4.40
	S40) Accumulator Temp.(K)	297 ~ 310
	S41) HPSI Temperature (K)	295 ~ 308
	S42) LPSI Temperature (K)	295 ~ 308
	S43) Pressurizer Pressure (MPa)	14.88 ~ 15.00
	S44/S45) Power (MW)/PowerM (MW)	34.2 ~ 37.8

Uncertainty ranges of parameters except for S10 of Table I were 0.5 ~ 1.5 conservatively. The uncertainty range for S10 was specified as 0K ~ 200K for the additive mode. Uncertainty ranges of six fuel models (blue color) of Table II were reasonably determined by reviewing some documents [8,9]. Uncertainty ranges of system parameters were also defined from the experimental document [3]. The uncertainty distribution of all uncertainty parameters was assumed as a normal distribution.

The number '124' was specified on one-sided third order Wilk's formula for 95% probability and 95% confidence level [10]. The random values of 43 uncertainty parameters were sampled by DAKOTA, and 124 code runs were conducted by TRACE to obtain the peak cladding temperature with 95% probability and 95%

confidence level ($PCT_{95/95}$). The third highest PCT was considered as the upper tolerance limit for $PCT_{95/95}$.

3. Impact of Uncertainty Parameters on PCT

3.1 Multiple Linear Regression Analysis

Generally, the Pearson and Spearman correlations were widely used to identify the relationship between independent parameters and PCT and they could be obtained from DAKOTA [5]. However, these correlations just show the relationship for PCT. It is advantageous to use the regression analysis to know the effect of the independent parameters on the PCT.

The linear regression model (LRM) is one of the most popular regression techniques. The multiple LRM is used to find the relationship between one dependent parameter (Y) and several independent parameters [11]. The general multiple LRM is as the following equation.

$$Y = \beta_1 + \beta_2 X_1 + \beta_3 X_2 + \cdots + \beta_n X_{n-1} + u \qquad (1)$$

Where Y is the response parameter or the dependent parameter, X is the predictor or the independent parameter, β_1 is the intercept term, $\beta_2 \sim \beta_n$ is the coefficients, and u is the error or the disturbance term.

The backward elimination method of 'R' program was applied to remove the least significant parameter one by one because of a large number of independent parameters. Table III shows the summary output of the backward elimination. 23 parameters of the 43 independent parameters were eliminated, and eight independent parameters with a P-value of less than 0.001 were presented in Table III.

Table I: List of Uncertainty Parameters

Coefficients	Estimate	Pr(>|t|)	Standardized Estimate
S09	-2.96E+01	1.57E-07	-0.1436
S10	-1.29E-01	3.11E-08	-0.1525
S11	-4.26E+01	2.80E-14	-0.2268
S12	-2.21E+01	9.85E-07	-0.1334
S16	-3.91E+01	<2E-16	-0.4574
S17	-2.13E+02	<2E-16	-0.5649
S35	-4.24E+01	<2E-16	-0.2696
S44	6.33E+02	<2E-16	0.3764
...S04, 05, 13, 14, 21, 22, 27, 28, 29, 31, 34, 43			
Multiple R-square:		0.9335	

For every one unit of each independent parameter increase, the PCT changed by the estimated coefficient. Therefore, the power and the fuel thermal conductivity appeared to have the most significant effect on PCT in order. However, it could not provide the relative magnitude of the effect of each parameter on PCT. To not consider the independent parameter's scale of units and compare the impact of them easily, the standardized coefficient was obtained that the means and variances of dependent and independent parameters are 0 and 1, respectively. From the standardized regression coefficients, the independent parameters that significantly affect the PCT were in order of fuel thermal conductivity, gap conductance, power, clad specific heat although the uncertainty range for the parameters of Table I was conservatively defined. It produced the same results with the Spearman correlation which showed the monotonic association between other parameters and PCT [12]. Therefore, it showed that the fuel thermal conductivity and the gap conductance had the significant effect on the PCT. The p-value (Prob>|t|) was used statistically, and the regression coefficient means "statistically significant" if the p-value is less than the level of significance (~ 0.05). The R-square means the proportion of variation in the PCT that is explained by this model. The R-square (~0.9335) indicates 93% variations of PCTs can be explained by the independent parameters of this model. It means the PCT changes relatively in line with the parameters of this approach.

3.2 124 Code Runs with 20 UPs Reduced from the Backward Elimination Method

23 independent parameters were removed, and 20 parameters were left from the backward elimination method. 124 code runs were conducted again to compare the PCT between the original case with 43 parameters and the recalculation case with 20 parameters. Fig. 1 shows the comparison result of the PCTs of 124 code runs. The maximum and minimum PCT between two cases have not changed much. The quenching of maximum PCT went faster in the recalculation case, but this does not matter since the dependent parameter was the PCT. The third highest PCT was considered as the upper tolerance limit for $PCT_{95/95}$. The third highest PCT for the original case was 1109.4 K in 9th code run, and that for the recalculation case was 1110.5 K in 6th code run. It was also shown in Fig.1 that the PCT of two cases are almost the same. It can be known that the independent parameters affecting less the $PCT_{95/95}$ are not important to the final result even if they are not considered in the 124 code runs.

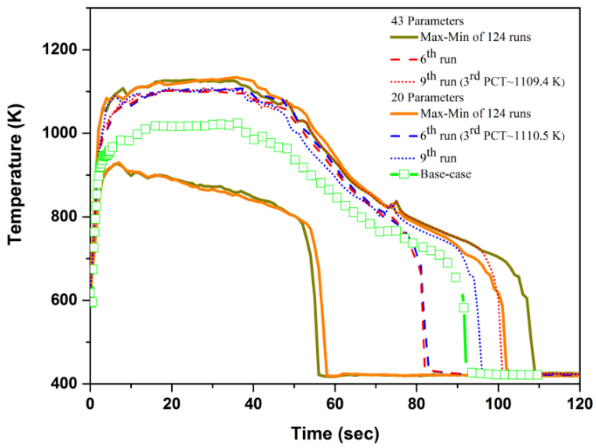

Fig.1 PCT results with 43 parameters and 20 parameters

According to recent BEPU calculations, the number of uncertainty parameters is increasing by treating possible parameters as the uncertainty through the increase of experimental verification and the application of new design. It can give a significant technical burden on determining the range of parameters. In view of reducing the technical burden, this approach would be one option to consider the removable uncertainty parameters are not affecting the PCT. However, it took a lot of care to use this approach since the determination of removable parameters could be affected dramatically by the time of PCT, the number, the range, and the distribution of uncertainty parameters.

4. Conclusions

The impact of uncertainty parameters on PCT was evaluated by the linear regression analysis for LBLOCA results of the LOFT L2-5 test using BEPU. 43 uncertainty parameters including seven system parameters were considered in this study. From the regression analysis, there was the more significant effect on the PCT in order of the fuel thermal conductivity, the gap conductance, the power, the clad specific heat, and so on. When the original case with for 43 uncertainty parameters compared with the recalculation case for 20 parameters which was determined from the backward elimination method, the PCT of two cases has changed little. The further study will be needed on whether parameters with significantly small impact on PCT can be removed from the uncertainty parameters.

ACKNOWLEDGMENTS

This work was supported by the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KOFONS), granted financial resource from the Nuclear Safety and Security Commission (NSSC), Republic of Korea (No. 1805004-0118- SB120)

REFERENCES

[1] KHNP, Topical report for the LBLOCA best-estimate evaluation methodology of the APR1400 type nuclear power plants, TR-KHNP-0018 (Rev. 0), 2008.
[2] KINS, Evaluation for Applicability of MARS Code for KINS-REM and Regulatory Audit Calculation for APR1400 LBLOCA, KINS/AR-893, 2009.
[3] Paul D. Bayless, Janice M. Divine, Experiment Data Report for LOFT Large Break Loss-of-Coolant Experiment L2-5, NUREG/CR-2826, EGG-2210, August 1982.
[4] USNRC, TRACE V5.0 Patch5 User's manual, 2017.
[5] Brian M. Adams et al., Dakota, A multilevel parallel object-oriented framework for design optimization, parameter estimation, uncertainty quantification, and sensitivity analysis: Version 6.0 user's manual, Sandia National Laboratories, Albuquerque, 2014.
[6] W.N. Venables, D.M. Smith and the R core team, An Introduction to R, Version 3.4.3, 2017.
[7] USNRC, TRACE V5.0 Assessment manual, 2012.
[8]USNRC, Predictive bias and sensitivity in NRC fuel performance codes, NUREG/CR-7001, PNNL-17644, 2009.
[9]USNRC, Material property correlations: Comparisons between FRAPCON-3.5, FRAPTRAN-1.5, and MATPRO, NUREG/CR-7024 Rev1, PNNL-19417 Rev1, 2014.
[10] Wilks, S. S., Statistical prediction with special reference to the problem of tolerance limits, Annals of Mathematical Statistics, Vol. 13, 400, 1942.
[11] Dan Campbell, Sherlock Campbell, Introduction to Regression and Data Analysis, Statlab Workshop, 2008.
[12] Byung Gil Huh, et al., Sensitivity Study for Uncertainty Range and Distribution by Using TRACE Code, ANS Best Estimate Plus Uncertainty International Conference (BEPU2018), May 13-19, 2018.