Impacts of Thermal-hydraulic Uncertainty on Fuel Particles Mobility Analysis during LBLOCA

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1. Introduction

Fuel fragmentation, relocation and dispersal (FFRD) phenomena have been considered as one of the potential safety issues on a postulated loss-of-coolant accident (LOCA) with light water nuclear power plants. Thereby, Nuclear Regulatory Commission (NRC) in U.S. had developed an evaluation methodology to estimate the amount of dispersed fuel into the core during LOCA. [1] Developed methodology in NRC consists of three steps such as (1) the analyses of system thermal-hydraulic (TH) and fuel thermal-mechanical condition, (2) assessment of fuel dispersal and (3) fuel mobility. TRACE and FRAPTRAN computer code were used as analysis tools on thermal-hydraulics system and thermal-mechanical condition of fuel rod. Total dispersed fuel mass into the core from ruptured rod was estimated by the experimental results, which were mainly obtained from Studsvik LOCA test. The fuel mobility analysis estimates critical size of fuel particles which could be used as criteria for residual fuel particles in core region.

With these safety issues, KINS also has assessed the fuel mobility analysis in APR1400 plant preliminarily based on the NRC developed methodology. [2] Sensitivity studies on estimation of critical size of fuel particle has been conducted with sphericity of fuel particle, viscosity, density and velocity of coolant as variates. However, BEPU (Best Estimate Plus Uncertainty) approach is common in safety analysis since the inherent uncertainty of system codes which can influence the TH conditions of coolant during LOCA. Impacts of these variates should be assessed and identified to understand the result of fuel mobility analysis more clearly.

In this paper, the effects of thermal-hydraulic uncertainty variates on critical size of fuel particle during LOCA have been evaluated with APR1400 as a reference plant. And then, significance of uncertainty variates to the critical size were measured with Monte-Carlo statistical treatment.

2. NRC Mobility Analysis Model

Critical size of fuel particles would be determined with the fuel particles mobility analysis. The critical size of particles is calculated by finding force balance between drag and buoyancy force. In core region, homogeneous state of two-phase flow is assumed. The equation of motion was defined as below.

$$\mathrm{m}\frac{dv_{rel}}{dt} = \frac{4}{3}\pi R^3(\rho_{fuel} - \rho_m)g - 0.5C_D\pi R^2\rho_m v_{rel}^2$$

While, C_D is drag coefficient defied as below. [3]

$$\mathrm{C_D} = \frac{24}{Re}(1 + 0.1806Re^{0.6459}) + \frac{0.4251}{1+6880.95/Re}$$

$$\mathrm{Re} = 2\rho_\mathrm{m}Rv_{rel}/\mu_m$$

Re = Reynolds number of two-phase flow,
μ_m *= homogeneous viscosity,*
R = fuel particle radius,
ρ_m *= homogeneous density,*
ρ_{fuel} *= fuel density,*
v_{rel} *= relative velocity between particle and fluid*

In the above equations, critical radius of fuel particles can be calculated as net force on fuel was given as zero.

$$\mathrm{R_{critical}} = \frac{3}{8}\left(\frac{\rho_m}{\rho_{fuel} - \rho_m}\right)C_D v_{rel}^2/g$$

For the calculation of critical radius, iterative calculation has to be conducted because the Drag coefficient is also influenced by the fuel particle radius. Shape of fuel particles are assumed as spherical.

The dispersed fuel particles of which size are smaller than the critical size are considered as having sufficient mobility to escape from the core due to the mixed flow of steam and/or liquid water coolant in this method.

3. Methods of Mobility Analysis

3.1 LBLOCA analysis and uncertainty variates

The double-ended guillotine break at downstream of reactor coolant pump is assumed for the mobility analysis on APR1400. MARS-KS V1.5 is used to determine states in core region during LBLOCA. PLUS7 fuel with fuel burnup of 30 MWd/kgU condition [4], and ANS 1979 decay heat model is applied.

Total 29 uncertainty variates are considered in this study, as listed in Table 1. These variates are considered as the main thermos-hydraulic variables for estimating peak cladding temperature during LBLOCA [5,6]. *Table 1* also shows distributions and ranges of uncertainty on each variate.

Table 1 Considered uncertainty variates and its' distributions (U:uniform, N:normal, L:lognormal)

#	Model/Variables	Distrib.	Mean	Uncertainty (σ or deviation)
1	Gap conductance	U	0.95	±0.55
2	Fuel conductivity	N	1.0	0.051
3	Core power	N	1.0	0.0068
4	Decay heat	N	1.0	0.022
5	Dittus-Boelter Liq. Conv.	N	0.998	0.1306
6	Chen nucleate boiling	N	0.995	0.155
7	Groneveld CHF	N	0.985	0.2715
8	Chen transition boiling	N	1.0	0.1535
9	Bromley film boiling	N	1.004	0.192
10	Dittus-Boelter vapor Conv.	N	0.998	0.127
11	Zuber CHF correlation	N	1.0	0.31
12	Weismann transition boiling correlation	L	1.021	EF 1.51
13	QF Bromley correlation	N	1.0	0.125
14	Forslund-Rohsenow FB correlation	N	1.0	0.25
15	Reflood superheated vapor correlation	N	1.0	0.25
16	Break Cd	N	0.947	0.0728
17	Pump 2 phase head	U	0.5	±0.5
18	Pump 2 phase torque	U	0.5	±0.5
19	SIT pressure (MPa)	U	4.245	±0.215
20	SIT initial level	U	1.0	±0.093
21	SIT temperature (K)	U	308.0	±14.0
22	IRWST temperature (K)	U	302.5	±19.5
23	Dry/wet wall criteria	N	0.91845	0.17259
24	Weber number	N	0.33605	0.53333
25	Droplet interfacial heat transfer	N	1.26494	0.45840
26	Burst temperature dial	U	1.0	±0.1
27	Burst strain dial	U	1.0	±0.7
28	Oxidation dial	N	1.0	0.0125
29	Oxidation thickness	U	$1.8682e^{-5}$	$\pm1.8682e^{-5}$

3.2 Combined uncertainty analysis method

Total 200 calculations are conducted with combining 29 uncertainty variates while the maximum value of critical radius of fuel particles for each case is chosen as the figure of merit (FOM). DAKOTA is utilized for determining values of each variates with Monte-Carlo sampling which are applied to MARS-KS input. [7,8]

Critical radius on each case is calculated with 2 step process with 'Extract Data' and 'Python' applications of SNAP environment. Critical radius is calculated based on state variables with 0.2 sec of time step.

If the fuel rod was not ruptured, value of critical radius was treated as zero. Zero critical radius of fuel particles represents that none of the particles is able to escape from the core region.

Spearman's rank correlation coefficients (SCC) between each variate and the FOM were calculated. And then, influence of each variate to critical radius is compared with the Spearman partial rank correlation coefficient (SPCC). R is used for both correlation analyses.

4. Results and Discussion

4.1 Frequency distribution of critical radius

Fig. 1 shows the frequency of maximum critical radius results with 200 analysis cases. Fuel rod rupture occurred in 179 cases (89.5%). And maximum critical radius ranges from 0.04 mm to 3.5 mm. Mean value is 0.90 mm and median value is 0.82 mm for total ruptured cases.

Fig. 2 shows the scatter plot between PCT and maximum critical radius. Two data shows 0.18 of p-value for Spearman rank correlation for 179 ruptured cases. It implies that impact of each variates' uncertainty may not be equivalent to PCT and maximum critical radius.

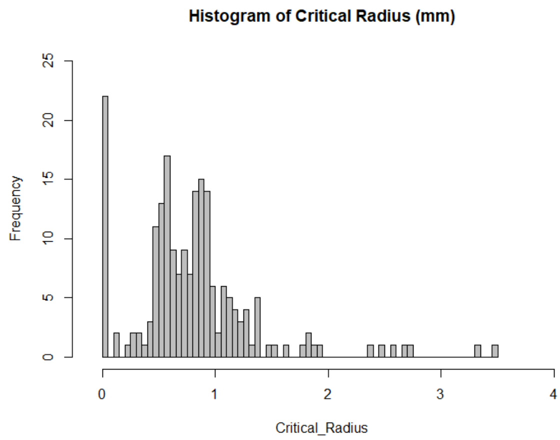

Fig. 1 Histogram for maximum critical radius of fuel particles

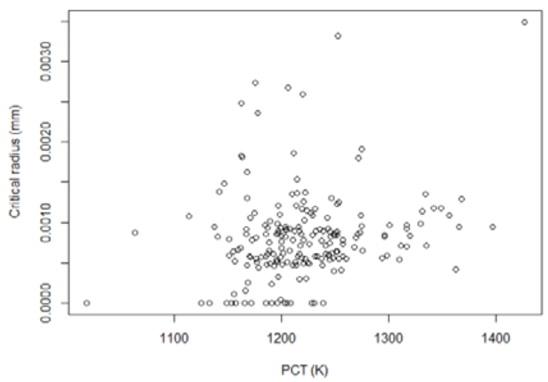

Fig. 2 Scatter plot between peak cladding temperature and maximum critical radius

Table 2 Spearman correlation coefficient with p-value on the critical radius of fuel particles

#	*Model/Variables*	SCC (P-value)	
		All cases	Ruptured cases
1	**Gap conductance**	**-0.141 (4.7E-2)**	-0.129 (8.6E-2)
2	**Fuel conductivity**	**-0.144 (4.2E-2)**	-0.089 (2.4E-1)
3	Core power	0.035 (6.2E-1)	-0.010 (8.9E-1)
4	Decay heat	-0.024 (7.3E-1)	0.014 (8.6E-1)
5	Dittus-Boelter Liq. Cnv.	-0.047 (5.1E-1)	-0.023 (7.6E-1)
6	Chen nucleate boiling	0.072 (3.1E-1)	0.003 (9.7E-1)
7	**Groneveld CHF**	-0.012 (8.7E-1)	**0.206 (5.9E-3)**
8	**Chen transition boiling**	**-0.194 (5.9E-3)**	-0.121 (1.1E-1)
9	Bromley film boiling	0.051 (4.7E-1)	0.099 (1.9E-1)
10	**Dittus-Boelter vapor**	**-0.152 (3.2E-2)**	-0.096 (2.0E-1)
11	**Zuber CHF correlation**	-0.090 (2.0E-1)	**-0.160 (3.2E-2)**
12	Weismann transition boil.	0.090 (2.0E-1)	0.051 (4.9E-1)
13	QF Bromley correlation	0.080 (2.6E-1)	0.082 (2.8E-1)
14	Forslund-Rohsenow FB	-0.057 (4.2E-1)	-0.106 (1.6E-1)
15	Reflood superheated vapor	-0.069 (3.3E-1)	-0.088 (2.4E-1)
16	**Break Cd**	**-0.150 (3.4E-2)**	-0.105 (1.6E-1)
17	**Pump 2 phase head**	**-0.259 (2.1E-4)**	-0.146 (5.1E-2)
18	**Pump 2 phase torque**	**0.142 (4.5E-2)**	0.069 (3.6E-1)
19	SIT pressure (MPa)	-0.043 (5.4E-1)	-0.018 (8.1E-1)
20	**SIT initial level**	0.089 (2.1E-1)	**0.268 (3.0E-4)**
21	SIT temperature (K)	0.056 (4.3E-1)	0.048 (5.2E-1)
22	IRWST temperature (K)	-0.047 (5.1E-1)	-0.037 (6.2E-1)
23	Dry/wet wall criteria	0.029 (6.9E-1)	0.018 (8.1E-1)
24	Weber number	-0.042 (5.6E-1)	-0.084 (2.6E-1)
25	Droplet interfacial HT	0.024 (7.4E-1)	0.055 (4.6E-1)
26	Burst temperature dial	-0.118 (9.5E-2)	-0.118 (1.2E-1)
27	Burst strain dial	-0.031 (6.6E-1)	-0.015 (8.4E-1)
28	Oxidation dial	0.078 (2.7E-1)	0.053 (4.8E-1)
29	Oxidation thickness	0.100 (1.6E-1)	0.072 (3.4E-1)

4.2 Spearman Rank Correlations

Table 2 shows the evaluated Spearman rank correlation coefficient on the critical radius with p-value. The coefficients are measured with all cases (200 cases) and ruptured cases (179 cases), respectively.

With 0.05 of confidence level, seven variates showed monotonic relationship with critical radius in all cases, while three variates showed monotonic relationship in ruptured cases. Other variates did not show any evidence of monotonic relationship with critical radius by using the data of this study.

While zero critical radius cases would skew the value of SCC, variates which showed relationship for all cases but not for ruptured cases could be considered as main variates to occur the fuel rod rupture which are the *Gap conductance*, the *Fuel conductivity*, the *Chen transition boiling model multiplier*, the *Dittus-Boelter vapor convection model multiplier*, the *break discharge coefficient*, the *pump two phase head multiplier*, the *pump two phase torque multiplier*.

Variates which showed monotonic relationship for ruptured cases could be considered as main variates to determine value of critical radius which are the *Groneveld CHF correlation multiplier* and the *Zuber CHF correlation* and the *SIT initial level multiplier*.

4.3 Spearman Partial Rank Correlations

Table 3 shows the Spearman partial rank correlation coefficient on the critical radius with p-value. The coefficients are measured with ruptured cases (179 cases), respectively.

Three variates which are *Groneveld CHF correlation multiplier* and *Zuber CHF correlation multiplier* and *SIT initial level multiplier* showed significant Spearman partial coefficients with the maximum critical radius of fuel particles with 0.05 of significance level. Impact of those variates is compared as Table 4.

Table 3 Spearman partial correlation coefficient with p-value on the critical radius of fuel particles

#	*Model/Variables*	SPCC (p-value) - Ruptured cases -
1	Gap conductance	-0.122 (1.3E-1)
2	Fuel conductivity	-0.105 (2.0E-1)
3	Core power	0.014 (8.6E-1)
4	Decay heat	0.040 (6.2E-1)
5	Dittus-Boelter Liq. Conv.	-0.029 (7.2E-1)
6	Chen nucleate boiling	-0.013 (8.8E-1)
7	**Groneveld CHF**	**0.246 (2.3E-3)**
8	Chen transition boiling	-0.134 (1.0E-1)
9	Bromley film boiling	0.143 (8.0E-2)
10	Dittus-Boelter vapor Conv.	-0.068 (4.1E-1)
11	**Zuber CHF correlation**	**-0.179 (2.8E-2)**
12	Weismann transition boiling correlation	0.034 (6.8E-1)
13	QF Bromley correlation	0.084 (3.0E-1)
14	Forslund-Rohsenow FB correlation	-0.140 (8.6E-2)
15	Reflood superheated vapor correlation	-0.102 (2.1E-1)
16	Break Cd	-0.151 (6.4E-2)
17	Pump 2 phase head	-0.139 (9.0E-2)
18	Pump 2 phase torque	0.074 (3.7E-1)
19	SIT pressure (MPa)	-0.053 (5.2E-1)
20	**SIT initial level**	**0.289 (3.2E-4)**
21	SIT temperature (K)	0.063 (4.4E-1)
22	IRWST temperature (K)	-0.042 (6.1E-1)
23	Dry/wet wall criteria with 30℃	-0.008 (9.2E-1)
24	Weber number	-0.087 (2.9E-1)
25	Droplet interfacial heat transfer	0.092 (2.6E-1)
26	Burst temperature dial	-0.118 (1.5E-1)
27	Burst strain dial	-0.006 (9.4E-1)
28	Oxidation dial	0.056 (4.9E-1)
29	Oxidation thickness	0.086 (2.9E-1)

Table 4 Main variates to determine the maximum critical radius of fuel particles

Impact priority	Main variates
1st	SIT initial level multiplier
2nd	Groneveld CHF correlation multiplier
3rd	Zuber CHF correlation multiplier

5. Conclusions

Effects of TH uncertainty variates on critical size of fuel particle during LOCA have been evaluated in APR1400 reference plant. Following results can be drawn preliminarily.

- Critical radius of fuel particles was strongly affected by the combined uncertainty variates during LBLOCA. It was ranging from 0.04 mm to 3.5 mm.
- *Groneveld CHF correlation multiplier and Zuber CHF correlation multiplier and SIT initial level multiplier* are considered as important variates to determine the maximum critical radius and fuel mobility of fuel particles.

However, as calculated critical radius has sensitive characteristics to data time-step or homogeneous state models or particle shape, the value of critical radius should be understood carefully with these background. Also, correlation coefficients and p-values could be varied with different set of variates or different sample data. More sample with additional calculation cases or limiting number of variates would help to improve significance of the results of correlation analyses.

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