Distribution estimation for the critical size of dispersed fuel particle result from LBLOCA

Min ki Cho[a*], Joosuk Lee[a]
[a] *Korea Institute of Nuclear Safety, 62 Gwahak-ro, Yusong-gu, Daejeon, 305-338, Republic of Korea*
[*]*Corresponding author: mkcho@kins.re.kr*

1. Introduction

Fuel dispersal, high burn-up fuel phenomena with loss-of-coolant accident (LOCA), has been considered as one of the safety issues with light water nuclear power plants. US NRC had developed an evaluation methodology to estimate the amount of dispersed fuel in the core during LOCA. [1] Residual amount of fuel particles in core region is estimated by the criteria of critical particle size which is determined by force balancing between drag and buoyancy force. KINS had assessed the effects of thermal hydraulic uncertainties by utilizing the NRC methodology for the determination of critical fuel particle size. [2,3,4] It is identified that the uncertainty parameters used for the assessment of peak cladding temperature (PCT) during LOCA also affect the critical size of dispersed fuel particle [2].

In this paper, the tolerance interval of the critical sizes of dispersed fuel particle is estimated with various uncertainty parameters including the sphericity of fuel particle.

2. Methods and Results

In this section methods for analyses used to estimate the distribution of the critical radius of dispersed fuel particles are described. Thermal-hydraulic behaviors in core region during LBLOCA are calculated with MARS-KS. Statistical analyses are performed with the program R [5].

2.1 LBLOCA analysis and uncertainty parameters

The double-ended guillotine break at downstream of reactor coolant pump in APR1400 is assumed to simulate the thermal-hydraulic state in core region. PLUS7 fuel with 30 MWd/kgU fuel burnup condition and ANS 1979 decay heat model is used [6]. Uncertainty parameters and their probability density function (PDF) considered in this study are listed in Table I. Total 29 parameters are considered as the thermal-hydraulic variables related to core region during LBLOCA. [7,8]

1000 inputs for running MARS-KS V1.5 are prepared with Monte-Carlo sampling. DAKOTA software is used to input generation. Each calculation is conducted with 200 sec transient time. Cladding rupture is calculated with MARS-KS internal model, which is an empirical cladding deformation model, FRAP-T6. [9]. 818 cases among 1000 cases showed occurrence of fuel cladding rupture.

Table I. MARS-KS uncertainty parameters and probability density function (PDF) (U: uniform, N: normal, L: lognormal)

#	Model/Variables	PDF	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	$1.8682e^{-5}$	$\pm 1.8682e^{-5}$

2.2 Analysis for critical radius of dispersed fuel particles

In the NRC methodology critical size of fuel particle is determined by the fuel particles mobility analysis [1]. The critical size of particles is calculated with condition of force balance between drag and buoyancy based on fluid flow rate and coolant density. Flow rate and coolant density in core region is calculated with the assumption of homogeneous state of two-phase flow. The equation for critical radius of fuel particles is defined as below.

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

Here, C_D is drag coefficient [10] defied as below.

$$\mathrm{C_D} = \frac{24}{Re}(1 + ARe^B) + \frac{C}{1 + D/Re}$$

A = $e^{(2.3288 - 6.4581\phi + 2.4486\phi^2)}$
B = $0.0964 + 0.5565\phi$
C = $e^{(4.905 - 13.8944\phi + 18.4222\phi^2 - 10.2599\phi^3)}$
D = $e^{(1.4681 + 12.2584\phi - 20.7322\phi^2 + 15.8855\phi^3)}$
Phi (ϕ) *= particle sphericity (0.0 ~ 1.0)*

And, Re is Reynolds number defined as below.

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

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*

Table II. Assumed sphericity uncertainty of dispersed fuel particle.

Variable	PDF	Mean	Deviation
Sphericity	Uniform	0.5	±0.5

From the above equation sphericity of fuel particle is required. Authors previous study showed that the sphericity is sensitive to the critical size of fuel particle [3]. In this study sphericity is included as additional uncertainty parameter. Assumed uncertainty range and PDF is listed in Table II.

With 29 thermal-hydraulic parameters and the sphericity parameter, critical radius is calculated for each time-step of transient after rupture occurred. While the maximum value of critical radius could be considered as the minimum size to remain, the dispersed fuel particle smaller than the critical size could be considered to be escaped from the core due to sufficient buoyancy.

2.3 Estimated Distribution of Critical Size

Calculation results of maximum critical radius are shown in Fig. 1. For the unruptured cases, maximum critical radius is treated as zero. In the ruptured cases, maximum critical radius shows log-normal distribution (μ: -0.5173, σ: 0.44417) while p-value is achieved as 4.252E-11 from Shapiro Wilk test [11]. The minimum value, the maximum value and the median are estimated as 0.04962 mm, 3.27656 mm and 0.5894 mm, respectively.

Tolerance limit of maximum critical radius is investigated with 95% of probability and 95% confidence level. The lower and upper limit is estimated as 0.2403 mm and 1.479 mm, respectively [12].

3. Conclusions

Uncertainty of critical size of dispersed fuel particle is estimated by the combined uncertainty analysis. Critical size is determined by NRC proposed methodology. Maximum critical radius of dispersed fuel particle shows log-normal distribution. Lower and upper limit with 95%/95% probability/confidence level is estimated as 0.2403 mm and 1.479 mm, respectively. It is expected that this result can be used to evaluate the core coolability analysis.

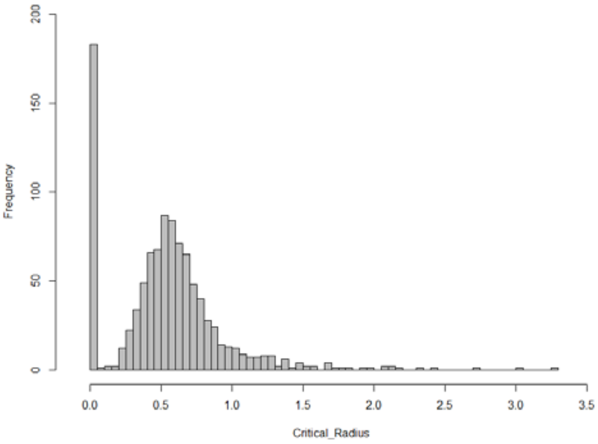

Fig. 1. Histogram of maximum critical radius of dispersed fuel particle (mm).

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