Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 29-30, 2014

Axial Power Shape Consideration for the SPACE Realistic Evaluation Model

Tong Soo Choi*, Tae Beom Lee, Jae Il Lee
KEPCO Nuclear Fuel, 242 Daedeok-daero 908beon-gil, Yuseong-gu, Daejeon, 305-353
*Corresponding author: tschoi@knfc.co.kr

1. Introduction

SPACE is the first safety analysis computer code which has been developed by the Korean nuclear society. The code is regarded as a best-estimate system code as it predicts the thermo-hydraulic behavior of two-phase flows using nine governing equations for vapor, liquid, and droplets. The code has been developed for the purpose of analyzing various transients in nuclear power plants, but its main use will be the analysis of a LBLOCA (Large Break Loss-Of-Coolant Accident) and KNF has been developing a REM (Realistic Evaluation Model) for LBLOCA analyses using the SPACE code.

A LBLOCA REM need an appropriate methodology to quantify the uncertainties in analysis results. In the case of SPACE REM, the uncertainty quantification methodology having been used for the licensing analysis of APR1400, so called KREM (KEPRI Realistic Evaluation Methodology) [1] is adopted with slight modifications.

According to the KREM or the concept of CSAU (Code Scalability, Applicability, and Uncertainty) demonstrated by the USNRC [2], LBLOCA analyses using a REM have to consider the uncertainties in the initial and boundary conditions of the analyzed plant such as the core power distribution at the time of accident.

The core power distribution can be described in general as the combination of radial and axial distributions. In other words, the total power peaking factor (F_Q) can be expressed by the product of axial peaking factor (F_{NZ}) and radial peaking factor (F_r). As the radial power distribution changes slowly in time and it is not much sensitive to power level, a bounding high F_r is assumed during the entire plant lifetime in a conventional LBLOCA analysis. However, the axial power distribution depends on core burn-up, control rod position, Xenon concentration or power level. Besides, F_Q is treated as one of uncertainty variables in a realistic LBLOCA analysis. It means that F_{NZ} also has a variation range defined by the F_Q divided by F_r. Thus, a LBLOCA REM must have an appropriate method to take into account the effect of axial power profiles having various values of F_{NZ}.

To develop a method considering various axial power profiles for the SPACE REM, all possible axial power shapes under the full power condition were investigated and a power shape generator capable of generating a reasonable power profile with a given F_{NZ} was devised. The power shape generator was used in power shape related sensitivity studies including a set of 124 SRS (Simple Random Sampling) calculations for APR1400.

2. Power Shape Generator

To quantify the overall calculation uncertainty in a LBLOCA analysis at a 95% probability with a 95% confidence level, SPACE REM uses non-parametric statistics. To get the result to be compared to the Acceptance Criteria, 124 calculations are performed with the same number of combinations of uncertainty parameters. As each calculation has a randomly selected F_Q or F_{NZ}, an axial power shape having the F_{NZ} should be assumed. If an immense power shape database were available, it might be possible to randomly select one shape among a number of shapes having the given F_{NZ}. However, that large power shape database does not exist, a program capable of generating an axial power shape having a specific value of F_{NZ} is required.

In this power shape generator, it is assumed that the real power shape can be approximated using a 6th order polynomial function of axial position. In other words,

$$f(z) = c_0 + c_1 z + c_2 z^2 + c_3 z^3 + c_4 z^4 + c_5 z^5 + c_6 z^6 \quad (1)$$

where f(z) is the normalized peaking factor at an axial position z and $c_0 \sim c_6$ are unknown constants.

The assumption of 6th order polynomial function can be validated by comparing real power shapes to the approximated shapes as in Fig. 1. In this figure, 3 different power shapes extracted from a nuclear design database for Shin-Kori-3/4 are compared to their 6th order polynomial fitting curves. Only negligible differences can be found between a real power shape and its fitting curve.

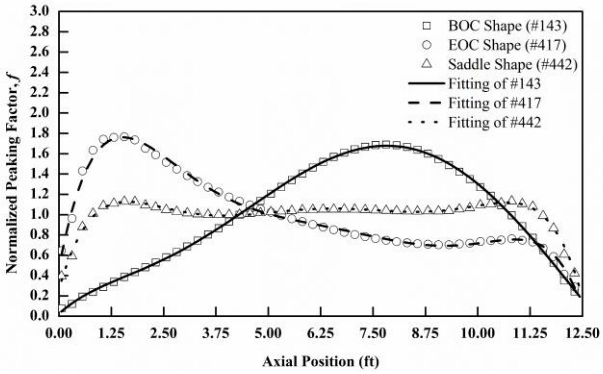

Fig. 1. Real power shapes and their fitting curves

As Eq. (1) has seven unknowns, the following seven boundary conditions are needed.

$$\frac{df}{dz}(z_p) = 0.0 \quad (2)$$

$$f(z_p) = F_{NZ} \quad (3)$$

$$F(z_t) - F(0.0) = z_t \quad (4)$$

$$F(z_t) - 2F(z_h) = 0.01AO \cdot z_t \quad (5)$$

$$F\left(\frac{z_t}{3}\right) - F(0.0) = P_{bot} \cdot z_t \quad (6)$$

$$F\left(\frac{2z_t}{3}\right) - F\left(\frac{z_t}{3}\right) = P_{mid} \cdot z_t \quad (7)$$

$$F(z_t) - F\left(\frac{2z_t}{3}\right) = P_{top} \cdot z_t \quad (8)$$

where z_p and z_t are the peak power elevation and the top elevation, respectively. F(z) is the integral function of f(z) and AO means the axial offset in percent. P_{bot}, P_{mid}, and P_{top} are lower, middle, and top third integrals of f(z) divided by the total length integral.

Among the boundary conditions, F_{NZ} and z_t are known values but z_p, AO, and third integrals should be assumed appropriately. In this power shape generator, z_p and AO are random-sampled independently in their own range. P_{bot} and P_{top} have relations with AO and P_{top} is equal to (1- P_{bot} - P_{top}) by its definition.

To get the relation between AO and P_{bot} or P_{top}, real power shapes in a database, which was generated from the nuclear core design of Shin-Kori-3/4, cycle 1, were analyzed. The power shape database includes a variety of axial power shapes likely to happen under wide range of core power, peaking factors, Xenon concentration, control rod positions, and burn-up. Among more than 8,000 shapes in the database, only 443 shapes under the full power condition having F_{NZ} from 1.137 to 1.888, AO from -30 to +30%, and z_p from 1.188 to 10.812 ft were analyzed. It was found from the analysis that P_{bot} or P_{top} can be expressed as a linear equation of AO.

$$P_{bot} = d_1 - d_2 AO \quad (9)$$

$$P_{top} = d_1 + d_2 AO \quad (10)$$

where d_1 and d_2 are fitting constants of real data which reside in a band of fitting line$\pm$0.05.

Applying Eq. (2) ~ (8) to Eq. (1) makes easily solved seven simultaneous equations. The solution of equations using a set of boundary conditions is mathematically right but it cannot be always an appropriate power shape function. For example, a power shape function can be obtained from the equations with F_{NZ} of 1.6, z_p of 6.25 ft, and zero AO but the solution must have a negative peaking factor at both ends of core. In other words, a process of filtering out unphysical f(z) must come after the equation solving process.

In this power shape generator, f(z) is discarded when one of the following conditions is met.

$$f(z_b < z < z_t) < MIN(f(z_b), f(z_t)) \quad (11)$$

$$\text{Number of peaks} > 2 \quad (12)$$

$$\frac{df}{dz}(z_b) < 0.0 \text{ or } \frac{df}{dz}(z_b) > 0.0 \quad (13)$$

$$\text{Peak } f(z) > F_{NZ} \quad (14)$$

$$z_p < z_b + 0.5 \text{ ft or } z_p > z_t - 0.5 \text{ ft} \quad (15)$$

$$f(z_b) > \alpha \text{ or } f(z_t) > \beta \quad (16)$$

$$|f(z_b) - f(z_t)| > \gamma \quad (17)$$

where α and β are linear functions of AO and γ is a constant which can be obtained from the analysis of real power shapes.

In Fig. 2, the overall calculation algorithm of the power shape generator is presented. As shown in the figure, the whole process includes three iteration loops. When a shape function obtained using a combination of F_{NZ}, z_p, and AO is revealed to be unreasonable in the above mentioned filtering-out process, the innermost iteration loop works. In this iteration, P_{bot} and P_{top} are adjusted little by little within the fitting uncertainty of Eq. (9) and (10). If no reasonable shape function is obtained from the first iteration loop, the second iteration loop words. In this loop, AO is newly sampled as long as the number of sampling is less than 200. The outermost iteration loop works when both the first and the second iteration loops fail to produce a reasonable shape. In this iteration, z_p is newly sampled until the number of trials reaches 200.

Several example power shapes produced using the generator are presented in Fig. 3.

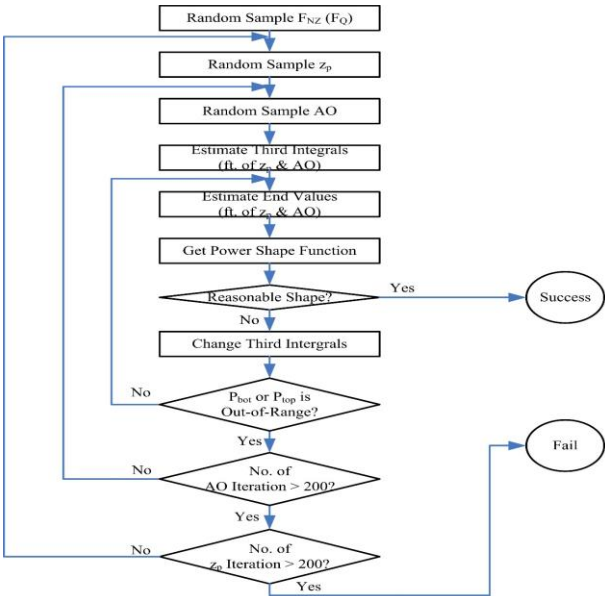

Fig. 2. Power Shape Generator Algorithm

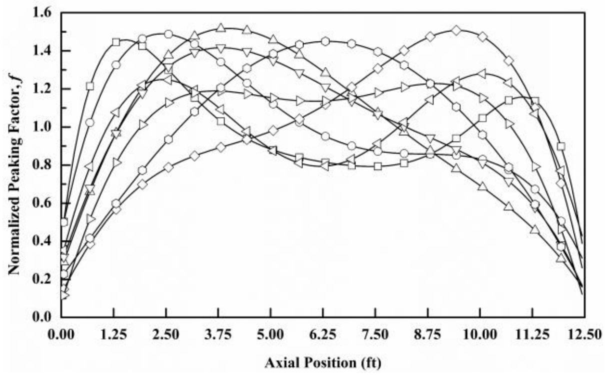

Fig. 3. Example of generated power shapes

3. Power Shape Sensitivity Studies

Two kinds of power shape related sensitivity studies utilizing the power shape generator described in the prior section were performed for Shin-Kori-3/4 for the following purposes, respectively.

- To know if it is possible to find a range of limiting peak power location for a LBLOCA analysis considering a spectrum of break size
- To know much the result of a full scope LBLOCA analysis may be changed by considering additionally the uncertainty in axial power shapes.

3.1 Peak Power Location Sensitivity Study

In the case of the original KREM [1], it is assumed that top skewed power shapes rather than bottom skewed power shapes result in more limiting LBLOCA results. The assumption may be valid because only the BOC (Beginning-Of-Cycle) shapes were considered when the KREM was developed and only a 100% DEGCL (Double-Ended Guillotine Cold Leg) break is assumed in uncertainty analysis.

However, in the case of SPACE REM, break size is one of the uncertainty parameters and it varies from 60% to 100% of the DEGCL break. In addition, not only BOC shapes but also middle-of-cycle or end-of-cycle shapes should be considered as the possible power shape at the time of break. It means that assuming only top-skewed power shapes may not be appropriate in the case of SPACE REM. Thus a peak power location sensitivity study was conducted assuming various size of breaks.

In this sensitivity study, no other uncertainty parameters except break size were assumed to vary and F_Q of Tech. Spec. limit was assumed. Nine power shapes having different peak power locations, which are presented in Fig. 4, were assumed for each break size.

The blowdown PCTs (Peak Clad Temperatures) and reflood PCTs obtained from this study are presented in Fig. 5 and 6, respectively.

As shown in Fig. 5, the predicted blowdown PCTs depend significantly on the break size. In many cases, bottom skewed shapes rather than top skewed shapes made higher PCTs. It means that assuming only top skewed shapes in a LBLOCA analysis using the SPACE REM is not appropriate, at least in terms of blowdown PCT. In addition, it seems not possible to set a confined range of peak power location making higher blowdown PCTs.

On the contrary, reflood PCTs in Fig. 6 have a general trend of increasing when peak power location moves to the upper part of core. In most cases, the highest PCT occurred when peak power located around 8.75±1.5 ft. It means that if we concern about only the reflood PCT, confining peak power location to 8.75±1.5 ft would make a more conservative result in a LBLOCA analysis using the SPACE REM.

Based on these sensitivity study results, it can be said that there is no golden rule of assuming power shapes which makes analysis results conservative in a LBLOCA analysis using the SPACE REM. In other words, power shapes or their attributes like peak power location should be randomly selected in LBLOCA uncertainty quantification calculations.

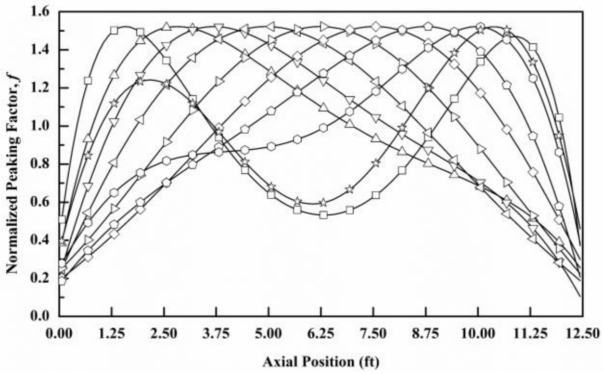

Fig. 4. Power shapes for peak power location sensitivity study

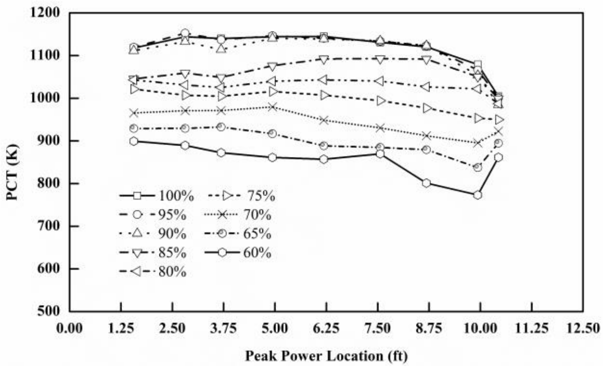

Fig. 5. Peak power location sensitivity (blowdown PCT)

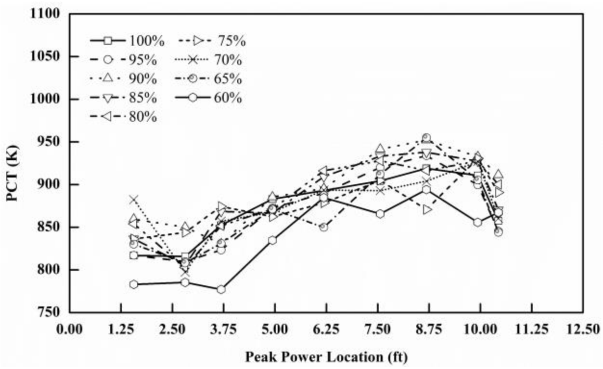

Fig. 6. Peak power location sensitivity (reflood PCT)

3.2 Full Scope LBLOCA Sensitivity Study

For a LBLOCA analysis using the SPACE REM, 124 SRS calculations are performed considering 38 uncertainty parameters. Among the calculated 124 PCTs, the third highest PCT is regarded as the critical PCT exceeding 95% probability with a confidence level of 95%.

To find out how much effect can be made on the critical PCT by considering the uncertainty of power shapes, two sets of SRS calculations were conducted. In one set, only chopped cosine power shapes were assumed in all SRS calculations and in the other set, power shapes were randomly sampled using the power shape generator explained in Section 2. All the uncertainty parameters related to the code uncertainty and initial and boundary condition uncertainty were randomly sampled in both sets of SRS calculations. As the same random sampling seed number was used, the two sets of SRS calculations are identical except the power shapes assumed in each calculation. The power shapes assumed in each set of SRS calculations are presented in Fig. 7 and 8, respectively.

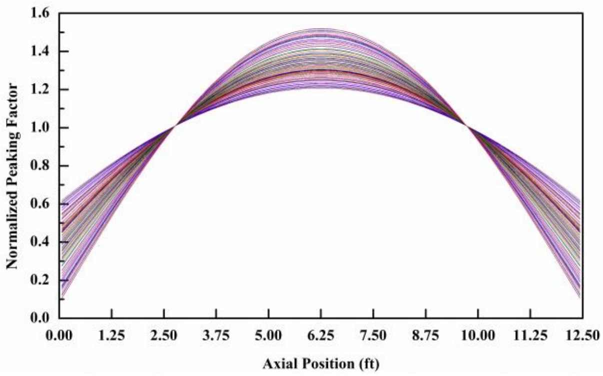

Fig. 7. Chopped cosine shapes for SRS calculations

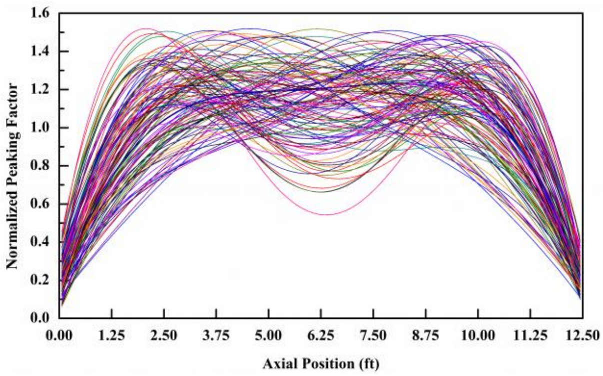

Fig. 8. Randomly selected shapes for SRS calculations

The differences between two sets of SRS calculations in blowdown and reflood PCTs are presented in Fig. 9. As shown in the figure, the PCT difference may reach ~120 K depending on peak power location.

However, the critical PCT or the third highest PCT assuming chopped cosine power shapes was only ~12 K different from that calculated using randomly selected power shapes. In other words, considering the uncertainty of power shapes seems not have a significant impact on the critical PCT which includes the influence of other uncertainty parameters.

4. Conclusions

A new axial power shape generator was developed based on the information extracted from a real power shape database. The generator can be used to approximate all kinds of real power distributions under the full power condition.

Using the newly developed power shape generator, a peak power location sensitivity study was conducted. It was found from this study that there is no golden rule making an always conservative power shapes, at least when the break size uncertainty should be considered together.

Two sets of 124 SRS calculations were conducted using the new power shape generator. In one set, chopped cosine power shapes were assumed and in the other set, peak power location and axial offset were randomly selected. From the results of these calculations, it was revealed that considering the uncertainty of power shapes does not make a significant impact on the critical PCT.

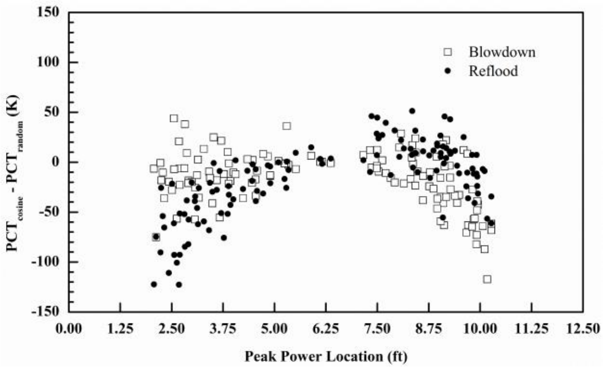

Fig. 9. PCT differences between two sets of SRS calculations

Acknowledgments

The SPACE code has been jointly developed by KEPCO E&C, KAERI, KNF, and KHNP and this work has been supported by the Ministry of Knowledge Economy (MKE) of the Republic of Korea.

REFERENCES

[1] KHNP, LBLOCA Best-Estimate Evaluation Methodology of the APR1400 Type Nuclear Power Plants, TR-KHNP-0018, 2010.

[2] INEL, Quantifying Reactor Safety Margins, NUREG/CR-5249, 1989.