Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 23-24, 2019

Evaluation of Rod Bow Augmentation Factor for PLUS7™ Fuel of APR1400 Plant

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1. Introduction

The fuel rod bowing is a phenomenon resulting in a deviation in straightness of fuel rods caused by irradiation effects. This phenomenon leads to local power increase as well as lower DNBR. Local power increases in fuel rods located near fuel rods which bow away from them result from improved local neutron moderation. Through running a series of calculations of MCNP5(A General Monte Carlo N-Particle Transport Code, Version 5)[1] with ENDF-B/VII Library from design methodology based on CE Topical Report[2], we tried to evaluate a rod bow augmentation factor for PLUS7™ fuel(0.374 inch of rod pellet diameter), which might be the first trial for current power plants in Korea. The rod bow augmentation factor of CE 16 × 16 type fuel(0.382 inch of pellet diameter), which has been conservatively used for most of CE type power plant for long time since YGN Unit 3, is originated from various CE design materials licensed from NRC. As a result of this calculation, we confirmed that a conventional value of bowing is still conservative as well as effective even now for a value of fuel rod bow augmentation factor of PLUS7™ fuel loaded in APR1400 Plant.

2. Methods and Results

The fuel rod bowing is a phenomenon resulting in a deviation in straightness of fuel rods caused by irradiation effects. This phenomenon leads to local power increase as well as lower DNBR. Local power increases in fuel rods located near fuel rods which bow away from them result from improved local neutron moderation. The major purpose of this evaluation is to predict more accurate rod bow augmentation factor value for PLUS7™ fuel instead of CE 16 x 16 fuel rods. This value is applied for COLSS/CPC(or RCOPS) OUA(Overall Uncertainty Analysis) of APR1400 plant, to which it gives an additional penalty related to LHR power increase at rods surrounding from a bowed fuel rod. Therefore, it is necessary to evaluate a tolerance limit factor to be conservatively applied to power peaking factor(F_{xy} or F_r) of fuel rod.

2.1 Calculation Tool and Modeling

As a calculation tool to describe and model a rod bow phenomenon in an assembly composed of PLUS7™ fuel rods, MCNP5 code runs were used with a history (100,000 particle/cycle × 1100 cycles with std. of 0.00006) through a sensitivity study on history from an off-line technique and its isotopic inventories were obtained from KARMA code[3] to reflect a variation from number density of main isotopes at according to burnup points. Generally, the rod bow augmentation factor is sensitive from U^{235} enrichment of fuel rod as well as fuel exposure. Thus, all of MCNP5 branch job cases followed by KARMA for bowed rod calculation are consisted of 24 cases(4 enriched rods: 3.50, 4.10, 4.65 and 4.95 w/o ; 6 burnups: 0, 10000, 20000, 30000, 45000 and 60000 MWD/MTU) except of main depletion cases. For simple modeling of these calculation, 5 × 5 test section type assembly(*See Fig. 1*) composed of only 25 fuel rods is constructed using PLUS7™ fuel rod specification of Table I.

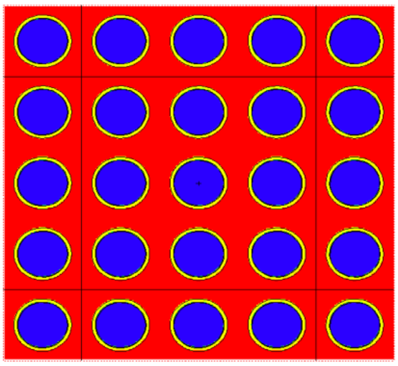

Fig. 1. Typical 5 × 5 cross-sectional drawing for PLUS7™ fuel rod bowing calculation

Table I: Fuel assembly(PLUS7™) specifications

Fuel Temperature	900.00 °K
Moderator Temperature	600.00 °K
Pressure	2250 PSI (155.13bar)
Assembly Geometry	5×5
Pin Pitch	1.2623 cm
Fuel Composition	UO_2
Fuel Enrichment(U-235/U)	3.5, 4.1, 4.65 & 4.95 w/o
Cladding Material	Zircaloy-2
Fuel Pin Geometry(based on Pellet Cold Diameter of 0.374 in)	

The above 5 × 5 array type assembly composed of 25 discrete fuel rods was modeled with reflecting boundary conditions. Before and after bowing, a local power difference (increase or decrease) occurs at each fuel rod. At this time, the expected maximum power increase at a rod, which covering all of fuel rod burnup and enrichment, needs to be calculated quantitatively to a conservative direction.

For more conservative calculation, following a few of assumptions were considered at our calculation methodology and modeling;

- Consideration of bowing direction of uniform 8 values (representatively, lateral and diagonal)
- The absence of soluble boron in the moderator was conservatively assumed for MCNP 5 lattice calculation(0 ppm)
- The net effect of bowing on the power generated in the bowed rod is always negative, which may be conservatively taken to zero
- Conservative statistical treatment (data number, selecting worst data)
- Usage of smaller bowed displacement(δ) : using $C_0/2$ instead of C_0 for more conservative result, where C_0 is an initial gap between fuel rods and can be calculated as follows;

Clad O.R = 0.476 cm
Rod Pitch =1.28774 cm
C_0 = (1.28774 – 2 X 0.476) = 0.33574 cm
δ = $C_0/2$ = 0.16785 cm

By using above assumptions, a maximum rod power difference (%) obtained from MCNP5 calculation result at 30,000 MWD/MTU of 4.65 w/o Fuel is given as 1.5% as a result of a typical sample run at Fig. 2 .

CENTER Rod Bowing Direction	Rod Power % Difference(After - Before) by MCNP				
Case 01	0.2%	0.4%	0.5%	0.4%	0.2%
↓	0.2%	0.6%	**1.5%**	0.6%	0.2%
	0.1%	0.2%	0.0%	0.1%	0.0%
	-0.2%	-0.5%	-1.7%	-0.6%	-0.2%
	-0.2%	-0.4%	-0.5%	-0.4%	-0.2%
Case 02	0.0%	0.2%	0.5%	0.4%	0.4%
↙	-0.2%	0.0%	**1.1%**	0.8%	0.5%
	-0.4%	-1.1%	0.0%	1.1%	0.4%
	-0.4%	-0.8%	-1.1%	0.1%	0.2%
	-0.4%	-0.4%	-0.4%	-0.1%	0.0%

Fig. 2. Typical Rod Power Diff. at 30,000 MWD/MTU of 4.65 w/o Fuel

2.2 Rod Bow Augmentation Factor Calculation

The definition of rod bow augmentation factor($t_{95/95}$) is the increase in power due to fuel rod bowing which is a 95% probability that 95% of the fuel will not exceed can be given equation from Ref 2 & 4 as following:

$$t_{95/95} = [1.1882]\ B\ S_c \qquad (1)$$

where:

[1.1882]: chi-square distribution coefficient between population and sample for 56 measured bowing data.

S_c : standard deviation of measured gap closure data due to bowing.

B: rod bow augmentation coefficient, which can be given from a following equation;

$$B = f(A_{ij}, S_0, C_0) \qquad (2)$$

where:

A_{ij}: Response Attenuation Factors of rod i displaced in direction j

S_0: Reference Power Change

C_0: initial gap between fuel rods

When a center rod(i) is bowed toward a surrounding rod with a bowing direction(j), by using reciprocity(from a distance and a direction) between a center rod and its surrounding rod from one MCNP5 calculation set composed of two jobs(lateral and diagonal direction) at one enrichment(ε) and one burnup(Bu) of branch depletion case, we can set up the response attenuation factor, A_{ij}. Therefore, total cases of 24 A_{ij}'s were generated from a combination of an enrichment(ε) and a burnup(Bu) mentioned above for this calculation. Thus, a relation with all rods(24 rods) surrounding from one center rod, which are having one distinct distance and one direction of 8 isotropic directions can be constructed through this definition(or concept) of response attenuation factor to explain a bowing mechanism sufficiently.

The above B value can be fitted as a function of enrichment(ε) and burnup(Bu) by the following equation;

$$B = a + b\,\varepsilon + c\,[Bu] + d[Bu]^2 \qquad (3)$$

where:

ε = fuel enrichment (w/o U-235)

Bu = fuel exposure (MWD/MTU)

After all, using a least square fitting technique, these constants a, b, c and d mentioned above were obtained as follows;

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a= 0.452549E+2,  b=  0.587191E+1
c= 0.249733E-3,  d= -0.426825E-8
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By substituting above values to Eq (3), we can obtain trends of B values according to fuel enrichment and burnup as shown in Fig. 3.

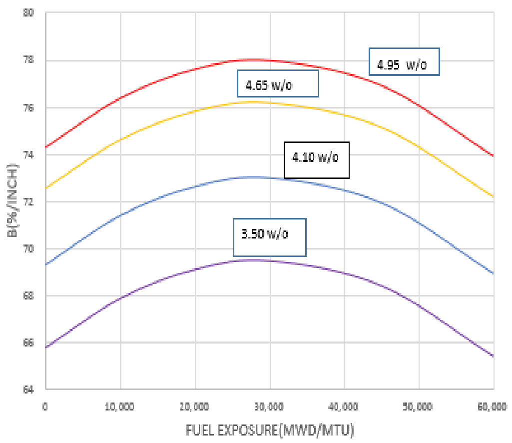

Fig. 3. Linear heat rate augmentation coefficient vs. fuel burnup

The standard deviation(S_c) of measured gap closure data due to bowing can be obtained from Ref.4 as shown in Fig .4:

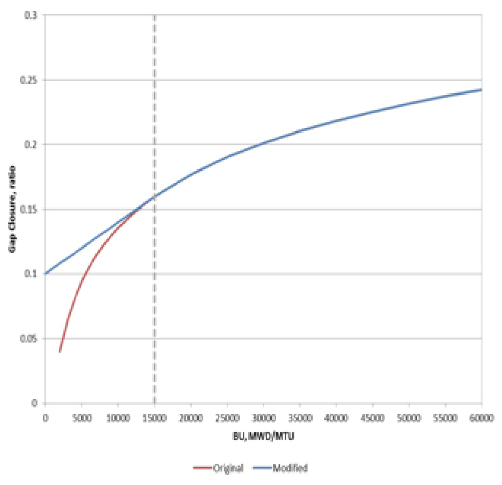

Fig. 4. Standard deviation(S_c) of worst gap closure data

The rod bow augmentation factor of above Eq. (1) can be easily obtained according to fuel enrichment as a function of burnup(Fig. 5) by combining B(*See Fig. 3*) and S_c(*See Fig 4*) values.

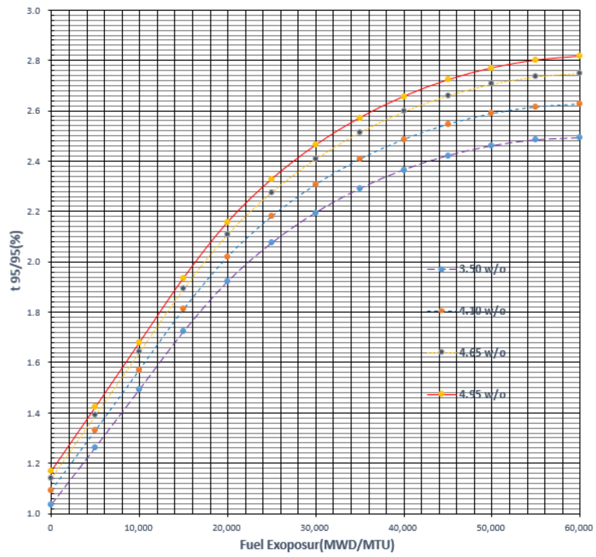

Fig. 5. Linear heat generation augmentation factor trends

By considering that fuel rod powers of fuel exposure over 30,000 MWD/MTU are much lower than the fuel rods with burnup less than 30,000 MWD/MTU as shown in the conventional fuel burndown curve of Fig. 6, we can find the conservative bow augmentation factor is about 2.5 % at the highest enrichment of 4.95 w/o in Fig. 7.

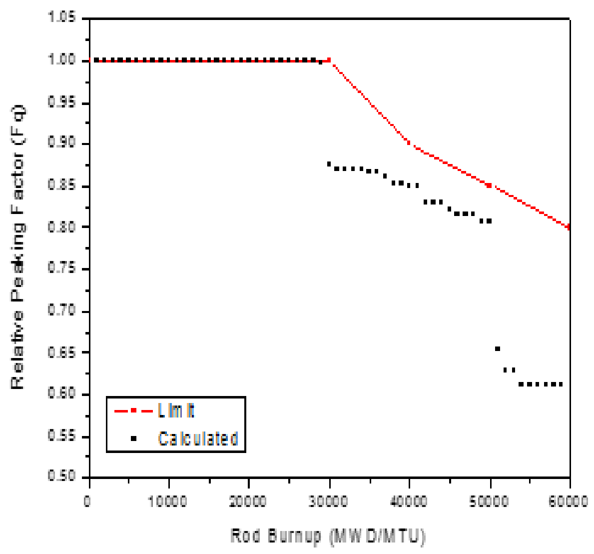

Fig. 6. Peak rod power burndown curve of PLUS7™ fuel

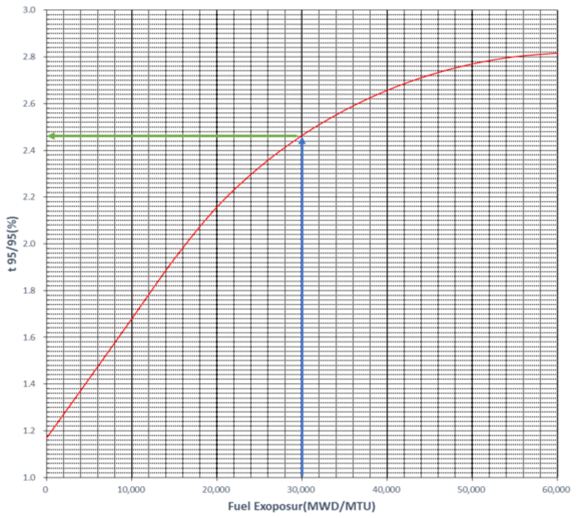

Fig. 7. Rod bow augmentation factor for PLUS7^{TM} fuel

3. Conclusions

The calculation of new rod bow augmentation calculation for PLUS7^{TM} fuel was performed using MCNP5 based on isotopic inventories from KARMA depletion chain. As mentioned in earlier part, although additional assumption or conservatism is considered for this calculation, the fuel rod bow augmentation factor of about 2.5% is shown as still less than the conventional value for CE 16 $\times$ 16 design.

REFERENCES

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