BENCHMARK RESULTS OF BURN-UP CALCULATION FOR LWR NEXT GENERATION FUELS

Keisuke OKUMURA
Japan Atomic Energy Research Institute
Tokai-mura, Naka-gun, Ibaraki, 319-1195, Japan
okumura@mike.tokai.jaeri.go.jp

Hironobu UNESAKI
Kyoto University Research Reactor Institute
Kumatori-cho, Sennan-gun, Osaka, 590-0494, Japan
unesaki@kuca.rri.kyoto-u.ac.jp

Takanori KITADA
Osaka University
Yamadaoka, Suita-shi, Osaka, 565-0871, Japan
kitada@nucl.eng.osaka-u.ac.jp

Etsuro SAJI
Secretariat of the Nuclear Safety Commission
Kasumigaseki 3-1-1, Chiyoda-ku, Tokyo, 100-8970, Japan
esaji@op.cao.go.jp

ABSTRACT

Burn-up calculation benchmark has been carried out for the LWR fuels aiming at high burn-up up to 70GWd/t with UO_2 and MOX. This paper shows the comparison results for the burn-up dependence of k-infinity, void and temperature reactivities, and atomic number densities of major nuclides.

1. INTRODUCTION

In order to draw subjects in reactor physics for LWR next generation fuels by studying differences of predicted nuclear characteristics among nuclear design codes, the Research Committee on Reactor Physics organized by Japan Atomic Energy Research Institute has proposed "Reactor Physics Benchmark for LWR Next Generation Fuels" [1]. The next generation fuels aim at very high burn-up of about 70GWd/t in PWR and BWR with UO_2 and MOX fuels whose fissile enrichments may exceed limitations such as 5wt.% ^{235}U for current LWR fuels.

The benchmark problems consist of UO_2 fuel and MOX fuel problems, each of which has a pin cell configuration, a PWR assembly configuration and a BWR assembly configuration. In a pin cell configuration, the basic nuclear parameters such as an infinite multiplication factor, temperature and void reactivities and various isotopic concentrations as functions of burn-up are required to be evaluated. The isotopes to be evaluated were selected from the viewpoint of the back-end requirement as well as the reactivity point of view. In the assembly configurations, the important characteristics

that can be investigated only in an assembly calculation, a power peaking factor and the effect of burnable poison (Gadolinia) on the reactivity coefficients or burn-up change in an infinite multiplication factor, are required to be evaluated. Complete benchmark specifications are described in References 1 and 2.

As shown in Table I, twelve organizations have participated in the benchmark analysis with different codes and libraries. Various calculation methods are used in the codes to solve the neutron transport equation. They are collision probability method (CP), method of characteristics (MOC), current coupling collision probability method (CCCP), discrete ordinates method (S_N), continuous-energy or multi-group Monte Carlo method (MC) and so on. Details of the participants' codes and their calculation conditions are described in Reference 1. The 14 solutions submitted to the pin cell problems include contributions based on JENDL-3.2 (5 solutions), JEF-2.2 (3 solutions) and ENDF/B-IV, -V, -VI (6 solutions). Three results of the SRAC code with different libraries are helpful to identify effects of different nuclear data files.

This paper summarizes comparison results of the benchmark study. It is expected that the subjects for future high burn-up LWRs can be drawn from the present comparison. The benchmark problem focuses on the ideal next generation fuels whose specifications exceed those of current fuels (e.g. fuel ^{235}U enrichment or Pu content is much higher than that of current one), so the true solution of the benchmark problem is not known. Therefore quality of a nuclear design code can't be discussed if some discrepancy is found in a particular solution of this study.

2. PIN CELL PROBLEMS

2.1 OVERVIEW OF BENCHMARK PROBLEMS

Figure 1 shows an infinite lattice model in the pin cell problems, which is common for the UO_2 and MOX problems. The ^{235}U enrichment of the UO_2 fuel and fissile Pu enrichment of the MOX fuel is 6.5 wt.% and 11.0 wt.% (17.2wt.% as total Pu), respectively. As the pin cell problems are designed for studies of both PWR and BWR, soluble boron is not contained in the moderator region.

In the pin cell problem, it is requested to evaluate burn-up dependences of 1) k-infinity, 2) moderator void reactivity defined as the instantaneous reactivity change from 0% voided condition to 40% or 70% voided condition, 3) Doppler reactivity between "Doppler" condition (pellet 1800 K / cladding & moderator 600 K) and "Hot" condition (pellet 900 K / cladding & moderator 600 K), 4) Hot-to-Cold reactivity between the "Hot" condition and "Cold" condition (300K for all materials and corresponding water density), 5) atomic number densities of 17 heavy nuclides and 12 fission products, and 6) one group microscopic and macroscopic cross sections for important nuclides, at nine exposure points up to 70GWd/t.

2.2 RESULTS AND DISCUSSIONS

Figure 2 shows the burn-up changes of k-infinities in the UO_2 and MOX problems. The spread of k-infinities, which is defined as the maximum value minus the minimum one, is 2.3%Δk for UO_2 and 4.0%Δk for MOX. Participant-H provides somewhat lower k-infinity especially at BOL (0GWd/t, no xenon) in the MOX problem. However, his employed code is widely used and well validated for current LWR, as well as for MOX cores[3]. In the UO_2 problem, all results based on JENDL-3.2 give higher k-infinities compared with those based on ENDF/B libraries by about 1.3%Δk at BOL and 0.51%Δk at EOL (70GWd/t). The three results with JEF-2.2 are dispersed within other results. In the

MOX problems, apparent dependence on nuclear data libraries was not observed. Additional results with SRAC based on JENDL-3.3[4], though they are not provided in Fig.2, give closer k-infinities to the ENDF/B results in both of the UO_2 and MOX problems.

The results of void, Doppler and Hot-to-Cold reactivities at BOL and EOL are summarized in Table II. The spreads of the above reactivies in the UO_2 problem become larger as the burn-up increases. On the other hand, the spreads in the MOX problem are large at BOL and they don't change so much during burn-up period. A sensitivity study is in progress to clarify contribution of each nuclide, each reaction and each energy range.

Figure 3 shows the maximum differences among the participants' results for the atomic number densities of evaluated nuclides at EOL in the UO_2 problem. The differences among the three SRAC results are also shown in the same figure to distinguish contribution caused by the different nuclear data libraries based on JENDL-3.2, JEF-2.2 and ENDF/B-VI(R5). The differences among all results are large (>20%) for ^{237}Np, ^{238}Pu, ^{242m}Am, ^{243}Am, ^{245}Cm, ^{246}Cm, ^{152}Sm and ^{155}Gd. From the SRAC results, the contribution by the different nuclear data libraries is large for ^{243}Am, ^{243}Cm, ^{244}Cm, ^{245}Cm (~10%) and ^{155}Gd (58%). Therefore, it is considered that most of the participants' differences except ^{155}Gd are caused by the differences of resonance absorption treatments, burn-up chain models and related data like isomeric ratio, fission yield and so on. As for the ^{155}Gd, the significant difference is attributed to nuclear data evaluations for ^{154}Eu, ^{155}Eu and ^{154}Gd, because one-group absorption cross sections of these nuclides are different over 30% among the libraries. In general, contributions of the nuclides with large differences are not large to reactor physics parameters like k-infinity, though they are important for back-end fields or burn-up credit problems.

3. PWR FUEL ASSEMBLY PROBLEMS

3.1 OVERVIEW OF BENCHMARK PROBLEMS

Figure 4 shows two types of fuel assembly for PWR problems. One is a UO_2 assembly with UO_2-Gd_2O_3 pins and the other is a MOX fuel assembly. The Both assemblies have the same geometrical configuration, a 17x17 PWR fuel design for a typical 3-loop or 4-loop PWR. The UO_2 assembly contains 32 UO_2-Gd_2O_3 pins, and the averaged enrichment is 6.2 wt%. The MOX assembly has three types of MOX pins, and the averaged fissile Pu enrichment is 11.0 wt%. The fissile contents of both assemblies are determined to achieve mean discharge burn-ups of up to 70GWd/t. The required results are burn-up dependence of 1) k-infinity, 2) fission rate distribution and local peaking factor, 3) void, Doppler, and Hot-to-Cold reactivities, for the steps at 0, 0.1, 5, 10, 15, 20, 30, 50 and 70GWd/t.

3.2 RESULTS AND DISCUSSIONS

Figure 5 shows the burn-up dependence of the k-infinities for the UO_2 and MOX problems. The maximum differences in k-infinity results are 1.5%Δk for UO_2 and 2.7 %Δk for MOX. The burn-up behavior of the k-infinities in the MOX problem is similar to that in the pin cell problem.

The results of local peaking factor show a good agreement among the participants; the differences lie within a band of ±1% through the burn-up period for both UO_2 and MOX problems. The results of power distribution within the assembly show that the relative deviation is large in UO_2-Gd_2O_3 pins for the UO_2 assembly and assembly corner pins for the MOX assembly.

The properties of Doppler and Hot-to-Cold reactivities are shown in Figures 6 and 7. The results of Doppler reactivity show a fairly good agreement for the UO_2 assembly with maximum difference of 7%, whereas the deviation among the results is more significant for the MOX assembly. The results of Hot-to-Cold reactivity show an increasing discrepancy with burn-up for UO_2, whereas the large deviation is observed among the results throughout the whole burn-up period for the MOX assembly.

4. BWR FUEL ASSEMBLY PROBLEMS

4.1 OVERVIEW OF BENCHMARK PROBLEMS

Figure 8 shows the UO_2 and MOX fuel assembly models for BWR problems. The UO_2 assembly has the geometrical configuration of a modern 9x9 BWR fuel design (GE11 type), and the MOX assembly has the configuration of ATRIUM-10[5] type, one of a modern 10x10 fuel design. The lattice geometry of the MOX fuel assembly is the same as that of the BWR-MOX benchmark performed by OECD/NEA/NCS[6] except for fuel compositions. The fissile contents of both assemblies are determined to achieve mean discharge burn-ups of up to 70GWd/t. The required parameters are the same as those of the PWR problem except void reactivity.

4.2 RESULTS AND DISCUSSIONS

Figure 9 shows the burn-up dependence of the k-infinities for the UO_2 and MOX problems. The maximum differences in the k-infinity results are 1.8 (0GWd/t) to 2.8%Δk (70GWd/t) for UO_2, and 1.5 (0GWd/t) to 0.8%Δk (70GWd/t) for MOX. The burn-up of UO_2-Gd_2O_3 pins is fairly well treated for both fuel assemblies. The results of local peaking factor almost lie within a band of ±1% through the burn-up period for both the UO_2 and MOX problems.

The properties of void (from 0% to 40%) and Hot-to-Cold reactivities are shown in Figures 10 and 11. The maximum differences in void reactivity results are 19% (0GWd/t) to 21% (70GWd/t) for UO_2, and 41% (0GWd/t) to 12% (70GWd/t) for MOX, and the maximum differences in the Hot-to-Cold reactivates are 4% (0GWd/t) to 100% (70GWd/t) for UO_2, and 37% (0GWd/t) to 31% (70GWd/t) for MOX. The large differences come mainly from the small absolute values of the reactivity.

CONCLUSIONS

Numerical burn-up benchmark comparison has been carried out for the future LWR fuels aiming at high burn-up up to 70GWd/t with UO_2 and MOX. From the comparison of benchmark results, the following conclusions and future subjects are drawn:

- The differences among the benchmark results are somewhat large for the k-infinities at BOL in the MOX-pin cell and MOX-PWR problems. A reference experimental data is desired for high Pu content fuels (about 17 wt.% as total Pu) with typical Pu isotope vector discharged from LWRs.
- For the PWR-UO_2 and BWR-UO_2/-MOX problems with Gadolinia, overall burn-up behavior of k-infinities shows fairly good agreements among participants' results.
- Spreads for void, Doppler, Hot-to-Cold reactivities in the UO_2 problems show a tendency to become larger as burn-up increases, whereas the spreads in the MOX problems are large from BOL.
- Local peaking factors show good agreements within ±1% for both of the PWR and BWR assembly problems.

- Difference more than 20% is observed at 70GWd/t for the atomic number densities of nuclides ^{237}Np, ^{238}Pu (mainly produced via capture of ^{237}Np and α-decay of ^{242}Cm), ^{242}Am, ^{243}Am, ^{245}Cm, ^{152}Sm, and ^{155}Gd (not burnable poison). Effects of different nuclear data files are large (>10%) for the productions of ^{243}Am, ^{243}Cm, ^{244}Cm, ^{245}Cm, ^{246}Cm and ^{155}Gd (mainly produced via fission, capture of ^{154}Gd and β-decay of ^{155}Eu).

For further investigation, the following activities are in progress:

- Addition of benchmark calculation results for the assembly problems and new results based on JENDL-3.3 published recently.
- Sensitivity study to breakdown of void, Doppler and Hot-to-Cold reactivities into contributing nuclides, reaction types and energy ranges.
- Post irradiation analyses with different nuclear data libraries (JENDL-3.2/3.3, JEF-2.2, ENDF/B-VI) for high burn-up fuel samples irradiated in Japanese PWRs.

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Table I. List of benchmark participants and their codes

ID	Organization	Code (method*)	Base Library	Pin Cell		PWR		BWR	
				UO_2	MOX	UO_2	MOX	UO_2	MOX
A	JAERI	MVP-BURN (MC_{CE})	JENDL-3.2	X	X				
B	JAERI	SRAC (CP)	JENDL-3.2	X	X		X		
C	JAERI	SRAC (CP)	ENDF/B-VI(R5)	X	X				
D	JAERI	SRAC (CP)	JEF-2.2	X	X				
E	KURRI	MVP-BURN (MC_{CE})	JENDL-3.2			X	X		
F	Osaka Univ.	MVP-BURN (MC_{CE})	JENDL-3.2					X	X
G	TEPSYS	CASMO-4 (CP+MOC)	JEF-2.2	X	X			X	X
H	NFI	CASMO-4 (CP+MOC)	ENDF/B-IV, V	X	X	X	X		X
I	NFI	NULIF (ABH)	ENDF/B-V	X					
J	NUPEC	CASMO-4 (CP+MOC)	ENDF/B-IV, V					X	X
K	SEPCO	SHETRAN (MOC)	ENDF/B-VI(R3)	X	X	X	X		
L	GNF-J	TGBLA (DIF)	ENDF/B-V	X	X			X	
M	GNF-J	VMONT (MC_{MG})	JENDL-3.2	X	X			X	
N	Toshiba	MCNP-BURN (MC_{CE})	JENDL-3.2	X	X				
O	CRIEPI	FLEXBURN (SN)	JENDL-3.2	X	X	X	X		
P	EPDC/KCC	LWRWIMS (CP)	JEF-2.2	X	X				
Q	KAERI	HELIOS (CCCP)	ENDF/B-VI	X	X	X	X		X

*MC: Monte Carlo(Continuous-Energy or Multi-Group), CP: Collision Probability, MOC: Method of Characteristics,

SN: Discrete ordinate method with arbitrary meshes, DIF: Diffusion with L-method, CCCP: Current coupling CP

CP+MOC: CP for pin cell calculation and MOC for Assembly calculation

Table II. Results of the reactivities in the pin cell problems at BOL/EOL

		Void (0%→40%)	Void (0%→70%)	Doppler (900K→1800K)	Hot-to-Cold (Hot→300K)
UO_2	Average (%Δk/kk')	-2.13 / -4.89	-6.04 / -13.6	-1.45 / -2.79	4.90 / 9.75
	Spread (%Δk/kk')	0.20 / 0.70	0.68 / 2.25	0.23 / 0.34	0.38 / 1.01
	Max. difference (%)	9.3 / 14.4	11.2 / 16.6	16.0 / 12.0	7.8 / 10.4
MOX	Average (%Δk/kk')	-0.71 / -1.35	-1.03 / -2.40	-1.79 / -1.99	4.68 / 5.93
	Spread (%Δk/kk')	0.31 / 0.33	0.85 / 0.83	0.40 / 0.35	1.49 / 1.92
	Max. difference (%)	43.7 / 24.8	82.0 / 34.5	22.7 / 17.5	31.7 / 32.4

Spread = (Max. value) - (Min. value), Max. deference = Abs.(Spread/Average)x100

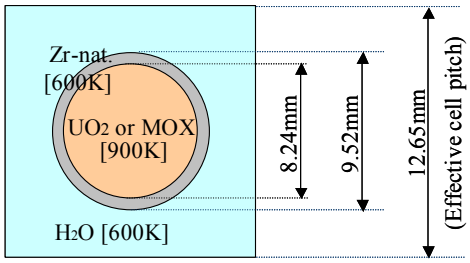
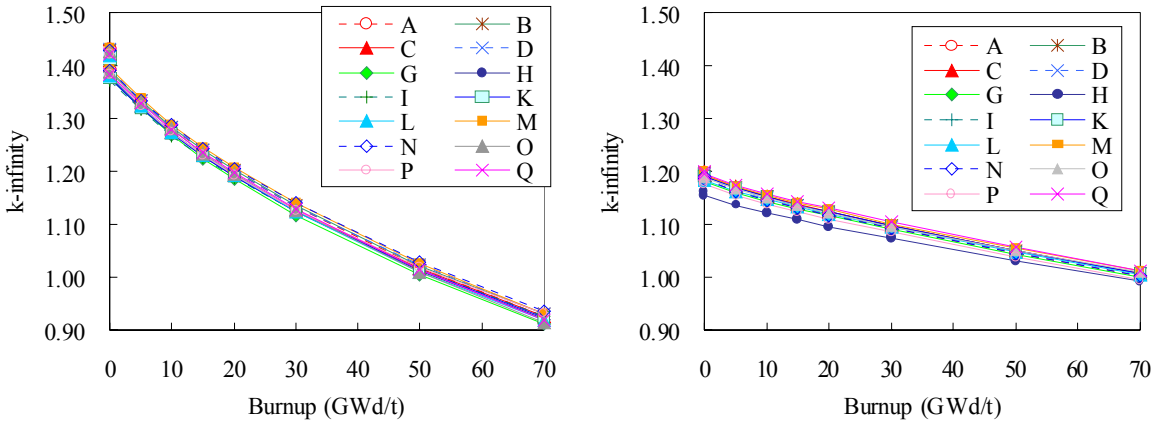


Figure 1. Benchmark calculation model for the pin cell problems
(Specified temperatures are for "Hot" condition)



(a) UO_2 fuel pin (b) MOX fuel pin

Figure 2. Results of k-infinities in the pin cell problems

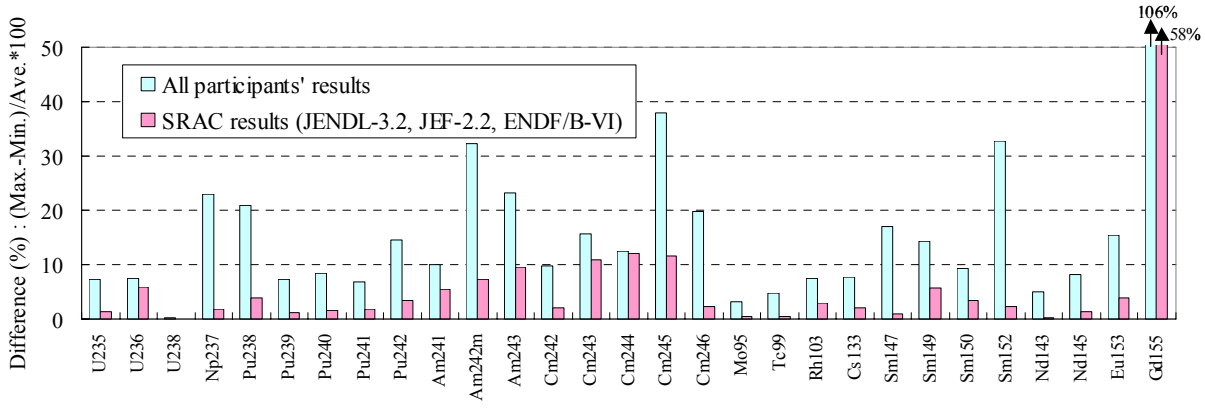
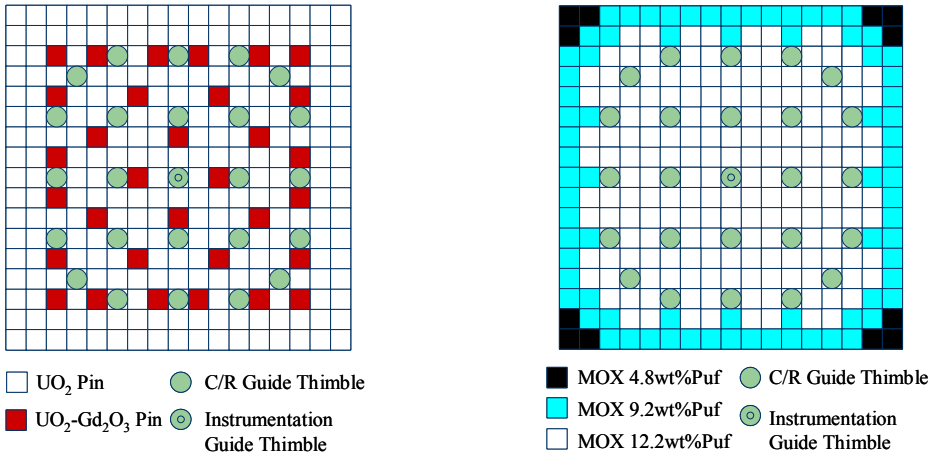


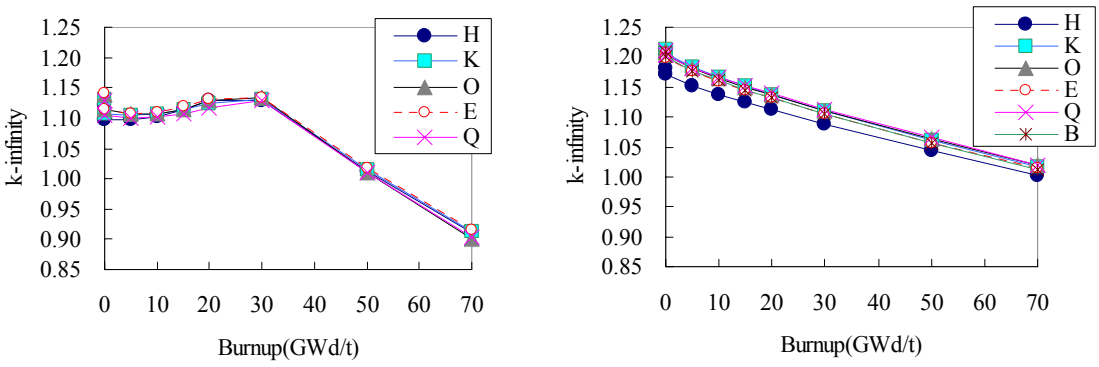
Figure 3. The maximum differences among the UO_2 pin cell results for the atomic number densities of evaluated nuclides at 70GWd/t

Some extreme results caused by incomplete burn-up chain models are dropped from the all participants' results (e.g. no consideration of α-decay from Cm to Pu)



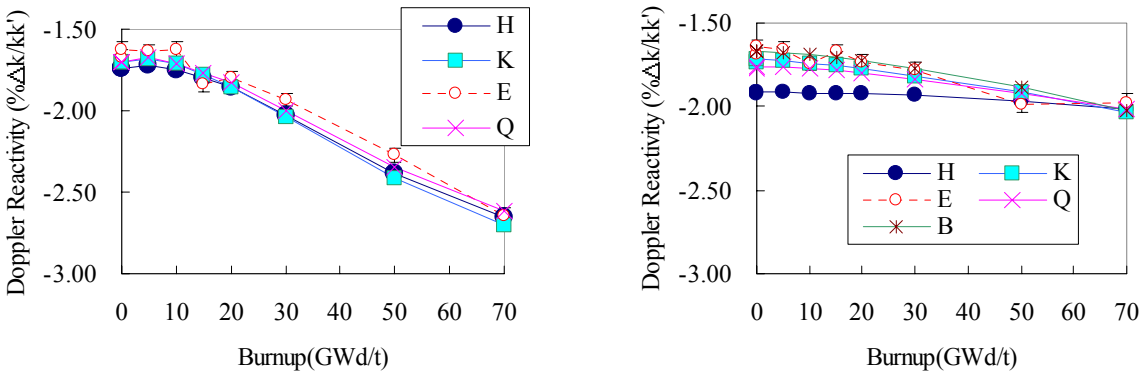
(a) UO_2 Assembly (b) MOX Assembly

Figure 4. Benchmark calculation models for the PWR fuel assembly problems



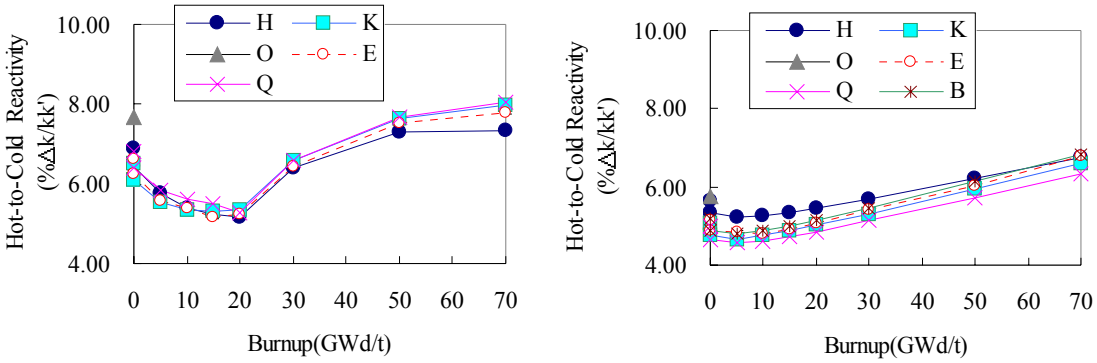
(a) UO_2 Assembly (b) MOX Assembly

Figure 5. Results of k-infinities in the PWR fuel assembly problems



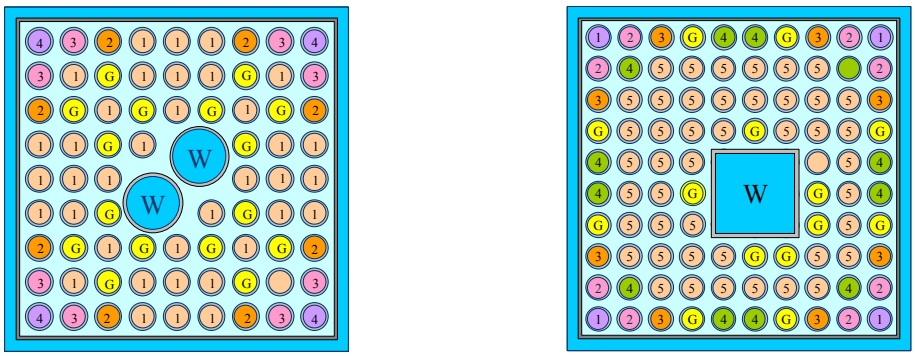
(a) UO_2 Assembly (b) MOX Assembly

Figure 6. Results of Doppler reactivities in the PWR fuel assembly problems



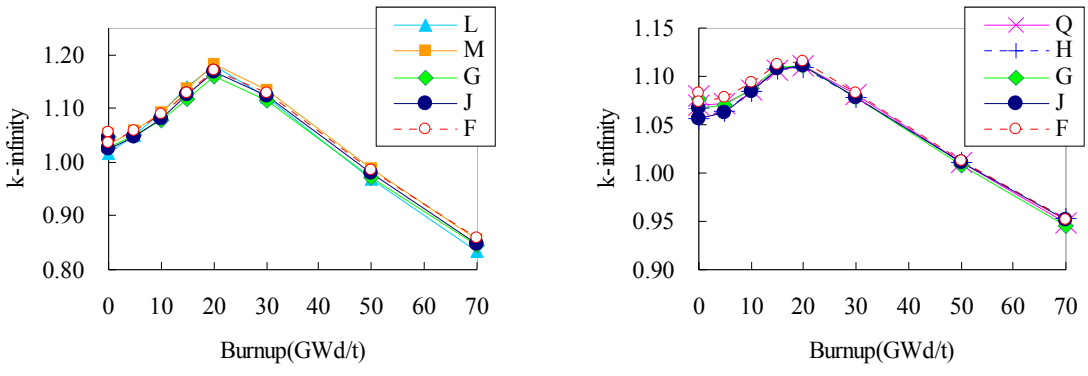
(a) UO_2 Assembly (b) MOX Assembly

Figure 7. Results of Hot-to-Cold reactivities in the PWR fuel assembly problems
(Results of Participant-O are submitted only at BOL)



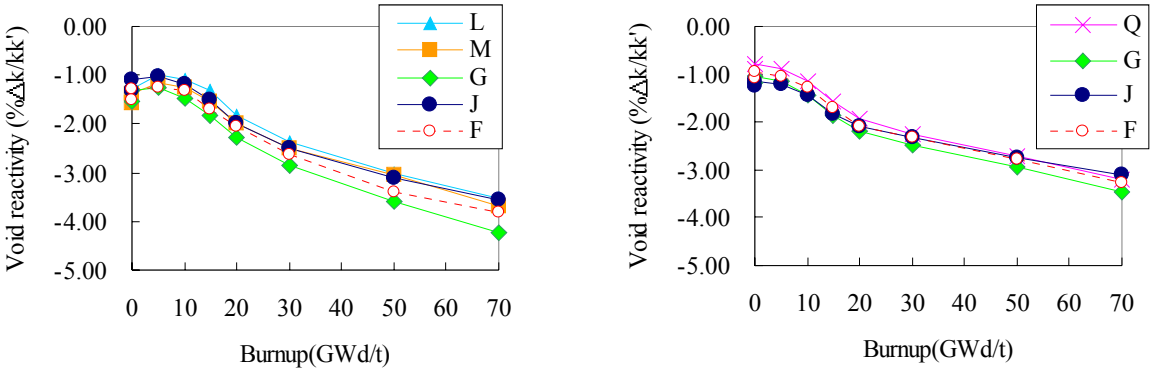
(a) UO_2 Assembly (b) MOX Assembly

Figure 8. Benchmark calculation models for the BWR fuel assembly problems



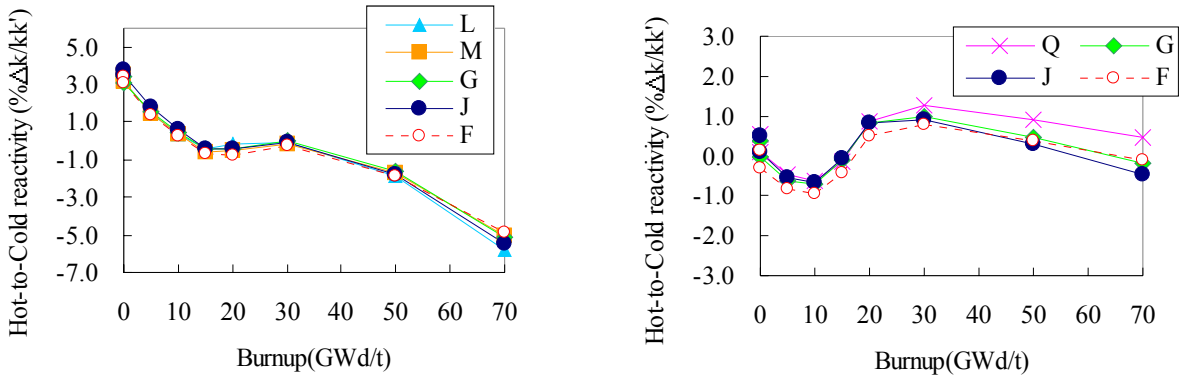
(a) UO_2 Assembly (b) MOX Assembly

Figure 9. Results of k-infinities in the BWR fuel assembly problems



(a) UO_2 Assembly (b) MOX Assembly

Figure 10. Results of void reactivities (0%→40%) in the BWR fuel assembly problems



(a) UO_2 Assembly (b) MOX Assembly

Figure 11. Results of Hot(0% void)-to-Cold reactivities in the BWR fuel assembly problems