REATIVITY CONTROL OF SOLUBLE BORON FREE PWR BY INTRODUCING Pu-238 ADDED FUEL

Soon Young Kim*, Jong Kyung Kim, Gyoo Dong Jeun, and Shane Park
Department Of Nuclear Engineering
Hanyang University
17 Haengdang, Sungdong, Seoul, 133-791 Korea
turbo@kaeri.re.kr ; jkkim@nural.hanyang.ac.kr ;
que@thlab.hanyang.ac.kr ; psi@nuclear.hanyang.ac.kr
*Current Address : Korea Atomic Energy Research Institute
150 Dukjin, Yusong, Taejon, 305-353 Korea

Un Chul Lee
Department Of Nuclear Engineering
Seoul National University
San 56-1, Shinlim, Kwanak, Seoul, 151-742 Korea
uclee@plaza.snu.ac.kr

Ho Chun Suk
Korea Atomic Energy Research Institute
150 Dukjin, Yusong, Taejon, 305-353 Korea
hcsuk@kaeri.re.kr

ABSTRACT

A new concept of Pu-238 added fuel is introduced to control the reactivity and power distribution in soluble boron free (SBF) pressurized water reactor (PWR) core. Though extensive use of burnable poison and control rods is inevitable for reactivity suppression in SBF core, it causes the core power distribution control to be so difficult that practical SBF operation is difficult to achieve. In this work, it is confirmed that the excess reactivity can be greatly suppressed by introducing the Pu-238 added fuel. As the result of the conceptual core design of the 600MWe SBF PWR using the Pu-238 added fuel, the core power distribution is well controlled in comparison with the results obtained from the previous 600MWe SBF core design works[1-5]. Safety analysis of the SBF core is tested about two limiting accidents, steam line break and rod cluster control assembly ejection accidents, and it is verified that the SBF core is safer than the previous SBF core against the two limiting accidents. Hence, one of the difficult control problems arising in SBF core design can be greatly mitigated by introducing the new fuel concept. It is further expected that the Pu-238 added fuel introduced in this study can be directly applicable to practical SBF core design.

1. INTRODUCTION

Because of design problems associated with heavy reliance upon movable control rods (CRs), soluble boron (SB) has been introduced as one of the major control features in all modern pressurized water reactor (PWR) designs. The uniform distribution of SB at the proper concentration throughout the core minimizes the need for CR insertion and the consequent spatial distortion of the core power distribution. However, since many drawbacks due to the use of SB had been identified in spite of its satisfactory performance, the elimination of SB reactivity control from the PWRs had been studied to offer a number of attractive features[1-5].

Hence, soluble boron free (SBF) operation is preferable to satisfy the advanced light water reactor (ALWR) requirements, which recommend adopting more passive safety features. In SBF operation, extensive use of burnable poison (BP) rods and CRs are inevitable. The reactivity and power distribution control without using SB can be hardly achieved in modern PWRs having longer cycle lengths of more than 12-months.

In the last two decades, several researches as a part of ALWR design have been carried out using only CRs and BP rods in reactivity and power distribution control for SBF operation. In the feasibility studies[1-5], a 600MWe SBF PWR core was designed, and SBF operation in a commercial medium-sized PWR was considered to be technically feasible. Extensive use of BP rods in the feasibility studies caused, however, the power peaking factor to be higher, and thus, the axial and radial power shape control to be difficult. Hence, reduction of the enormous number of BP rods for compensation of the reactivity associated with fuel depletion seems to be an important design factor in SBF core.

In this work, a new Pu-238 added fuel, which reserves a sufficient reactivity hold-down capability, was introduced to reduce the number of BP rods, and tested for 600MWe SBF PWR core design. Safety analyses of the SBF core designed in this work were performed for the most limiting accidents, steam line break (SLB) and rod cluster control assembly (RCCA) ejection accidents.

2. ALTERATION OF FUEL COMPOSITION

Since reactivity is, as is generally known, an almost linear function of burnup for LWR lattices, considerable amounts of excess reactivity at beginning of cycle (BOC) are required to achieve the target cycle length. Excess reactivity in SBF core should be compensated with only BP rods and CRs instead of SB. To limit the worth of CR insertions necessary to adjust the reactivity over the cycle, BP loading has to be increased. However, extensive use of BP rods increases assembly power peaking. In that case a practical SBF operation cannot be accomplished without a reduced BP loading scheme, since a reduction of the number of BP rods is an important design factor of SBF core. Hence, a new device for reactivity control other than BP rods and CRs is keenly requested.

In order to reduce the number of BP rods, the fuel itself was, in this study, considered as an alternative device for reactivity control instead of SB in primary coolant. A new fuel, which contains a certain nuclide having an excellent capability of thermal neutron capture, may effectively replace the reactivity control shared by SB. Furthermore, the new fuel is expected to provide a relatively uniform control for the core, since fuel rods are distributed throughout the core just as SB is in borated PWRs. This is also expected to reduce the effect of BP rods on the power peaking factor.

In order to apply the new fuel concept to SBF PWR core design, several nuclides such as neptunium, plutonium, and americium were considered excluding fissile isotopes and very strong and weak neutron absorbers. Among the nuclides considered the two plutonium isotopes, Pu-238 and Pu-240 were regarded as preferable to this work by investigating the burnup behavior of plutonium added fuel assemblies. In this work, Pu-242 was excluded because it has a relatively low neutron capture cross section compared to those of the two plutonium isotopes. In Figure 1, infinite multiplication factor of the different fuel assemblies was shown as a function of burnup. The fuel assembly design employed in the calculations was a 17×17 fuel lattice, which is the same configuration as the design used in the Westinghouse AP600 reactor,[6] except that it incorporates 28 guide tubes. The modified fuel assembly design is for accommodating increased CR reactivity control in SBF core to meet the shutdown margin requirements, though CR reactivity control is not necessary at the present stage. The fuel enrichment of 3.5 w/o U-235 was used in the calculations, and all assembly calculations were carried out using CASMO-3 code. From Figure 1, it is confirmed that excess reactivity at zero burnup can be considerably suppressed without any BP rods, and when the same amount of plutonium was substituted, Pu-240 was shown to be more effective to reactivity suppression at zero burnup than Pu-238. This is caused by the fact that the neutron capture capability of Pu-240 is better than that of Pu-238 at low neutron energies, especially at 0.1 ~ 2 eV. In order to compare the depletion characteristics between the Pu-238 added fuel and Pu-240 added one, the fuel assembly containing 0.3 w/o Pu-240, which can show the same reactivity suppression as 1.0 w/o Pu-238 does at zero burnup, was also employed as already shown in Figure 1. In spite of the same reactivity suppression at zero burnup, it can be found that the two fuel assemblies show different depletion characteristics from each other. This is mainly due to the fissile isotopes of plutonium, Pu-239 and Pu-241, which are additionally produced by the substitution of the non-fissile isotope of plutonium. It is noted that Pu-241 production due to Pu-240 addition is considerably larger than that due to Pu-238 addition, while Pu-239 production is comparable. This means that the total macroscopic fission cross section of the Pu-240 added fuel assembly is higher than that of the Pu-238 added one at every burnup state. In Pu-240 added fuel assembly, rapid rise in reactivity over burnup is, therefore, caused as the Pu-240 content increases. However, the large reactivity change over the burnup is not desirable in SBF core, since it causes the core reactivity and power shape control to be difficult. If BP rods are used in the fuel assembly to suppress the residual excess reactivity, the reactivity rise over the burnup becomes more severe. It is, therefore, judged that the Pu-238 added fuel is very suitable for excess reactivity suppression in SBF core.

Pu-238 has been used as a power source for the long-range space missions since this isotope has a half-life of 87.7 years. Though the amounts of Pu-238 obtained from the commercial nuclear power reactors are very small, Pu-238 can be produced at the special facilities by the following reactions:

- Np-237 + n ⇒ Np-238
- Np-238 ⇒ (2.1days, beta) ⇒ Pu-238

Hence, the use of Pu-238 added fuel might not be a difficult problem considering that the processes for handling and using plutonium are well developed and plutonium has been safely used for past decades.

3. APPLICATION OF THE Pu-238 ADDED FUEL TO 600MWe SBF CORE DESIGN

3.1 DESIGN APPROACH AND FUEL MANAGEMENT

A conceptual SBF core design of 600MWe PWR was performed with the new fuel having a small amount of Pu-238 in its composition to validate the concept of the alteration of fuel composition. The SBF core was, in this work, based on the Westinghouse AP600 reactor, and the evaluated fuel cycle design was an 18-month equilibrium cycle with approximately one third of the fuel replacement in each cycle. The fuel management and BP loading scheme were designed such that the requirement for CR reactivity adjustment over the cycle is as low as possible at nominal full power conditions. The fuel enrichments and the Pu-238 concentrations used in the first and equilibrium cycle design are shown in Table 1. Axial zoning of the fuel assembly was used to control the bottom-shifted axial power distribution, which is an inherent characteristic in SBF operation. In all feed assemblies, including the B and C type fuels, the simple form of axial zoning was adopted by using enrichment zoning of Pu-238 in the fuel composition, as shown in Figure 2. In all fuel assemblies, 28 CRs were accommodated to secure a large CR worth, as compared to the 24 CR configuration in the AP600 designs.

The equilibrium core loading pattern is shown in Figure 3. In reload SBF core design, more careful determination of the core loading pattern should be required than that of a borated reactor, because reactivity release characteristic of the feed assembly is different from that of the burned fuel assembly. Since the reactivity of the burned fuel assembly decreases rapidly during a burnup due to the exhaustion of burnable absorbers, the reactivity of the feed assembly should be increased rapidly to compensate for the decreasing reactivity of the burned fuel. However, fuel management becomes more difficult when the reactivity in the fresh fuel rises steeply during burnup. An Out-in scheme was, therefore, employed to minimize the effects of the feed assembly on core reactivity instead of the in-out scheme that is a general L3P (Low Leakage Loading Pattern). Though the feed assemblies were located at the core periphery region, the neutron leakage problem is not serious, since the reactivity of all feed assemblies is strongly held by BP rods and Pu-238 added fuel rods. In each feed assembly, sixteen BP rods were equally loaded. In this work, a novel BP rod was designed, which can provide a proper reactivity hold-down at BOC by a relatively small number of BP rod and prevent a rapid change in the core excess reactivity over burnup. The BP rod, which was designed by combining WABA and Pyrex, uses alumina-boron carbide as an absorber material, and takes the shape of Pyrex, since the absorber thickness of Pyrex and the absorber material of WABA are preferable for this work.

The RCCA configuration was modified to adjust long-term reactivity control over the cycle and to secure a sufficient shutdown margin. The RCCAs were divided into two categories as shown in Figure 4: RCB for reactivity and power distribution control and SDB for shutdown. RCB was divided into 4 banks: RCB1, RCB2, RCB3, and RCB4, and SDB into 4 banks: SDB1, SDB2, SDB3, and SDB4. RCBs were comprised of silver-indium-cadmium absorber, and SDBs were modeled as strong absorbing rods consisting of a boron carbide absorber to secure a sufficient cold shutdown margin.

3.2 ANALYSIS RESULTS

The unrodded reactivity as a function of cycle burnup at nominal full power is shown in Figure 5.

The maximum unrodded reactivity was controlled within 2.3 $\%\delta\rho$ with a relatively small number of BP rods by using the Pu-238 added fuel rods. CR adjustment for long term reactivity control over the cycle was analyzed for the RCBs. The rodded axial offset (AO) and F_{xy} as a function of burnup are shown in Figures 6 and 7, respectively, together with the results of the previous work[5], which had employed an enormous number of enriched BP rods in excess reactivity control instead of using the Pu-238 added fuel. Compared with the results of the previous work, it is noted that the radial peaking factors of this work at every burnup state are lower than those of the previous work, while axial power distribution control is well performed in both works. It is noted that axial and radial power distribution control can be well performed in SBF core by using the Pu-238 added fuel assemblies.

The cold shutdown capability of the 600MWe SBF core was evaluated at BOC. The actual calculations proceeded directly from hot full power (HFP) with equilibrium xenon to the N-1 configuration at cold zero power (CZP) with no xenon. For an effect by redistribution, the value given in the AP600 design was directly used to calculate the cold shutdown margin. When the rod worth at the N-1 rod condition was calculated and reactivity insertion due to power and temperature changes was offset, the net shutdown margin with 10 % adjustment to accommodate uncertainties was about 2.8 % $\Delta\rho$, which is thought to be sufficient.

The xenon stability characteristics were also evaluated by using the 3-D core model to excite a xenon oscillation and then observing the changes in AO as a function of time. The result at end of cycle (EOC) is shown in Figure 8 together with that of the previous work. Though xenon control is, in general, most difficult at EOC, in this work it is confirmed that AO as a function of time could be immediately converged to its original value in the SBF core designed after the perturbation had been introduced. Therefore, the SBF core in which the Pu-238 added fuel assemblies are loaded can be more stable against xenon-induced oscillation than the previous designed SBF core.

4. SAFETY ANALYSIS

Safety analysis was performed for the most limiting accidents selected by considering the changed thermal parameters caused by nuclear parameter change at the accident situation. RELAP5/MOD3 code was employed for SLB analysis and COBRA IV code for RCCA ejection accident analysis. The boundary conditions required by COBRA IV code were supplied by core calculations and RELAP5/MOD3 simulation results.

4.1 STEAM LINE BREAK ACCIDENT

SBF reactor is safer than the current PWRs for the usual temperature rising accidents. However, in the case of temperature dropping accidents more positive reactivity is inserted into the core because the SBF core has a more negative MTC value. In this work, SLB accident, one of the temperature dropping accidents, was thus selected for the analysis.

The SLB accident was simulated by RELAP5/MOD3 code. The main point is that post-trip return-to-power should be avoided. Therefore, according to the known methodology[7] to analyze the response of the nuclear steam supply system parameters to the SLB events, a sensitivity study of the total four cases was conducted. The selected four cases are as follows:

- Case 1 : BOC, hot zero power (HZP), reactor coolant pump (RCP) on
- Case 2 : BOC, HZP, RCP off
- Case 3 : BOC, HFP, RCP on
- Case 4 : BOC, HFP, RCP off

For all cases, the BOC condition was included because MTC at BOC showed the largest absolute value during the cycle. Simulated results are shown in Figures 9 through 12, respectively, together with that of the previous SBF reactor core. As a result, the least wanted negative reactivity was all satisfied by the design values, and this SBF core showed more advanced safety feature than the previous work.

4.2 ROD CLUSTER CONTROL ASSEMBLY EJECTION ACCIDENT

RCCA ejection accident was simulated by COBRA IV code[8]. For its input requirements, RELAP5/MOD3 code was used to simulate the core coolant system's thermal-hydraulic response. In this work, RCCA at the core center was assumed to have rods ejection and pressure boundary failure was not considered because the supposed elapsed time for this accident is relatively short. A sensitivity study was performed for BOC and EOC, on the basis of an HFP condition. Fuel centerline temperatures were obtained by a finite difference method using the conditions from the code simulation results.

mDNBR changes during the transient are shown in Figures 13 and 14. It is noted that in each case mDNBR does not violate the limit value, 1.2. In Figures 15 and 16, the fuel peak temperatures are shown. It can be seen that fuel peak temperatures also did not violate the limit value, 4,700 °F. Hence, it is confirmed that fuel melting does not occur.

CONCLUSIONS

A new Pu-238 added fuel was developed to suppress the excess reactivity in the SBF PWR core with using less BP rods, and to provide a relatively uniform power shape just as SB does in a borated reactor. It is verified that the new Pu-238 added fuel is promising to the SBF PWR core design through the analysis for the conceptual SBF core designs of 600MWe PWR. The number of BP rods to suppress the excess reactivity can be greatly reduced, and thus the reactivity and power distribution in the SBF core can be well controlled with the aid of the Pu-238 added fuel to the extent of those in borated PWR. Axial power shape was controlled over cycle burnup by using the axial zoning of Pu-238 enrichment to provide the desired axial shape during steady operation. It is noted that the axial zoning scheme is very simple in comparison to those employed in the earlier SBF core design works. In the case of SLB accident, the least wanted negative reactivity was satisfied by the design values. In the case of RCCA ejection, mDNBR and the maximum fuel centerline temperature did not violate the design limit. It is, therefore, concluded that the reactivity control and safety feature in the SBF PWR can be well improved through the alteration of fuel composition.

ACKNOWLEDGEMENTS

This work has been carried out under the Nuclear Research and Development Program of Korea Ministry of Science and Technology.

REFERENCES

1. Electric Power Research Institute, "Soluble Boron Free Passive PWR Study Phase II Summary Report," Combustion Engineering, November (1989).

2. Electric Power Research Institute, "Elimination of Soluble Boron for a New PWR Design," Combustion Engineering, EPRI NP-6536, Project 2614-24, September (1989).

3. Korea Atomic Energy Research Institute, "A Study on the Optimum Core Design of Small/Medium Sized Reactor for Soluble Boron Free Operation," Hanyang University Radiation Research Laboratory, KAERI/CM-266/98, April (1999).

4. Korea Atomic Energy Research Institute, "A Study on the Improvement of Operation Method for Soluble Boron Free Operation," Electrical Engineering and Science Research Institute, KAERI/CM-148/94, August (1995).

5. J. K. Kim, *et al.*, "A Study on the Conceptual Core Design of 600MWe Reactor for SBF Operation," *Proc. of the Korean Nuclear Society Autumn Annual Meeting*, Seoul, Korea, Vol. I, (October 30-31, 1998).

6. US Department of Energy, "Simplified Passive Advanced Light Water Reactor Plant Program: AP600 Standard Safety Analysis Report," Westinghouse, DE-AC03-90SF18495, Vol. 3, June (1992).

7. Electric Power Research Institute, "Steam Line Break Analysis Methodologies; Simulation of PWR Steam Line Break Accidents-EPRI Sponsored Projects," EPRI TR-100521 Projects 2941-1 Final Report, April (1992).

8. C. W. Steward, C. A. McMonagle, M. J. Thurgood, T. L. George, D. S. Trent, J. M. Cuta, G. D. Seybold, "Core Thermal Model: COBRA-IV Development and Applications," USNRC, BNWL-2212 NRC-4, January (1977).

Table 1. Fuel Assembly Description of 600MWe SBF Core (First and Equilibrium Core)

F/A TYPE	U-235 Enrichment (w/o)	Pu-238 Content (w/o)	Constituent
A	3.1	0.5	-
B	3.5	0.6	B1
	3.5	1.0	B2
C	3.9	0.1	C1
	3.9	0.7	C2
F (Feed Assembly)	4.3	0.5	F1
	4.3	1.1	F2

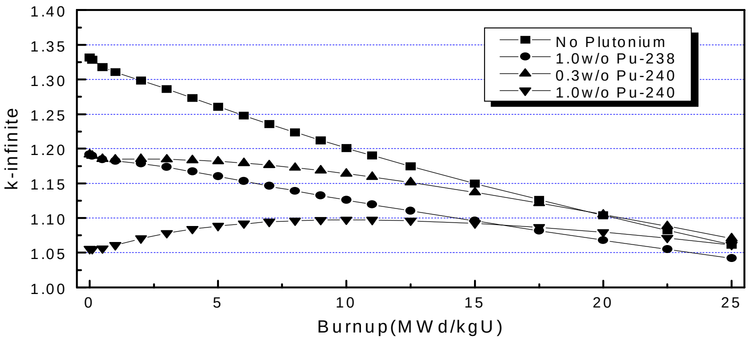


Fig. 1 Depletion Characteristics of Plutonium Added Fuel Assembly

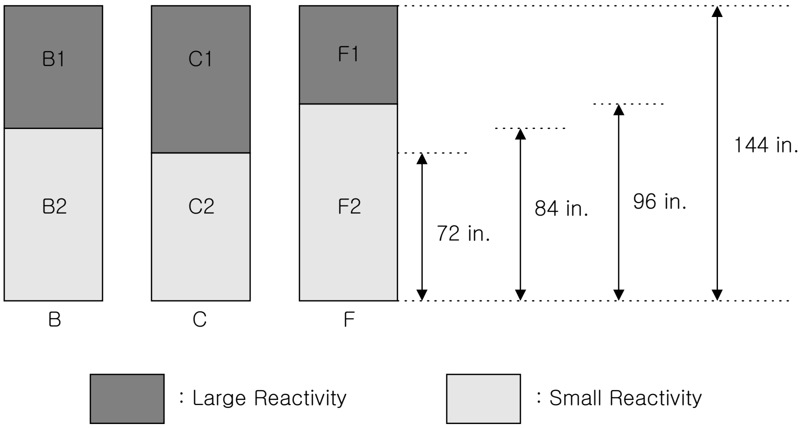
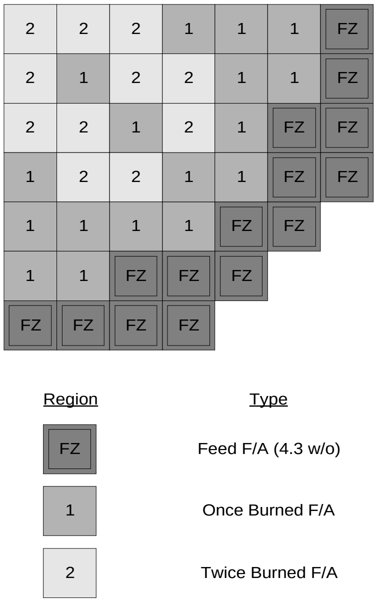


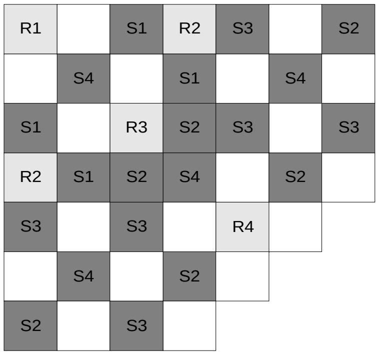
Fig. 2 Fuel Assembly Axial Zoning Scheme



2	2	2	1	1	1	FZ
2	1	2	2	1	1	FZ
2	2	1	2	1	FZ	FZ
1	2	2	1	1	FZ	FZ
1	1	1	1	FZ	FZ	
1	1	FZ	FZ	FZ		
FZ	FZ	FZ	FZ			

Region	Type
FZ	Feed F/A (4.3 w/o)
1	Once Burned F/A
2	Twice Burned F/A

Fig. 3 Equilibrium Core Loading Pattern of 600MWe SBF Core



Index	Control Bank Name	Material
R1, R2, R3, R4	RCB 1, 2, 3, 4	Ag-In-Cd
S1, S2, S3, S4	SDB 1, 2, 3, 4	B_4C

Fig. 4 Control Rod Configuration of 600MWe SBF Core

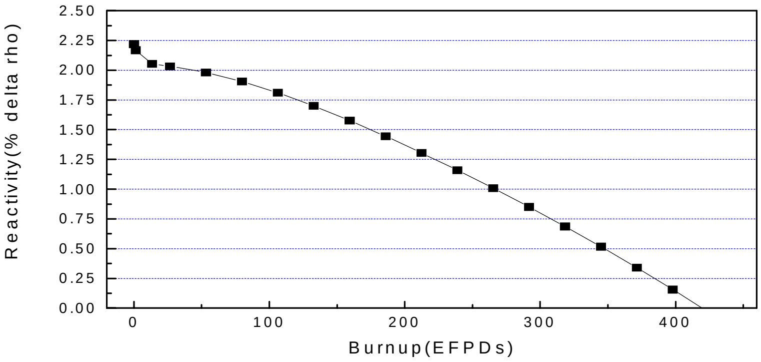


Fig. 5 Unrodded Reactivity over Cycle (Equilibrium Core, HFP, Eq. Xe)

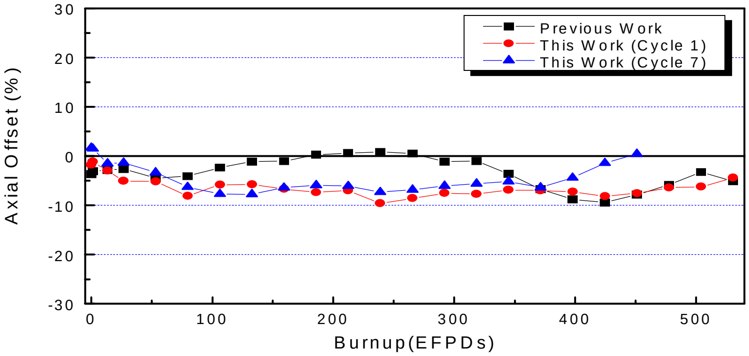


Fig. 6 Comparison of AO Values over Cycle (HFP, Eq. Xe)

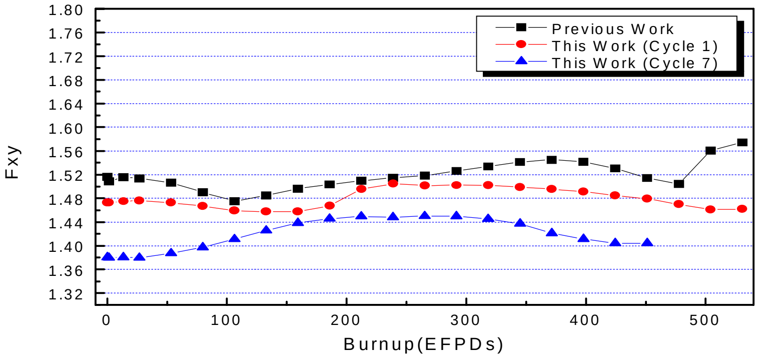


Fig. 7 Comparison of F_{xy} Values over Cycle(HFP, Eq. Xe)

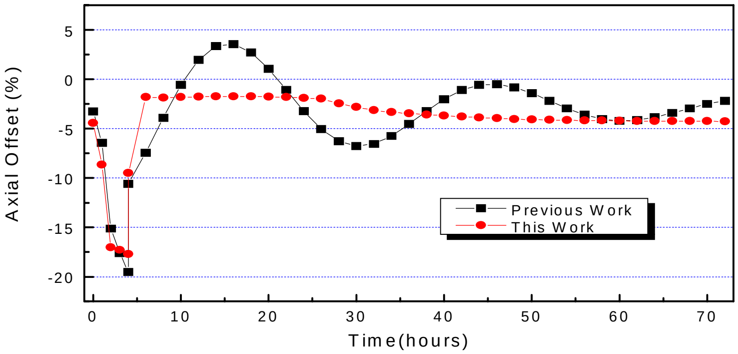


Fig. 8 Comparison of Xenon Stability Behavior

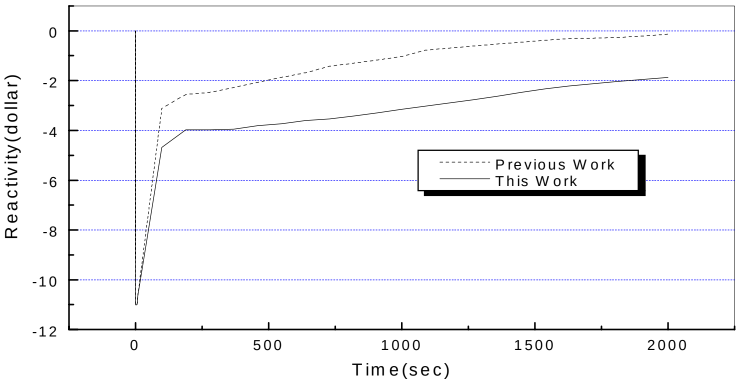


Fig. 9 Overall Reactivity in Case 1 (BOC, HZP, RCP on)

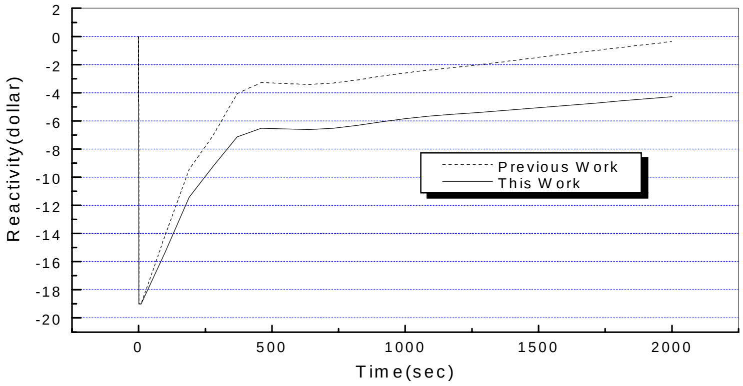


Fig. 10 Overall Reactivity in Case 2 (BOC, HZP, RCP off)

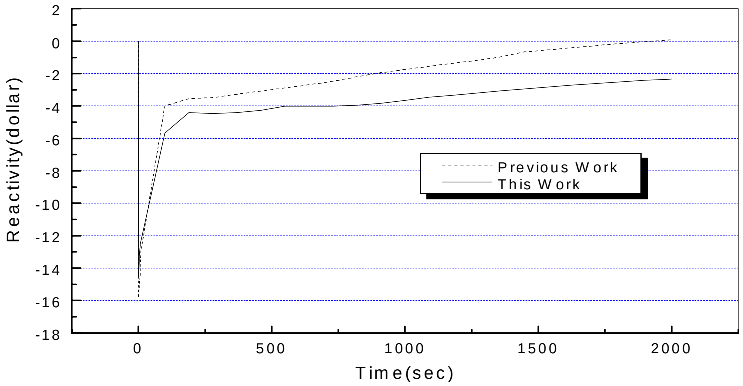


Fig. 11 Overall Reactivity in Case 3 (BOC, HFP, RCP on)

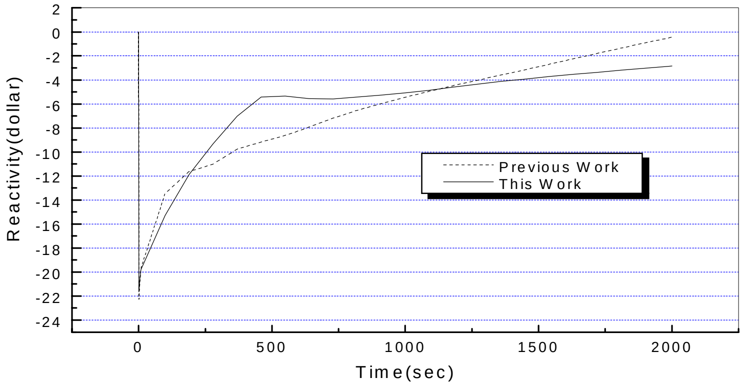


Fig. 12 Overall Reactivity in Case 4 (BOC, HFP, RCP off)

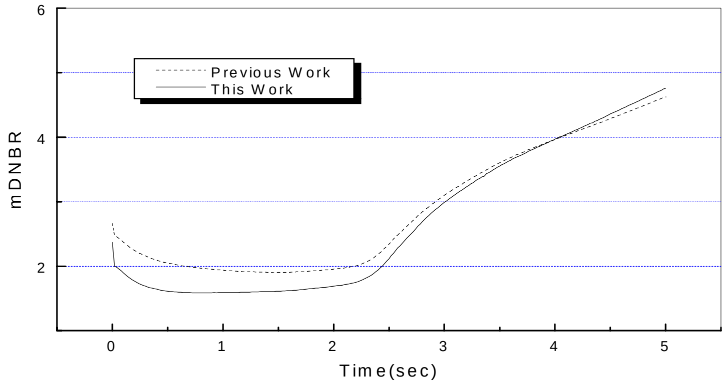


Fig. 13 mDNBR I (HFP, BOC)

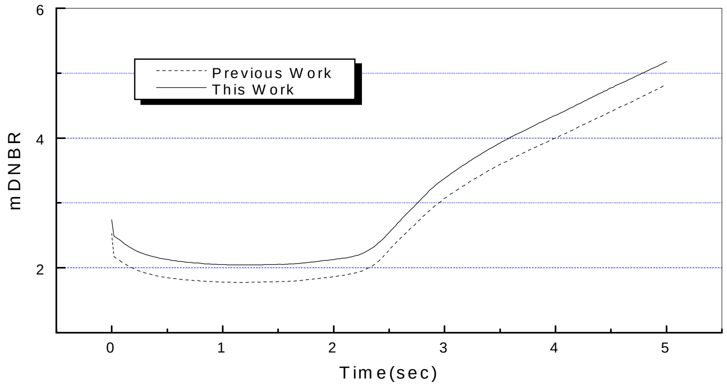


Fig. 14 mDNBR II (HFP, EOC)

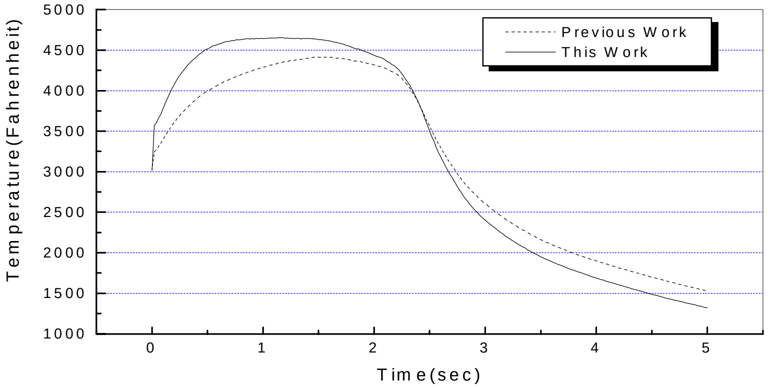


Fig. 15 Fuel Peak Temperature (HFP, BOC)

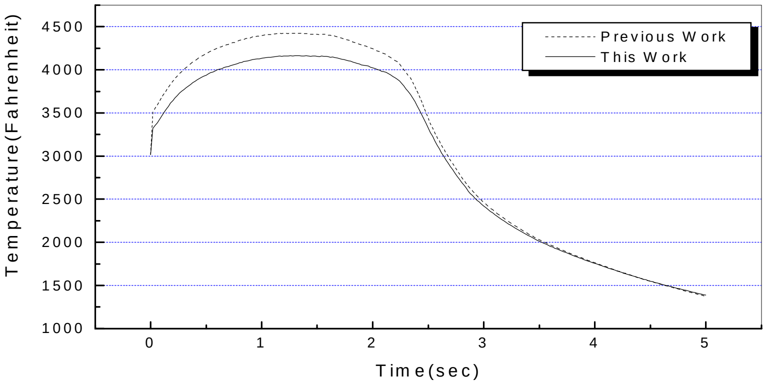


Fig. 16 Fuel Peak Temperature (HFP, EOC)