STUDY ON LONG LIFE CORE WITH URANIUM FUEL FOR LSBWR

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ABSTRACT

This paper describes an innovative core concept currently being developed for long operating cycle simplified BWR (LSBWR). LSBWR is a modular, direct cycle, light water cooled, small power reactor. The long cycle operation (15 years) of LSBWR is for the elimination of the fuel pool and the refueling machines and for the capacity usage ratio improvement. We adopt the medium enriched uranium oxide fuels with loose pitched lattice in consideration of the natural circulation for core cooling. To achieve long cycle operation, a combination of enriched gadolinium and 0.7-times sized small bundle with peripheral-positioned gadolinium rod was adopted as a key design concept. A nuclear design for fuel bundle was determined based on three dimensional nuclear and thermal hydraulic calculation. A core performance was evaluated based on this bundle design. Maximum enrichment needed for 15-years operation was estimated below 20wt%. The thermal performance indicated preferable value. Void reactivity coefficient kept negative throughout the operation. The behavior of parameter for the typical abnormal operation transient events was analyzed using computer code. The results showed that the transient performance satisfied the judgment criteria for transient event and was almost the same as the operation plant in Japan.

1. INTRODUCTION

In Japan, more than 50 units of nuclear power plants are playing important role in electric power generation. Currently, the next generation reactor with large electric power output (1700MWe) is under development. On the other hand, modular type small or medium size reactor is anticipated to be a candidate of next generation reactor, because of its smaller investment risk and competitiveness of power generation cost derived from modular design.

The reactor core concept evaluated here is for LSBWR[1]. LSBWR is a modular, direct cycle, light water cooled, small power (100-300MWe) reactor. A schematic view of the LSBWR is shown in Figure 1. LSBWR has a new BWR core concept optimized for long cycle operation, a small power output and a simplified BWR configuration.

The long cycle operation of LSBWR has the following objectives:

-Elimination of the fuel pool and the refueling machines
-Improvement of the capacity usage ratio

Purpose of this paper is to show the design concept for the fuel bundle and core to realize long cycle operation and to show the performance of the core.

2. CORE DESIGN CONSIDERATION FOR LONG CYCLE OPERATION

One way to achieve the super long operating cycle (over the 15 years) is adoption of high conversion core, which is attainable with a hard neutron spectrum[2]. Some designs use combination of tight lattice core and plutonium MOX fuel to attain hard spectrum[3]. Instead of hardening neutron spectrum, we adopt the combination of medium enriched uranium oxide fuels and loose pitched lattice bundle, because this configuration facilitates natural circulation for core cooling. To realize this idea, we have to resolve various design challenges.

Figure 2 shows the relationship among these challenges. Two lines indicate the k-infinity with or without burnable poison using loose pitched UO_2 lattice. Increased initial poison worth and extension of poison life are required for suppression of reactivity for a long cycle operation. The increase of control rod worth and extension of control rod life are also required to control the excess reactivity for super-long operation.

In LSBWR, gadolinia (Gd_2O_3) in fuel pellets is used as a burnable poison like existing BWR. For the realization of long burnable poison life, isotope-enriched gadolinium is powerful candidate. Isotope-enriched gadolinium is enriched in content of ^{157}Gd isotope. Isotope-enriched gadolinium is an essential technology for long cycle operation, because uranium enrichment should be increased in large amount to compensate the reactivity penalty caused by non-enriched gadolinium currently used in core design. The reactivity penalty is caused by negative reactivity which comes from existence of even-numbered gadolinium isotopes and a reduction of uranium inventory.

For suppression of large initial reactivity and realization of negative void reactivity coefficient, location of fuel rods including Gd_2O_3 (Gd rods) should be selected carefully. Peripheral location of Gd rod is effective measure for reduction of the number of Gd rods, because thermal neutron flux at the peripheral position is higher than inner position. Furthermore, peripheral position is preferable to prevent positive void coefficient, because the sensitivity of void fraction becomes smaller.

An excess reactivity might be required to be adequately large compared with current BWR design, because estimation error of the reactivity should be considered. For example, the estimation error in the reactivity comes from analytical error which accompanies long range estimation and comes from anticipated operation condition change such as reduction in natural circulation flow. Control rod worth might be required to enlarge so that large excess reactivity can be suppressed. Control rod combined with smaller bundle is effective measure. Because control rod worth increases greatly in smaller bundle design. Other countermeasure to increase control rod worth such as enriched boron is not so effective compared with smaller bundle.

A control rod for BWR is replaced each 5 or 6 years in consideration of rod worth reduction, therefore extension of control rod life is important in long cycle operation. There are a few methods for extension of control rod life time. One is to increase amount of poison contents in a control rod; another is to increase the number of control rods. Fortunately, the number of control rods becomes larger in combination with smaller bundle, therefore smaller bundle design is preferable for long cycle operation.

3. CORE DESIGN AND CORE PERFORMANCE EVALUATION

3.1 BUNDLE AND CORE DESIGN

Fuel bundle design specification is summarized on Table I and Figure 3. Active length of fuel rod is set 2.0m in consideration with pressure drop of the core, which value is shorter than that of SBWR[4]. Bundle pitch is 0.7-times size compared with current BWR bundle. As the result, the area of fuel bundle cell is half of current BWR.

Core design specification for LSBWR is summarized on Table II. Thermal output and cycle length are 900MW and 15 years respectively based on basic design of LSBWR[1]. Downward insertion control rod mechanism is utilized. The power density is almost the same as that of SBWR[4].

Bundle nuclear characteristics are evaluated by lattice design code. Core nuclear and thermal performances are evaluated by 3D simulator. Bundle design is shown on Figure 4. Bundle loading pattern is shown on Figure 5. These bundles design has been determined from various lattice calculations and 3D core calculations. Since bundle shuffling is not performed, two types of fuel bundle, center bundle and peripheral bundle are needed to suppress residual gadolinium worth in peripheral bundle and to flatten the bundle power distribution of the core. The number of Gd rods has been determined to flatten excess reactivity. In peripheral bundle, the number of Gd rods and the concentration of Gd_2O_3 are decreased compared with center bundle. Average uranium enrichment has been estimated to be 18wt% in both center bundle and peripheral bundle. Maximum enrichment is less than 20.0wt%, which is preferable in several processes of enriched uranium handling, such as conversion, fabrication and transportation. Almost all Gd rods are located at peripheral positions according to the design consideration. Additionally, isotope enriched gadolinium is applied to Gd rod. The enrichment of ^{157}Gd in total gadolinium is assumed 80wt%.

In the in operation, the number of control rods which have been inserted in the same time is less than 1/4 whole. Then, we have regularly changed the control rod which has been inserted. Figure 6 shows the total residence time for each control rod. Control rod operation plan has been successfully determined so that the maximum residence time is kept less than 6 years.

3.2 REACTIVITY PERFORMANCE

Excess reactivity is shown on Figure 7. We achieved cycle exposure 111GWd/t for 15 years operating period with the margin. Maximum value of excess reactivity throughout the operation is 3%Δk, which value was considered to be larger than ordinary nuclear design on BWR based on the design consideration. Shut down margin satisfies the design limit of 1.0%Δk.

Void coefficient of the core is shown on Figure 8. The reason why absolute value of void coefficient at BOC is less than half of end of core (EOC) is that the residual concentration of gadolinium as a thermal absorber is larger than EOC.

3.3 THERMAL PERFORMANCE

Bundle peaking factor is shown in Figure 9. The power output in the outer part of the core is raised by adopting peripheral bundle and bundle peaking factor is reduced. The value of the bundle peaking factor is little smaller than ordinary BWR. The value of axial peaking factor and local peaking factor is almost the same level as ordinary BWR. Maximum linear heat rate in operating period is 28kw/m. This small value is due to a low power density and small bundle peaking factor.

4. ANALYSIS OF ABNORMAL OPERATION TRANSIENT

In the safety evaluation for boiling water reactor in Japan, the abnormal transient events and accident events are evaluated. The definition of transient event is the plant abnormal which is caused by operator's miss operated or a single failure of dynamic equipment like a valve, pump, control system etc. The Japanese safety evaluation guide line specifies the judgment criteria which the transient and accident event must meet for entire plant life. The fuel thermal margin and the peak vessel pressure are the most important judgment criteria for transient event. In this section, the behavior of reactor related parameter are analyzed for LSBWR, by using computer code called REDY. One point neutron kinetics and thermal hydraulics, the models for actual control system and reactor protection system are also incorporated in this code. Loss of feedwater heating and Generator load rejection with turbine bypass valve failure are the typical transient which has considerably less thermal margin or greater peak vessel pressure in the boiling reactor water.

Figure 10 shows the analysis result for Loss of feedwater heating. In this event, the reactor power increases due to the abnormal increase of core inlet subcool caused by decrease of feed water temperature. However, the increase of the reactor power is limited up to 120% of rated, since the high neutron flux scram is initiated. Therefore, thermal margin and the peak vessel pressure are kept within the judgment criteria a for transient event.

Figure 11 shows analyses results for Generator load rejection with turbine bypass valve failure. In this event, the vessel pressure rapidly increases due to the fast closure of the turbine control valve caused by the detection system for the mismatch reactor power and generator load. The reactor power also increases, but it is immediately suppressed, since the reactor scram is initiated detecting the fast closure of turbine control valve. The vessel pressure is controlled by the opening of safety relief valves. Therefore, thermal margin and the peak vessel pressure are kept within the judgment criteria a for transient event.

In this section, the behavior of parameter for the typical events of LSBWR was analyzed using computer code. The results showed that the transient performance satisfied the judgment criteria for transient event and was almost the same as the operation plant in Japan.

CONCLUSIONS

An innovative core design concept for LSBWR is proposed. LSBWR assumes 15-year continuous operation, natural circulation cooling and upper entry control rod system. Addition to this, we adopt the key technologies as below;

1. 0.7-times size small bundle coupled with cruciform control rod
2. Isotope enriched gadolinium
3. Peripheral positioning of Gd rods

The design study on a fuel bundle and a core has been done. A bundle nuclear design is determined based on 3-dimensional calculation and core performance has been evaluated.

1. Two types bundle design is needed for the reduction of residual gadolinium worth.
2. Void reactivity coefficient kept negative throughout the operation.
3. Maximum enrichment needed for 15-years operation has been estimated below 20wt%.
4. Maximum residence time of control rod is kept less than 6 years

The behavior of parameter for the typical abnormal operation transient events was analyzed using computer code. The results showed that the transient performance satisfied the judgment criteria for transient event and was almost the same as the operation plant in Japan.

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Table I. Specification of fuel bundle

Active Fuel Length	200cm
Bundle Pitch	10.9cm
Outer Water Gap Width	1.3cm
Channel Box Thickness	0.13cm
Fuel Rod Array	7x7
Number of Fuel Rods	46
Number of Water Rods	3
Fuel Rod Pitch	1.26cm
Fuel Rod Diameter	1.00cm
Fuel Pellet Diameter	0.85cm
Fuel Pellet Stuck Density	95%TD
^{157}Gd concentration in Gd	80%
Control Rod Thickness	0.7cm

Table II. Specification of core design

Thermal Output	900MW
Operating Cycle Length	15years
Number of Fuel Bundles	956
Power Density	40kW/l
Bundle Array	34x34
Number of Control Rods	225
Control Rod Insertion Direction	Upper Entry
Reactor Dome Pressure	7.2MPa
Feed Water Temperature	215^{o}C
Core Flow Rate	12000t/hr
Cycle Exposure	111GWd/t

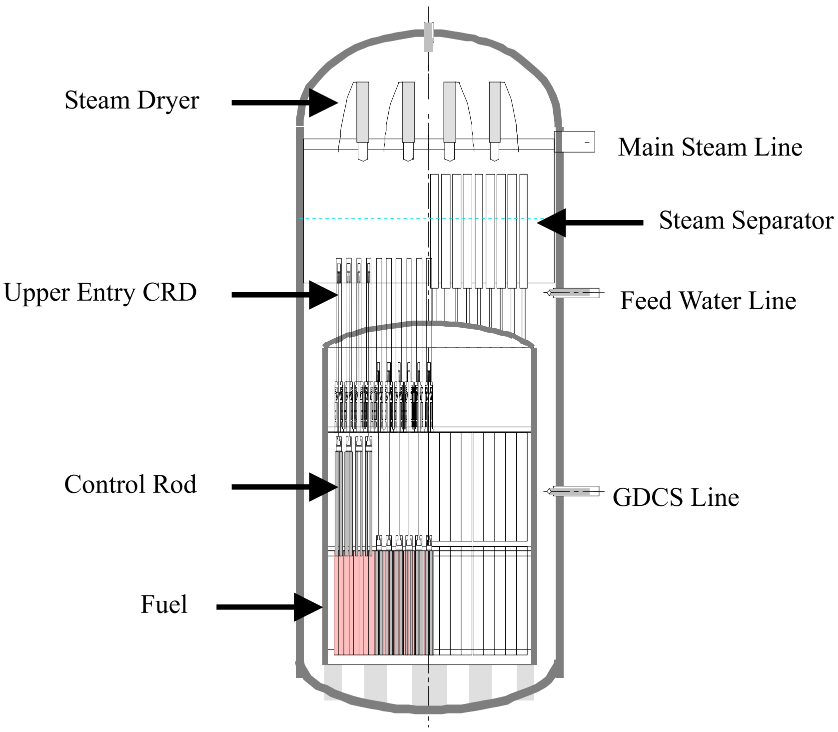
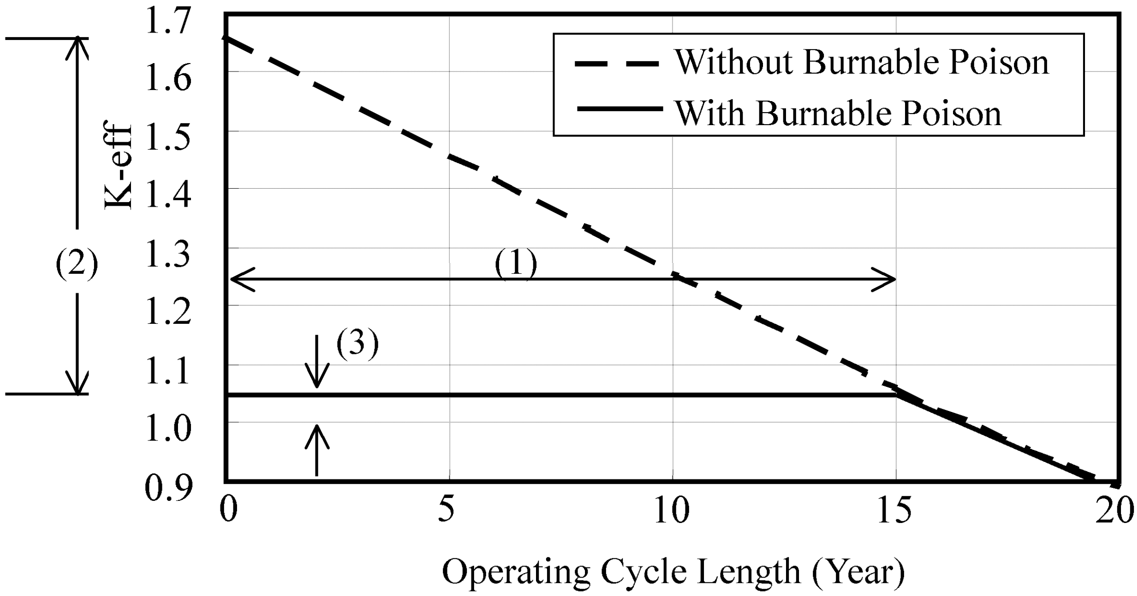


Figure 1. Schematic vertical view of reactor vessel



Category	Burnable Poison	Control Rod	Bundle / Core Design
Extented reactivity life (1) required by 15 year operation	Long life burnable poison and suppresion of large Initial reactivity (2)	Extension of reactivity life(1) required by over 15 year operation	Limitation on maximum uranium enrichment (< 20.0 wt%)
Large excess reactivity (3) required by long lerm flexibility and operability	-	Large excess reactivity (3) required by long lerm flexibility and operability	-

Figure 2. Design challenges in each core design area

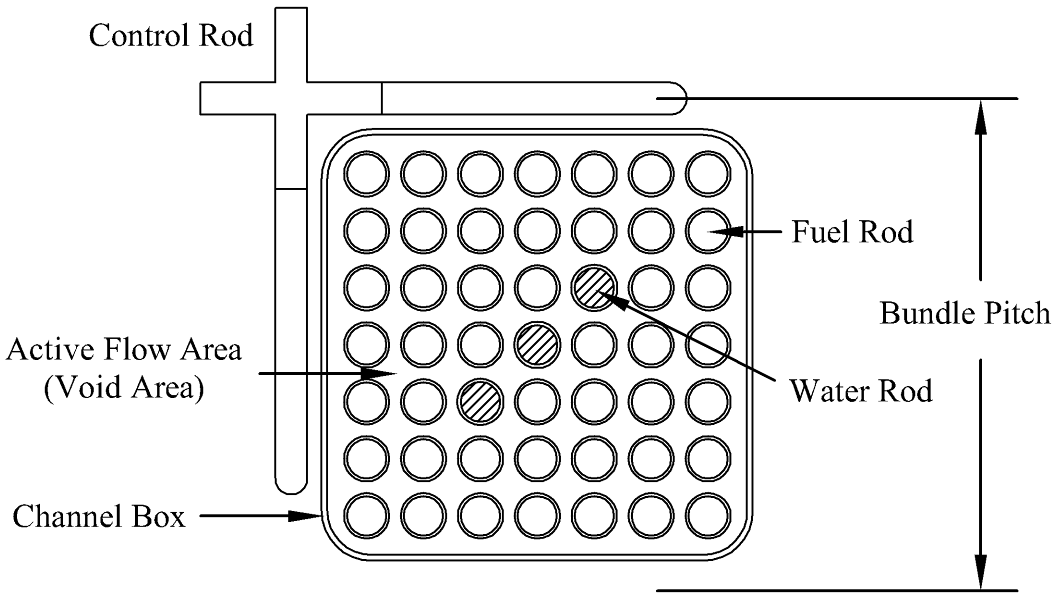
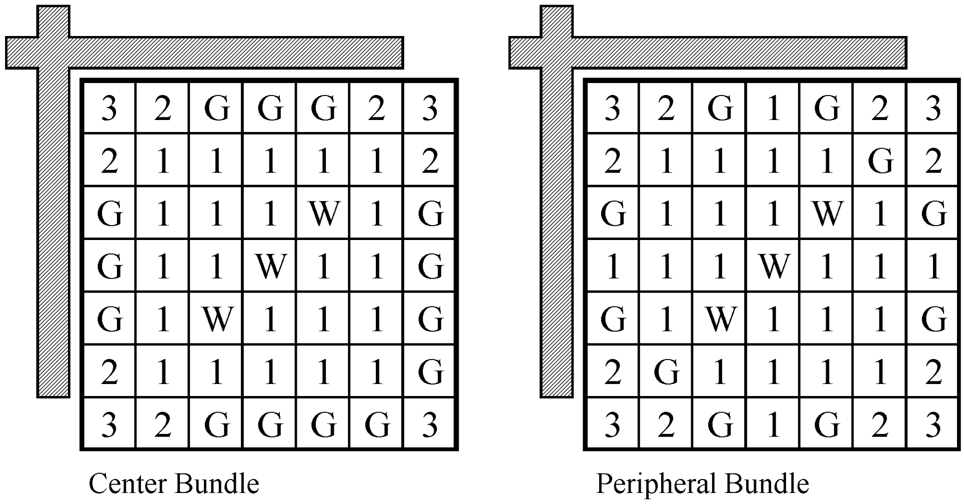
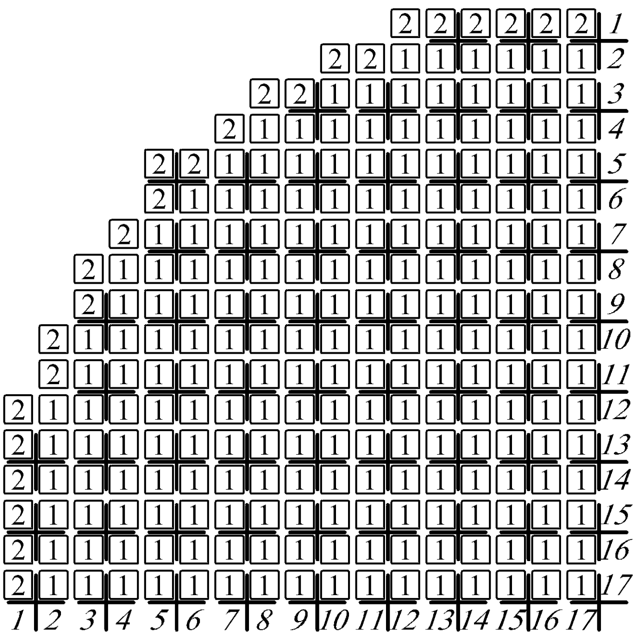


Figure 3. Fuel bundle horizontal view



1 – 3	UO_2 Rod	^{235}U/U 1: 19.9wt% 2: 15.0wt% 3: 8.0wt% (axial enrichment distribution: uniform)
G	$UO_2 + Gd_2O_3$ Rod	Gd_2O_3: 3.0wt% - 14.0wt% ^{235}U/U: 15.0wt% - 19.9wt% (axial distribution Gd_2O_3: 2or3region UO_2: uniform)
W	Water Rod	
Bundle average enrichment		Center Bundle: 17.9wt% Peripheral Bundle: 18.0wt%

Figure 4. Bundle nuclear design



1 Center Bundle 856
2 Peripheral Bundle 100

Figure 5. Bundle loading pattern

						0.0	0.0	0.1
				0.0	4.5	0.0	1.5	0.0
		1.6	1.5	4.5	3.0	3.7	0.0	6.0
		1.5	4.5	4.5	3.0	0.0	4.5	3.0
	0.0	4.5	4.5	4.5	0.0	6.0	4.6	4.5
	4.5	3.0	3.0	0.0	4.5	4.5	3.0	0.0
0.0	0.0	3.7	0.0	6.0	4.5	6.0	0.0	6.0
0.0	1.5	0.0	4.5	4.6	3.0	0.0	4.6	4.6
0.1	0.0	6.0	3.0	4.5	0.0	6.0	4.6	4.5

Figure 6. Control rod residence time (year)

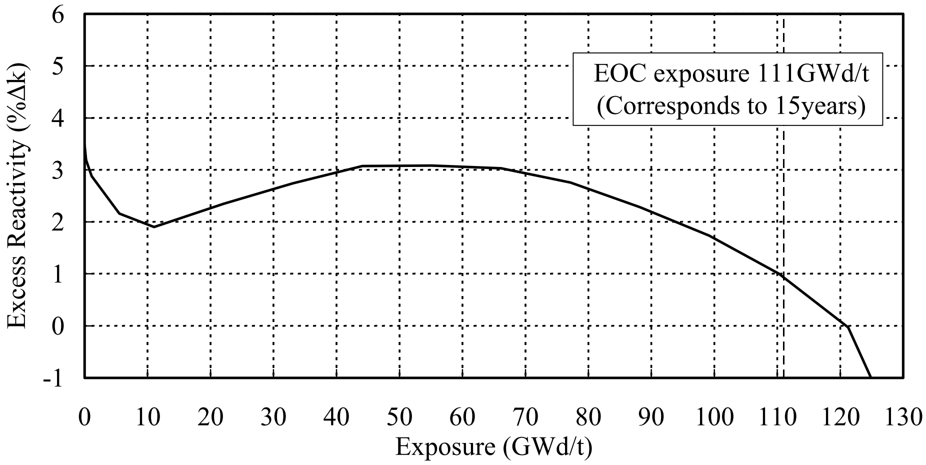


Figure 7. Excess reactivity

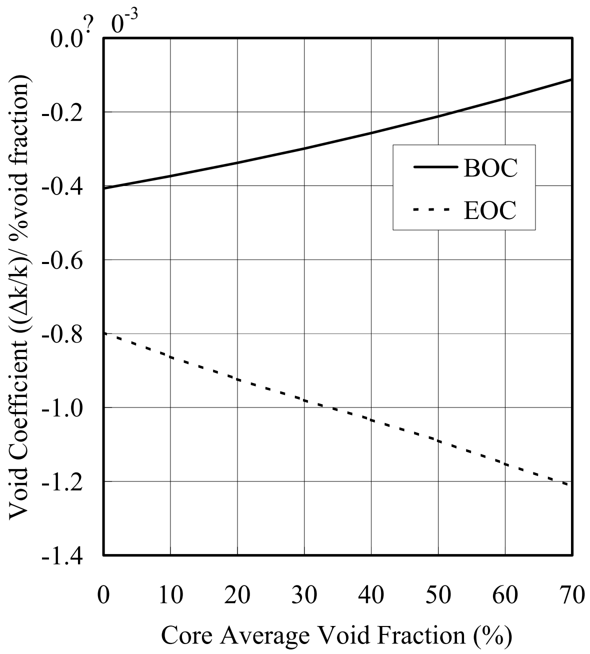


Figure 8. Void reactivity coefficient

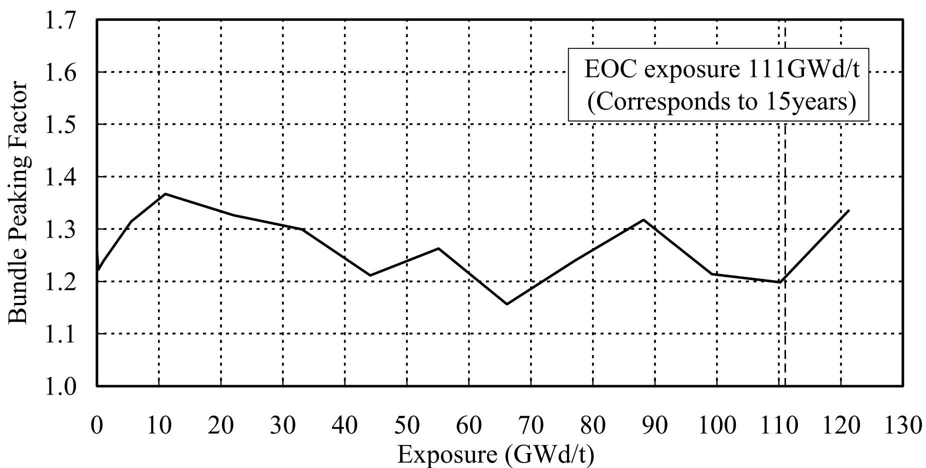
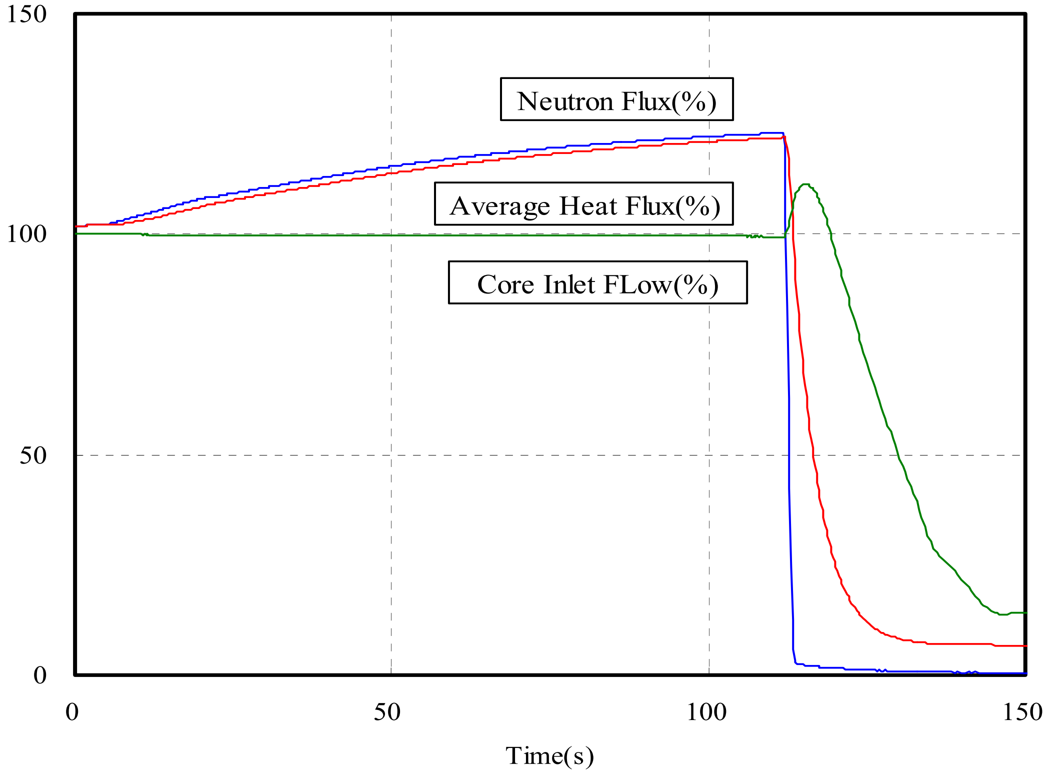


Figure 9. Bundle peaking factor



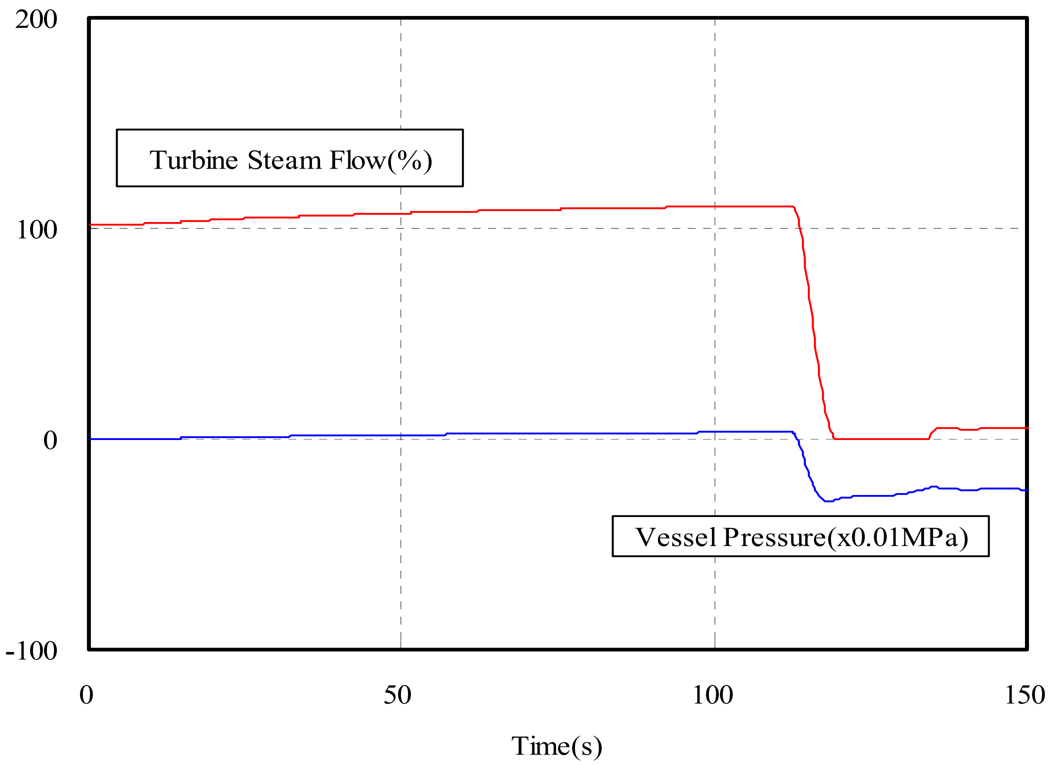
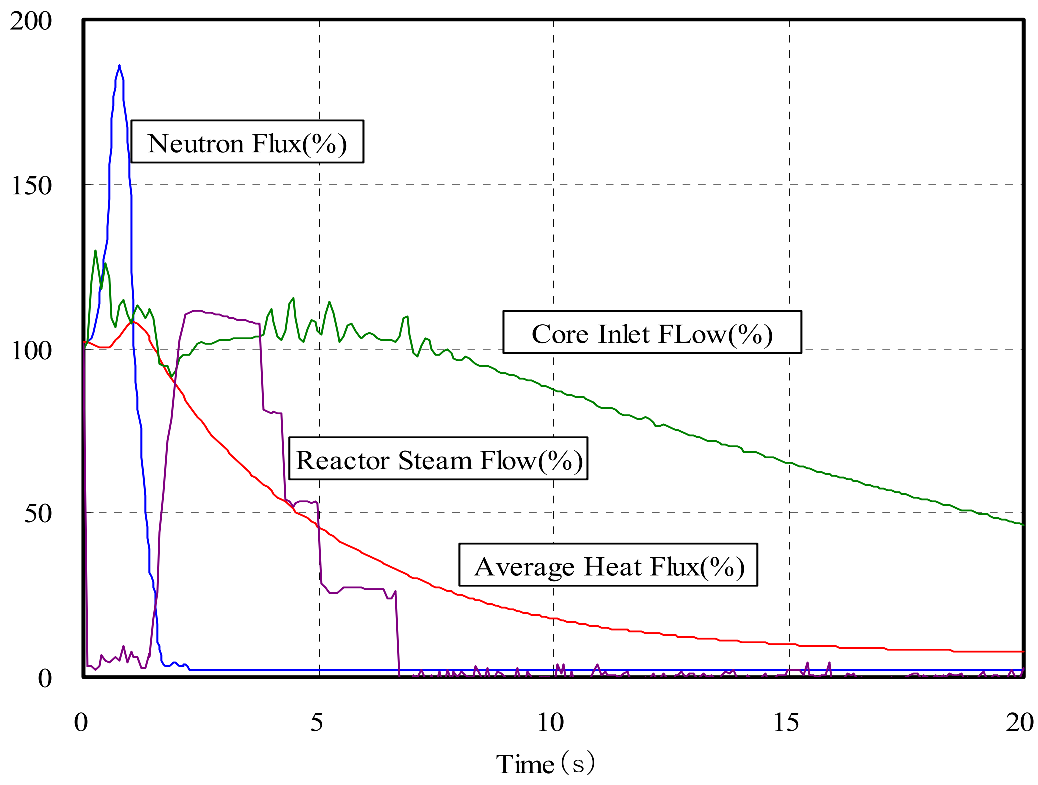


Figure 10. Loss of feedwater heating



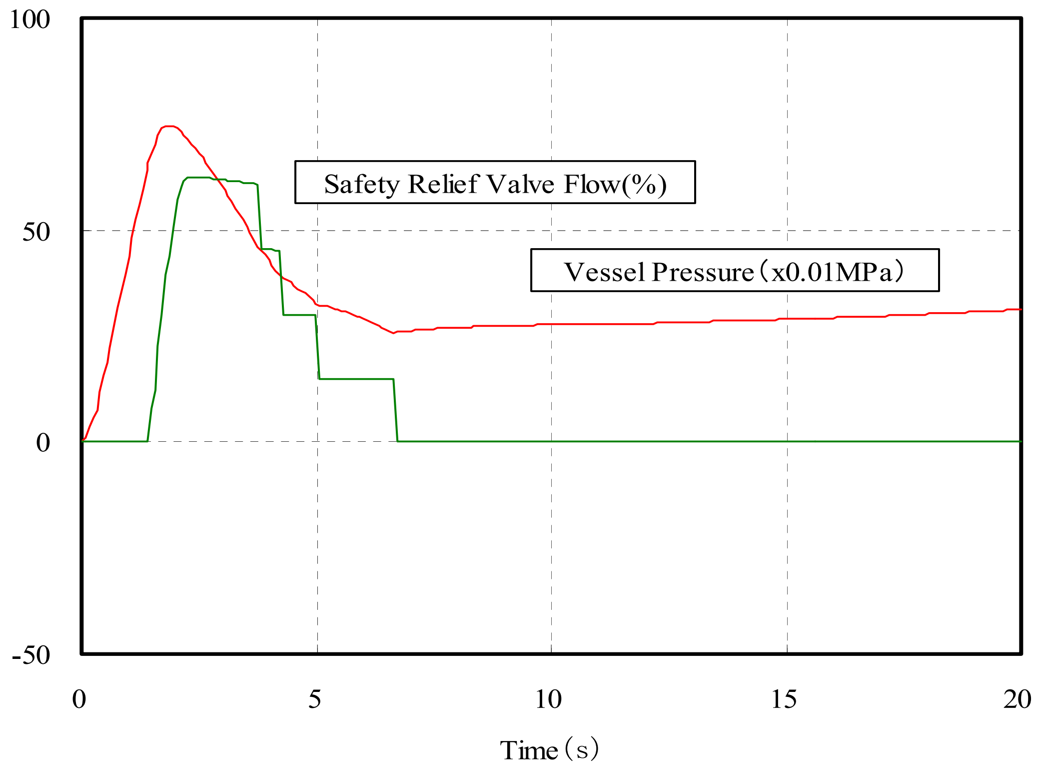


Figure 11. Generator Load Rejection with turbine bypass valve failure