BASIC EVALUATION ON NUCLEAR CHARACTERISTICS OF BWR HIGH BURNUP MOX FUEL AND CORE

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Abstract

MOX fuel will be used in existing commercial BWR cores as a part of reload fuels with equivalent operability, safety and economy to UO_2 fuel in Japan. The design concept should be compatible with UO_2 fuel design. High burnup UO_2 fuels are being developed and commercialized step by step. The MOX fuel planned to be introduced in around year 2000 will use the same hardware as UO_2 8 x 8 array fuel developed for a second step of UO_2 high burnup fuel. The target discharge exposure of this MOX fuel is about 33 GWd/t. And the loading fraction of MOX fuel is approximately one-third in an equilibrium core. On the other hand, it becomes necessary to minimize a number of MOX fuels and plants utilizing MOX fuel, mainly due to the fuel economy, handling cost and inspection cost in site. For the above reasons, it is needed to develop a high burnup MOX fuel containing much Pu and a core with a large amount of MOX fuels. The purpose of this study is to evaluate basic nuclear fuel and core characteristics of BWR high burnup MOX fuel with batch average exposure of about 39.5 GWd/t using 9 x 9 array fuel. The loading fraction of MOX fuel in the core is within a range of about 50% to 100%. Also the influence of Pu isotopic composition fluctuations and Pu-241 decay upon nuclear characteristics are studied.

1. INTRODUCTION

We have been studying MOX fuel which can be applied to existing commercial BWR cores as a part of reload fuels. We have established three fundamental policies on the MOX fuel design from operability, safety and economy points of view.

(1) to maintain compatibility with UO_2 fuel
(2) to meet same safety design criteria as UO_2 fuel
(3) to adopt same hardware as UO_2 fuel

Accordingly, a design concept of MOX fuel should be compatible with UO_2 fuel design. We describe the current status on our recent BWR UO_2 fuel developments and relationship between UO_2 and MOX fuel design development in section 2.

On the other hand, the needs to decrease a number of MOX fuel bundles and plants introducing MOX fuel will increase more and more in future. Because a amount of MOX fuels strongly affects the costs of fabrication and transportation. Also, an introduction of MOX fuel will need to install new equipment for handling and inspection and safeguard in the plant site. Considering these situations, it is important to develop higher burnup MOX fuel containing more Pu and a core with a larger amount of MOX fuels.

The purpose of this study is to make clear the feasibility of high burnup MOX fuel and core through nuclear characteristics evaluations. The next target exposure of the MOX fuel is about 39.5 GWd/t, and the fuel hardware is 9 x 9 array fuel, which has been developed for a third step of high burnup UO_2 fuel. The loading fraction of MOX fuel in the core is about 50% to

100%. Both the discharge exposure and MOX fuel loading fraction in the core are larger than those of the 8 x 8 MOX fuel and core.

The nuclear design has been performed on 9 x 9 MOX fuel. One design example of the MOX fuel is made, and the core characteristics are evaluated on equilibrium cores in 1100 MWe BWR/5 plant.

Larger Pu inventory in a MOX fuel and larger loading fraction of MOX fuel in a core will increase the effects of Pu isotopic composition fluctuations and Pu-241 decay upon nuclear characteristics. So such influences were also studied.

2. STATUS OF UO_2 AND MOX FUEL DEVELOPMENTS

The status of high burnup UO_2 fuel developments[1] is shown in Table I. These fuels have been developed and commercialized in stepwise manner to improve fuel cycle cost and decrease amounts of spent fuel. They are named high burnup STEP-1, STEP-2, STEP-3 fuel respectively and are applicable in current BWR plants. STEP-1 and STEP-2 fuel with 8 x 8 array have been introduced, while STEP-3 fuel with 9 x 9 array is planned to be introduced after about year 2000.

STEP-2 fuels are mainly used in Japanese BWR plants at present. STEP-2 fuel is designed to achieve a batch average exposure of about 39.5 GWd/t within a maximum assembly exposure of 50 GWd/t. STEP-2 fuel is composed of sixty zirconium liner fuel rods and one large central water rod.

At a first batch-size introduction of MOX fuel to BWR, STEP-2 fuel hardware will be adopted from standpoints of reliability and compatibility with existing UO_2 fuels. We have developed the design of this type of MOX fuel. The target discharge exposure of this MOX fuel

Table I Development Step of High Burnup UO_2 and MOX Fuel

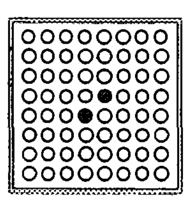
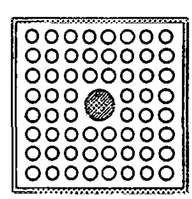
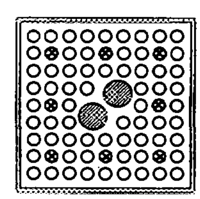
UO_2 fuel	Step	STEP−I	STEP−II	STEP−III
	Batch Average Exposure (GWd/t)	33	39.5	45
	Max Assembly Exposure (GWd/t)	40	50	55
	Bundle Average U^{235} enrichment (w/o)	~3.0	~3.4	~3.7
Fuel Lattice Design		 · 8x8 Array · 2 Water Rods	 · 8x8 Array · 1 Large Water Rod	 · 9x9 Array · 2 Large Water Rods · 8 Part Length Rods
MOX fuel	Step	−	I	II
	Batch Assembly Exposure (GWd/t)	−	33	~39.5
	Max Bundle Average Exposure (GWd/t)	−	40	~50

Table II Summary of Core Characteristics

Item	50% MOX CORE	100% MOX CORE	STEP-3 UO_2 CORE	Operational Limit
Min. Shut Down Margin (%Δk)	2.0	2.8	3.1	>1.0%Δk
Max. Linear Heat Generation Rate (kW/m)	40	39	38	<44kW/m
Min. Critical Power Ratio	1.45	1.45	1.47	>1.23
MOX fuel batch average exposure (GWd/t)	39.8	40.2	–	(Target) 39.5GWd/t
MOX fuel max. assembly exposure (GWd/t)	41.7	46.0	–	<50GWd/t

Table III Summary of Safety Parameters

Item	50% MOX CORE	100% MOX CORE	STEP-3 UO_2 CORE	note
Static Void Coefficient (Relative)	1.08	1.17	1.0 (base)	at EOC, 40% void fraction
Dynamic Void Coefficient (Relative)	1.19	1.44	1.0 (base)	at EOC, 40% void fraction
Doppler Coefficient (Relative)	1.005	1.01	1.0 (base)	at EOC, Cold
Delayed Neutron fraction (%)	0.48	0.43	0.53	at EOC

is about 33 GWd/t, and the loading fraction of the MOX fuels is approximately one-third in an equilibrium core. This core meets all design and safety criteria and w as very similar to that of UO_2 fuel core.

We are interested in the MOX fuel and core design after STEP-3 fuel will have succeeded to STEP-2 fuel. STEP-3 UO_2 fuel is aimed at increasing burnup to about 45 GWd/t as a batch averaged exposure within a maximum assembly exposure of 55 GWd/t. STEP-3 fuel has sixty-six full length rods and eight partial length rods and two large central water rods within a 9 x 9 array. This configuration has been optimized in order to maintain performance at a higher burnup.

We think also a next high burnup MOX fuel will prefer to adopt the STEP-3 fuel hardware in order to have a compatibility with UO_2 fuel and core. So we expect that a development step of high burnup MOX fuel design will be like as shown in Table I . The target exposure of this MOX fuel using STEP-3 hardware is tentatively set to about 39.5 GWd/t under a principal of stepwise manner, which is lower than that of STEP-3 UO_2 fuel.

3. HIGH BURNUP MOX FUEL AND CORE

One design example of MOX fuel was made. The Pu inventory is determined to be able to achieve a target discharge exposure of 39.5 GWd/t. Fuel nuclear calculations were performed by using TGBLA[2] code, which is BWR fuel lattice physics code. Two MOX cores of different MOX fuel loading fractions were studied on a typical 1,100 MWe (3,293 MWt) BWR/5 plant. Core design and performance calculations were performed by LOGOS[3] code, which is three dimensional BWR core physics simulator. A weight fraction of Pu fissile in Pu used here is 67% as a reference.

3.1 Nuclear Fuel Design Concept

The nuclear design of MOX fuel was made. Pu inventory is considered to be as large as possible. Generally, BWR fuel includes several gadolinia fuel rods (UO_2-Gd_2O_3) in order to suppress an excess reactivity at the beginning of life (BOL). MOX fuel also must have them. But in this study it is not allowed to use PuO_2-Gd_2O_3 rods. Accordingly, increasing gadolinia fuel rods in the bundle leads to fewer Pu inventory. Number of gadolinia fuel rods must be optimized between Pu inventory and allowable reactivity at BOL. The optimized number of gadolinia fuel rods is sixteen in this design.

BWR fuel is composed of several different enrichment fuel rods. An enrichment distribution is established to make a local power distribution flat.

The number of different enrichment types must be reduced as few as possible from a fabrication standpoint under an acceptable local power peaking factor. There are four fuel types of different Pu enrichment in this design. Outer rods are relatively low Pu enrichment and inner rods are high.

A matrix blended with PuO_2 is depleted uranium. Gadolinia is contained in enriched uranium fuel rods.

K-infinity comparison among this MOX fuel, STEP-2 and STEP-3 UO_2 fuel is shown in Fig. 1. Reactivity of MOX fuel is established to be same K-infinity as STEP-2 UO_2 fuel at exposure 25 GWd/t, which corresponds to an average exposure at the end of cycle (EOC) of STEP-2 fuel equilibrium core achieving an average exposure of 39.5 GWd/t.

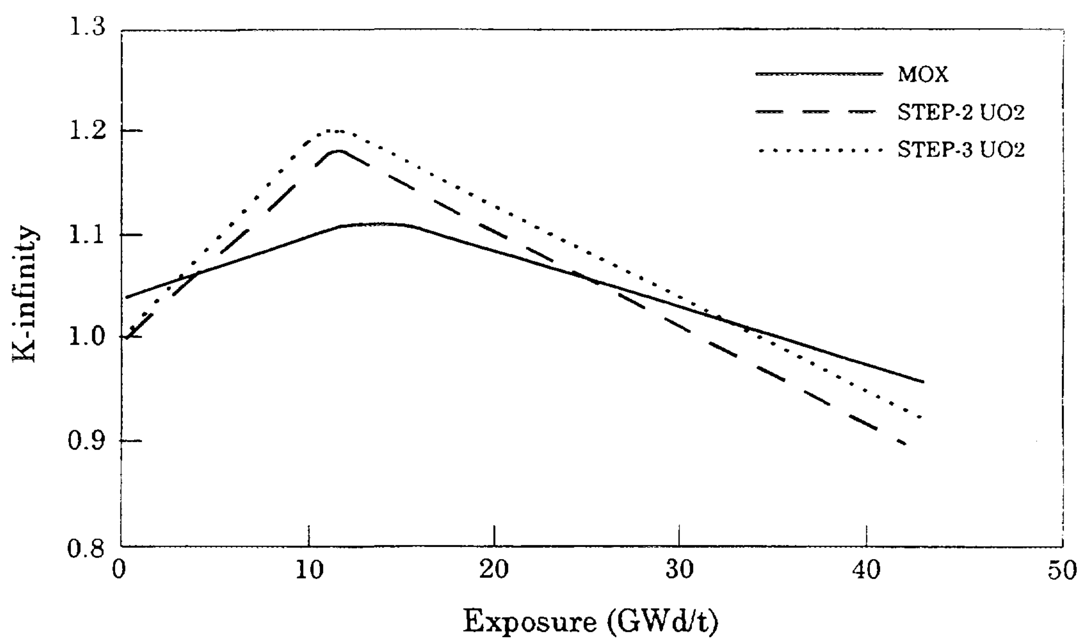


FIG. 1. K-Infinity comparison among MOX, STEP-2 & STEP-3 UO_2 Fuel

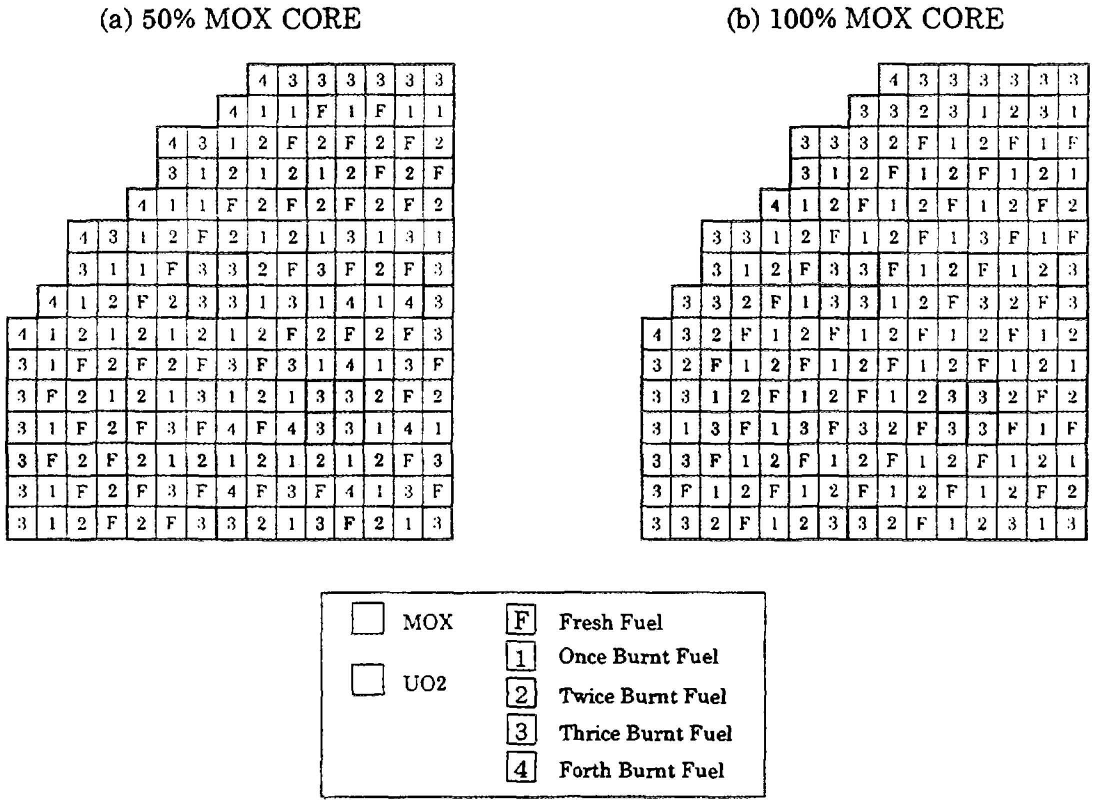


FIG. 2. Fuel Loading Patterns

3.2 Core Design Concept and Core Characteristics

Two MOX cores of different MOX fuel loading fraction were studied. One is the mixed core of the MOX and STEP-3 UO_2 fuel, and the loading fraction of MOX fuel is about 50%. Another is 100% MOX fuels loading core. Both fuel loading patterns are shown in Fig. 2. The cores are designed under the following plant and operating conditions.

- Plant and operating conditions
  - plant type — BWR/5
  - electric power — 1,100 MWe
  - core rated thermal power — 3,293 MW
  - core rated flow — 483,000 t/h
  - number of bundles — 764
  - number of control rods — 185 rods
  - cycle length — 13 months

(a) 50% MOX fuel loading core

The total number of MOX fuels in the equilibrium cycle core is 352 bundles including fresh and burnt fuels. The rest are STEP-3 UO_2 fuels of 412 bundles. The refueling batch size of MOX fuels is 88 bundles per a cycle, then the batch number is 4.0. The refueling batch size of UO_2 fuels is 88 bundles, the batch number is 4.7. Therefore the MOX fuels can achieve substantially the target average discharge exposure of 39.5 GWd/t, and STEP-3 UO_2 fuels can also achieve that of 45 GWd/t. Meanwhile the fuel loading concept are the following, basically same as adopted in current UO_2 core.

(1) to scatter MOX fuels and UO_2 fuels uniformly in the core in order to flatten radial power distribution

(2) to load higher burnt fuels at the most peripheral in the core in order to reduce a neutron leakage

(3) to load higher burnt UO_2 fuels in Control Cell, which is composed of four bundles at the location of control rod insertion during a power operation

(b) 100% MOX fuel loading core

The core is composed of MOX fuels only. The refueling batch size of MOX fuels a cycle is 188 bundles, then the batch number is about 4.1. The MOX fuels can achieve substantially the target average discharge exposure of 39.5 GWd/t under this refueling plan. The core configuration concept is almost same as those of 50% MOX fuel core except that MOX fuels are loaded in Control Cells.

Calculations on core characteristics for both cores were performed at rated power condition. Main results are shown in Fig. 3 and summarized in Table II. All of Shut-down margin at one control rod stuck condition, MLHGR (Maximum Linear Heat Generation Rate), MCPR (Minimum Critical Power Ratio), which are key parameters for BWR core characteristics, meet each operational limit with margins.

Generally, a MOX core tends to reduce the control rod worth, but the cores have enough shut-down margin. Because the K-infinity peak value of MOX fuel is relatively low compared with that of UO_2 fuel, which cancels control rod worth decrease.

Thermal performances such as MLHGR, MCPR of both MOX cores are fairly good. The thermal performance of 100% MOX fuels core is better than that of 50% MOX core and UO_2 core because of smaller power mismatch and neutron spectrum mismatch between bundles.

3.3 Safety Parameters

Moderator void coefficient, Doppler coefficient and dynamic parameters were evaluated to investigate influences upon a transient and accident behavior of a high burnup MOX fuel and core. The results are summarized in Table III.

Generally a static void coefficient of MOX fuel tends to be more negative compared with that of UO_2 fuel. Consequently increasing a loading fraction of MOX fuel in a core leads to larger core average void coefficient. Dynamic void coefficient taking delayed neutron fraction into consideration is important from transient behavior standpoints. An increase of dynamic void coefficient of MOX core will be larger than that of static void coefficient because of smaller delayed neutron fraction of MOX fuel.

Generally, a transient behavior such as Turbine Trip event will be severe because of larger void coefficient. But, since current BWR has fast speed SCRAM mechanism, void coefficient increase does not affect a operational limit.

Doppler coefficient of MOX fuel is slightly more negative than that of UO_2 fuel. This will moderate a behavior of reactivity initiated accident such as control rod drop accident. A power excursion is suppressed by large Doppler effect, and a fuel enthalpy increase will be in low.

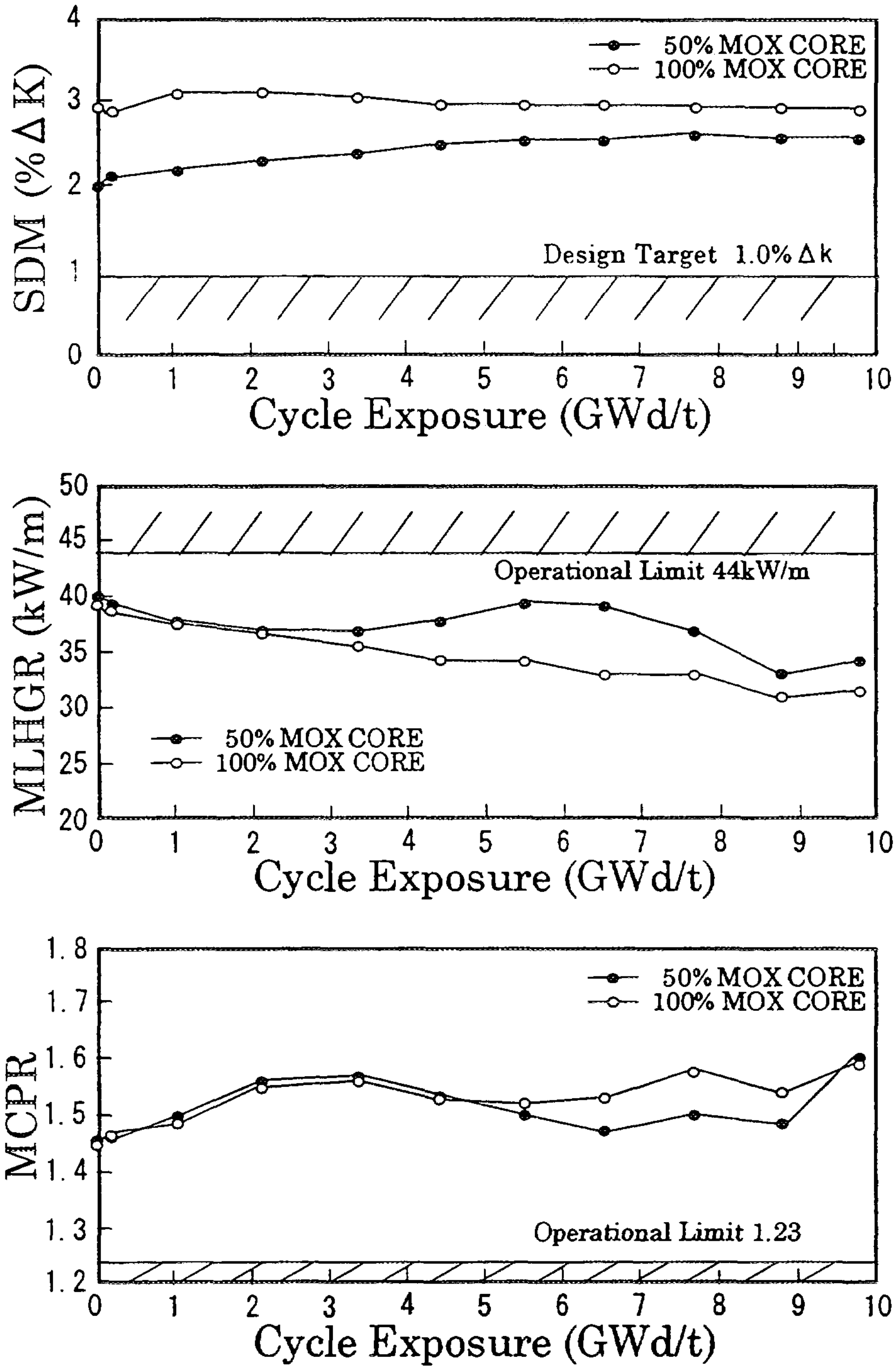


FIG. 3. Core Characteristics

Prompt neutron life time of MOX core is smaller than that of UO_2 core. But it is known that a prompt neutron life time dose not practically affect a transient and accident behavior.

3.4 MOX Fuel and Core Specific Considerations

(a) Influences of Pu isotopic composition

It is expected that an increase of Pu inventory in fuel and core has more influences upon a core characteristics due to a fluctuation of Pu isotopic composition ('Pu vector'). Two Typical MOX fuels with different Pu vector from the reference Pu vector used here were studied. One is higher quality Pu with large fraction of Pu fissile than the reference. Another is lower quality than the reference. Pu contents of these MOX fuels are adjusted to have equivalent reactivity to the reference MOX fuel. Figure 4 shows a relationship between Pu vector and a required Pu inventory or void coefficient of 100% MOX core. This result shows that void coefficients among three kinds of MOX fuel are almost same. It is found that a influence of Pu vector fluctuation is eliminated by adjusting Pu content to achieve equivalent reactivity according to the Pu vector.

(b) Influences of Pu-241 decay

It is also expected that an increase of Pu inventory have more influence upon a core characteristics due to a decay of Pu-241 with half life of 14.4 year, which decays to Am-241. Influence of Pu-241 decay upon core reactivity was studied on 100% MOX core. Figure 5 shows

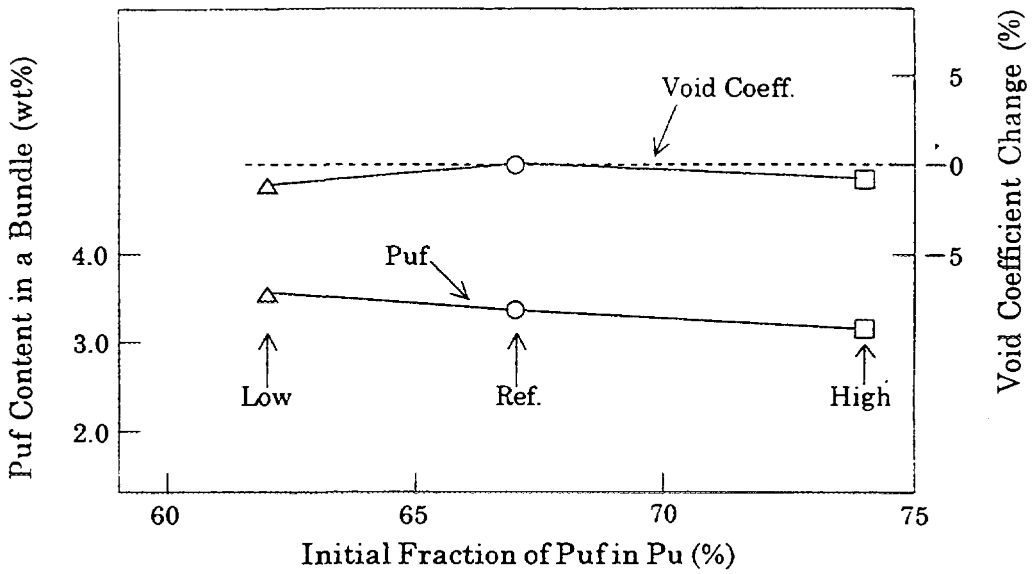


FIG. 4. Relationship between initial fraction of Puf and Pu content, void coefficient

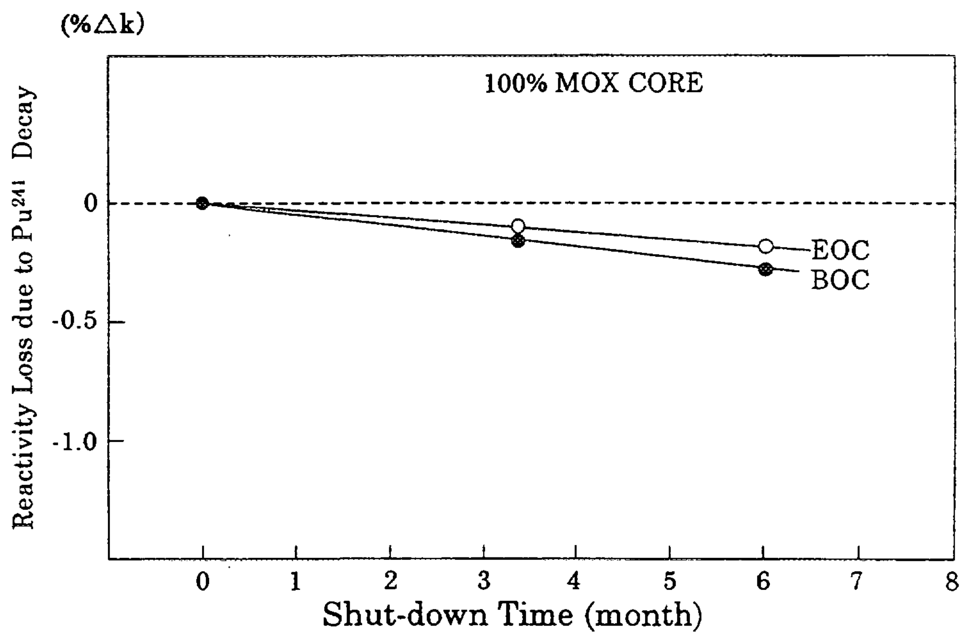


FIG. 5. Relationship between shut-down time during periodic inspection and reactivity loss at BOC and EOC due to Pu^{241} decay

a relationship between a shut-down time during a periodic inspection and reactivity loss at BOC and EOC. A reactivity loss due to a reduction of Pu-241 and a production of Am-241 during a shut-down is proportional to its length and is not negligible in magnitude.

While a reactivity loss at EOC is relatively small compared with that of BOC because of a consumption of Am-241 through burnup, so the effect to a cycle length is not so large in a case of short shut-down time, but it is not negligible in a case of longer shut-down time.

It must be taken account of a Pu-241 decay effect exactly in a nuclear characteristics evaluation for MOX fuel and core.

The above LOGOS code can treat the effect of Pu-241 decay on reactivity during operation and shut-down.

4. CONCLUSION

High burnup MOX fuel and core with a large amount of MOX fuels were studied. The following were found through nuclear characteristics evaluations.

(1) 100% MOX fuels loading core with a batch average exposure of 39.5 GWd/t is feasible from core characteristics standpoint in a typical 1,100 MWe BWR/5 plant.

(2) 100% MOX core has better core characteristics than the mixed core of MOX and UO_2 fuels because of smaller power mismatch and neutron spectrum mismatch between bundles.

(3) Increasing MOX fuel in a core leads to more negative void coefficient. This generally tends to cause severe on a transient behavior, but this doesn't affect a transient of current BWR with fast speed SCRAM mechanism.

(4) Pu inventory within a bundle is limited by the existence of gadolinia fuel rods in BWR MOX fuel. In order to in.crease Pu inventory further, it will be necessary to permit to use a mixed fuel rod of gadolinia and Pu.

(5) The effect of Pu vector and decay of Pu-241 should be treated for the MOX fuel and core especially with much Pu inventory.

(6) The influence of Pu vector upon a nuclear characteristics is eliminated by adjusting Pu content to have equivalent reactivity according to the Pu vector.

(7) The effect of Pu-241 decay during shut-down under periodic inspection must be considered in nuclear characteristics evaluation to predict a exact core reactivity and performance.

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