HIGH BURN-UP BWR MOX FUEL DESIGN WITH MAXIMIZED PLUTONIUM INVENTORY

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ABSTRACT

A concept of high burn-up (45GWd/mt) MOX fuel design is proposed for BWR (ABWR). It is characterized mainly by three design features: (1) The bundle contains only plutonium and depleted uranium as the fuel material. (2) The depleted uranium rods are placed at the corners and neighboring positions of the bundle. (3) Gadolinia is contained in these depleted uranium rods.

The first advantage of this design is the fuel cycle economy. The plutonium inventory of the bundle and the average enrichment of MOX pellets are very high. And natural uranium and separation work are unnecessary. Thus the manufacturing cost per unit plutonium amount is minimized.

The second advantage is its nuclear performances. To prevent the ΔMCPR increase during some transients by the reduction of delayed neutron fraction, depleted uranium rods are placed near the four corners of the bundle to enhance over-moderation and improve the static void coefficient. This feature also reduces the local peaking factor. Thus both MCPR and its operating limits are improved.

1. INTRODUCTION

Recently first batch reload of MOX fuels was applied in Japan. Their average discharge exposure is 33GWd/mt, which is the same as that of old 8x8 uranium fuel. On the other hand, the uranium fuels loaded together with MOX will be 9x9 design and their discharge exposure is 45GWd/mt. Thus the need to extend the discharge exposure of MOX fuel is very strong to reduce the total costs. The pace of developing high burn-up MOX is accelerated these years.

2. PROBLEM FOR BURN-UP EXTENSION

Current MOX design for Japanese BWR plants employs 8x8 lattice with a large center water rod (see Figure 1). Gadolinia (Gd_2O_3) is mixed into enriched uranium rods which are located in the interior region of the bundle. MOX rods do not include gadolinia, because of the manufacturing cost requirement and the lack of irradiation experience.

In extending the discharge exposure of MOX fuels to the same level (45GWd/mt) of uranium fuels, use of 9x9 lattice is recommended to improve the margin of maximum linear heat generation rate (MLHGR). In addition, we have two more major problems as described below.

(1) PLUTONIUM CONSUMPTION RATE

To extend discharge exposure of MOX bundle, it is necessary to increase the bundle enrichment. Naturally the number of gadolinia rods should be increased and the number of MOX rods will be decreased to the contrary. A typical design of 9x9 MOX fuel with 13 months cycle operation and the discharge exposure of 45GWd/mt is shown in Figure 2, which has 18 gadolinia rods (26% of total heavy metal weight) whereas the current 8x8 MOX design has 12 (20% of total heavy metal weight). Consequently the total plutonium inventories of these two designs are almost the same. In this comparison, the number of reload MOX bundles is reduced by 27% in inverse proportion to discharge exposure. Therefore the annual consumption rate of plutonium is reduced by 27%. Once reprocessing of spent fuels starts operation to generate plutonium in Japan, this becomes a serious problem from the non-proliferation viewpoint.

(2) VOID COEFFICIENT

If we could settle the problem stated above, it in turn means the weight fraction of U235 in a bundle is decreased, and the dynamic void coefficient becomes more negative with smaller delayed neutron fraction. This has an effect to increase ΔMCPR during pressure increasing transients and MCPR operating limits, and also to deteriorate core stability.

3. IMPROVED MOX FUEL DESIGN

To settle all these problems simultaneously, we propose a new MOX design concept. Figure 3 shows an example designed on the conditions in Table I. This concept is characterized mainly by three design features.

(1) CORNER GD

In the improved design, gadolinia rods are located in the corner of the bundle. Since the thermal neutron flux is very high near the bundle corner, gadolinia rods at this region have about four times larger reactivity worth than that located in the bundle interior region. As the results, only four main gadolinia rods, which contain more than 6wt% gadolinia, are necessary to control the excess reactivity during the whole cycle. The other four rods of low gadolinia concentration in Figure 3 are not essential but provide the fine adjustment of the reactivity and the power shape at the beginning of cycle. Totally we can use 62 MOX rods in this design whereas the design in Figure 2 has only 56.

The corner Gd design has another effect to flatten the bundle cross sectional power distribution and improve the thermal margin.

(2) ENRICHED URANIUM FREE

In order to increase plutonium inventory in a bundle, depleted uranium is used as the matrix of all fuel rods including Gd and UO_2 rods. Accordingly the plutonium inventory is theoretically maximum under a given design condition, e.g. average discharge exposure, cycle length, plutonium isotopic composition, lattice, etc..

Another advantage of this feature is that there is no anxiety about the pellet-clad interaction and internal pressure increase of gadolinia rods. Usually we should very carefully suppress the LHGR of gadolinia rods and fuel rod temperature because of low thermal conductivity of gadolinia pellets. But in this design the LHGR of gadolinia rods is always kept low enough even if they are placed at the corner of a bundle.

The last advantage of this feature is the fuel cycle cost benefit. That is, using no enriched uranium, the costs of natural uranium and separation work are eliminated.

(3) DEPLETED URANIUM RODS

In the basic concept of proposed design, fuel rods adjacent to corner rods are composed of depleted uranium and include no plutonium.   This concept has following advantages.

Reduction of void coefficient

The H/HM (hydrogen to heavy metal ratio) is very large in the region near the corner of a bundle. Reducing the amount of fissile as low as possible at this region, a big pool of thermal neutron is formed, which reduces the void coefficient. Thus we can compensate for the deterioration of dynamic void coefficient caused by the elimination of enriched uranium and resultant reduction of delayed neutron fraction.

Increase the plutonium enrichment of MOX rods

It is well known that the manufacturing costs of MOX fuel rods are very high.   Therefore, in order to minimize the number of MOX rods per unit plutonium amount, the plutonium enrichment of MOX fuel rods should be increased as high as the thermal and nuclear characteristics of the bundle allow.

So one of the role of depleted uranium rods in this design is to raise the plutonium enrichment of MOX rods.   Their optimum positions are near the corner, because it is difficult to put there high enriched MOX rods under the restriction of thermal margin.

Decrease the number of plutonium enrichment types

The manufacturing cost of MOX fuel has deep relationship with the capacity factor of the factory. Thus the number of plutonium enrichment types should be minimized because it takes several days to clean up the manufacturing line when the pellet type changes. Excluding MOX rods from corner region, we have no use for very low enrichment MOX rods and can reduce the number of pellet types.

Local peaking factor at cold condition

In the reactivity insertion event during start-up, the local peaking factor has a significant effect on the resultant fuel pellet enthalpy. Usually it is considerably larger than that in hot operation, because the peaking of the corner rod increases considerably.   For the fuel design in Figure 3, the hot local peaking is 1.39 and the cold local peaking is 1.40. That is, this design concept has no enriched rod near the corner, and thus it suppresses the local peaking increase and decreases the peak pellet enthalpy during reactivity insertion event.

4. CORE PERFORMANCE

ABWR equilibrium cycle cores are designed using three types of MOX fuels in Figures 1, 2 and 3. The nuclear characteristics of unit fuel assembly are calculated by BWR lattice physics code, TGBLA[(1)], and the core performances are calculated by BWR core simulator, LOGOS[(2)]. The core performances are shown in Table 2.

Comparing with the current (8x8) and standard (9x9) MOX design, the improved (9x9) MOX fuel has about 50% larger plutonium inventory, although the nuclear and thermal margins, and dynamic void coefficient are almost equal and sufficient.

5. CONCLUSIONS

Comparing with conventional MOX design, the proposed design concept of high burn-up MOX fuel has about 50% larger plutonium inventory per bundle and reduces manufacturing costs by elimination of enriched uranium and simplified nuclear design, although the dynamic void coefficient is same and the operating margins are sufficient.

REFERENCES

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Table I.　Core Design Conditions

Plant	1350MWe ABWR
Core Power density	50.6kW/l
Cycle length	13 months operation
Capacity factor	100%
MOX fuel loading fraction	100%
Plutonium composition	(Pu-fissile)/(Total Pu) = 0.68
MOX pellet matrix	Depleted uranium

Table II.　Core Performances

Lattice	8x8	9x9	
MOX design concept	Current (Figure 1)	Standard (Figure 2)	Improved (Figure 3)
Discharge exposure (GWd/mt)	33	45	45
Number of reload batch	3.0	4.2	4.2
Total plutonium weight (kg/bundle)	7.1	7.3	10.6
Total fissile enrichment (wt%)	3.9	4.4	4.6
Pu-fissile enrichment (wt%)	2.9	3.0	4.4
Annual Pu consumption* (t-Puf)	1.1	0.8	1.2
Shut-down margin (%Δk)	> 3.7	> 3.1	> 3.5
MLHGR margin (%)	> 8	> 13	> 14
MCPR margin (%)	> 21	> 17	> 14
Delayed neutron fraction	(Base)	+2%	-8%
Void coefficient			
Static	(Base)	+2%	-8%
Dynamic	(Base)	0%	0%

* Two months are assumed for an inspection period.

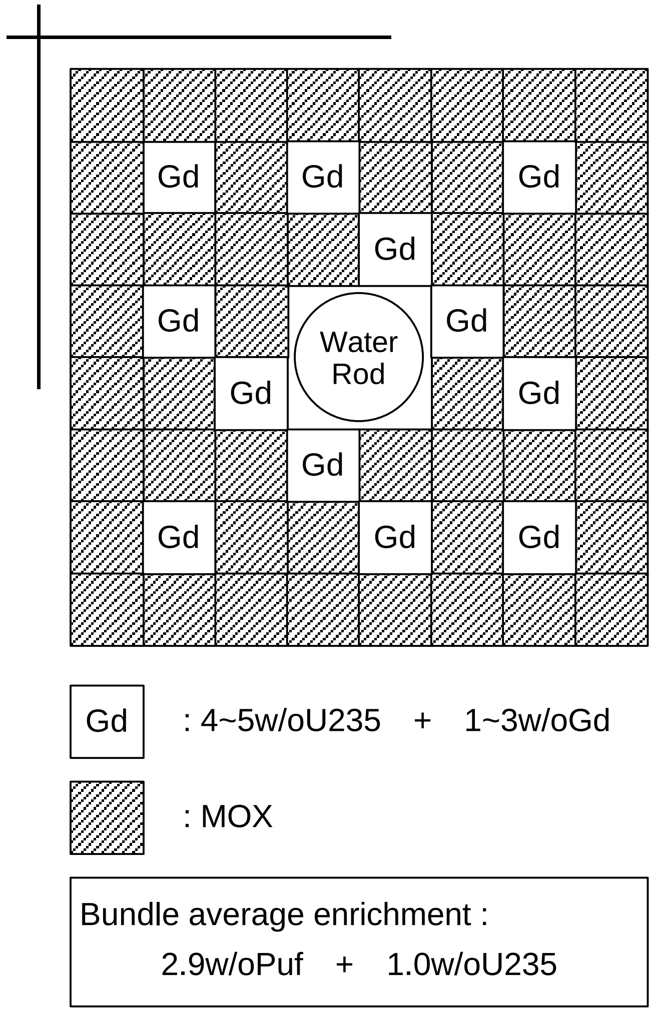


Figure 1. Current 8x8 MOX fuel design

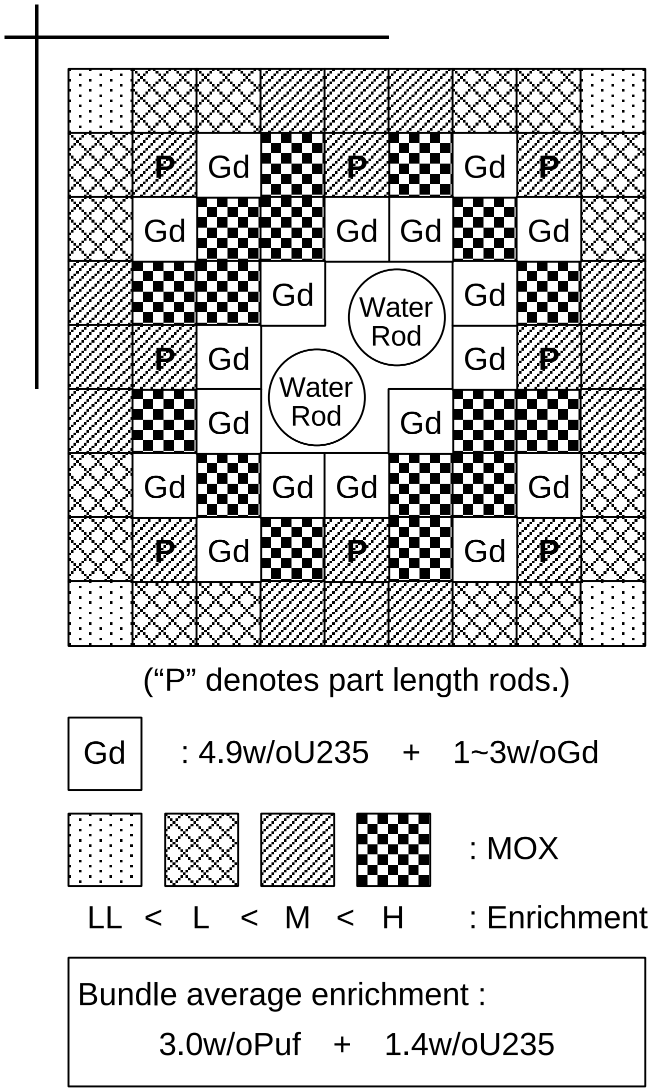
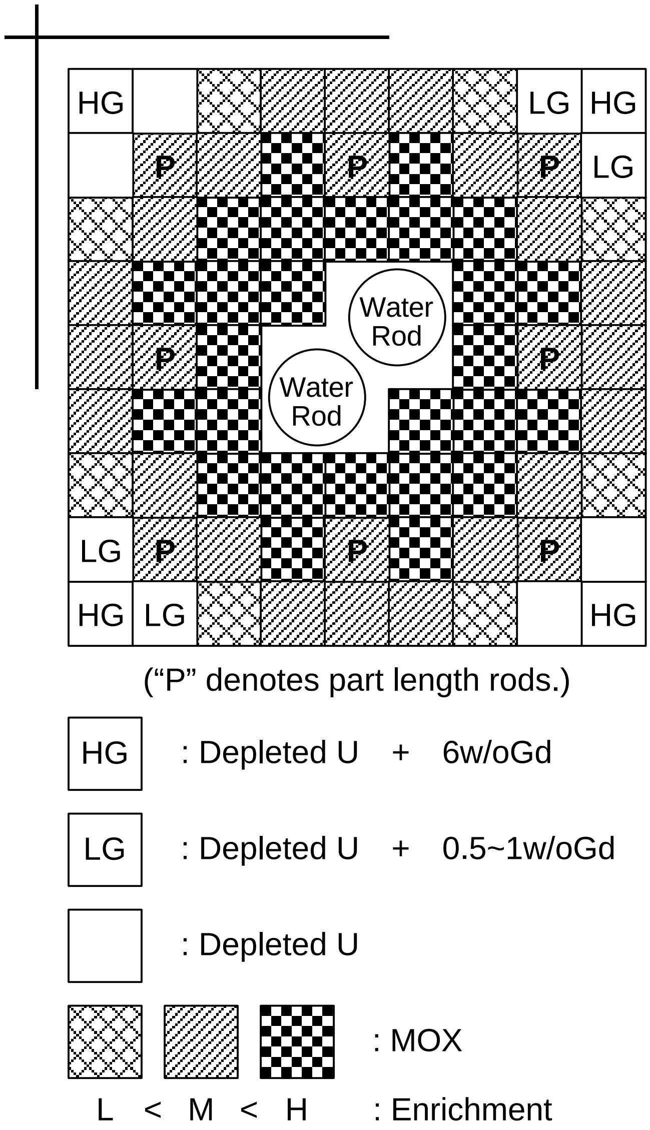


Figure 2. Standard 9x9 MOX Fuel Design



Bundle average enrichment :
Depleted U + 4.4w/oPuf

Figure 3. Improved 9x9 MOX Fuel Design