Development of Cask Basket for High Burnup and MOX Spent Fuels

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INTRODUCTION

At present, in Light Water Reactor the shift to high burnup of nuclear fuel is going on, and also the use of MOX fuel is planned (e.g., Ichikawa 1993). These high burnup and MOX spent fuels have higher radioactivity, higher decay heat, and higher emission of gamma-ray and neutron. So it is necessary that a new cask and cask basket be developed. The cask basket is very important to keep subcriticality of a system of spent fuels and remove decay heat. Using a single superior material which fulfills the requirements of neutron absorption, heat removal, and mechanical strength, we can design a simple basket structure and reduce costs. We investigated some structural materials which may or may not contain a high level of boron or enriched boron, such as (1) Borated stainless steel (S.S.), (2) Borated aluminum alloy, and (3) Composite material (three-layered clad plate composed of B-S.S./Cu/B-S.S. structure).

PROBLEM OF CASK BASKET STORING HIGH BURNUP AND MOX SPENT FUELS

Characteristics of High Burnup and MOX Spent Fuels

Table 1 shows specifications of high burnup and MOX spent fuels for this study (e.g., Takahashi et al. 1994). We calculated decay heat and radioactivity of these spent fuels by ORIGEN-2. In this report, a target of the study is spent fuel of PWR of which decay heat and radioactivity strength per weight are higher than spent fuel of BWR. Figure 1 compares decay heat and radioactivity of these spent fuels and a current PWR spent fuel with a burnup of 48 GWd/tU (e.g., Saegusa 1994). The neutron emissivity of the MOX spent fuel is about 18 times higher than the current PWR spent fuel, so it is necessary to develop neutron shielding design of the cask body.

Problem of Cask Baskets

At present, cask baskets are mainly made of stainless steel or aluminum alloy. In order to improve subcriticality of the cask baskets, the above structural materials may be added by about 1 wt% boron or may be used with neutron absorbers at the same time. For neutron absorbers, sintered alloy mixed with B_4C powder and aluminum powder or copper powder are usually used. But the structure of the cask basket becomes complicated. So we investigated to use materials which have a higher neutron absorption ability, heat removal and mechanical strength for the structural material of a cask basket. The structure of a cask basket becomes simpler by using these materials, and manufacturing costs may be reduced and reliability may be improved.

STRUCTURAL MATERIAL WITH HIGH NEUTRON ABSORPTION ABILITY

We have been using stainless steel or aluminum alloy which contains up to 1 wt% boron as the structural material with neutron absorption ability. By high burnup and MOX spent fuels, boron contents of the material may have to be increased to more than 1 wt%. If requirements of neutron absorption still cannot be met, enriched boron instead of natural boron may be used.

In addition, there are requirements for heat removal and mechanical strength of these materials. Generally speaking, improvement of heat removal is necessary for stainless steel, and improvement of mechanical strength is necessary for aluminum alloy. In borated stainless steel (B-S.S.), improvement of heat removal may be expected by use of a composite material made of borated stainless steel and copper (three-layered structure of B-S.S./Cu/B-S.S.).

Borated Stainless Steel

Borated stainless steel (B-S.S.) has been used as a shielding material, a control rod material, etc., and borated stainless steel which contains up to about 2 wt% boron has been studied well (e.g., Yamamoto et al. 1990, Stephens et al. 1992, Lomburdo 1955). The reason why borated stainless steel contained more than 1 wt% boron was not used for the cask basket is because of deterioration of the processing property. But recently, borated stainless steel containing up to 1.4 wt% boron can be manufactured by a special rolling process in which a temperature drop is small during rolling, and plating of about 4 meters for the cask basket can be manufactured (e.g., Yamamoto and Seki 1989). Therefore, warrantable value of boron contents may be 1.3 wt%. Also we investigated the cask basket design which has higher performance of heat removal, because of the heat transfer characteristics of borated stainless steel cannot be changed.

Borated Aluminum Alloy

Although borated aluminum alloy has low mechanical strength, it may satisfy the requirement of neutron absorption, high thermal conductivity, and superior corrosion resistance. Giving priority to the mechanical strength, A6061 alloy (Al-Mg-Si system) was selected for this study. The requirement of neutron absorption may be satisfied by use of enriched boron.

Composite Material (B-S.S./Cu/B-S.S.)

As the structural material for the cask basket, a composite material made of borated stainless steel and copper (B-S.S./Cu/B-S.S.) manufactured by hot rolling was selected. Borated stainless steel has high mechanical strength and performance of neutron absorption, and copper has high-performance heat removal. Moreover, the thickness ratio of borated stainless steel and copper can be changed as appropriate by the requirements.

PERFORMANCE OF CASK BASKETS

Requirement of Subcriticality

Figure 2 shows a cross section of a cask basket made of borated stainless steel 10 mm thick. Figure 3 shows a structure of a cask basket made of borated aluminum alloy 10 mm thick. In regard to these cases, the necessary concentration of ^{10}B which keeps the requirement of subcriticality was analyzed by KENO code. In borated stainless steel, enriched boron which contains 70 wt% ^{10}B must be added to 1.3 wt%. In borated aluminum alloy, enriched boron which contains 60 wt% ^{10}B must be added to 1.0 wt%. In addition, the water gap can influence the requirement of subcriticality. Figure 4 shows the effect of the water gap.

Requirement of Heat Removal

The decay heat of the spent fuel is transferred to the cask body by radiation, heat conduction of gas, and heat conduction of the basket material. The requirement of heat removal was assumed for the PWR fuel cladding temperature of 390 ℃ which keeps the integrity of the fuel claddings for a long time.

In the case of Figure 2, the requirement of heat removal cannot be satisfied for the water gap and the thickness of the borated stainless steel. So the water gap was removed and the thickness of borated stainless steel was increased to 20 mm. But, for requirement of subcriticality, enriched boron which contains 90 wt% ^{10}B must be added to 1.3 wt%. Figure 5 shows this basket structure for high burnup spent fuel.

If we use the composite material for cask basket, the requirement of heat removal can easily be satisfied without decreasing the number of the fuel assembly for storage. Figure 6 shows this basket structure.

Borated aluminum alloy is about 10 times superior to borated stainless steel in heat conductivity. So the cask basket shown in Figure 3 satisfied the requirement of heat removal, although it must use enriched boron as mentioned above.

CONCEPT OF CASK FOR HIGH BURNUP AND MOX SPENT FUELS

Based on the above study, a whole cask design was investigated. The investigated points are the requirement of subcriticality, heat removal, structural strength, shielding efficiency, size, and weight. Table 2 shows the evaluation method and the design criteria.

Table 3 shows the result of the investigation for borated stainless steel. The design with high-performance heat removal was adopted, but the number of the spent fuel assembly per cask could not be increased.

Table 4 shows the result of the investigation of borated aluminum alloy. By adding enriched boron of 60 wt% ^{10}B and providing the water gap, the requirement of subcriticality for high burnup and MOX spent fuels could be satisfied. The cask basket made of borated aluminum alloy has high-performance heat removal.

Table 5 shows the result of the investigation of the composite. In the basket made of the composite material, the number of the spent fuel assembly per cask is more than that of borated stainless steel basket. Further, for providing the water gap, the costly enriched boron was useless.

As a result of the above investigation, the designs of casks and cask baskets which corresponded to high burnup and MOX spent fuels could be specifically indicated.

CONCLUSIONS

Three materials which contain a higher level of boron or enriched boron as the material for a cask basket were investigated. Borated stainless steel has high-performance neutron absorption but has lower thermal conductivity. So the number of spent fuel assembly per cask basket made from it will be decreased by limitation of heat removal. Borated aluminum alloy has higher-performance heat removal. For the requirement of subcriticality, the borated aluminum alloy which contains about 1 wt% boron is inferior to borated stainless steel. But by use of enriched boron and the design with water gaps, it satisfied the subcriticality requirement. In the Composite material (B-S.S./Cu/B-S.S.), copper compensates for thermal conductivity of stainless steel. So we can rationally design cask baskets.

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Table 1. Specifications of High Burnup and MOX Spent Fuels for Study.

Type of Fuels		Initial Enrichment	Burnup(GWd/tU) (ave., max.)	Cooling Time (year)
High Burnup Fuel	PWR	4.7 wt% ^{235}U	49.0, 55.0	5
	BWR	4.3 wt% ^{235}U	49.0, 55.0	5
MOX Fuel	PWR	0.2 wt% ^{235}U, 5.8 wt%Puf	43.0, 48.0	10
	BWR	0.8 wt% ^{235}U, 3.4 wt%Puf	40.0, 50.0	10

Table 2. Evaluation Method and Design Criteria.

Item	Method	Criteria
1) Subcriticality	KENO code, etc.	On handling in water pool keff + 3 σ $\leqq$ 0.95
2) Requirement of heat removal	TRUMP code, etc.	Cladding temperature is kept below 390 ℃ (for PWR)
3) Strength of basket structure	From analysis or analysis code	Yield stress > Stress on 9 m drop test
4) Shielding	DOT.3.5 code, ANISN code, etc.	Dose at cask surface $\leqq$ 2 mSv/h Dose at 1 m from cask surface $\leqq$ 0.1 mSv/h
5) Size and weight of cask	It can be handled by general crane.	Cask weight $\leqq$ 125 t Cask width $\leqq$ 2.5 m Cask length $\leqq$ 6.25 m

Table 3. The Result of Investigation for Borated Stainless Steel.

Item			B-S.S. Cask I	B-S.S. Cask II
Fuel (PWR)			High burnup spent fuel	MOX spent fuel
Number of fuel assembly			12	12
Generated heat (kW/Cask)			16.6	21.9
Cask	Size	External / internal diameter (mm)	2,208 / 1,200	2,406 / 1,238
		Thickness of body (mm)	300	310
		Thickness of shielding (mm)	100	170
	Shielding performance (at 1 m, mSv/h)		0.097	0.0452
	Weight (t)		99.5	115.3
Basket	Boron concentration (wt%)		90wt% enriched boron 1.3wt%	natural boron 1.0wt%
	Thickness (mm)		20	30, 20
	keff + 3 σ		0.94473	0.92323
	Temp. of cladding temperature (℃)		318	365
	Strength of basket material (MPa)*		260.6	260.6
	Stress on drop (MPa)**		51.0	below 51.0

* A permissible stress of S.S.304

** Bend + Membrane stress

Table 4. The Result of Investigation for Borated Aluminum Alloy.

Item			B-Al Cask I	B-Al Cask II
Fuel (PWR)			High burnup spent fuel	MOX spent fuel
Number of fuel assembly			17	7
Generated heat (kW/Cask)			23.6	12.8
Cask	Size	External / internal diameter (mm)	2,396 / 1,430	2,186 / 1,100
		Thickness of body (mm)	250	400
		Thickness of shielding (mm)	160	170
	Shielding performance (at 1 m, mSv/h)		0.08	0.058
	Weight (t)		115.3	115.6
Basket	Boron concentration (wt%)		60wt% enriched boron 1.0wt%	60wt% enriched boron 1.0wt%
	Thickness (mm)		10	10
	keff + 3 σ		0.94473	0.92323
	Temp. of cladding temperature (℃)		316	221
	Strength of basket material (MPa)*		244	244
	Stress on drop (MPa)**		164	below 164

* Yield stress of B-Al (by a preliminary test)

** Bend stress

Table 5. The Result of Investigation for Composite.

Item			Composite Cask I	Composite Cask II
Fuel (PWR)			High burnup spent fuel	MOX spent fuel
Number of fuel assembly			17	12
Generated heat (kW/Cask)			23.6	21.9
Cask	Size	External / internal diameter (mm)	2,430 / 1,470	2,360/ 1,280
		Thickness of body (mm)	480 (include shielding)	540 (include shielding)
		Thickness of shielding (mm)	80 ϕ, 2 layers	80 ϕ, 3 layers
	Shielding performance (at 1 m, mSv/h)		0.078	0.083
	Weight (t)		112	107
Basket	Boron concentration (wt%)		natural boron 1.0wt%	natural boron 1.0wt%
	Thickness (mm)		20 (7/6/7), 10 mm B-S.S.	30 (10/10/10), 20 (7/6/7)
	keff + 3 σ		0.943	0.944
	Temp. of cladding temperature (℃)		354	357
	Strength of basket material (MPa)*		545	545
	Stress on drop (MPa)**		354	189

* Yield stress of B-S.S. only

** Primary membrane stress + Primary bend stress

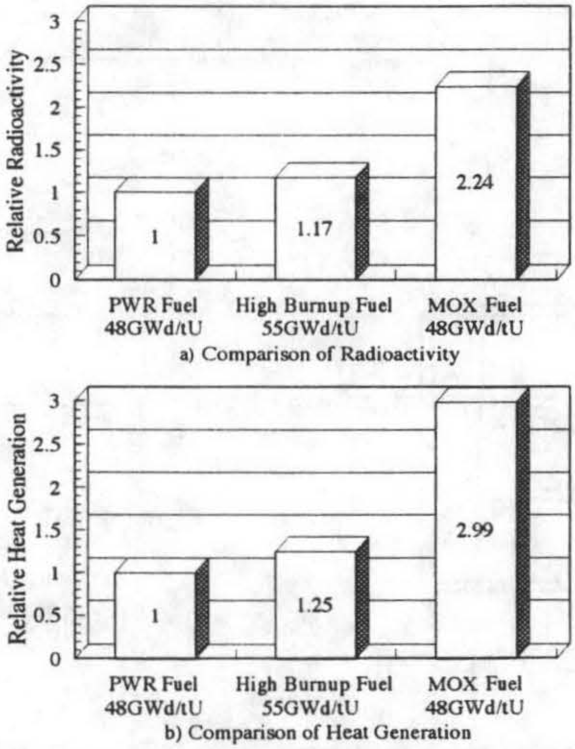

Figure 1. Characteristics of High Burnup and MOX Spent Fuels (for PWR).

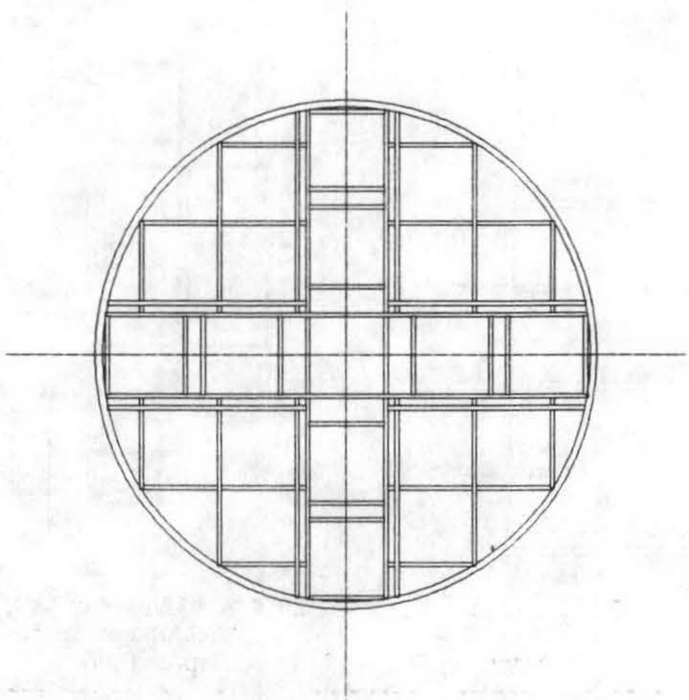

Figure 2. Example of cask basket made of borated stainless steel [for PWR Spent Fuel (35 GWd/tU)].

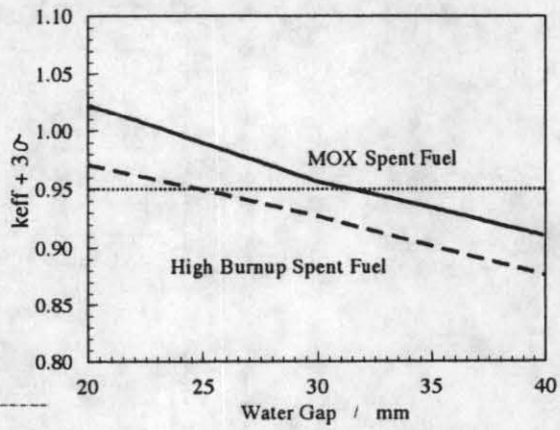

Figure 4. Effect of the Water Gap. (Borated Aluminum Alloy with 1.0wt% enriched boron containing 60 wt%^{10}B)

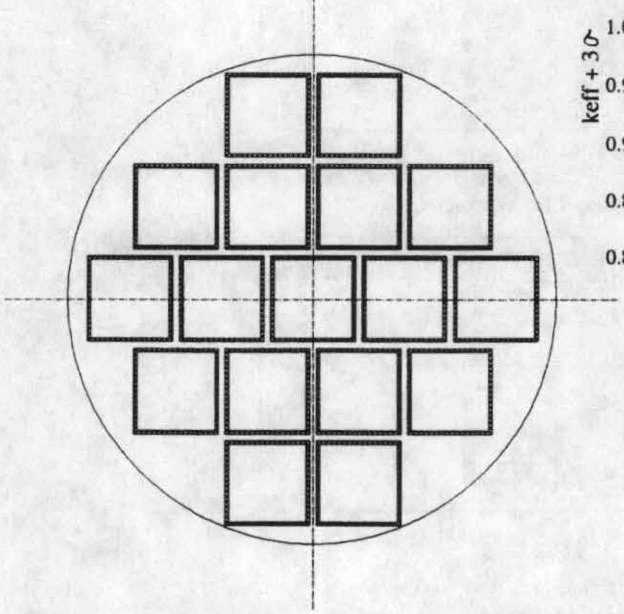

Figure 3. Example of cask basket made of borated aluminum alloy (for high burnup spent fuel) .

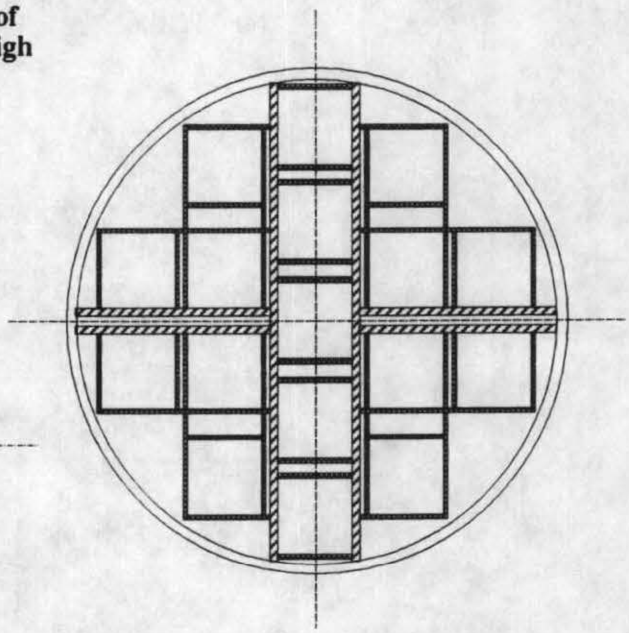

Figure 6. Example of cask basket made of composite material (for high burnup spent fuel).

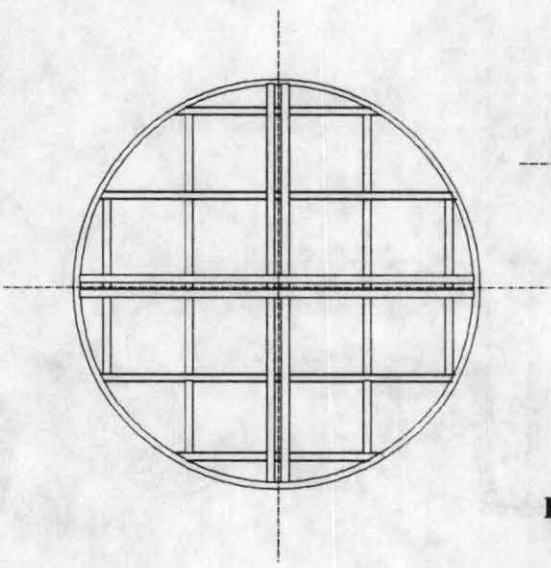

Figure 5. Example of cask basket made of borated stainless steel (for high burnup spent fuel) .