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Application of High Burnup 9x9 Fuel Model Bundles for Spent Fuel Transport Package Systems

Yoshiyuki Fujita
Nuclear Fuel Transport Co., Ltd.

Hirotaka Nojima
Nuclear Fuel Transport Co., Ltd.

Mitsuo Matsumoto
Nuclear Fuel Transport Co., Ltd.

Takehiro Isono
Toshiba Corporation Energy Systems & Solutions Company, Isogo Nuclear Engineering Center

Tetsuro Takeshita
Toshiba Corporation Energy Systems & Solutions Company, Isogo Nuclear Engineering Center

Naotsugu Kikuchi
OCL Corporation

Abstract

It is generally assumed in the criticality safety design of spent fuel transport packages that extremely conservative virtual spent fuel, such as fuel having the composition of fresh fuel without taking into account the effect of burnable poisons, is loaded into transport packagings. However, when this assumption is applied to highly enriched fuel for high burnup, it is excessively conservative for creating the criticality safety design for transport packages.

Meanwhile, in the actual design of BWR fuel, a neutron multiplication factors in each core during the early stage of burnup are suppressed by means of gadolinium, which is a burnable poison. Currently, BWR fuel in Japan is designed so that infinite multiplication factors (k_{inf}) in cold state loaded core systems during the whole burnup period do not exceed 1.3.

Accordingly, criticality safety assessments can be performed which have the appropriate tolerance for transport packages with virtual fuel bundles taking into account this characteristic designed to have a k_{inf} of 1.3 in cold state loaded core systems (model bundles).

This paper describes criticality safety assessments conducted for NFT-38B spent fuel transport package systems with high burnup 9x9 fuel assumed to be the virtual fuel based on the traditional assumption and assumed to be model bundles. We compared the effective multiplication factors (k_{eff}) of the traditional virtual fuel bundles and that of the model bundles. The k_{eff} value of the traditional virtual fuel under accident conditions exceeded 0.95, which is the aim sought for criticality safety. Meanwhile, the k_{eff} value of the model bundles under accident conditions was sufficiently smaller than 0.95. Moreover, we verified representativeness of the model bundle for the package systems by comparing it with existing fuel. Therefore the application of model bundles can be expected for rational subcritical safety assessments of transport packages for high burnup 9x9 spent fuel.

Introduction

It is generally assumed in the criticality safety design of spent fuel transport packages that extremely conservative virtual spent fuel, such as fuel having the composition of fresh fuel without taking into account burnable poisons, is loaded into transport packagings. Meanwhile, with fuel improved for high burnup, the neutron multiplication factor of high burnup fuel in cores is not so different from that of low burnup fuel because the high burnup fuel is not only highly enriched but also contains adequate burnable poisons. Therefore, when this assumption about the virtual fuel without taking into account burnable poisons is applied to highly enriched fuel for high burnup, it is excessively conservative for creating the criticality safety design of transport packages.

Meanwhile, in the actual design of BWR fuel, neutron multiplication factors in each core during the early stage of burnup are suppressed by means of gadolinium, which is a burnable poison. Thereafter, following gadolinium burnup, neutron multiplication factors reach each peak and then decrease. Currently, BWR fuel in Japan is designed so that infinite multiplication factors (k_{inf}) in cold state loaded core systems during the whole burnup period do not exceed 1.3.

In other words, criticality safety assessments with fuel assemblies that have a virtual enrichment set to have k_{inf} in cold state loaded core systems of 1.3, which is greater than any existing fuel, are more conservative than any existing fuel. Accordingly, it is conceivable that criticality safety assessments can be performed which have appropriate tolerance for transport package systems with virtual fuel bundles taking into account this gadolinium characteristic designed to have k_{inf} in cold state loaded core systems of 1.3 (we refers to such bundles taking into account the effect of gadolinium as model bundles in this paper)[1]. Actually, such fuel bundles taking into account the effect of gadolinium have been used for criticality safety assessments for spent fuel storage systems in BWR nuclear power plants in Japan for a long time. Meanwhile, in recent years, it has been reported that, under accident conditions of 9 meter drop tests specified in the IAEA Transport Regulations, fuel assembly deformation (bird-caging) may occur in BWR fuel assemblies between the first and second spacers (2nd span)[2]. Therefore, when applying model bundles to transport package systems, it is important to verify representativeness of model bundles for transport package systems which are different from cold state loaded core systems.

This paper describes criticality safety assessments conducted for NFT-38B spent fuel transport package systems with high burnup 9x9 fuel assumed to be the virtual fuel based on the traditional assumption and assumed to be the model bundles. This paper describes comparing the effective multiplication factors (k_{eff}) of the traditional virtual fuel bundles and k_{eff} of the model bundles, verifying representativeness of the model bundle for the package systems through a comparison with existing fuel. This paper concludes that the application of model bundles can be expected for rational subcritical safety assessments of transport packages for high burnup 9x9 spent fuel.

Criticality Safety Assessments for Package Systems with High Burnup 9x9 Fuel

The criticality safety assessments are performed for NFT-38B spent fuel package systems under normal conditions and under accident conditions with high burnup 9x9 fuel assumed to be the virtual fuel based on the traditional assumption and assumed to be the model bundles. A comparison is made of the k_{eff} values of the virtual fuel bundles based on the traditional assumption, which are extremely conservative virtual fuel bundles having the composition of fresh fuel without taking into account burnable poisons, and the k_{eff} values of the model bundles taking into account the effect of gadolinium.

Assessment Method for k_{eff} Calculations and Assessed Transport Package Systems

In the analysis model, assessments are performed of NFT-38B transport packages, which are wet type packages and are used in transporting existing BWR spent fuel. The schematic illustration of criticality analysis model for the NFT-38B transport package system is shown in Figure 1. This analysis model takes into account bird-caging so that the fuel rod pitch in the 2nd span of all fuel assemblies is changed[2] for accident conditions. Also, in areas where there is no change in the pitch, fuel assemblies are positioned towards the center of the package.

The SCALE code system is used to perform the criticality calculations. The calculations are made using the SCALE Code System 238 Group Cross-Section Library and the KENO-V.a Code for the assembly model homogenized for each fuel rod.

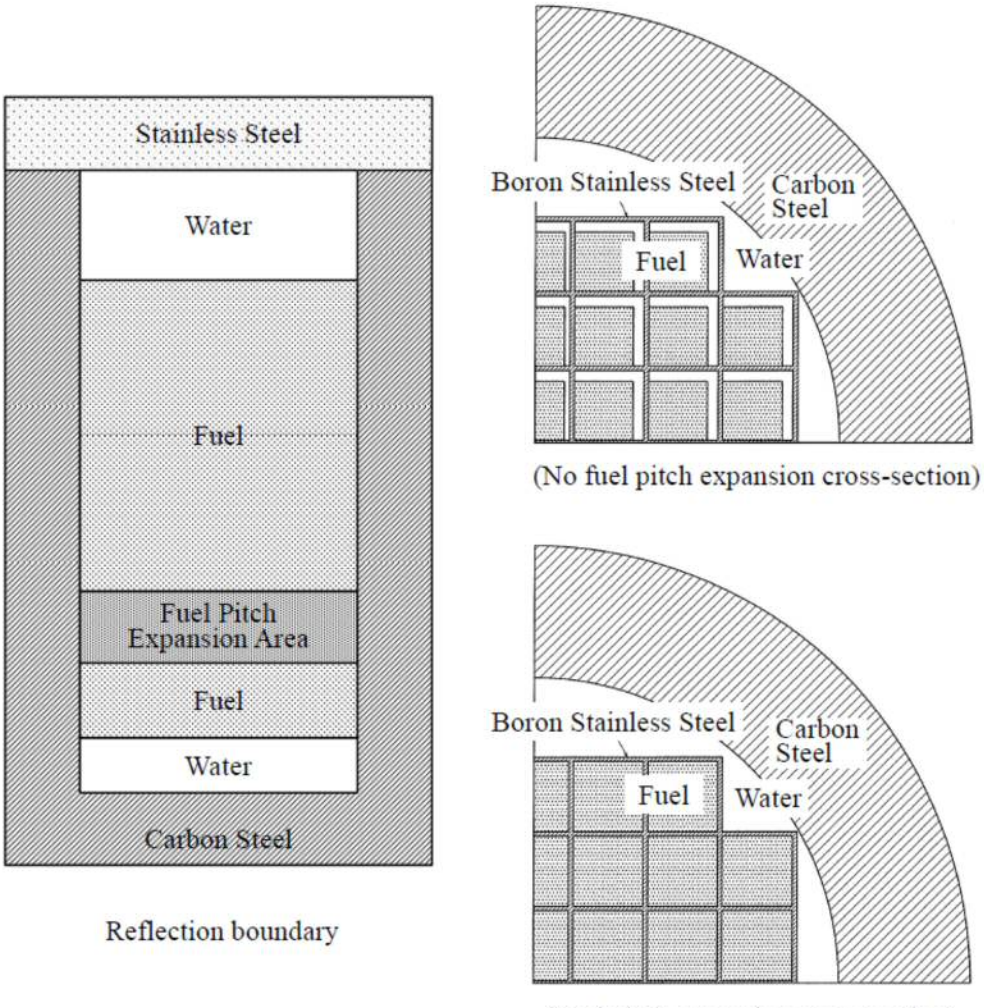
Assessed Spent Fuel Bundles

The traditional virtual fuel bundle and the model bundle are prepared based on high burnup 9x9 fuel. The traditional virtual fuel bundle has a homogeneous cross-section enrichment, which is the average of the fuel assembly (4.19wt-%), and this cross-section is distributed uniformly in an axial direction. Meanwhile, the model bundle used in the assessments, which takes into account the effect of gadolinium, has fuel rods having two enrichment levels in two areas. The interior enrichment is the maximum used for BWR fuel (4.9wt-%) and the exterior enrichment is set so that k_{inf} in cold state loaded core systems will be 1.3. A cross-section of the model bundle is shown in Figure 2. The cross-section is distributed uniformly in an axial direction in the model bundle, the same as the traditional virtual fuel bundle.

Results of k_{eff} Calculations

We performed criticality calculations of the NFT-38B spent fuel package systems under normal conditions and under accident conditions with the traditional virtual fuel bundles and with the model bundles.

Table 1 shows the results of the k_{eff} calculations with the traditional virtual fuel bundles and the model bundles for the transport package systems under normal conditions and under accident conditions. Based on the results, we found that the k_{eff} value of the traditional virtual fuel bundles under accident conditions exceeded 0.95, which is the aim for criticality safety. By contrast, the k_{eff} value of the model bundles under accident conditions was sufficiently smaller than 0.95 and was subcritical. The k_{eff} values of the model bundles under normal conditions and under accident conditions were approximately 0.08 or 0.09 smaller than the k_{eff} values of the traditional virtual fuel bundles under normal conditions and under accident conditions. This result shows that it is excessively conservative to formulate the criticality safety design for transport packages when the assumption of the traditional virtual fresh fuel without taking into account burnable poisons is applied to the highly enriched fuel for high burnup.



Reflection boundary

(No fuel pitch expansion cross-section)

(Fuel pitch expansion cross-section)

Figure 1. Schematic illustration of criticality analysis model for the NFT-38B transport package system

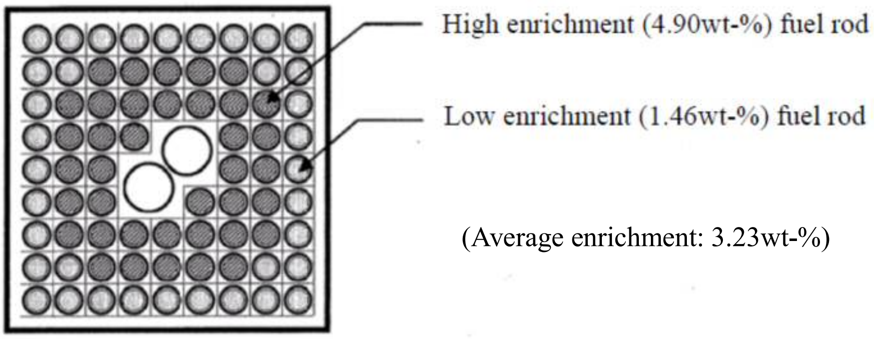


Figure 2. Model bundle of high burnup 9x9 fuel

Table 1. k_{eff} for NFT-38B transport package systems

Bundles	Normal conditions		Accident conditions	
	$k_{\mathrm{eff}}+3\sigma$	(standard deviation σ)	$k_{\mathrm{eff}}+3\sigma$	(standard deviation σ)
Traditional virtual fuel bundles	0.918	(less than 0.001)	0.981	(0.001)
Model bundles	0.837	(less than 0.001)	0.893	(less than 0.001)
Differences between the traditional virtual bundles and the model bundles	0.081		0.088	

Verification of Representativeness of Model Bundles for Transport Package Systems

When applying model bundles to transport package systems, it is important to verify representativeness of model bundles for transport package systems which are different from cold state loaded core systems. The model bundle used in the assessments has been verified its representativeness for package systems by comparing it with existing fuel. In order to demonstrate representativeness of a model bundle in a transport package system, it is confirmed that all k_{eff} values of all existing fuel design cross-sections for a transport package system are lower than a k_{eff} value of the model bundle.

Assessment Method for Burnup Calculations and k_{inf} Calculations

BWR fuel has a heterogeneous enrichment distribution in both the radial and axial directions, and the enrichment is set by taking into account plants, use (initial load or reload) and other factors. Moreover, because steam is generated in a BWR core, the historical void fraction (0%, 40% or 70%) is taken into account in fuel design and core design. Therefore, assessment cases are set as combinations of fuel cross-sections taking into account these elements. Meanwhile, although actual fuel assemblies are designed with enrichment distribution in an axial direction, each assessment case is considered as a certain fuel cross-section distributed uniformly in an axial direction.

The fuel assembly neutronics calculation code is used for the burnup calculations and the k_{inf} calculations. With the fuel assembly neutronics calculation code, in each simulated BWR cold state loaded core, burnup calculations are performed for existing fuel to find each composition at each burnup level, and k_{inf} calculations are performed with fuel having each composition at each burnup level.

Examinations of Assessment Cases for k_{inf} Calculations

First of all, in advance of k_{inf} calculations for existing fuel, qualitative examinations are conducted to identify and exclude those assessment cases of some existing fuel clearly enveloped by the model bundle.

We excluded the fuel cross-sections comprised only of natural uranium on the top and the bottom of the actual fuel assemblies (natural uranium blanket) from the assessment cases because the enrichment level of these fuel cross-sections is very low and the fuel cross-sections are clearly enveloped by the model bundle.

We excluded the combinations of a 0% void fraction and the uppermost cross-sections excluding natural uranium blankets from the assessment cases because fuel in the upper BWR core does not continue to burn at a 0% void fraction.

Pairs of fuel are designed for replacing fuel, that is, each pair is designed with similar enrichment distribution and different number of fuel rods containing gadolinium to suppress neutron multiplication (Gd fuel rods). Such twins are called lower Gd fuel and higher Gd fuel, respectively. In comparing lower Gd fuel and higher Gd fuel, lower Gd fuel has a somewhat higher k_{inf} peak value in a cold state loaded core system. In order to verify representativeness of lower Gd fuel for a transport package system, we performed criticality calculations with a pair of replacing fuel. As a result, it was confirmed that each higher Gd fuel is enveloped by each lower Gd fuel. Therefore, we excluded higher Gd fuel from the assessment cases.

Examinations of the Assessment Cases for k_{eff} Calculations

Following the qualitative examinations to exclude some assessment cases of existing fuel clearly enveloped by the model bundle, we performed burnup calculations and k_{inf} calculations with the survived assessment cases in cold state loaded core systems. In advance of final k_{eff} calculations for existing fuel, based on the calculated k_{inf} values, the quantitative examinations are conducted to exclude those assessment cases of some existing fuel enveloped by the model bundle.

Transferring from cold state loaded core systems to transport package systems decreases neutron multiplication factors of fuel bundles due to neutron absorption effect of baskets of transport packagings and other factors. Although a ratio of changes from k_{inf} (in cold state loaded core systems) to k_{eff} (in the transport package system) is not constant and varies due to various fuel compositions and other factors, k_{eff} values can be simply predicted based on the already calculated k_{inf} values by investigating these tendencies and estimating the conservative amount of change from k_{inf} to k_{eff}.

In estimating the amount of change from k_{inf} to k_{eff} of existing fuel, we grouped the assessment cases by a combination of core lattices, fuel cross-sections and void fractions, so that we selected representative cases showing the highest k_{inf} value and the second highest k_{inf} value out of each group. With the representative cases at each burnup point for the highest k_{inf} as well as at the next burnup point since the neutron multiplication factor peak of each case could move towards higher burnup when transferring to the transport package system, we performed criticality calculations for the transport package systems under normal conditions and under accident conditions. As a result of the criticality calculations, we collected the differences between k_{eff} and k_{inf} (Δk), so that we configured formulas to predict k_{eff} values by both the least squares method and the addition of certain conservative values to envelope all cases. With the prediction formulas, we obtained predicted k_{eff} values from the already calculated k_{inf} values.

For the most part, the predicted k_{eff} values of existing fuel are less than the k_{eff} values of the model bundle, but the result showed no tolerance in relation to the k_{eff} value of the model bundle only for the system under normal conditions. For the system under accident conditions, the increase in the neutron multiplication, which resulted from pitch expansion of the higher enriched fuel rod area in the fuel center, is considered to be dominant, and the model bundle which has a significant difference between the center and outer circumference compared to actual fuel is thought to allow k_{eff} values to easily increase and be a conservative condition. Therefore, we performed criticality calculations of the transport package system under normal conditions for the cases to verify the model bundle envelops them.

Results of k_{eff} Calculations

The results of the k_{eff} calculations for the transport package system are shown in Table 2. Based on the results, we found that k_{eff} values of the existing fuel were sufficiently smaller than the k_{eff} value of the model bundles. We found that the prediction formulas were configured conservatively and a tolerance for the model bundle in relation to existing fuel is sufficiently ensured.

Table 2. k_{eff} for NFT-38B transport package system

Calculation System	Fuel design	Burnup (GWd/t)	Cross-section (Node number)	Void fraction (%)	k_{inf}	Predicted k_{eff}	k_{eff}+3σ
Normal conditions	Reload	7.7	21-22	40	1.267	0.838	0.828
	Reload	8.8	21-22	40	1.263	0.837	0.828
	Reload	9.9	21-22	40	1.271	0.837	0.827
	Reload	9.9	21-22	40	1.271	0.837	0.827
	Reload	12.1	09-15	0	1.253	0.836	0.818
Accident conditions	Not applicable						
					k_{inf}		k_{eff}-3σ
Normal conditions	Model Bundle				1.305		0.835

Conclusions

We performed criticality safety assessments for NFT-38B spent fuel transport package systems with high burnup 9x9 fuel assumed to be the virtual fuel based on the traditional assumption and assumed to be the model bundles. We compared the effective multiplication factors (k_{eff}) of the traditional virtual fuel bundles and k_{eff} of the model bundles. The k_{eff} value of the traditional virtual fuel under accident conditions exceeded 0.95, which is the aim for criticality safety. Meanwhile, k_{eff} value of the model bundles under accident conditions was sufficiently smaller than 0.95. The k_{eff} value of the model bundles was much smaller than the k_{eff} value of the traditional virtual fuel bundles. This shows that it is excessively conservative for creating the criticality safety design for transport packages when the assumption of the traditional virtual fresh fuel without taking into account the effect of burnable poisons is applied to the highly enriched fuel for high burnup. Moreover, we verified representativeness of the model bundle for the package systems by comparing with existing fuel. Therefore, the application for model bundles can be expected for rational subcritical safety assessments of transport packages for high burnup 9x9 spent fuel.

Acknowledgments

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