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Determination of McCARD Upper Subcritical Limit for LWR Fuel Storage System

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1. Introduction

10 CFR 70.61 (d) noted that all systems using nuclear fuel under normal or abnormal conditions must be in a subcritical state, including acceptable margins for critical safety. In order to verify that the system is in a subcritical state, which is used to select critical experiments similar to the actual or predicted calculation, and then to set a statistical criterion to determine the subcriticality of the system to be computed in the future. This criterion is defined as the Upper Subcritical Limit(USL) [1]. The United States National Standard for Nuclear Critical Safety of Nuclear Reactor allows the use of computer codes in determining the USL for systems using fissile materials and requires the validation of computer codes and data to quantify the bias and uncertainty of the calculations.

The McCARD, one of the Monte Carlo codes developed by Seoul National University, has been approved by the Korea Institute of Nuclear Safety(KINS) as a nuclear design code and has experience as a reactor design code. However, this code has not been used for critical safety analysis of nuclear fuel systems and has not been validated. Therefore, in this study, the methodology and the code for the establishment of the statistical criteria for determining the criticality of the system have been validated. The sample data for setting the USL is based on the multiplication factors calculated using the McCARD for the critical experimental problems for the spent fuel storage and transport system proposed by NUREG/CR-6361 [2]. In addition, the five methodologies presented in NUREG/CR-6361 and NUREG/CR-6698 were applied to the USL settings. Details of the methodology are included in the main text.

2. Upper Subcritical Limit

The American National Standards Institute(ANSI) and American Nuclear Society(ANS) standards define the USL as a conservative criterion to ensure that a system that is supposed to be in a subcritical state is actually in a subcritical state [3]. The USLs are determined based on the uncertainty of the bias and bias associated with the calculational code and experiments used in the calculations for well-known systems. This section will briefly describe the methodologies for establishing the USLs suggested in NUREG/CR-6361 [4] and NUREG/CR-6698 [5].

2.1. Methods of setting USL in NUREG/CR-6361 [4]

To ensure that an unknown system is in a subcritical state, the multiplication factor(k_s) of the computed system must be less than or equal to the maximum allowed multiplication factor based on the benchmark calculation and uncertainty terms:

$$k_s \le k_c - \Delta k_s - \Delta k_c - \Delta k_m , \qquad (1)$$

where

k_c = mean value of resulting from the calculation of benchmark criticality experiments using a specific calculational method and data,
Δk_s = uncertainty in the value of k_s,
Δk_c = uncertainty in the value of k_c,
Δk_m = additional margin to ensure subcriticality.

If the calculational bias(β) is defined as $\beta = k_c - 1$, the uncertainty of the calculational bias is equal to the uncertainty of k_c (i.e., $\Delta\beta = \Delta k_c$). The uncertainty of the calculational bias includes uncertainty in critical experiments, uncertainty in benchmark calculation, and uncertainty due to geometric modeling approximations. If β is a positive value, then the USLs is established assuming that β is 0 from a conservative point of view. Using the newly defined β and the $\Delta\beta$, Eq (1) can be rewritten as Eq (2) and consequentially the USL can be defined as Eq (3):

$$k_s + \Delta k_s \le 1 - \Delta k_m + \beta - \Delta\beta, \qquad (2)$$

$$USL_{6361} = 1 - \Delta k_m + \beta - \Delta\beta. \qquad (3)$$

NUREG/CR-6361 proposes two methodologies based on Eq (3). It consists of a confidence band with administrative margins with an additional margin of 0.05, and a single-side uniform width closed-interval approach that deduces additional margins using a statistical method. Details of the two methodologies are described in reference 4.

2.2. Methods of setting USL in NUREG/CR-6698 [5]

NUREG/CR-6698, which was officially published in January 2001, suggests three methodologies for setting USLs through statistical technique [5]. The equation representing the USLs are similar to Eq (3). The USL is represented by the following equation:

$$USL_{6698} = 1.0 - Bias - \sigma_{bias} - \Delta_{sm} - \Delta_{AOA}, \quad (4)$$

where

$Bias$ = calculated as the difference between the calculated keff and the critical experiment,
σ_{bias} = the statistical uncertainty in the bias,
Δ_{sm} = the subcritical margin,
Δ_{AOA} = additional subcritical margin.

A characteristic of NUREG/CR-6698 is that additional margin(Δk_m) given in Eq (3) is separated by subcritical margin(Δ_{sm}) and additional subcritical margin(Δ_{AOA}). Δ_{sm} is the margin due to system design errors, and Δ_{AOA} is margin due to the expansion of applicability, typically 0.02 and 0.03, respectively.

The NUREG/CR-6698 proposes three methodologies that can be chosen depending on the tendency and normality of data. In the first one, the single-sided tolerance limit is suitable for cases where there is no trend of data but the distribution follows a normal distribution. Second, single-sided tolerance band is preferred when there is a tendency of the data and the distribution follows a normal distribution. The last one, non-parametric statistical treatment is mainly used when the distribution of data does not follow the normal distribution, or when the number of data is insufficient to determine the distribution. A detailed of the three methodologies are given in reference 5.

3. Determination of Upper Subcritical Limits

In this section, the USLs are established based on the results of the multiplication factor for critical experimental problems calculated using McCARD. These problems were provided in NUREG/CR-6361, and a total of 167 results refer to reference 2. The USLs used the five methodologies described in sections 2.1 and 2.2. The most important part of the USL setting process is the determination of the experimental problems to be used and the main parameters that influence the multiplication factor of the experiments. In this section, a total of six parameters affecting the multiplication factor are determined by the characteristics of the experiments. In addition, critical experimental problems are classified into five categories depending on the structural characteristics. Table I summarizes the design parameters affecting the multiplication factor and classified critical experimental problems.

Table I: Subsets of LWR-type fuel experiments

Subset	No. of experiments (#)	Correlated key parameters*
All experiments	167	AEF, Enr, H/X
Separator plates	80	AEF, H/X
Reflecting walls	50	Enr, Assembly separation
Soluble boron	32	AEF, W/F
Separator plates-reflecting wall	15	AEF, H/X

* AEF-Average Energy of Fission; Enr-Enrichment of U^{235}; H/X-hydrogen-to-fissile ratio; W/F-water/fuel volume ratio;

The USLs are established on the basis of the linear regression line derived from the regression analysis between design parameters and the multiplication factors calculated using the McCARD. As a result, the USLs are determined by applying the uncertainty and additional margin presented in each methodology to the derived linear regression line. In this section, a representative USLs graph and USL equations based on the design parameters will be presented.

Fig. 1 shows the USLs established for Average Energy of Fission(AEF) based on the 167 results calculated using McCARD. Method 1, 3, and 5 were more conservative than the commonly used subcritical criterion 0.95, of which method 5 using non-parametric analysis presented in NUREG/CR-6698 is most conservative at 0.9403. Also, method 3 based on parametric analysis and method 5 based on non-parametric analysis show similar results. This is because the number of experiments is large enough to be 167, so there is no much difference between the non-parametric and parametric analysis.

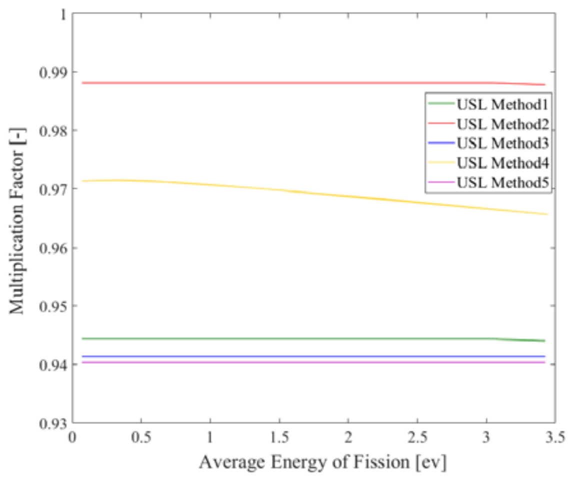

Fig. 1. USLs for all experiments based on AEF

Fig. 2 is the USLs established for AEF based on 80 experimental problems including separator plates that serve to separate the fuel assembly in spent fuel storage system. As a result, USL set by method 3 and method 5 was the most conservative at 0.9408 and 0.9403, respectively, and method 2 showed the highest level at about 0.9866.

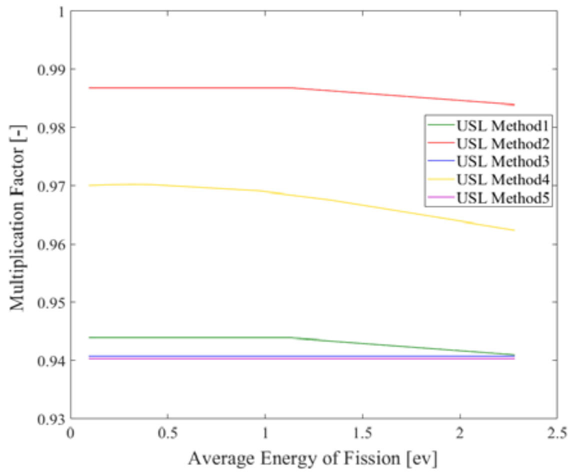

Fig. 2. USLs for separator plate experiments based on AEF

Fig. 3 is USLs established depending on the enrichment of U^{235} based on 50 experimental problems including a reflecting wall to prevent neutron leakage outside the system. The USLs set using methods 1, 3 and 5 was determined in the range of 0.9421 to 0.9462, while the non-conservative methods, method 2 and 4, were determined to be in the range exceeding 0.9700. In other cases, method 5 based on non-parametric analysis is more conservative than method 3 based on the parametric analysis. However, this case is characterized by method 3 being more conservative.

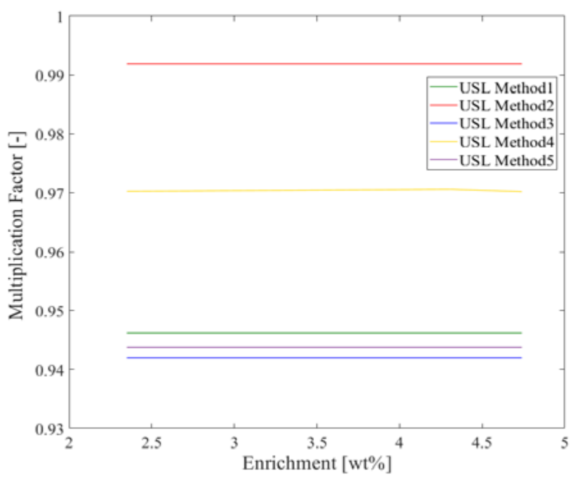

Fig. 3. USLs for reflecting wall experiments based on Enrichment

Fig. 4 is USLs established for AEF using five methodologies based on 32 experimental problems in which soluble boron is dissolved in the moderator in the system. USL was set at 0.9303 using method 5 based on non-parametric analysis, and USL was determined using method 3 based on the parametric analysis at 0.9409.

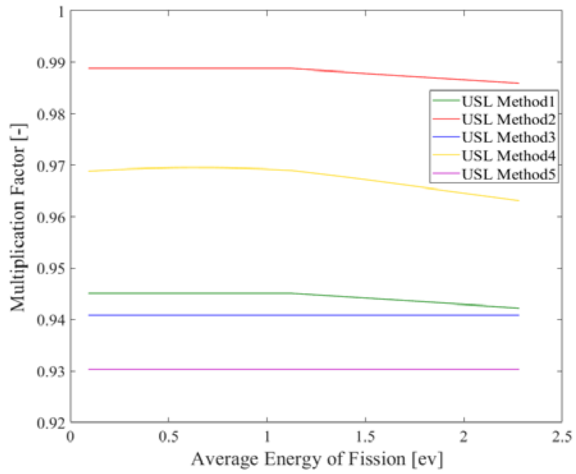

Fig. 4. USLs for soluble boron experiments based on AEF

Fig. 5 is USLs established using 15 experimental problems including both a separator plate surrounding the fuel assembly and a reflecting wall located at the outer of the core. The design parameters used in the USL setup are AEF. Since the USLs that were previously set had a large number of samples (>30), method 5 using non-parametric analysis and method 3 using parametric analysis showed a similar tendency. However, since the separator plate-reflecting wall experimental problems have a relatively small sample size of 15, method 5 has much more conservative results than method 3. The USL established using method 3 and method 5 is 0.9407 and 0.9038, respectively, which have a difference of 0.04.

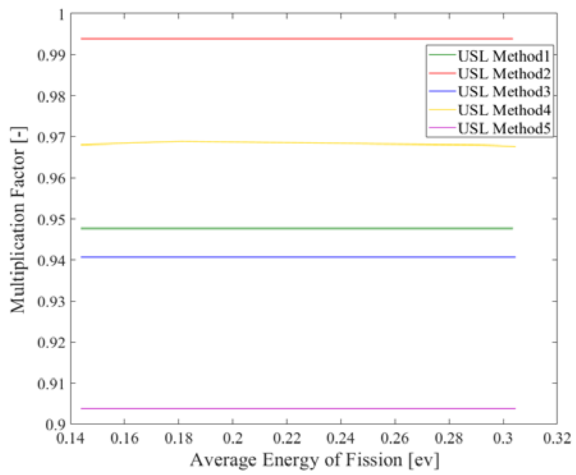

Fig. 5. USLs for separator plate-reflecting wall experiments based on AEF

Table II lists the USL equations established using statistical techniques depending on the key parameters selected based on the results of the critical experimental problems divided into five categories.

Table II: Equations of USL based on all categories and design parameters

Category (#)	Key Parameters	Method 1	Method 2	Method 3	Method 4	Method 5
All experiment (167)	AEF	0.9469-8.2558E-04*X (X > 3.0400) 0.9444 (X<=3.0400)	0.9905-8.2558E-04*X (X>3.0400) 0.9880 (X<=3.0400)	0.9414	0.9713+1.00E-04*X	0.9403
	Enrichment	0.9454	0.9909	0.9414	0.9712+4.00E-05*X	0.9403
	H/X	0.9450	0.9900	0.9414	0.9716-1.99E-06*X	0.9403
Separator plate (80)	AEF	0.9468-2.5323E-03*X (X > 1.1323) 0.9439 (X<=1.1323)	0.9895-2.5323E-03*X (X > 1.1323) 0.9866 (X<=1.1323)	0.9408	0.9709-3.08E-03*X	0.9403
	H/X	0.9442	0.9876	0.9408	0.9701-2.92E-06*X	0.9403
Reflecting wall (50)	Enrichment	0.9462	0.9917	0.9421	0.9700+1.33E-04*X	0.9438
	Assembly sep.	0.9459+4.0014E-04*X (X<3.9082) 0.9475 (X >=3.9082)	0.9928+4.0014E-04*X (X < 3.9082) 0.9943 (X>=3.9082)	0.9421	0.9710+4.06E-05*X	0.9438
Soluble boron (32)	AEF	0.9479-2.4813E-03*X (X > 1.1208) 0.9451 (X<=1.1208)	0.9912-2.4813E-03*X (X > 1.1208) 0.9884 (X <= 1.1208)	0.9409	0.9700-2.06E-03*X	0.9303
	H2O/Fuel vol.	0.9429+3.2351E-03*X (X < 1.0563) 0.9463 (X>= 1.0563)	0.9879+3.2351E-03*X (X < 1.0563) 0.9913 (X>=1.0563)	0.9409	0.9660+2.33E-03*X	0.9303
Separator Plate-Reflecting wall (15)	AEF	0.9477	0.9937	0.9407	0.9690-3.89E-03*X	0.9038
	Wall sep.	0.9457	0.9884	0.9407	0.9655+7.90E-04*X	0.9038

4. Conclusions

In this study, the USL was established based on the critical experimental problems of NUREG/CR-6361 used for the validation of the McCARD. Among the 173 results of critical experimental problems, 168 results of the experimental problem were used, except for five experiments using two types of fuel rods with different enrichment of uranium. And, the five methodologies for set USL presented in NUREG/CR-6361 and NUREG.CR-6698 were used. The USLs established using method 1 presented in the NUREG/CR-6361 is determined to be within the range from 0.9434 to 0.9477, with an average of 0.9453. The USLs determined using method 2 is in the range of 0.9801-0.9984. This is in the higher range of USL compared to other methods presented in this study. This is because method 2 is intended to confirm that the conventional margin (0.05) conventionally used in method 1 is sufficiently conservative. The average USL set using method 3 is 0.9405, which is the most conservative result of the parametric analysis. The USLs set using method 4 is roughly in the range from 0.9574 to 0.9716. Lastly, the USLs set using method 5, which is the only non-parametric analysis, has a range from 0.8903 to 0.9438. Method 5 has a very large deviation of USLs from the other methods. This is because method 5 uses a non-parametric analysis and thus tends to be more conservative in cases where the number of samples is small (<30). As a result, when the number of samples is small, method 5 derives the most conservative USLs. Generally, USL set using method 3 based on the parametric analysis tends to be similar to the USL set using method 5 when the number of samples is large (>30).

The USLs of McCARD, based on critical experimental problems of spent fuel storage transport systems, is sufficiently conservative and evaluated for its applicability in the field of criticality analysis. Additionally, USL was used to perform the criticality analysis, which was published as a separate paper [6].

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