A Criticality Safety Analysis of Dry Storage Cask Loaded with Accident-Tolerant Fuel

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1. Introduction

Nuclear power is currently an economically efficient and environmentally friendly source of electricity that emits less carbon than other sources. However, after the Fukushima nuclear accident, which caused a hydrogen explosion due to hydrogen generated by the oxidation of nuclear fuel cladding, lots of concerns about the operation of nuclear power plants have arisen, and various accident-tolerant fuels (ATFs) are being developed around the world to improve the safety of nuclear power plants [1].

However, molybdenum and chromium, which are considered ATF materials, have relatively large thermal neutron absorption cross sections, resulting in a shorter fuel cycle length compared to the performance of conventional nuclear fuel. Because of these ATF characteristics, increased fuel enrichment is being considered for efficient use of ATF. Due to the improved performances of ATF compared to conventional nuclear fuel, it would consider an increase of ^{235}U enrichment.

Therefore, in this study, a criticality analysis of dry storage cask loaded with ATF within ^{235}U-10 wt% enrichment was performed to identify the applicability of ATF to the storage cask using KENO-VI code, one of the SCALE 6.2.4 packages developed by Oak Ridge National Laboratory [2]. The assumption for this analysis is that loaded fuel is fresh fuel, not spent nuclear fuel (SNF), with no burnup credits applied. The criticality results were validated against the USL. Both code simulations were performed with ENDF/B-VII.1 library using 10000 histories, 350 active cycles and 50 inactive cycles [5].

2. Analysis methodology and analysis model

2.1. Validation and Verification using critical experiments

The NUREG/CR-6361 report describes statistical analysis methodology for criticality safety analysis and contains 180 critical experiments for PWR in storage and storage packages: 173 homogeneous models, 7 heterogeneous models [3]. These benchmark experiments are categorized by various variables.

The NUREG/CR-6698 report describes another statistical analysis methodology for criticality [4]. Both reports use a statistical method using uncertainty and bias to calculate the USL, but there are some differences. Because NUREG/CR-6698 method is more reliable for calculating the USL than NUREG/CR-6361 method, NUREG/CR-6361 report was adopted for critical experiment benchmark calculations and NUREG/CR-6698 report was adopted for USL calculations.

2.2. Mo microcell UO_2 pellet with CrAl coating

Mo microcell UO2 pellet is an ATF pellet concept being developed by Korea Atomic Energy Research Institute (KAERI) [6]. The Mo cells created in the pellet by the manufacturing process improve the ability to retrain fission products and, due to the properties of Mo metal, also improve thermal conductivity. KAERI has also considered CrAl coating on the conventional zirconium-based cladding to reduce oxidation of the cladding [7]. The design of a Mo microcell UO2 pellet to be used in this analysis are illustrated in **Figure 1** and dimensions are summarized in **Table 1**. It is difficult to implement Mo microcells created within pellets in the simulation code such as SCALE as shown in the **Figure 1**. Ulsan National Institute of Science and Technology calculated and compared the heterogeneous and homogeneous models of Mo microcell UO2 pellets, and found the difference is acceptable [8]. Thus, the homogeneous pellet model was used in this analysis.

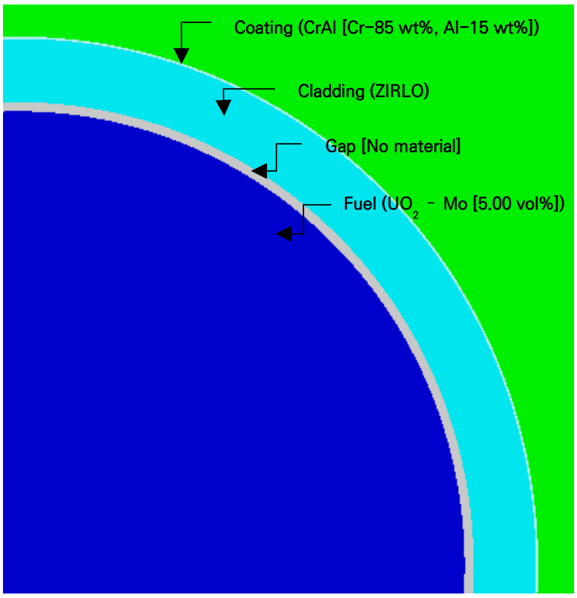

Figure 1. Illustration of Mo Microcell UO_2

Table 1. Design Data for ATF

Description	Dimension
<Fuel rod>	
Fuel type	Plus7 [a]

Fuel enrichment	^{235}U - 5 wt%
Density [g/cm^3]	10.96
Fuel pellet diameter [cm]	0.819
<Clad>	
Material of clad	ZIRLO
Cladding inner diameter [cm]	0.836
Cladding outer diameter [cm]	0.95
Fuel rod pitch [cm]	1.285
<Guide/Instrument tube>	
Material of tube	ZIRLO
Inner diameter [cm]	2.286
Outer diameter [cm]	2.489
<Fuel assembly>	
Height [cm]	381
Assembly pitch [cm]	20.7772
<Neutron absorber plate> [b]	
Type	METAMIC
^{10}B areal density [g/cm^2]	0.0336
Thickness [cm]	0.25
<ATF features> [c]	
Fuel pellet composition	UO2 - Mo [5.00 vol%]
Pellet density [g/cm^3]	10.506
Coating material	CrAl [Cr - 85 wt%, Al - 15wt%]
Coating material density [g.cm^3]	6.4825
Coating thickness [cm]	0.002

a: Adopted from [10]
b: Adopted from [11]
c: Adopted from [8]

3. Analysis results

3.1. USL determination

When SNFs are loaded in dry storage cask, subcriticality must be maintained at any situations in accordance with 10 CFR72.144, and the effective neutron multiplication factor must not exceed 0.95, including all biases and uncertainties with 95% confidence level [9]. However, since it can exceed 0.95 due to bias and uncertainty, it is necessary to determine the USL and prove that the criticality calculation value of the target model does not exceed it. The USL is calculated as shown in Equation 1. A total of 110 criticality experiments with similar characteristics to dry storage cask were selected to calculate the USL, and only some variables are shown in **Table 2.**

$$USL = 1.0 + Bias - \sigma_{Bias} - \Delta_{SM} \quad Eq\ (1)$$

Bias = k_c – 1 (if k_c > 1, k_c = 1 for conservatism)
σ_{Bias}: Statistical uncertainty
Δ_{SM}: Subcritical margin (= 0.05 for requirement)

Table 2. Selected Experiments for USL

Experiment name	Enrichment [wt%]	Lattice	Exp #
ANS33	4.742	Square	4
B1645	2.459	Square	2
BW1231	4.02	Square	3
BW1484	2.459	Square	10
BW1810	2.459, 4.02	Square	10
EPRU	2.35	Square	2
NSE	4.742	Square	3
P2438	2.032	Square	5
P2615	4.31	Square	4
P2827	2.35	Square	1
P3314	2.35, 4.31	Square	19
P3602	2.35, 4.31	Square	20
P3926	2.35, 4.31	Square	2
P4267	4.31	Square	7
P62, 71	4.306	Square	5
PAT80	4.742	Square	2
W3269	2.72, 3.7, 5.7, 5.742	Square	11
Sum			110

The distribution of these data is shown in **Figure 2**, and the chi-square test was performed to check for normality, and it was determined to have normality, and the results are summarized in **Table 3**.

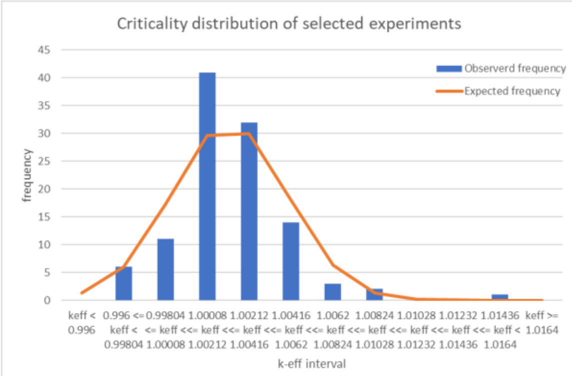

Figure 2. Selected Experiments Distribution

Table 3. Normality Check

H_0: Sample ~ Normal distribution	
Chi-square score	1.35736
Degree of freedom	9
Significance level_Chi-square	0.05
Chi-square_P-value	0.99807
Check normality	O

Since the data has normality, the correlation coefficient of each variable was calculated, and t-test was performed to check the significance of each variable. As a result, only the enrichment, ratio of moderator to fuel, plate thickness and assembly separation distance were found to have significance, and the results are summarized in the **Table 4**.

Table 4. Significance Test from T Test

T-test level	0.05	H0: No significance between each variable and keff						
	Enrich	Pitch	M/F	Plate_thick	Asep	AEG	AEF	Dancoff
Variable mean	3.66436	1.75760	1.79936	0.17952	4.84079	33.97966	0.27864	0.18079
Delta	2.041E+17	1.671E+16	2.032E+16	1.259E+16	4.37E+18	3.5742E+17	6.739E+15	8.904E+14
Alpha	0.99825	0.99971	0.99660	1.00186	1.00148	1.01272	1.00202	1.00239
Beta	0.00107	0.00140	0.00310	0.00170	0.00014	-0.00031	0.00055	-0.00120
Correlation coefficient	0.41422	0.15498	0.37802	0.16374	0.25429	-0.15892	0.03834	-0.03077
T-score	4.72959	1.63035	4.24331	1.72495	2.73253	-1.67279	0.39879	-0.31996
Degree of fredom	108	108	108	108	108	108	108	108
T_P-value	3.42E-06	0.0529705	2.335E-05	0.0436987	0.0036722	0.95136807	0.3454193	0.6251926
Check trend	O	X	O	O	O	X	X	X

The USLs were calculated based on normality and significance for each variable and 0.94322, the smallest of these, was taken as the USL for conservatism. The calculated USLs for all variables are shown in **Table 5.**

Table 5. USL Results for Variables

	Enrich	Pitch	M/F	BconP	Plate_thick	Asep	AEG	AEF	Dancoff
Check trend	O	X	O	X	O	O	X	X	X
variance_fit(s2_fit)	6.1E-06	Non	6.31E-06	Non	7.16E-06	6.88E-06	Non	Non	Non
Average of total uncertainty	2.53E-07	Non	2.53E-07	Non	2.53E-07	2.53E-07	Non	Non	Non
Pooled variance_fit	0.00252	Non	0.002561	Non	0.002723	0.002671	Non	Non	Non
Weighted mean of X(Variable)	3.664357	Non	1.799357	Non	0.179522	4.840789	Non	Non	Non
	118.9852	Non	11.84556	Non	7.337077	2546.963	Non	Non	Non
F-score	3.078819	Non	3.078819	Non	3.078819	3.078819	Non	Non	Non
Z-score	1.644854	Non	1.644854	Non	1.644854	1.644854	Non	Non	Non
Chi-score	81.13292	Non	81.13292	Non	81.13292	81.13292	Non	Non	Non
USL_SSLTB	0.943887	0.944329	0.943311	0.944329	0.943221	0.94335	0.944329	0.944329	0.944329

Additionally, **Figure 3** shows trend lines and USLs for the four variables that were determined to be significant.

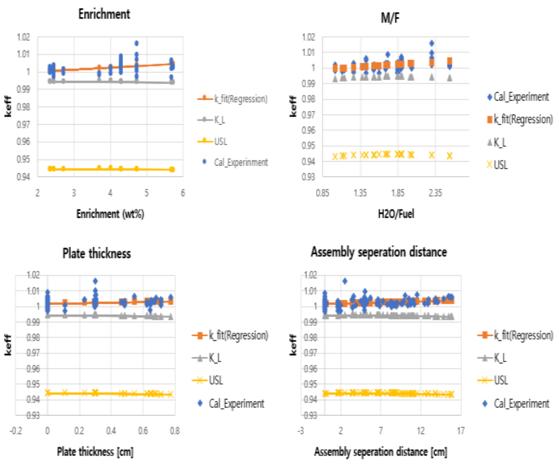

Figure 3. USL Band for Variables

4.2. Criticality calculation

The criticality safety analysis must ensure that the criticality calculation value plus twice the uncertainty is less than the USL. The design of a dry storage cask to be used in this analysis are illustrated in **Figure 4** and dimensions are summarized in **Table 6.** To identify if ATF within ^{235}U-10 wt% enrichment is applicable to storage cask, the criticality calculations of dry storage cask loaded with varying enrichment of ATF were performed. and the results are shown in **Table 7**. Criticality calculation value becomes larger than the USL above ^{235}U-7 wt%. To identify the enrichment of ATF that does not exceed the USL, the criticality calculations were calculated again at ^{235}U-0.1 wt% between ^{235}U-6.5 wt% and ^{235}U-7 wt% and the results are shown in the **Table 8**. The results show that the maximum ATF enrichment that can be loaded into the cask under fresh fuel conditions is ^{235}U-6.7 wt%.

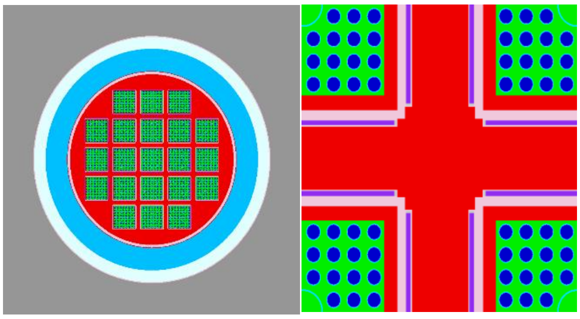

Figure 4. Cross-sectional View of Cask Modeled with SCALE

Table 6. Design Data for Dry Storage Cask

Design Parameters	Specification
Material	Stainless Steel 304
Cask Body Radius (cm)	106.3
Cask Body Length (cm)	528.5
Cask Cover Radius (cm)	97.8
Cask Cover Length (cm)	15.0
Number of Assemblies	21
Radius of Assembly Rack (cm)	81.3

Table 7. k-eff Results for 5 ~ 10 wt%

	k-eff	Uncertainty(σ)	k-eff + 2σ
Enricment	SCALE		
Reference	0.91063	± 0.00026	0.91115
5%	0.89699	± 0.00022	0.89743
5.50%	0.91217	± 0.00026	0.91269
6%	0.92484	± 0.00021	0.92526
6.50%	0.93548	± 0.00023	0.93594
7%	0.94725	± 0.00026	0.94777
7.50%	0.9573	± 0.00022	0.95774
8%	0.96478	± 0.00021	0.9652
8.50%	0.97265	± 0.00024	0.97313
9%	0.97907	± 0.00026	0.97959
9.50%	0.98729	± 0.00022	0.98773
10%	0.9931	± 0.00021	0.99352

Table 8. k-eff Results for 6.5 ~ 7 wt%

	k-eff	Uncertainty(σ)	k-eff + 2σ
Enricment	SCALE		
6.50%	0.93548	± 0.0002	0.93588
6.60%	0.93956	± 0.00024	0.94004
6.70%	0.94085	± 0.00021	0.94127
6.80%	0.94415	± 0.00022	0.94459
6.90%	0.94437	± 0.00022	0.94481
7%	0.94725	± 0.00025	0.94775

4. Summary and Conclusions

In expectation of increased enrichment of the ATF, criticality safety analysis for the SNF storage cask were performed for various enrichments within ^{235}U-10 wt% under fresh fuel conditions to confirm the applicability of increased enrichment of the ATF to the storage cask. The statistically calculated USL based on the report is 0.94322, and the maximum ATF enrichment that can be loaded into the cask without exceeding it was found to be ^{235}U-6.7 wt%. For accurate criticality safety analysis of storage cask and determination of maximum ATF enrichment, it is necessary to consider the uncertainty caused by analyzing abnormal operation conditions and considering manufacturing tolerances. In addition, benchmark problems of critical experiments of at least 5% and no more than 10% are required to calculate an accurate USL. For more accurate analysis and efficient use of storage cask, burnup credits should be applied.

Acknowledgement

This work was supported by Nuclear Safety Research Specialist Training Project through the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2020M2C7A1A0207823522) and Technology Development Project for safe operation of nuclear power plants through the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government (MTIE) (No. 20222B10100040).

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