Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 17-19, 2023

Criticality Study of HALEU Storage in APR1400 New Fuel Storage Using Erbium Absorber

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1. Introduction

The use of high assay low enriched uranium (HALEU) is becoming increasingly important in the nuclear industry, HALEU is a U-235 enriched between 5% and 20%. The benefits of using higher enriched uranium with more than 5% of U-235 include longer core lifetime and fuel cycle length, it also enhances the overall fuel cycle efficiency with a higher discharge burnup [1], in addition to the quantity reduction of high-level waste disposed of per unit energy generated [2]. The new fuel storage room (NFR) for APR1400 type reactor was designed to meet the criticality design criteria with initial enrichment of up to 5% of U-235 under different conditions [3]. However, it’s important to properly store the new fuel before and after residence time in the reactor, and switching to HALEU fuel requires a reevaluation of current the design with the addition of a neutron absorber under normal and accident conditions to ensure that safety limits are met.

Erbium is a promising material for use as a neutron absorber in nuclear fuel due to its relatively low capture cross-section of ranges from 558 to 770 barns in the thermal neutron energy region [7]. Recent research in the field of burnable absorbers has shown that erbium isotopes offer favorable neutronic and nuclear safety properties, including reducing fuel swelling and improving the mechanical properties of the fuel [6].

This paper investigates the possibility of using the existing APR1400 NFR design to store HALEU with different levels of U-235 enrichments, up to 10% without the need of storage room design modification. It’s necessary to calculate the effective multiplication factor (k_{eff}) to determine the whether the new enrichments are below the acceptable limits or not. Using higher U-235 enrichments of more than the current design is likely to increase the criticality state of the current NFR. To meet the design acceptance criteria and reduce criticality, we need to add a new fuel composition containing an absorber material. Erbium in the form of erbium oxide (Er_2O_3) and homogeneously dispersed in the UO_2 fuel matrix is considered as a neutron absorber material to be used.

2. Calculation Methods

The configuration of the NFR is based on the APR1400 design control document released by the NRC. It consists of two regions, each of which has an array of 7x8 rack cells of stainless steel, with a total of 112 fuel assemblies. However, due to a lack of detailed design information, some parameters had to be roughly estimated, the design input data are summarized in table I. The criticality calculations were performed using the MCNP6 simulation tool [8] under normal and postulated accident conditions, the storage room input model was built and the effective multiplication factor (keff) was calculated, all MCNP input models used the ENDF/B-VII.1 ENDF/B-VII.0 cross-section library.

The calculations were performed under various conditions, ranging from a dry room to a flooded one with pure water, and with different U-235 enrichments. The acceptance criteria of the results must be met in order for the NFR to be licensed for HALEU storage, according 10 CFR 50.68 [5], the fresh fuel storage racks flooded with unborated water k_{eff} must not exceed the value of 0.95.

Table I: Design Description

	Parameter	Value
Fuel Rod	Pellet Material	UO2
	Pellet Diameter (cm)	0.8192
	Pellet Density (g/cm3)	10.44
	Cladding material	ZIRLO
	Cladding thickness (cm)	0.05715
	Gap thickness (cm)	0.01651
	Rod active length (cm)	381
Fuel Assembly	Array pitch (cm)	1.2852
	Array size	16 x 16
Rack Cell	Material	SS-304
	Thickness (cm)	0.6
Storage room	Width(cm)	319.5
	Length (cm)	639
	Number of Assemblies	112
	Regions (Array size)	2 x (7x8)
	Center-to-center spacing (cm)	30.5
	Wall material	Concrete
	Wall thickness (cm)	30

According to the original design documents [4], the NFR with 5% of enrichment maintains subcriticality within acceptable limits under both normal and accident conditions. Previous criticality analysis results serve as a reference point for validating the current model's input parameters and assumptions, as they demonstrated the same criticality value under flood accident conditions with the same enrichment, as shown in Table II. Here, the design k_{eff} represents the reference value for evaluating the model's k_{eff}.

Table II: Comparison of K_{eff} between original design and current model

U-235 (%)	Design k_{eff}	Model k_{eff}	Δk	σ (pcm)
5%	0.91257	0.91528	0.00271	35.8

2.1 Model Description and Assumptions

The fuel assembly is a square lattice with a 16 x 16 array which consists of 236 per assembly as shown in Fig.1, the NFR consists of two storage regions each with an array of 7 x 8 fuel assemblies, with 30.5 center to center spacing. The two regions are separated by a distance of 91.6 cm, the model is shown in Fig.2.

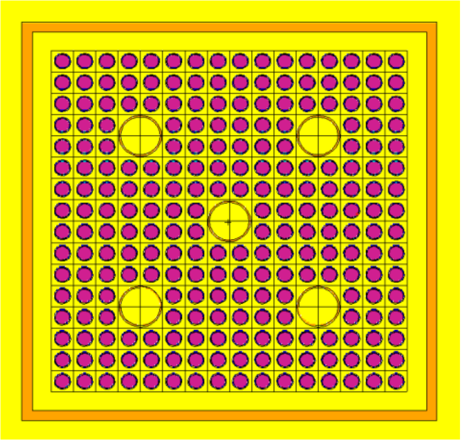

Fig.1 Rack fuel assembly design

The effective neutron multiplication factors were evaluated with the following assumptions:

- Single enrichment has been applied to all the UO2 fuel rods in the NFR for each simulation run,
- Assembly grid, spring, caps are not included in the calculation model
- Burnable absorber rods in fuel assembly are not considered in the calculation model, and
- Rack cell thickness was assumed to be 0.6 cm
- Center to center from the adjacent two regions was assumed to be 91.6 cm

The criticality evaluation for the NFR was performed under different HALEU enrichments ranging from 6% up to 10%, under different postulated accident events where the room would be flooded by pure water with a density of 1 g/cm3. Then the results were evaluated against the acceptance criteria and the reference value to determine whether they met or not.

For those who exceed the acceptance criteria, the fuel is modified by adding erbium oxide (Er_2O_3) at different weight percentages beginning from 0.005 w/o to reduce the criticality until it meets the acceptance criteria. Erbium atoms play an important role reduce the k_{eff}, Er has an absorption cross-section of around 660 barns, Erbium isotopes included in the simulations are Er-162, Er-164, Er-166, Er-167, Er-168, and Er-170

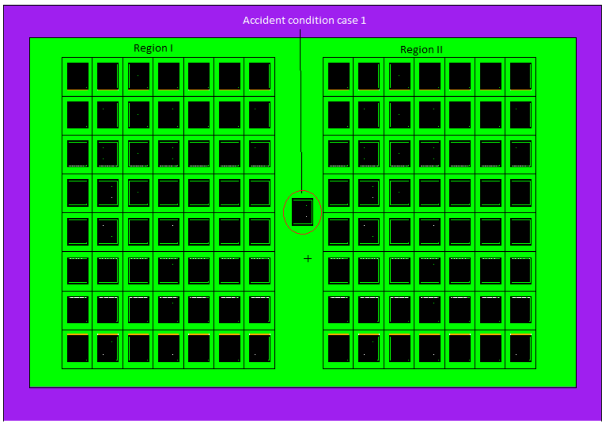

Fig.2 New Fuel Storage Pit model

3. Results and Discussion

3.1. Dry Room Condition

Under normal dry air conditions, the multiplication factor k_{eff} was evaluated by increasing the U-235 enrichment by 1% from 5% up to 10%. It was found that the room remained subcritical at all enrichments, with the highest k_{eff} value being 0.62965 at 10%. Therefore, all values meet the safety acceptance criteria.

3.2. Complete Flood Condition

The first postulated accident scenario assumed that the storage pit was flooded with pure water along with all empty spaces inside the cask area. In this case, water acts as a moderator and the effective multiplication factor is expected to be increased.

The result obtained for the 6% U-235 enrichment level met the acceptance criteria set by 10 CFR 50.68. However, this value was slightly higher than the reference design value. On the other hand, enrichments above this level exceeded the allowable limits. Table III summarizes the results for each enrichment level.

Table III: Change of K_{eff} with different U-235 % at 1.0 water density

U-235 (%)	keff
5%	0.91528
6%	0.94529
7%	0.96904
8%	0.98749
9%	1.00331
10%	1.01613

To reduce the multiplication factor, Er_2O_3 was added to the fuel composition in varying weight percentages (ranging from 0.005 to 0.015 w/o in increments of 0.001). The effective multiplication factor was then evaluated for all enrichment levels.

The addition of erbium to the fuel composition act as a neutron absorber and it reduces the k_{eff} multiplication factor of the NFR and enable the safe storage of the HALEU in the NFR without the need for facility modification. The reduction of k_{eff} below the criticality reference point mentioned in Table II would provide additional safety margins to the current design.

It was found that the amount of erbium varied for each enrichment, for the case of uranium enrichment of 10%, only minimum 0.011 w/o of Er_2O_3 is needed to reduce the k_{eff} to below reference value (0.91257), table IV summarizes the minimum Erbium needed for each enrichment.

Table IV: Minimum erbium oxide weight ratio needed to reduce the criticality below the reference value

U-235 (%)	Er_2O_3 (w/o)	k_{eff}
6%	0.003	0.90289
7%	0.005	0.90537
8%	0.007	0.90750
9%	0.008	0.90835
10%	0.011	0.89172

3.3 Dropped Fuel Assembly Accident Condition

In one of the postulated accident scenarios, a fresh fuel assembly is presumed to be accidentally dropped and positioned in the gap between the fuel racks in a dry-air environment. To evaluate the potential consequences of this situation, a fully loaded NFR model was analyzed with a dropped fresh fuel assembly placed between the fuel racks.

The accident scenario was carried out for two cases, Case one was conducted at the center point between the two regions as shown in Fig.2, while case two was performed between the two regions in contact with region II. The k_{eff} values for the dropped fuel assembly were calculated and presented in Table V, as there would be no moderator in these scenarios, all results of k_{eff} for the NFR satisfy the safety limits.

Table V: k_{eff} values during normal and accident conditions with the selected erbium fractions at different enrichments

U-235 (%)	Er_2O_3 (w/o)	k_{eff} Normal Condition	k_{eff} Accident Condition Case 1	k_{eff} Accident Condition Case 2
6%	0.003	0.49605	0.49877	0.49872
7%	0.005	0.52576	0.52871	0.52880
8%	0.007	0.55427	0.55698	0.55687
9%	0.009	0.58078	0.58371	0.58360
10%	0.011	0.57773	0.58085	0.58047

3. Conclusions and Future Work

This paper studied the possibility of using the existing APR1400 New Fuel Storage Room design to store HALEU from 5% up to 10%. The study aimed to evaluate the need for an absorber material to meet the criticality safety limits under different conditions. The results showed that the existing NFR design with an initial enrichment of 6% U-235 meets the subcriticality safety limits under both normal and postulated accident conditions.

However, increasing the enrichment beyond 6% will lead to criticality safety issues, and adding an absorber material is necessary to meet safety requirements. Erbium oxide (Er_2O_3) was identified as a suitable absorber material to be used due to its favorable neutronic and nuclear safety properties. The effective multiplication factor (k_{eff}) was calculated using the MCNP6 simulation tool, which showed that the current storage design for HALEU, when fully flooded, does not meet safety criteria. However, adding low concentrations of erbium oxide can effectively reduce k_{eff} and meet safety requirements. With the adoption of an Er-U fuel design, the current storage design specifications for the APR1400 NFR can be used for HALEU without the need for facility modification.

Further analysis will be performed to evaluate criticality at the water's optimum moderation density. The use of the HALEU requires criticality evaluation of the spent fuel storage using the same material composition introduced in this paper, which will be investigated in the future.

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