Design of the Dry Modular Storage System for the Damaged PWR Fuel

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1. Introduction

In some parts of the world, nuclear power plants have experienced nuclear fuel damage, making it necessary to evaluate fuel rod integrity and establish reliable methods for the safe handling of damaged fuel. Damage to fuel rods due to cladding imperfections can lead to the release of fission products and accelerate oxidation. Therefore, precise inspections are essential during scheduled maintenance periods.[1]

The DUPIC (Direct Use of Spent PWR Fuel in CANDU Reactors) technology enables the recycling of spent PWR fuel by converting it into CANDU reactor fuel.[2] Through the dry processes involved in the DUPIC method, volatile fission products such as cesium and iodine can be removed, while the remaining fissile materials are effectively utilized in CANDU reactors. Thus, the DUPIC process helps reduce the burden of spent fuel management.

This study proposes a storage solution for damaged PWR nuclear fuel by adapting the DUPIC process. It incorporates the MACSTOR (Modular Air-Cooled Storage)[2] system, which is used for storing CANDU fuel. The focus of this study is to assess the applicability of the MACSTOR system—with minor modifications—by conducting Monte Carlo criticality and radiation shielding evaluations.

2. Modeling and Method

The MACSTOR system is a dry storage facility currently in use at the Wolsong Nuclear Power Plant. It employs passive air cooling, allowing efficient decay heat removal and high storage density. The system can accommodate approximately 60 fuel bundles in 540 storage cylinders, using corrosion-resistant materials to ensure long-term durability.[3,4]

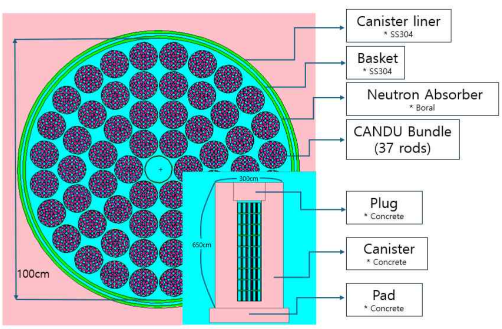

Fig.1. CASK model designed using MCNP

Figure 1 shows the MACSTOR model developed using the MCNP6.2 code.[5] As the original MACSTOR system was designed for spent CANDU fuel, modifications are necessary to store PWR spent fuel, which has higher initial enrichment. To ensure subcriticality in the modified MACSTOR design, this study proposes changes to the fuel loading configuration and the incorporation of neutron absorbers. Radiation shielding evaluations are also performed to determine the optimal storage configuration.

3. Calculation Analysis

To maintain subcriticality in the modified MACSTOR system with damaged PWR fuel, the study considers optimizing fuel placement and positioning annular neutron absorbers. Four models are proposed by increasing the spacing between spent fuel bundles and using partially annular neutron absorbers, as shown in Figure 2.

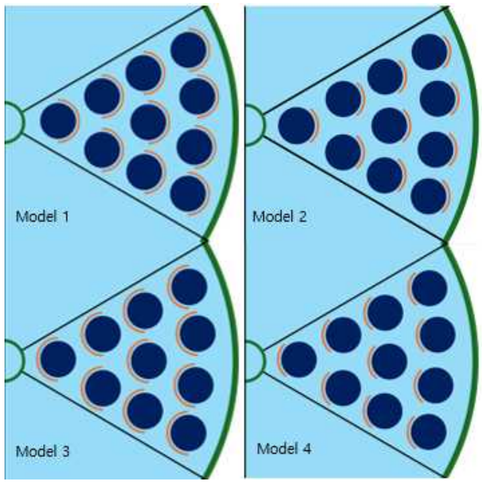

Fig.2. Models based on absorber placement and length

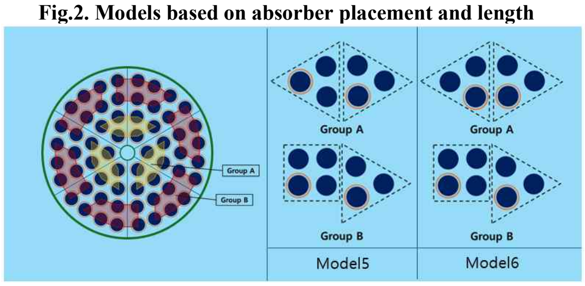

Fig.3. Models 5 and 6 with group-based absorber placement

Because partially annular neutron absorbers (e.g., half or one-third) are difficult to manufacture, two additional models (Models 5 and 6) were examined using a full annular design with fewer absorbers, as illustrated in Figure 3.

The ORIGEN-S code[6] was used to generate source terms for the shielding evaluations. The analysis used the following assumptions: Westinghouse 17x17 fuel with 4 wt% enrichment, a burnup of 50,000 MWd/MTU, an average power of 40 MW/MTU, and a cooling period of 10 years. The neutron and gamma spectra shown in Figure 4 from ORIGEN-S served as input for the MCNP-based shielding analysis.

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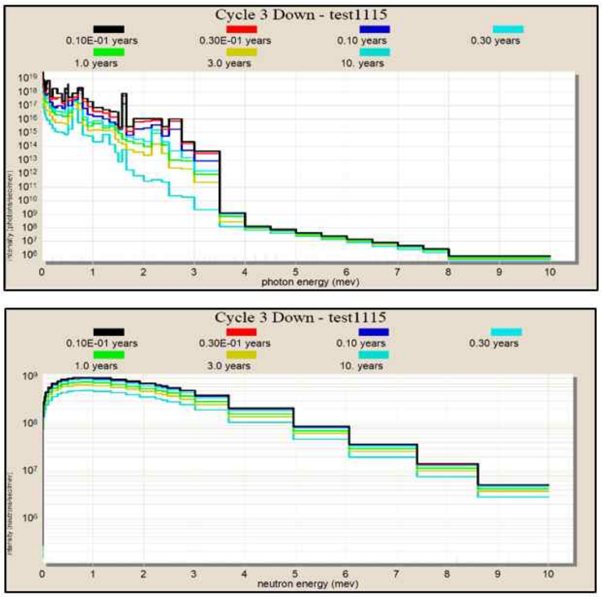

Fig.4. Gamma and neutron spectra from ORIGEN-S

4. Results

4.1 Criticality result from MCNP6.2

Table.1. Criticality Results for Various Models

	Normal condition	Flood condition
Default	0.31614	1.20368
Model1	0.31418	0.82886
Model2	0.31415	0.95970
Model3	0.31064	0.72677
Model4	0.31174	0.83728
Model5	0.31284	0.87302
Model6	0.31215	0.89017

±0.00026

Criticality results for the six proposed cask models are presented in Table 1. Increasing the distance between fuel bundles and introducing neutron absorbers effectively reduces reactivity. All models satisfy the subcriticality requirement under normal dry storage conditions. However, under accident (flooded) conditions, only the original MACSTOR and Model 2 fail to meet subcriticality criteria. Among the rest, Models 3 and 4 show lower k-effective values than Models 1 and 2. Although Models 1 through 4 use the same amount of absorber material, variations in absorber placement lead to differences in neutron leakage. Notably, Models 5 and 6 outperform the other models by optimizing absorber placement into two region groups (Group A and Group B), as shown in Figure 3. This configuration reduces the total mass of neutron absorbers while maintaining criticality safety.

4.2 Radiation shielding evaluation

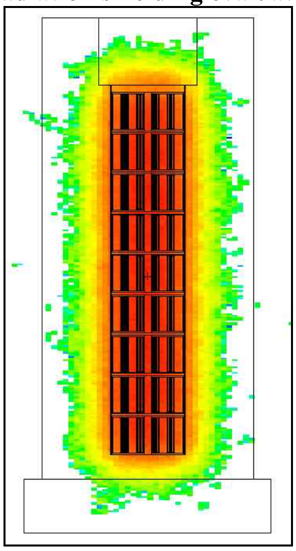

Fig.5. Neutron flux distribution

Fig. 5 depicts neutron flux distribution around the modified MACSTOR system.

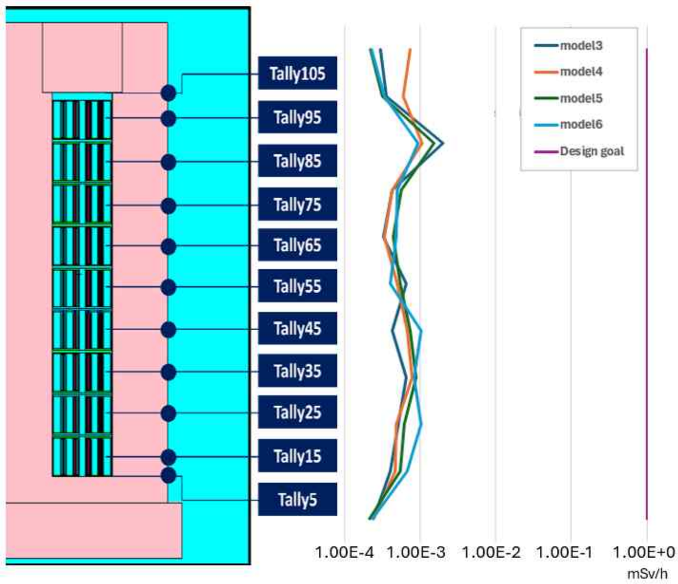

Fig.6. Surface dose rate by tally point

Shielding analyses were conducted for Models 3, 4, 5, and 6, evaluating surface dose rates of the casks as shown in Figure 6. The results indicate that surface dose rates for all evaluated models are significantly below the regulatory threshold of 2 mSv/h, which is the typical safety limit for spent fuel casks.[7]

5. Conclusion

This study proposes a modified dry storage system based on the MACSTOR design to store damaged PWR spent fuel. The introduction of annular neutron absorbers and strategic fuel spacing ensures compliance with criticality safety requirements. Additionally, shielding analyses confirm that all proposed models meet surface dose rate criteria.

Among the configurations, Model 6 is particularly promising, as it reduces the total amount of neutron absorber material while maintaining subcriticality. Although this study only evaluates limited absorber arrangements using two region groups, there is potential for further optimization by refining the absorber layout.

In conclusion, the findings of this study can contribute to the development of safe and efficient storage systems for damaged PWR spent fuel and offer valuable insights for future applications of dry storage technologies.

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