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# Development of Fuel (GIFT) and Thermal analysis (COBRA-SFS) Integrated Code for Advanced Spent Fuel Safety Analysis during Extended Dry Storage

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## 1. Introduction

Several codes have been developed to evaluate the state of spent nuclear fuel, including parameters like hoop strain, stress and hydrogen concentration. However, because they do not support temperature calculations involving radiation, convection, they rely on simplified enthalpy-based models for temperature estimation, necessitating user-defined inputs [1]. Considering the regulation on peak cladding temperature (PCT) limits, there's a need for a precise approach to analyze both the nuclear fuel and thermal aspects comprehensively. Therefore, we developed an analysis code by coupling the fuel analysis code, GIFT, and COBRA-SFS, the thermal analysis code for dry storage systems, and conducted safety assessments for PWR spent fuel.

## 2. Code Integration

In this section, we provide explanations for both GIFT and COBRA-SFS, as well as details on how they are integrated.

### *2.1 Fuel Analysis Code, GIFT*

GIFT is a C++ based single rod fuel performance code developed in Seoul national university. GIFT includes two dimensional axis-symmetric structural model and multi-layer model to analyze coated cladding [2]. Especially it includes features for spent fuel which are α-decay induced pellet swelling, limited fission gas release, EDF cladding creep model [3], and hydrogen behavior [4]. GIFT has been compared and validated with the experiments included in OECD NEA databank.

### *2.2 Thermal Analysis Code for Dry Storage System, COBRA-SFS*

COBRA-SFS is a Fortran based thermal analysis code which is designated to simulate dry storage system incorporating conduction, convection and radiation heat transfer [5]. It simulates geometric components including metallic canister, basket racks, and fuel rod. COBRA-SFS has been validated through several dry storage experiments.

### *2.3 Integrated Code Scheme*

As shown in Fig. 1, the coupled code starts with normal operation with user-defined information such as linear pin power, coolant temperature, and geometric details of fuel rod. Following normal operation, a wet storage simulation is conducted before transitioning to dry storage.

When dry storage begins, the coupling process is initiated, where GIFT transfers cladding hoop strain ($\epsilon(z)$) and volumetric decay heat ($q'''$) to COBRA-SFS, which then assigns flow channels and view factors using COBRA-SFS input file and transferred data. After conducting thermal analysis, COBRA-SFS transfers the distribution of cladding outermost temperature to GIFT, which then proceeds with spent fuel analysis.

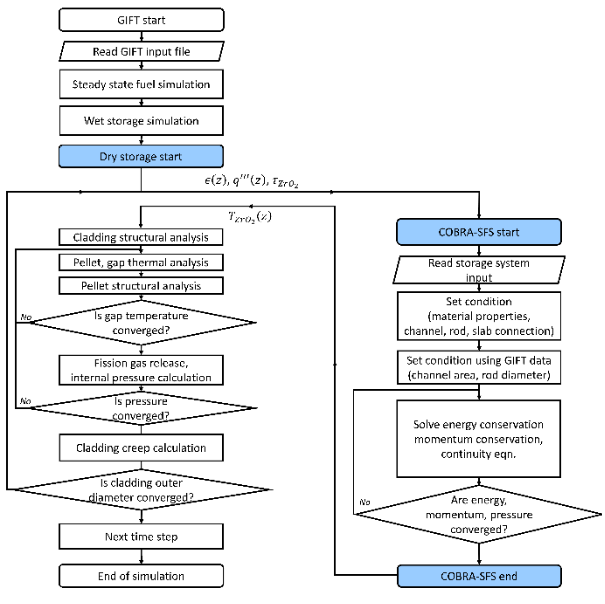



Fig. 1. The flowchart of integrated dry storage analysis code.

## 3. Simulation results

### *3.1 Simulation Conditions*

In this section, the normal operation, fuel assembly, and dry storage system conditions are provided for the high burnup spent fuel safety assessment during dry storage. Fig. 2 shows the details of fuel rod and reference 17 by 17 fuel assembly with 25 guide tubes. The plenum length of the rod is set to two different lengths to observe the effect of rod internal pressure, particularly in high burnup scenarios. Table I shows the normal operation and dry storage system input data.

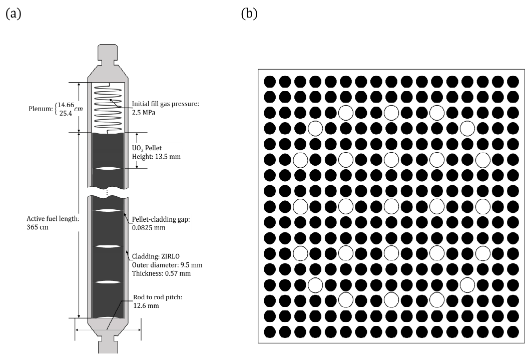
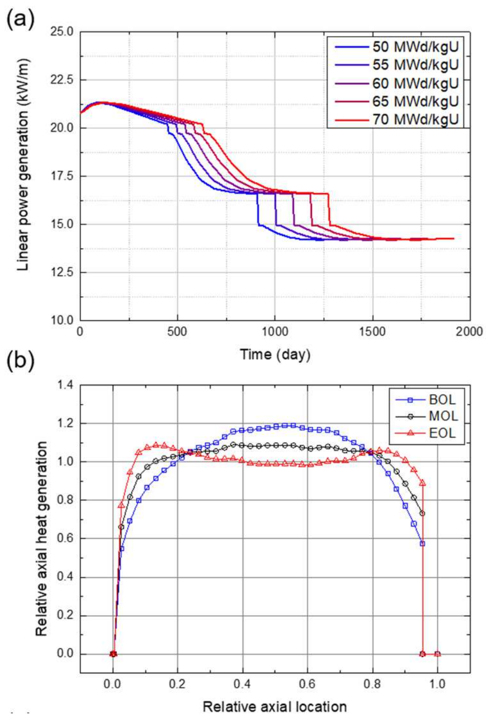



Fig. 2. (a) Reference fuel rod schematic and details, (b) Reference fuel assembly schematic.

Table I: Normal operation and dry storage system input Description

| Feature | Information |
|---|---|
| Averaged linear pin power [kW/m] | 18 |
| System pressure [MPa] | 15.5 |
| Coolant inlet temperature [K] | 564 |
| Coolant mass flux [kg/m2s] | 3465 |
| Number of batches | 3 |
| Discharge burnup [MWd/kgU] | 50, 55, 60, 65, 70 |
| Initial U-235 enrichment [ %] | 4.2, 4.5, 4.95, 5.5, 6.0 |
| Decay heat | ORIGEN data |
| Wet storage time | 3.5 to 12 years |
| Dry storage cask | TN-24P |
| Basket cavity length [cm] | 22.1 |
| Basket channel axial length [cm] | 405 |
| Cask outer diameter [cm] | 228.1 |
| Backfill gas | Helium |
| Backfill gas pressure [MPa] | 0.1 |
| Background temperature [K] | 293 |



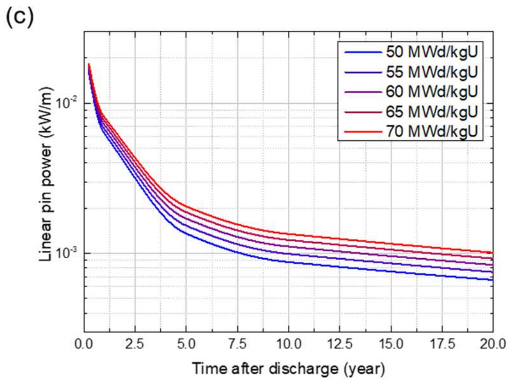




Fig. 3. (a) Linear pin power during normal operation, (b) Relative axial power distribution, (c) Linear pin power after discharge

### *3.2 Simulation results*

The maximum cladding temperature of each discharge burnup is depicted according to the wet storage period in Fig. 4. Each data point in Fig. 4 corresponds to 20 years of dry storage simulation.

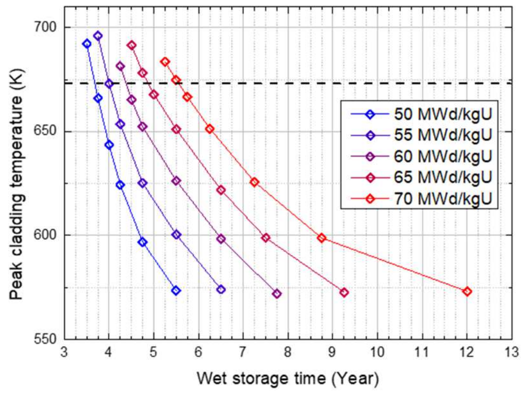
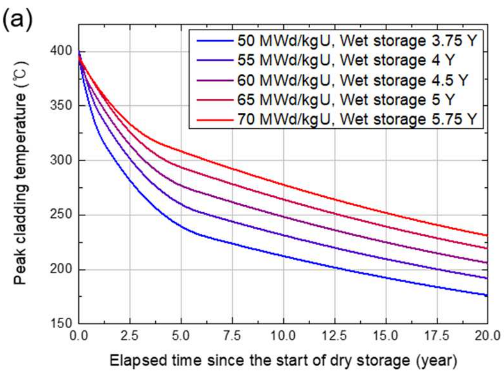



Fig. 4. The initial PCT of the highest temperature fuel rod within the dry storage system depending on the discharge burnup and the wet storage time.

The PCT, rod internal pressure, cladding hoop strain, cladding hoop stress, and hydrogen concentration of various discharge burnup near the PCT of 400 ℃ with the plenum length of 14.66 cm are illustrated in Fig. 5.



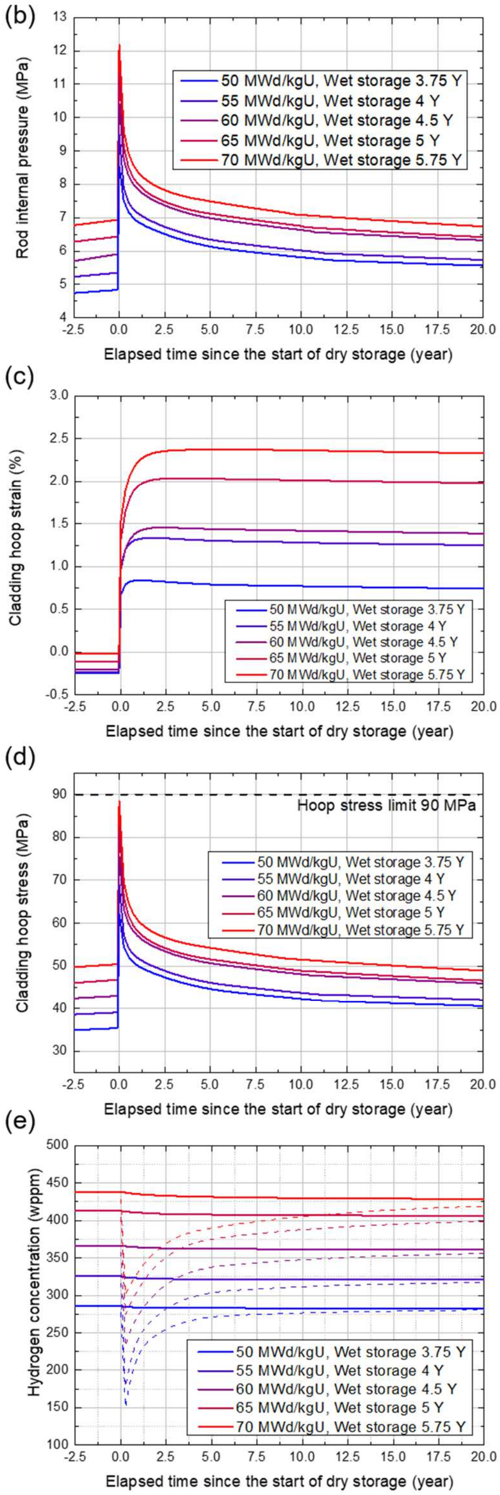
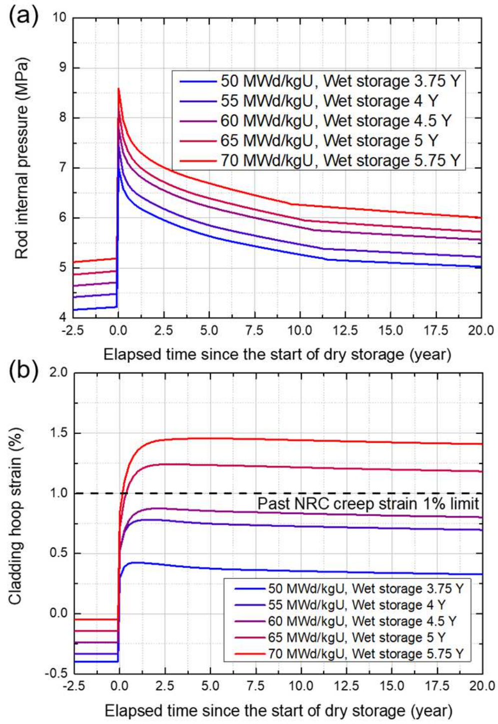



Fig. 5. Dry storage results of fuel rod with plenum length of 14.66 cm with respect to dry storage time (a) PCT, (b) Rod internal pressure, (c) Cladding hoop strain, (d) Cladding hoop stress, (e) Hydrogen concentration at the peak temperature node

Fig. 5(a) illustrates the PCT for spent fuel, showing that higher discharge burnup leads to slower cooling during dry storage. For instance, at a discharge burnup of 50 MWd/kgU, cooling from 400°C to 250°C takes about 4 years, compared to around 15 years for a discharge burnup of 70 MWd/kgU. In Fig. 5(b), it's observed that rod internal pressure at the onset of dry storage increases due to fission gas content and increase of temperature. The cladding hoop strain, shown in Fig. 5(c), also increases as dry storage begins, potentially exceeding past NRC creep strain limits but staying within safe margins based on studies on cladding creep [6-8].

The cladding hoop stress is shown in Fig. 5(d), which corresponds to rod internal pressure. In the early stages of dry storage, hoop stress increases due to the increase of temperature, but as creep strain leads to an increase in void volume, the hoop stress decreases rapidly. In Fig. 5(e), the hydrogen concentration at the peak temperature node is illustrated, with the solid line representing the total hydrogen concentration and the dashed line indicating the hydride concentration. During dry storage, the maximum amount of hydrogen capable of causing hydride reorientation is approximately 200 wppm, and this amount precipitates within 10 years as the temperature decreases.

Results show that hoop stress decreases rapidly due to temperature reduction and the increase in internal void volume caused by cladding creep. The results also indicate that the spent nuclear fuel is most vulnerable at the early stage of dry storage. However, the hoop stress illustrated in Fig. 5(d) is close to the limit of 90 MPa. Therefore, to mitigate stress level, simulations were conducted for a plenum length of 25.4 cm, and the rod internal pressure, cladding hoop strain, and cladding hoop stress are presented in Fig. 6.



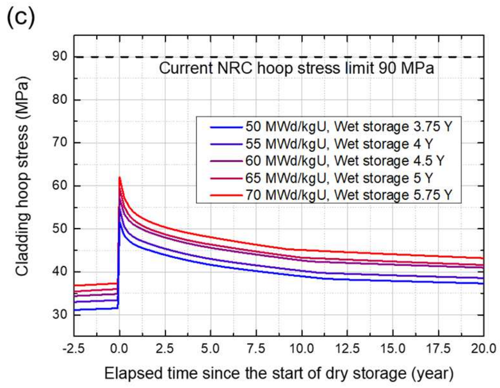



Fig. 6. Dry storage results of fuel rod with plenum length of 25.4 cm with respect to dry storage time (a) Rod internal pressure, (b) Cladding hoop strain, (c) Cladding hoop stress

The results for rod internal pressure are shown in Fig. 6(a), ranging from 8 to 8.5 MPa, which differs by approximately 4 MPa compared to a plenum length of 14.66 cm under the same conditions. When the plenum length is smaller, as shown in Fig. 5(c), only a discharge burnup of 50 MWd/kgU does not exceed cladding hoop strain of 1%. However, as shown in Fig. 6(b) increasing the plenum length allows for discharge burnups up to 60 MWd/kgU to stay below 1%. The Cladding hoop stress in Fig. 6(c) exhibits a similar trend to the rod internal pressure, significantly reducing the threat of cladding reorientation.

## 3. Conclusions

The integrated fuel-thermal analysis code for dry storage analysis is developed in this study. Simulation conditions for high burnup spent fuel have been established, and dry storage has been simulated. The results indicate a rapid decrease in hoop stress due to cladding creep and temperature reduction, highlighting the greatest threat during the early stages of dry storage. Additionally, increasing the plenum length proved effective in reducing hoop stress.

## ACKNOWLEDGEMENT

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