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Leak Detection Method for Integrity Monitoring of Spent Nuclear Fuel Dry Storage Casks

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1. Introduction

Spent nuclear fuel (SNF) dry storage casks have been operated at commercial nuclear power plant sites over more than 30 years [1]. The storage term of SNF in dry storage casks has been sought to extend due to continued delays in establishing permanent disposal facilities in most countries that operate nuclear power plants. As the storage terms of SNF are extended, aging management and monitoring issues become progressively more important for ensuring the safe operation of the dry storage casks.

Variety of technologies are in use for confinement monitoring of SNF dry storage systems [2]. Recently, canister surface temperature (CST) has been studied for detecting helium gas leak from canister, experimentally and analytically [3,4]. It would be beneficial for prolonged storage term of casks if the canister internal pressure can be predicted without making any pressure port through the canister wall.

In this study, a leak detection method based on CST is proposed for integrity monitoring of SNF dry storage casks. Artificial neural network models are used for predicting internal pressure and peak cladding temperature (PCT) and the prediction method is validated through a pressure variation test.

2. Pressure Variation Test and CFD Analyses

2.1 Description of the Test Rig

A test rig has been constructed to investigate thermal behaviors of the vertical dry storage cask with reference to the domestic design of storage cask having a metallic canister with concrete overpack [5]. The main purpose of the test rig is to analyze relationships among the state parameters such as the internal pressure, PCT, and CST and to validate the prediction models.

The test rig is scaled-down with 1/3 height of the reference cask design and loaded with a single 16x16 fuel assembly, as shown schematically in Fig. 1. The fuel rods are simulated by electric heaters with a power supply which allows variation of decay heat of the fuel assembly. The fuel assembly is composed of 236 rods and enclosed by a basket. The canister containing the fuel assembly is filled with helium gas. Downflows are developed through the holes of support disks installed between the basket and the canister shell due to natural convection of helium in the canister. Upward air flow is caused in the annular gap between the canister shell and the cask body.

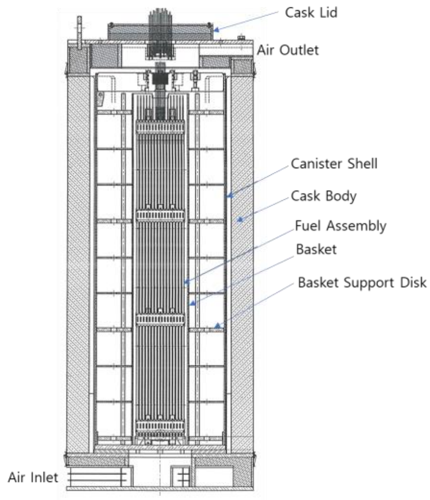

Fig. 1. Vertical cross-sectional view of the test rig.

Fig. 2 shows the test rig equipped with the multi-channel data recorder connected to sensors for measuring fuel rod cladding temperature, inlet air temperature, cannister surface temperature, and canister internal pressure.

Fig. 2. Photo of the test rig.

Fuel temperature sensors are attached to six fuel rods along the diagonal and transverse directions in the fuel assembly, as shown in Fig. 3, at five axial levels corresponding to 10%, 30%, 50%, 70%, and 90% of the active fuel length.

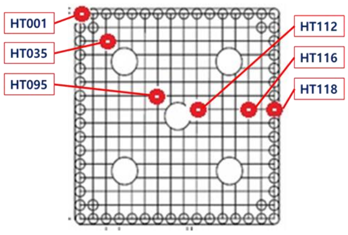

Fig. 3. Sensor-attached rods in the fuel assembly.

Canister surface temperature sensors are attached to the canister surface at positions of four axisymmetric directions as shown in Fig. 4 and axially at the same five axial levels.

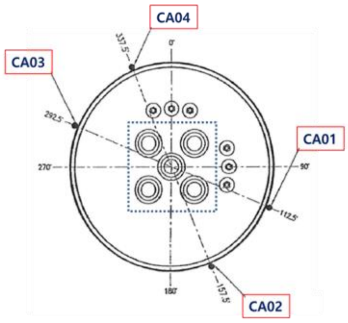

Fig. 4. CST measurement positions on the canister.

2.2 Pressure Variation Test

An experiment was performed to simulate helium leak in the test rig. Initial gas fill pressure was chosen to be 0.35 MPa with fuel assembly power of 1.7 kW. Helium pressure was decreased slowly over 250 hours with several drops as shown in Fig. 5. Ambient air temperature was maintained around 16 ℃.

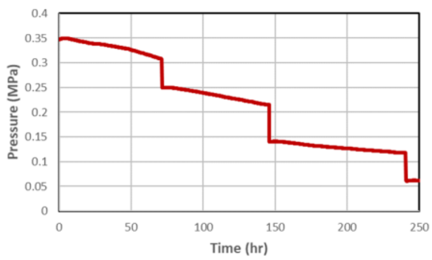

Fig. 5. Pressure variation during the test.

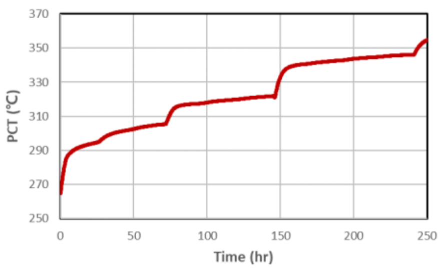

Fig. 6. Measured PCT during the test.

The measured PCT during this test is shown in Fig. 6. Generally, PCT increases as the helium pressure decreases. An exponential increase of PCT at the initial stage of the test indicates that the thermal state of the test rig during this period is not in thermal equilibrium. The same kind of thermal transients are observed at the time points of abrupt pressure drops. PCT is shown to follow the inverse helium pressure with a time delay.

2.3 Thermal Analysis of the Test

The pressure variation test was analyzed using ANSYS FLUENT R18.0 code [6]. The analyses were performed with the steady time option at canister pressures where thermal state is in quasi-equilibrium.

Fig. 7 is the temperature distribution results for an 1/8 section of a 3D model of the test rig at the time point right before the first pressure drop when the internal pressure reached 0.308 MPa. The total number of mesh cells used was 1.82 million. Fig. 7(b) shows the temperature distribution on the symmetry boundary and Fig. 7(c) shows the temperature distribution on the canister shell surface.

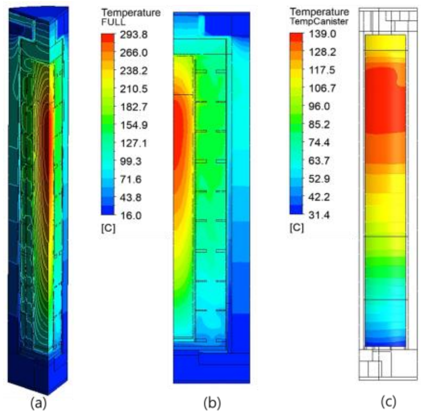

Fig. 7. Temperature distribution at 0.308 MPa.

The viscous model was the realizable k-ε model with standard wall function option. Thermal radiation was modeled with the discrete ordinates model with 5x5 divisions. The pressure-velocity coupling scheme was the ‘coupled’ algorithm. Ideal-gas law option was chosen for helium density property which is considered significant for calculating driving force for natural convection flow.

The fuel assembly was modeled by a porous media. Separate FLUENT calculations were carried out to determine the transverse effective thermal conductivity and the flow resistance of the porous media in accordance with the known guidelines [7].

Fig. 8 shows the calculated cladding temperature axial profiles of the hottest rod (HT095 of Fig. 3) at three different canister pressures which correspond to the time points right before the pressure drops shown in Fig. 5. Fig. 9 shows the calculated canister surface temperature axial profiles at the circumferential position shown in Fig. 4 at the three different canister pressures. Figs. 8 and 9 also show the corresponding measured temperature profiles for comparison purposes.

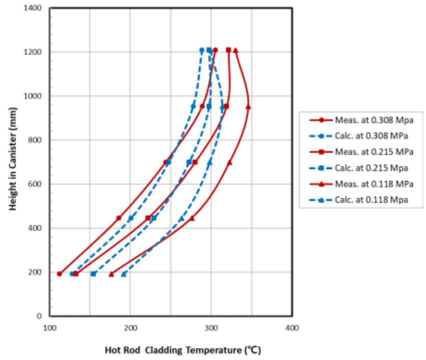

Fig. 8. Cladding temperature profiles of the hottest rod.

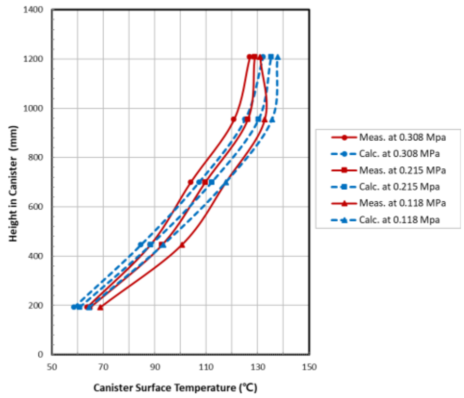

Fig. 9. Canister surface temperature profiles.

It is noted that heat conduction and convection in the canister become less active when the helium pressure becomes lower. As shown in the figures, the cladding and the canister surface temperatures increase and the position of the peak values tends to move towards the central zone from the upper position as the helium pressure decreases.

It is observed that the current FLUENT model underestimates the cladding temperature while overestimates the canister surface temperature, and the prediction performance deteriorates as the canister pressure is lowered. However, the thermal behavioral tendency as a function of canister pressure was predicted well to a certain degree in general.

3. Neural Network Prediction Engine Based on FLUENT Analysis Data

3.1 Database for Neural Network Training

A database for neural network training was generated using the FLUENT model developed in the previous section. The reference state for the FLUENT calculation was set at canister pressure of 0.308 MPa, assembly power of 1.7 kW, and ambient temperature of 16 ℃. For the construction of database matrix, canister pressure was varied from 0 to 0.46 MPa for 7 different value points, fuel assembly power was varied from 1.6 to 1.84 kW for 3 value points, and ambient air temperature was varied from 10 to 35 ℃ for 4 value points, resulting in 84 calculation cases in total.

3.2 Neural Network Prediction Models

For the purpose of integrity monitoring of dry storage casks, the prediction engine is comprised of neural network models for PCT and canister pressure prediction using CST as inputs signals which can be obtained by temperature sensors attached outside the canister shell.

The neural network models represent the physical and numerical relationships between PCT and CSTs and between the internal pressure and CSTs. Fundamental 3-layered network structure such as Fig. 10 was employed, using delta rule with the backpropagation algorithm.

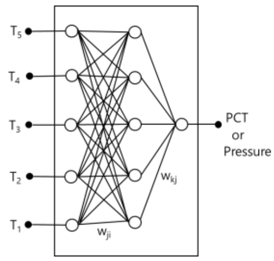

Fig. 10. Schematic depiction of neural network model.

The input variables shown in Fig. 10 are CSTs at the five axial levels as explained in Section 2.1 and output variable is the PCT or the canister internal pressure. Weight vectors, w_{ji} and w_{kj}, that define synaptic connectivity between nodes in the neural network are to be determined through the iterative learning process of backpropagation algorithm on the database constructed with the FLUENT results.

Since the dependency characteristics of the PCT and the internal pressure on the CSTs are quite different, neural network models of the prediction engine were developed separately for the PCT and the internal pressure. It is expected that the pressure dependency on the CSTs is much more complex and sensitive than the PCT dependency on the CSTs. Therefore, in case of the pressure prediction network model, variables of temperature slope derived from CSTs were added as additional secondary inputs to improve prediction performance.

4. Prediction Engine Application to Leak Detection

The neural network prediction engine described in the previous section has been applied to the PCT and pressure predictions for the pressure variation test.

Fig. 11 shows the predicted results of PCT compared with the measured PCT and Fig. 12 shows the predicted results of canister pressure compared with the measured pressure.

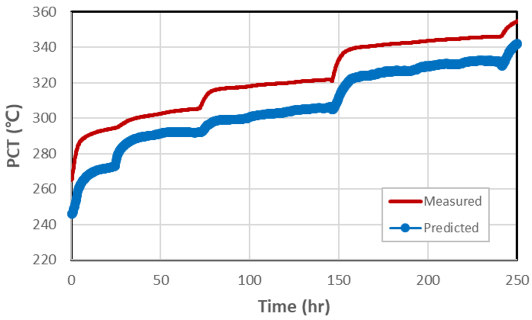

Fig. 11. Monitoring results of peak cladding temperature.

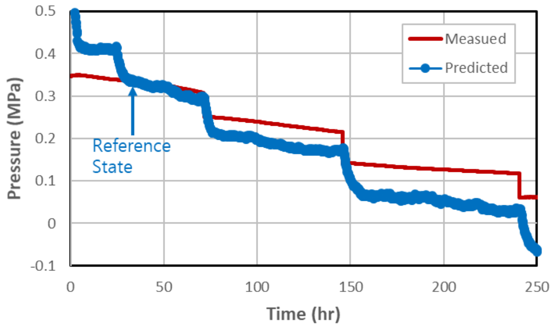

Fig. 12. Monitoring results of canister pressure.

The prediction results of the prediction engine show a certain amount of deviation between the prediction and the measurement for both the PCT and pressure. The prediction performance over the overall time period of the test is better for the PCT than for the canister pressure, which is expected because the PCT is more directly correlated with the surface temperature than the pressure is.

The primary goal of the integrity monitoring of SNF dry storage casks is not to obtain the PCT and the pressure with a high degree of accuracy, but to detect any leakage occurrence in the canister resulting from confinement degradation. Therefore, it is important for the monitoring purpose to detect any changes in the PCT and the canister pressure from the reference values.

It is assumed that the initial canister pressure is known, because the canister is filled with helium to a prespecified pressure value before it is sealed by welding according to the relevant work procedure. In the pressure variation test, a stabilized thermo-fluidic state was obtained as the reference state at 0.335 MPa after 33 hours of thermal transient. In order to improve the prediction performance of the prediction engine, input temperature signals were compensated by the deviations between the calculated and the measured values obtained for the reference state.

Once the canister thermal state is stabilized to the reference state after initial transient, the prediction engine can perceive even a very slow loss of pressure as well as a sudden drop of pressure as shown in Fig. 12. Helium leak can be detected by a pressure decrease accompanied with PCT increase. When the pressure and the PCT changes exceed the specified limit values, the engine should raise the alarm for maintenance action for that cask. Although the amount of pressure decrease is overpredicted at the lower range of pressure, this is not considered disadvantageous for leak detection purpose.

5. Conclusions

A leak detection method has been developed for integrity monitoring of dry storage casks. The method employs a prediction engine comprising of neural network models for predicting PCT and canister pressure. The prediction engine uses only canister surface temperatures as input for prediction without need of sensors installed through canister wall. Database for training neural networks was generated using FLUENT calculations.

The prediction engine has been applied to a pressure variation test for validation. The test results showed that helium leak in the cask can be easily detectable by pressure and PCT changes predicted with the proposed method.

ACKNOWLEDGMENTS

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REFERENCES

[1] O.K. Chopra, et. al, Managing Aging Effects on Dry Cask Storage Systems for Extended Long-Term Storage and Transportation of Used Fuel, ANL-12/29, Argonne National Laboratory, 2012.
[2] Chang-Yeal Baeg and Chun-Hyung Cho, Status Analysis for the Confinement Monitoring Technology of PWR Spent Nuclear Fuel Dry Storage System, JNFCWT, Vol.14, No.1, pp.35-44, 2016.
[3] Hirofumi Takeda, et. al, Development of the Detecting Method of Helium Gas Leak from Canister, Nuclear Engineering and Design, Vol. 238, pp.1220-1226, 2008.
[4] Jie Li and Yung Y. Liu, Thermal Modeling of a Vertical Dry Storage Cask for Used Nuclear Fuel, Nuclear Engineering and Design, Vol. 301, pp.74-88, 2016.
[5] Tae-Man Kim, et. al, Preliminary Shielding Analysis of the Concrete Cask for Spent Nuclear Fuel Under Dry Storage Conditions, JNFCWT, Vol.15, No.4, pp.391-402, 2017.
[6] ANSYS Fluent User's Guide, Release 18.2, ANSYS, Inc., 2017.
[7] Ghani Zigh and Jorge Solis, Computational Fluid Dynamics Best Practice Guidelines for Dry Cask Applications, NUREG-2152, U.S.NRC, 2013.