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Technical note

An assessment of temperature history on concrete silo dry storage system for CANDU spent fuel

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ABSTRACT

Concrete silo is a dry storage system for spent fuel generated from CANDU reactors. The silo is designed to remove passively the decay heat from spent fuel, as well as to secure the integrity of spent fuel during storage period. Dominant heat transfer mechanisms must be characterized and validated for the thermal analysis model of the silo, and the temperature history along storage period could be determined by using the validated thermal analysis model. Heat transfer characteristics on the interior and exterior of fuel basket in the silo were assessed to determine the temperature history of silo, which is necessary for evaluating the long-term degradation behavior of CANDU spent fuel stored in the silo. Also a methodology to evaluate the temperature history during dry storage period was proposed in this study. A CFD model of fuel basket including fuel bundles was suggested and temperature difference correlation between fuel bundles and silo's internal member, as a function of decay heat of fuel basket considering natural convection and radiation heat transfer, was deduced. Temperature difference between silo's internal cavity and ambient air was determined by using a concept of thermal resistance, which was validated by CFD analysis. Fuel temperature was expressed as a function of ambient temperature and decay heat of fuel basket in the correlation, and fuel temperature along storage period was determined. Therefore, it could be used to assess the degradation behavior of spent fuel by applying the degradation mechanism expressed as a function of spent fuel temperature.

1. Introduction

Concrete silos (300 silos with 540 fuel bundles per silo) for storing spent fuel are in operation at Wolsong nuclear power plant site in Korea. It is a cylindrical reinforced concrete structure with lined cavity to store nine seal-welded fuel baskets, each containing sixty bundles of CANDU spent fuel, and concrete structure with its inner lining provides an effective radiation shield. A concrete plug and a cover plate are seal-welded at the top of silo.

The decay heat generated from spent fuel is passively removed to ambient environment, while the integrity of fuel must be maintained during dry storage period. The fuel integrity is one of the most important factors for long-term dry storage, and it is difficult to separate the interrelated degradation mechanisms to affect the integrity of spent fuel. Since nearly all potential degradation mechanisms are sensitive to temperature and in some cases, temperature history, the need for realistic, detailed temperature and temperature distributions in spent fuel has been identified. For this reason, temperature history of spent fuel is required to evaluate its integrity, and thermal analysis of the silo by Computational Fluid Dynamics (CFD) model provides general insight into the expected thermal behavior of silo including spent fuel temperature.

The silo naturally employs a passive heat removal system that releases the decay heat from spent fuel to the external environment by heat transfer processes. This main heat transfer modes in the basket storing spent fuel are classified into conduction, radiation and convection heat transfers. Heat from the basket flows to the concrete silo wall through the processes of thermal radiation and conduction heat transfer, and is then transferred to the exposed surfaces of the silo through the concrete wall by thermal conduction heat transfer. The exposed surfaces dissipate heat by thermal radiation and natural convection heat transfer.

Most thermal analyses of dry storage systems and facilities were related to PWR spent fuel. There has been very little research regarding the thermal behavior of CANDU spent fuel in dry storage environment (Chun and Ryu, 2000). Taralis and Nash (1983) conducted a thermal analysis for several alternative designs of a CANDU irradiated fuel transport cask under normal operating conditions (Taralis and Nash, 1983). Their work focused on the

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Nomenclature

ρ_0	operating density
ρ	density
W	velocity vector
U	velocity
μ	viscosity
P	pressure
g	acceleration due to gravity
β	thermal expansion coefficient
T	temperature
T_0	operating temperature
I	radiation intensity
$\vec{r}$	position vector
$\vec{s}$	direction vector
Φ	phase function
Ω'	solid angle
T_{liner}	liner temperature of concrete silo
T_s	surface temperature of concrete silo
Q_b	decay heat per basket
R_1	thermal resistance in liner region
R_2	thermal resistance in concrete region
T_{amb}	ambient temperature
Q_s	insolation
R_3	thermal resistance by convection from outer surface of concrete silo
R_4	thermal resistance by radiation from outer surface of concrete silo
r_1	inner radius of liner
r_2	outer radius of liner
k_l	thermal conductivity of liner
L	length of concrete silo
r_3	outer radius of concrete silo
k_c	thermal conductivity of concrete
h_{conv}	convective heat transfer coefficient on outer surface of concrete silo
h_{rad}	radiative heat transfer coefficient on outer surface of concrete silo
k_a	ambient air conductivity
H	height of concrete silo
Gr	Grashof number
Pr	Prandtl number
σ	Stefan–Boltzmann constant
ε_c	emissivity on concrete surface
Ra_b	Rayleigh number in basket
D_b	basket diameter
T_{max}	maximum temperature in basket
T_b	basket wall temperature
α	thermal diffusivity
ν	kinematic viscosity
Q_c	lumped convection/conduction heat transfer rate
Nu_b	Nusselt number
T_f	maximum fuel temperature

influences of the external heat transfer fins of cask, the form of internal medium, decay heat, ambient condition and geometric shape on the temperature of spent fuel. Sermer (1986) developed an analytic model to obtain the maximum temperature of a spent fuel residing in air environment and showed that his numerical analysis results agreed with the existing experimental data of 19 and 28 electric heater bundles (Sermer, 1986). Patterson and Swanson (1990) obtained the radial temperature profile of the fuel basket with sixty simulated fuel bundles operating at 6 W each having a total of 360 W (Patterson and Swanson, 1990). This basket was modeled as being inside the concrete canister assuming that it contained sixty bundles of six-year cooled CANDU fuel element. Recently, Moffett (1996) reported experimental results regarding the thermal behavior of a spent fuel dry storage module, CANSTOR, which is AECL's air cooling concrete vault (Moffett, 1996). The CANSTOR module is capable of storing 12,000 bundles of spent fuel in 200 baskets loaded in two rows of ten storage cylinders. Moffett showed that fuels cooled much less than 8 years could be loaded into the CANSTOR module.

However, previous research focused on maximum temperature evaluations from the perspective of design during an initial phase of storing spent fuel in a storage facility, and there have been almost no temperature history evaluations during the required storage periods for degradation behavior evaluation. This temperature history can be as important as the maximum temperatures in assessing the long-term behavior of the dry storage system.

Important heat transfer mechanisms must be characterized and validated for a development of a thermal analysis model, which could be employed in estimating the temperature history with respect to the required storage period, and this temperature history has to be generalized as a function of ambient temperature and the decay heat of a basket for evaluating the long-term degradation behavior of CANDU spent fuel stored in the concrete silo.

The main objective of this study is to predict the temperature distribution and history in the silo including fuel basket by a CFD code using additional input data and heat transfer correlations. In addition, the results generalized to the temperature difference correlations are presented in order to assess the degradation behavior of spent fuel.

2. Concrete silo dry storage facility

2.1. Specifications of spent fuel and basket

A spent fuel basket stored in the silo, which is a dry storage facility for CANDU spent fuel, is a cylinder made of stainless steel type 304L with external diameter of 1.06 m and height of 0.56 m, and it is capable of storing sixty bundles of CANDU spent fuel. As

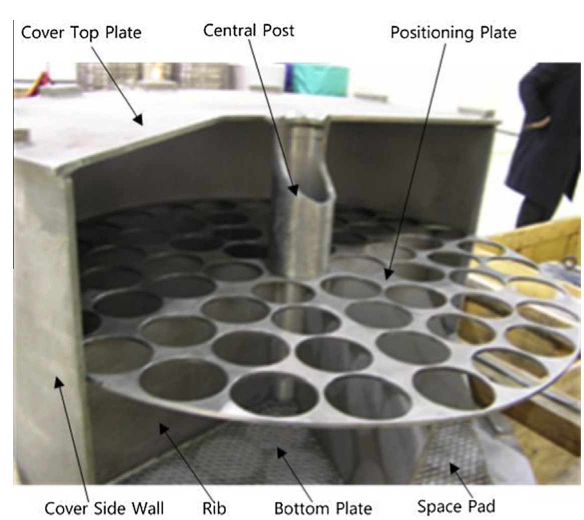

Fig. 1. Fuel basket structure.