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Parametric Effects of Ambient Conditions on Thermal Safety of Wolsong (CANDU) Unit 1 Spent Fuel Dry Storage Canister

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월성1호기 사용후 핵연료 건식저장 캐니스터의 열적 안전성에 미치는 대기 조건 인자의 영향

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Abstract

A simplified thermal analysis method to evaluate the maximum temperature of the CANDU 37-element fuel bundle within a fuel basket in a given spent fuel dry storage canister has been presented along with the results of sample analyses performed to examine the parametric effects of the ambient conditions on the maximum fuel temperature within a canister. To solve the multi-dimensional heat transfer problem of the complex geometry of rod bundles within a canister where three modes of heat transfer are superimposed, the CANDU spent fuel bundles stored in the dry storage canister are first replaced by equivalent concentric fuel cylinders. The simplified axi-symmetric two-dimensional multi-mode heat transfer problem of the equivalent fuel cylinders is then analyzed with an existing computer code, HEATING5, using additional input data and heat transfer correlations. A comparison between the predicted temperature profile and the mock-up test results shows that the agreement is quite satisfactory.

요 약

사용후 핵연료 건식 저장 캐니스터의 핵연료 바스켓 안에 있는 CANDU 37소자 핵연료 다발의 최대 온도를 계산하기 위한 단순화된 열해석 방법과 함께 대기 조건 인자들이 캐니스터 내부의 최대 핵연료 온도에 미치는 영향을 조사하기 위해 수행한 표본 해석 결과를 제시하였다. 3가지 모우드(mode)의 열전달이 공존하는 캐니스터 내부 핵연료 다발의 복잡한 기하학적 구조에 대한 다차원

열전달 문제를 풀기 위하여 건식저장 캐니스터에 저장된 CANDU 사용후 핵연료 다발들을 등가 및 동심의 핵연료 실린더(cylinder)로 대치하였다. 추가적인 입력 자료 및 열전달 상관식을 이용하여 등가 핵연료 실린더의 단순화된 축대칭, 2차원, 복수 모우드(*multi-mode*)의 열전달 문제를 기존의 컴퓨터 코드인 HEATING5로 해석하였다. 예측한 온도 분포와 실물 모형 실험 결과의 비교는 만족스러울 정도로 일치함을 보여주고 있다.

1. Introduction

Most recently, the concept of interim dry storage of spent fuel in concrete canisters for Wolsong nuclear power plant unit 1 (a CANDU-PHWR) has been approved by the licencing authority. The Wolsong canister is identical to the Point Lepreau's dry storage system and is an adaptation of the original Whiteshell Nuclear Research Establishment design.

An in-depth review of the safety analysis report of the Wolsong spent fuel dry storage canister project [1] shows that there are two central thermal safety issues for any storage canister design :

(1) What would be the maximum fuel temperature within a dry storage canister under given design conditions, and would the maximum fuel temperature exceed the potential fuel oxidation temperature?

(2) What are the parametric effects of the ambient conditions on the maximum fuel temperature within a canister?

The thermal safety questions are mainly coming from the design requirement that fuel temperature should not exceed the fuel oxidation temperature. The potential for oxidation of the UO_2 fuel inside a storage basket is a function of the storage temperature. Under current design of the Wolsong canister (i.e., the atmosphere in the storage baskets will be air ; design life is 50 years; the minimum cooling time in the spent fuel bay is 6 years), for example, it has been established that a fuel temperature of at least 180℃ would be required to support a rate of oxidation sufficient to cause a contamination problem [1].

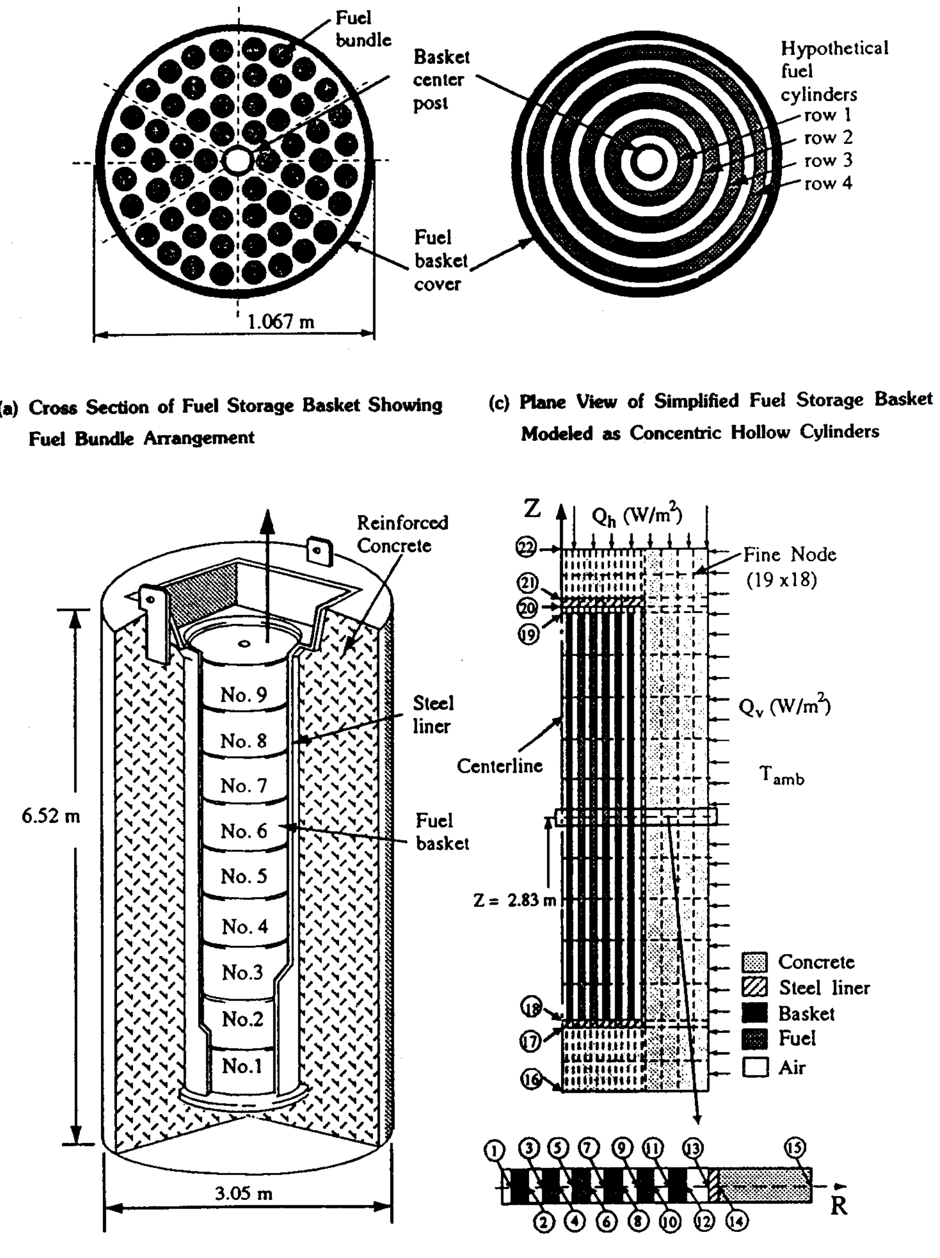
To resolve the above primary safety issues, one has to solve a multi-dimensional heat transfer problem of a complex geometry shown in Figs.1(a) and 1(b) where three modes of heat transfer are superimposed.

For a given decay heat level, the analysis must include at least the heat transfers through fuel bundles in a basket, air gap, steel liner, and concrete canister under various ambient conditions of natural convection and insolation loads.

There are a number of previous analytical and experimental studies in subject areas directly related to the present analysis. The existing works may be broadly classified into (1) analytical and experimental studies which involve one, two or three modes of heat transfer simultaneously in rod bundle geometry, and (2) computer codes developed to solve numerically three-dimensional generalized heat transfer problems. The studies by Cox [2], Ohta [3], Reilly et al. [4], Keyhani et al. [5], Sermer [6], Lee [7], Vafai and Ettefagh [8] are good examples of the former category, whereas in the latter category there are a number of computer codes such as HEATING5 [9], COBRA-SFS [10], and HYDRA-I [11].

However, since the geometry of rod bundles and the heat transfer phenomena in a canister is so complicated that any single analytical model or any computer code without additional modifications cannot effectively handle the present heat transfer problem with given design and ambient conditions.

The main objective of the present work is to predict the mean temperature distributions of the fuel bundles within a fuel basket in a given canis-



(a) Cross Section of Fuel Storage Basket Showing Fuel Bundle Arrangement

(c) Plane View of Simplified Fuel Storage Basket Modeled as Concentric Hollow Cylinders

(b) Wolsung Dry Storage Canister Showing Fuel Basket Loading Arrangement

(d) Simplified Physical Model for Thermal Analysis Showing Radial and Axial Position Numbers and Fine Mesh Lines

Fig. 1. Prototype Wolsong Concrete Canister and Two Dimensional (R–Z) Model

ter by HEATING5 code [9] using additional input data and heat transfer correlations. In addition, results of sample thermal analyses for Wolsong canister design conditions obtained by present approach are presented.

2. Outline of Wolsong Spent Fuel Dry Storage Canister Design

2.1. Canister

The Wolsong concrete canister is a cylindrical reinforced concrete shell with a capacity to store nine sealed fuel baskets each containing 60 CANDU spent fuel bundles as shown in Figs. 1(a) and 1(b). The canister is a 6.52 m high cylindrical container with an internal carbon steel liner that has 3.05 m outside diameter, and has an inner cavity 1.12 m in diameter. It provides a combined shielding of 0.96 m concrete and 0.0095 m of steel [1]. The carbon steel liner is covered with concrete on the outside and epoxy on the inside.

2.2. Fuel Basket

The fuel basket used for the dry storage of Wolsong spent fuel is constructed of type 304L stainless steel. It is 1.067 m in diameter and 0.556 m high and has a capacity of 60 CANDU fuel bundles. As shown in Fig.1(a), the 60 fuel bundles in each basket are arranged to form 4 rows of concentric cylinders with 6, 12, 18, and 24 bundles on the first (inner–most), second, third, and fourth (outer–most) row, respectively. The basket consists of two subassemblies: the basket base and the basket cover. The basket base provides both support for the fuel and the means to handle the basket. It consists of a horizontal baseplate, a vertical lifting post welded to the center of the baseplate and a horizontal positioning plate. The positioning plate has 60 holes to accommodate the bundles, thereby providing individual lateral support at the bundle wear pads. The central post consists of a length of 10.16 cm, schedule 120 pipe to which a lifting collar has been welded [1].

2.3. Spent Fuel

The Wolsong CANDU fuel bundle is a zircaloy–2 (Zr–2) clad, 37–element design as shown in Fig. 1(a). There are 30 uranium dioxide (UO_2) pellets per element. The maximum bundle diameter is 10.21 cm and the overall bundle length is 49.50 cm. The weight of each unirradiated bundle is 23.6 kg, of which 21.3 kg is due to the uranium dioxide. The decay heat of 6 and 7 years cooled spent fuel bundle are 6 W and 5.2 W (the design burnup for dry storage system is set to be 7,800 MWD/MTU), respectively.

3. Estimation of Temperature Distributions Within a Fuel Basket

3.1. Simplified Physical Model and Assumptions

To solve the entire multi–dimensional, multi–mode heat–transfer problem of the given spent fuel dry storage canister using an existing computer code, such as HEATING5 [9], the geometrically complicated dry storage canister loaded with spent fuels shown in Figs. 1(a) and 1(b) is replaced by geometrically simpler multiple vertical concentric hollow cylinders as depicted in Figs. 1(c) and 1(d). That is, the radius of each equivalent cylinder is formed in such ways as follows: (1) The volume of the first, second, third, and fourth fictitious hollow fuel cylinders concentric with the canister is equal to the total volume of the fuel bundles placed on the first to fourth circles shown in Fig.1(a), i.e.,

$$\pi (R_o^2 - R_i^2) L_b = N_b \cdot \frac{\pi}{4} D_b^2 L_b \tag{1}$$

where R_i and R_o are the inner and outer radii of a concentric fuel cylinder, L_b is the length of a fuel bundle, N_b is the number of fuel bundles placed on the same circle, and D_b is the fuel bundle diameter. (2) The sizes of three gaps between four fuel cylinders are twice those of the inner and outer-most gaps within the basket. (3) Equivalent fuel cylinders of the nine baskets are assumed to be axially connected as shown in Fig.1(d).

The fuel temperature during dry storage in a canister is a function of the fuel decay heat output, the ambient temperature, insolation loads (the amount of solar radiation which impinges on a unit area of a surface), and the geometry of the basket and canister system. The decay heat generation of spent fuel, on the other hand, increases with the fuel burnup and decreases with post-irradiation cooling time. Also, the combination of dominant heat transfer modes is different and depends on the position along the heat flow path from the inner-most fuel to the exterior surface of the canister. Therefore, it is necessary to introduce a number of simplifying assumptions (mainly based on design conditions) as follows:

(1) The spent fuel bundle in each basket has been cooled a minimum of 6 years in the spent fuel bay. The decay heat of each fuel bundle is the same and is only a function of cooling time (e.g., a 6-year cooled fuel bundle has 6 W of decay heat). Therefore, the heat generation within the fuel basket is axisymmetric.
(2) The decay heat of an equivalent hollow cylinder [Figs. 1(c) and 1(d)] is directly proportional to the actual number of fuel bundles placed on the circle [(Fig.1(a)] corresponding to the given fuel cylinder. Note that the inner--most fuel cylinder in Fig.1(c) that corresponds to the first row in Fig.1(a) has 6 fuel bundles. The internals of the fuel bundles are ignored. The radial and axial positions thus obtained are presented in Table 1.
(3) The thermo-physical properties of the equivalent fuel cylinders can be obtained by volume and/or mass averaging. More specifically, the density ($\bar{\rho}$) and conductivity ($\bar{k}$) of the equivalent fuel cylinders are obtained by volume averaging, whereas the specific heat capacity ($\bar{c}_p$) is obtained by mass averaging as follows:

$$\bar{\rho} = \sum_i \rho_i \phi_i, \quad \bar{k} = \sum_i k_i \phi_i, \quad \bar{c_p} = \sum_i c_{pi} \gamma_i \qquad (2)$$

where ϕ_i and γ_i denote volume fraction and mass fraction of a constituent i, respectively and the subscript i denotes the metal constituents, i.e., UO_2 or Zr-2. The volume and mass fractions for UO_2 and Zr-2 of the 23.6 kg mass CANDU fuel bundle are $\phi_{UO_2}=84.9$ %, $\phi_{Zr-2}=15.1$ %, $\gamma_{UO_2}=90.39$ %, and $\gamma_{Zr-2}=9.61$ %, respectively. The temperature dependent thermo-physical properties of the equivalent cylinders ($\bar{\rho}$, $\bar{k}$, and $\bar{c}_p$) can then be obtained using the above volume and mass fractions along with the thermo-physical properties of reactor materials given as a function of temperature [12].

3.2. Procedure for Thermal Analysis

The HEATING5 [9] program solves the steady-state or transient heat conduction problem in either one, two, or three dimensions. The finite difference heat balance equation for node i having M_i neighbors is given by [9]

$$C_i \frac{T_i^{n+1} - T_i^n}{\Delta t} = P_i^n + \sum_{j=1}^{M_i} K_{ij} (T_j^n - T_i^n) \qquad (3)$$

where T_i^n, T_j^n, K_{ij}, C_i, P_i^n are the temperatures of the i-th and the j-th nodes at time t_n, the effective conductance between nodes i and j, the heat capacitance of the material associated with node i, and the heat generation rate of the i-th node material at time t_n, respectively.

For a two-dimensional problem, one C, one P, and four K's will be associated with each internal node at a particular time, t_n. For nodes i and j, these parameters are calculated as follows:

Table 1. Radial and Axial Coordinates for the Physical Model in Fig. 1(d).

Radial location(m)						Axial location(m)	
R_0	0.000	R_7†	0.300	R_{14}	0.568	Z_{16}	0.000
R_1	0.046	R_8†	0.370	R_{15}	1.525	Z_{17}	0.327
R_2	0.057	R_9†	0.412			Z_{18}	0.365
R_3†	0.078	R_{10}†	0.482			Z_{19}	5.302
R_4†	0.147	R_{11}	0.503			Z_{20}	5.496
R_5†	0.189	R_{12}	0.533			Z_{21}	5.505
R_6†	0.258	R_{13}	0.558			Z_{22}	6.518

† : values obtained from Eq.(1)

$$C_i = \sum_j c_{p_j} \rho_j V_j \tag{4}$$

$$P_i^n = \sum_j \dot{q}_j^n V_j \tag{5}$$

$$K_{ij} = \frac{1}{L_{ij}} \sum_{m=1}^{M_i} k_{jm} A_{jm} \tag{6}$$

where $\dot{q}_j^n$ is the heat generation rate per unit volume in region j at time t_n, c_{pj}, ρ_j, and V_j are the specific heat, the density, and the volume of region j, respectively, L_{ij} is the distance between node i and adjacent node j, k_{jm} is the thermal conductivity for region m between nodes i and j, A_{jm} is the cross-sectional area, normal to heat flow path, of region m between nodes i and j, and M_i is the number of nodes connected to node i.

Equation (6) is used for the region where heat transfers solely by conduction. For region where heat flows simultaneously by natural convection and radiation, in particular, the overall effective conductance K_{ij} is given by

$$K_{ij} = h_{eff} A_i \tag{7}$$

where h_{eff} and A_i are the effective heat transfer coefficient and the surface area, normal to the heat flow path, of node i. In Eq.(7), the h_{eff} is defined as

$$h_{eff} = \mathfrak{F}_{ij}\, \sigma (T_i^2 + T_j^2)(T_i + T_j) + h_n (T_i - T_j)^c \tag{8}$$

where $\mathfrak{F}_{ij}$ is the gray-body shape factor, σ is the Stefan-Boltzmann constant, T_i and T_j are the surface temperatures of nodes i and j, and h_n and c are, respectively, the coefficient and exponent for natural convective heat transfer. The gray-body shape factor for diffuse-gray concentric cylinders of infinite height is given by

$$\mathfrak{F}_{ij} = \frac{1}{\frac{1}{\varepsilon_i} + \left(\frac{A_i}{A_j}\right)\left(\frac{1}{\varepsilon_j} - 1\right)} \tag{9}$$

where A_i and A_j and ε_i and ε_j are the areas and emissivities of two surfaces.

The coefficient for natural convection h_n in Eq.(8), on the other hand, is defined by

$$h_n = \frac{k}{L} \frac{Nu}{(T_i - T_j)^c} \tag{10}$$

where Nu and L are the average Nusselt number for natural convection and a characteristic length, respectively.

HEATING5 [9] possesses a variety of boundary conditions to enable the user to model his physical problem as accurately as possible. It is also designed so that, simultaneously, one may consider surface-to-surface heat transfer across a region as well as conduction through the region.

The radial heat flow path for the present simplified two-dimensional (R and Z) cylindrical model shown in Figs. 1(c) and 1(d) is composed of (1) solid regions (i.e., homogenized four equivalent concentric fuel cylinders, two stainless steel layers of the fuel basket, steel liner, and concrete wall of the canister), (2) annular air gaps (between the central post and the first fuel cylinder, between four equivalent fuel cylinders, between the fourth fuel cylinder and the basket, and also between the basket and steel liner), and (3) the exterior surface of the canister (where the decay heat is finally being dissipated to the environment by convection and radiation). The heat transfer through the solid region is conduction, whereas in the latter two regions, the decay heat flows simultaneously by convection and radiation.

The average Nusselt number for natural convection in an annular gap is strongly dependent on the geometry of the system such as aspect ratio, H, radius ratio, K, and Rayleigh number, Ra [13,14]. The H values for the annular air gaps in Fig.1(d) are between 12.5 and 189.9, the K values are between 1.05 and 1.40, and the Rayleigh numbers are between 6.39×10^2 and 9.27×10^4 for the temperatures between 0℃ and 300℃. When H, K and Ra values are compared with the result of Thomas and De Vahl Davis [14], the flow field in annular air gaps of the Wolsong canister falls within the category of conduction regime. Therefore, the second term on the right hand side of Eq.(8) reduces to a conduction heat transfer form for the annular gap regions.

For the exterior surface of the canister, however, the Ra_L number is in the range of $10^{10}\sim10^{11}$ with the characteristic length scale L of cylindrical canister height and for air. Therefore, the following Nusselt number correlation for vertical cylinder in the turbulent range ($10^9<Ra_L<10^{12}$) [15] can be used in Eq.(10)

$$Nu_L = 0.13\, Ra_L^{1/3} \tag{11}$$

The calculated values of the coefficient h_n defined by Eq.(10) using Eq.(11) at several temperatures are presented in Table 2.

Nodalization of Wolsong canister is made such that there are 19 radial nodes and 18 axial nodes as shown in Fig.1(d). Using this nodalization and all the required input data such as temperature dependent thermo-physical properties and the applicable heat transfer relations presented above, the mean temperature distributions of the fuel bundles within a fuel basket in a given canister under various ambient conditions can be estimated by HEATING5 [9].

4. Results and Discussion

4.1. Predicted Temperature Versus Measured Temperature

To examine whether the present method can predict the temperature distribution in a basket containing fuel bundles of equal decay heat within an acceptable margin of error, predictions made are first compared with existing thermal mock-up test results [16].

In the thermal mock-up test, fuel bundles were simulated by brass containers (50 cm long by 10.2 cm diameter) filled with silica sand, and each con-

Table 2. The Values of Coefficient h_n Used for Vertical Cylinder as a Function of Temperatures (Canister Height L = 6.52 m and ΔT Assumed to be 10℃)

Temperature(℃)	Ra_L	$h_{n,L}$	c
0	0.420×10^{12}	1.648	0.33
50	0.198×10^{12}	1.488	〃
100	0.902×10^{11}	1.298	〃
200	0.345×10^{11}	1.146	〃
300	0.152×10^{11}	1.017	〃

taining three 300-ohm, 10 W resisters, centrally located and connected in series. With the simulated fuel bundles operating at 6 W each, and when the average steel liner temperature reached 96℃ at steady state conditions, the average maximum fuel temperature of the simulated bundles is 159℃ as shown in Fig.2.

In Fig.2, the radial temperature profile obtained by the present method is compared with the mock-up test results. Thermo-physical properties of the fuel cylinder and other properties and conditions used in the prediction are presented in Tables 3 and 4, respectively. The agreement between the two results is quite good. As can be seen in this comparison, the predicted values are slightly higher than the measured values and the difference in the maximum fuel temperatures is about 2 ℃. However, the magnitude of 2 ℃ difference could easily be within the uncertainty range of cumulative errors of measurement, input thermo-physical properties, and modeling.

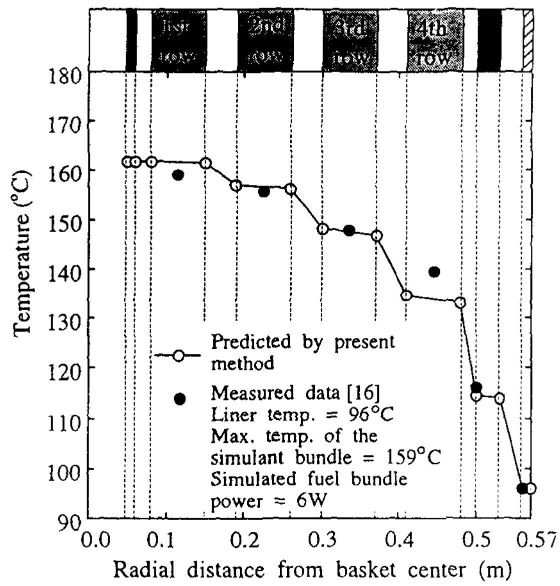


Fig. 2. Measured Versus Predicted Thermal Gradient Through Cylindrical Fuel Basket.

Table 3. Thermo-Physical Properties of UO_2 and Zr-2 and the Volume and Mass Averaged Thermo-Physical Properties of the Hypothetical Fuel Cylinder

T(℃)	k		$\bar{k}$	ρ		$\bar{\rho}$	c_p		$\bar{c}_p$
	UO_2	Zr-2		UO_2	Zr-2		UO_2	Zr-2	
37.8	8.70	11.82	9.17	10958	6504	10284	238.9	292.9	243.9
93.3	7.73	11.94	8.37	-	-	-	256.5	304.6	261.1
204.4	6.31	12.32	7.21	-	-	-	281.2	319.7	284.9
315.6	5.34	12.77	6.47	-	-	-	295.4	330.1	298.7

(Note) : All of the Thermo-physical Properties are in the SI System Unit.

Table 4. Other Properties and Conditions

Item	Value
Emissivitiy of Zr-2 clad	0.65 (probable range : 0.6~0.7)
stainless steel	0.33
carbon steel	0.41
concrete	0.88
Decay heat power	6.00 W/bundle (6-year cooled fuel)
	5.20 W/bundle (7-year cooled fuel)
Volumetric heat generation rate	1480 W/m^3
Ambient temperature	38℃

4.2. Effects of Natural Convection and Constant Insolation Load

In the foregoing analysis, the performance of the present method has been shown to be satisfactory. Now, an application of the present approach is made to determine the effects of insolation loads specified in Ref. [17] and natural convection at the exterior surface of the Wolsong concrete canister.

To evaluate the effects of ambient conditions (i.e., insolation and natural convection at the exterior surface of the Wolsong canister) on the fuel temperature, fuel temperature distributions of the Wolsong canister have been calculated for three different combinations of ambient conditions at the canister surface as follows :

Case Ⅰ : With exterior natural convection but without insolation loads ;

Case Ⅱ : With both exterior natural convection and insolation loads;

Case Ⅲ : Without exterior natural convection but with insolation loads.

The steady state radial temperature distributions (at the midplane Z=2.83m from the canister bottom) obtained from the present thermal analysis for the above three cases are shown together in Fig. 3 (The row numbers of fuel cylinders and the axial positions that correspond to the temperature distribution curve are shown at the top of Fig.3).

The results shown in Fig.3 can be summarized as follows :

(1) When insolation loads are neglected while the effect of natural convection at the exterior surface of the canister is included in the present analysis, the predicted maximum fuel bundle temperature is 159 ℃ (as shown for case Ⅰ).

(2) When the effects of insolation loads (800 W/m^2 and 400 W/m^2 for canister top and side, respectively) are included with and without exterior natural convection, the maximum fuel bundle temperatures become 178 ℃ for case Ⅱ and 192 ℃ for case Ⅲ, respectively.

(3) The results of cases Ⅱ and Ⅲ show that the maximum fuel bundle temperature decreases by 14 ℃ when the natural convection at the exterior surface is included. This result indicates that the exterior natural convection is an effective heat removal mechanism for the fuel bundles within the Wolsong concrete canister.

(4) The maximum fuel bundle temperature occurs when insolation loads are included while the exterior natural convection effect is neglected (i.e., case Ⅲ).

(5) When the effect of insolation loads is neglected while the natural convection at the exterior surface is included (case Ⅰ), the maximum fuel bundle temperature becomes the lowest.

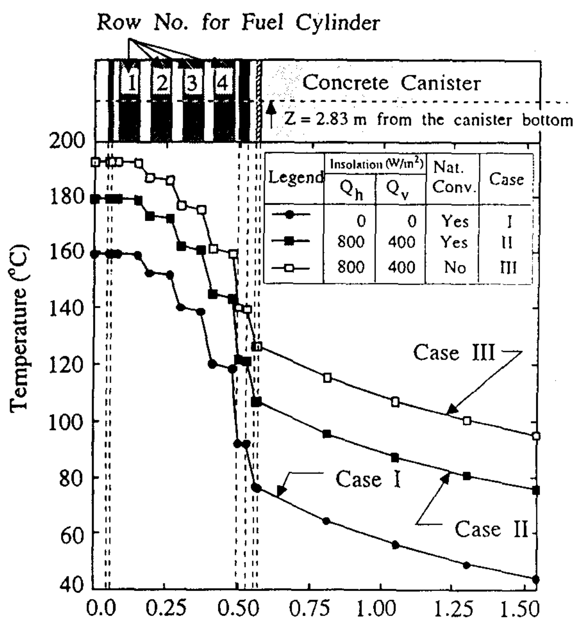


Fig. 3. Steady State Concrete Canister Fuel Temperature Distributions With and Without Insolation Loads and Natural Convection at the Exterior Surface of the Canister.

5. Conclusions

A simplified thermal analysis method to evaluate the maximum temperature of the CANDU 37-element fuel bundle within a fuel basket in a given spent fuel dry storage canister has been presented along with the results of sample analyses performed for Wolsong canister. The calculation has been performed with an existing computer code, HEATING5 [9], using additional input data and heat transfer correlations.

The agreement between the results of analysis and the mockup test, in particular, is quite satisfactory. In addition, from the results of sample calculations performed to assess the central thermal safety issue of the Wolsong dry storage canister for given design and ambient conditions (i.e., insolation loads and ambient temperature of 38 ℃), following conculsions can be made :

(1) When the effects of insolation loads are included with and without exterior natural convection, the maximum fuel bundle temperature reaches very close to (i.e., 178 ℃ for case Ⅱ) or exceeds (192 ℃ for case Ⅲ) the potential fuel oxidation temperature of 180 ℃ for Wolsong canister design conditions.

(2) Additional calculations [16] show that for the given Wolsong canister design parameters and ambient conditions, there is an alternative method to satisfy the thermal safety criteria : That is to increase the minimum cooling time in the spent fuel bay to 7 years from the original design of 6 years, thereby decreasing the decay heat level of the spent fuel bundle from 6 W to 5.2 W. For the typical case Ⅱ, the peak fuel bundle temperature of the 7-year cooled fuel is about 13 ℃ lower than that of the 6-year cooled fuel [16].

Finally, it is recommended that the present thermal analysis method be used (1) to find optimum combination of design parameters for a spent fuel dry storage canister system, and (2) to assess the parametric effects of ambient conditions on the fuel bundle temperature within a canister and the thermal safety of the spent fuel dry storage canister system under given design conditions.

Acknowledgement

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Nomenclature

A	area
A_{jm}	cross-sectional area, normal to heat flow path, of region m between nodes i and j
C_i	heat capacitance of the material associated with node i
c	exponent for a natural convection heat transfer correlation
c_p	specific heat
$\bar{c}_p$	mass averaged specific heat of equivalent fuel cylinders
D_b	fuel bundle diameter
$\mathfrak{F}_{ij}$	gray-body shape factor between two concentric cylindrical surfaces
g	gravitational acceleration
H	aspect ratio, $L_a/(R_o-R_i)$
h_{eff}	effective heat transfer coefficient
h_n	Nusselt number for vertical cylinder multiplied by $k/L\Delta T^c$
K	radius ratio, R_o/R_i
K_{ij}	effective thermal conductance between nodes i and j
k	thermal conductivity
$\bar{k}$	volume averaged thermal conductivity of equivalent fuel cylinders
k_{jm}	thermal conductivity for region m between nodes i and j

L	canister height and/or a characteristic length
L_a	annulus height
L_b	length of a fuel bundle
L_{ij}	distance between nodes i and j
M_i	number of nodes connected to node i
N_b	number of fuel bundles
Nu	Nusselt number
Nu_L	Nusselt number based on characteristic length L
P_i^n	heat generation rate of the material associated with node i at time t_n
Q_h	insolation on the top of the concrete canister
Q_v	insolation on the cylindrical side of the concrete canister
$\dot{q}_j^n$	volumetric heat generation rate in region j at time t_n
R	radial coordinate
Ra	Rayleigh number
Ra_L	Rayleigh number based on characteristic length L; $g\beta\ L^3 \Delta T/\alpha\nu$
R_i	inner radius of a concentric fuel cylinder and/or annular gap
R_o	outer radius of a concentric fuel cylinder and/or annular gap
T_{amb}	ambient temperature
T_i	temperature of the i–th node
T_i^n	temperature of the i–th node at time t_n
T_j	temperature of the j–th node
T_j^n	temperature of the j–th node at time t_n
ΔT	characteristic temperature difference
Δt	time increment
t_n	time of n–th step
V_j	volume of region j
Z	axial coordinate

Greek

α	thermal diffusivity
β	isobaric coefficient of thermal expansion
γ_i	mass fraction of the metal constituent i
ε	emissivity
μ	viscosity
ν	kinematic viscosity
ρ	density
$\bar{\rho}$	volume averaged density of equivalent fuel cylinders
σ	Stefan–Boltzmann constant
ϕ_i	volume fraction of the metal constituent i

Subscripts

b	fuel bundle
eff	effective
i	node number and/or inner fuel cylinder
ij	between two surfaces i and j
j	node number
L	characteristic length scale
m	region number
n	time step and/or natural convection
o	outer fuel cylinder

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