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Modeling transient heat transfer in nuclear waste repositories

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ABSTRACT

The heat of high-level nuclear waste may be generated and released from a canister at final disposal sites. The waste heat may affect the engineering properties of waste canisters, buffers, and backfill material in the emplacement tunnel and the host rock. This study addresses the problem of the heat generated from the waste canister and analyzes the heat distribution between the buffer and the host rock, which is considered as a radial two-layer heat flux problem. A conceptual model is first constructed for the heat conduction in a nuclear waste repository and then mathematical equations are formulated for modeling heat flow distribution at repository sites. The Laplace transforms are employed to develop a solution for the temperature distributions in the buffer and the host rock in the Laplace domain, which is numerically inverted to the time-domain solution using the modified Crump method. The transient temperature distributions for both the single- and multi-borehole cases are simulated in the hypothetical geological repositories of nuclear waste. The results show that the temperature distributions in the thermal field are significantly affected by the decay heat of the waste canister, the thermal properties of the buffer and the host rock, the disposal spacing, and the thickness of the host rock at a nuclear waste repository.

1. Introduction

Nuclear waste disposal is a world-wide issue and attracts much public attention. High-level nuclear waste has a very high level of radioactive harmfulness and a long decay period. At present time, many countries consider geologic disposal of high-level nuclear waste is a feasible and safe technology. There are two methods, known as in-room and borehole emplacements, for placing high-level nuclear waste in a vault. In-room emplacement, the containers or canisters are placed on the bed of the prepared buffer, with additional buffer being packed around and above them. In borehole emplacement, the containers or canisters are surrounded by the buffer in a large-diameter hole drilled in the floor of the vault [1].

Avila et al. [2] created an equation describing transient thermal response in high-level nuclear waste repositories. They compared their results, developed for linear and non-linear cases, with both an analytical solution and two-dimensional predictions obtained by Estrada-Gasca and Alvarez-Garcia [3]. Buscheck et al. [4] presented a multi-scale model to simulate coupled thermal and hydrological behavior driven by radioactive decay heat from an underground nuclear waste repository at Yucca Mountain, Nevada. Their model is used to evaluate the repository performance of different designs in regard to major design goals. Chang et al. [5] investigated the heat transfer effects in deep geologic repositories designed by the Taiwan Institute of Nuclear Energy Research for high-level nuclear waste. The effects of the influent factors from the in situ material responses, including the buffer material and thermal gap, were assessed using finite element modeling. Their result showed that only the $8\,\mathrm{m} \times 40\,\mathrm{m}$ case conforms to the standard of a low-temperature disposal site (less than $100\,^{\circ}\mathrm{C}$; [6,7]). Chijimatsu et al. [8] studied thermal–hydraulic–mechanical (THM) effects numerically on the near-field safety of a hypothetical nuclear waste repository within the international DECOVALEX III project. The project was to perform an in situ THM experiment at Kamaishi mine in Japan. Their experiment used a simplified axisymmetric model with the temperature at the center of the heater maintained at $100\,^{\circ}\mathrm{C}$ during a heating phase of 258 days and then turned off heat for the natural cooling phase of approximately 180 days. Sizgek [9] developed a three-dimensional thermal model to investigate the temperature distribution in one of the boreholes of a hypothetical tunnel for a basic geometrical setting as well as the effect of varying the distance between adjacent boreholes and the distance between adjacent tunnels. Their result showed that decreasing the spacing between the canisters had a larger effect on temperature distribution than decreasing the spacing between the tunnels. Blaheta et al. [10] investigated the efficiency of the overlapping Schwarz methods for both elliptic and parabolic problems with an application to a nuclear waste repository model. They mentioned that the two-level Schwarz method was necessary for the efficient solution of discrete elliptic problems and the one-level Schwarz method was sufficiently efficient for elliptic problems.

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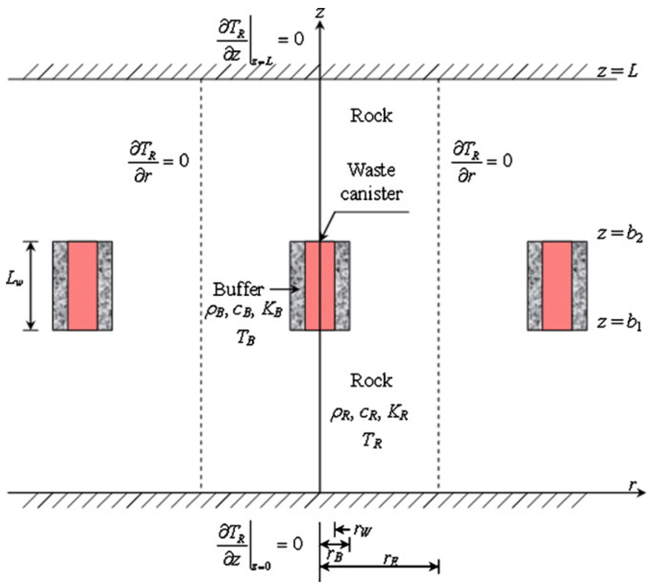

Fig. 1. Schematic diagram of a high-level nuclear waste disposal site in a deep geological formation.

This study first proposes a mathematical model for modeling heat transfer in a deep geological repository for high-level nuclear waste. Then, the Laplace-domain solutions of temperature distribution are developed using Laplace transforms and their corresponding time-domain solutions are numerically calculated using the modified Crump method [11]. The present analytical model is used to investigate the effects of the property and thickness of the buffer, the spacing of the waste canister, the type of host rock, and the depth of the tunnel on the heat conduction as well.

2. Mathematical model

2.1. Mathematical statement

Fig. 1 gives a schematic view of a deep geological repository system for high-level nuclear waste. The system assumes: (1) the host rock of the geological repository is homogeneous, isotropic, impermeable, and of a constant thickness; (2) the waste canister is surrounded by the buffer within a finite radius disposal borehole; (3) the initial temperature is constant and uniformly distributed throughout the whole repository site; (4) the physical parameters and thermal properties of the buffer and the rock are constant in space and time; (5) the lower and upper boundaries of the host rock consist of fractures and no heat is transferred in the fractures; (6) the values of physical parameters and thermal property of the backfill material in an emplacement tunnel are the same as those in the host rock; (7) the heat transfer through the waste canister, buffer, and host rock is dominant by conduction and the heat transfer by radiation and convection are negligible. Under these assumptions, the governing equations of the time-dependent conduction heat transfer of temperatures in the buffer (e.g., bentonite or crushed magnesium oxide) and host rock (e.g., crystalline rock or sedimentary rock) can, respectively, be written as

$$\frac{\partial^2 T_B(r,z,t)}{\partial r^2}+\frac{1}{r}\frac{\partial T_B(r,z,t)}{\partial r}+\frac{\partial^2 T_B(r,z,t)}{\partial z^2}=\frac{1}{\alpha_B}\frac{\partial T_B(r,z,t)}{\partial t},\quad r_W\le r\le r_B,\quad 0\le z\le L \tag{1}$$

and

$$\frac{\partial^2 T_R(r,z,t)}{\partial r^2}+\frac{1}{r}\frac{\partial T_R(r,z,t)}{\partial r}+\frac{\partial^2 T_R(r,z,t)}{\partial z^2}=\frac{1}{\alpha_R}\frac{\partial T_R(r,z,t)}{\partial t},\quad r\ge r_B,\quad 0\le z\le L \tag{2}$$

where the subscripts B and R denote the buffer and rock, respectively; $T(r, z, t)$) is the temperature; $\alpha = K/(\rho c)$ is the thermal diffusivity; K is the thermal conductivity; ρ is the density; c is the specific heat; r is the radial distance from the centerline of the waste canister; z is the vertical distance; r_W is the radius of the waste canister; r_B is the radial distance from the waste canister centerline to the outer buffer envelope; L is the rock thickness of the geological repository; and t is the time.

The temperatures of the buffer and rock are initially equal to a constant, T_0, that is

$$T_B(r,z,0)=T_R(r,z,0)=T_0 \tag{3}$$

The boundary conditions for the buffer and rock give

$$\frac{\partial T_R(r_E,z,t)}{\partial r}=0 \tag{4}$$

and

$$\frac{\partial T_B(r_W,z,t)}{\partial r}=\frac{-Q_W(t)}{2\pi r_W L_W K_B}[U(z-b_1)-U(z-b_2)] \tag{5}$$

with

$$Q_W(t)=Q_0[a_1e^{-a_2t}+(1-a_1)e^{-a_3t}] \tag{6}$$

where $Q_W(t)$ is the heat flux of the waste canister from nuclear waste; Q_0 is the constant heat flux of the waste canister for high-level nuclear wastes at the initial time stage of the geological disposal; a_1, a_2, and a_3, are the constant coefficients; K_B is the heat conductivity of the buffer; $L_W = b_2 - b_1$ is the height of the waste canister; L is the thickness of the geological repository; b_1 and b_2 are the lower and upper z-coordinates of the waste canister, respectively; $U(\cdot)$ is the unit step function.

The continuity of temperature and heat flux at the interface of the buffer and rock, respectively, require

$$T_B(r_B,z,t)=T_R(r_B,z,t) \tag{7}$$

and

$$K_B\frac{\partial T_B(r_B,z,t)}{\partial r}=K_R\frac{\partial T_R(r_B,z,t)}{\partial r} \tag{8}$$

The no-flux boundary conditions at the lower and upper impervious boundaries of a geological repository are, respectively

$$\frac{\partial T_B(r,0,t)}{\partial z}=\frac{\partial T_R(r,0,t)}{\partial z}=0 \tag{9}$$

and

$$\frac{\partial T_B(r,L,t)}{\partial z}=\frac{\partial T_R(r,L,t)}{\partial z}=0 \tag{10}$$

2.2. Laplace-domain solutions

The Laplace-domain solutions for the temperatures in the buffer and rock can be obtained by taking Laplace transforms with respect to time and the finite Fourier cosine transforms with respect to the z-coordinate from Eqs. (1)–(10). Setting $T'_B(r,z,t) = T_B(r,z,t) - T_0$ and $T'_R(r,z,t) = T_R(r,z,t) - T_0$ and taking the Laplace transforms to Eqs. (1)–(10) yield

$$\frac{d^2\tilde{T}'_B(r,z,p)}{dr^2}+\frac{1}{r}\frac{d\tilde{T}'_B(r,z,p)}{dr}+\frac{d^2\tilde{T}'_B(r,z,p)}{dz^2}=\frac{p}{\alpha_B}\tilde{T}'_B(r,z,p),\quad r_W\le r\le r_B,\quad 0\le z\le L \tag{11}$$

$$\frac{d^2\tilde{T}'_R(r,z,p)}{dr^2}+\frac{1}{r}\frac{d\tilde{T}'_R(r,z,p)}{dr}+\frac{d^2\tilde{T}'_R(r,z,p)}{dz^2}=\frac{p}{\alpha_R}\tilde{T}'_R(r,z,p),\quad r\geq r_B,\quad 0\leq z\leq L \tag{12}$$

$$\frac{d\tilde{T}'_R(r_E,z,p)}{dr}=0 \tag{13}$$

$$\frac{d\tilde{T}'_B(r_W,z,p)}{dr}=\frac{-\tilde{Q}_W(p)}{2\pi r_W L_W K_B}[U(z-b_1)-U(z-b_2)] \tag{14}$$

$$\tilde{Q}_W(p)=Q_0\left[\frac{a_1}{p+a_2}+\frac{1-a_1}{p+a_3}\right] \tag{15}$$

$$\tilde{T}'_B(r_B,z,p)=\tilde{T}'_R(r_B,z,p) \tag{16}$$

$$K_B\frac{d\tilde{T}'_B(r_B,z,p)}{dr}=K_R\frac{d\tilde{T}'_R(r_B,z,p)}{dr} \tag{17}$$

$$\frac{d\tilde{T}'_B(r,0,p)}{dz}=\frac{d\tilde{T}'_R(r,0,p)}{dz}=0 \tag{18}$$

and

$$\frac{d\tilde{T}'_B(r,L,p)}{dz}=\frac{d\tilde{T}'_R(r,L,p)}{dz}=0 \tag{19}$$

Following the work of Chiu et al. [12], one can develop a general solution for the heat transfer problem given above. Applying the finite Fourier cosine and inverse finite Fourier cosine transforms with respect to the z-coordinate to Eqs. (11)–(19), the Laplace-domain solutions for the temperature distribution in the buffer and rock are, respectively

$$\tilde{T}_B(r,z,t)=\left(\frac{-\tilde{Q}_W(p)}{2\pi r_W L_W K_B}\right)\times\left[\left(\frac{L_W}{L}\right)f_1(p)+\left(\frac{2}{L}\right)\sum_{n=1}^{\infty}f_2(p)W(b_1,b_2)\cos(w_n z)\right]+\frac{T_0}{p} \tag{20}$$

and

$$\tilde{T}_R(r,z,p)=\left(\frac{-\tilde{Q}_W(p)}{2\pi r_W L_W K_B}\right)\times\left[\left(\frac{L_W}{L}\right)f_3(p)+\left(\frac{2}{L}\right)\sum_{n=1}^{\infty}f_4(p)W(b_1,b_2)\cos(w_n z)\right]+\frac{T_0}{p} \tag{21}$$

with $f_1(p), f_2(p), f_3(p), f_4(p)$, and $W(b_1,b_2)$ defined as

$$f_3(p)=\frac{K_1(q'_R r_E)I_0(q'_R r)+I_1(q'_R r_E)K_0(q'_R r)}{r_B(q'_R)^2 B_1} \tag{22}$$

$$f_2(p)=\frac{A_3 I_0(q_B r)+A_4 K_0(q_B r)}{q_B B_2} \tag{23}$$

$$f_3(p)=\frac{K_1(q'_R r_E)I_0(q'_R r)+I_1(q'_R r_E)K_0(q'_R r)}{r_B(q'_B)^2 B_1} \tag{24}$$

$$f_4(p)=\frac{K_1(q_R r_E)I_0(q_R r)+I_1(q_R r_E)K_0(q_R r)}{r_B(q_B)^2 B_2} \tag{25}$$

and

$$W(b_1,b_2)=\frac{[\sin(w_n b_2)-\sin(w_n b_1)]}{w_n} \tag{26}$$

Table 1
Definition of the parameters.

Parameters	Expressions
A_1	$K_1(q'_B r_B)\psi_3+\beta' K_0(q'_B r_B)\psi_4$
A_2	$I_1(q'_B r_B)\psi_3-\beta' I_0(q'_B r_B)\psi_4$
A_3	$K_1(q_B r_B)\psi_1+\beta K_0(q_B r_B)\psi_2$
A_4	$I_1(q_B r_B)\psi_1-\beta I_0(q_B r_B)\psi_2$
B_1	$\phi_4\psi_3+\beta'\phi_3\psi_4$
B_2	$\phi_2\psi_1+\beta\phi_1\psi_2$
ϕ_1	$I_1(q_B r_W)K_0(q_B r_B)+K_1(q_B r_W)I_0(q_B r_B)$
ϕ_2	$I_1(q_B r_W)K_1(q_B r_B)-K_1(q_B r_W)I_1(q_B r_B)$
ϕ_3	$I_1(q'_B r_W)K_0(q'_B r_B)+K_1(q'_B r_W)I_0(q'_B r_B)$
ϕ_4	$I_1(q'_B r_W)K_1(q'_B r_B)-K_1(q'_B r_W)I_1(q'_B r_B)$
ψ_1	$I_0(q_R r_B)K_1(q_R r_E)+K_0(q_R r_B)I_1(q_R r_E)$
ψ_2	$I_1(q_R r_B)K_1(q_R r_E)-K_1(q_R r_B)I_1(q_R r_E)$
ψ_3	$I_0(q'_R r_B)K_1(q'_R r_E)+K_0(q'_R r_B)I_1(q'_R r_E)$
ψ_4	$I_1(q'_R r_B)K_1(q'_R r_E)-K_1(q'_R r_B)I_1(q'_R r_E)$
β	$K_R q_R/(K_B q_B)$
β'	$K_R q'_R/(K_B q'_B)$
q_B^2	w_n^2+p/α_B
q_R^2	w_n^2+p/α_R
q'^2_B	p/α_B
q'^2_R	p/α_R

where the parameter p is the Laplace variable [13]; $w_n=n\pi/L, n=0, 1, 2, \ldots$; the functions of $I_0(\cdot)$ and $K_0(\cdot)$ are the modified Bessel functions of the first and second kinds of order zero, respectively; and $I_1(\cdot)$ and $K_1(\cdot)$ are the modified Bessel functions of the first and second kinds of order one, respectively. In addition, the parameters in $f_1(p), f_2(p), f_3(p)$, and $f_4(p)$ are defined in Table 1.

3. Results and discussions

Eqs. (20) and (21) are rather complicated; therefore, they are inverted numerically by the routine INLAP of IMSL [14] which was developed based on a numerical algorithm originally proposed by Crump [15] and modified by de Hoog et al. [11]. The algorithm approximates the Laplace inversion by expressing the inverted function in a Fourier series and accelerates the evaluation by the Shanks method [16,17]. This method has been successfully applied to evaluate the analytical solutions of groundwater problems (see, e.g., [18,19]).

The transient temperature distributions for the single- and multi-borehole cases are simulated in the hypothetical geological repositories for high-level nuclear waste. The thermal properties of the materials are adopted from the typical data given by Borgesson et al. [20] and listed in Table 2. It is assumed that the thermal properties of the buffer and the host rock remain constant in space and time. This assumption is applicable when the change of temperatures in the geological repository is not very large [21]. The decay heat function utilized for the calculations, based on the data of the Taiwan Nuclear Power Factory and the coefficients a_1, a_2, and a_3 in Eq. (6), are chosen as 0.696, 0.02, and 0.0013, respectively (adopted from Chang et al. [5]). Based on the requirement of the safety design, the standards of low-temperature disposal sites for high-level nuclear waste commonly require that the temperatures should be less than 100 °C at the outside of the waste canister r_W, 80 °C at the borehole-rock boundary r_B, and 70 °C at the center between adjacent boreholes r_E [6,7].

Table 2
The thermal properties of the materials.

Material	K (W/(m °C))	c (J/(kg °C))	ρ (kg/m^3)
Buffer	1.15	1100	2175
Rock	3.6	800	2700

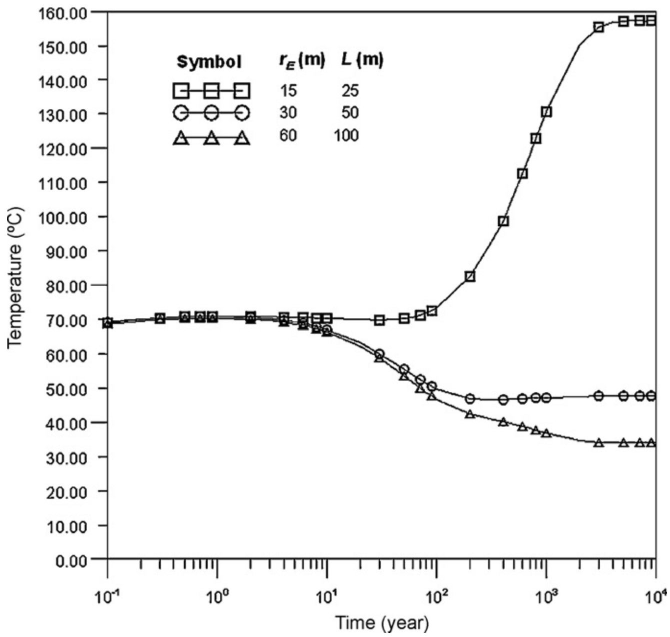

Fig. 2. The temperature distribution curves at the vertical centerline and the buffer mid for r_E = 15 m and L = 25 m, r_E = 30 m and L = 50 m, and r_E = 60 m and L = 100 m for a single-borehole case.

3.1. Single disposal borehole

The thermal properties of the materials are adopted from the data given by Borgesson et al. [20] and shown in Table 1. In the following simulations, the values of parameters are: the radius of the waste canister r_W = 0.19 m, the height of the waste canister L_W = 1.50 m, the radial distance from the waste canister centerline to the outer buffer envelope r_B = 0.376 m, and the constant heat flux of the waste canister Q_0 is 600 W. The ratio of cylinder surface area to total surface area for the waste canister is 0.94. Thus, the constant heat flux of the waste canister is modified as $0.94Q_0$. The initial temperatures of the buffer and rock are set as an average of 32 °C. The temperature–time curves at the vertical centerline and the buffer mid ($r_{WB} = r_W + (r_B - r_W)/2$) for r_E = 15 m and L = 25 m, r_E = 30 m and L = 50 m, and r_E = 60 m and L = 100 m are shown in Fig. 2. The figure shows that the temperature increases slowly with time, reaches the maximum at 1 year, then decreases with time and gradually approaches a steady value at about 2000 years for the r_E = 60 m and L = 100 m boundary and at about 200 years for the r_E = 30 m and L = 50 m boundary. The temperature at the boundary for r_E = 15 m and L = 25 m also increases slowly with time, reaches the maximum at 1 year, then decreases with time. However, this temperature curve increases again with time after about 40 years and approaches a steady value at about 2000 years. This result indicates that the heat transfer of a single disposal borehole may be modeled as the heat transfer in a finite boundary. So, the temperature in a nuclear waste repository site is higher than that in a case with an infinite-extent boundary.

3.2. Multi-borehole model

The thermal properties of the buffer and rock are listed in Table 2. Chang et al. [5] provided a conceptual design of a deep hypothetical geological repository for high-level nuclear waste. Based on their data, the values of parameters used in the present model simulations are as follows: r_W = 0.525 m, L_W = 4.91 m, r_B = 0.85 m, b_1 = 497.545 m, b_2 = 502.455 m, z = 500 m (at vertical centerline), and L = 1000 m. The constant heat flux of the waste canister Q_0 is

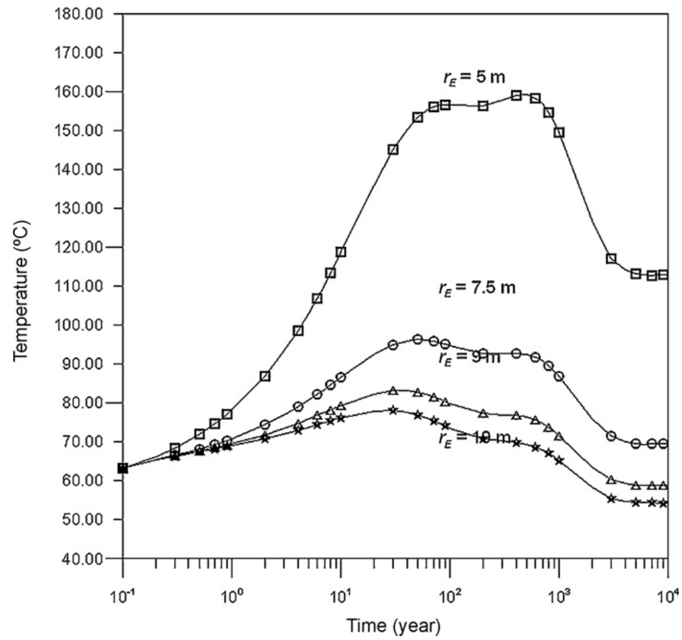

Fig. 3. The effect of varying waste canister spacing on the buffer mid temperatures for a multi-borehole case.

1714.4 W. The ratio of cylinder surface area to total surface area for the waste canister is 0.90. Thus, the constant heat flux of the waste canister is modified as $0.90Q_0$. The initial temperatures of the buffer and rock are set as an average of 35 °C. The effects of varying waste canister spacing on the buffer mid temperature shown in Fig. 3 indicate that there are two peaks in the temperature distribution curves. The first peak of the temperature distribution comes from the decay heat supplied continuously. On the other hand, the second peak of temperature distribution is attributed to both the decay heat and heat accumulated within the buffer. The maximal temperatures are 159.23 °C at about 460 years for the r_E = 5 m case, 96.31 °C at 51 years for the r_E = 7.5 m case, 83.21 °C at 36 years for the r_E = 9 m case, and

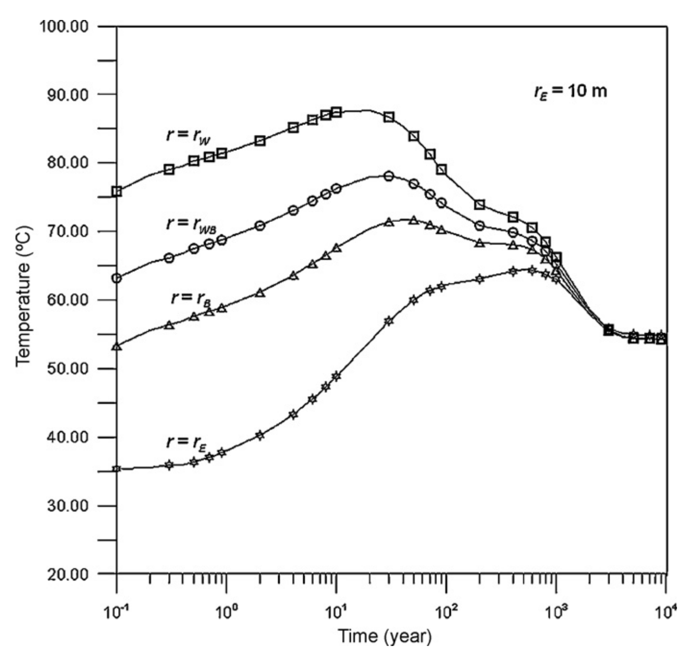

Fig. 4. Plots of the temperature distribution curves at the outside of the waste canister, the buffer mid, the borehole-rock boundary, and the center between adjacent boreholes temperatures for r_E = 10 m.

78.16 °C at 26 years for the $r_E = 10$ m case. These results indicate that only the case of $r_E = 10$ m satisfies the requirements of low-temperature disposal site standards (i.e., less than 80 °C) out of four cases. Therefore, the temperature distribution curves for $r_E = 10$ m are plotted in Fig. 4 to investigate the effects on the temperatures of the outside of the waste canister r_W, the buffer mid r_{WB}, the borehole-rock boundary r_B, and the center between adjacent boreholes r_E. The maximum temperatures are 87.86 °C at 16 years for r_W, 78.16 °C at 26 years for r_{WB}, 71.70 °C at 42 years for r_B, and 64.44 °C at about 530 years for r_E. The results satisfy the requirement of the low-temperature disposal site standards since the temperatures are less than 100 °C at r_W, 80 °C at r_B, and 70 °C at r_E, respectively.

These results demonstrate that the present analytical model can be used to assess the effects of the varying waste canister spacing on the temperatures of the waste canister outside, the buffer mid, the borehole-rock boundary, and the center between adjacent boreholes in a geological repository for high-level nuclear waste. The present analytical solutions have practical use in the design of high-lever nuclear waste geological repositories.

4. Concluding remarks

1. A mathematical model describing the heat transfer in transient temperature fields in final nuclear waste repositories is presented. Laplace-domain solutions for temperature distribution are developed using Laplace transforms and the corresponding solutions in time domain are calculated using the modified Crump method.
2. The present analytical model can be used to assess the effects of heat transfer on temperature distribution in a deep geological nuclear waste repository as a function of waste canister size, spacing, and decay heat. The model can be used to simulate the temperature distribution of a disposal site when nuclear waste is reposited in a deep geological formation.
3. The simulation results of the present model indicate that the temperature distribution at a disposal site may be over the safety standard if the design width and thickness is too small. In addition, four main parameters involved in the design of nuclear waste repository, namely the decay heat of the waste canister, the thermal properties of the buffer and rock, the disposal spacing, and the thickness of the host rock, have significant effects on the temperature distribution in a thermal field at a final nuclear waste repository.

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