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FORCED-AIR COOLING OF A WIPP MINE DRIFT

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A WIPP MINE DRIFT

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July 1978

ABSTRACT

A one-dimensional model has been developed to predict the time, t^* , required to cool a WIPP mine drift. Comparisons have been made with a two-dimensional model and are found to be in good agreement for four months $\leq t^* \leq$ two years. If the mean roughness of the WIPP mine surface is greater than 1/8 inch, the mine floor can be cooled to 120°F in less than one year, depending on the time after waste emplacement at which mine ventilation commences.

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NOMENCLATURE

a	Half life of radioactive waste
B_i	Biot number, hD/k
B'_i	$= B_i (\rho C_p)_s (\rho C_p)_a^{-1}$
C_p	Specific heat, Btu/Lbm $^{\circ}$ F
D	Hydraulic diameter, ft
D_W	Distance away from salt mine surface to which salt is heated for $t \leq t_i$, ft
H	Height of mine drift, ft
k	Thermal conductivity of salt
L	Length of mine drift, ft
P	Perimeter of mine drift cross-section, ft
P_L	Modified Peclet number, $v_o D^2 (La)^{-1}$
Q''	Dimensionless heat flux, $q'' D [k(T_o - T_a)]^{-1}$
q''	Heat flux, kW/acre
t	Time, s
t_i	Time after waste emplacement at which mine ventilation begins, years
t^*	Time required to cool mine floor to a chosen safe temperature, years
T	Temperature, $^{\circ}$ F
T_o	Initial temperature of the salt mine surface, $^{\circ}$ F
T_a	Inlet temperature of the air, $^{\circ}$ F
T_m	Mean temperature of the air over the length of the mine drift, $^{\circ}$ F
T^*	Safe temperature of the mine drift floor, $^{\circ}$ F
v, v_o	Constant velocity of the air through the mine drift, ft/s
W	Width of the mine drift, ft
$\tilde{x}, \tilde{y}, \tilde{z}$	Cartesian coordinates, ft
x, y, z	Dimensionless cartesian coordinates, $(\tilde{x} - \lambda)/D, \tilde{y}/D, \tilde{z}/D$

Greek

α	Thermal diffusivity of the salt, $k(C_p \rho)^{-1}$, ft^2/s
$\tilde{\delta}$	Thermal penetration depth, ft
δ	Dimensionless thermal penetration depth, $\tilde{\delta}/D$
ϵ	Mean roughness of mine surface
ρ	Density, lbm/ft^3
θ	Dimensionless temperature, $[T(t, t_i) - T_O(t_i)][T_O(t_i) - T_a]^{-1}$
λ	Exponential decay heat constant for the radioactive waste, $a^{-1} \ln 2$
$\bar{\lambda}$	Dimensionless exponential decay heat constant, $\lambda D^2 \alpha^{-1}$
σ_1	Ratio of the area from which heat is extracted from the mine or which has been heated substantially for $t < t_i$ to the total surface area of the mine
τ	Dimensionless time or Fourier number, $\alpha t D^{-2}$
τ'	Dimensionless time, $P_k \tau$
τ_i	Dimensionless time at which mine ventilation begins, $\alpha t_i D^{-2}$
τ^*	Dimensionless time at which a safe mine floor temperature is reached $\alpha t^* D^{-2}$

Subscripts[†]

1	Refers to the property of the air
2	Refers to the property of the salt
a	Refers to the inlet properties of the air at the inlet to the mine
m	Refers to the mean property of the air over the length of the mine
w	Refers to the property of the salt at $\tilde{x} = D_w$
f	Refers to the property of the salt
2F	Refers to the property of the salt floor at the mine exit
1e	Refers to the property of the air at the mine exit

[†] Unless otherwise specified

INTRODUCTION AND SUMMARY

In the Waste Isolation Pilot Plant (WIPP) Program, it is important to know the time required to cool by forced air the drifts within a salt mine repository which contains buried nuclear waste. In order to re-enter the mine for possible retrieval of waste canisters, it is necessary to remove a sufficient amount of energy from the waste and surrounding salt such that a safe floor temperature is reached in the mine. In addition, it is important to know the required air flow rates and inlet temperature necessary to cool the repository to a safe temperature in a reasonable time period. Since thermal stress considerations may become important when the relatively hot salt surface is exposed to the cool air, it is also important to know the floor temperature gradient during cooling.

Although a number of two- and three-dimensional computer codes^{1,2,3} have been developed or can be used to examine portions of this problem, it is difficult to evaluate the validity of the models, identify all the important parameters and most importantly evaluate new cases and conditions with minimal effort. Since the WIPP program is in its conceptual design stage, it is important for the designers and planners to have a capability to assess a given design or to examine the effect of required design changes. This usually becomes impractical and expensive with large computer codes.

A one-dimensional model has been formulated as a first attempt at providing the designer and project group with an approximate analysis of the forced air cooling of a WIPP mine drift. Results are in terms of a set of nondimensional parameter groups identified in the analysis. The important parameters are the ratio of the temperature difference between the salt surface and the initial salt temperature to the initial temperature difference between the salt and

the flowing air, the Biot number, a modified Peclet number, a dimensionless heat flux at the time (t_1) ventilation begins, and an average dimensionless half life of the radioactive waste. If there are large uncertainties in the salt density and/or specific heat, another parameter, which becomes important, is the ratio of the products of the density and specific heat for salt to that of air. There will probably be large uncertainties in the Biot number because of uncertainties in the thermal conductivity and the turbulent heat transfer coefficient (which is related to the relative roughness of the mine surface) between the flowing air and the salt surfaces.

The one-dimensional model estimates the time, t^* , required to cool the floor of the salt mine to a safe temperature, T^* . The present one-dimensional (1-D) analysis compares favorably with a two-dimensional (2-D) model developed by Science Application, Inc. (SAI).^{2,3} At very small values of t^* (weeks), the 1-D predictions are ~40% lower than the 2-D predictions; for moderate values of t^* (four months to ~two years), the agreement between the 1-D and 2-D predictions is good (<10%). For large values of t^* (> two years), the 1-D predictions are ~25% higher than the 2-D predictions.

One-dimensional predictions were made for a repository loading of 75 kW/acre and an inlet air velocity and temperature of 2.57 ft/s and 92°F, respectively. The results indicate that the time, t^* , required to cool the floor of a salt mine drift which has had radioactive waste emplaced for more than ~15 years is independent of the time at which ventilation begins (t_1). In addition, if the velocity is significantly increased (e.g., doubled), t^* appears to decrease accordingly; however, for the typical WIPP design specifications (see Equation 10), t^* is not substantially affected by changes in the inlet flow rate above ~70,000 cfm. Further, if the mine surface is rough, i.e., the mean heat transfer coefficient (h) is high (≥ 1.3 Btu/hr-ft²-°F), it is estimated that, depending on the time (t_1) at which cooling is begun, less than one year will be required to cool the floor of the salt mine down to $T^* = 120^\circ\text{F}$. However, if the mine surface is smooth, i.e., h is relatively low (≤ 0.3 Btu/hr-ft²-°F), it is estimated that less than ten years (depending on the value of t_1) will be required to cool the floor of the salt mine to 120°F.

At this point, the relative roughness ($2 \epsilon/D$) of the salt mine surface is unknown. Since the turbulent heat transfer coefficient is related to the relative roughness, it is obvious that before reliable estimates of t^* can be made, the roughness of the mine surfaces must be determined. Isolated heat transfer measurements are necessary to verify those computed values using the measured roughnesses and the available correlations for rough surfaces. It should be pointed out that, based on existing correlations for sand roughnesses in pipes, if the roughness (ϵ) of the salt surface is at least $1/8$ inch ($D = 15$ ft), it appears that the resulting heat transfer coefficient will be $1.0 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$ ($\approx 1.4 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$ for Reynolds number $\sim 2 \times 10^5$). This implies that the predictions made for $h = 1.0 \text{ Btu/hr-ft}^2$ are conservative, provided $\epsilon \geq 1/8$ inch and the typical design specifications are applicable.

ANALYTICAL APPROXIMATION

The present approximate analysis represents a first attempt at providing the designer with formulae and approximations which can be used to estimate: (1) the time required to cool the salt mine floor to a safe temperature level, and (2) the exit air temperature and the mine floor temperature variation with respect to time.

The analysis is based on a global energy balance and hence will not accurately predict local temperature distributions (see Figure 1). The region around the mine drift is assumed to be initially at a constant temperature, T_0 , and has a constant thermal conductivity, k . Effects of temperature-dependent thermal conductivity and initial temperature distribution are not included but can be added possibly later. The energy generated by the radioactive waste at approximately ten feet below the mine floor is replaced by an equivalent heat flux at the level of the floor. The heat transfer coefficient, h , between the air and the drift walls is assumed constant. The air velocity, v_0 , is also assumed to be constant along the length of and across the mine drift. Since the analysis is one-dimensional, the isotherms in the salt are assumed to possess geometric similarity (see Figure 1, $\tan \theta = d\tilde{x}/d\tilde{y}$).

Thermal Approximation for the Salt Rock

Consider the differential increase in the total heated volume, $L dA_T$, at a location $\tilde{x} = \tilde{\delta}$ in the salt rock which surrounds the mine drift (see Figure 1). The thermal penetration depth is denoted by $\tilde{\delta}$. Since it is assumed that the isotherms in the salt possess geometrical similarity, this differential volume is given by,

$$L dA_T = 2L[W + 2\tilde{\delta}/\tan \theta + d\tilde{y}]d\tilde{x} + 2L[H + 2\tilde{\delta} + d\tilde{x}]d\tilde{y}.$$

The thermal energy balance on this volume is (note: $x = (\tilde{x} - \tilde{\delta})/D$, $y = \tilde{y}/D$ and $\delta = \tilde{\delta}/D$)

$$L dA_T \rho_s C_{ps} \frac{\partial T_2}{\partial t} = 2kL \left[\frac{\partial^2 T_2}{\partial x^2} \frac{W}{D} dx + \frac{\partial^2 T_2}{\partial y^2} \frac{H}{D} dy \right],$$

where T_2 and D are the salt temperature and the hydraulic diameter, respectively.

If dx is taken to be arbitrarily small and noting that $\tan \theta = dx/dy = H/W$, the above equations reduce to,

$$\alpha \frac{\partial T_2}{\partial t} = \frac{\partial^2 T_2}{\partial x^2}, \quad (1)$$

where,

$$\alpha = [2 + 8\delta(1 + \tan \theta)^{-1}][1 + \tan^2 \theta]^{-1}, \text{ and}$$

$$D = 4WH/[2(W + H)] = 2W \tan \theta (1 + \tan \theta)^{-1}.$$

In the above equation and those which follow, $\alpha (= D^2\tau/t)$ and τ are the thermal diffusivity and the dimensionless time (or Fourier number), respectively. The dimensionless thermal penetration depth is δ and represents the distance over which energy has been conducted in or out of the salt medium after cooling begins. If T_o and T_a represent the initial salt and inlet air temperatures, respectively, the boundary conditions are,

$$\text{at } x = \delta, \quad -\frac{\partial \theta_2}{\partial x} = \sigma_1 B_i (\theta_2 - \theta_1) - \frac{1}{2} Q'' [1 + \tan^2 \theta]^{-1} e^{-\bar{\lambda}(\tau + \tau_1)}$$

$$\text{at } x = 0, \quad \theta_2 = 0 = \frac{\partial \theta_2}{\partial x}, \quad (2)$$

where,

$$x = \delta - \frac{\tilde{x}}{D}; \quad Q'' = \frac{q'' D}{(T_0 - T_a)k}; \quad B_i = \frac{hD}{k};$$

$$\bar{\lambda} = \frac{\lambda D^2}{a}; \quad \tau = \frac{ta}{D^2}; \quad \theta_2 = \frac{T_2 - T_0}{T_0 - T_a}; \quad \text{and} \quad \theta_1 = \frac{T_1 - T_0}{T_0 - T_a}.$$

In the above expressions, B_i is the Biot number; h is the mean heat transfer coefficient along the mine drift; q'' is the heat flux; τ is the dimensionless time; τ_i is the dimensionless time at which the forced air cooling begins; $\lambda (= \frac{\lambda n^2}{a})$ is related to the half life, a , of the radioactive waste; and, T_1 is the local temperature of the flowing air. From Figure 1, estimations of $D_{\frac{1}{2}}$ at respective values of τ_i are obtained using the present analysis by computing the thermal penetration depth in the heated salt, in the absence of cooling (i.e., $B_i = 0 = v_0$).

In Equation (2), the quantity σ_1 has special significance since it controls the rate at which energy is removed from the surface of the mine. The quantity σ_1 is defined as the ratio of the surface area from which energy is removed from the mine walls (or the area adjacent to the portion of the salt which has been heated substantially) to the total surface area of the mine drift. In fact, it is through σ_1 that simple characteristics of the two-dimensional nature of the problem are included. For short periods of time [$\tau_i \leq 0(1 \text{ year})$] after the emplacement of the canisters and before cooling begins, the heat generated in the vicinity of the floor will diffuse in directions parallel and normal to the floor. Consequently, the salt strata near the floor and vertical walls will have been heated considerably. However, the salt strata above the ceiling will have been heated only slightly. On the otherhand, for long periods of time [$\tau_i = 0(10 \text{ years})$], sufficient time will have transpired such that all the salt surrounding the mine drift will have been sufficiently heated. The above observations have been verified by two- and three-dimensional computations.^{4,6}

After cooling begins, the value of σ_1 will also depend on whether the thermal energy is removed rapidly or slowly. If, for example, the time, t_i , of canister emplacement before cooling is small and if the thermal energy is removed slowly (i.e., small h : smooth mine surface), sufficient time will exist for the salt surrounding the mine drift to thermally equilibrate due to radioactive heating and subsequent thermal diffusion. Inversely, if t_i is small but h is large (rough mine surface), the thermal energy will be removed due to cooling before the area in the vicinity of the mine drift ceiling has been sufficiently heated. As a result, energy is only extracted from the vicinity of the floor and the vertical walls. Therefore, the parameter, σ_1 , is approximated as follows:

$$\sigma_1 = \begin{cases} 1 & \left\{ \begin{array}{l} \text{Smooth pipe flow (small values of } h \text{) and any value of } t_i^+ \\ \text{Large values of } t_i \text{ and the transition regime between} \\ \text{smooth and rough pipe flow (moderate values of } h \text{)} \end{array} \right. \\ (1 - \frac{W}{P}) & \left\{ \begin{array}{l} \text{Small values of } t_i \text{ and the transition regime between} \\ \text{smooth and rough pipe flow (moderate values of } h \text{)} \\ \text{Rough pipe flow (large values of } h \text{) and any values of } t_i \end{array} \right. \end{cases} \quad (3)$$

A first order profile approximation is assumed for θ_2 such that the boundary conditions in Equation (2) are satisfied. Different profiles result depending on whether δ is equal to or less than D_w/D (see Figure 1). If T_m is the mean salt temperature over the length of the mine drift, the following formulae result for the temperature profiles on the salt when $\delta \leq D_w/D_i$:

[†]The computational experience which has been obtained with the present formulae indicates that small and large values of t_i are 0(≤ 1 year) and 0(≥ 10 years) respectively. Small and large values of h are 0(0.2 Btu/hrft²-°F) and 0(~ 2 Btu/hrft²-°F), respectively. Moderate values of the mean turbulent heat transfer coefficient would be from ~ 0.4 to ≤ 2.0 Btu/hrft²-°F. These limits have not been well established but can be by matching the results of computations for both values of σ_1 for the respective limits in each case of interest.

A. For $\delta < D_W/D$

$$\theta_2 = [\sigma_1 B_i \theta_m + \frac{1}{2} Q'' (1 + \tan^2 \theta)^{-1} e^{-\bar{\lambda}(\tau + \tau_i)}] x^2 / (2 + \sigma_1 B_i \delta) \quad (4)$$

After this equation is substituted into Equation (1) and the result integrated from $x = \delta$ to $x = 0$, the equation governing $\delta(\tau)$ results,

$$A(\tau) \frac{d\delta^2}{d\tau} + B(\tau) \delta^2 = b/\sigma(\tau) \quad ,$$

where,

$$A = 1 - \sigma_1 B_i \delta / (2 + \sigma_1 B_i \delta) \quad , \quad \text{and} \quad (5a)$$

$$B = [\sigma_1 B_i \frac{d\theta_m}{d\tau} - \frac{1}{2} Q'' \bar{\lambda} (1 + \tan^2 \theta)^{-1} e^{-\bar{\lambda}(\tau + \tau_i)}] \\ [\sigma_1 B_i \theta_m + \frac{1}{2} Q'' (1 + \tan^2 \theta)^{-1} e^{-\bar{\lambda}(\tau + \tau_i)}]^{-1} \quad .$$

Because of computational difficulties which arose in the solution of the equation for the exit air temperature, the expression for the dimensionless time, τ , had to be modified to,

$$\tau' = P_2 \tau \quad . \quad (5b)$$

B. For $\delta = D_W/D$

$$\theta_2 = \theta_W(\tau) + b(\tau) x^2 \quad , \quad (6)$$

where,

$$b(\tau) = [-\sigma_1 B_i (\theta_W - \theta_m) + Q'' e^{-\bar{\lambda}(\tau + \tau_i)}] / [(2 + \sigma_1 B_i \frac{D_W}{D}) \frac{D_W}{D}] \quad ,$$

and $\theta_W(\tau)$ is related to the temperature at $\bar{x} = D_W$ (or $x = 0$) which is constant and equal to T_0 for $\delta < D_W/D$, and which varies with respect to τ for $\delta = D_W/D$. After θ_2 is substituted into Equation (1) and integrated from $x = 0$ to $x = D_W$, the governing differential equation for θ_W is,

$$4(3 + \sigma_1 B_i) \frac{d\theta_W}{d\tau} + 12 \frac{\sigma_1}{\sigma} B_i (\theta_W - \theta_m) + u(\tau) = 0 \quad , \quad (7a)$$

where,

$$u(\tau) = 2\sigma_1 B_1 \frac{d\theta_m}{d\tau} - (2\bar{\lambda} + 12/\sigma) Q' e^{-\bar{\lambda}(\tau + \tau_1)} \quad (7b)$$

Approximation for the Flowing Air

The air which cools the floor and walls of the salt mine drift is assumed to have a temperature variation only in the flowing direction. Since the flow is turbulent and the mine surface is possibly rough, there may be a considerable pressure loss, and hence a velocity defect along the drift. However, effects of drag and variations in the air velocity, v_o , are neglected. These effects should be included in later analyses.

The conservation of thermal energy for the flowing air is given by,

$$\frac{\partial \theta_1}{\partial \tau} + P_2 \frac{\partial \theta_1}{\partial z} = B_1' [\theta_2(x = \delta) - \theta_1] \quad (8a)$$

and the boundary conditions are,

$$\text{at } \tau = 0, \theta_1 = 0 \text{ and at } z = 0, \theta_1 = -1 \quad (8b)$$

where,

$$P_2 = \frac{v_o D^2}{L \alpha}$$

$$B_1' = 4\sigma_1 B_1 \frac{(\rho C_p)_s}{(\rho C_p)_a}$$

$$z = \frac{\bar{z}}{L}$$

If Equation (8) is integrated over the length of the mine drift, the following equation results,

$$\frac{d\theta_m}{d\tau} + B_1 (\theta_m + 1) = P_2^{-1} B_1' [\theta_2(x = \delta) - \theta_m] \quad (9)$$

$$B_1 = \begin{cases} 1, & \text{for long mine drifts where } \theta_m \approx \theta_1(z = 1) \approx \text{Exit Air Temperature} \\ 2, & \text{for short mine drifts where } \theta_m \approx [\theta_1(z = 0) + \theta_1(z = 1)]/2 \end{cases}$$

$$\theta_m = \frac{T_m - T_o}{T_o - T_a} ,$$

where θ_m is related to the average air temperature, T_m , over the length of the mine drift, and P_2 is a modified Peclet number. Since the mine drifts of interest are long ($L/D = 0[40]$), $B_1 = 1$ should be used. Also, note that in Equation (8a), the second term on the left-hand-side of the equation is $0[P_2] = 0[10^4]$ and the term on the right-hand-side is $0[B_1] = 0[10^4]$. This will present a stability problem in the numerical solution since the difference of two relatively large numbers is being evaluated. This is remedied by substituting $\tau = \tau' P_2^{-1}$ in Equations (5), (7) and (8).

RESULTS

The results are presented in the form of two design examples for different radioactive waste levels. The first example has been provided by the WIPP project group.⁵

$$\alpha'' = 75 \text{ kW/acre}$$

$$a = 30 \text{ years}$$

$$H = W = 15 \text{ feet}$$

$$L = 558 \text{ feet}$$

$$v_o = 2.57 \text{ ft/s}$$

$$T_a = 92^\circ\text{F}$$

$$T^* = 120^\circ\text{F}$$

$$k_s (\text{Btu/hrft}^2\text{-}^\circ\text{F}) = \begin{cases} 3.26 @ 32^\circ\text{F} \\ 3.26 @ 125.6^\circ\text{F} \\ 2.72 @ 179.6^\circ\text{F} \\ 2.20 @ 377.6^\circ\text{F} \end{cases}$$

$$\rho_s = 135 \text{ lbm/ft}^3 \text{ (2.16 gm/cm}^3\text{)}$$

$$C_{p_s} = 0.22 \text{ Btu/lbm}^\circ\text{F} \text{ (0.92 J/gm-K)}$$

$$\rho_a = 0.071 \text{ lbm/ft}^3$$

$$C_{p_a} = 0.24 \text{ Btu/lbm}^\circ\text{F}$$

$$t_i = 1, 5, 10, 20 \text{ and } 30 \text{ years} \tag{10}$$

$$3.5 \text{ kW/canister}$$

Values of T_o for corresponding values of t_i were obtained from three-dimensional calculations performed by C. Sisson.⁶ At chosen values of t_i , the respective values of T_o were averaged from the value of the temperature of the surface node #88 (located along the mine floor) and the analogous nodes in the five remaining sectors of the mesh (see Table I). The value for the mean turbulent heat transfer coefficient over a smooth surface is estimated to be $\sim 0.33 \text{ Btu/hrft}^2\text{-}^\circ\text{F}$. Since the turbulent heat transfer coefficient for a rough surface can be considerably higher than that for a smooth one, calculations are performed $h = 0.33$ and $1.0 \text{ Btu/hrft}^2\text{-}^\circ\text{F}$.[†]

The second example was common to the analysis performed by Science Applications, Inc. (SAI),^{2,3} who made calculations using a two-dimensional model for the salt strata. The one-dimensional model, of Figure 1, was compared with the two-dimensional SAI model for the following problem specifications:

$$q'' = 120 \text{ kW/acre}^\ddagger$$

$$H = W = 18 \text{ feet}$$

$$L = 558 \text{ feet}$$

$$v_o = 2.57 \text{ ft/s}$$

$$T_a = 75^\circ\text{F}$$

$$t_i = 2, 5, 10 \text{ and } 15 \text{ years}$$

$$a \approx 23, 30, 30 \text{ and } 30 \text{ years, respectively}$$

$$k_s (\text{Btu/hrft}^\circ\text{F}) = \begin{cases} 2.53, 32^\circ\text{F} \\ 2.90, 122^\circ\text{F} \\ 2.43, 212^\circ\text{F} \\ 2.08, 302^\circ\text{F} \end{cases}$$

$$\rho_s = 135 \text{ lbm/ft}^3$$

$$c_{p_s} = 0.22 \text{ Btu/lbm}^\circ\text{F}$$

$$\rho_a = 0.071 \text{ lbm/ft}^3$$

$$c_{p_a} = 0.24 \text{ Btu/lbm}^\circ\text{F}$$

$$h = 0.2 \text{ and } 0.8 \text{ Btu/hrft}^2\text{-}^\circ\text{F}$$

(11)[‡]

[†]Using the specifications of Equation (10) and a relative roughness ($2 \epsilon/D$) of 10^{-3} , the flow is barely in the rough-pipe-flow regime. For this case, $h \sim 1.3 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$.

[‡]This value of 120 kW/acre was selected as an estimate for q'' . Using the data given in Ref. 3 (pg. 2-1), the correct value of q'' should be 112 kW/acre which differs only slightly from the value used.

TABLE I
PREDICTIONS FOR THE FORCED AIR COOLING OF A WIPP MINE DRIFT[†]

Years Before Cooling Begins, t_i (years)	Initial Temperature of Salt, $T_o(t_i)$ (°F)	Time Required to Cool Mine Floor to T^* , t^* (years)	Heat Transfer Coefficient, h (Btu/hrft ² -°F)	Salt Thermal Conductivity @ T_o , k (Btu/hrft°°F)	$C_1 B_i$	$P_2 \times 10^{-4}$	Q''
1	164	0.26	1.0	2.27	5.0	4.9	0.54
5	195	~0.75		2.20	5.1	5.0	0.39
10	210	~1.02		2.18	6.9	5.1	0.34
20	224	1.28		2.16	6.9	5.1	0.31
30	227	1.32		2.15	7.0	5.2	0.30
1	164	1.62	0.33	2.27	2.2	4.9	0.54
5	195	5.83		2.20	2.3	5.0	0.39
10	210	8.68		2.18	2.3	5.1	0.34
20	224	11.40		2.16	2.3	5.1	0.31
30	227	11.45		2.15	2.3	5.2	0.30

[†]Inlet Air Temperature = $T_a = 92^\circ\text{F}$, Safe Temperature Level = $T^* = 120^\circ\text{F}$, Heat Flux = $q'' = 75 \text{ kW/acre}$, Air Velocity = $v_o = 2.57 \text{ ft/s}$, Half Life = $a = 30 \text{ years}$, Mine Width and Height (W and H) = 15 ft, $B_1 = 1$ (long mine drift), B_i = Biot Number, P_2 = Peclet Number, Q'' = Dimensionless Heat Flux = $q''D/k(T_o - T_a)$. Also, see Equation (10).

WIPP Predictions

The time, t^* , required for the salt mine floor to reach a safe temperature level is strongly related to the mine surface roughness (ϵ) and the mean heat transfer coefficient (h). Considerable data is available for turbulent heat transfer between air and a smooth surface. However, depending on the roughness of the salt rock, the heat transfer coefficient may be up to an order of magnitude higher than that predicted by the smooth pipe flow data. Such a variation will greatly affect the prediction of t^* . For example, using the WIPP problem specifications, if the actual mean heat transfer coefficient is three times larger than that computed for air flow over a smooth surface, the time t^* required to reach a safe temperature (T^*) will decrease by an order of magnitude (see Figure 2). This emphasizes the need for experimental determination of the mean roughness and heat transfer coefficient.

When the heat flux is 75 kW/acre, the predictions of t^* (see Figure 2) approach, in an asymptotic manner, a maximum and then slowly decay. This indicates that approximately the same time is required to cool the salt mine floor when the radioactive waste has been emplaced for more than ~15 years (see Table I). If the actual heat transfer coefficient were the same as that predicted for smooth surfaces ($0.33 \text{ Btu/hrft}^2\text{-}^\circ\text{F}$), it would require from two to ten years, depending on the time (t_i) at which cooling begins, to cool the mine floor (Figure 2a). However, if the heat transfer coefficient were three times larger, it would take, depending on the value of t_i , from several weeks to one year (see Figure 2c).

In Figure 2, Curves b ($\sigma_1 = 1 - W/P$) and d ($\sigma_1 = 1$) represent the limits for small values of t_i (or large values of h) and large values of t_i (or small values of h), respectively. Curve c represents the transition or matching curve from Curve b to Curve d as t_i increases. Curve c is only approximate since it was sketched with a french curve between Curves b and d. It is not clear how such a matching procedure should be performed; it is, however, believed that the benefit of defining such a procedure does not justify the required effort. In cases where h is large ($\geq 0.2 \text{ Btu/hrft}^2\text{-}^\circ\text{F}$) or small

FIGURE 2. Predictions for the Forced Air Cooling of a WIPP Mine Drift. Safe Floor Temperature $\equiv T^* = 120^\circ\text{F}$. Air Velocity $\equiv v_0 = 2.57 \text{ ft/s}$. $q'' = 75 \text{ kW/acre}$.

($h = 0.3 \text{ Btu/hrft}^2\text{-}^\circ\text{F}$) curves similar to Curve b ($\sigma_1 = 1 - W/P$) or Curve d ($\sigma_1 = 1$), respectively, in Figure 2 should be used regardless of the values of t_1 . This point is demonstrated in Curve a which represents predictions of t^* for a smooth surface or a relatively small value of h . Finally, the effect of changes in the air velocity (v) or the modified Peclet number (P_L) on the time, t^* , is shown in Figure 2 for $h = 1 \text{ Btu/hrft}^2\text{-}^\circ\text{F}$ and $t_1 = 30$ years. It appears that below a certain limiting value of the air velocity, the time, t^* , required to cool the mine floor to a safe temperature (T^*) decreases in an inverse manner with an increase in v (see Figure 2). Based on the limited cases considered and for the specifications in Equation (10), this limiting value of v is approximately 300 ft/min (or $\sim 70,000$ cfm and $P_L \approx 10^5$). Above this limit, further increases in the air velocity will result in progressively smaller changes in t^* . Obviously, an increase in the velocity will increase the heat transfer coefficient. Although this has not been considered presently, the effect would be to lower the two points ($v/v_0 = 2$ & 3) in Figure 2, therefore, making the above limiting value of v more accurate.

Figures 3 and 4 show the influence of h on the time-dependent mine floor and exit air temperatures. Again, Figure 3 emphasizes the large changes in τ^* for moderate changes in h . The difference between the predictions for $\sigma_1 = 1$ (Curve 3c) and $\sigma_1 = 1 - W/P$ (Curve 3b) is important; for the indicated case ($h = 1 \text{ Btu/hrft}^2\text{-}^\circ\text{F}$ and $t_1 = 30$ years) Curve 3c, rather than Curve 3b, should be used. For all values of h , the exit air temperature decreases rapidly and then asymptotically approaches the inlet air temperature. The time, at which the asymptotic behavior begins, appears to be independent of the value of h (or B_1 , see Figure 4). However, the temperature at which this occurs is dependent on h . At first glance, the effect of h (or B_1) seems to have a pronounced effect on the exit air temperature (e.g., at $\theta_{1e} \approx -0.7$, $\tau' \approx 2$ for $B_1 = 2.3$ and $\tau' \approx 10^3$ for $B_1 = 7.0$). However, the time, τ^* , required to cool the mine floor down to a safe level will be usually greater than $\tau' \approx 10^4$, and in this region, the dependence of τ^* on h (or B_1) is significant but not as great as alluded to above.

FIGURE 3. Time-Dependent Mine Floor Temperature Variation for $t_i = 30$ Years and $P_g = 5.16 \times 10^4$. $\sigma_1 = 1$: Smooth Surfaces and/or Large Values of t_i . $\sigma_1 = 1 - W/P$: Rough Surfaces and/or Small Values of t_i .

FIGURE 4. Time-Dependent Exit Air Temperature Variation for $t_i = 30$ Years and $P_k = 5.16 \times 10^4$. $\sigma_1 = 1$: Smooth Surfaces and/or Large Values of t_i . $\sigma_1 = 1 - W/P$: Rough Surfaces and/or Small Values of t_i .

The effects of thermal stresses in the salt rock as cooling proceeds is directly related to the surface temperature gradients normal to the mine surface. Figure 5 shows the dimensionless surface temperature gradient at the mine exit. The gradient rapidly increases with time as the air near the exit begins to cool the mine surface. It reaches a maximum as the cooling front begins to propagate into the salt strata. The gradient will eventually approach zero as cooling proceeds. It should, however, be emphasized that the maximum temperature gradient occurs near the entrance. This maximum temperature gradient occurs at $\tau = 0$ and is approximated by,

$$\left. \frac{d\theta_2}{dx} \right|_{\text{entrance}} = -B_i + \frac{1}{2}(1 + \tan^2 \theta)^{-1} Q_1' e^{-\bar{x}\tau_i} ,$$

$$\theta_2 = \frac{T_2 - T_0}{T_0 - T_a} ,$$

$$dx = -D^{-1} d\bar{x} , \quad (12)$$

where $dT_2/d\bar{x}$ represents the temperature gradient in the salt at the entrance of the mine.

As stated earlier, all computations were performed for constant salt thermal conductivity. However, it has been found that changes in the thermal conductivity are important and, therefore, should be included in the one-dimensional model. In Figure 6, computations were made for $h = 1.0 \text{ Btu/hrft}^2\text{-}^\circ\text{F}$, $k = 2.9 \text{ Btu/hrft}^\circ\text{F}$ ($B_i = 5.17$) and the specifications in Equation (10). If the computations are repeated with a 20% increase in k ($= 3.5 \text{ Btu/hrft}^\circ\text{F}$ or $B_i = 4.3$), the corresponding time, t^* , required to cool the mine floor to a safe temperature increases by ~35%. Further, when k is decreased by ~14% ($2.5 \text{ Btu/hrft}^\circ\text{F}$ or $B_i = 6.0$), the values of t^* decrease by ~25%. Therefore, temperature-dependent thermal conductivity for the salt rock is important. In order to include, to some extent, the effects of temperature-dependent thermal conductivity, all predictions presented were made using the thermal conductivity of the salt at the initial temperature, T_0 (t_i), of the salt before forced air cooling begins.

FIGURE 5. Time-Dependent Surface Temperature Gradient in the Salt at the Exit of the Mine Drift for $h = 1.0$ Btu/hrft²°F and $t_i \approx 30$ Years.

FIGURE 6. Predictions of the Time at Which a Safe Mine Floor Temperature is Reached as a Function of the Parameters, t_i and B_i . $\sigma_1 = 1$. $T^* = 120^{\circ}$ F.

Since the ratio of heat transfer coefficient to the thermal conductivity appears in the governing equations as the Biot number ($= hD/k$), the important quantity to be measured is B_i/D . In this respect, Figure 6 also shows the effect of variations in the time, t^* , with respect to B_i . Since B_i is a function of h , D and k , the effects of either of these quantities can be examined by considering their effect on the value of B_i and using the curves in Figure 6.

In addition to the predictions given in Figure 2 for a safe salt mine floor temperature, $T^* = 120^\circ\text{F} = T_{2F}$, and based on the previous discussion, a family of curves have been generated for values of the cooling time, $t^* \leq 12$ years (see Figures 7 and 8). Most of the specifications in Equation (10) apply; however, these are independent of the chosen value of the safe mine floor temperature, T^* . The corresponding time-dependent exit dimensionless air temperature is given in Figure 8. It should be emphasized that these predictions apply only to the case for $v_o = 154.32$ ft/min (volume flow rate = 34,722 cfm). Quantitative predictions for other values of v_o can only be obtained by running the computer program which has been developed. However, the qualitative (to within ± 15 -20% of the correct one-dimensional predictions) effect of different values of v_o (or P_i) can be obtained from Figure 7 without making further computer runs. Since only a limited number of cases have been considered, it is suggested that this qualitative approach should not be used for $v_o = 300$ ft/min ($\sim 70,000$ cfm). Based on the relationship, $\tau^* = tv_o/L$, the time, t^* , required to cool the surface of the salt mine drift to a safe temperature level is reduced (or increased) in an inverse manner when v_o is increased (or decreased). Therefore, the curves in Figure 7 provide quantitative predictions for any value of T^* and the specifications given in Equation (10), and qualitative predictions of t^* for other cases with different values of $P_i (= v_o D^2/La)$ and t_i (or T_o). Relative to the one-dimensional model, Curves (see Figure 7) b and g will underestimate τ^* by $\sim 10\%$; Curves a, d, f, e and i will reasonably estimate τ^* and Curves c and h will over estimate τ^* by $\sim 30\%$.

FIGURE 7. Time-Dependent Mine Floor Temperature Variations for the WIPP Mine Drift (see Equation (10)). See Table I for the Value of R which corresponds to t_i .

FIGURE 8. Time-Dependent Exit Air Temperature Variations for the WIPP Mine Drift. See Table I for the Value of R which corresponds to t_i .

The dimensionless cooling penetration depth, for $t_i = 30$ years is shown in Figure 9 for the value of the turbulent heat transfer coefficient, h , which corresponds to flow (Reynolds number $\sim 2 \times 10^5$) over a smooth surface ($h = 0.33$ Btu/hrft²-°F or $B_i = 2.3$) and a value three times this value ($B_i = 7.0$).

It should be noted that the subroutines describing Equations (6) and (7) have not been completely debugged in the present program and were not used in the cases where $\delta = D_w/\delta$. However, in most cases which have been considered, δ was less than D_w/D . This indicates that Equations (6) and (7) were unnecessary in most cases.

Comparison of One-Dimensional and Two-Dimensional Models

A two-dimensional unit cell conduction model was used by Science Applications, Inc., (SAI) for the salt rock surrounding the mine drift.^{2,3} Apparently, a one-dimensional model characterized the variation of the air temperature along the length of the drift. The air mass flow rate was assumed constant. Radiation heat transfer approximations between the drift walls, and temperature-dependent thermal conductivity for the salt were also included.

The problem specification for which comparisons are made with the present one-dimensional model is given in Equation (11). As noted in Equation (11), the calculations are performed for a heat flux of 120 kW/acre and 3.5 kW/acre. The values of the initial salt mine floor temperature at the time, t_i , cooling begins are given in Table II. The comparisons are made for the cases of the mine floor safe temperature being 120°F and 130°F for $h = 0.8$ and 2.2 Btu/hrft²-°F, respectively.

The agreement between the one-dimensional and two-dimensional models is fair (see Table II). At relatively large values of h or B_i (rough surfaces), the one-dimensional model predicts lower (from ~35% at low values of $t_i = 0$ [months] to ~9% at larger values of $t_i = 0$ [months]) values of t^* than the two-dimensional model (see Figure 10, curve a). At low values of h or B_i (smooth surfaces), there is good agreement for $0.5 \text{ year} \leq t^* \leq 2 \text{ years}$ and above ~2 years, the one-dimensional model predicts higher (by an average of ~25%) than the two-dimensional model (see Figure 11).

FIGURE 9. Time-Dependent Variation in the Thermal Penetration Depth for $t_i = 30$ Years and $P_g = 5.16 \times 10^4$, and $\sigma_1 = 1$.

TABLE II*

COMPARISONS OF THE ONE-DIMENSIONAL AND SAI^{2,3} PREDICTIONS FOR THE TIME, t^* , REQUIRED TO FORCE COOL A MINE DRIFT[†]

Years Before Cooling Begins, t_i (years)	Initial Temp. of Salt, $T_o(t_i)$ (°F)	Time at Which a Safe Mine Floor Temperature is Reached, t^* (years)		Heat Transfer Coefficient, h (Btu/hrft ² -°F)	Salt Thermal Conductivity @ T_o , k (Btu/hrft-°F)	$c_1 B_i$	$P_\ell \times 10^{-4}$	Q''
		SAI Predictions [‡]	I-D Predictions					
2	151	0.077	0.05	0.8	2.76	3.91	5.79	2.54
5	182	0.31	0.23		2.58	4.20	6.20	1.93
10	216	0.50	0.40		2.42	5.95	6.60	1.56
15	230	0.56	0.50		2.36	6.10	6.77	1.22
2	151	0.13	0.15	0.2	2.76	1.30	5.79	2.54
5	182	1.50	1.4		2.58	1.40	6.20	1.93
10	216	3.00	4.25		2.42	1.12	6.60	1.56
15	230	5.00	5.67		2.36	1.53	6.77	1.22

[†]Inlet Air Temperature $\equiv T_a = 75^\circ\text{F}$, Safe Temperature Level $\equiv T^* = 120^\circ\text{F}$ (for $h = 0.8$) and 130°F (for $h = 0.2$), Heat Flux $\equiv q'' = 120 \text{ kW/acre}$, Mine Width and Height (W and H) = 18 ft. $B_1 = 1$ (long mine drift), B_i = Biot Number, P_ℓ $\equiv$ Peclet Number, Q'' $\equiv$ Dimensionless Heat Flux = $q''D/k(T_o - T_a)$ (also see Equation (11)).

[‡]Temperature-dependent thermal conductivity was used. Two-D Predictions.

* See the footnote for Equation (11).

FIGURE 10. Comparison of the One-Dimensional Predictions with the Two-Dimensional Predictions Performed by Science Applications, Inc. (SAI) for $h = 0.8 \text{ Btu/hrft}^2\text{-}^\circ\text{F}$. See the footnote for Equation (11).

FIGURE 11. Comparison of the One-Dimensional Predictions with the Two-Dimensional Predictions Performed by Science Applications, Inc. (SAI) for $h = 0.2 \text{ Btu/hrft}^2\text{-}^\circ\text{F}$. See the footnote for Equation (11).

DISCUSSION AND RECOMMENDATIONS

In order for reasonable estimates to be made for the time, t^* , required to cool the salt mine floor to a safe temperature level, the mean mine surface roughness and/or the turbulent heat transfer coefficient for air flow over rough salt surfaces must be known. Initially, it would suffice to make measurements of the roughness and roughness variation along a typical mine surface. Heat transfer coefficients can be estimated based on this data. Later, it will be necessary to make a few heat transfer measurements to verify the estimates. Using the specifications in Equation (10), present estimates indicate that for a relative roughness ($2\epsilon/D$) of ~ 0.002 , the heat transfer coefficient, h , will be $1.3 \text{ Btu/hrft}^2\text{-}^\circ\text{F}$ and, therefore, the cooling times will be below those predicted in Curve c of Figure 2.⁷ However, it remains to be determined what values of relative roughness are typical of the salt mine drifts. A lower bound for h can be obtained from a host of data for turbulent air flow over smooth plates. In this case, the predicted values of t^* are at least an order of magnitude above the values of t^* computed for rough surfaces. Finally, since the variation in the salt thermal conductivity (k) with respect to temperature is important, and since B_1 ($= hD/k$) is an important parameter which appears in Equations (4) through (9), a more appropriate quantity to be measured is B_1/D . Therefore, in experiments where the heat transfer coefficient is measured, the thermal conductivity of the salt at the surface temperature must also be known.

The predictions reported in Table I, Figures 2, 7 and 8, were presented for a safe mine floor temperature of $T^* = 120^\circ\text{F}$. This value of T^* does not appear to be a safe thermal environment for humans to work for prolonged periods of time. As mentioned previously, values of t^* for smaller values of T^* can be obtained from Figure 7. However, it will be found that the corresponding values of t^* , at smaller values of T^* , increase substantially for a given

value of the heat transfer coefficient. For example, if T^* is 110°F , $T_a = 92^{\circ}\text{F}$ and $t_i = 5$ years, the time (t^*) required to cool mine floor is ~ 4.6 years (compared to 0.74 years for $T^* = 120^{\circ}\text{F}$) and 34.5 years (compared to ~ 5.8 years for $T^* = 120^{\circ}\text{F}$) for relatively rough surfaces ($h = 1.0 \text{ Btu/hrft}^2\text{-}^{\circ}\text{F}$) and smooth surfaces ($h = 0.33 \text{ Btu/hrft}^2\text{-}^{\circ}\text{F}$), respectively. Further, based on Figure 7, there exist no values of $t^* < 12$ years for which the dimensionless mine floor temperature, θ_{2F} , is less than -0.9 , for $h = 1.0 \text{ Btu/hrft}^2\text{-}^{\circ}\text{F}$, and less than -0.8 , for $h = 0.33 \text{ Btu/hrft}^2\text{-}^{\circ}\text{F}$. This implies that if a value of T^* is assumed and if the corresponding values of θ_{2F} is < -0.9 , for $h = 1.0$, or < -0.8 , for $h = 0.33$, then t^* will be > 12 years.

If a safe mine floor temperature below 120°F is required for the case of 75 kW/acre, it is apparent that some modifications would be necessary in either or possibly all of the following: the inlet air temperature (T_a), the mine drift length (L), the heat transfer coefficient (h), the inlet air velocity (v_o), the mine hydraulic diameter (D), or the equivalent heat flux (q''). Although the effect of the aspect ratio ($\tan \theta = H/W$) has not been evaluated here, there may exist an optimum aspect ratio for which t^* is a minimum. Intuition indicates that the optimum value of $\tan \theta$ is 1.0. Obviously, one could reduce the time, t^* , by reducing the time (t_i) at which forced cooling begins, or by periodically venting the drift for a prescribed period of time. Since increases in the heat transfer coefficient significantly reduces t^* , one could deliberately make the mine drift walls rough. There is, however, a limit to how rough the walls should be since the pressure losses may become too large for very rough surfaces. The effect of reducing the inlet air temperature (T_a) has not been evaluated here but this can easily be assessed by re-running the computer program which has been developed. In cases where the effect of decay heating (Q'') is small, Figures 7 and 8 can be used, quantitatively, for different values of T_o (t_i) and T_a .

It is important to again note that the agreement between the one-dimensional and two-dimensional predictions (see Table II)^{2,3} is good for ~ 4 months $\leq t^* \leq 2$ years. Since it probably will be desired to achieve complete mine cool-down on a time scale of the order of months, the present one-dimensional model is

adequate. However, it should be emphasized that the present model does not consider axial variations in the mine surface temperature, the temperature of the flowing air (implicitly but not explicitly), and the air velocity. When these effects are considered, it will probably be found that the time required to cool the bulk of the mine is in agreement with the present predictions, but that the downstream end of the mine will remain much hotter for a longer period of time than the upstream end. Therefore, for more detailed physical models, later computations should include axial variations in the temperature (salt and air),[†] air velocity and an estimate of the drag and pressure losses. Profile approximations for the cross-sectional air velocity and temperature distributions may be used. In addition, the effect of the entrance flow and heat transfer on the mean heat transfer coefficient and pressure losses should also be considered. Fully developed air flow occurs in portions of the downstream half of the mine drift. Therefore, effects of the developing boundary layers, in the entrance region, on the local air velocity and temperature should be investigated. In these more detailed calculations, it would be possible to compute the shear stress exerted on the mine surface by the flowing air. This stress could be used by the stress analyst to investigate effects of fracturing (at elevated temperatures) the burrs which exist on the mine surface, and, hence, smoothing the surface. If this smoothing effect exists, it would be detrimental to the forced air cooling process in that the time t^* would be increased drastically.

Finally, there are a number of accident safety studies which should be considered. Among these are: (1) the rate of rise at the mine surface temperature in the event of a loss of air flow accident (LOAFA), and (2) the rate of increase in the surface heat flux after the cover has been removed from the waste canister.

[†]It should be noted that axial thermal conduction in both the salt and the air in most cases will be negligible and, therefore, should not be included in future models.

CONCLUSIONS

At some period of time (many years) after the radioactive waste from nuclear reactors has been emplaced in the Waste Isolation Protection Plant, it may become desirable to cool the salt mine drifts in the plant. A one-dimensional model has been developed which predicts the time, t^* , required to cool by forced air the floor of the mine drift to a safe temperature level. Comparisons have been made with a two-dimensional conduction model which was developed by Science Applications, Inc. The comparisons are, generally, fair. More specifically, when t^* varies from weeks to ~half a year, the one-dimensional model predictions vary from ~35% to ~9% lower than those for the two-dimensional case. Further, when t^* varies from ~half a year to ~2 years, the one-dimensional predictions agree very well with the two-dimensional predictions.

If the salt mine drift walls are rough ($\epsilon > 1/8$ inch), the time, t^* , required to cool the mine floor to 120°F will be less than one year, regardless of the time, t_i , at which ventilation begins. If the time at which ventilation begins is greater than 15 years, the time required to cool the mine floor to 120°F is approximately constant and equal to one year (see Figure 2). If the air velocity is doubled, t^* is reduced by approximately half. Further reductions in the air velocity result in progressively smaller changes in t^* . For smooth mine drift walls, the time required to cool the mine floor to 120°F will be less than ~10 years--an order of magnitude increase over that for rough surfaces. Therefore, serious efforts must be exercised in determining the nature (smooth or rough) and relative roughness ($2\epsilon/D$) of the salt mine drift walls.

A family of curves have been generated so that the effects of variations in the relevant physical parameters can be made (Figures 7 and 8). These curves have been generated for $q'' = 75 \text{ kW/acre}$ and relate the dimensionless mine

floor and exit air temperatures to a dimensionless time, with t_i and B_i as parameters. Under certain conditions (which were described in the previous two sections), these curves can be used independent of q'' , T_o and T_a as long as $T_o(t_i)$ is known. For a mass flow rate which is $\leq 70,000$ cfm, the curves can be used in a qualitative manner for different values of velocity. For other cases where decay heating is significant or where the quantitative effects of different values of air velocity, mine aspect ratio, etc., a computer program has been developed and is available for use. The model does not include entrance effects on the heat transfer and axial variations in air velocity and salt mine temperature.

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