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MASTER

Thermal Analysis of a Fuel Cladding Repository Pilot Plant in Salt

H. C. Claiborne

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CHEMICAL TECHNOLOGY DIVISION

THERMAL ANALYSIS OF A FUEL CLADDING REPOSITORY PILOT PLANT IN SALT

H. C. Claiborne

APRIL 1976

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ABSTRACT

Fuel cladding wastes (hulls) remaining after a chop-leach process used in the recovery of nuclear fuel from spent fuel elements are high level with respect to radiation but rather low level with respect to thermal power. Cost considerations dictate rather large waste canisters with compacted contents; however, such a storage scheme can create thermal problems if the canisters are packed too closely together in a disposal horizon within a geological formation.

The design criteria for a pilot plant for these wastes include retrievability and ready access to the rooms for several years, a condition that restricts the maximum floor temperature to less than 110°F and probably to the order of 100°F. Initial planning calls for waste canisters to be 15 ft long (active length of 13 ft) and made from standard 12-in. steel pipe, with the hulls compacted to near 70% theoretical density. A reasonable arrangement for the canisters is emplacement in 20-in.-diam holes drilled in several rows in the salt comprising the floor of an excavated room. The empty space would be filled with sand, which should facilitate retrievability.

For this study it was assumed that the canisters were filled with PWR fuel hulls, which had a heat generation rate of 0.35 kW per canister in the case of 1-year-old wastes, and that the material loadings were the same for all of the canisters regardless of the age of the waste.

A number of two-dimensional thermal calculations for a unit cell were made to determine the effects of pitch, burial depth, waste age, and canister stacking on the maximum mine floor temperature. It was found that considerably less burial area is required for 10-year-old waste as compared with 1-year-old waste. A concept that utilizes a 4-ft pitch has been studied from an excavation viewpoint. The results show that the waste must be aged about 7 years in order for the maximum floor temperature not to exceed 100°F when single canisters are buried 15 ft deep (i.e., so that the top of each canister lies at a depth of 15 ft) in an array with a 4-ft square pitch. In the case of two canisters stacked vertically with a 5-ft sand-filled separation distance, at least a 4-1/2-ft pitch and an age of 10 years are required for a burial depth of 5 ft.

For selected maximum floor temperatures, the required excavation of salt per waste canister (rooms plus canister holes) varies as some inverse function of waste age, burial depth, and the number of canisters stacked vertically in an array mode. The required excavation per canister is

greatly affected by the choice of parameters, particularly the age of the waste. For example, if a 100°F maximum floor temperature is selected, the required room excavation (for the conditions examined) ranges from 200 ft^3 per canister for 10-year-old waste contained in two vertically stacked canisters and buried to a depth of 15 ft over the top canister to 650 ft^3 per canister for 1-year-old waste in single canisters buried 5 ft deep.

1. INTRODUCTION

The disposal of any radioactive waste in geologic formations requires rather detailed thermal analyses in order to determine whether the temperature in the vicinity of the waste will remain within the limitations that are necessary to ensure mine operability; also, such analyses are needed to verify that the resulting conditions will not cause breaching of the confinement or thermal pollution of the regions near the disposal horizon.

Cheverton and Turner[1] made thorough thermal analyses of a number of waste canister array configurations for high-level waste in a single disposal horizon in bedded salt; however, they only briefly examined in a general way the thermal problems associated with the disposal of fuel cladding waste (usually called fuel hulls). On a reactor production basis, the thermal power generated by the fuel hulls varies between 1 and 2% of that generated by the fission product waste during the first 20 years after chemical reprocessing to remove uranium and plutonium. However, cost considerations dictate rather large waste containers with compacted contents that can create thermal problems if the canisters are too close together in a disposal horizon within a geological formation.

The purpose of this investigation was to make a thermal analysis of a pilot-plant repository that would be designed for storage of fuel hulls in salt and could be enlarged into a full-scale repository. Easy retrievability of the waste and ready access for many years to the mined cavities or rooms in which the waste is buried are presently irrevocable design criteria for the pilot plant. Consequently, backfilling of the rooms is precluded during operation as a pilot plant and the floor temperatures assume a greater importance than would be the case for a full-scale repository because of human comfort requirements and potential limitations of equipment temperature.

Parametric studies were made with the objective of relating the maximum floor temperature in a room and the maximum salt temperatures to parameters such as the age of the waste, canister spacing or pitch, burial depth, and vertical stacking of the two canisters in one burial hole. The results were then used to relate the maximum floor temperature to the required excavation of salt per canister; this information, in turn, can be used to estimate excavation costs for selected maximum floor temperatures.

2. GEOMETRICAL CHARACTERISTICS OF THE WASTE CANISTERS AND DISPOSAL HORIZON

The design criteria for a pilot plant for fuel hull wastes include retrievability and ready access to the rooms for several years, a condition that restricts the maximum floor temperature to less than 110°F and probably to the order of 100°F. Initial planning[2] calls for 15-ft-long waste canisters made from standard 12-in. steel pipe. Thirteen feet of this length will be filled with fuel hulls compacted to, at most, about 70% of the theoretical density of Zircaloy. The remaining 2 ft will contain some metallic components but will be mostly void space.

A disposal horizon will probably consist of long rooms that are 16 ft high and 30 to 50 ft wide, with the necessary shafts and passageways excavated in the salt at a depth of about 2000 ft. A reasonable arrangement for the canisters is emplacement in 20-in.-diam holes drilled in several rows in the salt comprising the room floor (applicable to either bedded or dome salt), with the tops of the canisters being a minimum of 5 ft below floor level. The empty space surrounding the canister can then be filled with sand, which should facilitate retrievability. Calculations based on the use of sand for backfilling gave a dose rate at floor level of <0.1 mrem/hr.

Each disposal room will contain several rows of waste canisters. Consequently, the interior canisters will have similar temperature histories, and a two-dimensional unit cell in R-Z geometry can be devised for calculational purposes. The unit cell selected consisted of the waste canister with an annular area of salt (insulated at the outer edge) bounded on the top by the mine floor, where heat is transferred to the ventilating air, and on the bottom by an insulated boundary sufficiently removed so that the temperature rise is essentially zero during the period of interest. Although the circular boundary does not correspond exactly to either a square or an equilateral triangular pitch (it is closer to the latter), the results will be sufficiently accurate for a square pitch when the diameter of the unit cell (which is equivalent to pitch dimension) is determined from the area of the actual unit cell; in the case of the square pitch, this area is equal to the square of the pitch dimension.

Figure 1 shows a schematic of the calculational model for two vertically stacked canisters. The depth of burial to the top of the upper canister was either 5 or 15 ft in the calculations. When calculations were made for only a single canister per cell, the model was altered by eliminating the bottom canister and surrounding sand and by considering the lower 500 ft of salt to abut against the bottom of the remaining canister.

3. THERMAL CHARACTERISTICS OF FUEL HULLS AND SALT

Fuel hull waste that remains after a chop-leach process used in the recovery of nuclear fuel from spent fuel elements consists principally of fragments of Zircaloy cladding and Inconel (and possibly some stainless steel) spacers that are contaminated with actinides and fission products. For these calculations, it was assumed that 0.05% of the actinides and fission products in the spent fuel remained as contaminants. A previous study by Blomeke and Perona[3] on the economics of the disposal of fuel hulls favored compacting the hulls as densely as possible; however, the cost of compaction was not considered. Their comments on the possibilities of compaction are as follows:

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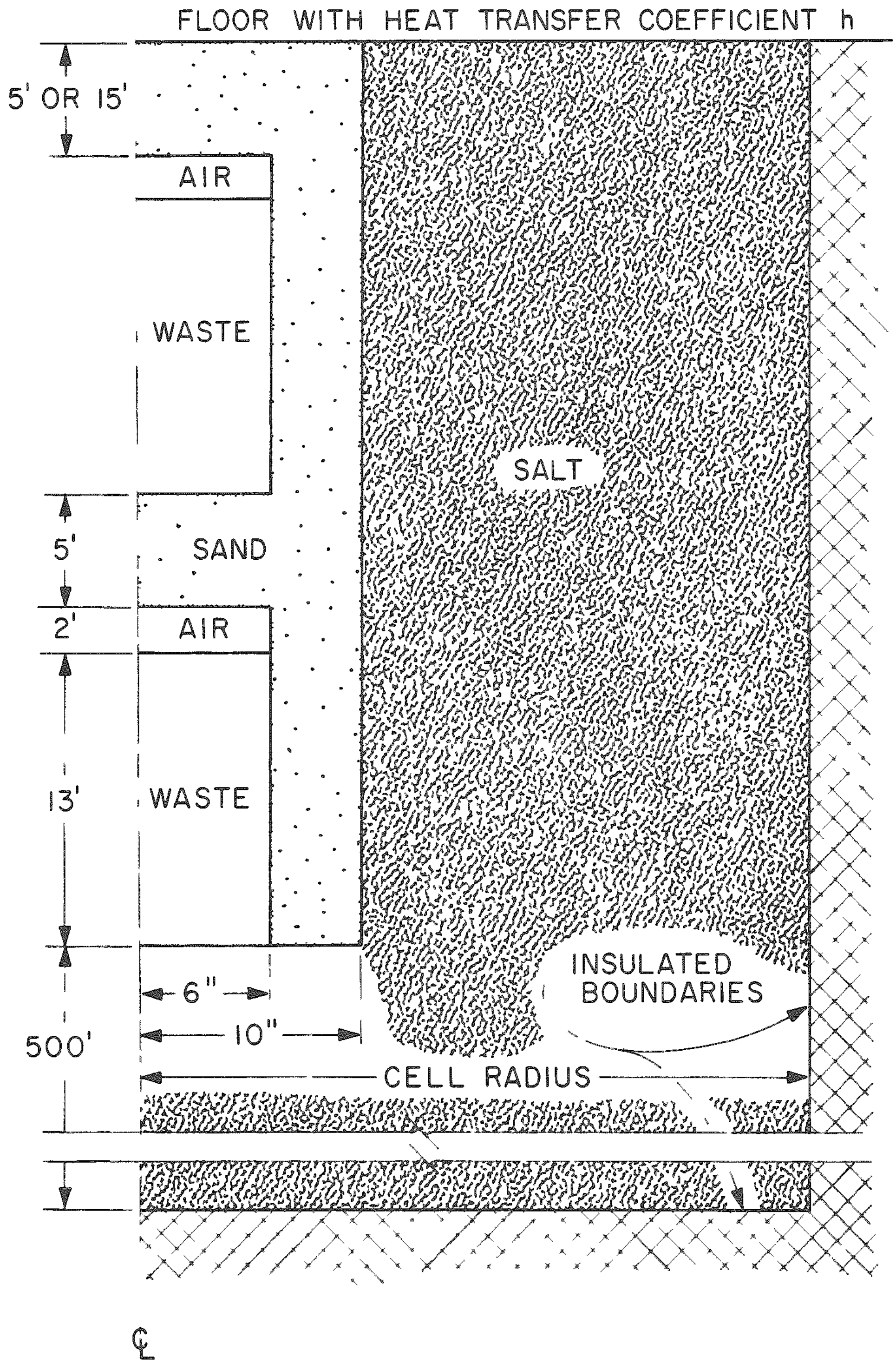

Fig. 1. Heat transfer model.

> After discharge from the leacher, the cladding is dried and put into cans at either of three packing densities. If the cladding is canned as discharged from the leacher, the fraction of void volume is about 0.8. One feasible method of treatment, however, is to pass the hulls between steel rollers, flattening the rings, and reducing the void fraction to about 0.5. A third possibility is to compact the cladding in a die under 20,000 to 100,000 psi pressure, reducing the fraction of voids to 0.3. Flattening and compacting of metallic scrap materials are standard practices in industry; however, neither of these techniques has been demonstrated with fuel cladding, except to produce a few experimental briquettes of unirradiated material.

Work aimed at developing techniques for compaction up to 70% of the theoretical density is currently under way.[4] The brittleness of irradiated Zircaloy and its pyrophoricity make this a difficult goal.

The contaminated hulls associated with 4.8 metric tons of uranium metal fuel and generating 0.45 kW of heat in the case of 1-year-old waste* would constitute a canister loading if it is assumed that the fuel hulls are compacted to 70% of the theoretical density of Zircaloy and completely fill the 13-ft active length. However, this has yet to be demonstrated with irradiated hulls and, in view of the probable difficulty in achieving such a goal in a loaded canister, a heat generation rate of about 25% less (or 0.35 kW) was used in all the calculations. This rate is equivalent to the heat liberated from the hulls associated with 3.8 metric tons of fuel plus the small amount arising from the actinide and fission products that are present as contaminants.

Heat generation rates of the hulls associated with 1 metric ton of uranium metal fuel, as calculated with the ORIGEN code[5] for several time periods after reprocessing, are shown in Table 1. Calculated values of the decay constant for the time intervals for an assumed exponential fit are also included in this table. Using piece-wise exponential fits to the decay curve is slightly conservative since a plot on semilog paper shows a slight upward concavity.

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*Waste allowed to decay for 1 year after reprocessing.

Table 1. Heat generation rates associated with 1 metric ton of uranium metal fuel

Time after reprocessing (years)	Heat generation rate (kW/metric ton of fuel) from:				Decay constant ($year^{-1}$)
	Hulls	Actinides[a]	F.P.[a]	Total	
1	8.90×10^{-2}	1.1×10^{-4}	3.90×10^{-3}	0.0930	0.163
3	6.56×10^{-2}	5.0×10^{-5}	1.49×10^{-3}	0.0671	0.136
5	5.01×10^{-2}	4.0×10^{-5}	8.5×10^{-4}	0.0510	0.132
10	2.63×10^{-2}	3.0×10^{-5}	5.1×10^{-4}	0.0263	0.124
30	1.90×10^{-3}	2.0×10^{-5}	2.8×10^{-4}	0.0022	--

[a]Assumes that 0.05% of the total quantity present in the spent fuel remains with the hulls.

Table 2. Material properties used in most thermal analyses.

Material	Thermal conductivity (Btu/hr-ft-°F)	Heat capacity (Btu/lb-°F)	Density (lb/ft^3)
Air	0.04	0.25	0.07
Hulls	3.5	0.05	280
Salt	2.4	0.22	135
Sand	0.2	0.22	115

The material properties used in most of the thermal calculations are listed in Table 2. The thermal conductivity shown for air is about twice that for molecular conductivity. This should compensate for some convective heat-transfer effect. The thermal conductivity of the hulls was taken as one-half of that for Zircaloy. Any reasonable value used for these materials will suffice since the salt temperature will be very insensitive to the thermal properties of the materials in the canister. The variation of the thermal conductivity of the salt with temperature will have only a small effect on the floor temperatures and the maximum temperature attained in the salt. Cheverton and Turner's values of thermal conductivity as a function of temperature[1] were used for the few calculations made to check on this effect; these values are shown in Table 3. Values for temperatures between those listed were linearly interpolated by the machine program used in the calculations.

It was assumed that the salt and waste were initially at 82°F and 120°F, respectively, and that the ventilating air was constant at 82°F. The exact value for the salt temperature will depend on the geothermal gradient at the mine location and the depth of the disposal horizon. Although the waste temperature will depend on the degree of cooling prior to burial, the exact value is unimportant because of the small amount of heat involved. Any reasonable initial value of the salt temperature will suffice since the effect on the thermal conductivity will be small; for the case of constant thermal properties, the results can be expressed exactly in terms of a temperature difference.

The floor temperature will vary with the local heat transfer coefficient (h), which, for a natural convection coefficient, will be a function of the floor temperature. The minimum heat-transfer coefficient should be that for free convection from a horizontal flat plate with an increase caused by ventilation flow (which has not yet been established with regard to amount and pattern). Using a 30% increase over the free convection correlation ($h = 0.38\ \Delta T^{0.25}$, where ΔT is the temperature difference between the ambient air and the surface[6]) gives a value of 1.0 Btu/hr-ft-°F (for ΔT = 100 - 82 = 18°F) for the heat-transfer coefficient at the floor. The latter heat-transfer coefficient was assumed

Table 3. Thermal conductivity of salt as a function of temperature

Temperature (°F)	Thermal conductivity (Btu/hr-ft-°F)	Temperature (°F)	Thermal conductivity (Btu/hr-ft-°F)
32	3.53	392	1.80
122	2.90	482	1.60
212	2.43	572	1.33
302	2.08	662	1.20

to exist uniformly along the floor for all calculations except some made simply for checking purposes. Allowing the heat-transfer coefficient to vary with the floor temperature increases the computing time, and the added expense did not seem warranted in view of the other uncertainties and the survey nature of the calculations. Also, the value of h = 1.0 seems to be in general agreement with intuitive feelings and experience. For example, the effective heat-transfer coefficient for large insulated pipes in ambient air is about unity.

4. METHOD OF SOLUTION

The flow of heat in this system can be described by the classical heat conduction equation

$$\nabla \cdot k \nabla T + Q = C_p \rho \frac{\partial T}{\partial \theta} , \qquad (1)$$

where

- k = thermal conductivity, Btu/hr-ft-°F,
- T = temperature, °F,
- Q = heat generation rate, Btu/hr-ft^3,
- C_p = heat capacity, Btu/lb-°F,
- ρ = density, lb/ft^3,
- θ = time, hr,
- ∇ = vector operator, ft^{-1}.

When $k \neq f(T)$, $\nabla \cdot k \nabla T = k \nabla^2 T$, and in RZ geometry

$$\nabla^2 T = \frac{1}{r} \frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} . \qquad (2)$$

In our model,

$$Q = Q_o e^{-\lambda \theta} , \qquad (3)$$

where

- λ = decay constant, $year^{-1}$ (see Table 1),
- Q_o = heat generation rate at θ = 0, Btu/hr-ft^3.

The boundary conditions are:

$$-k \frac{dT}{dz} = h(T_f - T_a) \text{ at } \theta = \theta,\ r = r,\ z = 0 \text{ (floor)}, \qquad (4)$$

$$\frac{dT}{dz} = 0 \text{ at } \theta = \theta \quad \begin{matrix} r = R,\ z = z \\ r = r,\ z = L \end{matrix} ,$$

and

$$T = T_i \text{ at } \theta = 0,\ r = r,\ z = z,$$

where

h = heat-transfer coefficient, Btu/hr-ft²-°F,

T_f = floor temperature, °F,

T_a = ambient air temperature, °F,

L = depth of unit cell, ft,

R = radius of unit cell, ft.

If k, C_p, ρ, h, and Q_o are functions only of position and not of temperature, both the differential equation {Eq. (1)} and the boundary condition equation {Eq. (4)} are linear and the form of the solution becomes independent of these properties and the heat source. Therefore, for $T_a = T_i$ and a specific value of λ, the temperature rise at any point within the domain of Eq. (1) will be proportional to Q_o, the heat generation rate at $\theta = 0$.

Equation (1) was solved numerically with the computer code HEATING-5, which is an improved version of HEATING-3.[7] The code is designed to solve a transient problem by one of several numerical schemes. The scheme used in these calculations involved the Crank-Nicholson differencing procedure; a solution of the system was obtained by the point-successive overrelaxation-iterative method.

5. RESULTS AND DISCUSSIONS

The results of the calculations for the maximum mine floor temperatures are shown in Figs. 2 and 3 for a single canister and two vertically stacked canisters, respectively, per unit cell. In these calculations it was assumed that the heat generation rate for 1-year-old waste (i.e., waste which had been allowed to decay for 1 year after reprocessing before being buried) was 0.35 kW per canister and that the same material loading was used for the canisters containing waste aged for longer periods. Because of the additional decay time (see Table 1), the corresponding heat generation rates for the 5- and 10-year-old wastes were 0.19 and 0.10 kW per canister. It is evident that considerably less area is required to limit the floor to some particular temperature for 10-year-old waste as compared with 1-year-old waste. The permissible floor temperatures are primarily related to accessibility and experimental procedures and equipment. Although the maximum permissible temperature has not been established, 100°F seems to be a reasonable design value. A concept that utilizes a 4-ft pitch has been studied from an excavation standpoint.[8] It can be seen from Figs. 2 and 3 that the waste must be aged at least 7 years in order for the maximum floor temperature to remain below 100°F when single cans are buried in an array with a 4-ft square pitch. In the case of two canisters stacked vertically with a 5-ft sand-filled separation distance, at least a 4-1/2-ft pitch and an age of 10 years are required.

The maximum floor temperature as a function of time always occurred in the salt at the outer edge of the unit cell; the radial temperature drop through the salt along the floor was minimal. The insulating effect of the sand resulted in a decrease of several degrees (approx. 8 to 12°F) along the floor between the edge of the sand and the center line of the can, where the lowest radial temperature existed at the time that the floor temperature at the outer edge reached its maximum. The maximum salt temperatures attained as a function of pitch and age are shown in Figs. 4 and 5 for the one-canister and two-canisters unit cells respectively. The maximum salt temperature can be related to the maximum

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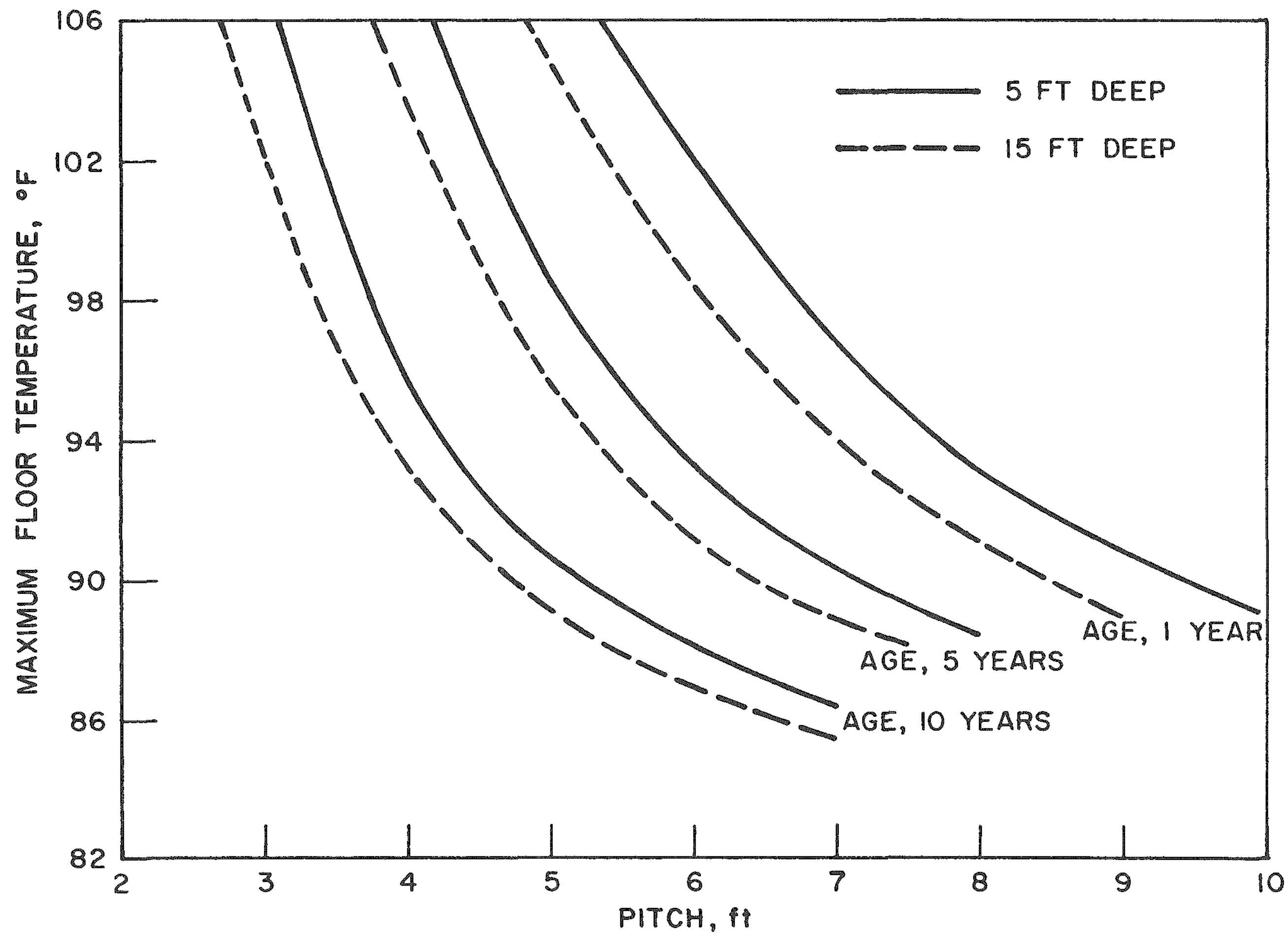

Fig. 2. Maximum floor temperature as a function of pitch for one canister in a unit cell.

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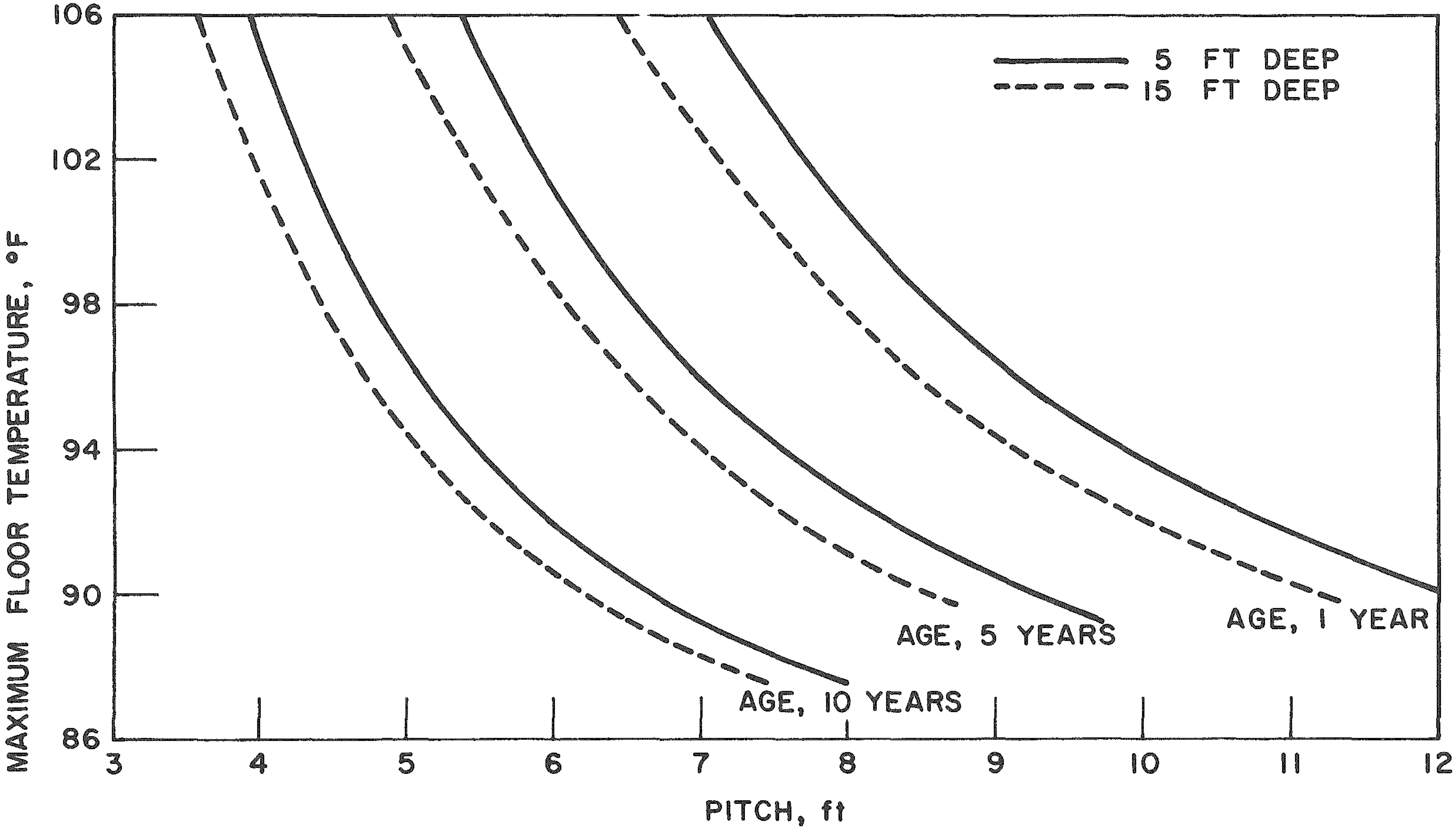

Fig. 3. Maximum floor temperature as a function of pitch for two canisters stacked vertically in a unit cell.

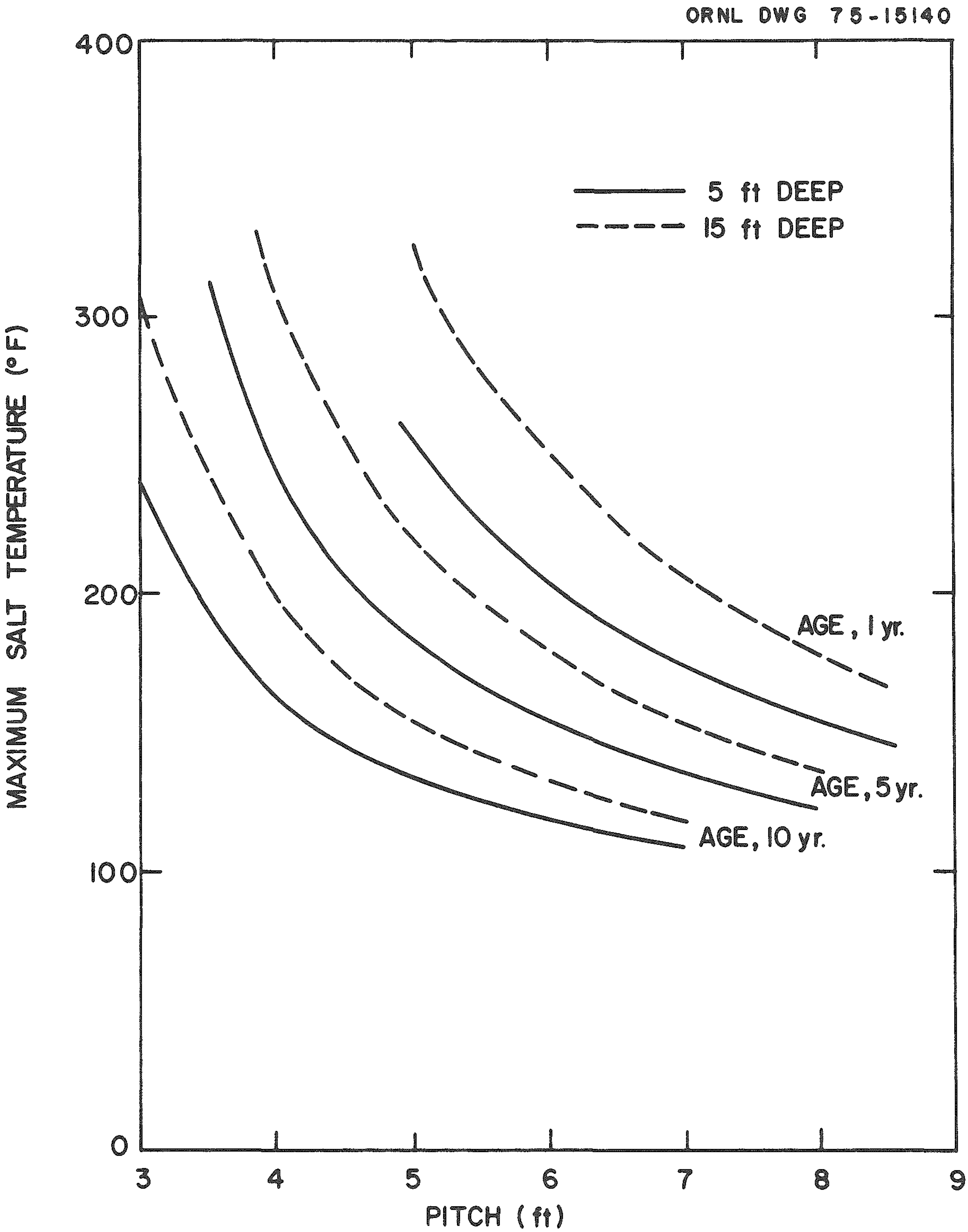

Fig. 4. Maximum salt temperature as a function of pitch for one canister in a unit cell.

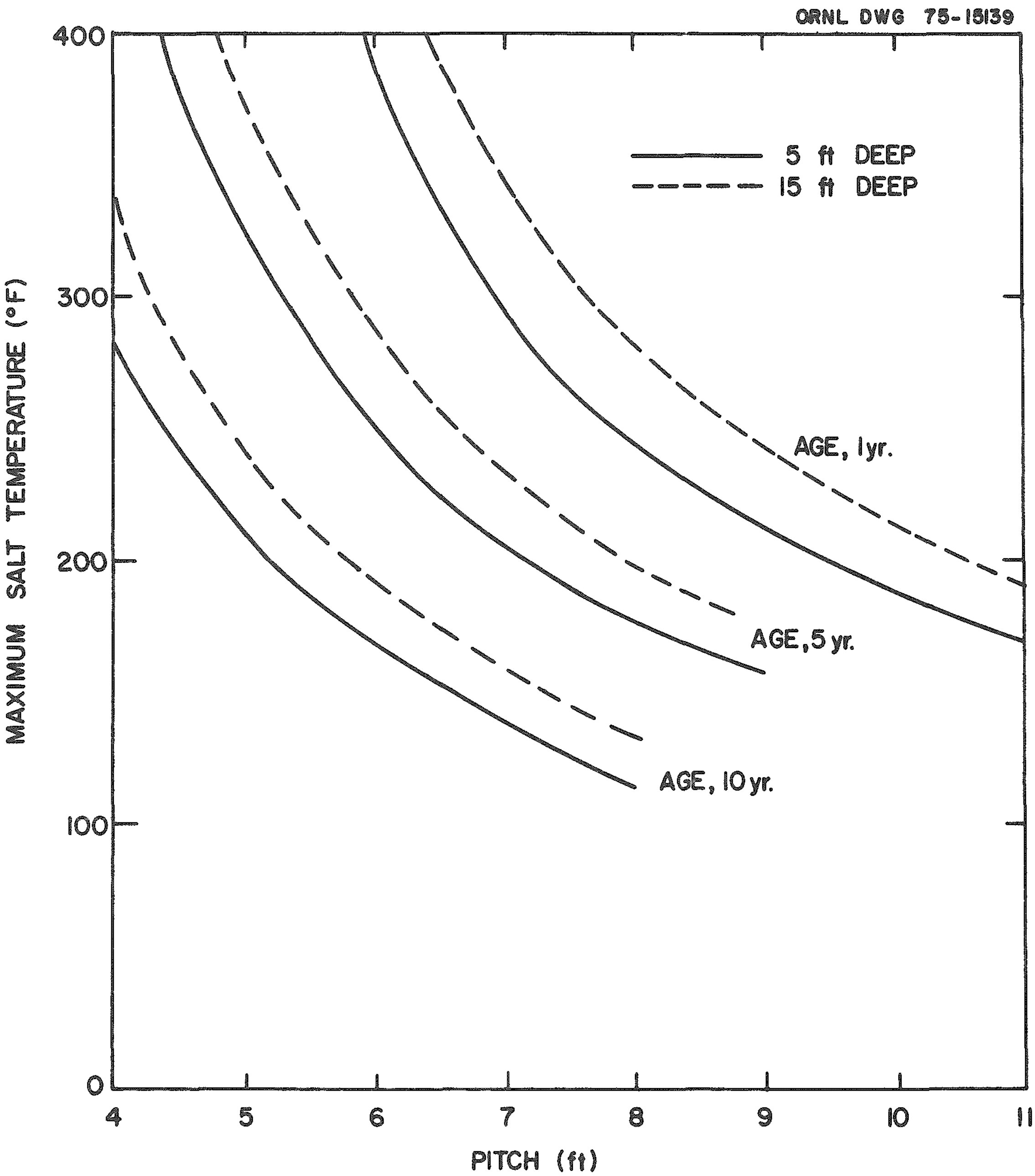

Fig. 5. Maximum salt temperature as a function of pitch for two canisters stacked vertically in a unit cell.

floor temperature by the pitch and by using Figs. 1-4. For example, Fig. 2 shows that a pitch of 6.32 will produce a maximum floor temperature of 100°F for 1-year-old waste buried 5 ft deep. The maximum salt temperature, 350°F, is obtained from Fig. 5.

This procedure can be used to show that the maximum salt temperature will not exceed 392°F (200°F) if the maximum floor temperature is less than 110°F, except in the case of the two vertically stacked canisters buried 15 ft deep.* This 200°C (392° F) temperature had previously been established as a maximum for 25% of the salt in a unit cell whose height equals that of the canister in order to avoid problems from salt creep, which could lead to floor upheaval and roof collapse during operation of a repository. An additional criterion was that no more than 1% could exceed 250°C (482°F). For two vertically stacked canisters buried 15 ft deep, the maximum floor temperature must be limited to about 106°F to prevent the temperature of the salt from exceeding 392°F. The relation between maximum floor temperature and maximum salt temperature was insensitive to the age of the waste.

In general, the 15-ft burial depth gave higher salt temperatures, but lower floor temperatures than the 5-ft depth for the same pitch. The time-temperature curve at the floor was fairly flat around the maximum, and the time required to attain the maximum floor temperature was an insensitive function of the pitch. The time to reach maximum temperature varied from about 1.3 years for a single canister that contained 1-year-old hulls and was covered by 5 ft of sand to about 3.2 years for two vertically stacked canisters that contained 10-year-old hulls and was covered by 15 ft of sand. These results are shown in Figs. 6 and 7.

For selected maximum floor temperatures, the required excavation of salt per waste canister (rooms plus canister holes) varies as some inverse function of waste age, burial depth, and the number of canisters stacked vertically in an array mode (see Fig. 8). In preparing this

*Depth to the top of the upper canister.

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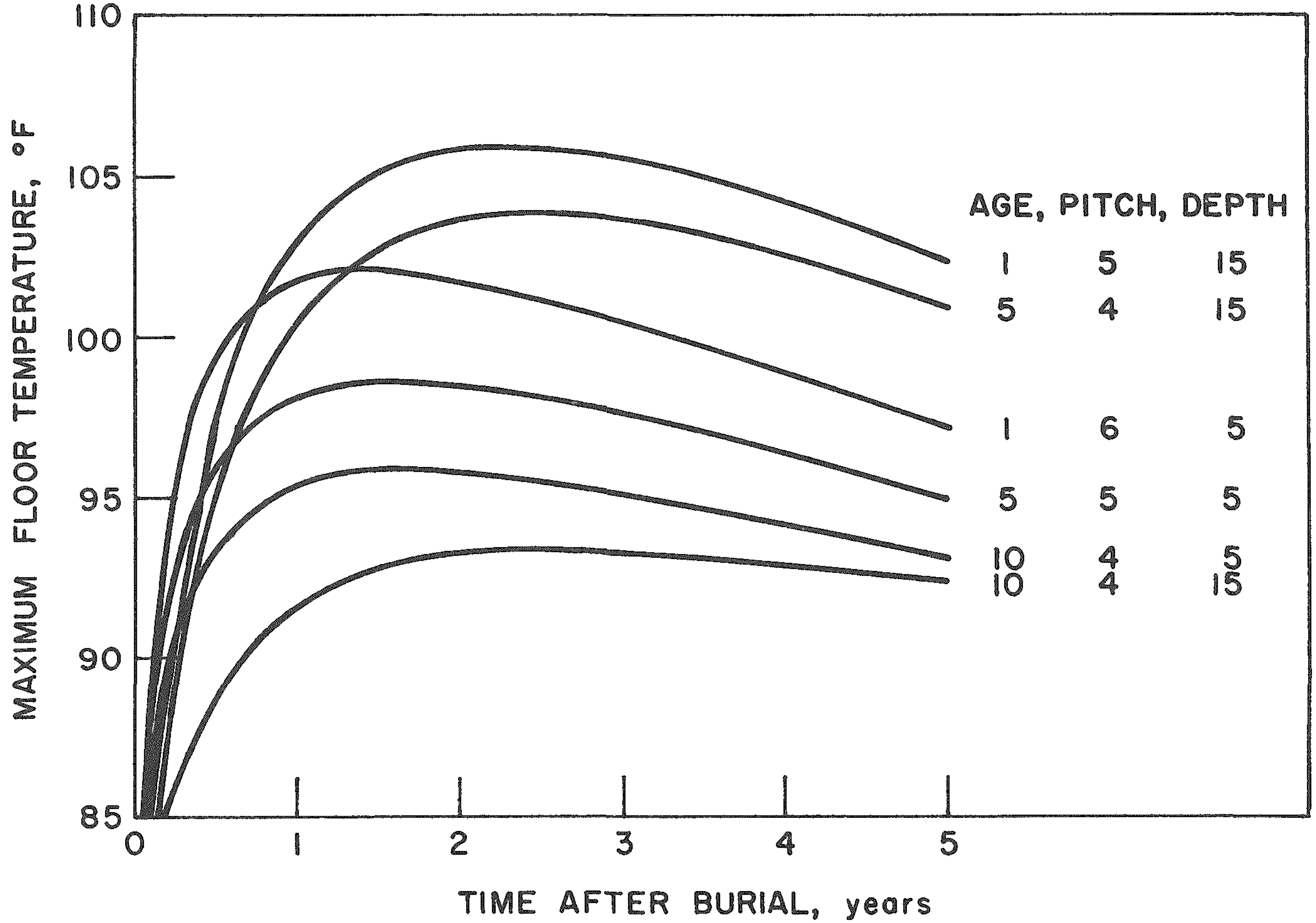

Fig. 6. Maximum floor temperature as a function of time for one canister in a unit cell.

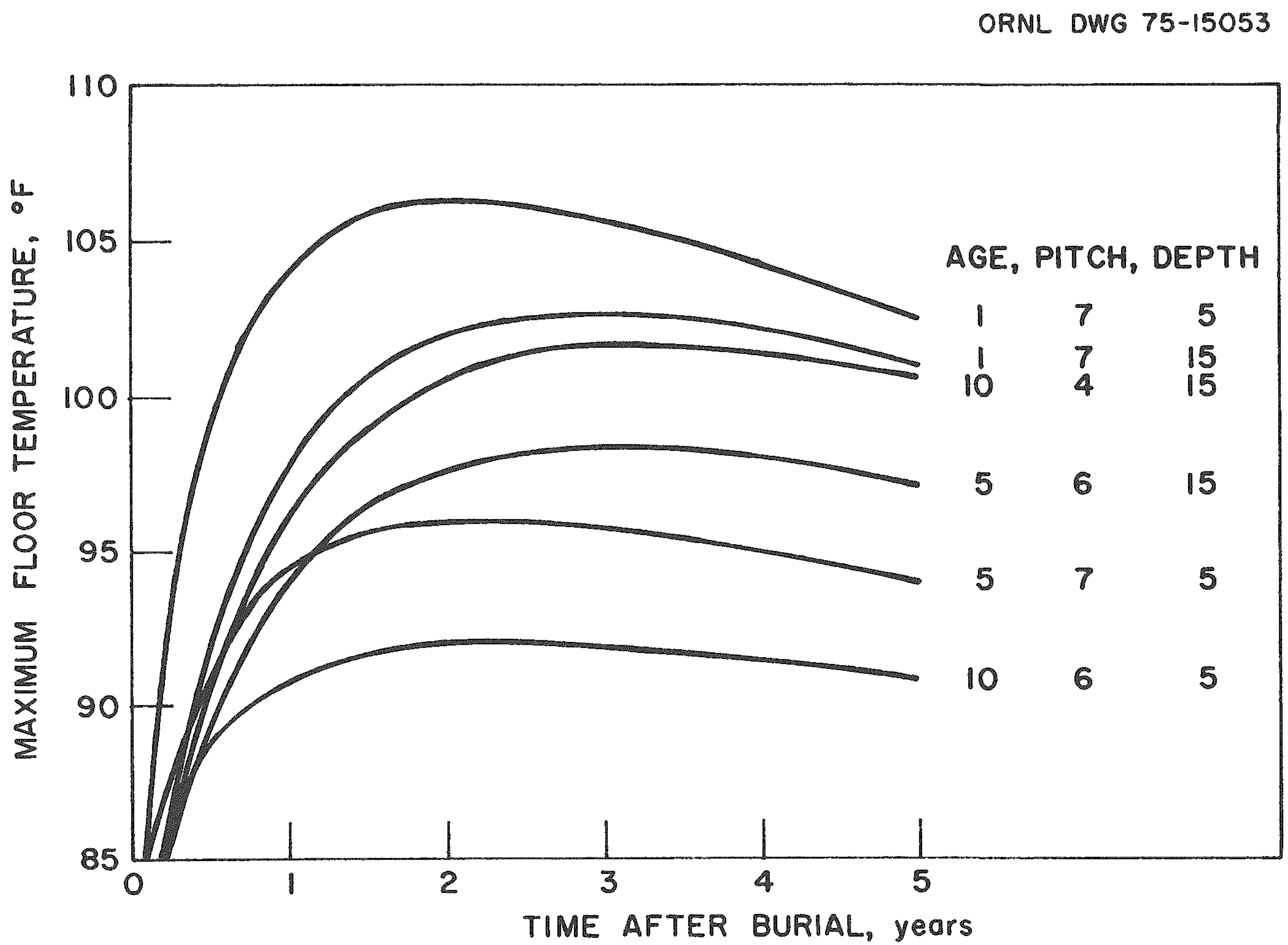

Fig. 7. Maximum floor temperature as a function of time for two canisters stacked vertically in a unit cell.

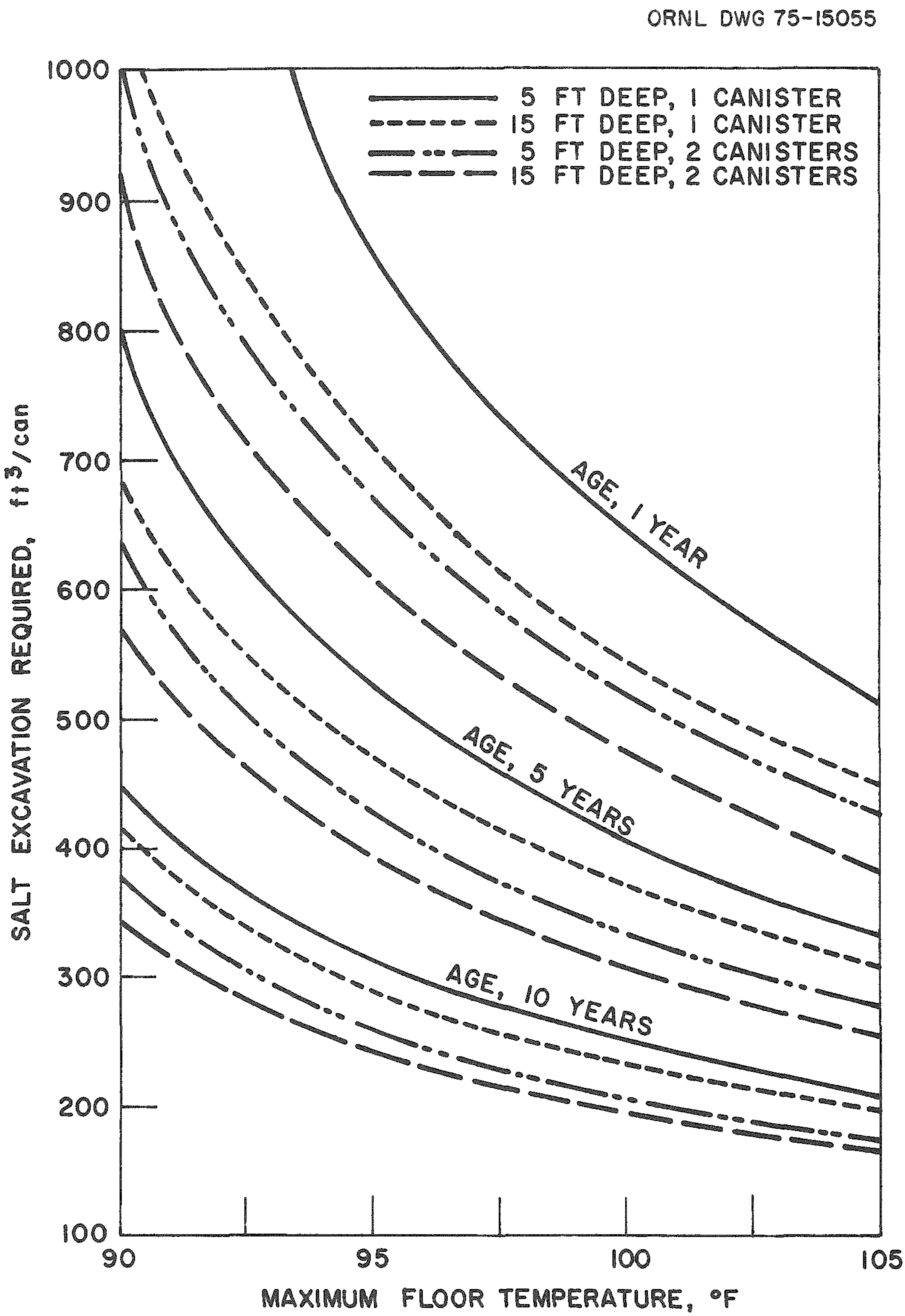

Fig. 8. Salt excavation requirements as a function of maximum floor temperature.

figure, the height of the room was taken as 16 ft; however, the width was allowed to vary to accommodate an integral number of canisters emplaced in a square array with an allowance of 1 ft between the canister edge and the wall of the room. For the floor temperature range examined, the number of holes (containing one or two canisters) per row (for very long rooms) along the width varied between 5 and 17 and the room width between 40 and 50 ft. It is quite evident that the required excavation per canister is greatly affected by the choice of parameters, particularly the age of the waste. For example, if a 100°F maximum floor temperature is selected, the required room excavation (for the conditions examined) ranges from 200 ft^3 per canister for 10-year-old waste contained in two vertically stacked canisters and buried 15 ft deep to 650 ft^3 per canister for 1-year-old waste in single canisters buried 5 ft deep.

Similar curves could be constructed for other room heights and spacings between canisters and the wall. Such results could then be used to obtain cost figures based on estimated unit costs for room excavation and canister hole drilling.

Figure 9 shows the effect of the natural convection coefficient on the maximum floor temperature (see Sect. 3). The calculations were made for a 5-ft burial and a pitch that produced a maximum floor temperature of 100°F when the heat-transfer coefficient was constant and equal to 1.0 Btu/hr-ft-F along the floor, namely, pitches of 8.12 and 6.32 ft for the two-canister and one-canister cases, respectively (see Figs. 2 and 3). The results for the two cases were within 0.2°F; consequently, only one curve could be used to represent both cases for the scale shown. It can be seen that the floor temperature is approximately 100°C at 1.3 times the natural convection coefficient for a horizontal flat plate, which is in agreement with the uniform heat-transfer calculations. Based on Fig. 9, the indication is that only about a 3 to 4°F rise in the maximum floor temperature would occur if the 30% increase in the free convection coefficient (the apparent minimum heat transfer coefficient) were not used. Consequently, the results appear to be reasonable and sufficiently conservative for preliminary design purposes.

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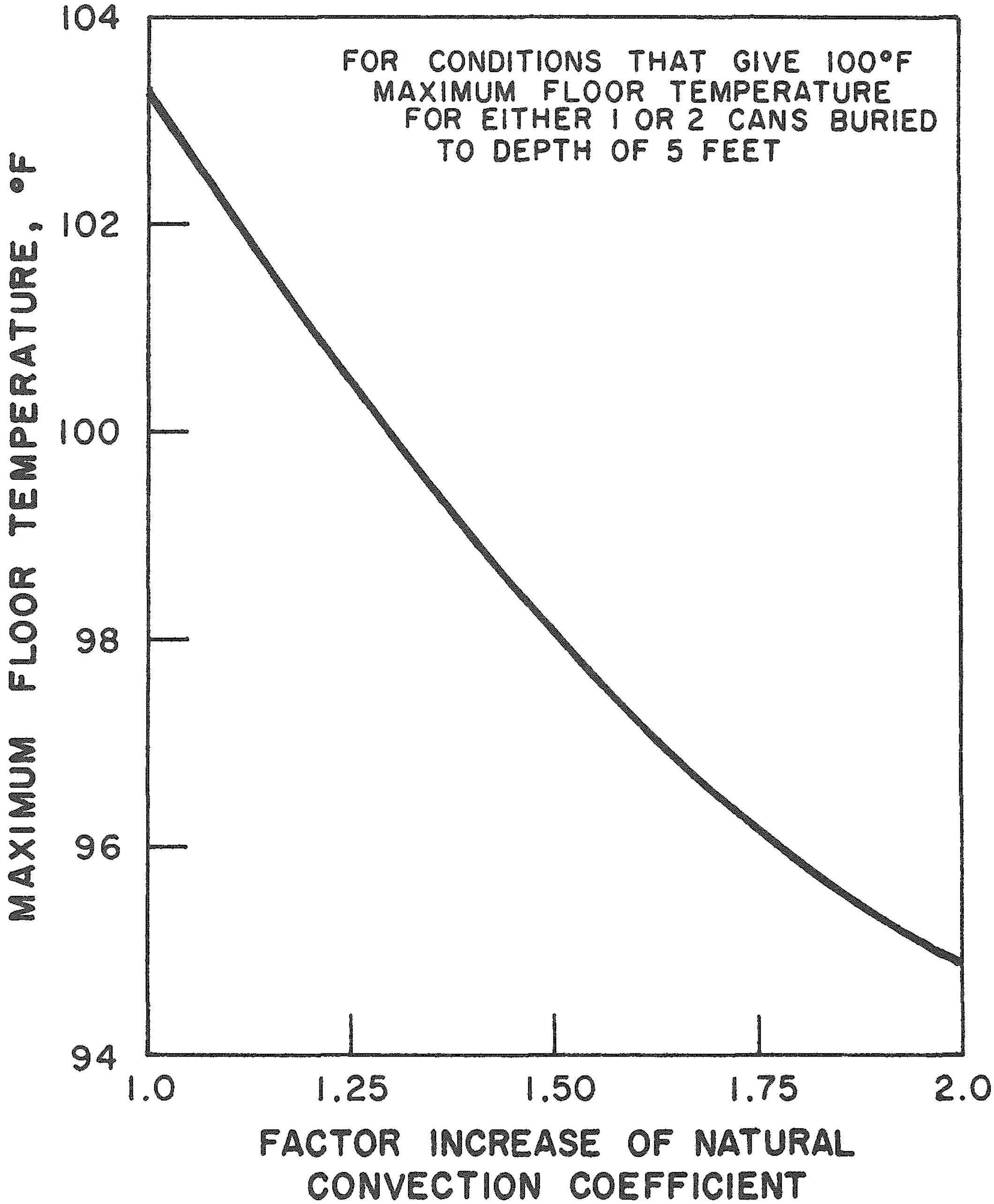

Fig. 9. Effect of changes in the natural convection coefficient on the maximum floor temperature.

As previously discussed, Cheverton and Turner[1] concluded that selecting a reasonable and constant value for the thermal conductivity was sufficiently accurate for most purposes. This conclusion was substantiated by some "check" calculations. For example, in the case of a 5-ft-deep burial of two stacked cans and a pitch of 8.12 ft, a floor temperature of 100.3°F and a maximum salt temperature of 228°F were obtained when the thermal conductivity was varied with temperature (see Table 3) as compared with 100.0°F and 238°F when the thermal conductivity was held constant.

The effect of the change of the density and heat capacity with temperature was not investigated since, for the range of interest, it will be too small to be significant. When the temperature is changing slowly with respect to time, the heat storage term (right-hand side) of Eq. (1) is small with respect to the other terms and large changes in the product of C_p and ρ will have little effect on the maximum temperature attained.

The heat generation rate of 1-year-old LMFBR fuel hulls is about four times greater per metric ton of fuel charged than that for PWR fuel hulls, but drops to slightly below the heat generation rate for the PWR hulls after 5 years and continues to decline with respect to the latter. Consequently, it seems clear that, compared with PWR hulls, much greater advantages accrue by aging the LMFBR hulls at least 3 to 5 years before their emplacement in salt or other geological formations.

The results of this study should be sufficient for preliminary design purposes. Any final designs should be analyzed in more detail, and allowance should be made for the change of all physical properties with temperature. In addition, a more careful definition of the heat transfer coefficient at the floor should be used.

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