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A PRELIMINARY STUDY OF THE STORAGE OF SOLIDIFIED HIGH-LEVEL RADIOACTIVE WASTES IN CONCRETE VAULTS

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A PRELIMINARY STUDY OF THE STORAGE OF SOLIDIFIED HIGH-LEVEL RADIOACTIVE WASTES IN CONCRETE VAULTS

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CONTENTS

A PRELIMINARY STUDY OF THE STORAGE OF SOLIDIFIED HIGH-LEVEL RADIOACTIVE WASTES IN CONCRETE VAULTS

J. J. Perona J. O. Blomeke

ABSTRACT

Concrete vaults offer a safe, reliable means of storing high-level solidified wastes for many decades until a method for the permanent disposal of these materials can be selected. A design study was made of vaults which utilized natural draft air cooling of wastes that were packaged in 6- and 12-in.-diam containers and enclosed in cylindrical steel sleeves. The optimal spacing for the containers was found to be the closest one considered practical, a pitch-to-diameter ratio of 1.25. Although a close spacing increases pressure drop, energy costs are trivial if fans are used. For practical purposes, minimum capital costs are a function of can size only, and are virtually independent of the heat-generation rate per can. Optimal entering air velocities range from 0.5 to 2 fps, increasing with can size and heat-generation rate. Vaults that are of optimal design and have a total storage volume of about 1.1 million ft^3 would be required to accommodate all the high-level solidified wastes expected to be generated in the United States through the year 2000, provided the wastes were initially stored for 10 years at the fuel reprocessing plants.

1. INTRODUCTION

An alternative to permanent emplacement of solidified high-level wastes in natural salt formations in the very near future is storage of these materials on a long-term basis in concrete vaults near the earth's surface. Although such storage would necessarily be a temporary measure, properly designed and maintained facilities of this type could serve as a safe method of containment for a century or so until the heat-generation rates of the wastes decline to negligible levels. At that time, provisions could be made for permanent storage, or ultimate disposal, based on the more advanced technology that would presumably then be in existence.

This report presents the results of a preliminary investigation of the design of a storage vault that should meet the requirements for long-term storage. While many details of the structural design were not considered, those features affecting heat dissipation were optimized on the basis of relative costs, and the total space requirements were estimated for storing all the high-level wastes projected for the United States through the end of this century.

2. CONCEPT

In contrast with an earlier study,[1] the assumption that cooling air is circulated through the vaults is made here. To prevent the escape of radioactive material from a defective can into the cooling air, secondary containment is provided by a cylindrical steel wall, or sleeve, around each can (Fig. 1). The use of cooling air allows much higher heat liberation rates per unit of vault floor area than in the previous study and reduces storage costs greatly; however, a cooling system must be guaranteed even in the event of natural or man-made catastrophes that might topple draft-inducing stacks or disrupt electrical power distribution lines. The feasibility of providing backup cooling systems is discussed in Sect. 6.

The vault must be designed so that temperature limits on the concrete and on the solidified waste are not exceeded. For the waste, those temperatures reached during solidification (e.g., 1650°F for pot calcination) should not be greatly exceeded. Temperatures of ordinary concrete should not be allowed to exceed 400 to 500°F;[2] however, it is possible to obtain special concretes that are composed of a high-temperature cement and an aggregate of magnesium oxide ore (dunite) and are capable of withstanding temperatures of 1000°F. In this study, we have chosen maximum allowable temperatures of 1650°F for the waste and 500°F for the concrete. Slabs of a hard insulating material (e.g., transite) are used to protect the concrete adjacent to the top and bottom of a can.

A sketch of the conceptual plan view of a vault is shown in Fig. 2. The air enters the vault through a bank of roughing filters and passes across the rows of sleeved cylinders of waste. On leaving the vault, it is routed through a second set of roughing filters and then through HEPA filters before being monitored for radioactivity and released through a

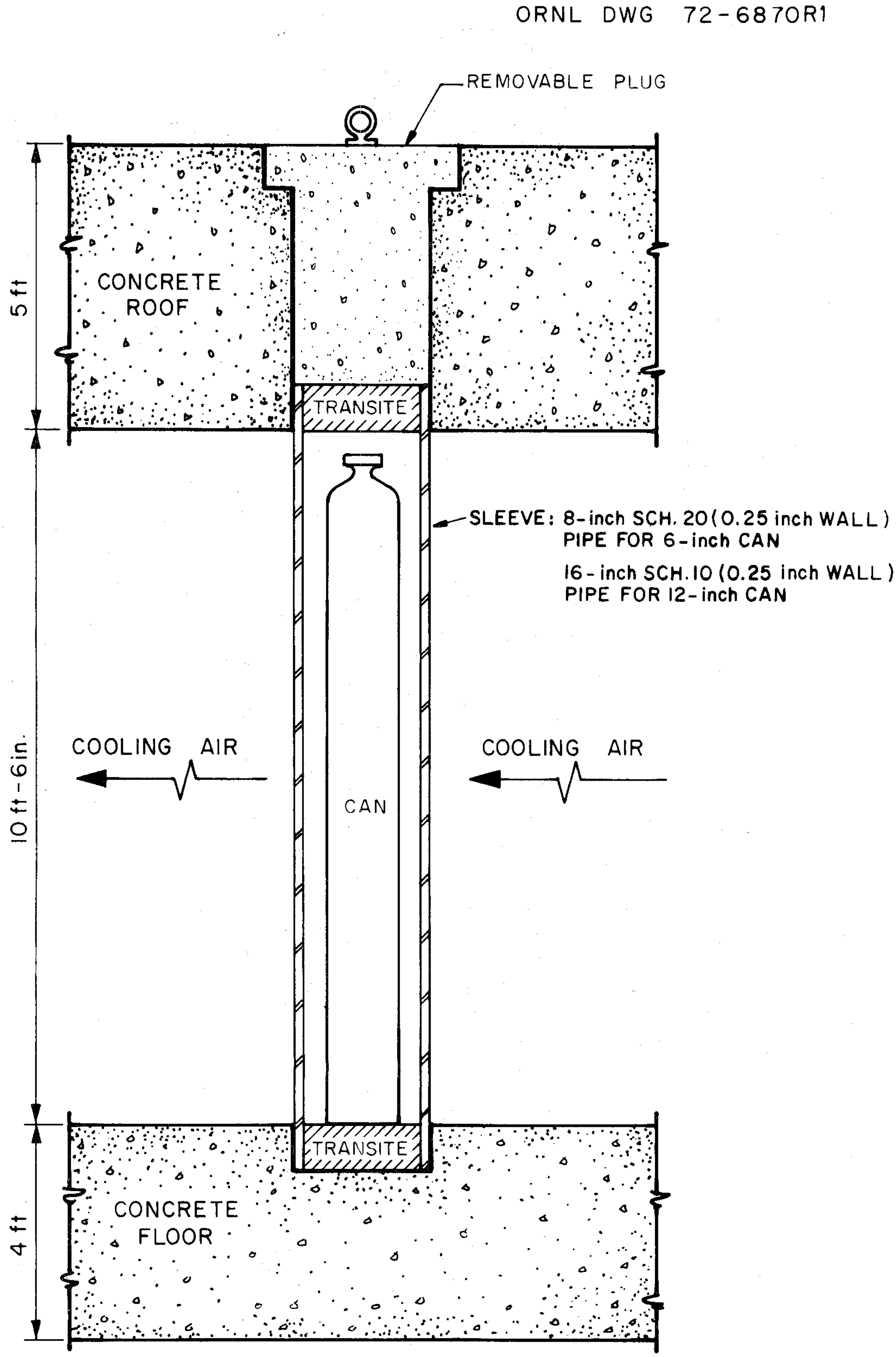

Fig. 1. Containment Scheme for a Can of Solidified Waste.

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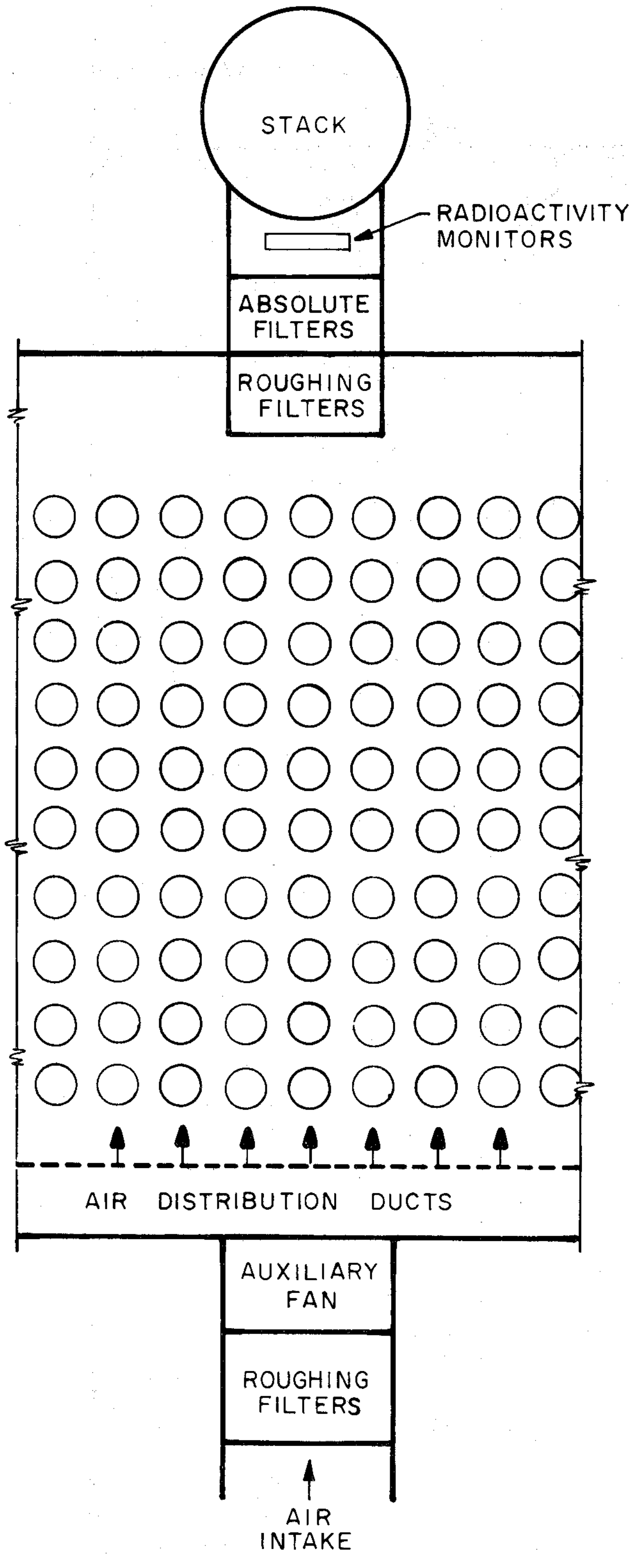

Fig. 2. Conceptual Plan View of Vault (In-Line Arrangement of Waste Cylinders).

stack. The stack is designed to provide the required draft to keep temperatures in the vault below maximum allowable values. As a backup, an auxiliary fan operated by a diesel-powered generator might also be provided.

As the air passes each row of cans, its temperature increases, and the temperature of each row of cans is higher than that of the preceding row. As the temperature of the air increases, its physical properties change, affecting the Reynolds number, friction factor, and film coefficient for heat transfer. The number of rows in a vault is fixed by the maximum allowable temperature of the waste or concrete; however, the number of cans per row is not limited.

For each case studied, the following variables were specified as input values:

(1) can diameter,
(2) longitudinal pitch-to-diameter ratio,
(3) transverse pitch-to-diameter ratio,
(4) heat-generation rate per can,
(5) entering air velocity and temperature,
(6) total number of cans in the vault,
(7) type of (in-line or staggered) can arrangements.

Optimum values of pitch-to-diameter ratio (PDR) and air velocity were determined for each can size and heat-generation rate.

For the storage of wastes in cans made of 6-in.-diam pipe (OD = 6.625 in.), the secondary containment pipe (sleeve) was chosen to be 8-in. sched 20 pipe (ID = 8.125 in., OD = 8.625 in.). For cans made of 12-in. pipe (OD = 12.75 in.), the sleeve was chosen to be 16-in. sched 10 pipe (ID = 15.50 in., OD = 16.00 in.). Can spacings calculated from PDRs were based on the outside diameter of the sleeve. For example, the center-to-center distance for 12-in. cans with a PDR of 1.25 was 20 in. (1.25 x 16).

3. HEAT TRANSFER CALCULATIONS

The calculations were begun with the first row of cans, where the velocity and the temperature of the entering air were known. The temperature of the air on passing the first row of cans was calculated from the mass flow rate and the heat capacity of air and from the heat-generation rate of the cans. In subsequent calculations, an arithmetic average of the temperatures of the entering and exiting air was used as the air temperature for the first row. A calculation was then carried out to find the film coefficient for heat transfer between the sleeve and air, and to find the temperature of the sleeve. Film coefficients were obtained from correlations for heat transfer in tube bundles[3] with the group $(hd/k)(Pr)^{-1/3}(\mu/\mu_s)^{-0.14}$, plotted against the Reynolds number for PDRs of 1.25 to 1.50.*

Temperature differences between sleeves and waste-can surfaces were calculated using the following equation for a combined conduction and natural-convection transfer coefficient:[4]

$$\frac{Ux}{k} = 0.0317\ Gr^{0.37}.$$

Transfer by radiation was also calculated, using an emissivity of 0.5 for both surfaces. The temperature of the solid waste at the center of the can was calculated using the following equation:

$$T_c - T_s = \frac{QR^2}{4k_w} .$$

This sequence of calculations yielded the increase in the temperature of the air after it had passed the first row of cans, the surface temperatures of the waste cans and their sleeves, and the maximum waste temperature. The same procedure was carried out for each succeeding row of cans until a maximum allowable temperature or pressure drop (see Sect. 3) was reached.

The radiant interchange of heat between rows of cans was determined to be an insignificant effect. Loss of heat through the concrete floor and roof by conduction was also insignificant. The interior surface of

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*For nomenclature, see Sect. 6.

concrete near a can will receive heat from the sleeve by radiation and conduction and will lose heat to the cooling air by convection. Thus the concrete near the sleeve will be at a temperature near that of the sleeve, and this restricts the temperature of the sleeve to about 500°F.

4. PRESSURE DROP AND STACK CALCULATIONS

A comparison was made by Boucher and Lapple[5] of the data and the methods used by many investigators to correlate pressure drop across tube banks. Their conclusion was that a graphical correlation of Grimison was the best method for both in-line and staggered arrangements over a Reynolds number range of 2000 to 40,000. In this graphical correlation, a friction factor is plotted against Reynolds number with transverse and longitudinal spacings as parametric curves. Empirical equations that represent Grimison's curves fairly well were devised by Jakob:[6]

For staggered-tube arrangements,

$$f = (Re)^{-0.16}\left[0.25 + \frac{0.1175}{(a-1)^{1.08}}\right];$$

for in-line arrangements,

$$f = (Re)^{-0.15}\left[0.044 + \frac{0.08\ b}{(a-1)^{0.43 + (1.13/b)}}\right].$$

These friction factors are of the type defined by Chilton and Genereaux.[7] Pressure drop is calculated by the following equation:

$$\Delta P = \frac{2fNG^2}{\rho g_c}.$$

A stack was designed to provide the required flow rate and pressure drop by natural convection. The draft provided by a chimney is given by:

$$\Delta P = H(\rho - \rho_o)\frac{g}{g_c},$$

where ρ is based on the average temperature of the hot air in the stack. The assumption was made that the temperature of the air did not decrease significantly on passage of the air through the stack; however, it was assumed that friction losses gave a draft 10% less than the theoretical value. A maximum allowable draft requirement of 2.0 in. H_2O was chosen; this limits stack heights to about 500 ft for exit air temperatures above 300°F.

Absolute filters are designed to operate with pressure drops in the neighborhood of 0.5 to 1.0 in. H_2O. The assumption was made in this study that the roughing and absolute filters caused a pressure drop of 1.0 in. H_2O in addition to the pressure drop caused by the flow of air through the vault.

Experience has shown that optimal stack designs generally have an average gas velocity of 25 to 30 fps.[8] The stack diameter in this study was calculated to give a velocity of 25 fps at the base of the stack.

5. COST ESTIMATION

An estimate of total costs was not attempted in this study; however, a simple cost estimation procedure was employed to provide a measure of relative costs so that important variables might be optimized. The estimate of capital costs included excavation and concrete costs for the vault building, costs of piping for secondary containment barriers, and stack costs. The inside dimensions of the vault were calculated from the number of rows of cans, the number of cans per row, the PDRs, and the can dimensions. The thicknesses of the vault walls, floor, and roof were selected as 4 ft, 4 ft, and 5 ft, respectively. The vault is buried with the top surface of the roof at, or slightly above, the surface of the ground. Excavation costs were calculated at $\$5.75/yd^3$, and concrete in place at $\$140/yd^3$.

The cost of the mild-steel pipe used for secondary containment, 8-in. sched 20 and 16-in. sched 10, was about \$5/ft in each case. The pipe segments were 2 ft longer than the height of the waste can. Therefore, for a waste can height of 10 ft, the cost of the sleeve was \$60/can.

Stacks made of brick, steel, and concrete were considered. Stack costs were estimated by the method of Stankiewicz,[9] in which curves for the costs of the column, foundation, and lining are given for stack heights of 100 to 500 ft and diameters of 10 to 25 ft. Steel stacks were slightly cheaper than those of brick or concrete for stack heights less than about 150 ft; however, for heights of 300 to 500 ft, concrete stacks cost much less than the others. Accordingly, concrete stacks were chosen for this study, and costs were escalated by 20% to account for inflation.

6. RESULTS

The effects of increasing the PDR are to increase the size of the vault required for a given number of cans (and hence the capital costs of the vault) and to decrease the pressure drop in the cooling air per row of cans. Also, for a given entering air velocity the mass flow rate of air per can is increased (by increasing the PDR), causing the air temperature increase to be less for each row of cans. If the PDR is fixed and the entering air velocity is varied, the rate of temperature increase for the air varies. Since the temperature of the sleeve is approximately the same as that of the concrete, the maximum permissible number of rows is given when the sleeve temperature reaches approximately 500°F (unless the maximum allowable waste temperature or pressure drop is exceeded first).

Effects of Pitch-to-Diameter Ratio and Entering Air Velocity. - An example of the effects of PDR and entering air velocity on capital costs is shown in Fig. 3 for storage of 6-in.-diam cans having heat-generation rates of 0.625 kW each. Additional information for this case is given in Table 1. The optimal spacing is the closest considered feasible, 1.25, and the optimal entering air velocity is 0.5 fps for all spacings. However, the costs are not very sensitive to these variables. For example, increasing the PDR to 1.33 or the entering air velocity to 1.0 fps increases the costs by only a few percent. The breaks in the curves of Fig. 3 are caused by a switch in the limiting condition from the maximum allowable concrete (or sleeve) temperature, which controls at the lower air velocities, to

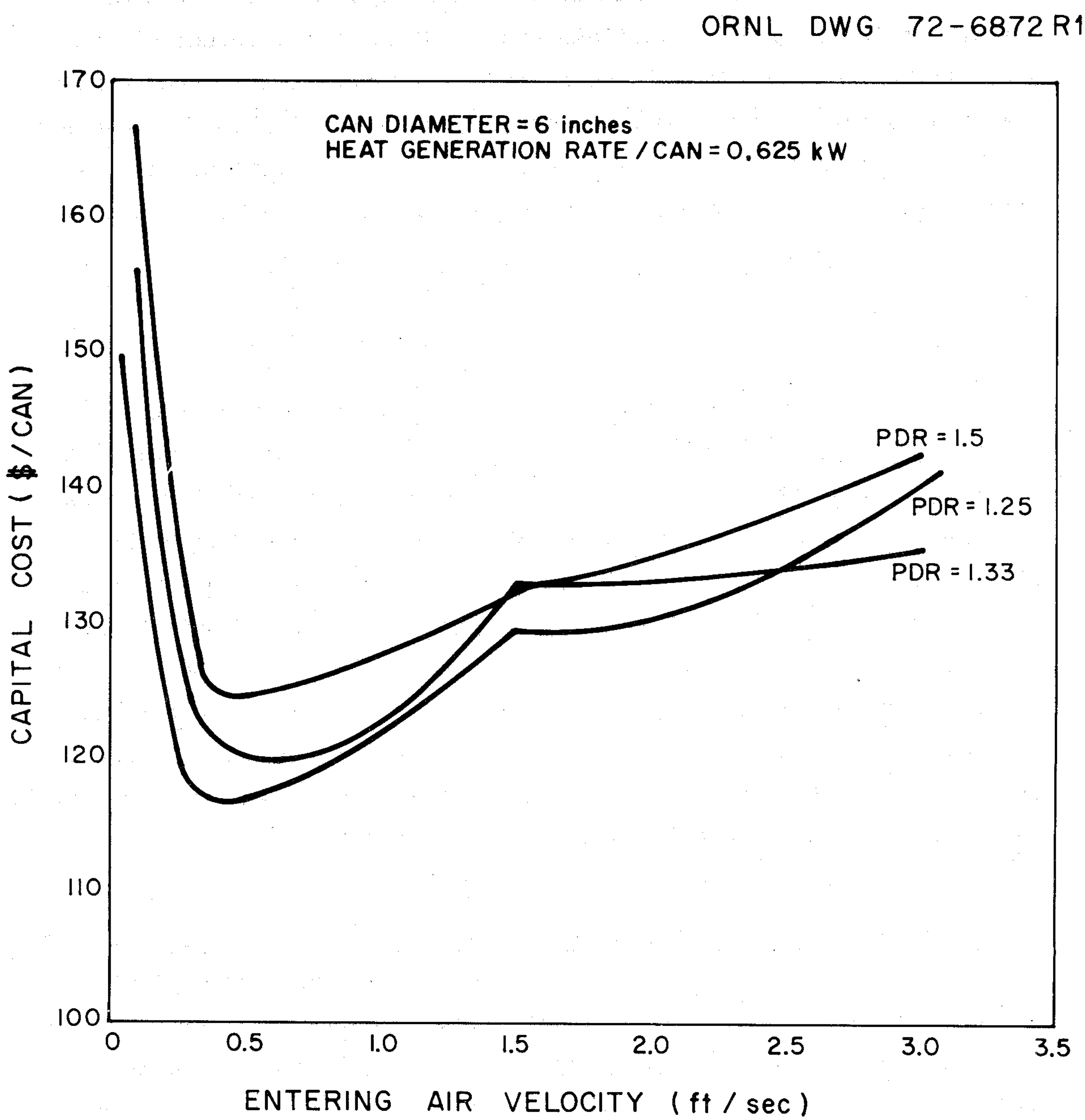

Fig. 3. Effects of Pitch-to-Diameter Ratio and Entering Air Velocity on Capital Costs.

Table 1. Effects of Pitch-to-Diameter Ratio and Entering Air Velocity on Capital Costs for Storage of 6-in.-diam Cans of Solidified Waste[a]

Pitch-to-Diameter Ratio	Entering Air Velocity (fps)	Maximum Number of Rows	Pressure Drop (in. H_2O)	Temperatures in Last Row (°F)			Cost per Can ($)
				Air	Sleeve	Waste	
1.25	0.1	10	1.00	399	500	725	139.5
	0.5	53	1.07	450	500	725	116.8
	1.0	110	1.49	468	500	726	121.7
	1.5	106	2.00	326	353	628	129.4
	2.0	70	2.00	196	220	555	130.4
	3.0	36	2.00	113	133	498	140.3
1.33	0.1	9	1.00	344	500	725	152.7
	0.5	56	1.04	447	500	725	119.7
	1.0	116	1.22	464	500	726	122.5
	1.5	177	1.80	472	500	726	132.8
	2.0	136	2.00	301	327	612	133.1
	3.0	74	2.00	153	176	521	135.5
1.50	0.1	9	1.00	313	500	725	163.4
	0.5	61	1.01	435	500	725	124.5
	1.0	128	1.10	457	500	725	127.5
	1.5	196	1.30	466	500	725	132.4
	3.0	184	2.00	256	281	586	142.6

[a]Each can is 10 ft high and has a heat generation rate of 0.625 kW.

the maximum allowable pressure drop of 2.0 in. H_2O, which controls at the higher velocities. Temperature profiles along the vault are presented for this case in Fig. 4. They are very nearly linear.

In-Line vs Staggered Arrangement of Cans. - Although all the results given above are for the in-line arrangement of cans, those for a staggered arrangement did not differ significantly in any way. A comparison of in-line and staggered arrangements for 6-in.-diam cans with a heat-generation rate of 2.5 kW/can is presented in Table 2.

Effect of Radioactive Decay. - As the heat generation rate in a filled vault diminishes with time, the air flow rate required to maintain permissible temperatures also decreases. In the case of natural draft cooling with a stack, the situation is self-regulating. A reduced draft results from a lower air temperature in the stack. These effects are illustrated in Table 3. When the heat-generation rates in filled vaults were decreased by factors of 2 and 4, lower sleeve and exit air temperatures resulted.

Costs of Mechanical Cooling. - The possibility of providing the vault with a fan instead of (or in addition to) a stack is of some interest. A diesel-driven generator supplying power to a fan could be designed to survive an earthquake more readily than could a stack several hundred feet in height. As a matter of interest, energy costs were calculated for fans in lieu of stacks. Using a cost of electricity of 1¢/kWhr, energy costs were found to be 5¢ to 10¢ per can per year at velocities of 0.5 to 1.0 fps for the cases given in Table 1. Therefore, energy costs are relatively inconsequential if fans are used.

Summary and Conclusions. - Optimal designs for 6- and 12-in.-diam cans and a number of heat-generation rates are presented in Table 4. In each of these cases, the pitch-to-diameter ratio is 1.25 and the condition that limits the number of rows is the concrete temperature of 500°F. For a given can size, the influence of heat-generation rate on costs is very

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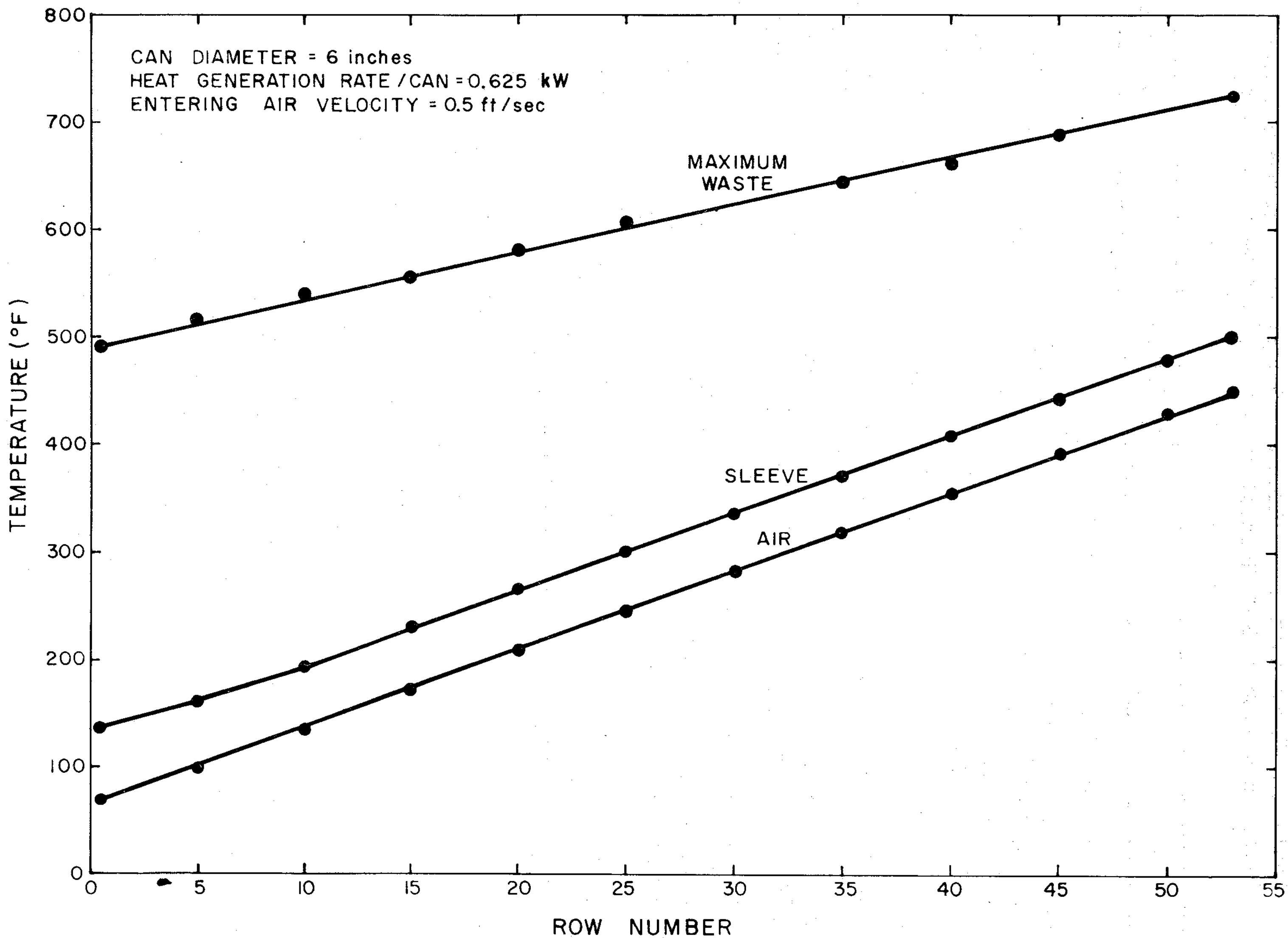

Fig. 4. Temperature Profiles Along the Vault.

Table 2. Comparison of In-Line and Staggered Arrangements for 6-in. Cans with a Heat-Generation Rate of 2.5 kW (PDR = 1.25)

	In-Line	Staggered
Velocity = 1 fps		
Maximum number of rows	22	24
Pressure drop, in. H_2O	1.06	1.08
Exit air temp., °F	377	406
Capital cost per can, $	126.5	125.6
Velocity = 2 fps		
Maximum number of rows	49	51
Pressure drop, in. H_2O	1.79	1.85
Exit air temp., °F	421	435
Capital cost per can, $	130.7	130.9
Velocity = 3 fps		
Maximum number of rows	58	57
Pressure drop, in. H_2O	2.91	2.91
Exit air temp., °F	348	343
Capital cost per can, $	171.2	171.2

Table 3. Effect of Radioactive Decay on Natural Draft Cooling

Can Diameter (in.)	Stack Height (ft)	Stack Diameter (ft)	Heat-Generation Rate per Can (kW)	Entering Air Velocity (fps)	Exit Air Temperature (°F)	Maximum Sleeve Temperature (°F)
6	227	8.7	1.25	1.0	435	500
6	227	8.7	0.625	0.6	380	420
12	325	18.1	5.0	2.0	385	500
12	325	18.1	2.5	1.4	301	372
12	325	18.1	1.25	0.8	272	322

Table 4. Optimal Designs of Storage Vaults for Different Can Diameters and Heat-Generation Rates (Pitch-to-Diameter Ratio: 1.25)

Case No.	Can Diameter (in.)	Heat-Generation Rate per Can (kW)	Total Number of Cans in Vault	Maximum Number of Rows	Entering Air Velocity (fps)	Pressure Drop (in. H_2O)	Exit Air Temperature (°F)	Stack Height (ft)	Stack Diameter (ft)	Cost per Can: Electricity ($/year)	Cost per Can: Capital ($)
1	6	0.625	5,000	53	0.5	1.07	450	190	6.1	0.05	117
2	6	1.25	5,000	51	1.0	1.20	435	226	8.7	0.13	119
3	6	2.5	5,000	22	1.0	1.10	377	231	12.8	0.27	126
4	12	2.5	5,000	45	1.0	1.15	417	224	12.5	0.26	225
5	12	2.5	10,000	45	1.0	1.15	417	224	17.7	0.26	217
6	12	5.0	5,000	41	2.0	1.55	385	320	18.1	0.78	236
7	12	5.0	10,000	41	2.0	1.55	385	320	25.6	0.78	227

small; for example, costs vary only a few percent as the heat-generation rate is increased by a factor of 4. Changing the capacity of the vault from 5000 to 10,000 cans decreases costs only a few percent.

The following conclusions can be drawn:

1. The optimal pitch-to-diameter ratio is about 1.25.
2. For practical purposes, capital costs are a function of can size only.
3. Optimal entering air velocities range from 0.5 to 2 fps, increasing with can size and heat-generation rate.
4. If stacks are used, stack heights range from about 200 to 300 ft.
5. If fans are used, the energy costs are trivial.
6. The choice between an in-line and a staggered arrangement does not significantly affect capital or energy costs.

7. PROJECTED STORAGE VAULT REQUIREMENTS

Projections of the volume of storage space required to accommodate all the high-level solidified wastes expected to be generated in the United States through the end of this century are given in Table 5. These projections are based on the existence of installed nuclear electric capacities of 150,000, 500,000, and 1,100,000 MW by the end of calendar years 1980, 1990, and 2000, respectively. The waste is assumed to be packaged in containers 12 in. in diameter by 10 ft high, and to have been stored at the reprocessing plants for 10 years before emplacement in the vaults. At the time of emplacement in the vaults, each package has a thermal power of 2.5 kW. We estimate that, under these circumstances, vaults having a total volume of about 1.1 million ft^3 will be required by the end of the year 2000. The vaults would be of modular construction, with each module sized to contain either 5000 or 10,000 packages of waste. Inside dimensions of the 5000-package vaults would be 185 ft wide x 75 ft long x 10.5 ft high, while the 10,000-package modules would be 370 ft wide x 75 ft long x 10.5 ft high.

Table 5. Projected Storage Vault Requirements[a] for the United States

Calendar Year	Number of Waste Packages[b]		Vault Storage Volume Required (ft^3)	
	Annually	Cumulative	Annually	Cumulative[c]
1980	29	29	845	845
1981	42	71	1225	2070
1982	70	141	2040	4110
1983	129	270	3760	7870
1984	235	505	6850	14,700
1985	388	893	11,300	26,000
1986	589	1480	17,200	43,200
1987	804	2290	23,400	66,600
1988	1000	3290	29,200	95,800
1989	1230	4520	35,900	132,000
1990	1480	6000	43,100	175,000
1991	1740	7740	50,700	226,000
1992	2010	9750	58,600	285,000
1993	2330	12,100	67,900	353,000
1994	2610	14,700	76,100	429,000
1995	2990	17,700	87,200	516,000
1996	3380	21,100	98,500	615,000
1997	3770	24,800	110,000	725,000
1998	4190	29,000	122,000	847,000
1999	4680	33,700	136,000	983,000
2000	5180	38,900	151,000	1,130,000

[a]Based on installed capacities at 150,000, 500,000, and 1,100,000 MW(e) at the end of calendar years 1980, 1990, and 2000, respectively. Wastes are assumed to be 10 years old at the time of their storage in vaults.

[b]Assumes waste is packaged in containers 12 in. in diameter by 10 ft high, and that each package has a thermal power of 2.5 kW at the time of receipt.

[c]Vaults are modular in construction, with each module sized to contain either 5000 or 10,000 packages of waste. Inside dimensions of the smaller vaults are 185 ft wide x 75 ft long x 10.5 ft high; the larger vaults are 370 ft wide x 75 ft long x 10.5 ft high (see Table 4, Cases 4 and 5).

8. NOMENCLATURE

a = transverse pitch-to-diameter ratio

b = longitudinal pitch-to-diameter ratio (in the direction of flow)

d = cylinder diameter, ft

f = friction factor, dimensionless

G = fluid mass velocity based on minimum net free area, $lb_m/sec\text{-}ft^2$

g = local acceleration due to gravity, ft/sec^2

g_c = conversion factor, 32.17 $lb_m \cdot ft/lb_f \cdot sec^2$

Gr = Grashof number, dimensionless

h = film coefficient for heat transfer, $Btu/hr \cdot ft^2 \cdot {}^\circ F$

H = stack height, ft

k = thermal conductivity of air, $Btu/hr \cdot ft \cdot {}^\circ F$

k_w = thermal conductivity of solid waste, $Btu/hr \cdot ft \cdot {}^\circ F$

lb_m = pounds mass

lb_f = pounds force

N = number of tubes in the direction of flow

P = air pressure, lb_f/ft^2

Pr = Prandtl number, dimensionless

Q = heat-generation rate, $Btu/hr \cdot ft^3$

R = can radius, ft

Re = Reynolds number, dimensionless

T_c = temperature at center of can, °F

T_s = temperature at surface of can, °F

U = overall heat transfer coefficient, $Btu/hr \cdot ft^2 \cdot {}^\circ F$

x = thickness of gap, ft

ρ = density of air, lb_m/ft^3

ρ_o = ambient air density (0.075 lb_m/ft^3 at 70°F)

μ = viscosity of air, centipoises

μ_s = viscosity of air at cylinder temperature, centipoises

9. REFERENCES

1. J. J. Perona, R. L. Bradshaw, and J. O. Blomeke, Comparative Costs for Final Disposal of Radioactive Solids in Concrete Vaults, Granite, and Salt Formations, ORNL-TM-664 (October 1963).

2. H. S. Davis and O. E. Borge, "High Density Concrete," Journal of the American Concrete Institute, p. 106 (April 1959).

3. T. Tinker, "Shell-Side Characteristics of Shell-and-Tube Heat Exchangers," Trans. ASME 80, 36 (1958).

4. F. Kreith, Principles of Heat Transfer, p. 348, International Textbook Co., Scranton, Pa., 1965.

5. D. F. Boucher and C. E. Lapple, "Pressure Drop Across Tube Banks," Chem. Eng. Progr. 44, 118 (1948).

6. M. Jakob, Trans. ASME 60, 384 (1938).

7. T. H. Chilton and R. P. Genereaux, Trans. A.I.Ch.E. 29, 161 (1933).

8. H. L. Solberg, O. C. Cromer, and A. R. Spalding, Thermal Engineering, p. 553, Wiley, New York, 1960.

9. E. J. Stankiewicz, "How to Estimate Stack Costs," Chem. Eng., p. 239 (June 1955).

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