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THE EFFECTS OF INTERNAL HEAT GENERATION ON POT CALCINATION RATES FOR RADIOACTIVE WASTES

J. J. Perona

OAK RIDGE NATIONAL LABORATORY
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CHEMICAL TECHNOLOGY DIVISION

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ABSTRACT

Methods by which the radial deposition mechanism was determined in experiments with simulated waste solutions are briefly reviewed. Based on this mechanism, an expression for the rate of solid deposition with internal heat generation was developed by a combined heat and material balance. A sample calculation for Purex waste showed that a moderate heat generation rate of 5000 $Btu/hr \cdot ft^3$ would decrease the time to fill a 12-in.-dia calcination vessel from 78 to 55 hr.

For the calcination stage of the process, in which the deposited solids are heated in the absence of a liquid phase, a solution was developed for the equation of heat transfer with the temperature profile from the solid deposition stage as an initial condition. For the example Purex waste with a heat generation rate of 5000 $Btu/hr \cdot ft^3$, less than 15 min would be required for calcination, compared to about 8 hr in experiments with simulated wastes.

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1.0 INTRODUCTION

The pot calcination process for reducing highly radioactive liquid wastes to solid form has undergone several years of development at ORNL with simulated waste solutions.[1] A pilot plant for process development with radioactive wastes is now in the preliminary design stage. A critical aspect of the process is the average processing rate, which has been lower than those of other calcination processes in tests with simulated wastes but high enough to be feasible. Hence there is some interest in predicting the effects of internal heat generation on the average processing rate and in anticipating the scheduling of the process cycle, which consists of (1) placing a calcination vessel in the furnace with feed, off-gas, and instrument lines attached, (2) evaporating radioactive liquid waste in the vessel until it is filled with solid, (3) holding the vessel in the furnace until the solid uniformly reaches at least 900°C (calcination), (4) removing feed, off-gas and instrument lines and sealing the vessel, and (5) removing the vessel from the furnace for decontamination of the exterior and monitoring.

The determination of the mechanism of solids deposition in experiments with simulated (non-heat-generating) wastes is briefly reviewed. Based on this model, an expression for the rate of solid deposition with internal heat generation was developed by a combined heat and material balance. To develop an expression for temperature as a function of time and radial distance during the calcination stage, the equation of heat transfer was solved with the temperature profile in the depositing solid as an initial condition. The solution was obtained from the known solution for a unit instantaneous cylindrical surface source, which was developed through the use of Green's function for a cylinder. To ascertain the importance of internal heat generation on solid deposition rate and calcination time, the derived expressions were applied to the processing of Purex waste in a 1-ft-dia vessel.

2.0 DEPOSITION MECHANISM

Wastes are calcined in long thin cylindrical vessels (Fig. 1). Sizes used and planned in experiments at ORNL range from 6 to 12 in. dia and 6 to 10 ft length. Experiments are started with the calcination vessel partly filled with

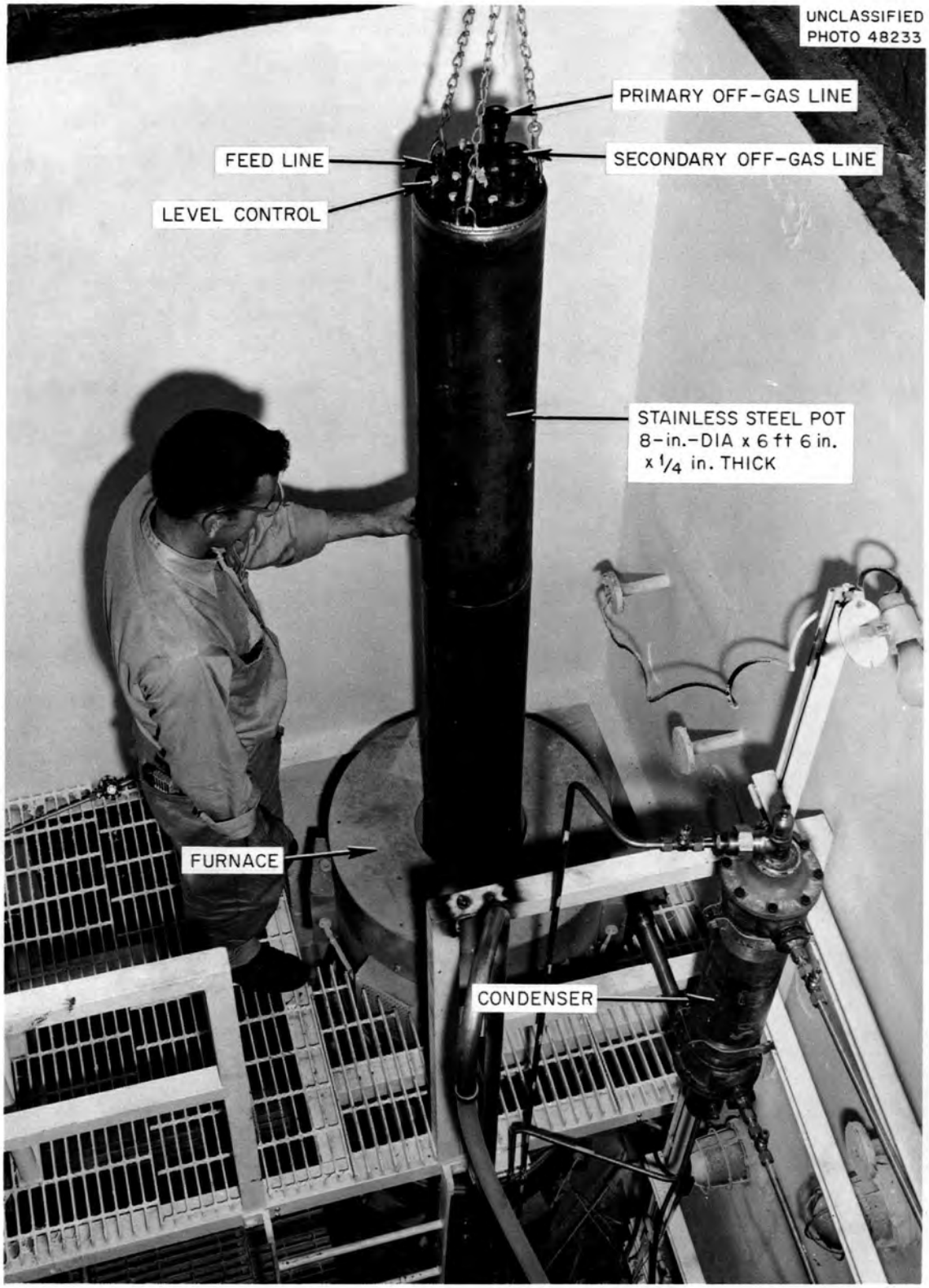

Fig. 1. Calciner vessel, 8 in. dia by 6.5 ft high, being removed from furnace.

Fig. 2. Vessel partially filled with calcined Purex waste.

boiling water. Liquid feed solution is pumped into the vessel until it is nearly full, with just enough freeboard to avoid excessive carryover of liquid into the off-gas system by entrainment. The liquid level is held constant, and the calcination vessel fills with solid by evaporation. By inspection of partly filled vessels, by the time sequence of the passage of variously located thermocouples above the boiling point of the liquid, and by the variation of condensate rate with time, it has been established that deposition of acid Purex, TBP-25, and Darex solid wastes starts at the cylindrical surface and grows radially toward the center of the vessel (Figs. 2 and 3).

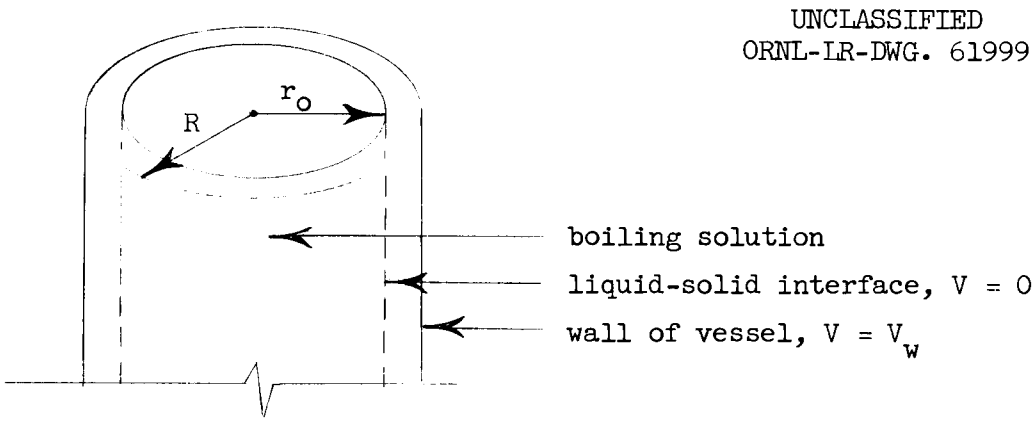

Fig. 3. Schematic diagram of partly filled calcination vessel during solids deposition process.

In order to illustrate how the radial deposition mechanism is confirmed by the variation of condensate rate with time, an expression for the rate of solids deposition without internal heat generation must be derived. The temperature distribution in the solid is obtained from the equation of heat conduction:

$$\frac{\partial^2 V}{\partial r^2} + \frac{1}{r}\frac{\partial V}{\partial r} = \frac{1}{\kappa}\frac{\partial V}{\partial t} \qquad (2\text{-}1)$$

with boundary conditions

$$V = 0 \qquad t = 0 \qquad (2\text{-}2)$$

$$V = 0 \qquad 0 \le r \le r_o \qquad (2\text{-}3)$$

$$V = V_w \qquad r = R \qquad (2\text{-}4)$$

where $V = T - T_b$

T = temperature

T_b = boiling point of solution

T_w = wall temperature of vessel (constant)

$V_w = T_w - T_b$

r_o = radial distance from axis of vessel to solid-liquid interface

R = radius of vessel

κ = thermal diffusivity of deposited solids

If the interface moves slowly with respect to the rate of heat transfer through the solids, which is a reasonable assumption due to the high heat of evaporation of the solution, the temperature profile for any r_o may be assumed to be at steady state. Equation 2-1 may be replaced by

$$\frac{\partial^2 V}{\partial r^2} + \frac{1}{r}\frac{\partial V}{\partial r} = 0 \tag{2-5}$$

Solving eq. 2-5 with eqs. 2-3 and 2-4,

$$V = V_w \left[1 - \frac{\ln (r/R)}{\ln (r_o/R)} \right] \tag{2-6}$$

To obtain the rate of interface movement, the heat flux into the liquid is equated to the rate of solids deposition:

$$-k\left(\frac{\partial V}{\partial r}\right)_{r_o} = \lambda \beta \frac{dr_o}{dt} \tag{2-7}$$

where k = thermal conductivity of deposited solid

λ = heat of vaporization of distillate per unit volume

β = volume ratio of distillate to deposited solid

Differentiating eq. 2-6 and substituting in eq. 2-7 gives

$$-\left(\frac{\partial V}{\partial r}\right)_{r_o} = \frac{V_w}{\ln (r_o/R)} \left(\frac{1}{r_o}\right) \tag{2-8}$$

$$\frac{kV_w}{\lambda\beta} dt = r_o \ln \frac{r_o}{R} dr_o \tag{2-9}$$

Integrating eq. 2-9 gives

$$t = \frac{\lambda\beta}{kV_w} \int_R^{r_o} r_o \ln \frac{r_o}{R} dr_o = \frac{\lambda\beta R^2}{4kV_w} \left[2 \left(\frac{r_o}{R}\right)^2 \ln \frac{r_o}{R} + 1 - \left(\frac{r_o}{R}\right)^2 \right] \tag{2-10}$$

If experimental values of β are available, test run data of distillate volume vs time may be converted to a table of r_o vs time. According to eq. 2-10, a plot of the terms in brackets vs time should yield a straight line with a slope of $\lambda\beta R^2/4kV_w$. A sample plot of a test run with Purex waste (Fig. 4) shows a good fit of the data to the model.

The time required to fill a calcination vessel in the absence of internal heat generation may be obtained from eq. 2-10 by letting $r_o \longrightarrow 0$, which yields

$$t_{fill} = \frac{\lambda\beta R^2}{4kV_w} \tag{2-11}$$

An interesting observation from this equation is that the average processing rate per unit length of vessel during the filling period, $\pi R^2/t_{fill}$, is equal to a grouping of constants, $4kV_w\pi/\lambda\beta$, and is independent of the vessel radius. This point has been proved experimentally.[2]

3.0 SOLID DEPOSITION RATE WITH INTERNAL HEAT GENERATION

The temperature distribution in the deposited solid with internal heat generation is obtained from

$$\frac{\partial^2 V}{\partial r^2} + \frac{1}{r}\frac{\partial V}{\partial r} + \frac{Q}{k} = \frac{1}{\kappa}\frac{\partial V}{\partial t} \tag{3-1}$$

where Q = heat generation rate per unit volume of solid with boundary conditions 2-2, 2-3, and 2-4. Again assuming that the interface moves slowly, eq. 3-1 becomes

$$\frac{\partial^2 V}{\partial r^2} + \frac{1}{r}\frac{\partial V}{\partial r} + \frac{Q}{k} = 0 \tag{3-2}$$

The general solution to eq. 3-2 is

$$V = C_1 + C_2 \ln r - \frac{Qr^2}{4k} \tag{3-3}$$

where C_1 and C_2 are constants to be determined by the boundary conditions. Applying conditions 2-3 and 2-4,

$$V - V_w = \frac{QR^2}{4k}\left[1 - \left(\frac{r}{R}\right)^2\right] - \left\{V_w + \frac{QR^2}{4k}\left[1 - \left(\frac{r_o}{R}\right)^2\right]\right\}\frac{\ln (R/r)}{\ln (R/r_o)} \tag{3-4}$$

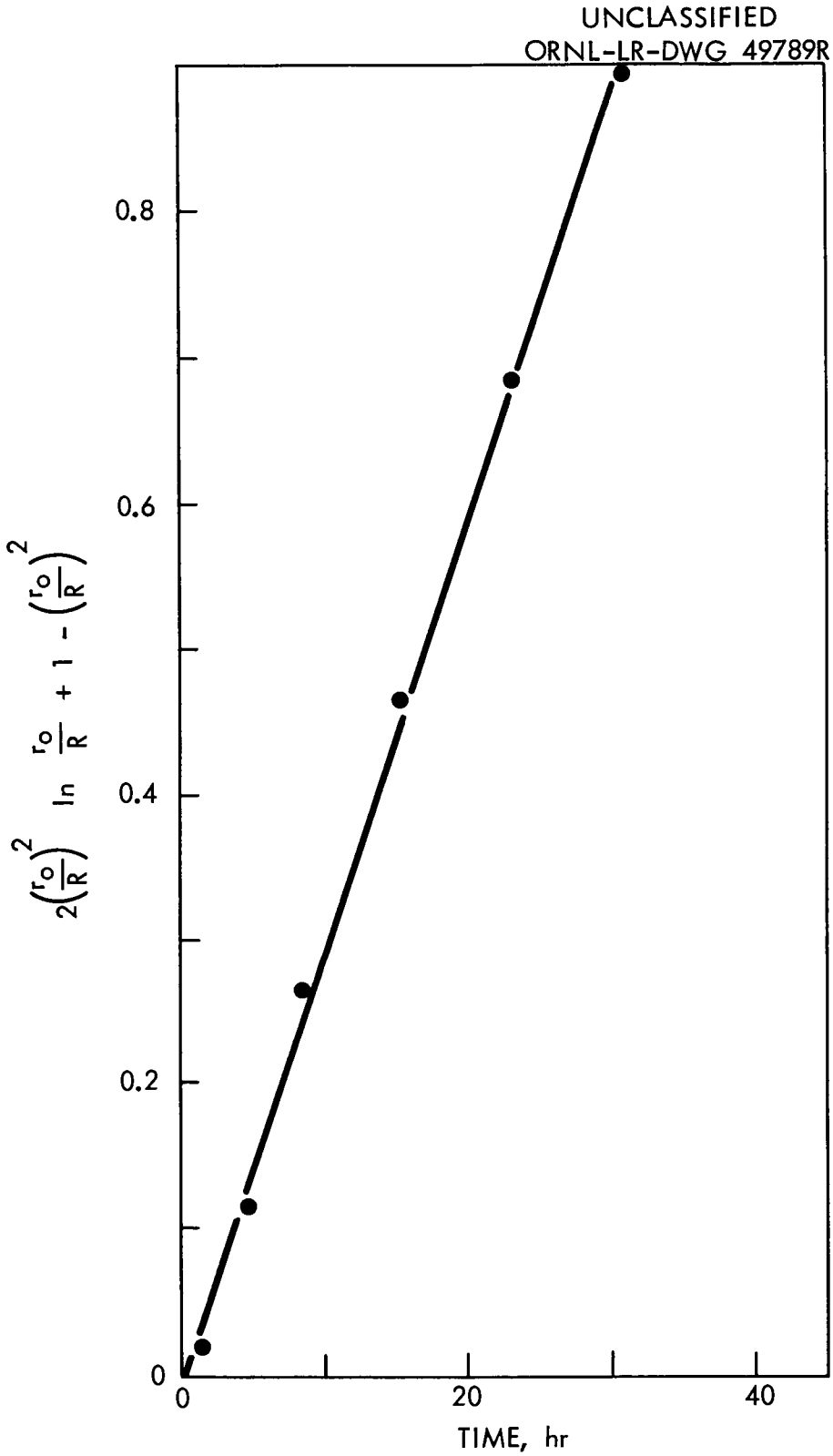

Fig. 4. Fit of experimental data to radial deposition model (Run 29, Purex waste).

On setting $Q = 0$ in eq. 3-4, eq. 2-6 is obtained.

The rate of interface movement may be obtained by differentiating eq. 3-4 and substituting into eq. 2-7. The heat generation in the liquid phase may be neglected since it is about an order of magnitude less per unit volume than the heat generation in the solid:

$$-\left(\frac{\partial V}{\partial r}\right)_{r_o} = \frac{1}{r_o \ln (R/r_o)}\left\{V_w + \frac{QR^2}{4k}\left[1 - \left(\frac{r_o}{R}\right)^2\right]\right\} - \frac{Qr_o}{2k} \tag{3-5}$$

$$-\frac{k}{\lambda\beta}\,dt = \frac{dr_o}{\left[\dfrac{C_3}{r_o \ln (R/r_o)} - \dfrac{C_4 r_o}{\ln (R/r_o)} - 2C_4 r_o\right]} \tag{3-6}$$

where $C_3 = V_w + QR^2/4k$, $C_4 = Q/4k$

Rearranging eq. 3-6 and integrating we have

$$t = \frac{\lambda\beta}{k}\int_{r_o}^{R} \frac{r_o \ln (R/r_o)\, dr_o}{\left[C_3 - C_4 r_o^2 - 2C_4 r_o^2 \ln (R/r_o)\right]} \tag{3-7}$$

The numerator of the integrand is the derivative of the denominator, so that we have

$$t = -\frac{\lambda\beta}{4C_4 k} \ln\left[(C_3 - C_4 r_o^2 - 2C_4 r_o^2 \ln (R/r_o))\right]_{r_o}^{R} \tag{3-8}$$

Finally, substituting the limits,

$$t = \frac{\lambda\beta}{Q} \ln \frac{V_w + \frac{QR^2}{4k} - \frac{Qr_o^2}{4k}\left[1 + 2 \ln (R/r_o)\right]}{V_w} \tag{3-9}$$

The time required to fill a calcination vessel may be obtained from eq. 3-9 by letting $r_o \longrightarrow 0$, which yields

$$t_{fill} = \frac{\lambda\beta}{Q} \ln \frac{V_w + \frac{QR^2}{4k}}{V_w} \tag{3-10}$$

The importance of internal heat generation may be shown by comparing eq. 3-10 to eq. 2-11 for a case of interest. In the calcination of acid Purex waste, the following values for the parameters are typical:

$\lambda = 60{,}000$ Btu/ft^3 $\quad \beta = 7 \quad$ $V_w = 1350^\circ$F

$k = 0.25$ Btu/hr ft $^\circ$F $\quad \kappa = 0.100$ ft^2/hr $\quad R = 0.5$ ft

For the listed thermal conductivity and vessel radius, the highest heat generation rate that could be tolerated by a storage system which maintained a vessel wall temperature of 300°F and did not permit temperatures of the calcined solids to exceed the maximum calcination temperature of 1650°F would be about 5000 Btu/hr·ft^3; hence a range of heat generation rates up to about 5000 Btu/hr·ft^3 is of interest for the above values. Purex waste resulting from 2% enriched uranium irradiated to 10,000 Mwd/ton, decreased to 7 gal/ton by calcination, and allowed to decay two years would have a heat generation rate of about 5000 Btu/hr·ft^3. Therefore the heat generation rate of this waste is only moderate, being less by a factor of 8 to 10 than the same waste decayed 120 days.

The results are shown graphically in Fig. 5, in which the time to fill decreases from 78 to 55 hr as the heat generation rate increases from 0 to 5000 Btu/hr·ft^3. Temperature profiles in the deposited solid for heat generation rates of 0 and 5000 are given in Fig. 6. With internal heat generation, solids temperatures exceeding the wall temperature may occur during the filling process. In this case, a peak temperature of 2000°F was calculated in filling to an r/R of 0.05. It may be desirable in practice to stop filling when the calcination vessel is about 90% full ($r/R \approx 0.3$) in order to decrease the cycle time and to decrease temperature control problems for the vessel during calcination and flange-exchanging operations.

4.0 CALCINATION PERIOD

After the feeding of the radioactive waste solution into the vessel has been stopped, there would occur a short time in which the remaining liquid was evaporated from the vessel, assuming the vessel was not completely filled with solids. If the interior surface of the solid is assumed to be uniformly at T_b at the end of this time, the temperature distribution during the subsequent calcination is obtained from

$$\frac{\partial^2 W}{\partial r^2} + \frac{1}{r}\frac{\partial W}{\partial r} + \frac{Q}{k} = \frac{1}{\kappa}\frac{\partial W}{\partial t} \tag{4-1}$$

where $W = T - T_w$ and with boundary conditions $W = 0$ at $r = R$ (4-2)

$$\frac{\partial W}{\partial r} = 0 \text{ at } r = r_o \tag{4-3}$$

and at $t = 0$, $$W = \frac{QR^2}{4k}\left[1 - \left(\frac{r}{R}\right)^2\right] - \left\{V_w + \frac{QR^2}{4k}\left[1 - \left(\frac{r_o}{R}\right)^2\right]\right\}\frac{\ln (r/R)}{\ln (r_o/R)} \tag{4-4}$$

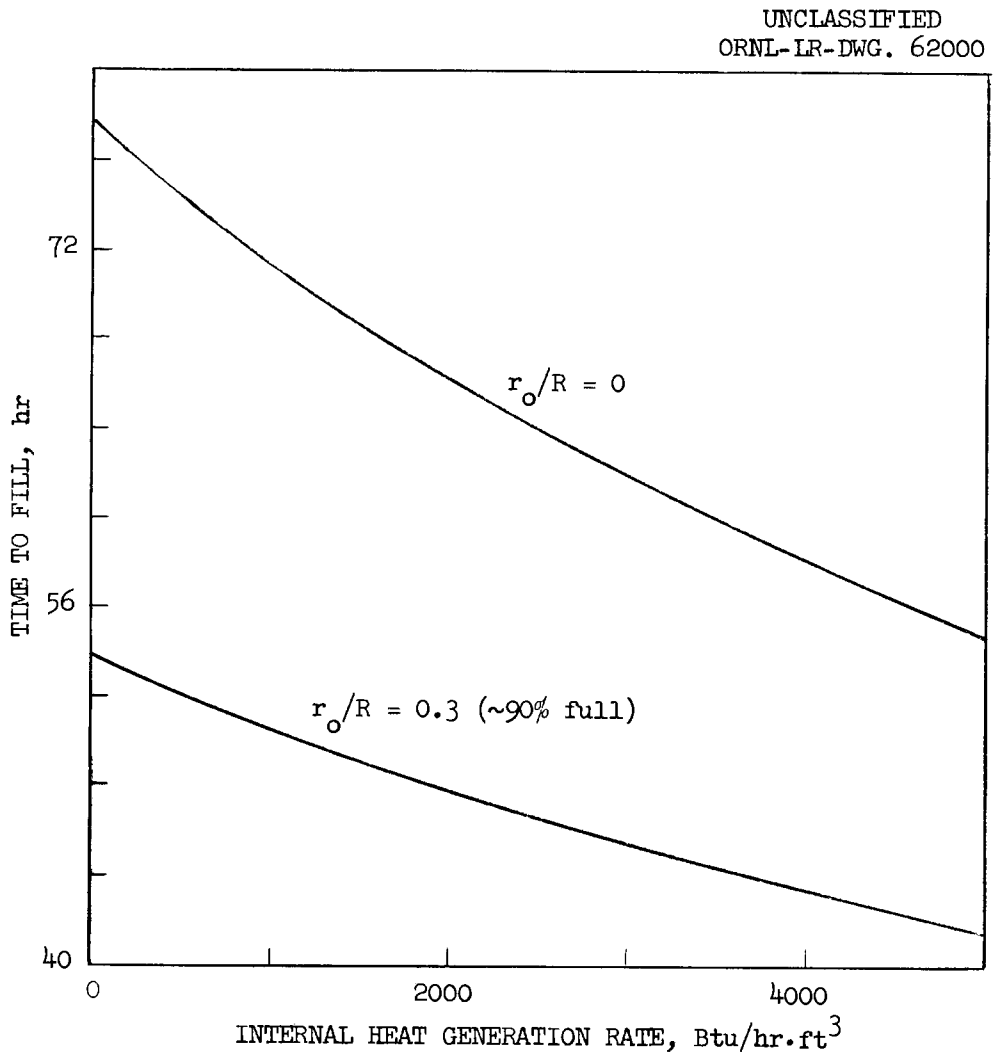

Fig. 5. Effect of internal heat generation rate on time to fill a 1-ft-dia calcination vessel with Purex waste.

Assume a solution of the form

$$W(r,t) = W_1(r,t) + W_2(r) \tag{4-5}$$

Thus eq. 4-1 may be separated into two equations

$$\frac{\partial^2 W_1}{\partial r^2} + \frac{1}{r}\frac{\partial W_1}{\partial r} = \frac{1}{\kappa}\frac{\partial W_1}{\partial t} \tag{4-6}$$

$$\frac{\partial^2 W_2}{\partial r^2} + \frac{1}{r}\frac{\partial W_2}{\partial r} + \frac{Q}{k} = 0 \tag{4-7}$$

with boundary conditions $W_1 = W_2 = 0$ at $r = R$ (4-8)

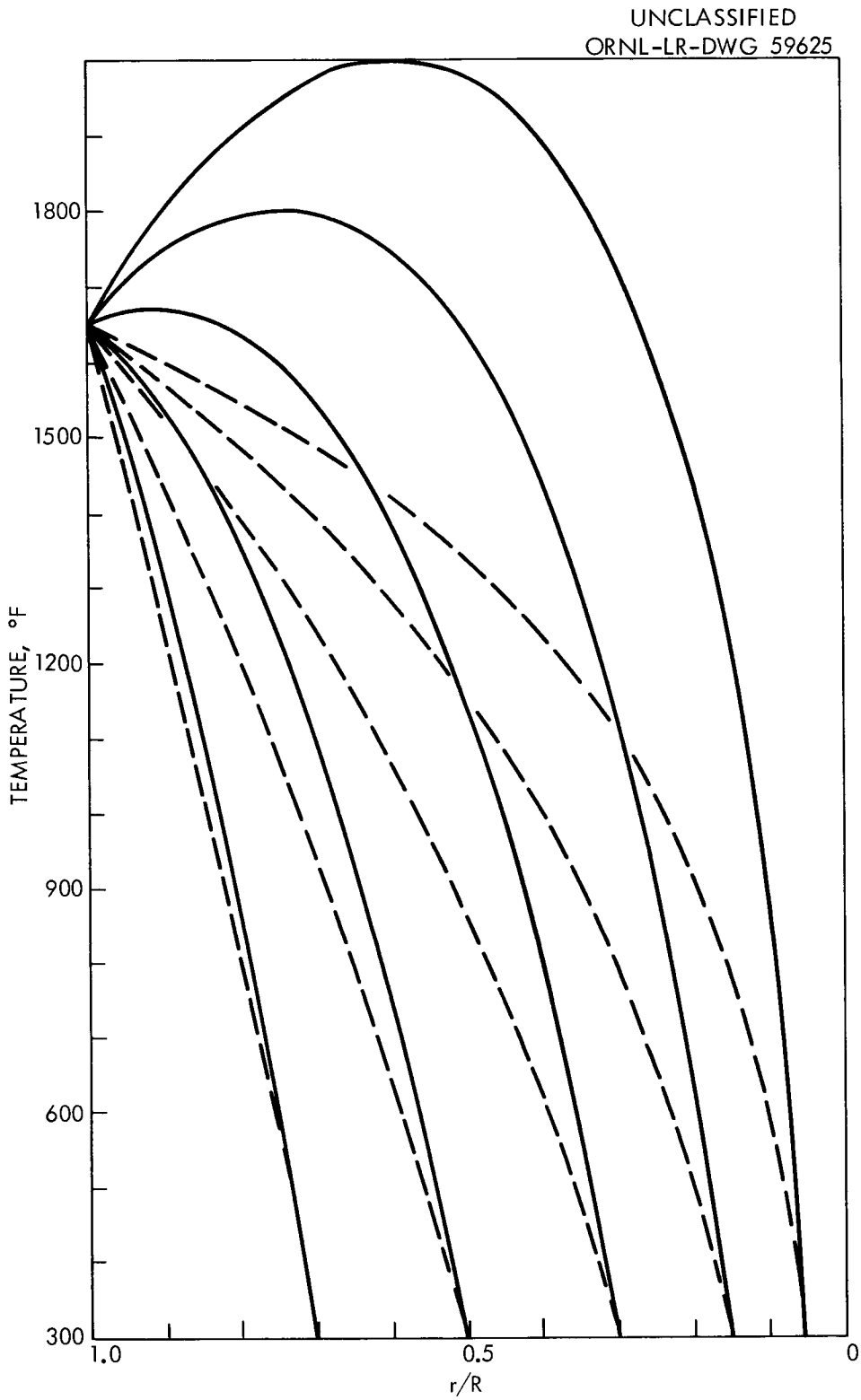

Fig. 6. Temperature profiles in deposited Purex solid waste in a 12-in.-dia vessel. Solid line, Q = 5000 Btu/hr.ft^3; dashed line, Q = 0.

$$\frac{\partial W_1}{\partial r} = \frac{\partial W_2}{\partial r} = 0 \text{ at } r = r_o \tag{4-9}$$

$$W_1 = \frac{QR^2}{4k}\left[1 - \left(\frac{r}{R}\right)^2\right] - \left\{V_w + \frac{QR^2}{4k}\left[1 - \left(\frac{r_o}{R}\right)^2\right]\right\}\frac{\ln\,(r/R)}{\ln\,(r_o/R)} - W_2 \text{ at } t = 0 \tag{4-10}$$

The set of equations 4-7, 4-8, and 4-9 are solved with eq. 3-3 to obtain

$$W_2 = \frac{QR^2}{4k}\left[1 - \left(\frac{r}{R}\right)^2\right] - \frac{Qr_o^2}{2k}\ln\frac{R}{r} \tag{4-11}$$

The set of equations 4-6, 4-8, 4-9, and 4-10 may be simply solved by starting with the published solution for a unit instantaneous cylindrical surface source at $t = 0$ and $r = r'$:[3]

$$T = \frac{\pi}{4}\sum_1^\infty \frac{\alpha_n^2}{F(\alpha_n)}\, J_o^2(\alpha_n)\, C_o\left(\frac{r}{R},\alpha_n\right) C_o\left(\frac{r'}{R},\alpha_n\right) e^{-\kappa\alpha_n^2 t/R^2} \tag{4-12}$$

where α_n satisfies $\quad J_o(\alpha)Y_1\left(\frac{r_o}{R}\alpha\right) - Y_o(\alpha)\, J_1\left(\frac{r_o}{R}\alpha\right) = 0 \qquad (4\text{-}13)$

$$F(\alpha_n) = \alpha_n^2\left[J_1^2\left(\frac{r_o}{R}\alpha_n\right) - J_o^2(\alpha_n)\right] \tag{4-14}$$

$$C_o\left(\frac{r}{R},\alpha_n\right) = \alpha_n\left[J_o\left(\frac{r}{R}\alpha_n\right) Y_1\left(\frac{r_o}{R}\alpha_n\right) - Y_o\left(\frac{r}{R}\alpha_n\right) J_1\left(\frac{r_o}{R}\alpha_n\right)\right] \tag{4-15}$$

Modifying eq. 4-12 by taking a source strength of $2\pi r' f(r')dr'$ at r', and integrating from r_o to R, the solution is obtained for an initial temperature distribution $f(r)$:

$$W_1 = \frac{\pi^2}{2}\sum_1^\infty \frac{\alpha_n^2}{F(\alpha_n)}\, J_o^2(\alpha_n)\, C_o\left(\frac{r}{R},\alpha_n\right) e^{-\kappa\alpha_n^2 t/R^2}\int_{r_o/R}^{1} \frac{r'}{R}\, f\left(\frac{r'}{R}\right) C_o\left(\frac{r'}{R},\alpha_n\right) d\left(\frac{r'}{R}\right) \tag{4-16}$$

In this case $f\left(\frac{r'}{R}\right)$ is given in eq. 4-10. In order to carry out the integration in eq. 4-16, the following formula given by Muscat[4] is needed:

$$\int x\, U_o(\alpha x)\, \ln x\, dx = \frac{1}{\alpha^2}\left\{U_o(\alpha x) - x\frac{d}{dx}\left[U_o(\alpha x)\right]\ln x\right\} \tag{4-17}$$

where $U_o(\alpha x) = J_o(\alpha x)$ or $Y_o(\alpha x)$. Equation (4-16) becomes

$$W_1 = \frac{\pi^2}{2}\sum_1^\infty \frac{J_o^2(\alpha_n)e^{-\kappa\alpha_n^2 t/R^2}}{J_1^2\left(\frac{r_o}{R}\alpha_n\right) - J_o^2(\alpha_n)}\, G\left(\frac{r_o}{R},\alpha_n\right)\left[J_o\left(\frac{r}{R}\alpha_n\right) Y_1\left(\frac{r_o}{R}\alpha_n\right) - Y_o\left(\frac{r}{R}\alpha_n\right) J_1\left(\frac{r_o}{R}\alpha_n\right)\right] \tag{4-18}$$

where $G\left(\frac{r_o}{R},\alpha_n\right) = \left[\frac{1}{\ln\,(r_o/R)}\left\{V_w + \frac{QR^2}{4k}\left[1 - \left(\frac{r_o}{R}\right)^2\right]\right\} + \frac{Qr_o^2}{2k}\right]$

$$\cdot\left[J_o\left(\frac{r_o}{R}\alpha_n\right) Y_1\left(\frac{r_o}{R}\alpha_n\right) - Y_o\left(\frac{r_o}{R}\alpha_n\right) J_1\left(\frac{r_o}{R}\alpha_n\right)\right] \tag{4-19}$$

The sum of eqs. 4-11 and 4-18 then gives the solution to eqs. 4-1 through 4-4. Returning to the previous example with Purex waste, temperature profiles were calculated during the calcination period for heat generation rates of 5000 and 500 Btu/hr·ft^3 with $r_o/R = 0.3$. Intermediate numbers for the calculations are given in the appendix, Tables A-1 and A-2. In contrast to experience with simulated waste, where it was necessary to hold the vessel wall temperature at 1650°F for 8 to 12 hr, temperatures in the solid everywhere exceeded the wall temperature within 15 minutes with a moderate heat generation rate of 5000 Btu/hr·ft^3 (Fig. 7-8). Even for a very slightly radioactive waste with a heat generation rate of 500 Btu/hr·ft^3, only short calcination periods of 2 or 3 hr will be required. For high-burnup short-decayed wastes, carefully devised controls may be necessary to avoid dangerously high temperatures.

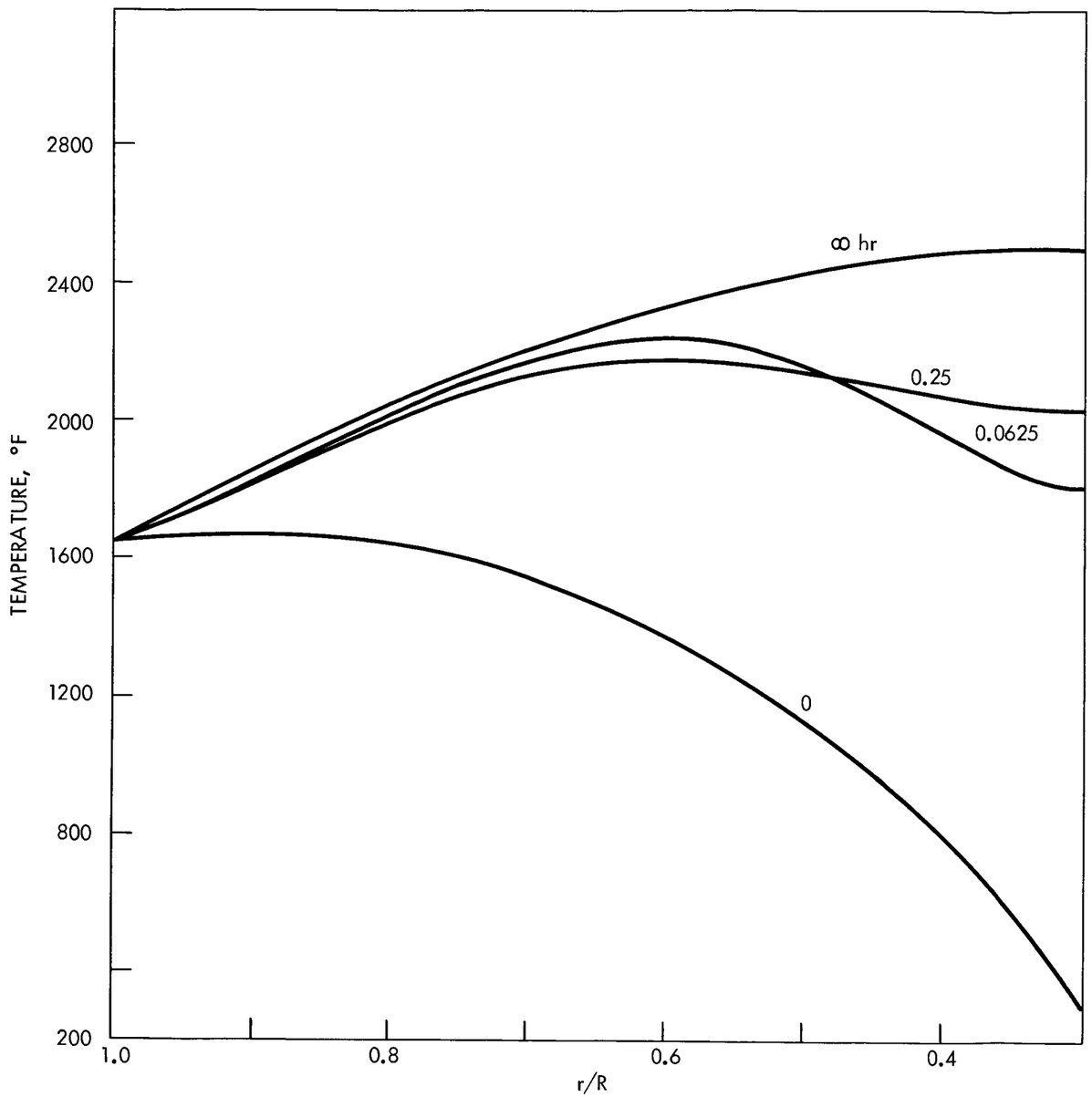

Fig. 7. Temperature profiles during calcination of Purex waste in a 1-ft-dia vessel. Q = 5000 Btu/hr.ft^3.

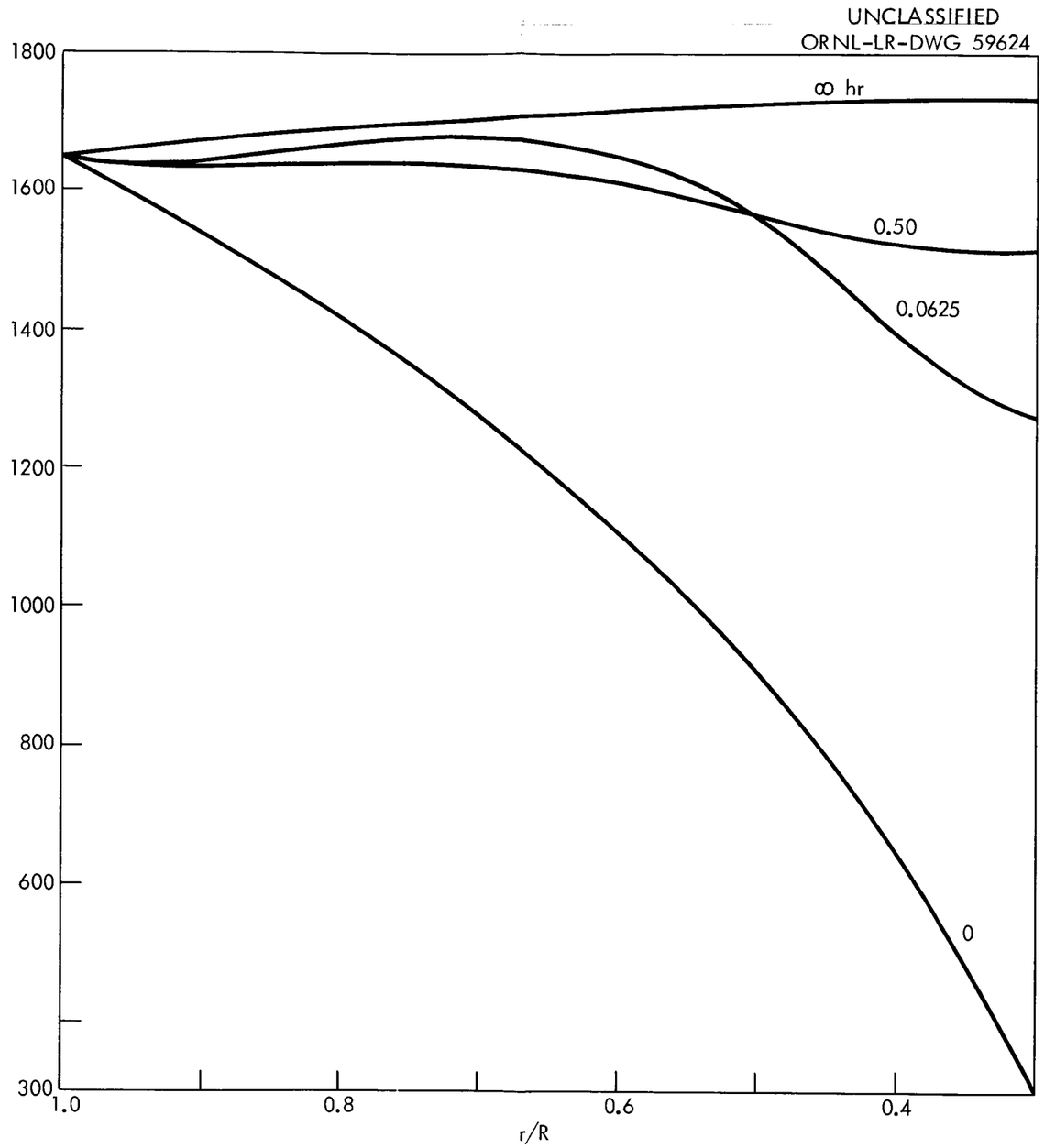

Fig. 8. Temperature profiles during calcination of Purex waste in a 1-ft-dia vessel. Q = 500 Btu/hr.ft^3.

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4. M. Muscat, Physics, 5: 71 (1934).

Table A-1. Calculation of Temperature Profiles During Calcination for Q = 5000 Btu/hr·ft^3 and $r_o/R = 0.3$

α_n	$J_o(\alpha_n)$	$J_1\left(\frac{r_o}{R}\alpha_n\right)$	A_n*	$Y_1\left(\frac{r_o}{R}\alpha_n\right)$	$J_o\left(\frac{r_o}{R}\alpha_n\right)$	$Y_o\left(\frac{r_o}{R}\alpha_n\right)$	B_n**	$G\left(\frac{r_o}{R}, \alpha_n\right)$
2.78	-0.177	+0.831	0.0475	-0.940	+0.833	-0.0542	-0.738	488
7.00	+0.300	+0.568	0.386	-0.0517	+0.167	+0.518	-0.303	79.4
11.39	-0.0924	+0.171	0.413	+0.403	-0.368	+0.221	-0.217	35.1
15.83	-0.157	-0.289	0.417	+0.229	-0.255	+0.261	-0.134	15.6
20.30	+0.140	-0.258	0.417	-0.197	+0.175	-0.270	-0.104	9.44
24.76	+0.0635	+0.117	0.411	-0.269	+0.275	+0.0988	-0.0856	6.37

	r/R = 0.9			r/R = 0.8			r/R = 0.7			r/R = 0.5			r/R = 0.4			r/R = 0.35		
α_n	$J_o\left(\frac{r}{R}\alpha_n\right)$	$Y_o\left(\frac{r}{R}\alpha_n\right)$	C_n***	$J_o\left(\frac{r}{R}\alpha_n\right)$	$Y_o\left(\frac{r}{R}\alpha_n\right)$	C_n***	$J_o\left(\frac{r}{R}\alpha_n\right)$	$Y_o\left(\frac{r}{R}\alpha_n\right)$	C_n***	$J_o\left(\frac{r}{R}\alpha_n\right)$	$Y_o\left(\frac{r}{R}\alpha_n\right)$	C_n***	$J_o\left(\frac{r}{R}\alpha_n\right)$	$Y_o\left(\frac{r}{R}\alpha_n\right)$	C_n***	$J_o\left(\frac{r}{R}\alpha_n\right)$	$Y_o\left(\frac{r}{R}\alpha_n\right)$	C_n***
2.78	-0.0484	+0.498	-0.368	+0.0993	+0.521	-0.526	+0.253	+0.504	-0.657	+0.572	+0.333	-0.815	+0.715	+0.169	-0.812	+0.777	+0.0643	-0.783
7.00	+0.224	-0.225	+0.116	+0.0270	-0.335	+0.189	-0.210	-0.292	+0.177	-0.380	+0.189	-0.0870	-0.185	+0.436	-0.238	-0.0232	+0.505	-0.286
11.39	-0.249	-0.00739	-0.0987	-0.116	+0.237	-0.0874	+0.179	+0.219	+0.0346	+0.0567	-0.329	+0.0790	-0.306	-0.212	-0.0868	-0.398	-0.0129	-0.158
15.83	+0.133	+0.164	+0.0778	+0.171	-0.145	-0.0028	-0.157	-0.181	-0.0882	+0.192	+0.208	+0.104	+0.230	-0.217	-0.0100	+0.00677	-0.338	-0.0962
20.30	+0.0369	-0.183	-0.0545	-0.191	+0.0499	+0.0506	+0.140	+0.158	+0.0132	-0.249	+0.0181	+0.0540	+0.142	+0.241	+0.0342	+0.299	+0.00418	-0.0579
24.76	-0.148	+0.0805	+0.0303	+0.177	+0.0309	-0.0512	-0.129	-0.143	-0.0180	+0.126	-0.188	-0.0118	-0.240	+0.0804	+0.0552	-0.00441	+0.271	-0.0306

	$\frac{\pi^2}{2} A_n G\left(\frac{r_o}{R}, \alpha_n\right) C_n$							$e^{-\kappa\alpha_n^2 t/R^2}$		
α_n	r/R = 0.9	r/R = 0.8	r/R = 0.7	r/R = 0.5	r/R = 0.4	r/R = 0.35	r/R = 0.30	t = 0.0625 hr	t = 0.25 hr	t = 0.5 hr
2.78	-117	-167	-208	-259	-258	-249	-234	0.981	0.926	0.858
7.00	+123	+200	+186	-92.0	-252	-302	-321	0.885	0.613	0.376
11.39	-80.2	-71.1	+28.1	+64.2	-70.5	-128	-177	0.725	0.274	0.0752
15.83	+39.5	-1.42	-44.9	+52.9	-5.08	-48.9	-68.2	0.535	0.0813	0.00658
20.30	-21.5	+20.0	+5.20	+21.3	+13.5	-22.8	-40.9	0.357	0.0162	-
24.76	+9.73	-16.3	-5.76	-3.78	+17.7	-9.83	-27.4	0.216	0.00218	-

$$* \quad A_n = \frac{J_o^2(\alpha_n)}{J_1^2\left(\frac{r_o}{R}\alpha_n\right) - J_o^2(\alpha_n)}$$

$$** \quad B_n = Y_1\left(\frac{r_o}{R}\alpha_n\right) J_o\left(\frac{r_o}{R}\alpha_n\right) - J_1\left(\frac{r_o}{R}\alpha_n\right) Y_o\left(\frac{r_o}{R}\alpha_n\right)$$

$$*** \quad C_n = J_o\left(\frac{r}{R}\alpha_n\right) Y_1\left(\frac{r_o}{R}\alpha_n\right) - Y_o\left(\frac{r}{R}\alpha_n\right) J_1\left(\frac{r_o}{R}\alpha_n\right)$$

Table A-2. Calculation of Temperature Profiles During Calcination for $Q = 500$ Btu/hr·ft^3 and $r_o/R = 0.3$

α_n	$G(\frac{r_o}{R},\alpha_n)$	$\frac{\pi^2}{2} A_n\left(G \frac{r_o}{R}, \alpha_n\right) C_n$						
		$r/R = 0.9$	$r/R = 0.8$	$r/R = 0.7$	$r/R = 0.5$	$r/R = 0.4$	$r/R = 0.35$	$r/R = 0.30$
2.78	316	-75.7	-108	-135	-168	-167	-161	-151
7.00	51.5	+79.8	+130	+121	-59.7	-163	-196	-208
11.39	22.7	-51.8	-46.1	+18.2	+41.6	-45.7	-83.0	-115
15.83	10.1	+25.5	-0.921	-29.1	+34.3	-3.29	-31.7	-44.2
20.30	6.12	-13.9	+13.0	+3.37	+13.8	+8.75	-14.8	-26.5
24.76	4.13	+6.31	-10.6	-3.73	-2.45	+11.5	-6.37	-17.8

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