$$\frac{dw}{d\theta} = \frac{2\pi k_f D_p}{\lambda}(t_a - t_s) \tag{6}$$

where

$\frac{dw}{d\theta}$ = evaporation rate, pounds per hour.

A similar expression based on mass transfer is:

$$\frac{dw}{d\theta} = \frac{2\pi M d_v D_p}{RT}(p_s - p_a) \tag{7}$$

where

M = molecular weight of the diffusing vapor.
d_v = diffusivity of the vapor, square feet per hour.
T = absolute temperature of the gas, Fahrenheit degrees.
R = gas constant, (cubic feet) (atmosphere) per (Fahrenheit degree).
p_s = vapor pressure at the particle surface corresponding to the liquid temperature, atmospheres.
p_a = vapor pressure of liquid in the drying medium, atmospheres.

Both Equations 6 and 7 are based on the assumption that Equation 5 applies. If Equation 6 is integrated for a constant drop diameter (*i.e.*, if it is assumed that the solid being dried in the liquid drop creates a structure which becomes rigid at a fixed D_p) and evaporation proceeds as from a pure liquid drop, an expression for the time of evaporation is obtained as follows:

$$\theta = \frac{W\lambda\rho_s D_p^2}{12k_f(t_a - t_s)} \tag{8}$$

where

θ = time, hours.
W = water content of the drop as it enters the drying chamber, pounds per pound.
ρ_s = density of dry particle, pounds per cubic foot.

The temperature difference between drop and gas $(t_a - t_s)$ is essentially constant for a single drop evaporating in a large mass of gas. However, in spray dryers this is not true, and an overall average temperature difference must be used in Equation 8 in this case.

When the drop diameter varies as evaporation proceeds, the expression for the time of evaporation becomes

$$\theta = \frac{\rho_L\lambda[(D_{p1})^2 - (D_{p2})^2]}{8k_f(t_a - t_s)} \tag{9}$$

where

ρ_L = density of the evaporating liquid, pounds per cubic foot.
D_{p1} = drop diameter at the start of evaporation, feet.
D_{p2} = drop diameter of dry particle, feet.

Equation 9 assumes that the drop density is essentially that of the liquid.

Drying at Air Temperatures above the Boiling Point of the Liquid. When the temperature of the drying air is maintained above the boiling point of the liquid being evaporated, or when superheated vapors are used for drying, the usual equations for mass transfer, expressing rate of evaporation

as a function of the vapor pressure difference, lose significance, since large errors are introduced in the expression for vapor pressure driving force due to its apparently small value. Such cases can be treated conveniently on a basis of heat transfer, since a temperature difference must always exist in order that drying may proceed. At drying temperature above 260 F, recirculation has no retarding effect on the drying process.

Constant-Rate Period When Heat Transfer Depends on Conduction and Radiation. In indirect drying, where heat transfer and drying do not depend on the flow of heated gases, the drying rate depends either on heat conduction through retaining walls to wet material in contact with such surfaces, or on radiation, or both. This applies to drum dryers, agitated pan dryers, indirect continuous sheeting dryers, steam tube rotary dryers, vacuum rotary and vacuum tray dryers, and infra-red dryers.

A principal difference between indirect drying and direct drying is that, with the former, the material is usually at a higher temperature than the surrounding air, so that heat is actually transferred to the air instead of from the air.

Generally, the individual heat transfer coefficients for indirect dryers are difficult to determine or estimate, and therefore, an overall coefficient, as defined by Equation 10, is generally used:

$$q = UA\,(t_h - t_s) \tag{10}$$

where

q = rate of heat transfer, Btu per hour.
U = overall heat transfer coefficient based on the temperature difference between the heating medium and the product, Btu per (hour) (square foot) (Fahrenheit degree).
t_h = temperature of the heating medium, Fahrenheit degrees.
t_s = temperature of the solid, Fahrenheit degrees.

The overall coefficient is a function of dryer type. Thus, in agitated pan dryers, U depends on the degree of agitation, temperature of the surface, physical properties of the wet material, etc., and will sometimes vary throughout a drying cycle as the physical properties of the solid vary with a changing moisture content.

As long as U and the temperature difference in Equation 10 remain constant, a constant drying rate will be maintained. However, as drying proceeds the material temperature will begin to increase after some critical moisture content is reached, and, as in the case of direct dryers, a falling-rate period is encountered. U is frequently defined, for the entire drying period, on the basis of an overall mean temperature difference. Therefore,

$$q = UA(\Delta t)_m \tag{11}$$

The Falling-Rate Period. In the discussion of the periods of drying, it was shown that the drying process is discontinuous, consisting of a period of a constant rate of evaporation and a period in which the rate continuously decreases. (See Figs. 3 and 4). This latter period is usually designated as the falling-rate period. It begins when the constant-rate period ends at the critical moisture content. If the critical moisture content is less than the required final moisture content, the constant-rate period will constitute the whole of the drying process. On the other hand, if the initial moisture content is less than the critical moisture content, as