COMPUTER ANALYSIS FOR MODIFICATION OF BASE ENVIRONMENTAL CONDITIONS TO PERMIT COLD WEATHER PAVING

by

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ABSTRACT

Temperature is a most important variable in the compaction of hot-mix asphalt concrete. Cooling rates differ significantly to affect the allowable time for compaction to specified density. The ability to predict the average mix temperature as a function of environment and time is of considerable importance in estimating the allowable time for compaction after placement of the mix. Altering the base environmental conditions by preheating has a profound lengthening effect on the time allowed for compaction to specified density. Mathematical expressions can describe the flow of heat or thermal energy from the hot-mix asphalt to the upper and lower surfaces of the mix. The environmental conditions which affect the upper surface of the mix are the wind velocity, the solar radiation and the atmospheric temperature. The environmental conditions which affect the lower surface of the mix are the initial temperature profile in the base and the percent moisture of the base. During the heating of the base, the controlling variables are the initial temperature profile and the percent moisture in the ground. During the time between the heater input and the actual laying of the asphalt onto the base the controlling surface variables are wind velocity, solar input, and atmospheric temperature, while the interior

controlling variables are the temperature profile and the percent moisture in the base.

A numerical or finite difference solution was used as the basis for a computer program for calculating temperatures as a function of time, place in the base, place in the mix, duration and magnitude of heating, duration between heater input and asphalt laydown (hereafter called stall), and the varying environmental conditions. For use in the computer program, data for wind velocities were converted to Biot numbers, and data for solar altitude were converted to solar-radiant flux. The flame temperature was set at 4000°F, the approximate flame temperature of propane. View factors were calculated and fed in as data. Stall times were assumed to be one minute, three minutes and ten minutes and fed in as data. Constant physical properties were assumed for the mix and the base with zero percent moisture, and fed directly in as data. The physical properties of the base with 10 percent and 20 percent moisture were calculated using literature values for dry sandy soil. A range of 2 degrees, from 31.0 to 33.0 degrees Fahrenheit, was used to calculate the fictive heat capacity of the soil during thawing. A range of 10 degrees, from 210 to 220°F, was used to calculate the fictive heat capacity during vaporization. The physical properties of the moist base were also fed directly in as data.

Since no experimental data for the artificial preheating of base material for asphalt are available, no complete comparison of actual temperature profiles can be made. However, with an assumed initial profile, comparisons are available. Close agreement between experimental and calculated (using part of this particular computer program) values has been obtained.

The computer program developed in this study was used as a means of investigating the effect of artificially preheating the base material prior to asphalt laydown. The existing environmental conditions are an important factor. In order to demonstrate the variance of the mix temperature a criterion was established: the elapsed time for the average temperature of the mix after laydown to reach an established level. Since preheating the base material results in extra expense, it is assumed it will not be used unless necessary. Therefore, the range of environmental conditions investigated was 10° to 30° Fahrenheit for base material in 10-degree increments with the same atmospheric temperature associated with each run. Also, the range of mix lifts investigated were from 0.5-inch to 2.0-inch lifts in half-inch increments.

In the upper part of both the mix and the preheated base material, the effect of wind velocity, solar radiation and atmospheric temperature have the greatest effect on the temperature profile, with moisture content also affecting the base. In the lower part of the mix after laydown, the greatest effect on the mix temperature profile is the initial temperature profile of the base material. In the upper part of the base material during preheat, the obvious greatest effect would be the temperature and view factor of the flame. The initial base temperature and the moisture in the base material also have an effect. Without preheating, it should be noted, temperatures in the lower part of the mix decrease much faster than those at the top. With preheating, this is not necessarily so.

The numerical method of determining the temperature distribution in the hot-mix asphalt concrete with artificial preheating lends itself well to computer programming and provides a means of investigating the almost limitless possibilities encountered when considering the environmental conditions possible for asphalt paving.

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INTRODUCTION

The purpose of this study is to develop methods for predicting the expected time to cool to a specified temperature an asphalt-concrete mix layered on artificially preheated base material. It is generally recognized that mix design, average temperature of the mix and compactive effort are the most important variables in compaction. For a particular mix, compactive effort and temperature are the most important factors to be considered during asphalt laying operations. Because of the wide range of environmental conditions encountered during possible asphalt construction, cooling rates will differ considerably. Artificially preheating the base material will significantly increase these cooling times. Because failure of asphalt concrete is usually related to insufficient compaction (low density and/or high voids content), it is highly desirable to extend the allowable time for compaction to a specified density. The primary objectives in determining the expected time to cool to specified density are to determine the economic feasibility of preheating the base material and to set marginal guidelines should a preheater be employed.

PREVIOUS WORK

Parker[1], Kieter[2], Serafin and Kole[3], McLeod[4], Beagle[5] and others have reported on the effect of temperature on compaction in various thickness of lifts. Dickson and Corlew[6,7] have made a computer analysis of the temperature profile on the mat and base for different environmental conditions and different mat thicknesses.

However, no previous work has been done on artificially preheating the base material prior to laydown. With the introduction of this work, it is hoped that experimental data can be developed for comparison with these results.

ANALYSIS OF THE PROBLEM

A simplified sketch showing the flow of heat into the base material during preheating, and out of the base material during stall is shown in Figure 1. It should be noted that during preheating, only the flow of heat into the base material is considered. During stall, heat flows out of the base material at the top by means of conduction, convection and radiation to the atmosphere. At the top the base material also gains some energy from the sun. Also during stall, heat flows deeper into the base, serving no useful purpose.

A simplified sketch showing the flow of thermal energy from hot-mix asphalt concrete during construction is presented in Figure 2. It should be noted that there is a heat flux upward towards the upper surface of the pavement and a heat flux downward towards the base material. This condition will only be true without preheating. With preheating during the first minutes and with a reasonable time of stall, heat initially flows into the mix from the base. After a sufficiently long time, heat will then flow back from the mix to the base. With or without preheating, there is a "net" flow of heat out the top of the mix. This will be discussed thoroughly later.

Because the flow of thermal energy results from a temperature gradient and because the heat content of both the preheated base and the hot-mix asphalt concrete is transient (heat flows down the temperature hill), it is clear that the temperature of the mix is fundamentally a function of time and position in the mix.

In both the preheated base material and in the hot-mix asphalt, the problem is basically a unidimensional flow of thermal energy in a finite-thickness slab.

The rate of heat flow through the upper and lower boundaries or finite-difference slabs in the mix is dependent on the environmental conditions, as well as the thermal properties and temperature distribution of the mix and base. The rate of heat flow through the base nodes is also a function of the environmental conditions and the temperature gradients and thermal properties of the asphalt and base-material. From this we can see that the temperature profiles in the mix and the base are functions of the same thing and can therefore be handled similarly, even with a frozen base. This will be explained more thoroughly later.

Before laydown, the base environmental conditions include flame temperature, atmospheric temperature, wind velocity, and solar radiation at the surface and the temperature profile and moisture content in the interior nodes. After laydown, the mix environmental conditions include atmospheric temperature, wind velocity, and solar radiation at the top surface as shown in Figure 4, and the base temperature profile and moisture content at the bottom surface. Also after laydown, the base environmental conditions include the mix temperature distribution at the upper surface and the temperature profile and moisture content elsewhere in the base. It is evident that the solution to the problem must necessarily take into account the appropriate environmental or boundary conditions pertaining to the problem.

Analytical Solution

Although the same energy equations govern both the asphalt mix and the base material, they have different boundary conditions at different times, leading to different analytical solutions. Therefore the analytical solutions will be divided into two sections, one for the base material and one for the mix.

Base

The basic principles governing the one-dimensional transient flow of thermal energy in the base are shown in the following partial differential equation which defines a relationship between θ_B, a dimensionless temperature; t, time; and y, a position coordinate.

$$\frac{\partial \theta_B}{\partial t} = \alpha \frac{\partial^2 \theta_B}{\partial y^2} \tag{1}$$

In the equation alpha, α, is defined as the thermal diffusivity. The thermal diffusivity is the ability to conduct heat compared to the ability to store heat. It is given by the relationship:

$$\alpha = \frac{k}{\rho C_p} \tag{2}$$

where k = thermal conductivity of the base Btu, ft^{-1}, hr^{-1}, $^oF^{-1}$

ρ = density of the base lb, ft^{-3}

C_p = specific heat of the base.

Although we are considering frozen ground with a fictive specific heat during melting, the governing partial differential equation still holds. The alpha simply changes value in steps as it passes from below 31.0, thru 31.0 to 33.0, and above 33.0 degrees Fahrenheit.

Again referring to the governing energy equation, θ_B is a dimensionless temperature and may be defined as:

$$\theta_B = \frac{T-T_a}{T_o-T_a} \tag{3}$$

where T = unknown temperature at a particular time and place in the base

T_a = ambient temperature (flame temperature during heating and atmospheric temperature during stall)

T_o = initial temperature of the base.

Solution to the above equation for temperature by the separation of variables technique from Corlew and Dickson[6] gives the following relationship:

$$\theta_B = e^{-\lambda^2 dt}(A\cos\lambda y + B\sin\lambda y) \tag{4}$$

where e = base of the natural logarithms

λ, B, A = constants to be evaluated from the boundary conditions of the problem.

Homogeneous boundary conditions will be needed to evaluate the constants λ, B, and A.

The homogeneous boundary conditions for the base can be determined as follows: At time zero, $\theta_B=1$ since $T=T_o$.

At the fictitious lower boundary of the base material (far into the base) the base is assumed insulated or $d\theta_B/dt = 0$. At the upper boundary we have two different situations, one of heating and stall and the other after the mat is laid down. First consider the situation of heating and stall.

During heating and stall, the upper boundary condition may be written

$$-K_b d\theta_B/dy = U_B \qquad (5)$$

where K_b = conductivity of the base

θ_B = dimensionless temperature of heating or stall

U_B = combined overall heat transfer coefficient for the base.

The U_B, or overall heat transfer coefficient for the base, should be explained further. Since the first node of the base is a full node, U_B is the combined resistance of the combined surface transfer coefficient (radiative and convective) and the half node of conduction. In formula, it may be written:

$$U_B = \left(\frac{1}{h_c + h_r} + \frac{\Delta y}{2k_B}\right)^{-1} \qquad (6)$$

where h_c = convective heat transfer coefficient

h_r = radiative heat transfer coefficient

k_B = conductivity of the base.

The radiative heat transfer coefficient during heating is calculated from:

$$h_r = \frac{\sigma((TFlame)^4-(\ TBS\ )^4)}{(TFlame-\ TBS)} \qquad (7)$$

where σ = Stephan-Boltzman constant

TFlame = flame temperature

TBS = temperature of surface of the base.

Since we are considering blast furnace type conditions, h_c is assumed to be 20 Btu, ft^{-2}, degree Fahrenheit^{-1}, hr^{-1}.

During heating and stall then, with the above homogeneous boundary conditions, the following expression for θ_B may be given:

$$\theta_B = 2 \sum_{n=1}^{\infty} e^{-\lambda_n^2 \alpha t} \frac{\sin\lambda_n L_B}{\sin\lambda_n L_B \cos\lambda_n L_B + \lambda_n L_B} \cos\lambda_n y \qquad (8)$$

where

$$\lambda_n = \frac{U_B}{k_b} \cot\lambda_n L_B$$

and α = thermal diffusivity of base ft^2, hr^{-1}

t = time, hr

L_B = depth of base considered, ft

y = position variable

U_B = combined overall heat transfer coefficient Btu, ft^{-2}, hr^{-1}, $^oF^{-1}$

After the mat is laid down on the base, the upper boundary condition changes to:

$$k_m d\theta_B/dy = -k_b d\theta_B/dy. \qquad (9)$$

With this boundary condition, in addition to the other homogeneous boundary conditions, the solution for θ_B becomes

$$\theta_B = 2 \sum_{n=1}^{\infty} e^{-\lambda_n^2 \alpha t} \frac{\sin\lambda_n L_B}{\sin\lambda_n L_B \cos\lambda_n L_B + \lambda_n L_B} \cos\lambda_n y \tag{10}$$

where

$$\lambda_n = \frac{k_m \cot\lambda_n L_B}{k_b \quad \pi\alpha t}$$

and k_m = conductivity of base Btu, hr^{-1}, ft^{-1}, $^oF^{-1}$.

Mix

The governing equation for the mix is the same equation as that for the base.

$$\frac{\partial\theta_m}{\partial t} = \alpha \frac{\partial^2\theta_m}{\partial y^2} \tag{11}$$

Alpha and θ_m for the mix are defined similar to those of the base.

Solution to the above equation by the separation of variables technique gives the following relationship.

$$\theta_m = e^{-\lambda^2 \alpha t} (A\cos\lambda y + B\sin\lambda y) \tag{12}$$

where e = base of the natural logarithm

A, B, λ = constants to be evaluated from boundary conditions.

In order to evaluate A, B, and λ, homogeneous boundary conditions will be needed.

A means of making the boundary condition homogeneous is suggested by an analysis of the flow of thermal energy in Figure 1. Since the heat flux out the top and bottom surfaces of the mix are in opposite directions, there must be a horizontal plane where the flux is zero, or $d\theta_m/dy=0$. The location of this plane is a function of time, since the heat flux out the bottom is a function of time. The problem can then be separated into two parts, one part above the zero flux plane and the other part below that plane. The zero flux plane would give $d\theta_1/dy=0$ and $d\theta_2/dy=0$. The upper and lower boundary conditions are shown in Figure 3. It should be noted here that if heat is flowing into the mix from the base material, the mat is simply fictitiously extended to the zero flux line and the lower portion of the mix made infinitesimally small. Since heat only flows from the base to the mat for a short time and the zero flux plane is very near the mix, the above assumption is not very inaccurate.

The mathematical expressions shown in Figure 3 for the upper and lower boundary conditions indicate the conductive heat flux traveling in the mix. The upward conduction in the mix is equal to the combined convective and radiative transfer of heat at the surface of the mix and the conductive heat flux downward is equal to the heat conducted into the base at the lower surface. The problem then becomes a search for the dimensions at L_1 and L_2 which for any particular time will indicate the zero flux plane.

The homogeneous boundary conditions will be as follows: at time = 0, the hot-mix asphalt concrete is at initial temperature or $T = T_o$; consequently $\theta_1 = \theta_2 = 1$. The second boundary will be at $x = L_1$, $d\theta_1/dy = 0$, and at $x = L_2$,

$d\theta_2/dy = 0$. The third boundary conditions will be the two surface boundary conditions shown in Figure 2. The expressions for θ_1 and θ_2 will therefore be:

$$\theta_1 = 2 \sum_{n=1}^{\infty} e^{-\lambda_n^2 \alpha t} \frac{\sin\lambda_n L_1}{\sin\lambda_n L_1 \cos\lambda_n L_1 + \lambda_n L_1} \cos\lambda_n y \qquad (13)$$

where $\lambda_n = \frac{U}{k_m} \cot\lambda_n L_1$

and α = thermal diffusivity of hot-mix asphalt concrete, ft^2, hr^{-1}

t = time, hr

L_1 = thickness of upper section of hot-mix asphalt concrete, ft

y = position variable (vertical distance from plane of $d\theta_1/dy=0$ to a point under consideration, ft

U = combined convective radiative heat transfer coefficient Btu, ft^{-2}, hr^{-1}, $^oF^{-1}$,

and

$$\theta_2 = 2 \sum_{n=1}^{\infty} e^{-\lambda_n^2 \alpha t} \frac{\sin\lambda_n L_2}{\sin\lambda_n L_2 \cos\lambda_n L_2 + \lambda_n L_2} \cos\lambda_n y \qquad (14)$$

where

$$\lambda_n = \frac{k_b \cot\lambda_n L_2}{k_m \quad \pi\alpha t}$$

and k_b = thermal conductivity of the base, Btu, ft^{-1}, hr^{-1}, $^oF^{-1}$.

From these expressions one can calculate the temperature at any point in the mix after determining the values of L_1 and L_2 at that particular time.

The equation for the heat flux at the upper surface is:

$$q_1 = -k_m\left(\frac{d\theta_1}{dy}\right)_{y=L_1} = 2k_m \sum_{n=1}^{\infty} \frac{\lambda_n e^{-\lambda_n{}^2\alpha t} \sin^2\lambda_n L_1}{\sin\lambda_n L_1 \cos\lambda_n L_1 + \lambda_n L_1} \; . \qquad (15)$$

The equation for the heat flux at the lower surface is:

$$q_2 = -k_m\left(\frac{d\theta_2}{dy}\right)_{y=L_2} = 2k_m \sum_{n=1}^{\infty} \frac{\lambda_n e^{-\lambda_n{}^2\alpha t} \sin^2\lambda_n L_2}{\sin\lambda_n L_2 \cos\lambda_n L_2 + \lambda_n L_2} \; . \qquad (16)$$

However, since the analytical solution involves an iterative determination of L_1 and L_2, since during each calculation the solution only gives one point of interest per calculation for each time step and since the analytical solution uses a combined heat transfer coefficient instead of the actual boundary conditions encountered in the problem, only the numerical
combined heat transfer coefficient instead of the actual bound-
solution procedure which uses the exact boundary conditions was used in this study.

<u>General Discussion</u>

After heat has been applied to the base, the upper surface of the base acts similar to the upper surface of the mat, after the mat is laid. Therefore a general discussion of both upper boundary conditions taken together will be given.

Interaction of the various individual modes of heat transfer at the upper surface is shown in Figure 4. The thermal energy flux, whose source is the body temperature, is directed upward in the body due to the temperature gradient and whose mathematical expression is $-kdT/dy$. A second mode of energy on the surface is the hemispherical radiant energy from the sun, denoted H_s. H_s is considered over all wavelengths incident on the surface. Only a portion of this radiant energy is actually absorbed on the surface. This portion is aH_s, where a is total absorbance (over all wavelengths) of the surface. The rest of the radiant energy equal to $(1-a)H_s$ is reflected back into the atmosphere. In addition there is a radiant energy emitted to the atmosphere due simply to the surface temperature. It is defined by the expression $\varepsilon\sigma T^4$ where ε is the emittance of the surface, σ is the Stephan-Boltzman constant and T is the surface temperature. The remaining mode of thermal energy transfer is surface convection to the atmosphere. The expression for convective transfer is $h(T-Ta)$ where h is the convective heat transfer coefficient, T is the surface temperature and Ta is the atmospheric temperature.

Considering now each of these effects on the surface temperature rather than a combined overall U, we get the expression:

$$-k\left(\frac{dT}{dy}\right)_{surface} = h(T-Ta) + \varepsilon\sigma T^4 - aH_s. \qquad (17)$$

In the base instead of h use the total resistance term U_B. In terms of a dimensionless temperature

$$-k\left(\frac{dT}{dy}\right)_{surface} = \frac{h\theta_1+\varepsilon\sigma\{\theta_1(T_o-T_a)+T_a\}^4-aH_s}{(T_o-T_a)}. \qquad (18)$$

From the above equations it should be apparent that if the convective and radiative modes of thermal energy transport are greater than the absorption of thermal energy, the body should lose heat to the atmosphere. This is the condition encountered after heating the base and after the mat is laid down until much below the temperature of interest in this study. Then the solution becomes steady state.

Numerical Solution

The numerical or finite difference solution is based on dividing the mat and base into finite elements as shown in Figure 5. The artificial heating of the base material is the first consideration in the numerical solution. Thermal energy is introduced into the base first node by two modes of energy transport. The first mode is radiation from the flame. A radiation heat transfer coefficient is calculated by a formula given in Perry's handbook[8]. The expression is:

$$h_r = \frac{0.173\left(\left(\frac{TFlame}{100}\right)^4 - \left(\frac{TBS}{100}\right)^4\right)}{(TFlame - TBS)} \tag{19}$$

where 0.173 = adjusted form of Stephan-Boltzman constant

TFlame = temperature of the flame

TBS = temperature of base surface

This radiative heat transfer coefficient is then combined with a convective heat transfer coefficient, in this case 20.0, to give a combined surface heat transfer coefficient. The combined heat transfer coefficient is then used to calculate the thermal energy transferred to the base from the expression

$$q = U_B(\text{TFlame} - \text{TB}(1)) \tag{20}$$

During stall, the first base node is cooled by both the atmosphere and the nodes below it. Writing an energy balance around the first node, the following expression is derived:

$$T_B(1)_{(t+\Delta t)} = T_B(1)_{(t)} \left\{1 - \frac{\alpha\Delta t}{(\Delta y)^2} - \frac{U_B\Delta t}{\rho C_p \Delta y}\right\} + \frac{\alpha\Delta t}{(\Delta y)^2} T_B(2)_{(t)} + \frac{U_B \Delta t}{\rho C_p \Delta y} T_a + \frac{2\alpha\Delta t}{K_b \Delta y}\{aH_s - \varepsilon\sigma\, \text{TBS}_{(t)}{}^4\} \tag{21}$$

where:

$T_B(1)(t+\Delta t)$ = temperature of node one in the base material at time $t+\Delta t$, degrees Fahrenheit

$T_B(1)_{(t)}$ = temperature of node one in the base material at time t, degrees Fahrenheit

$T_B(2)_{(t)}$ = temperature of node two in the base material at time t, degrees Fahrenheit

α = thermal diffusivity of the unfrozen base material, ft^2, hr^{-1}

Δt = time increment, hr

y = thickness of incremental element in the base material, ft

U_B = combined overall heat transfer coefficient Btu, ft^{-2}, hr^{-1}, degrees Fahrenheit^{-1}

T_a = atmospheric temperature, degrees Fahrenheit

$\text{TBS}_{(t)}$ = temperature of the surface, degrees Fahrenheit

K_b = conductivity of the base, Btu, ft^{-1}, hr^{-1}, degrees $Fahrenheit^{-1}$

H_s = solar radiant energy incident on the base Btu, ft^{-1}, hr^{-1}

a = total absorptance of the base, dimensionless

ε = total emittance of the base, dimensionless

σ = Stephan-Boltzman constant, 1.714×10^{-9}, Btu, ft^{-2}, hr^{-1}, degrees $Rankein^4$.

A finite difference energy balance over an internal base node (before or after laydown) gives the following expression:

$$T_B(2)_{(t+\Delta t)} = T_B(2)_{(t)} + \frac{\alpha\Delta t}{\Delta y^2}\{T_B(3)_{(t)} - 2T_B(2)_{(t)} + T_B(1)_{(t+\Delta t)}\}. \quad (22)$$

However, since we are working with a frozen base material, we have a changing alpha. This is taken into consideration by having one alpha for temperatures below 31.0 degrees Fahrenheit, a fictive thawing alpha for temperatures 31.0 degrees Fahrenheit to 33.0 degrees Fahrenheit, and a third alpha for temperatures above 33.0 degrees Fahrenheit. Care is taken so as not to skip by the thawing α. A similar procedure is used for vaporization of the water.

After the mat has been laid down, a different set of finite difference equations is used. For the first node in the hot-mix asphalt concrete, the following expression is derived:

$$TM(1)_{(t+\Delta t)} = TM(1)_t\{1 - \frac{2\alpha\Delta t}{(\Delta y)^2}(N_{Bi}+1)\} + \frac{2\alpha\Delta t}{(\Delta y)^2}$$

$$\{TM(2)_{(t)}+N_{Bi}T_a\} + \frac{2\alpha\Delta t}{k_m\Delta y}\{aH_s-\varepsilon\sigma TM(1)_{(t)}{}^4\} \quad (23)$$

where

N_{Bi} = Biot number, dimensionless.

An energy balance over an internal node (not the bottom node of the mix) gives the following expression:

$$TM(3)_{(t+\Delta t)} = TM(3)_{(t)} + \frac{\alpha\Delta t}{(\Delta y)^2}\{TM(4)_{(t)}$$

$$- 2TM(3)_{(t)} + TM(2)_{(t+\Delta t)}\}. \quad (24)$$

The equation for the bottom node of the mix adjacent to the base is as follows:

$$TM(N)_{(t+\Delta t)} = TM(N)_{(t)} + \frac{\alpha\Delta t}{(\Delta y)^2}\{T_B(1)_{(t)}$$

$$- 2TM(N)_{(t)} + T_M(N-1)_{(t+\Delta t)}\} \quad (25)$$

where α = thermal diffusivity of the mix.

For the 2.0-inch mat, N is equal to 10; for the 1.5-inch, N is equal to 7; for the 1.0-inch mat, N is equal to 5; and for the 0.5-inch mat thickness, N is equal to 4. This is done to maintain stability, and an easy comparison for results.

For the first node in the base after the mat is laid down, the finite difference energy equation is:

$$T_B(1)_{(t+\Delta t)}=T_B(1)_{(t)}+\frac{\alpha\Delta t}{(\Delta y)^2}\{T_B(2)_{(t)}-2T_B(1)_{(t)}+TM(N)_{(t+\Delta t)}\} \quad (26)$$

where alpha is the thermal diffusivity of the base. The set of finite difference energy equations needed to solve the problem is now complete.

The finite difference form for the energy leaving the upper surface of the mix is described in the following equation:

$$q_1 = \frac{N_{Bi} k_m}{\Delta y} \{TM(1) - T_a\} + 6\sigma TM(1)^4 - aH_s. \tag{27}$$

Similarly, the finite difference form for the energy leaving the lower surface of the mix is described in the following equation:

$$q_2 = \frac{\rho C_p \Delta y}{\Delta t} \{TM(N)_{(t)} - TM(N)_{(t+\Delta t)}\}$$

$$+ k_m \{TM(N-1)_{(t+\Delta t)} - TM(N)_{(t+\Delta t)}\} \tag{28}$$

All of the previous finite difference energy equations form the basis for the computer program listed in Appendix B.

APPROACH

Since it would be impossible to consider all possible combinations of all important variables, computations for time to cool to 225 degrees Fahrenheit, 200 degrees Fahrenheit, and 175 degrees Fahrenheit were performed for those combinations of the following variables:

a) mat thickness from 0.5 inches to 2.0 inches, in 0.5 inch increments for all data tables.

b) initial base temperature at 10 degrees Fahrenheit, 20 degrees Fahrenheit, and 30 degrees Fahrenheit for data tables 2 through 11.

c) base moisture content of 0%, 10%, and 20% moisture with checks on water vaporization assumption in data tables 11, 12, and 13.

d) view factor for the flame of 0.33, 0.67, and 1.0 for data tables 2 through 11.

e) time of heating of 3 seconds, 6 seconds, and 18 seconds for all data tables.

f) time of stall of 1 minute, 3 minutes, and 10 minutes for all data tables.

g) initial mat temperature of 275 degrees Fahrenheit for data tables 8 through 11 and 300 degrees Fahrenheit for the remaining data tables.

Atmospheric temperature was selected equal to initial base temperature. Wind velocity used was 10 knots with a comparison run for 0 knots, and a solar flux of 50 Btu/ft^2/hr used as being appropriate for the range of base temperature used.

The thermal properties of the asphalt and base are listed in Table 1. Some of the properties were calculated from Kersten [9], with the fictive heat capacity being calculated using a 2-degree range of freezing. The check on the effect of water vaporization used a 10-degree range of vaporization.

It should be noted that at this time, 175° F is considered a reasonable temperature at which compaction can be completed.

RESULTS

The results of this study consist of (1) the computer program that was developed to predict the time to cool to specified temperatures of a hot-mix asphalt concrete as a function of duration and magnitude of heating, duration between heater input and asphalt laydown (stall), and existing environmental conditions, and (2) a comparison with time to cool for unheated conditions as a function of environmental conditions.

Computer Program

The basic computer program was developed from finite difference equations governing the transfer of thermal energy. Similar equations were used for the asphalt and base material.

Listing

A complete listing of the computer program is presented in Table B.1, Appendix B. Also included in Appendix B is the Fortran code used in the computer listing. Instructions for data input are also included in Appendix B.

The computer program is presented in a form believed to be most easily understood, and can be easily modified to fit other types of computers. One thing of note, conditions without preheating can be investigated simply by giving VIEWFA(M) and TSTALL(M) and THEATB(M) any negative value.

Data Input

Some of the variables and environmental conditions that affect the time to cool to a specified temperature can be used directly for data input into the computer program. Other variables, such as solar altitude, wind velocity, and some of the physical properties must be changed to a form acceptable to the computer program.

View Factor and Flame Temperature

There are several assumptions to be made when calculating the view factor and flame temperature for the heater input. First of all, it was assumed that the flame temperature was 4,000 degrees Fahrenheit, the approximate flame temperature of propane and methane. If any other fuel were to be used, its appropriate flame temperature should be used. Another assumption was that although the burner unit would probably be hooded to direct the flame downward, the view factor could be calculated assuming a flat bottomed burner. It is felt that this introduces only a slight error. The view factors themselves were calculated using a three-foot-wide burner. From Bird, Stewart, and Lightfoot[10] using heights from burner to ground of 3 feet, 1 foot, and contacting the ground, view factors of 0.33, 0.67, and 1.0, respectively, were derived and fed directly into the computer as data.

Duration of Heating

The duration of heating used was calculated from paver speed, assuming the heater unit was either directly attached to the paver unit or immediately preceded it, and going the same speed. With paver speeds of 10, 30, and 60 ft-per-minute, the duration of heating used was 0.0050 hour (18 seconds), 0.00166 hour (6 seconds) and 0.00083 hour (3 seconds), respectively.

Duration of Stall

The length of time between heater input and asphalt laydown was set according to these assumptions: a one-minute stall was used to show the results of attaching the heater unit directly to the front of the paver unit. A three minute stall was used to show the possible results of a separate heater immediately preceding the paver. A few ten minute stalls were made to show the results of a temporary shutdown or interruption in paving operations.

Wind Velocity

Corlew and Dickson[6] have a complete discussion on methods to calculate convective heat transfer coefficients. In general, these procedures include finding the Reynolds number and Prandtl number and obtaining the convective heat transfer coefficient as a function of Nusselt number. For a 10-knot wind, this procedure gives a convective heat transfer coefficient of 4.4 Btu, ft^{-2}, hr^{-1}, degrees Fahrenheit^{-1}. For the special case of zero wind velocity, Hutchinson[11] shows the following empirical relationship for the convective heat transfer coefficient

$$h_c = (0.38)\Delta t^{0.25} \tag{29}$$

where Δt = temperature difference, degrees Fahrenheit.

The convective heat transfer coefficient is fed directly into the computer as data to calculate the Biot number for use in the finite difference energy equations.

Solar Radiation

Since the conditions considered in this study are winter-type conditions, a solar-radiant flux of 50 Btu, ft^{-2}, hr^{-1} was used throughout.[7]

Percent Moisture

Paving conditions proposed by the study include frozen subgrade. The percent moisture in the ground has a large effect on the time to cool to specified temperatures of the hot-mix asphalt concrete. The conditions considered in this study include 0%, 10%, and 20% moisture content of the subgrade.

Initial Temperature Profile

Initial steady-state profiles in the ground were investigated at 10 degrees Fahrenheit, 20 degrees Fahrenheit, and 30 degrees Fahrenheit. Although physically the surface temperature would be slightly higher because of solar flux, this introduces an extremely small error.

Physical Properties

Literature values for the hot-mix asphalt concrete [7] and base material are presented in Table 1. The base material used was sandy soil. The specific heats and densities for the moist and frozen soils were calculated from formulas presented by Kersten[9]. For the thawing soil (31.0 to 33.0 degrees Fahrenheit), a fictive heat capacity was calculated using the formula

$$C_{p_{\text{Fictive}}} = C_{p_{\text{Dry Base}}} \times (\%\ \text{Dry Base}) + \frac{\text{Heat of Fusion of Water}}{2^{\circ}\text{F}} \times (\%\ \text{Moisture}). \qquad (30)$$

The thermal conductivity and density for the thawing base were average values of the frozen and thawed base. Constant physical properties within each state of warming at the base and cooling of the mix were assumed. Some variation in the thermal properties of both the asphalt and the base material might be expected with temperature and degree of compaction. The thermal diffusivity, however, might be expected to remain constant with degree of compaction, since both thermal conductivity and density increase with compaction.

Since the thermal properties of both the asphalt and base material are fed directly in as data, the investigator may feed in the physical properties of the asphalt and base material he determines appropriate to his own conditions.

Table 1. Physical Properties.

	Asphalt	Dry	Sandy Soils Unfrozen 10%	Sandy Soils Unfrozen 20%
k	0.7	0.7	1.1	1.3
ρ	140.	120.	114.	108.
C_p	.22	.22	.29	.35

	Sandy Soils Thawing 10%	Sandy Soils Thawing 20%	Frozen 10%	Frozen 20%
k	1.1	1.5	1.2	2.1
ρ	114.	108.	113.	107.
C_p	7.6	14.6	.25	.27

Factors Affecting Cooling Time

In order to demonstrate the change in temperature with the varying factors involving the cooling of the mix, the following criterion was established as being the most meaningful and easily compared: the time for the mat to cool to an average temperature. This criterion was chosen for several reasons. Since temperature profiles in the mix vary drastically for the different environmental conditions, a comparison of profiles alone would be tedious at best. Looking at a specific plane in the mix was discarded because of the large effect of mat thickness above and below any specific plane chosen. The average temperature in the mix provides an easy basis of comparison and is most easily understood when considering compaction. Three different average temperatures were used: 225 degrees Fahrenheit, 200 degrees Fahrenheit, and 175 degrees Fahrenheit. To obtain the most representative time to cool as a function of the environmental conditions, comparison graphs are presented at 175 degrees Fahrenheit.

Effect of Preheating

Figures 6, 7, and 8 show quite clearly the beneficial effect of preheating the base material. Preheating the base greatly increases the time to cool to a specified temperature. In order to read the figures, the following procedure should be used: Decide the environmental conditions of interest. Refer to the beginning of the figures to determine which figures apply. Go to those figures. Refer to the extreme right. The numbers at the end of each line of the graph refer to the data varied for that run. Choose the line of interest. Choose the mat thickness of interest. Go up from the mat thickness until it intersects the line of interest. Go left from that point to determine the time to cool for that specified temperature. Using this procedure one should be able to read all the figures. Preheating the base very emphatically increases the time to cool to a specified temperature, and its merits should be thoroughly investigated.

Effect of View Factor and Duration of Heating

Figures 9, 10, and 11 quite clearly show the effect of view factor and duration of heating on the time to cool to a specified temperature. Closely examining these graphs we notice that the view factor, duration of heating combination for 0.33, 0.005 hour, and 1.0, 0.00166 hour lie very close together, as do 0.33, 0.001 hour, and 0.66, 0.00083 hour, and 0.66, 0.001 hour and 1.0, 0.00083 hour. This is quite reasonable, since approximately the same amount of energy is input to the base in both cases. Therefore we shall discuss view factor and duration of heating as a combination called duration of heating. The combination is simply the amount of energy input into the base from the flame. Quite obviously, as we increase the duration of heating (and increase the view factor), we extend the time to cool to a specified temperature. The effect of view factor and duration of heating is very important and can also be seen in Figures 12 through 20.

Effect of Stall

Figures 12 through 15 very clearly show the effect of time between heater input and asphalt laydown on the time to cool to specified temperature. Increasing stall decreases the time to cool to a specified temperature. Keeping stall to a minimum is very important and should be considered a primary variable when considering preheating.

Effect of Wind Velocity

Comparison of Figures 14 and 21 show the quite pronounced effect of wind velocity on the time to cool to specified temperatures. Decreasing wind velocity increases time to cool to a specified temperature. The large increase noted in time to cool to a specified temperature can be explained as follows: with a 10-knot wind, forced convection is almost the total driving force for thermal energy transport from the surface of both the asphalt and the base. The convective heat transfer coefficient for 10 knots was 4.4 Btu, ft^{-2}, hr^{-1}, degrees $Fahrenheit^{-1}$. With no wind, free convection is the main mode of thermal energy transport. Free convection is not so efficient as forced convection for thermal energy transport. For the mix, then, a convective heat transfer coefficient of 1.5 Btu, ft^{-2}, hr^{-1}, degrees Fahrenheit was used. For the heated base, 2.5 Btu, ft^{-2}, hr^{-1}, degrees Fahrenheit was used. The base transfer coefficient is larger because of the larger temperature driving force. Wind velocity plays a very important role in determining time to cool to a specified temperature.

Effect of Solar Radiation

Although solar radiation was not used as a variable in this study, its effect on cooling time should be noted. Corlew and Dickson[6] point out that a decrease in solar radiation from 350 Btu, ft^{-2}, hr^{-1} to 0 Btu, ft^{-2}, hr^{-1} decreases the elapsed time to reach 200 degrees Fahrenheit from about 25 minutes to about 16 minutes for a point ¼-inch into the mix from the upper surface. This was for a non-preheated base at 100 degrees Fahrenheit, to 72 degrees Fahrenheit, atmospheric temperature of 70 degrees Fahrenheit, initial mix temperature of 285 degrees Fahrenheit, wind velocity 5 knots and a 2.5-inch mix thickness. Since the conditions investigated in this study are more severe, solar radiation would have a much less pronounced effect on the time to cool to a specified temperature.

Effect of Atmosphere and Initial Base Temperature

Figures 6, 7, and 8 and Figures 15, 16, and 17 show the effect of atmosphere and initial base temperature. It should be remembered that the atmospheric temperature is assumed to be the same as the initial base temperature, and the initial base temperature is assumed at a constant temperature. Increasing base temperature increases time to cool to a specified temperature. It is concluded that with preheating, the atmospheric and base temperature is not a significant variable in the time to cool to a specified temperature.

Effect of Moisture

Figures 18, 19, and 20 show the effect of percent moisture on the time to cool to a specified temperature. Increasing the percent moisture in the base increases the thermal diffusivity of the base, therefore increasing the thermal energy transferred into the base. However, it should be remembered that figures 6 through 21 were prepared assuming that the first three nodes or half-inch of base was dry and that therefore no vaporization of water occurred in the base. The top half-inch was assumed to have been dried by the effects of wind and solar radiation. Figures 23 and 24 have been prepared assuming that the first three nodes were actually wet. Figure 23 shows the effect of the assumption that all the steam that was formed left the base, its heat of vaporization lost to the atmosphere. Figure 24 shows the effect of only the first node's steam leaving, with the other nodes retaining their steam. However, it should be pointed out that the importance of this study is not to investigate the effect of steam or water, but to show the beneficial effects of preheating. For very thin lifts, the asphalt will probably be laid on existing pavements, with 0% moisture. For a further discussion, see assumptive error analysis.

Effect of Initial Mix Temperature

Figures 6, 7, and 8 clearly show the effect of the initial base temperature on the time to cool to a specified temperature both with and without preheating. Increasing initial mix temperature increases time to cool to a specified temperature. Without preheating, however, initial mix temperature plays a much greater role. With preheating, initial mix temperature over the range used here of 275 degrees Fahrenheit to 300 degrees Fahrenheit is not a very important variable. Without preheating, it is quite important.

Effect of Thickness of Lift

The effect of thickness of lift can be seen quite clearly in all Figures 6 through 21. Increasing lift thickness increases time to cool to a specified temperature.

Without preheating, the largest amount of thermal energy was always lost to the base material according to Beagle(5) and Corlew and Dickson(6). With preheating, with a reasonable length of time between heater input and asphalt laydown, heat was actually transferred from the base material to the asphalt initially. After a length of time, thermal energy transport changed directions and flowed from the asphalt to the base material. Thermal energy was always being lost at the upper surface of the asphalt. Table 2 presents results for heat flux from the upper and lower surfaces of hot-mix asphalt concrete, 1 minute and 5 minutes after the asphalt has been laid, both with and without preheating.

Since most paving operations would have the greatest heat loss at the lower surface of the mix, preheating would reverse this trend, now having the greater heat loss at the upper surface. With reference to Table 2, the differences in heat flux from the upper and lower surfaces are the result of the temperature gradients shown in Figure 22.

Table 2. Heat flux from upper and lower surfaces of hot mix asphalt concrete, 1 minute and 5 minutes after placement of mix. 30 degrees Fahrenheit base, 0% moisture, 10 knot wind, 300 degrees Fahrenheit mix.

		Without Preheating		With preheating of 0.0050, stall of 0.0167, view factor 1.0	
	Thickness of Lift, in.	Heat Flux From Upper Surface Btu, ft^{-2}, hr^{-1}	Heat Flux From Lower Surface Btu, ft^{-2}, hr^{-1}	Heat Flux From Upper Surface	Heat Flux From Lower Surface
1 minute	0.5	1152.9	2529.5	1615.9	-1481.7
	2.0	1373.3	2941.4	1379.6	-1345.0
5 minutes	0.5	*	*	1357.8	20.1
	2.0	1086.2	1190.9	1120.5	530.1

*Cooled too low to consider.

ECONOMIC ANALYSIS

Now that it has been shown that preheating the base with a propane flame produces a workable time to cool to a specified temperature, it needs to be shown that preheating is economically feasible.

Using a price of 10 cents per gallon of propane, the cost to heat 1 ft^2 of base material for 18 seconds is 0.285 cents ft^{-2}. On the basis of hot-mix asphalt concrete ready to lay down at a cost of $15 per ton, the asphalt construction cost for a 2.0-inch mat is 17.5 cents, ft^{-2} and for a 0.5-inch mat is 4.4 cents, ft^{-2}. From these figures it can be seen that preheating the base material adds less than 2 percent cost to a 2.0-inch mat and less than 7 percent cost to 0.5-inch mat.

Considering the facts that the laying and compacting equipment would otherwise be idle, the workmen unemployed, and the road unfinished, the additional cost of preheating appears to be a small price to pay.

ERROR ANALYSIS

In this study, error analysis consists of an investigation of calculative errors and assumptive errors. The assumptive errors are the errors introduced by assumptions in the calculations. The analysis of the calculative error is worthy of careful consideration, because one must strike a balance between the accuracy desired and the time required to perform the calculations.

Assumptive Error

The first assumption made was in the discussion of the analytical solution of the mix concerning extending the mix into the base for the zero flux line. Since an analytical solution was not performed because of its great difficulty, one cannot judge accurately the error introduced by this assumption. It is the opinion, however, that it would be small.

The second assumption was that the convective heat transfer coefficient during heating was 20 Btu, ft^{-2}, hr^{-1}, degrees Fahrenheit^{-1}. From Bird, Stewart, and Lightfoot(10) (page 393) 20 Btu, ft^{-2}, hr^{-1}, degrees Fahrenheit^{-1} was the largest magnitude for a forced gaseous heat transfer coefficient. Since we are considering blast-furnace-type conditions, 20 Btu, ft^{-2}, hr^{-1}, degrees Fahrenheit^{-1} was chosen.

Sandy soil was assumed to be the base material. If other base material were encountered, its physical properties would simply be fed into the program as data. Since for very thin lifts, the mat would be probably laid on existing pavement, the physical properties of the base would then be the same as those of the lift. This situation would be very similar to the 0% moisture studied in this report.

The flame temperature was assumed to be 4,000 degrees Fahrenheit. Since the flame temperature of propane and methane are slightly higher than 4000 degrees Fahrenheit, this flame temperature was assumed to be appropriate. If the effect of view factor, water vapor, and carbon dioxide in the air, and excess air are determined by experiment to reduce the flame temperature, then the correction can be made in the program simply by setting TFLAM equal to the flame temperature determined.

With moisture in the ground, data tables 2 through 11 were made on the assumption that the top half-inch of ground was essentially dry due to wind and sun. The heat of vaporization would therefore not enter into consideration, because no nodes below half-an-inch reached 212 degrees Fahrenheit in temperature. However, this will not always be so. Assuming a wet base all the way to the surface, and assuming all steam that was formed was lost to the atmosphere, runs 1600-1688 were made. A comparison of these two assumptions appears in Figure 23. However, mass diffusivity (the rate of mass transfer through the ground) is a slow process. Runs 1500-1588 were made on the assumption that the mat was wet to the surface, that steam was formed, but that only the first node's steam was lost to the atmosphere because of mass diffusivity. The rest of the steam formed was recondensed and its energy of vaporization was recaptured. Figure 24 gives a comparison of the half-inch dry base and the steam recaptured assumptions. If moisture is in the base all the way to the surface, the results of the 1500's run would probably more nearly simulate the actual physical conditions. However, it should again be pointed out that the importance of this study is not steam or water assumptions, but is in the effect of preheating the ground. Further work on the mass transfer effects discussed above is suggested for subsequent investigators.

Calculative Error

Calculative errors in this study can be divided into two groups: first, those pertaining to the estimation of physical properties and other data used in the calculations, and second, those pertaining to the accuracy of the finite difference energy equations used to calculate the temperature profiles.

Dry sandy soil with a dry density of 120 lb, ft^{-3}, a dry specific heat of .22, and a dry thermal conductivity of 0.7 Btu, ft^{-2}, hr^{-1}, degrees $Fahrenheit^{-1}$ was assumed. From formulas given by Kersten(9), the specific heat of the ground was calculated. Charts for Kersten(9) gave the thermal conductivities for frozen soil. The wet density of the soil was calculated using a weighted density of dry soil and water and ice. The physical properties of the asphalt were taken from Dickson and Corlew(7).

Since physical property data, given and calculated, were first taken from graphs, some error has been introduced in this manner. However, Kersten(9) gives an error of 20% in his data, and Dickson and Corlew(7) have a table showing significant variation in literature values for base thermal properties. Large errors can be introduced, therefore, unless thermal properties of the base are known accurately.

As shown by Dusinberre(12), there are several methods of determining the stability of finite difference equations. However, he simply lays down the rule: "avoid negative coefficients."(12)

Applying this rule to equations 21 to 28 for this study gives, for the most stringent conditions, the following expressions:

$$1 - \frac{\alpha\Delta t}{(\Delta y)^2} - \frac{U_B\Delta t}{\rho C_p\Delta y} \geq 0 \tag{30}$$

$$\frac{(\Delta y)^2}{\alpha \Delta t} \geq 2 \tag{31}$$

In addition to the above stability requirements, a thermal energy balance over the mix was included in the computer program to establish a level of confidence in the calculations. This balance consisted of (1) calculating the thermal energy fluxes from the upper and lower surfaces for each time increment, (2) using these thermal energy fluxes to calculate the total thermal energy lost from the mix, and (3) comparing this total cumulative heat lost to the same quantity calculated by simply taking the difference between the initial heat content of the mix, and the heat content of the mix after the identical time increment. If these two values differ significantly, a possible source of error is indicated. In Table 3 are shown the relationships found to exist between the size of the incremental time and thickness elements and the percentage difference in the thermal energy balance. The first values in the table are the values used in this study. The second, third, and fourth values are from Corlew and Dickson(6).

As might be expected from a close examination of equations 21 through 26, the variance in the energy balance was found to be in direct proportion to the ratio $\Delta t/(\Delta y)^2$. By using the values in the first line of Table 3, the percent error is small. To maintain approximately the same incremental thickness of each element in the mix and base,

Table 3. Calculative Error Analysis.

Incremental Thickness Element Δy, ft	Incremental Time Element Δt, hr	Ratio $\Delta t/(\Delta y)^2$	Variance in Energy Balance (%)
0.01754	0.00050	1.62	0.2
0.02193	0.00104	2.16	3.7
0.02193	0.00208	4.32	7.6
0.01097	0.00104	8.64	15.3

to maintain ease of comparison, and to maintain the stability criterion, 10 nodes were used in the 2.0-inch mat, 7 nodes in the 1.5-inch mat, 5 nodes in the 1.0-inch mat, and 4 nodes in the 0.5-inch mat. Although by reducing the number of nodes, one might be decreasing the accuracy of the solution, the variance in the energy balance for the 0.5-inch node was still only 0.2%.

SUMMARY AND CONCLUSIONS

Methods of calculating time-and-space dependent temperature distribution in hot-mix asphalt concrete during compaction with a sandy soil as base material have been presented. The analytical solutions to the one-dimensional partial differential equation describe, in a manner that is mathematically exact, the flow of thermal energy in the mix and base. Its usefulness is quite limited by the necessary assumption of constant physical properties and simplified boundary conditions. The numerical solution presented displays a much greater versatility in handling the rather complex boundary conditions encountered in the asphalt and base. The numerical solution, however, is limited to the extent that the stability criteria must be maintained in order to avoid absurd results. The numerical solution lends itself well to computer programming, with its attendant advantages.

Results of this study indicate that preheating the base material has a pronounced effect on the time for the mix to cool to a specified temperature. Without preheating, the heat flux into the base is initially greater than the heat flux to the atmosphere. With preheating, with a reasonable stall, the heat flux goes into the mat from the base, a reversal in the direction of heat flux at the bottom surface of the mat. This is particularly significant when coupled with the fact that the compactive effort is less near the base than at the place of application on the surface of the material being compacted.

Increasing the duration of heating increases the time to cool to a specified temperature. Increasing the percent moisture in the ground decreases the time to cool to a specified temperature. Increasing wind velocity decreases time to cool to a specified temperature. Increasing initial base temperature and initial mix temperature increases time to cool to a specified temperature. However, it was found that the initial base temperatures and initial mix temperatures studied in this report do not appear to be important variables. However, care should be taken not to extend this conclusion beyond the range of this study.

Preheating appears to be economically feasible, and experimental work should be done to determine its exact value.

The problem and its solution have been presented to enhance understanding and appreciation of the various modes of thermal energy transport and to introduce the possibility of preheating the base material to lengthen the time for the mat to cool to a specified temperature.

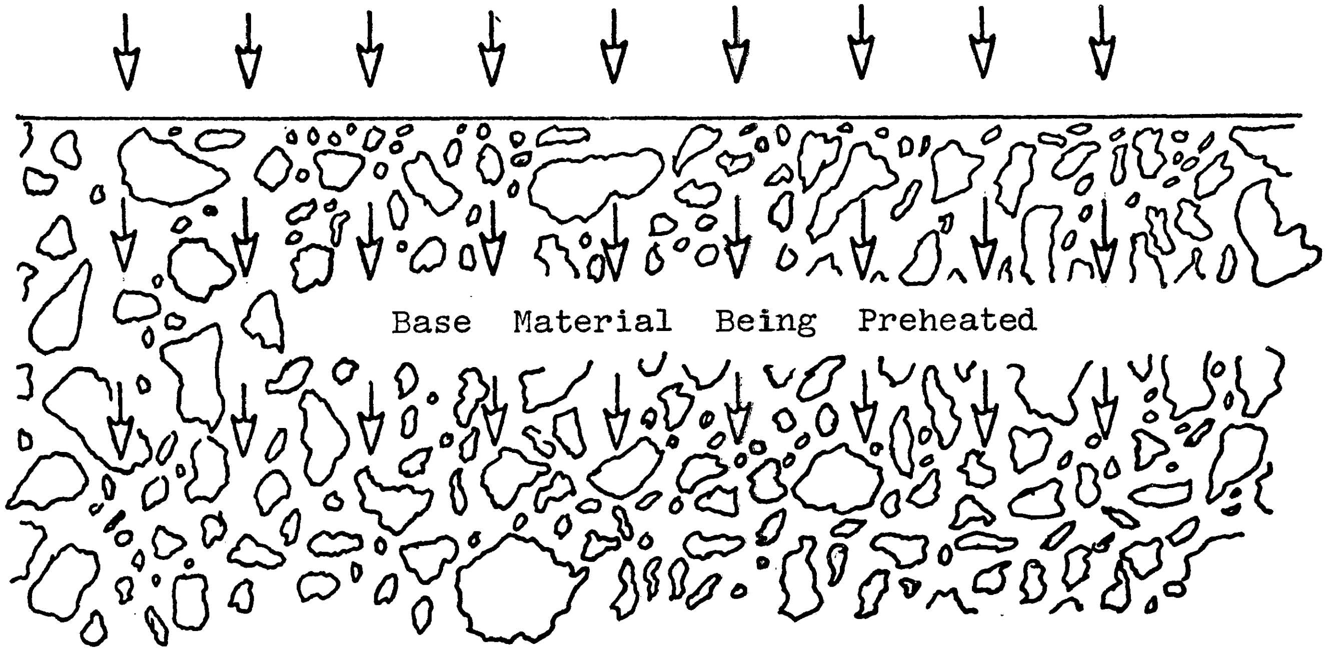


Figure 1a. Cross section of subgrade indicating directional flow of thermal energy (During Preheating)

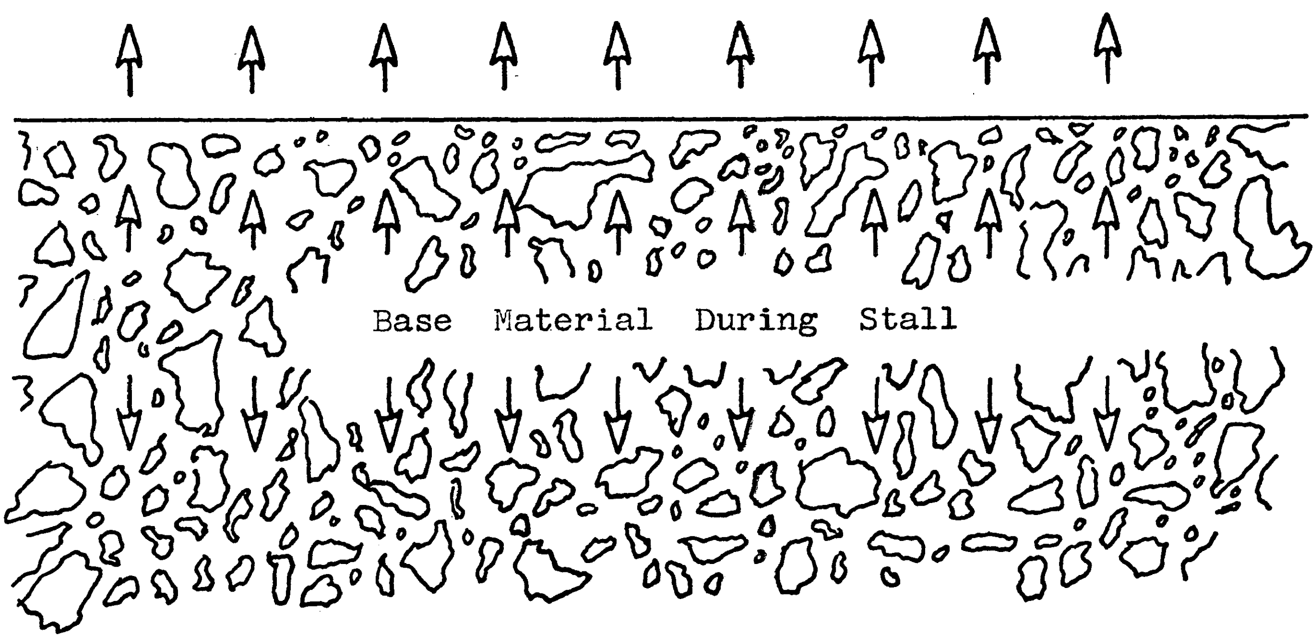


Figure 1b. Cross section of subgrade indicating directional flow of thermal energy (During Stall)

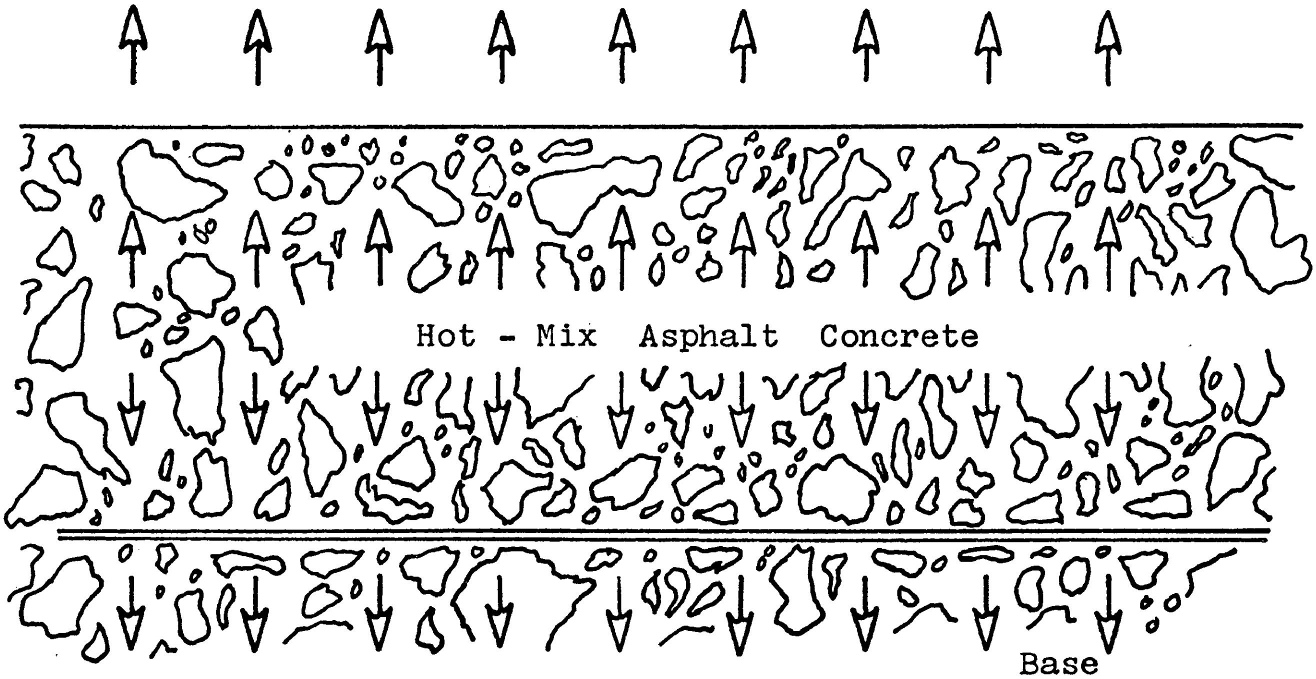


Figure 2. Cross section of hot-mix asphalt conctete indicating directional flow of thermal energy

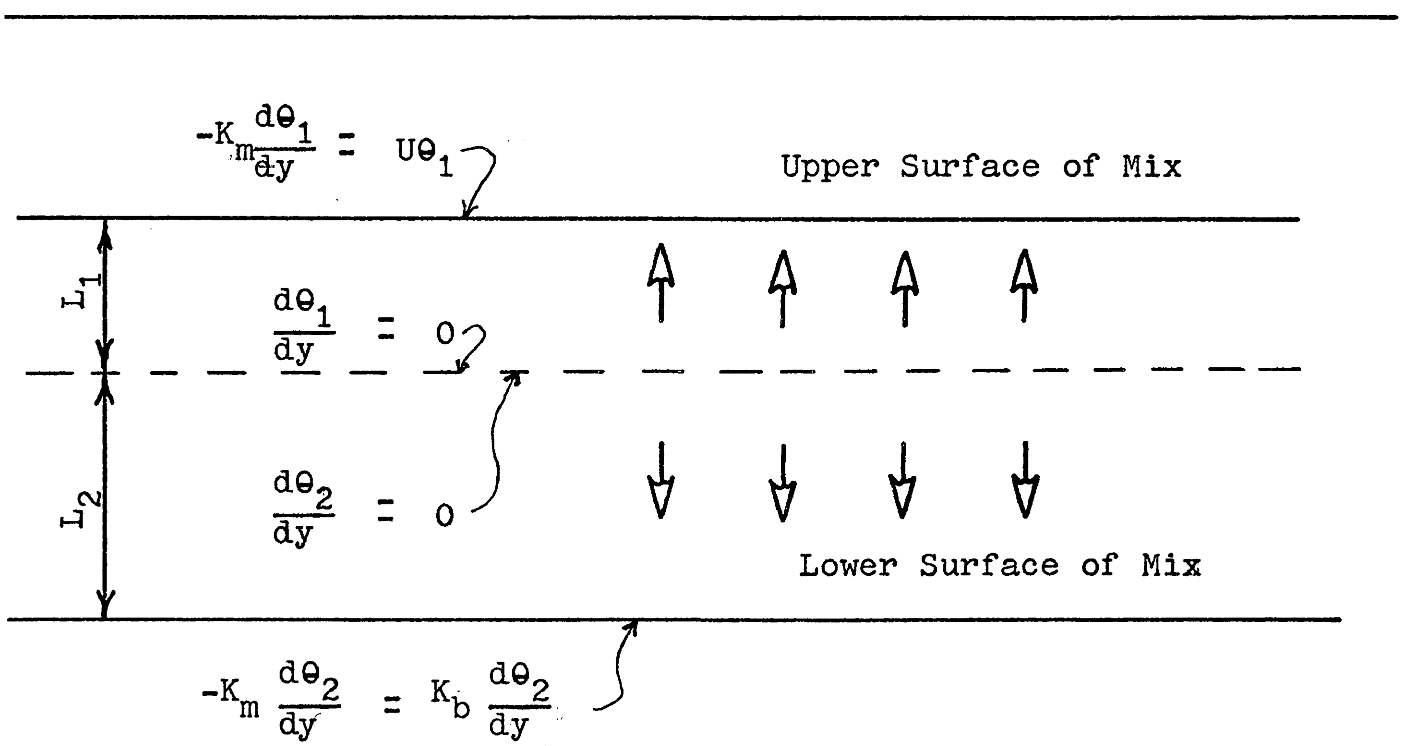


Figure 3. Boundary conditions for analytical solution

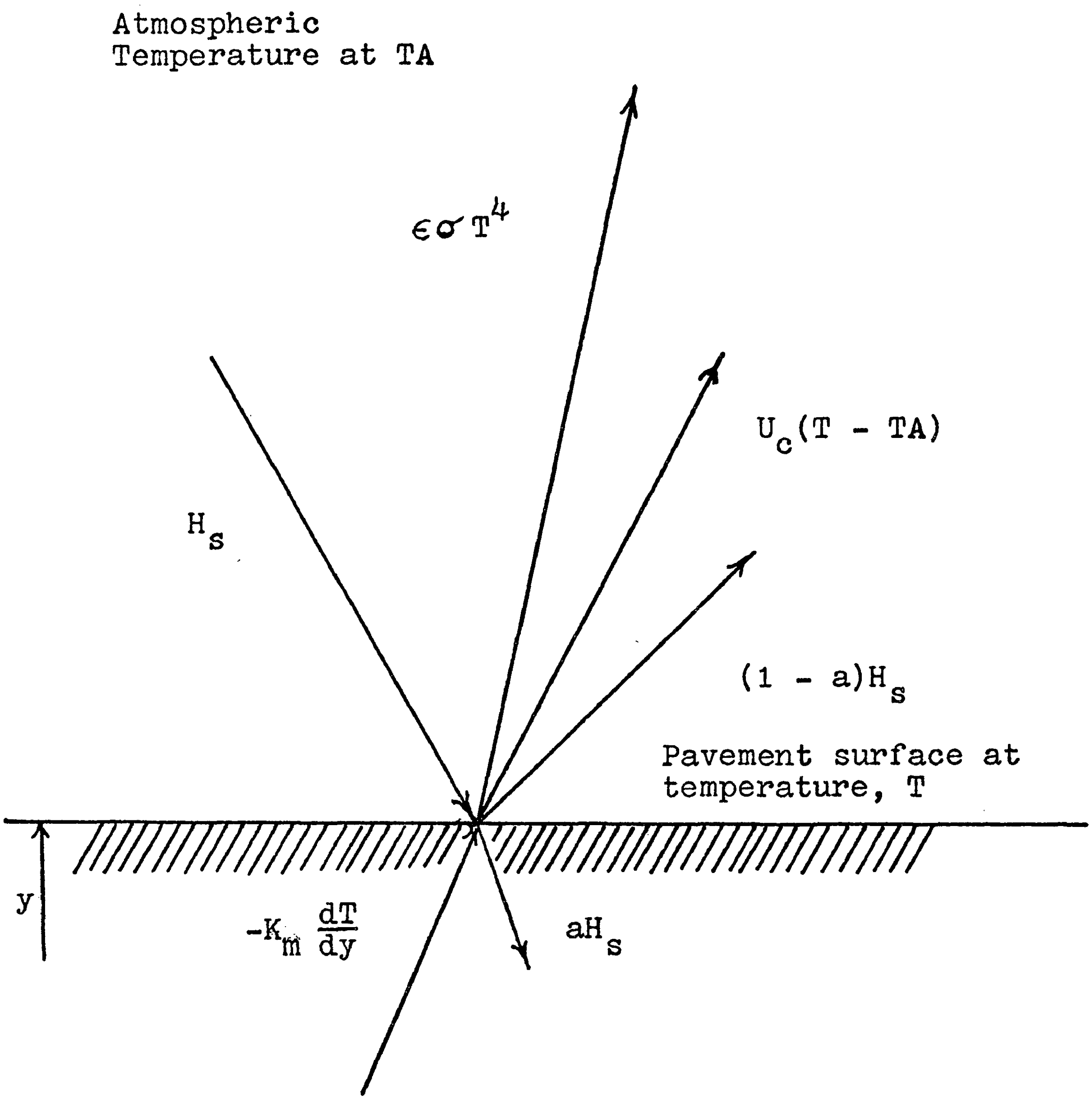


Figure 4. Interaction of various modes of thermal energy transfer at the pavement surface (also of the base during stall)

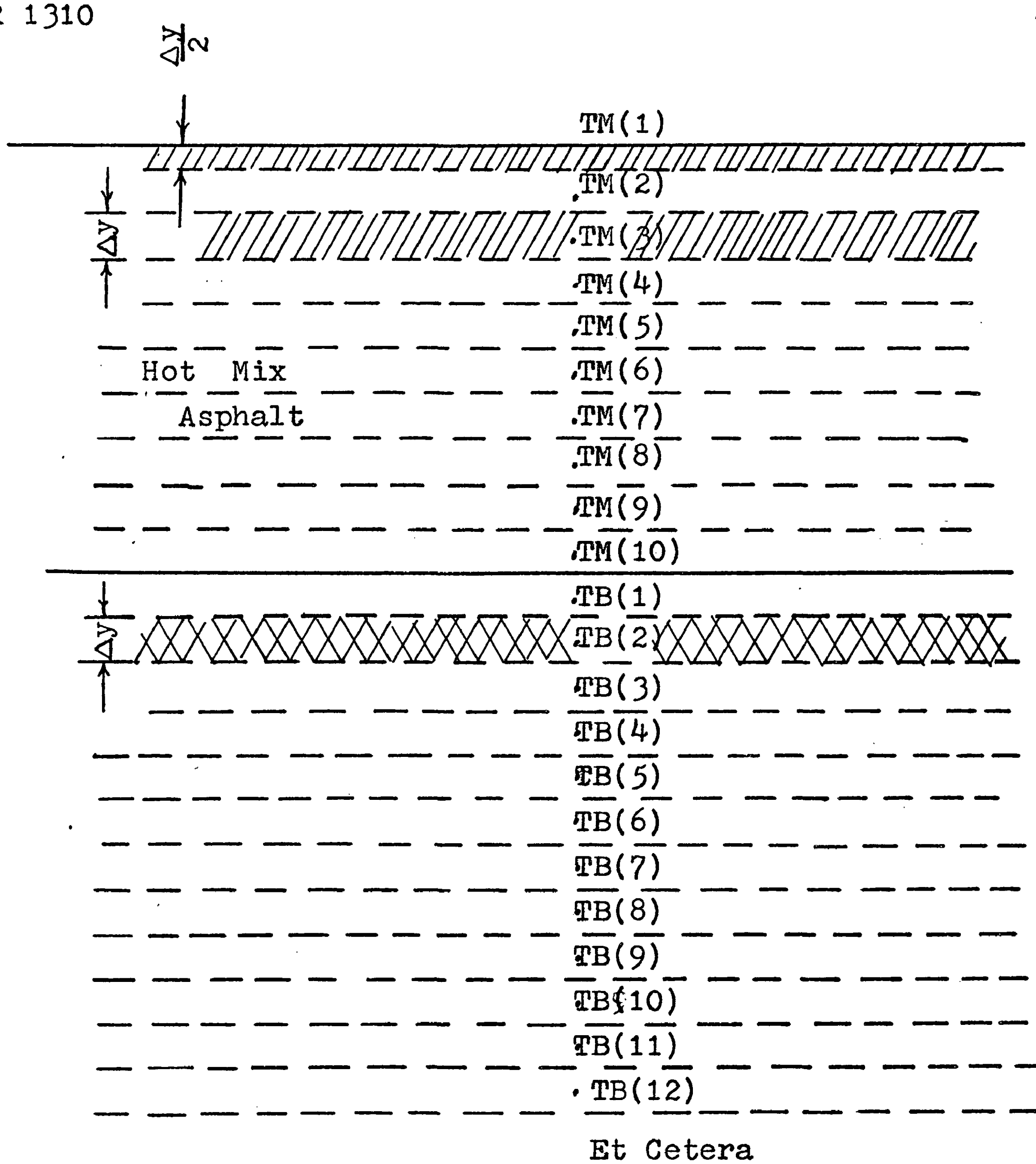


Figure 5. Typical incremental elements of hot-mix asphalt concrete and base used in numerical solution.

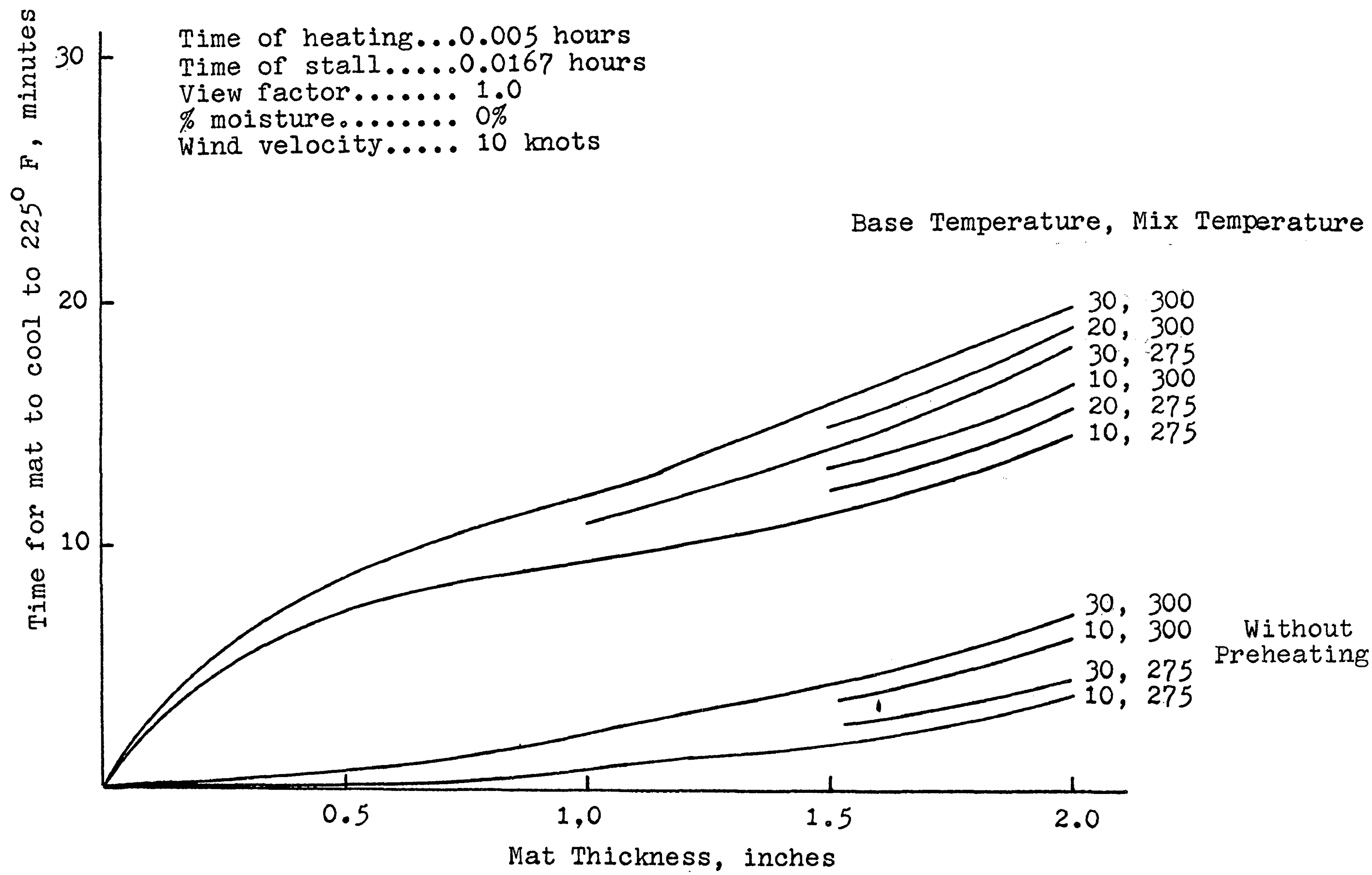


Figure 6. Time for mat to cool to 225° F vs. mat thickness for lines of constant mix and base temperature with and without preheating.

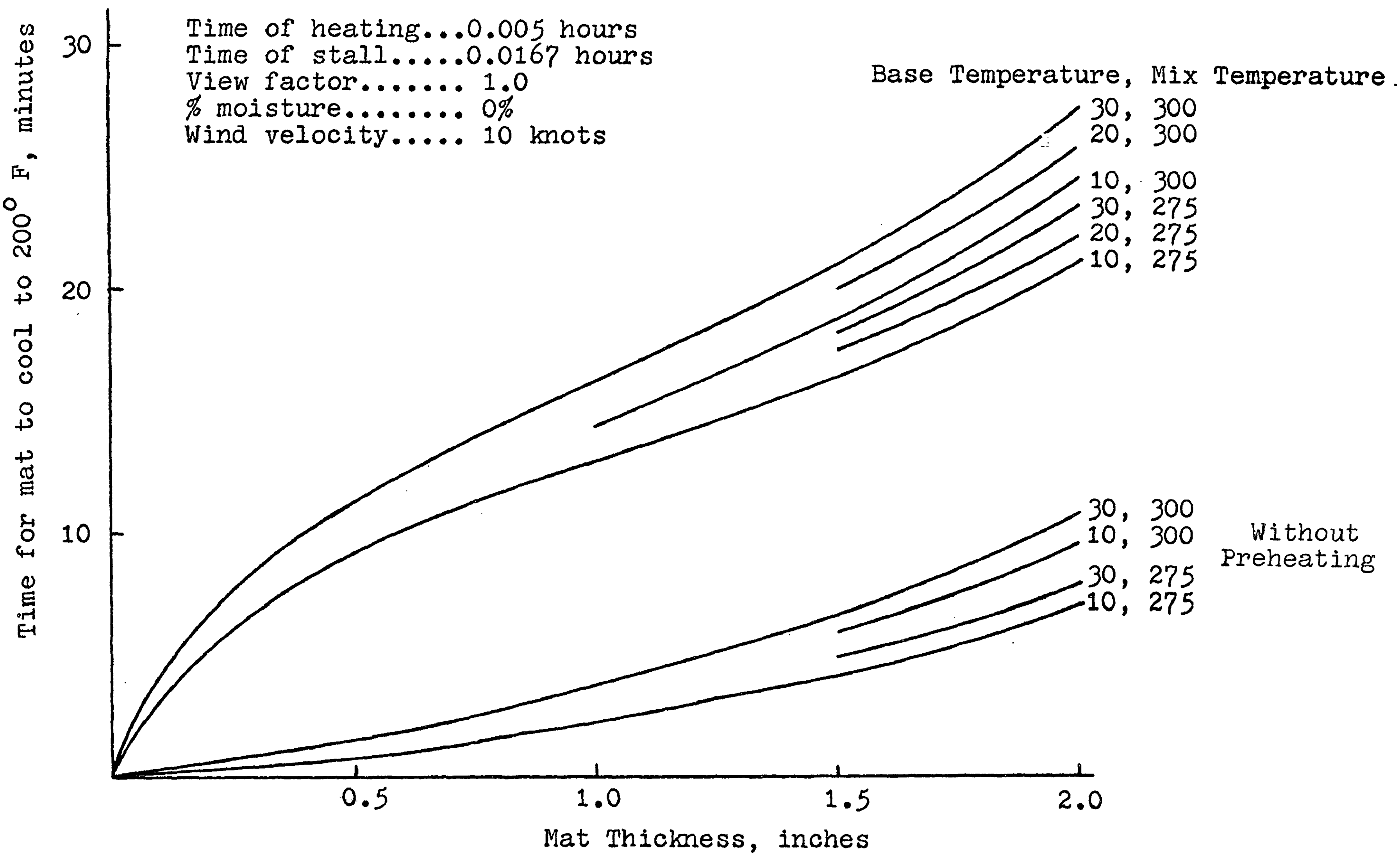


Figure 7. Time for mat to cool to 200° F vs. mat thickness for lines of constant mix and base temperature with and without preheating.

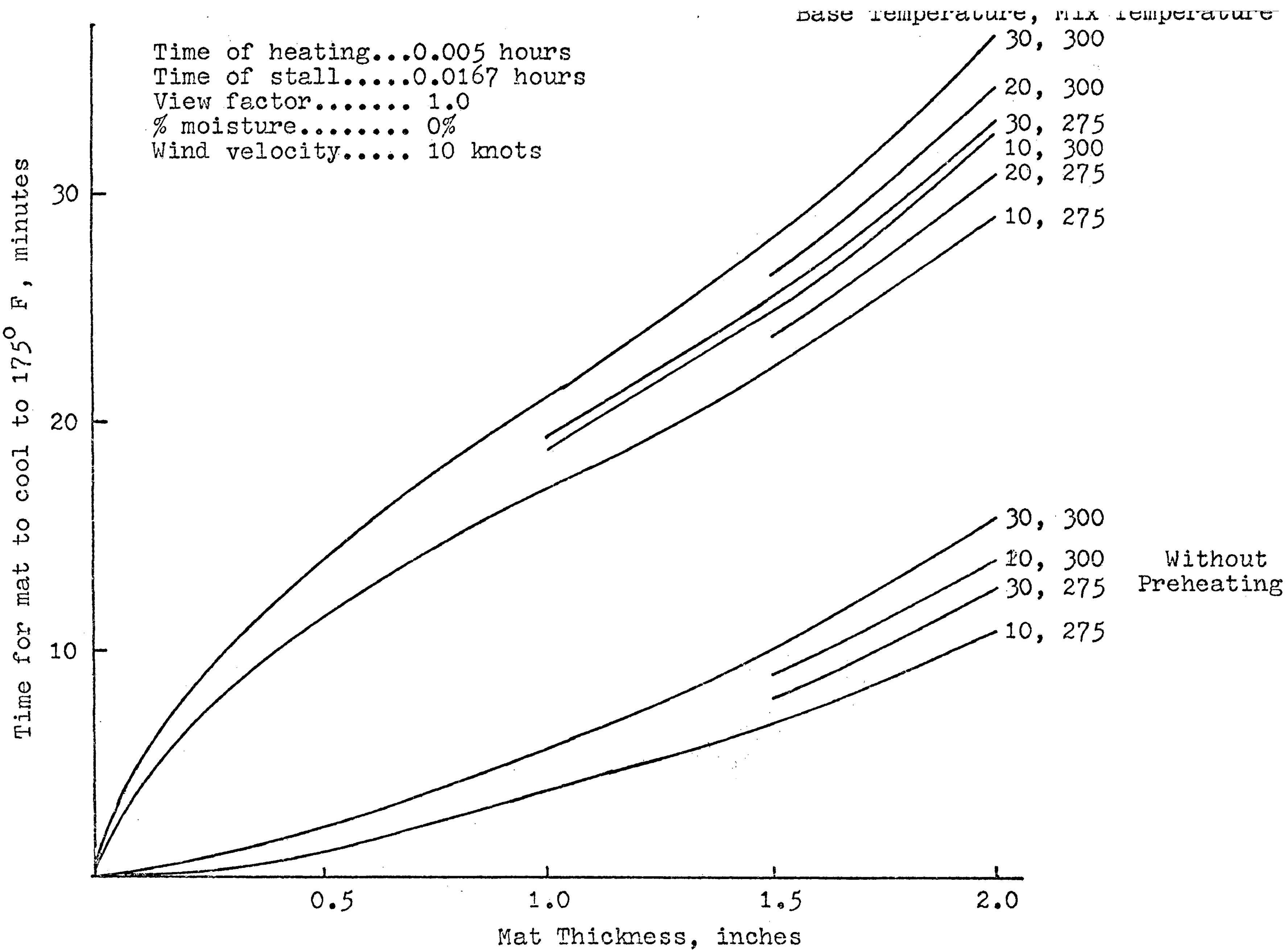


Figure 8. Time for mat to cool to 175° F vs. mat thickness for lines of constant mix and base temperature with and without preheating.

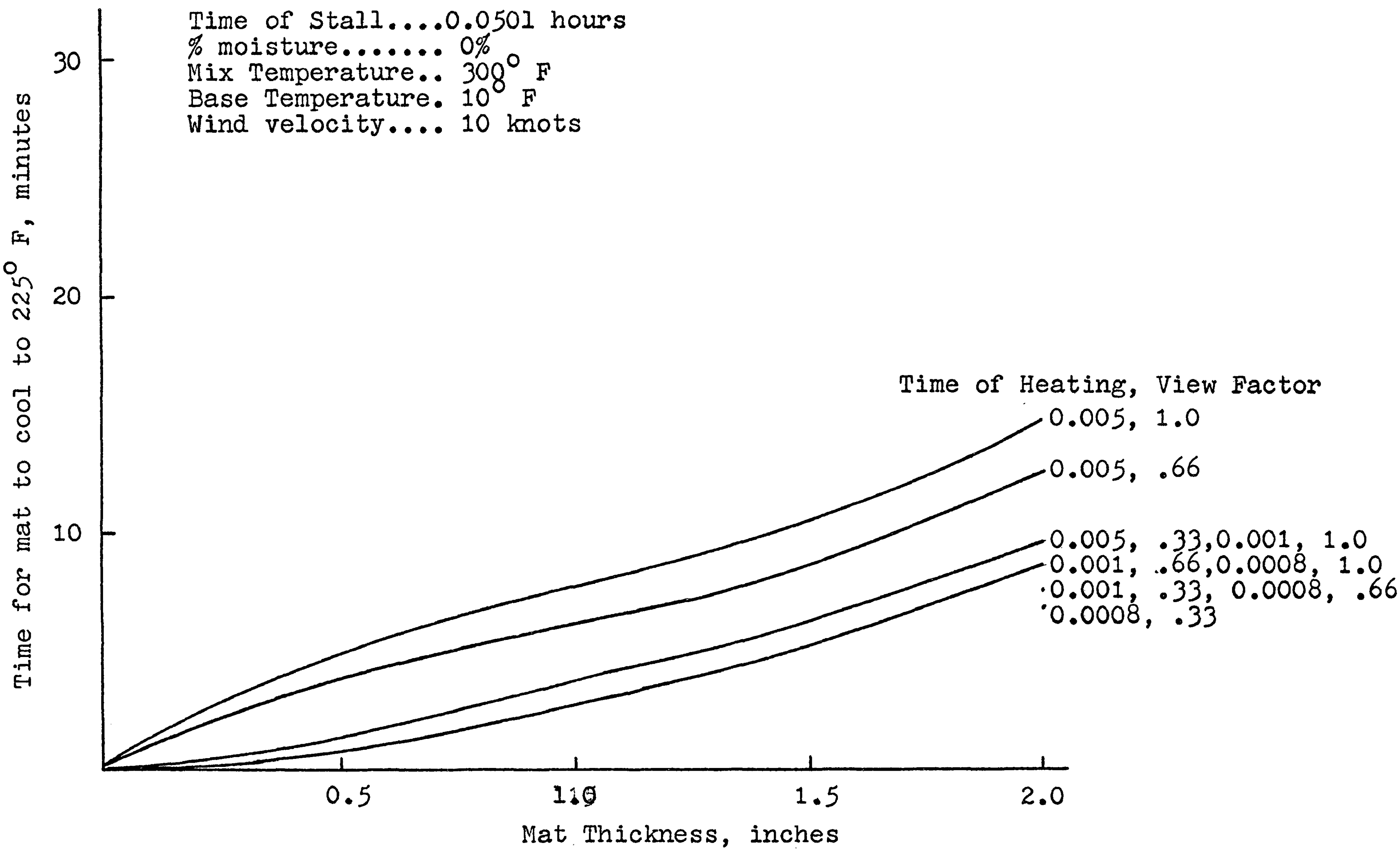


Figure 9. Time for mat to cool to 225° F vs. mat thickness for lines of constant heating and view factor.

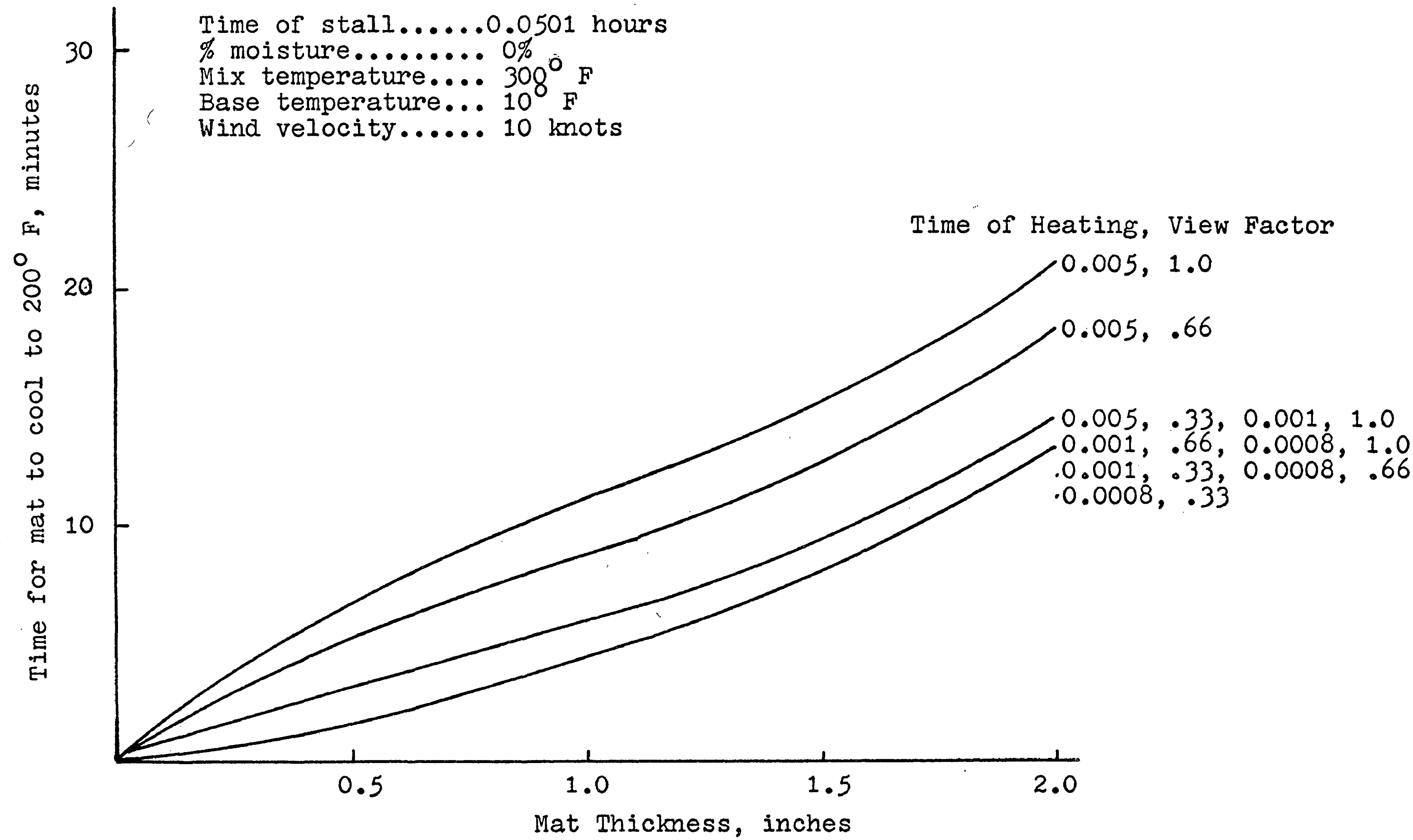


Figure 10. Time for mat to cool to 200° F vs. mat thickness for lines of constant heating and view factor.

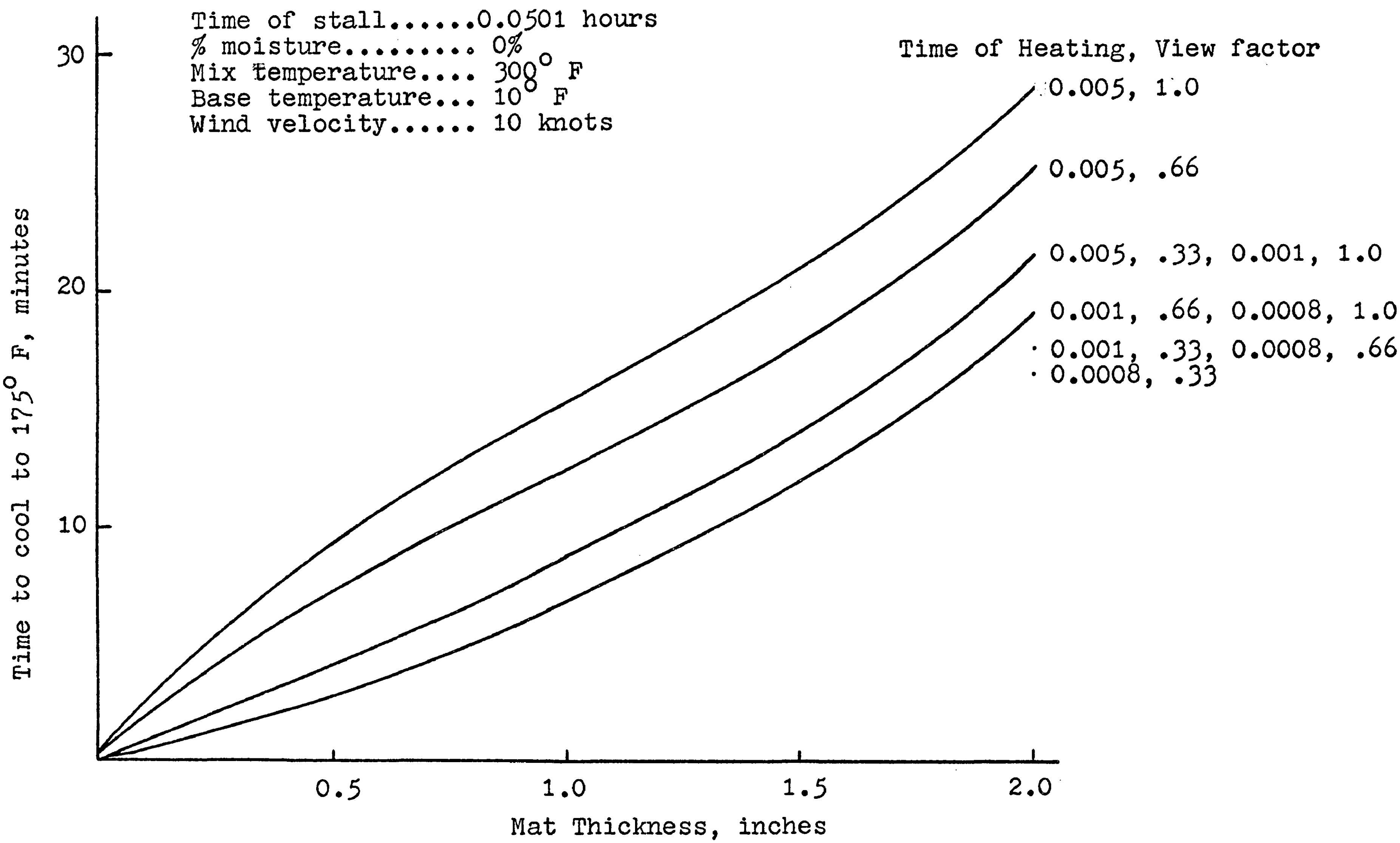


Figure 11. Time for mat to cool to 175° F vs. mat thickness for lines of constant heating and view factor.

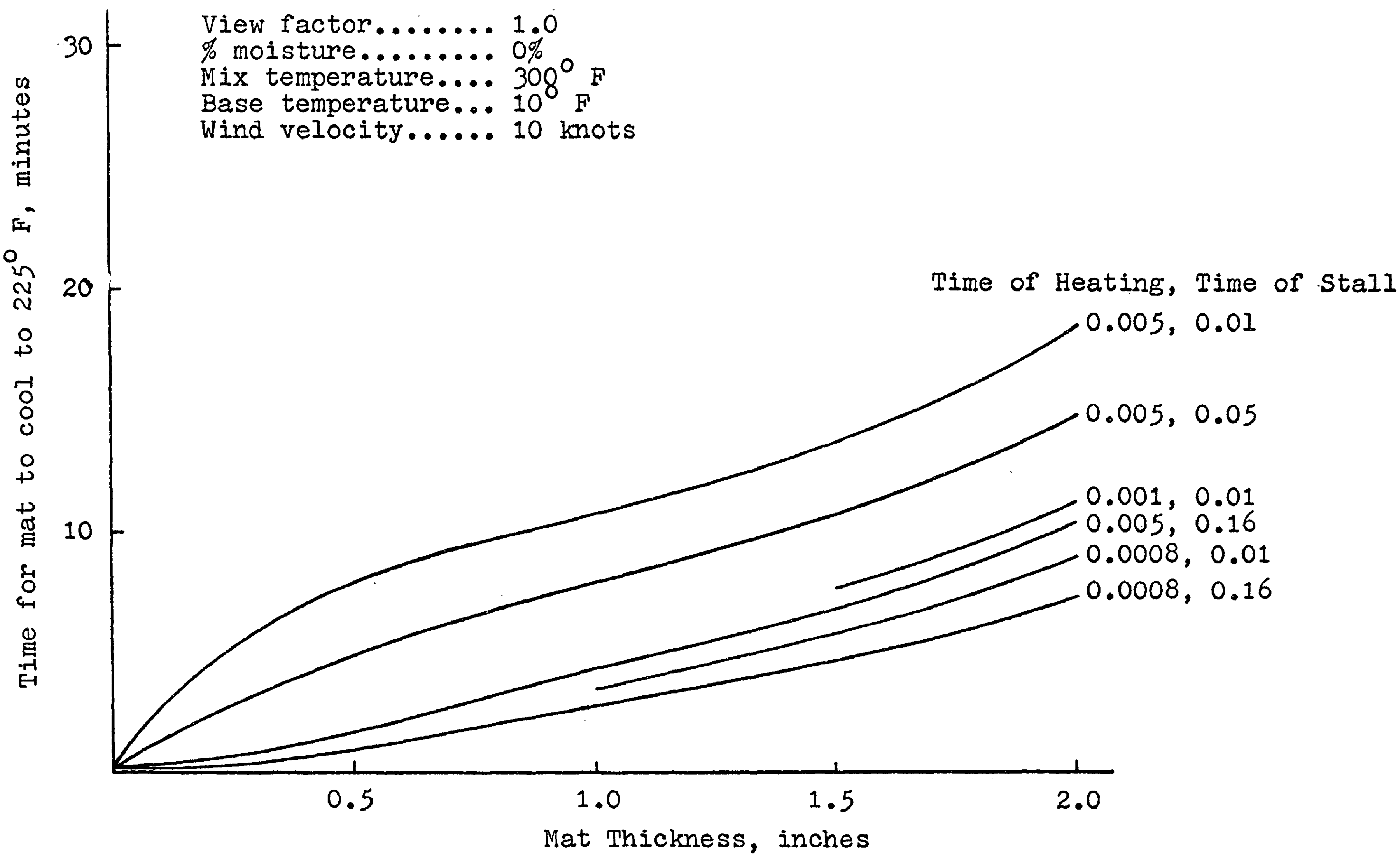


Figure 12. Time for mat to cool to 225° F vs. mat thickness for lines of constant heating and stall.

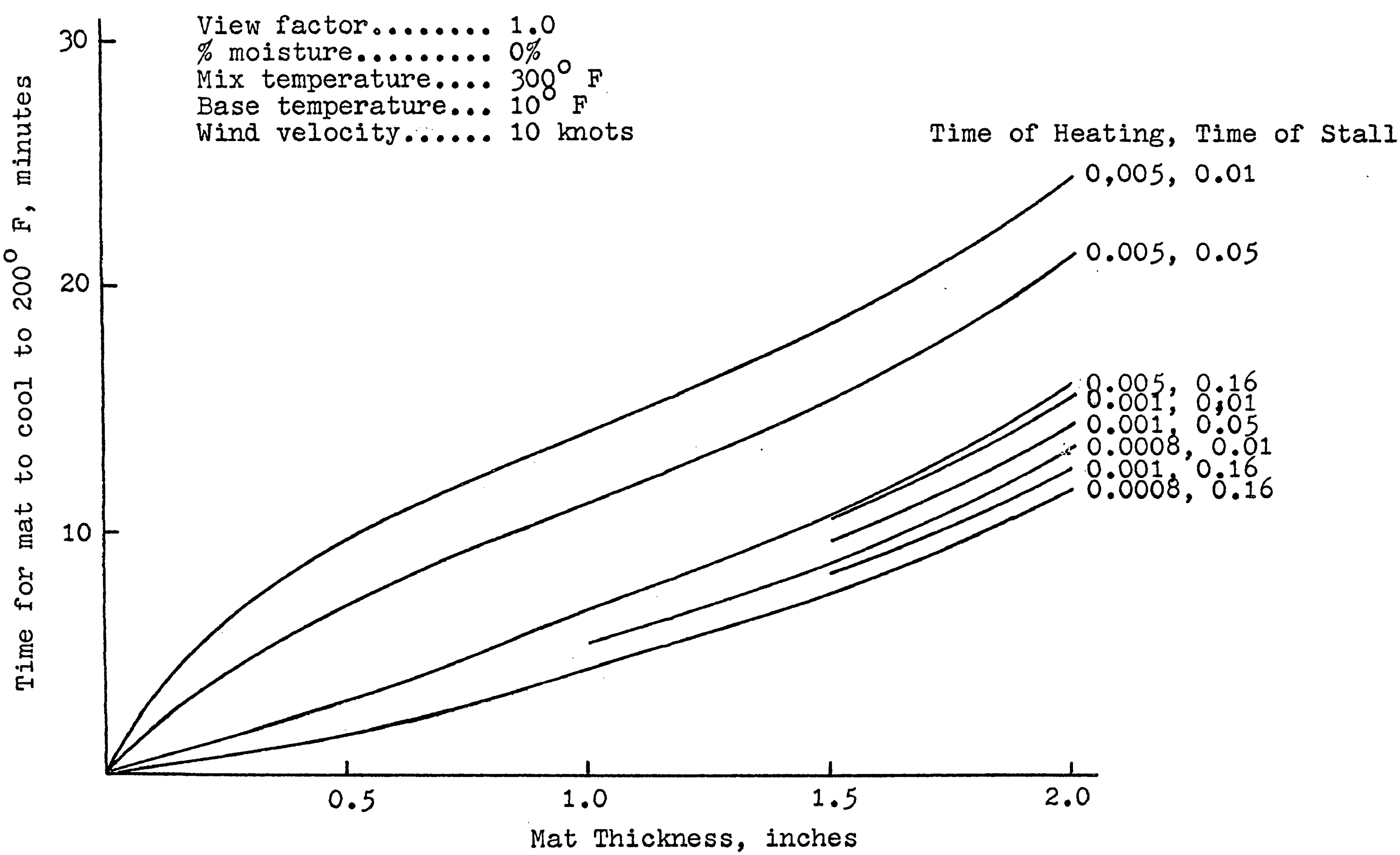


Figure 13. Time for mat to cool to 200° F vs. mat thickness for lines of constant heating and stall.

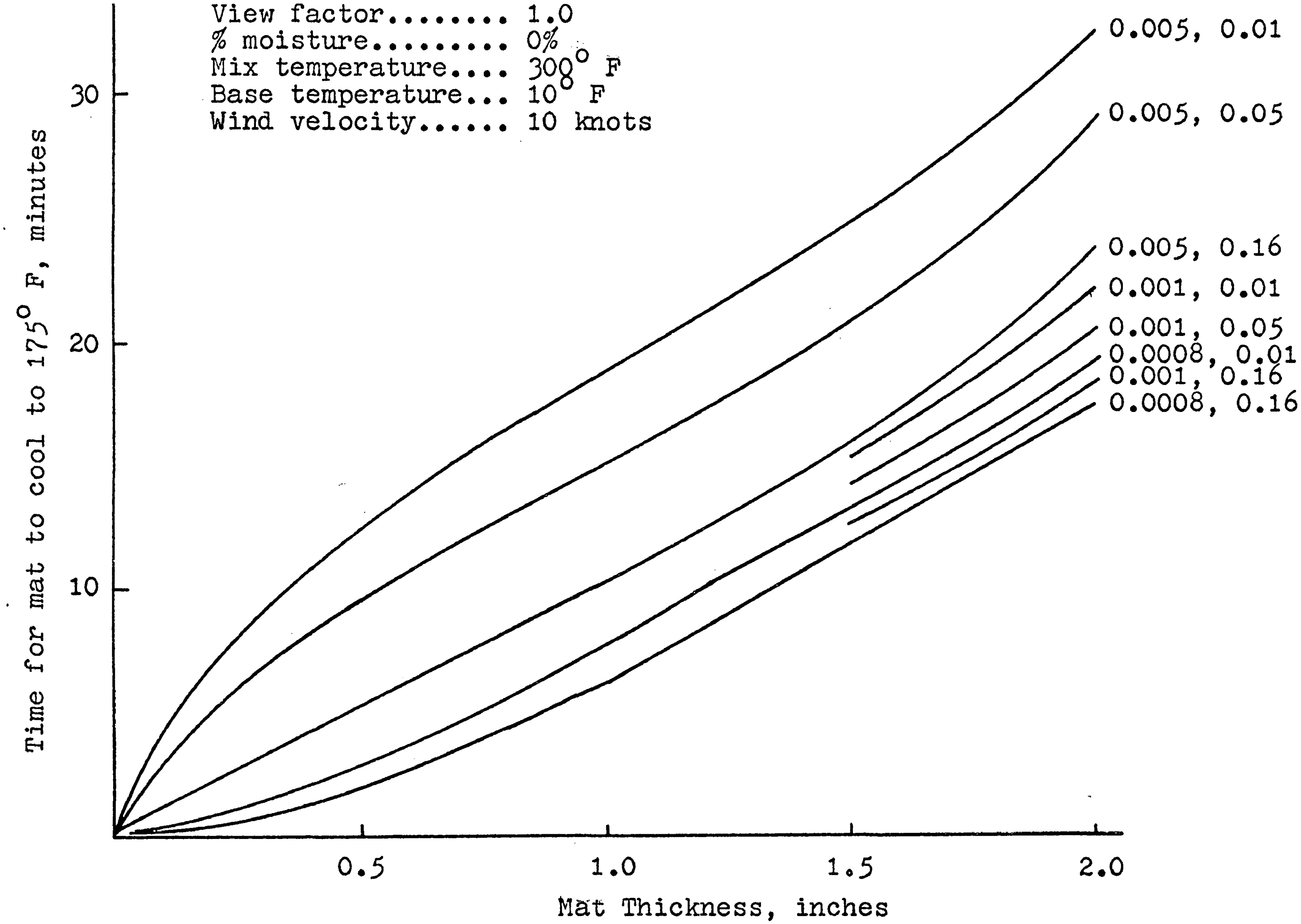


Figure 14. Time for mat to cool to 175° F vs. mat thickness for lines of constant heating and stall.

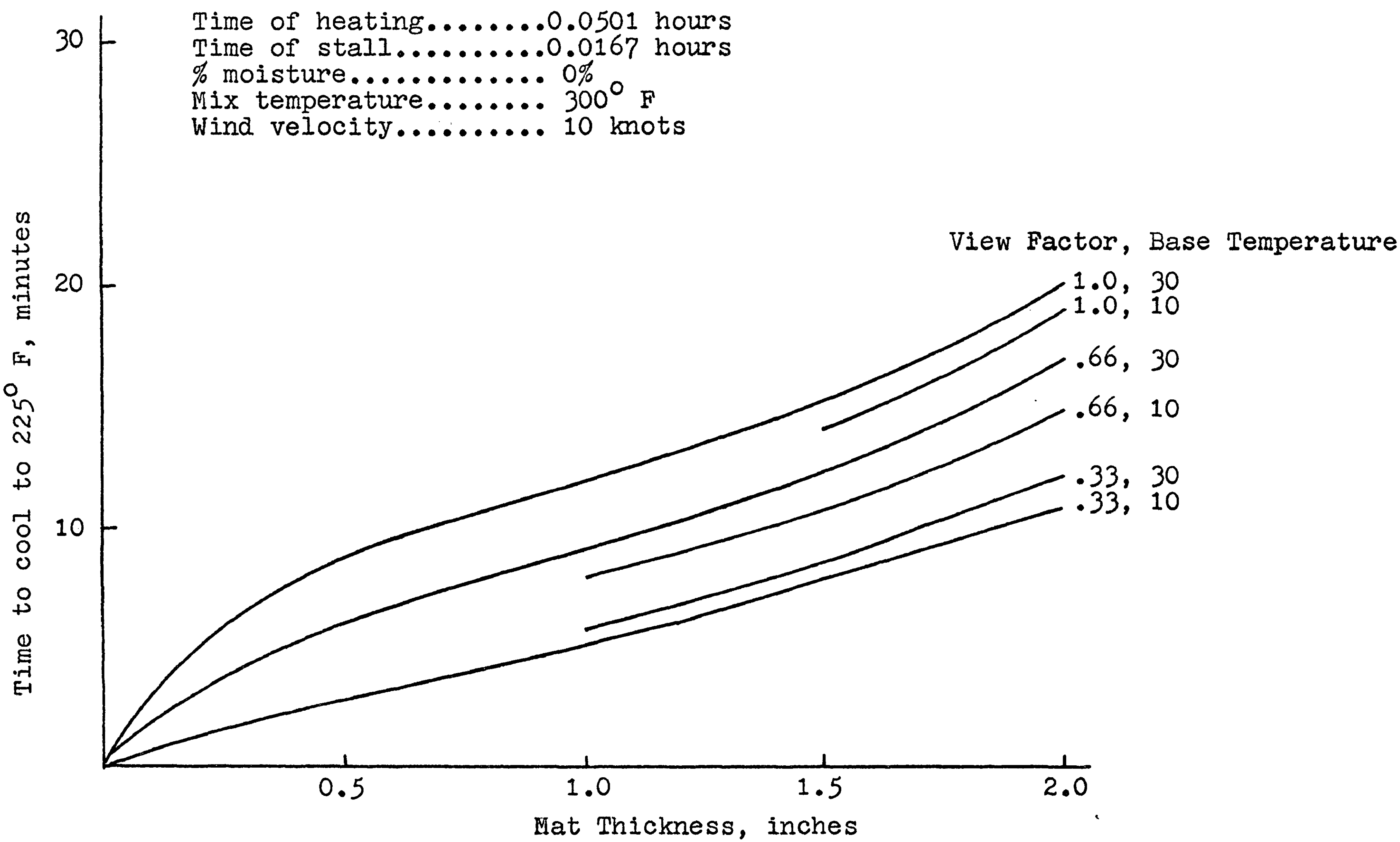


Figure 15. Time for mat to cool to 225° F vs. mat thickness for lines of constant view factor and base temperature.

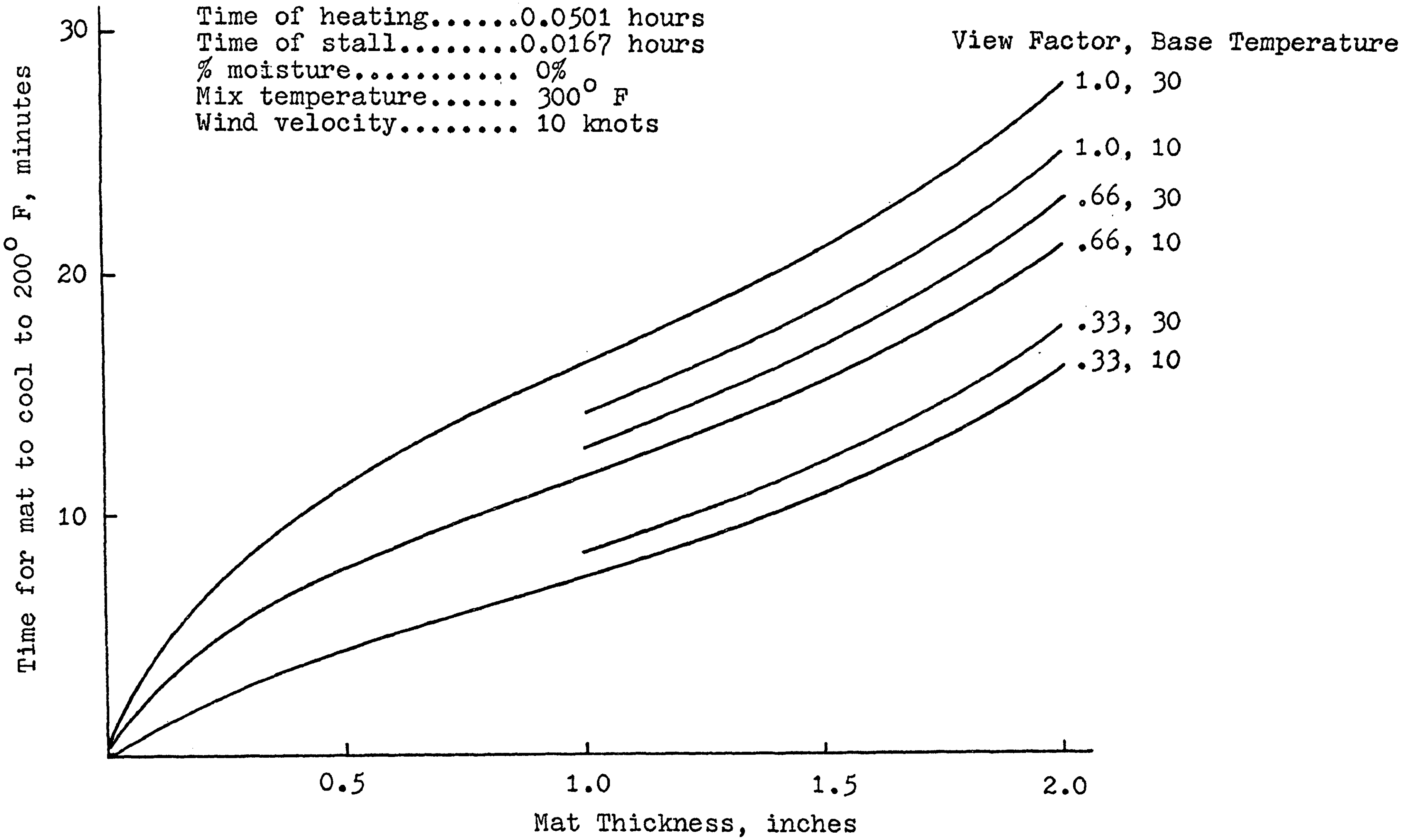


Figure 16. Time for mat to cool to 200° F vs. mat thickness for lines of constant view factor and base temperature.

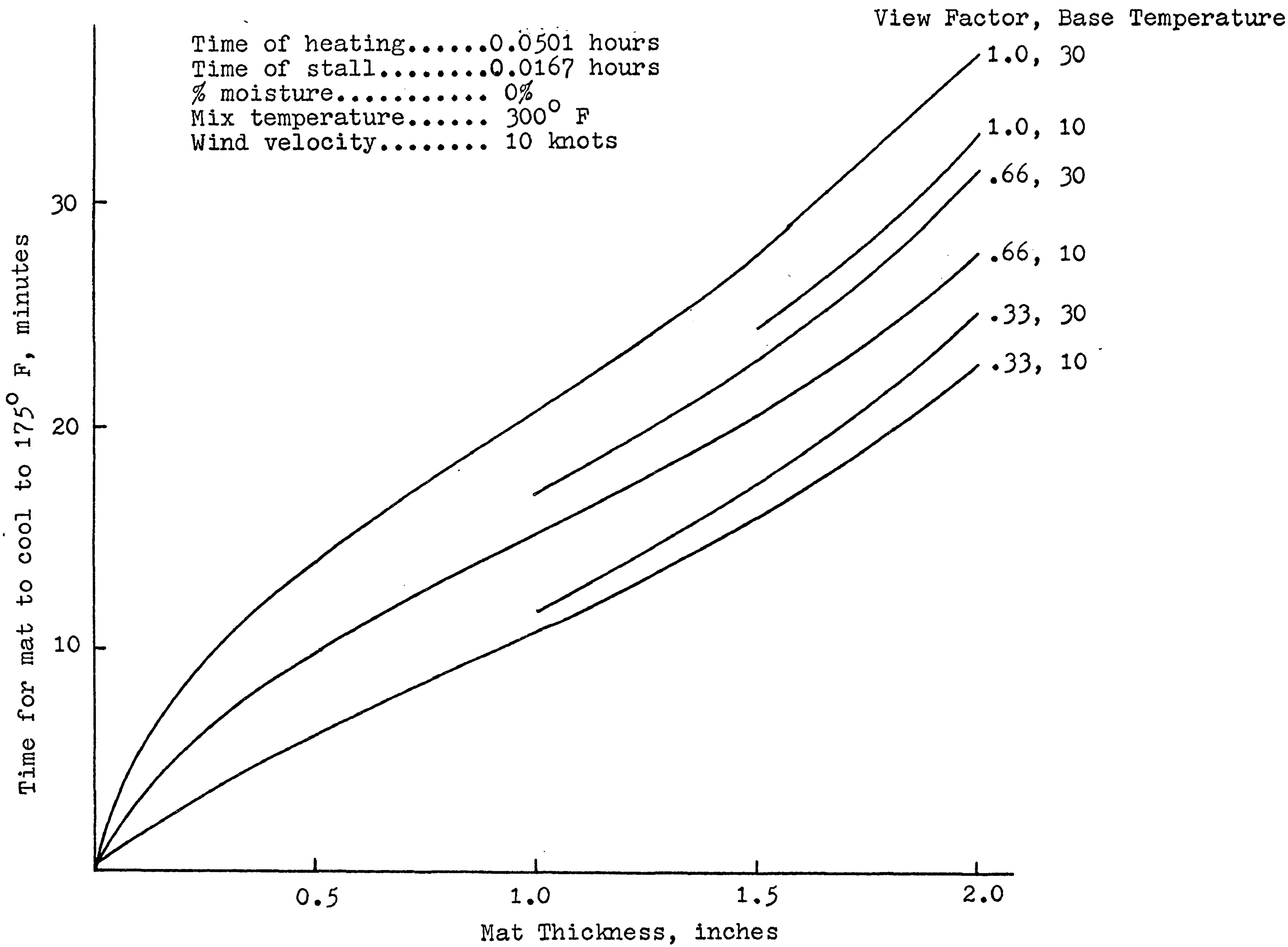


Figure 17. Time for mat to cool to 175° F vs. mat thickness for lines of constant view factor and base temperature.

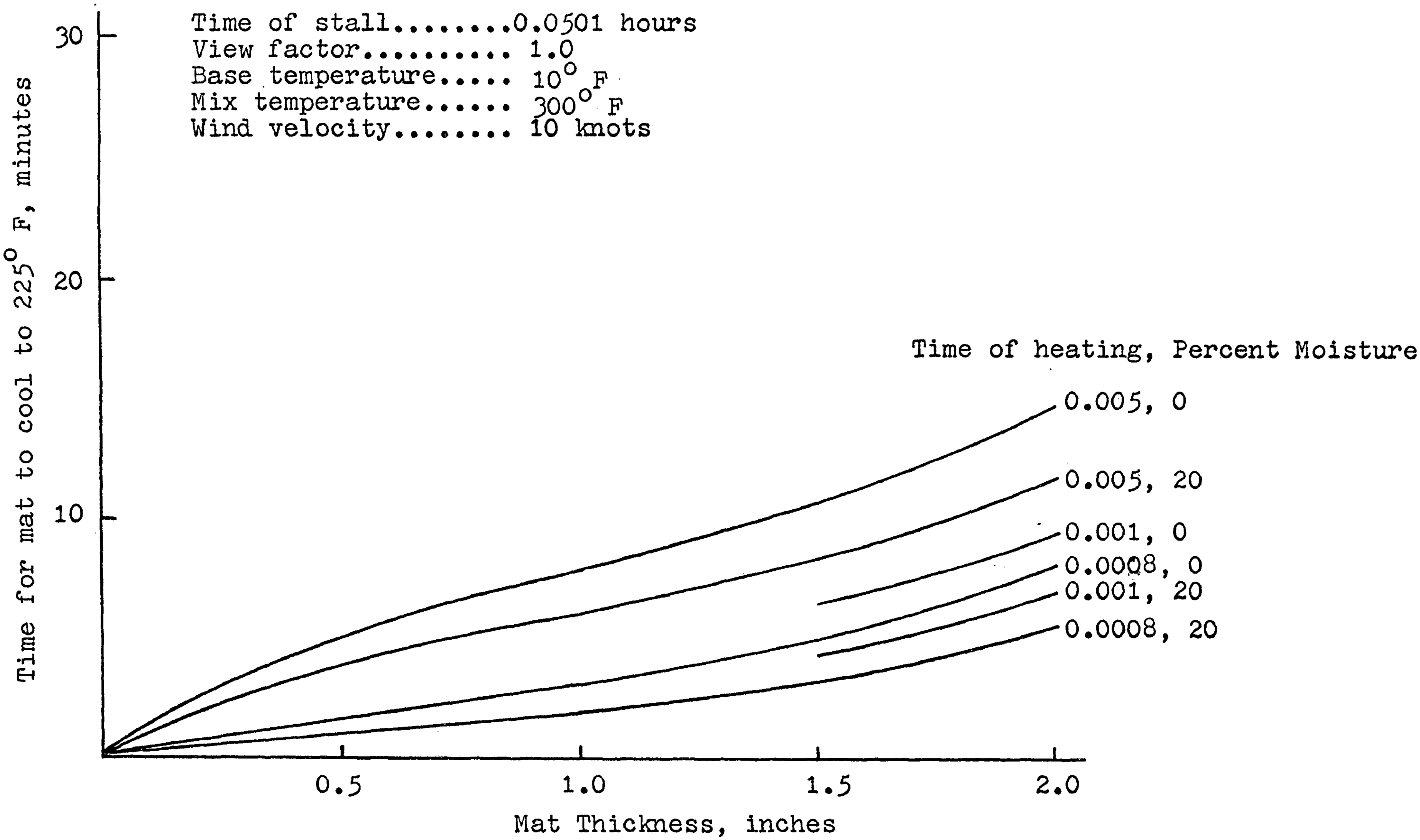


Figure 18. Time for mat to cool to 225° F vs. mat thickness for lines of constant heating and percent moisture.

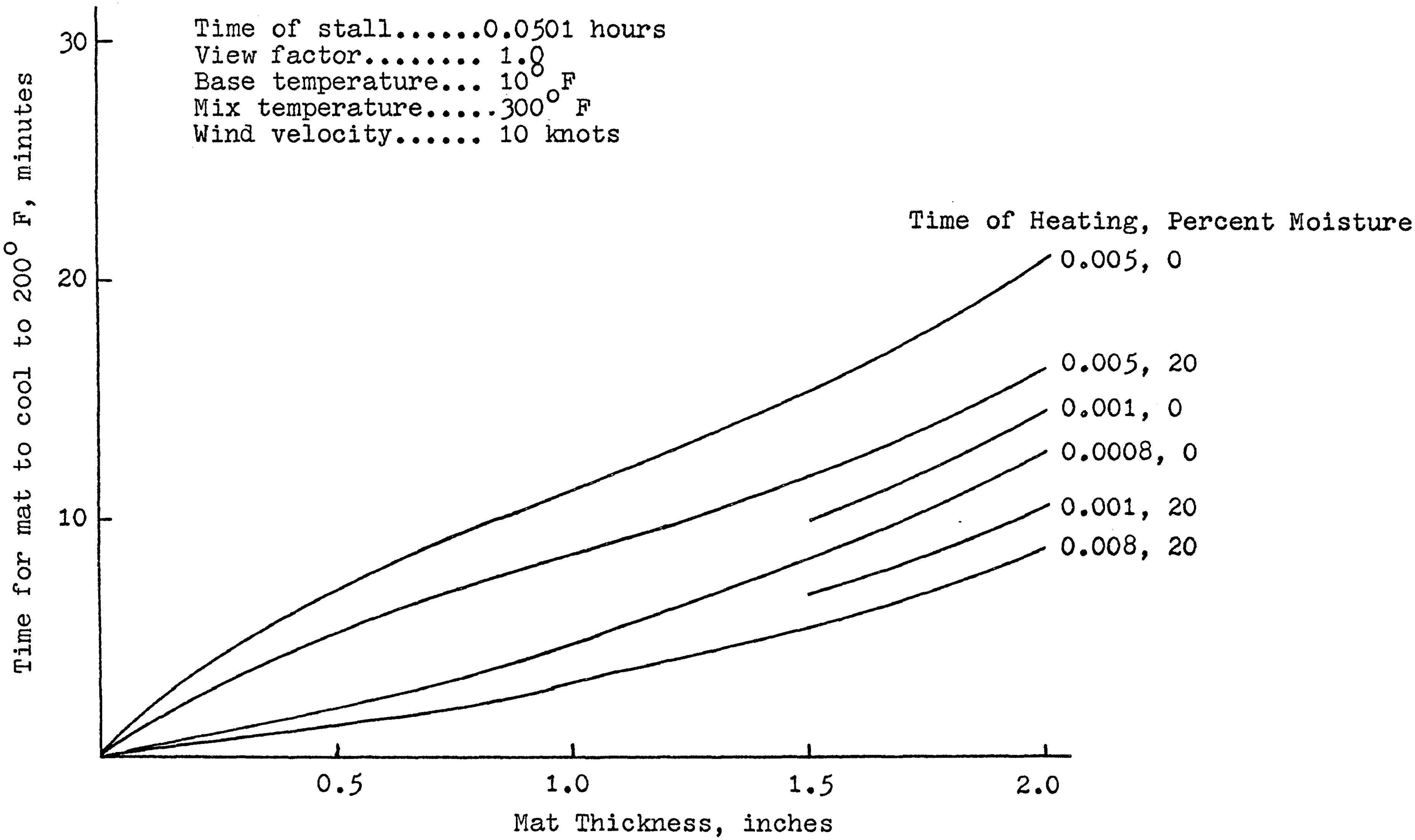


Figure 19. Time for mat to cool to 200° F vs. mat thickness for lines of constant heating and percent moisture.

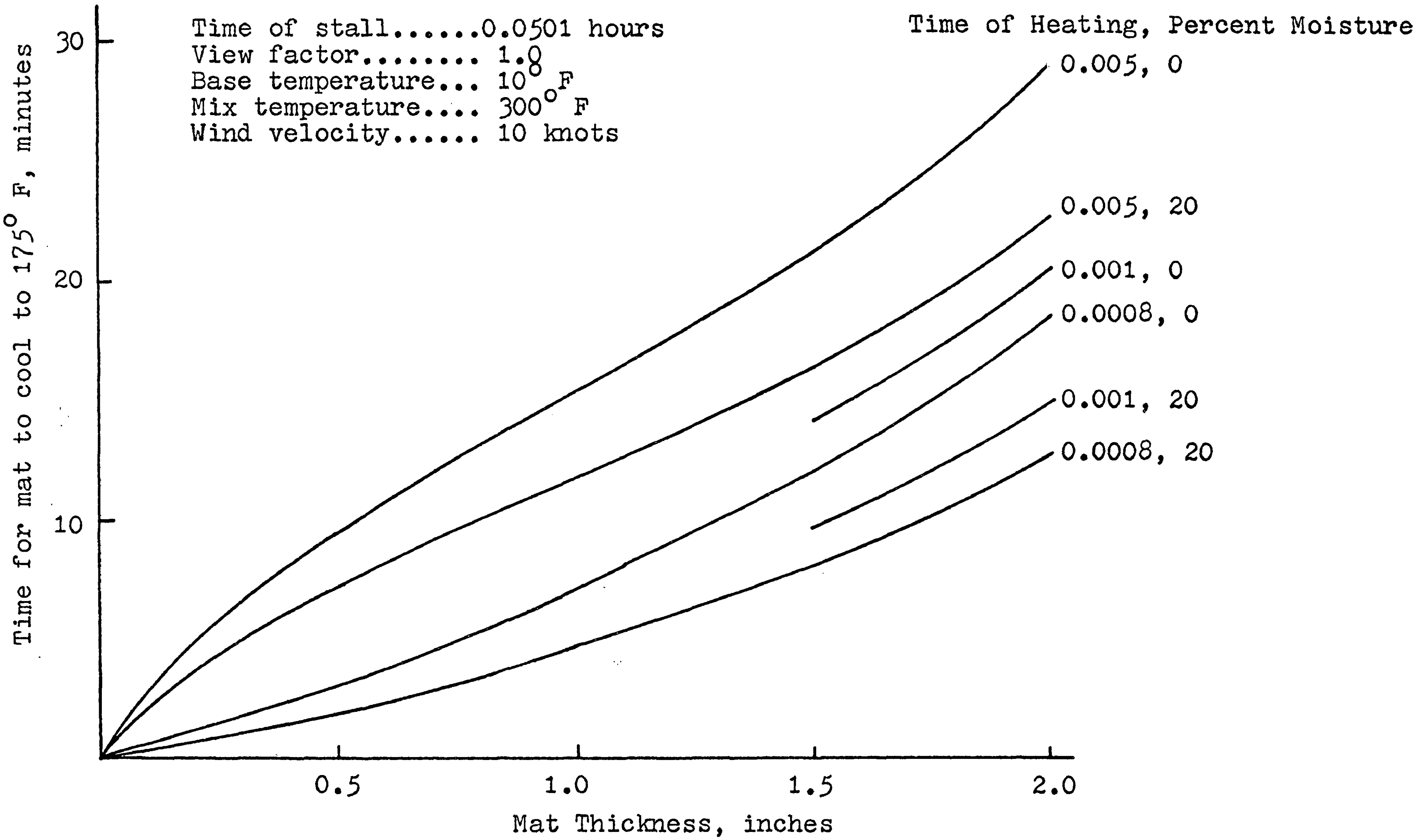


Figure 20. Time for mat to cool to 175° F vs mat thickness for lines of constant heating and percent moisture.

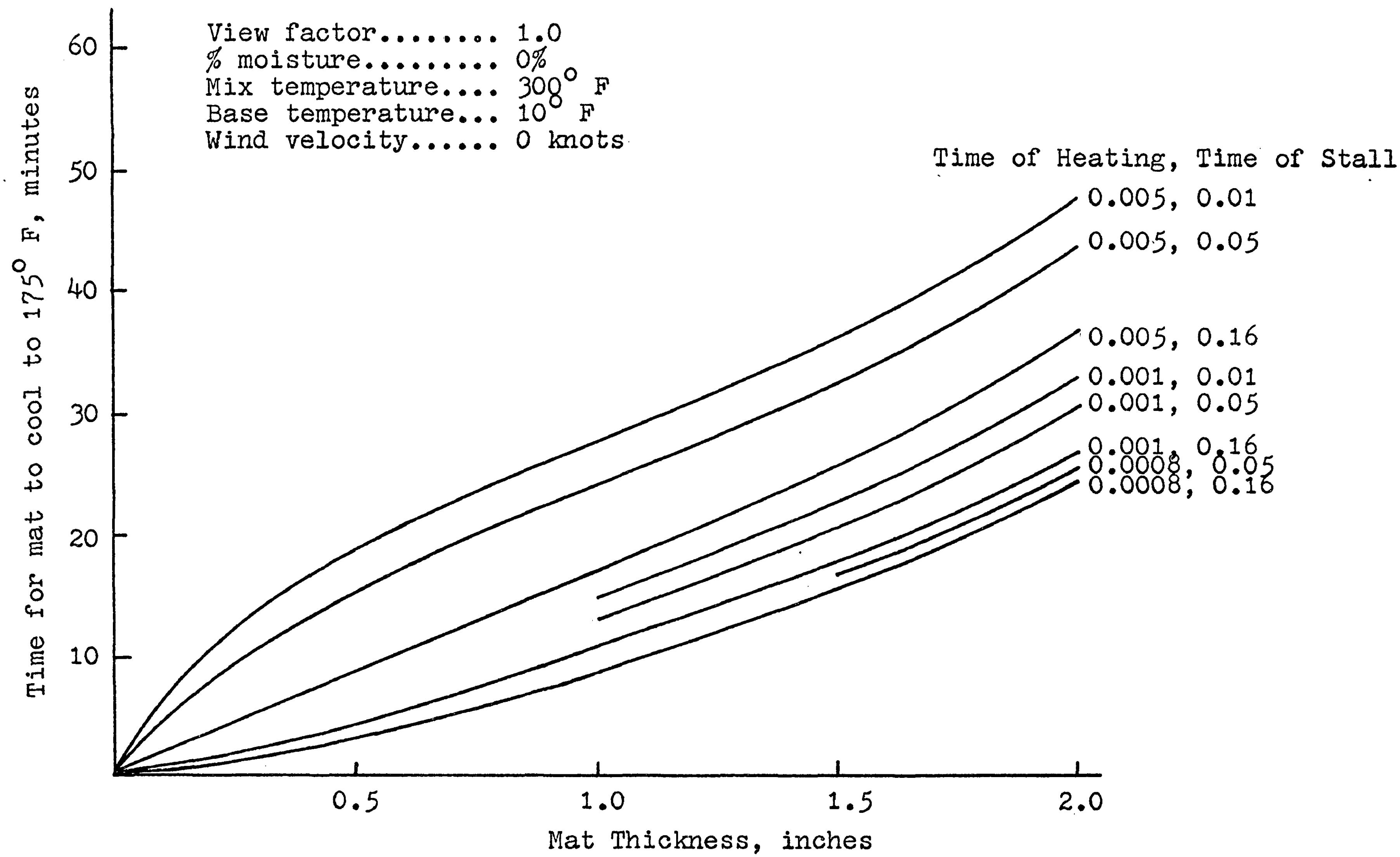


Figure 21. Time for mat to cool to 175° F vs. mat thickness for lines of constant heating and stall (0 knot wind velocity)

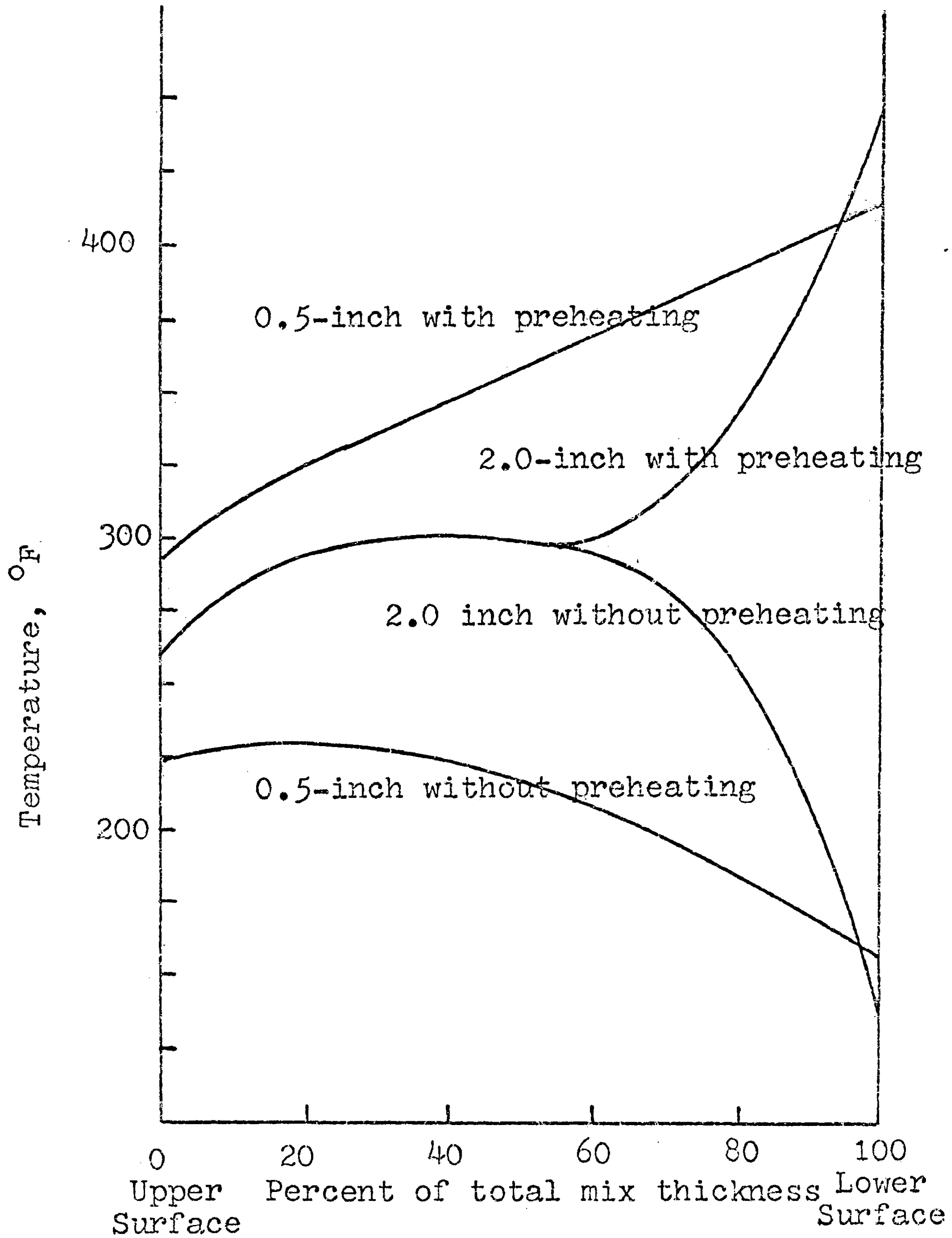
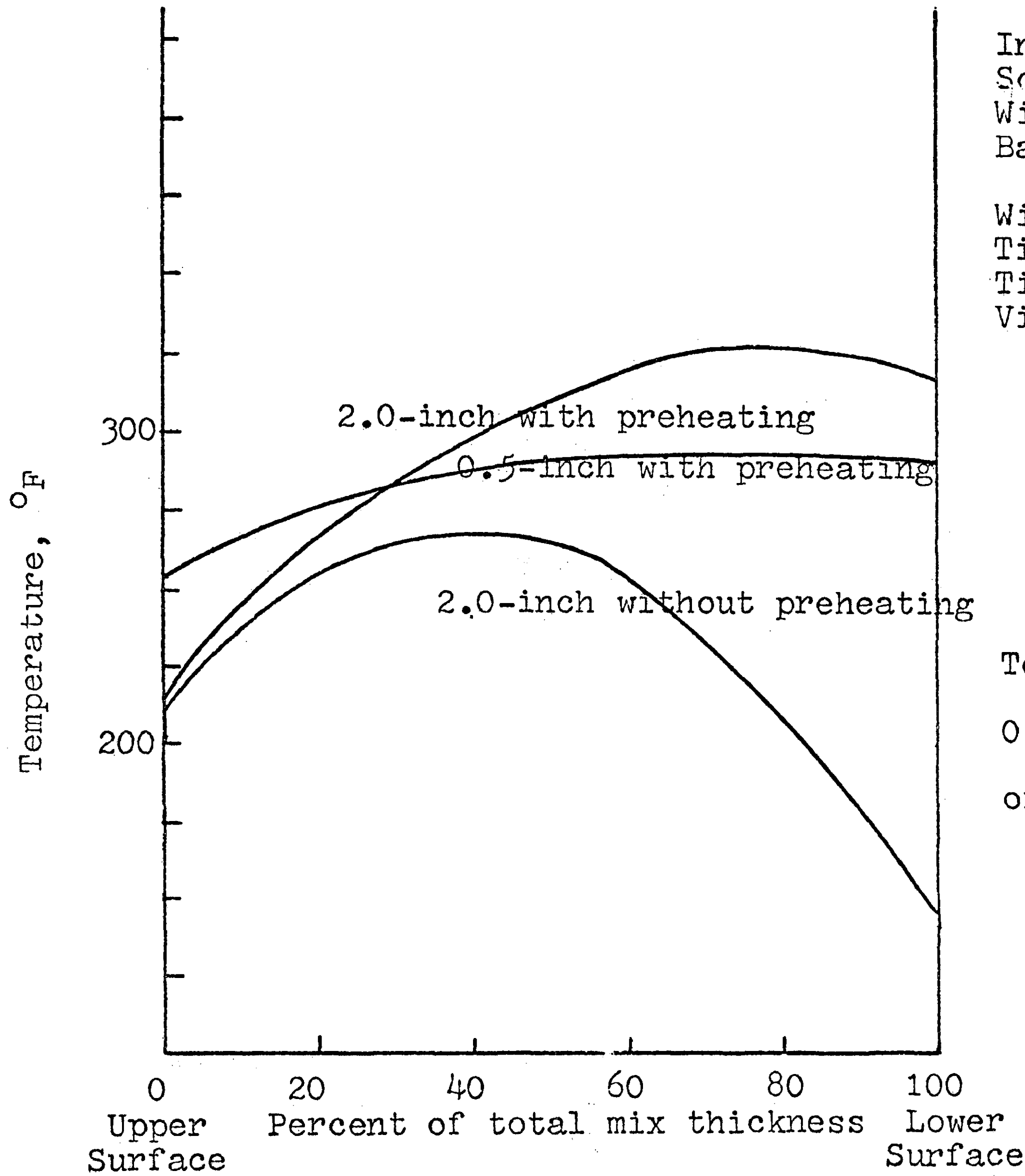


Figure 22a.

Initial mix temperature...	300° F
Solar radiant flux........	50 Btu, ft^{-2}, hr^{-1}
Wind velocity.............	10 knots
Base temperature..........	10° F
With preheating:	
Time of heating...........	0.005 hours
Time of stall.............	0.0167 hours
View factor...............	1.0

Temperature profiles of lift thickness of 0.5- and 2.0 inches 1 minute after placement of the mix with and without preheating.



Initial mix temperature.. 300^{o} F
Solar radiant flux....... 50 btu, ft^{-2}, hr^{-1}
Wind velocity............ 10 knots
Base temperature......... 10^{o} F

With preheating:
Time of heating..........0.005 hours
Time of stall............0.0167 hours
View factor.............. 1.0

Temperature profiles of lift thicknesses of 0.5 and 2.0 inches 5 minutes after placement of the mix with and without preheating.

Figure 22b.

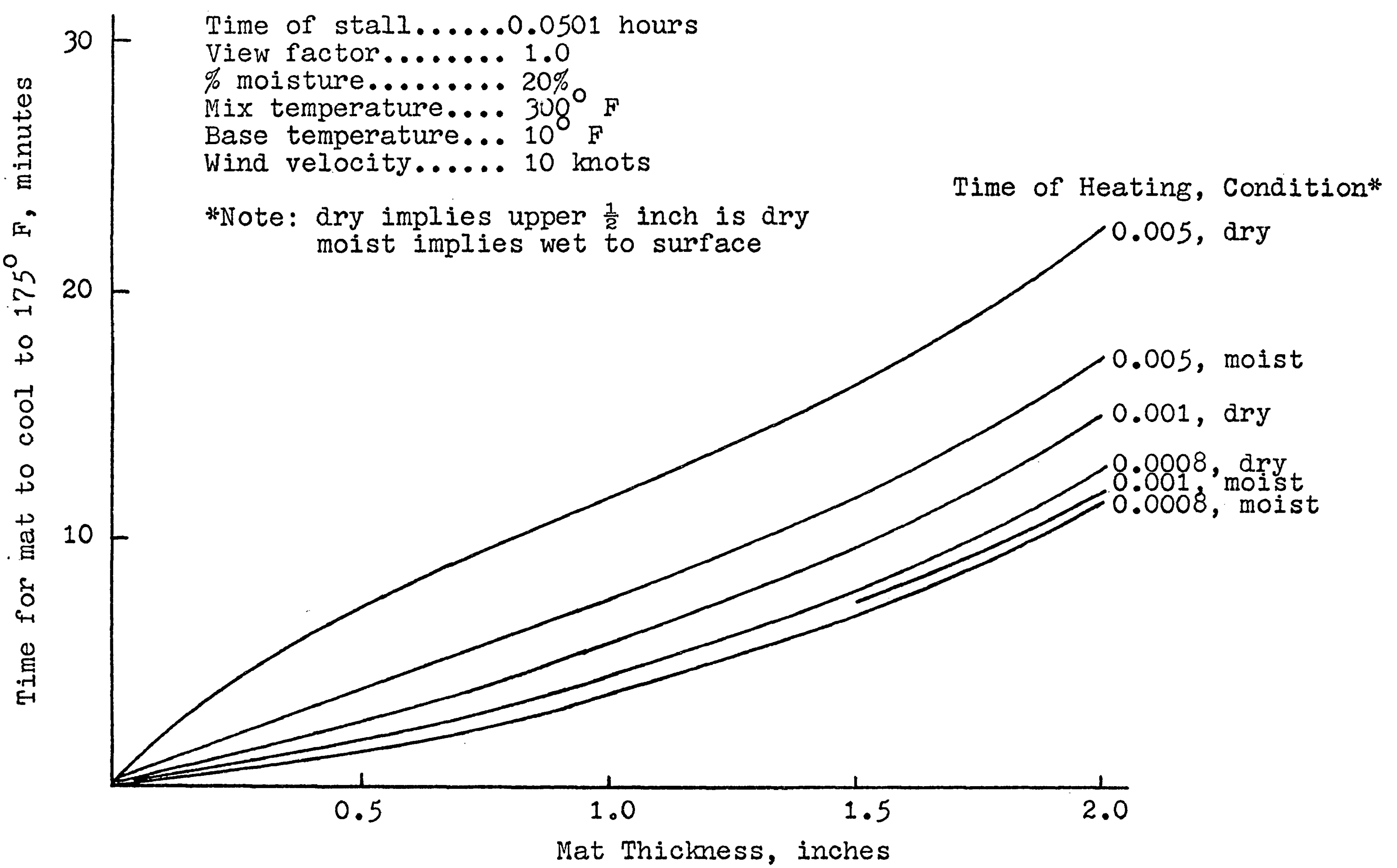


Figure 23. Comparison of assumptions of dry upper $\frac{1}{2}$ inch in the subgrade and steam with complete loss of steam from the subgrade for time to cool to 175° F vs. mat thickness for lines of constant heating.

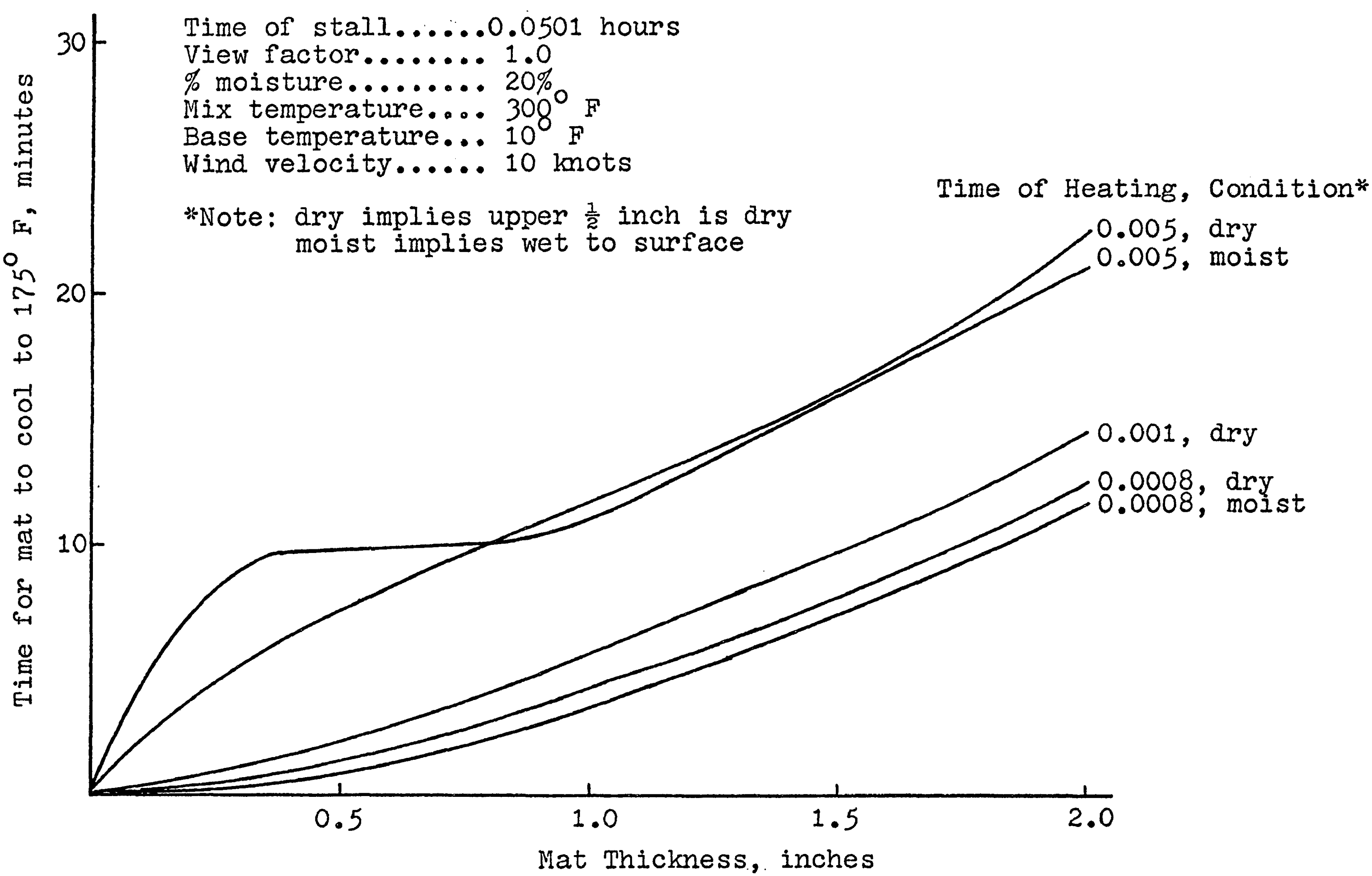


Figure 24. Comparison of assumptions of dry upper $\frac{1}{2}$ inch in the subgrade and steam with first node loss of steam from the subgrade for time to cool to 175° F vs. mat thickness for lines of constant heating.

APPENDIX A

How to Use Appendix A

Appendix A is divided into 19 tables.

General Instructions: Refer to the first line which tells you the data table type. This data table type is then combined (put side by side) with the data table of interest to give the complete picture of the results. Example: Data Table 1 is a data table type 0. Place data table type 0 next to Data Table 1, line for line. This gives you the complete picture of the results.

Areas of Interest:

Mat Thickness: Data Tables 2, 3, 4, and 8 are for 2.0-inch mats only. Data Tables 5 and 9 are for 1.0-inch mats only. Data Tables 6 and 10 are for 0.5-inch mats only. Data Tables 7 and 10 are for 1.5-inch mats only. All other data tables are for all mat thicknesses.

Time of Heating: Data Tables 2, and 5 through 11 are for 0.0050 hour of heating. Data Table 3 is for 0.00166 hour of heating. Data Table 4 is for 0.00083 hour of heating. Data Tables 12 through 19 are for all times of heating.

Time of Stall: Data Tables 2 through 19 contain all times of stall.

View Factor: Data Tables 2 through 11 contain all view factors. Data Tables 11 through 19 have a view factor of 1.0.

Temperature of Base: Data Tables 1 through 11 contain all base temperatures. All other data tables have a base temperature of 10°F.

Temperature of Mix: Data Table 1 contains all mix temperatures. Data Tables 8 through 11 have a mix temperature of 275°F. All other data tables have a mix temperature of 300°F.

Percent Moisture: Data Table 13 has 10% moisture. Data Table 14 has 20% moisture. Vaporization Data Tables 16 and 18 have 10% moisture, and Vaporization Data Tables 17 and 19 have 20% moisture. All other data tables have 0% moisture.

Wind Velocity: Data Table 15 has a 0-knot wind velocity. All other data tables have a 10-knot wind velocity.

DATA TABLE TYPE 0.

BASE TEMPERATURE	MIX TEMPERATURE	MAT THICKNESS
10.0	275.	0.5
20.0	275.	0.5
30.0	275.	0.5
10.0	300.	0.5
20.0	300.	0.5
30.0	300.	0.5
10.0	275.	1.0
20.0	275.	1.0
30.0	275.	1.0
10.0	300.	1.0
20.0	300.	1.0
30.0	300.	1.0
10.0	275.	1.5
20.0	275.	1.5
30.0	275.	1.5
10.0	300.	1.5
20.0	300.	1.5
30.0	300.	1.5
10.0	275.	2.0
20.0	275.	2.0
30.0	275.	2.0
10.0	300.	2.0
20.0	300.	2.0
30.0	300.	2.0

DATA TABLE TYPE 1.

VIEW FACTOR	STALL	TEMPERATURE OF BASE
0,33	0.0167	10.0
0,66	0.0167	10.0
1,00	0.0167	10.0
0,33	0.0501	10.0
0,66	0.0501	10.0
1,00	0.0501	10.0
0,33	0.1670	10.0
0,66	0.1670	10.0
1,00	0.1670	10.0
0,33	0.0167	20.0
0,66	0.0167	20.0
1,00	0.0167	20.0
0,33	0.0501	20.0
0,66	0.0501	20.0
1,00	0.0501	20.0
0,33	0.1670	20.0
0,66	0.1670	20.0
1,00	0.1670	20.0
0,33	0.0167	30.0
0,66	0.0167	30.0
1,00	0.0167	30.0
0,33	0.0501	30.0
0,66	0.0501	30.0
1,00	0.0501	30.0
0,33	0.1670	30.0
0,66	0.1670	30.0
1,00	0.1670	30.0

DATA TABLE TYPE 2.

TIME OF HEATING	TIME OF STALL	MAT THICKNESS
0.0050	0.0167	0.5
0.0050	0.0501	0.5
0.0050	0.1670	0.5
0.0017	0.0167	0.5
0.0017	0.0501	0.5
0.0017	0.1670	0.5
0.0008	0.0167	0.5
0.0008	0.0501	0.5
0.0008	0.1670	0.5
0.0050	0.0167	1.0
0.0050	0.0501	1.0
0.0050	0.1670	1.0
0.0017	0.0167	1.0
0.0017	0.0501	1.0
0.0017	0.1670	1.0
0.0008	0.0167	1.0
0.0008	0.0501	1.0
0.0008	0.1670	1.0
0.0050	0.0167	1.5
0.0050	0.0501	1.5
0.0050	0.1670	1.5
0.0017	0.0167	1.5
0.0017	0.0501	1.5
0.0017	0.1670	1.5
0.0008	0.0167	1.5
0.0008	0.0501	1.5
0.0008	0.1670	1.5
0.0050	0.0167	2.0
0.0050	0.0501	2.0
0.0050	0.1670	2.0
0.0017	0.0167	2.0
0.0017	0.0501	2.0
0.0017	0.1670	2.0
0.0008	0.0167	2.0
0.0008	0.0501	2.0
0.0008	0.1670	2.0

DATA TABLE NUMBER 1

DATA TABLE TYPE 0.
WIND VELOCITY = 10 KNOTS.
NO PREHEATING INVOLVED.

RUN NUMBER	TIME TO COOL TO 225 F	TIME TO COOL TO 200 F	TIME TO COOL TO 175 F
13.	0.4	0.8	1.3
14.	0.4	0.8	1.4
15.	0.5	0.9	1.5
19.	0.7	1.1	1.7
20.	0.7	1.2	1.8
21.	0.8	1.2	1.9
61.	1.2	2.4	3.9
62.	1.3	2.5	4.2
63.	1.4	2.7	4.5
67.	2.0	3.3	5.0
68.	2.2	3.5	5.3
69.	2.3	3.7	5.6
109.	2.3	4.5	7.4
110.	2.5	4.8	7.8
111.	2.6	5.1	8.4
115.	3.9	6.3	9.3
116.	0.0	0.0	0.0
117.	4.3	7.0	10.5
157.	3.7	7.0	11.3
158.	3.9	7.4	12.0
159.	4.1	7.9	12.8
163.	6.1	9.6	14.3
164.	6.5	10.2	15.1
165.	6.7	10.8	16.0

DATA TABLE NUMBER 2

DATA TABLE TYPE 1.
PERCENT MOISTURE = 0.0
TIME OF HEATING = 0.00500 HOURS.
MAT THICKNESS = 2.0 INCHES.
INITIAL MIX TEMPERATURE = 300. DEGREES FAHRENHEIT.
WIND VELOCITY = 10 KNOTS.

RUN NUMBER	TIME TO COOL TO 225 F	TIME TO COOL TO 200 F	TIME TO COOL TO 175 F
200.	10.8	16.0	22.5
201.	14.8	20.8	28.3
202.	18.0	24.6	32.7
203.	9.7	14.7	21.1
204.	12.5	18.4	25.7
205.	14.7	21.1	29.0
206.	8.2	12.9	18.9
207.	9.5	14.9	21.6
208.	10.6	16.4	23.7
209.	11.5	17.0	23.9
210.	15.7	22.1	30.2
211.	18.9	25.9	34.7
212.	10.2	15.6	22.4
213.	13.2	19.4	27.3
214.	15.5	22.3	30.8
215.	8.6	13.6	20.1
216.	10.1	15.8	23.1
217.	11.3	17.4	25.2
218.	12.1	17.9	25.4
219.	16.5	23.4	32.1
220.	19.9	27.4	36.9
221.	10.8	16.5	23.8
222.	14.0	20.6	29.1
223.	16.4	23.7	32.8
224.	9.1	14.5	21.4
225.	10.7	16.7	24.6
226.	11.9	18.5	26.9

DATA TABLE NUMBER 3

DATA TABLE TYPE 1.
PERCENT MOISTURE = 0.0
TIME OF HEATING = 0.00166 HOURS.
MAT THICKNESS = 2.0 INCHES.
INITIAL MIX TEMPERATURE = 300. DEGREES FAHRENHEIT.
WIND VELOCITY = 10 KNOTS.

RUN NUMBER	TIME TO COOL TO 225 F	TIME TO COOL TO 200 F	TIME TO COOL TO 175 F
300.	8.1	12.5	18.1
301.	9.5	14.4	20.4
302.	10.9	16.1	22.6
303.	7.7	12.1	17.6
304.	8.7	13.4	19.3
305.	9.7	14.7	21.1
306.	7.2	11.4	16.9
307.	7.7	12.2	17.9
308.	8.2	12.9	18.9
309.	8.5	13.2	19.2
310.	10.0	15.2	21.7
311.	11.5	17.0	24.0
312.	8.1	12.7	18.7
313.	9.1	14.2	20.5
314.	10.2	15.6	22.4
315.	7.6	12.1	17.8
316.	8.1	12.9	19.0
317.	8.6	13.6	20.1
318.	9.0	14.0	20.4
319.	10.6	16.0	23.1
320.	12.1	18.0	25.5
321.	8.5	13.4	19.8
322.	9.7	15.0	21.9
323.	10.8	16.5	23.8
324.	7.9	12.8	19.0
325.	8.5	13.6	20.2
326.	9.1	14.4	21.4

DATA TABLE NUMBER 4

DATA TABLE TYPE 1.
PERCENT MOISTURE = 0.0
TIME OF HEATING = 0.00083 HOURS.
MAT THICKNESS = 2.0 INCHES.
INITIAL MIX TEMPERATURE = 300. DEGREES FAHRENHEIT.
WIND VELOCITY = 10 KNOTS.

RUN NUMBER	TIME TO COOL TO 225 F	TIME TO COOL TO 200 F	TIME TO COOL TO 175 F
400.	7.4	11.6	17.0
401.	8.1	12.5	18.2
402.	8.8	13.5	19.3
403.	7.2	11.4	16.7
404.	7.7	12.1	17.6
405.	8.2	12.8	18.5
406.	6.9	11.1	16.3
407.	7.2	11.5	16.9
408.	7.4	11.8	17.4
409.	7.8	12.2	18.0
410.	8.5	13.2	19.3
411.	9.3	14.2	20.5
412.	7.6	12.0	17.7
413.	8.1	12.7	18.7
414.	8.6	13.5	19.7
415.	7.3	11.6	17.3
416.	7.6	12.1	17.9
417.	7.8	12.5	18.5
418.	8.2	12.9	19.1
419.	9.0	14.0	20.5
420.	9.8	15.0	21.8
421.	7.9	12.7	18.8
422.	8.5	13.5	19.9
423.	9.1	14.3	20.9
424.	7.7	12.3	18.3
425.	7.9	12.8	19.0
426.	8.3	13.2	19.6

DATA TABLE NUMBER 5

DATA TABLE TYPE 1.
PERCENT MOISTURE = 0.0
TIME OF HEATING = 0.00500 HOURS.
MAT THICKNESS = 1.0 INCHES.
INITIAL MIX TEMPERATURE = 300. DEGREES FAHRENHEIT.
WIND VELOCITY = 10 KNOTS.

RUN NUMBER	TIME TO COOL TO 225 F	TIME TO COOL TO 200 F	TIME TO COOL TO 175 F
700.	4.9	7.2	10.1
701.	8.0	11.0	14.6
702.	10.7	14.0	18.2
703.	3.9	6.1	8.8
704.	5.9	8.7	12.3
705.	7.7	11.0	15.0
706.	2.9	4.7	7.1
707.	3.6	5.8	8.7
708.	4.2	6.8	10.1
709.	5.3	7.7	10.8
710.	8.6	11.7	15.7
711.	11.3	14.9	19.3
712.	4.1	6.4	9.5
713.	6.3	9.3	13.2
714.	8.2	11.7	16.0
715.	3.1	5.0	7.6
716.	3.8	6.2	9.4
717.	4.5	7.2	10.9
718.	5.6	8.2	11.6
719.	9.1	12.5	16.8
720.	11.9	15.8	20.6
721.	4.4	6.9	10.1
722.	6.7	10.0	14.1
723.	8.7	12.5	17.2
724.	3.3	5.3	8.2
725.	4.1	6.6	10.2
726.	4.8	7.7	11.8

DATA TABLE NUMBER 6

DATA TABLE TYPE 1.
PERCENT MOISTURE = 0.0
TIME OF HEATING = 0.00500 HOURS.
MAT THICKNESS = 0.5 INCHES.
INITIAL MIX TEMPERATURE = 300. DEGREES FAHRENHEIT.
WIND VELOCITY = 10 KNOTS.

RUN NUMBER	TIME TO COOL TO 225 F	TIME TO COOL TO 200 F	TIME TO COOL TO 175 F
1000.	3.2	4.6	6.3
1001.	6.0	7.8	10.0
1002.	7.8	9.8	12.4
1003.	1.9	3.1	4.6
1004.	3.6	5.4	7.6
1005.	4.9	7.0	9.5
1006.	1.0	1.8	2.8
1007.	1.4	2.3	3.8
1008.	1.6	2.8	4.6
1009.	3.4	4.9	6.8
1010.	6.4	8.3	10.8
1011.	8.3	10.4	13.2
1012.	2.0	3.3	5.0
1013.	3.9	5.8	8.2
1014.	5.3	7.5	10.3
1015.	1.1	1.9	3.1
1016.	1.5	2.6	4.2
1017.	1.8	3.1	5.1
1018.	3.7	5.3	7.3
1019.	6.8	8.9	11.6
1020.	8.7	11.1	14.1
1021.	2.2	3.6	5.5
1022.	4.3	6.3	8.9
1023.	5.8	8.1	11.1
1024.	1.2	2.1	3.3
1025.	1.6	2.8	4.6
1026.	1.9	3.4	5.7

DATA TABLE NUMBER 7

DATA TABLE TYPE 1.
PERCENT MOISTURE = 0.0
TIME OF HEATING = 0.00500 HOURS.
MAT THICKNESS = 1.5 INCHES.
INITIAL MIX TEMPERATURE = 300. DEGREES FAHRENHEIT.
WIND VELOCITY = 10 KNOTS.

RUN NUMBER	TIME TO COOL TO 225 F	TIME TO COOL TO 200 F	TIME TO COOL TO 175 F
1300.	7.6	11.2	15.8
1301.	11.0	15.4	20.8
1302.	14.0	18.9	24.9
1303.	6.5	10.0	14.4
1304.	8.9	13.1	18.4
1305.	11.0	15.7	21.5
1306.	5.3	8.5	12.5
1307.	6.3	10.0	14.7
1308.	7.2	11.3	16.5
1309.	8.0	11.9	16.7
1310.	11.8	16.4	22.3
1311.	14.8	20.0	26.5
1312.	6.9	10.6	15.3
1313.	9.5	13.9	19.6
1314.	11.6	16.6	22.9
1315.	5.6	8.9	13.3
1316.	6.7	10.6	15.7
1317.	7.6	12.0	17.6
1318.	8.5	12.6	17.8
1319.	12.4	17.4	23.7
1320.	15.6	21.2	28.2
1321.	7.3	11.3	16.4
1322.	10.0	14.8	20.9
1323.	12.3	17.7	24.5
1324.	5.9	9.5	14.2
1325.	7.1	11.3	16.8
1326.	8.1	12.8	18.9

DATA TABLE NUMBER 8

DATA TABLE TYPE 1.
PERCENT MOISTURE = 0.0
TIME OF HEATING = 0.00500 HOURS.
MAT THICKNESS = 2.0 INCHES.
INITIAL MIX TEMPERATURE = 275. DEGREES FAHRENHEIT.
WIND VELOCITY = 10 KNOTS.

RUN NUMBER	TIME TO COOL TO 225 F	TIME TO COOL TO 200 F	TIME TO COOL TO 175 F
2200.	7.8	12.8	19.0
2201.	11.5	17.4	24.7
2202.	14.6	21.2	29.2
2203.	6.6	11.4	17.5
2204.	9.1	14.9	22.0
2205.	11.2	17.5	25.3
2206.	5.2	9.7	15.3
2207.	6.3	11.3	17.8
2208.	7.2	12.8	19.8
2209.	8.2	13.5	20.2
2210.	12.3	18.6	26.4
2211.	15.5	22.4	31.0
2212.	7.0	12.1	18.6
2213.	9.7	15.8	23.4
2214.	11.9	18.6	26.9
2215.	5.5	10.2	16.3
2216.	6.7	12.1	19.0
2217.	7.6	13.6	21.1
2218.	8.7	14.4	21.6
2219.	13.0	19.7	28.2
2220.	16.4	23.8	33.0
2221.	7.4	12.8	19.9
2222.	10.3	16.8	25.0
2223.	12.7	19.8	28.8
2224.	5.9	10.9	17.4
2225.	7.1	12.9	20.4
2226.	8.1	14.5	22.7

DATA TABLE NUMBER 9

DATA TABLE TYPE 1.
PERCENT MOISTURE = 0.0
TIME OF HEATING = 0.00500 HOURS.
MAT THICKNESS = 1.0 INCHES.
INITIAL MIX TEMPERATURE = 275. DEGREES FAHRENHEIT.
WIND VELOCITY = 10 KNOTS.

RUN NUMBER	TIME TO COOL TO 225 F	TIME TO COOL TO 200 F	TIME TO COOL TO 175 F
2700.	3.7	5.9	8.8
2701.	6.7	9.6	13.2
2702.	9.5	12.8	16.9
2703.	2.6	4.7	7.4
2704.	4.4	7.3	10.7
2705.	6.2	9.5	13.5
2706.	1.8	3.5	5.7
2707.	2.3	4.4	7.1
2708.	2.8	5.2	8.5
2709.	4.0	6.3	9.4
2710.	7.3	10.4	14.3
2711.	10.0	13.6	18.0
2712.	2.8	5.0	7.9
2713.	4.8	7.8	11.5
2714.	6.6	10.1	14.5
2715.	2.0	3.7	6.1
2716.	2.5	4.7	7.7
2717.	3.0	5.6	9.1
2718.	4.2	6.8	10.1
2719.	7.7	11.1	15.3
2720.	10.6	14.4	19.2
2721.	3.0	5.4	8.5
2722.	5.2	8.4	12.5
2723.	7.1	10.9	15.6
2724.	2.1	4.0	6.6
2725.	2.7	5.1	8.4
2726.	3.2	6.0	10.0

DATA TABLE NUMBER 10

DATA TABLE TYPE 1.
PERCENT MOISTURE = 0.0
TIME OF HEATING = 0.00500 HOURS.
MAT THICKNESS = 0.5 INCHES.
INITIAL MIX TEMPERATURE = 275. DEGREES FAHRENHEIT.
WIND VELOCITY = 10 KNOTS.

RUN NUMBER	TIME TO COOL TO 225 F	TIME TO COOL TO 200 F	TIME TO COOL TO 175 F
3000.	2.6	4.0	5.6
3001.	5.5	7.3	9.5
3002.	7.4	9.4	11.9
3003.	1.3	2.4	3.9
3004.	2.9	4.7	6.9
3005.	4.3	6.3	8.9
3006.	0.7	1.3	2.2
3007.	0.9	1.7	3.1
3008.	1.0	2.1	3.8
3009.	2.9	4.3	6.1
3010.	5.9	7.8	10.3
3011.	7.8	9.9	12.7
3012.	1.4	2.7	4.3
3013.	3.2	5.1	7.5
3014.	4.6	6.8	9.6
3015.	0.7	1.4	2.4
3016.	1.0	1.9	3.4
3017.	1.1	2.3	4.2
3018.	3.2	4.7	6.7
3019.	6.3	8.4	11.0
3020.	8.3	10.6	13.6
3021.	1.6	2.9	4.8
3022.	3.5	5.6	8.2
3023.	5.1	7.4	10.4
3024.	0.8	1.5	2.6
3025.	1.0	2.1	3.8
3026.	1.3	2.6	4.7

DATA TABLE NUMBER 11

DATA TABLE TYPE 1.
PERCENT MOISTURE = 0.0
TIME OF HEATING = 0.00500 HOURS.
MAT THICKNESS = 1.5 INCHES.
INITIAL MIX TEMPERATURE = 275. DEGREES FAHRENHEIT.
WIND VELOCITY = 10 KNOTS.

RUN NUMBER	TIME TO COOL TO 225 F	TIME TO COOL TO 200 F	TIME TO COOL TO 175 F
3300.	5.5	9.0	13.4
3301.	8.8	13.1	18.4
3302.	11.9	16.7	22.6
3303.	4.4	7.7	11.9
3304.	6.6	10.7	15.8
3305.	8.5	13.2	19.0
3306.	3.4	6.3	10.1
3307.	4.1	7.6	12.1
3308.	4.8	8.7	13.8
3309.	5.9	9.5	14.2
3310.	9.5	14.0	19.7
3311.	12.5	17.7	24.0
3312.	4.7	8.3	12.8
3313.	7.0	11.4	17.0
3314.	9.1	14.1	20.3
3315.	3.5	6.7	10.8
3316.	4.4	8.1	13.0
3317.	5.1	9.3	14.8
3318.	6.2	10.2	15.2
3319.	10.0	14.9	21.1
3320.	13.3	18.8	25.6
3321.	5.0	8.8	13.7
3322.	7.5	12.2	18.2
3323.	9.7	15.0	21.7
3324.	3.8	7.1	11.5
3325.	4.7	8.7	14.0
3326.	5.5	10.0	15.9

DATA TABLE NUMBER 12

DATA TABLE TYPE 2.
VIEW FACTOR = 1.0
INITIAL BASE TEMPERATURE = 10 DEGREES FAHRENHEIT.
INITIAL MIX TEMPERATURE = 300 DEGREES FAHRENHEIT.
PERCENT MOISTURE = 0.
WIND VELOCITY = 10. KNOTS.

RUN NUMBER	TIME TO COOL TO 225 F	TIME TO COOL TO 200 F	TIME TO COOL TO 175 F
800.	7.8	9.8	12.4
801.	4.9	7.0	9.5
802.	1.6	2.8	4.6
803.	3.2	4.5	6.1
804.	1.8	3.0	4.5
805.	1.0	1.8	2.8
806.	1.7	2.7	3.9
807.	1.2	2.0	3.1
808.	0.9	1.5	2.3
810.	10.7	14.0	18.2
811.	7.7	11.0	15.0
812.	4.2	6.8	10.1
813.	5.0	7.3	10.2
814.	3.9	6.1	8.9
815.	2.9	4.7	7.1
816.	3.5	5.4	7.8
817.	3.0	4.8	7.1
818.	2.6	4.2	6.3
820.	14.0	18.9	24.9
821.	11.0	15.7	21.5
822.	7.2	11.3	16.5
823.	7.6	11.3	15.8
824.	6.5	10.0	14.4
825.	5.3	8.5	12.5
826.	5.9	9.1	13.0
827.	5.4	8.4	12.3
828.	4.8	7.7	11.4
830.	18.0	24.6	32.7
831.	14.7	21.1	29.0
832.	10.6	16.4	23.7
833.	10.9	16.1	22.6
834.	9.7	14.7	21.1
835.	8.2	12.9	18.9
836.	8.8	13.5	19.3
837.	8.2	12.8	18.5
838.	7.4	11.8	17.4

DATA TABLE NUMBER 13

DATA TABLE TYPE 2.
VIEW FACTOR = 1.0
INITIAL BASE TEMPERATURE = 10 DEGREES FAHRENHEIT.
INITIAL MIX TEMPERATURE = 300 DEGREES FAHRENHEIT.
PERCENT MOISTURE = 10.
WIND VELOCITY = 10. KNOTS.

RUN NUMBER	TIME TO COOL TO 225 F	TIME TO COOL TO 200 F	TIME TO COOL TO 175 F
850.	7.1	8.9	11.1
851.	4.4	6.2	8.4
852.	1.3	2.3	3.7
853.	2.3	3.3	4.5
854.	1.3	2.1	3.2
855.	0.8	1.3	2.0
856.	1.2	1.8	2.6
857.	0.8	1.3	2.1
858.	0.7	1.1	1.7
860.	9.6	12.4	15.8
861.	6.8	9.5	12.9
862.	3.5	5.6	8.3
863.	3.9	5.7	7.9
864.	3.0	4.7	6.8
865.	2.3	3.7	5.5
866.	2.7	4.1	5.8
867.	2.3	3.6	5.3
868.	1.9	3.1	4.6
870.	12.4	16.4	21.3
871.	9.6	13.5	18.3
872.	6.1	9.5	13.7
873.	6.1	8.9	12.4
874.	5.2	7.9	11.3
875.	4.2	6.8	9.9
876.	4.6	7.0	10.0
877.	4.2	6.5	9.5
878.	3.6	5.8	8.6
880.	15.7	21.1	27.8
881.	12.8	18.1	24.6
882.	9.0	13.9	19.8
883.	8.7	12.8	17.8
884.	7.7	11.8	16.7
885.	6.6	10.4	15.1
886.	6.9	10.5	15.0
887.	6.4	10.0	14.5
888.	5.8	9.2	13.4

DATA TABLE NVMBER 14

DATA TABLE TYPE 2.
VIEW FACTOR = 1.0
INITIAL BASE TEMPERATURE = 10 DEGREES FAHRENHEIT.
INITIAL MIX TEMPERATURE = 300 DEGREES FAHRENHEIT.
PERCENT MOISTURE = 20.
WIND VELOCITY = 10. KNOTS.

RUN NUMBER	TIME TO COOL TO 225 F	TIME TO COOL TO 200 F	TIME TO COOL TO 175 F
900.	6.4	8.0	9.9
901.	3.8	5.4	7.4
902.	1.1	1.9	3.1
903.	1.8	2.6	3.6
904.	1.0	1.7	2.5
905.	0.7	1.1	1.7
906.	0.9	1.4	2.1
907.	0.7	1.1	1.7
908.	0.5	0.8	1.3
910.	8.5	11.0	14.1
911.	6.0	8.4	11.4
912.	3.1	4.9	7.3
913.	3.3	4.8	6.7
914.	2.6	4.0	5.8
915.	2.0	3.2	4.8
916.	2.3	3.5	5.0
917.	2.0	3.2	4.6
918.	1.6	2.6	3.9
920.	11.1	14.7	19.0
921.	8.5	12.0	16.3
922.	5.4	8.4	12.2
923.	5.3	7.7	10.7
924.	4.5	6.9	9.8
925.	3.8	6.0	8.8
926.	4.0	6.1	8.7
927.	3.7	5.8	8.3
928.	3.1	5.1	7.4
930.	14.1	19.0	24.9
931.	11.5	16.3	22.0
932.	8.1	12.5	17.8
933.	7.6	11.2	15.6
934.	6.8	10.4	14.7
935.	5.9	9.3	13.5
936.	6.0	9.2	13.1
937.	5.7	8.9	12.8
938.	5.0	8.1	11.8

DATA TABLE NUMBER 15

DATA TABLE TYPE 2.
VIEW FACTOR = 1.0
INITIAL BASE TEMPERATURE = 10 DEGREES FAHRENHEIT.
INITIAL MIX TEMPERATURE = 300 DEGREES FAHRENHEIT.
PERCENT MOISTURE = 0.
WIND VELOCITY = 0. KNOTS.

RUN NUMBER	TIME TO COOL TO 225 F	TIME TO COOL TO 200 F	TIME TO COOL TO 175 F
1400.	11.3	14.4	18.5
1401.	8.1	11.3	15.3
1402.	2.9	5.2	8.6
1403.	4.5	6.4	8.9
1404.	2.8	4.6	7.0
1405.	1.4	2.6	4.2
1406.	2.4	3.7	5.5
1407.	1.6	2.8	4.4
1408.	1.1	2.0	3.2
1410.	15.5	20.6	27.0
1411.	12.0	17.0	23.3
1412.	6.8	11.1	16.9
1413.	7.0	10.3	14.7
1414.	5.6	8.8	13.0
1415.	4.1	6.8	10.5
1416.	4.7	7.4	10.9
1417.	4.1	6.6	10.0
1418.	3.4	5.7	8.9
1420.	20.3	27.5	36.7
1421.	16.6	23.6	32.7
1422.	11.3	17.8	26.2
1423.	10.6	15.9	22.7
1424.	9.3	14.4	21.0
1425.	7.5	12.2	18.5
1426.	8.0	12.5	18.3
1427.	7.3	11.7	17.5
1428.	6.5	10.6	16.2
1430.	25.7	35.4	47.7
1431.	21.8	31.3	43.4
1432.	16.3	25.2	36.7
1433.	15.2	22.7	32.4
1434.	13.7	21.1	30.6
1435.	11.6	18.6	27.8
1436.	12.0	18.7	27.3
1437.	11.3	17.8	26.4
1438.	10.2	16.6	24.9

DATA TABLE NVMBER 16

DATA TABLE TYPE 2.
VIEW FACTOR = 1.0
INITIAL BASE TEMPERATURE = 10 DEGREES FAHRENHEIT.
INITIAL MIX TEMPERATURE = 300 DEGREES FAHRENHEIT.
PERCENT MOISTURE = 10.
WIND VELOCITY = 10. KNOTS.

RUN NUMBER	TIME TO COOL TO 225 F	TIME TO COOL TO 200 F	TIME TO COOL TO 175 F
1500.	4.5	6.5	13.4
1501.	2.6	4.6	11.3
1502.	1.9	3.2	5.0
1503.	2.0	2.8	4.0
1504.	1.1	1.9	2.8
1505.	0.7	1.2	1.9
1506.	0.9	1.3	2.0
1507.	0.7	1.1	1.7
1508.	0.6	0.9	1.4
1510.	7.1	10.5	15.3
1511.	5.4	8.7	13.0
1512.	3.6	5.7	8.5
1513.	2.9	4.4	6.3
1514.	2.4	3.9	5.6
1515.	2.1	3.4	5.0
1516.	2.2	3.5	5.0
1517.	2.1	3.3	4.8
1518.	1.8	2.9	4.3
1520.	10.1	15.1	20.4
1521.	8.5	13.2	18.1
1522.	6.1	9.5	13.7
1523.	4.8	7.3	10.4
1524.	4.4	6.8	9.8
1525.	3.9	6.2	9.1
1526.	4.1	6.3	9.1
1527.	3.8	6.1	8.8
1528.	3.4	5.5	8.2
1530.	13.8	20.2	27.1
1531.	12.2	18.1	24.6
1532.	9.3	14.1	20.0
1533.	7.4	11.2	15.8
1534.	6.8	10.5	15.1
1535.	6.2	9.8	14.3
1536.	6.1	9.5	13.6
1537.	5.9	9.2	13.4
1538.	5.4	8.6	12.7

DATA TABLE NUMBER 17

DATA TABLE TYPE 2.
VIEW FACTOR = 1.0
INITIAL BASE TEMPERATURE = 10 DEGREES FAHRENHEIT.
INITIAL MIX TEMPERATURE = 300 DEGREES FAHRENHEIT.
PERCENT MOISTURE = 20.
WIND VELOCITY = 10. KNOTS.

RUN NUMBER	TIME TO COOL TO 225 F	TIME TO COOL TO 200 F	TIME TO COOL TO 175 F
1550.	3.1	5.0	12.0
1551.	2.2	4.1	10.2
1552.	1.6	2.6	4.1
1553.	1.1	1.7	2.4
1554.	0.8	1.2	1.9
1555.	0.5	0.9	1.3
1556.	0.6	1.0	1.4
1557.	0.5	0.8	1.2
1558.	0.4	0.8	1.1
1560.	5.5	8.7	12.5
1561.	4.9	7.8	10.8
1562.	3.0	4.7	6.9
1563.	2.0	3.2	4.6
1564.	1.9	3.0	4.4
1565.	1.5	2.5	3.8
1566.	2.0	3.1	4.5
1567.	1.9	3.0	4.3
1568.	1.5	2.5	3.7
1570.	8.6	12.6	16.8
1571.	7.7	11.1	15.1
1572.	5.1	7.9	11.4
1573.	3.7	5.7	8.2
1574.	3.5	5.5	8.0
1575.	3.0	4.9	7.2
1576.	3.6	5.6	8.1
1577.	3.5	5.5	7.9
1578.	3.0	4.8	7.1
1580.	12.1	17.3	23.0
1581.	11.0	15.7	21.3
1582.	7.9	12.1	17.2
1583.	5.7	8.8	12.6
1584.	5.5	8.5	12.3
1585.	4.9	7.8	11.4
1586.	5.5	8.5	12.2
1587.	5.3	8.3	12.1
1588.	4.7	7.6	11.2

DATA TABLE NUMBER 18

DATA TABLE TYPE 2.
VIEW FACTOR = 1.0
INITIAL BASE TEMPERATURE = 10 DEGREES FAHRENHEIT.
INITIAL MIX TEMPERATURE = 300 DEGREES FAHRENHEIT.
PERCENT MOISTURE = 10.
WIND VELOCITY = 10. KNOTS.

RUN NUMBER	TIME TO COOL TO 225 F	TIME TO COOL TO 200 F	TIME TO COOL TO 175 F
1600.	4.4	5.7	7.4
1601.	2.3	3.6	5.2
1602.	1.9	3.2	4.9
1603.	1.5	2.3	3.2
1604.	1.2	1.9	2.8
1605.	0.7	1.2	1.9
1606.	0.9	1.3	2.0
1607.	0.7	1.1	1.7
1608.	0.6	0.9	1.4
1610.	6.8	9.1	12.0
1611.	4.8	7.1	9.8
1612.	3.6	5.7	8.4
1613.	2.9	4.4	6.3
1614.	2.4	3.9	5.6
1615.	2.1	3.4	5.0
1616.	2.2	3.5	5.0
1617.	2.1	3.3	4.8
1618.	1.8	2.9	4.3
1620.	9.1	12.6	16.8
1621.	7.2	10.6	14.7
1622.	6.1	9.5	13.7
1623.	4.8	7.3	10.4
1624.	4.4	6.8	9.8
1625.	3.9	6.2	9.1
1626.	4.1	6.3	9.1
1627.	3.8	6.1	8.8
1628.	3.4	5.5	8.2
1630.	12.3	17.2	23.0
1631.	10.2	14.9	20.6
1632.	9.2	14.0	19.9
1633.	7.4	11.2	15.8
1634.	6.8	10.5	15.1
1635.	6.2	9.8	14.3
1636.	6.1	9.5	13.6
1637.	5.9	9.2	13.4
1638.	5.4	8.6	12.7

DATA TABLE NVMBER 19

DATA TABLE TYPE 2.
VIEW FACTOR = 1.0
INITIAL BASE TEMPERATURE = 10 DEGREES FAHRENHEIT.
INITIAL MIX TEMPERATURE = 300 DEGREES FAHRENHEIT.
PERCENT MOISTURE = 20.
WIND VELOCITY = 10. KNOTS.

RUN NUMBER	TIME TO COOL TO 225 F	TIME TO COOL TO 200 F	TIME TO COOL TO 175 F
1650.	2.8	3.8	5.1
1651.	1.8	2.8	4.1
1652.	1.4	2.4	3.7
1653.	1.1	1.7	2.5
1654.	0.8	1.2	1.9
1655.	0.5	0.9	1.4
1656.	0.6	1.0	1.4
1657.	0.5	0.8	1.2
1658.	0.4	0.8	1.1
1660.	4.3	6.0	8.1
1661.	3.8	5.6	7.8
1662.	2.9	4.6	6.9
1663.	2.0	3.2	4.6
1664.	1.9	3.0	4.4
1665.	1.5	2.5	3.8
1666.	2.0	3.1	4.5
1667.	1.9	3.0	4.3
1668.	1.5	2.5	3.7
1670.	6.6	9.3	12.6
1671.	6.1	8.9	12.4
1672.	5.1	7.9	11.5
1673.	3.7	5.7	8.2
1674.	3.5	5.5	8.0
1675.	3.0	4.9	7.2
1676.	3.6	5.6	8.1
1677.	3.5	5.5	7.9
1678.	3.0	4.8	7.1
1680.	9.2	13.2	17.9
1681.	8.6	12.6	17.4
1682.	8.0	12.1	17.3
1683.	5.7	8.8	12.6
1684.	5.5	8.5	12.3
1685.	4.9	7.8	11.4
1686.	5.5	8.5	12.2
1687.	5.3	8.3	12.1
1688.	4.7	7.6	11.2

APPENDIX B

Table B.1

Computer Listing

```
      ODIMENSION TM(20), TB(41), TEMP(8), TIMIT(8),
      1 TMIX(50), BASE(50), TAS(50), SRS(50), TD(20), TE(41)
       DIMENSION VIEWFA(50), THEATB(50), TSTALL(50)
       READ 836, NOTURN
       DO 100 II = 1, NOTURN
       PRINT 837
       READ 830,CM,CB, TCB,FCB,SHAM,SHB, TSHB,FSHB, RHO,RHOB, TRHO,FRHO
       PRINT 831,CM,CB,TCB,FCB,SHAM,SHB, TSHB,FSHB, RHO,RHOB, TRHO,FRHO
;      FIN FRONT OF BASE PROPERTY INDICATES FROZEN BASE
;       T IN FRONT  OF BASE PROPERTY INDICATES THAWING BASE
;       NO PREFIX INDICATES BASE IS UNFROZEN
       DELT=.0005
       TFLAM = 4000.
       HEAT1 = .0
       AB=.85
       EM=.95
       SIGMA=1.714E-09
       DM=CM/(RHO*SHAM)
       DB=CB/(RHOB*SHB)
       TDB=TCB/(TRHO*TSHB)
       FDB=FCB/(FRHO*FSHB)
       READ 800, K,J,H, HC,HB
       READ 801, THICK, RUN
       READ 802, NO, (M, TMIX(M), BASE(M), TAS(M), SRS(M), VIEWFA(M),
      1  THEATB(M), TSTALL(M), MN=1,NO)
       Y = K
       DELY = (THICK/12.) / (Y-.5)
       BI = H * DELY / CM
       P=DM*DELT/DELY**2
       Q=DB*DELT/DELY**2
       R=(2.*DM*DELT)/(CM*DELY)
       S = SHAM * RHO * DELY
       V = S / DELT
       B = CM/DELY
       C = CB/DELY
       D = DELY/(2.*CM)
       E = DELY/(2.*CB)
       G = 1./(D+E)
C       W = RHO*SHB*DELY FOR UNFROZEN BASE
C     WFX=RHO*SHB*DELY FOR FROZEN BASE
C     WT=RHO*SHB*DELY FOR THAWING BASE
       W = RHOB * SHB * DELY
       WFX=FRHO*FSHB*DELY
       WT=TRHO*TSHB*DELY
       BUT=1./((DELY/(2.*CB))+(DELY/(2.*TCB)))
```

Table B.1--Continued

Computer Listing

```
      BFT=1./((DELY/(2.*TCB))+(DELY/(2.*FCB)))
      BFX=FCB/DELY
      BFU=1./((DELY/(2.*CB))+(DELY/(2.*FCB)))
      BTM=1./((DELY/(2.*CM))+(DELY/(2.*TCB)))
      BFM=1./((DELY/(2.*CM))+(DELY/(2.*FCB)))
      BT=TCB/DELY
      V=1./((1./HB) + (DELY/2.*CB))
      TZB = U * DELT / (RHOB * SHB * DELY)
      TOB = CB * DELT / (RHOB * SHB * DELY * DELY)
      TSUN = DELT / (RHOB * SHB * DELY)
      M = 1
    1 IF (M - NO) 2,2,100
    2 DO 3 N=1,K
      TO(N)=TMIX(M)
    3 TM(N) = TMIX(M)
      DO 4 I=1,J
      TE(I)=BASE(M)
    4 TB(I) = BASE(M)
      TA = TAS(M)
      SR = SRS(M)
      T = .0
      A = 1.
      L = 1
      TEST = 225.
      K1 = K-1
      J1 = J-1
      HEAT1 = 0.
      PRINT 805, RUN
      PRINT 803, THICK, TMIX(M), BASE(M), TAS(M), SRS(M), DELY, BI
      TOTAL = TM(1)/2.
      DO 31 N=2,K
   31 TOTAL = TOTAL + TM(N)
      PRINT 825,VIEWFA(M), THEATB(M), TSTALL(M)
      ALPHAH = S * TOTAL
      TH=0.0
      TS=0.0
      THEAT = THEATB(M)
      STALL=TSTALL(M)
      TF = TFLAM / 100.
      VIEWF = VIEWFA(M)
      HT = 9999999999.
      IF(VIEWF) 40,40,398
  398 TBS = TFLAM - (UT/HT)*(TFLAM- TB(1))
      TZ = TBS/100.
      HR = ((TF* TF* TF* TF) - (TZ* TZ* TZ* TZ)) * .173*AB/(TFLAM-TBS)
```

Table B.1--Continued

Computer Listing

```
      HT = HR + HC
      UT = 1./((1./HT) + ((DELY/2.) / CB))
      Q2Z = UT* (TFLAM - TB(1) )
      Q2B = Q2Z * VIEWF
      TE(1) = TB(1)
      DELT=.00005
      Q2F=Q2B*DELT
      IF(TB(1)-33.) 406,400,400
  400 Q2=Q2F
      Q3=C*DELT*(TB(1)-TB(2))
      TE(1)=TB(1)
      IF(TB(2)-33.)  401,405,405
  401 IF(TB(2)-31.) 402,403,403
  402 Q3=Q3*(BFU/C)
      GO TO 405
  403 Q3=Q3*(BUT/C)
  405 TB(1)=TB(1)+((Q2-Q3)/W)
      I=2
      GO TO 499
  406 IF(TB(1)-31.) 407,412,412
  407 Q2=Q2F
      Q3=BFX*(TB(1)-TB(2))*DELT
      TE(1)=TB(1)
      TB(1)=TB(1)+((Q2-Q3)/WFX)
      IF(TB(1)-31.) 408,408,409
  408 I=2
      GO TO 499
  409 SHU=WFX*(31.-TE(1))
      TB(1)=31.+((Q2-Q3-SHU)/WT)
      IF(TB(1)-33.) 410,411,411
  410 I=2
      GO TO 499
  411 XLM=WT*2.
      TB(1)=33.+((Q2-Q3-SHU-XLM)/W)
      I=2
      GO TO 499
  412 TE(1)=TB(1)
      Q2=Q2F
      Q3=BFU*DELT*(TB(1)-TB(2))
      IF(TB(2)-31.) 414,414,413
  413 Q3=Q3*(BT/BFU)
  414 TB(1)=TB(1)+((Q2-Q3)/WT)
      IF(TB(1)-33.) 415,415,416
  415 I=2
      GO TO 499
```

Table B.1--Continued

Computer Listing

```
416  SHL=Q2-Q3-(WT*(33.-TE(1)))
     TB(1)=33.+(SHL/W)
     I=2
499  CONTINUE
     TH=TH+DELT
480   GO TO 300
 40  TD(1)=TM(1)
     DELT=.0005
    0TM(1)=TM(1)*(1.-2.*P*(BI+1.))+2.*P*(TM(2)+BI*TA)+R*(SR*AB
    1 -(EM* SIGMA *(TM(1) + 460. ) **4))
     DO 30 N=2,K1
     TD(N)=TM(N)
     TM(N)=TM(N)+P*(TM(N+1)-2.*TM(N)+TD(N-1))
 30  CONTINUE
     IF(TB(1)-33.) 206,200,200
200  Q1=B*DELT*(TD(K-1)-TM(K))
     Q2=G*DELT*(TM(K)-TB(1))
     TD(K)=TM(K)
     TM(K)=TM(K)+((Q1-Q2)/S)
     Q3=C*DELT*(TB(1)-TB(2))
     TE(1)=TB(1)
     IF(TB(2)-33.)  201,205,205
201  IF(TB(2)-31.) 202,203,203
202  Q3=Q3*(BFU/C)
     GO TO 205
203  Q3=Q3*(BUT/C)
205  TB(1)=TB(1)+((Q2-Q3)/W)
     I=2
     GO TO 299
206  IF(TB(1)-31.) 207,212,212
207  Q1=B*DELT*(TD(K-1)-TM(K))
     Q2=BFM*DELT*(TM(K)-TB(1))
     TD(K)=TM(K)
     TM(K)=TM(K)+((Q1-Q2)/S)
     Q3=BFX*(TB(1)-TB(2))*DELT
     TE(1)=TB(1)
     TB(1)=TB(1)+((Q2-Q3)/WFX)
     IF(TB(1)-31.) 208,208,209
208  I=2
     GO TO 299
209  SHU=WFX*(31.-TE(1))
     TB(1)=31.+((Q2-Q3-SHU)/WT)
     IF(TB(1)-33.) 210,211,211
210  I=2
     GO TO 299
```

Table B.1--Continued

Computer Listing

```
211 XLM=WT*2.
    TB(1)=33.+((Q2-Q3-SHU-XLM)/W)
    I=2
    GO TO 299
212 TE(1)=TB(1)
    Q1=B*DELT*(TD(K-1)-TM(K))
    Q2=BTM*DELT*(TM(K)-TB(1))
    TD(K)=TM(K)
    TM(K)=TM(K)+((Q1-Q2)/S)
    Q3=BFU*DELT*(TB(1)-TB(2))
    IF(TB(2)-31.) 214,214,213
213 Q3=Q3*(BT/BFU)
214 TB(1)=TB(1)+((Q2-Q3)/WT)
    IF(TB(1)-33.) 215,215,216
215 I=2
    GO TO 299
216 SHL=Q2-Q3-(WT*(33.-TE(1)))
    TB(1)=33.+(SHL/W)
    I=2
299 CONTINUE
    T=T+DELT
300 IF(TB(I)-31.)301,316,316
301 Q2=BFX*DELT*(TE(I-1)-TB(I))
    IF(TE(I-1)-31.)  302,302,303
302 GO TO 310
303 IF(TE(I-1)-33.) 304,305,305
304 Q2=Q2*(BFT/BFX)
    GO TO 310
305 Q2=Q2*(BFU/BFX)
310 TE(I)=TB(I)
    Q3=BFX*DELT*(TB(I)-TB(I+1))
    TB(I)=TB(I)+((Q2-Q3)/WFX)
    IF(TB(I)-31.) 311,311,313
311 I=I+1
    IF(I-J) 300,399,50
313 SHU=WFX*(31.-TE(I))
    TB(I)=31.+((Q2-Q3-SHU)/WT)
    IF(TB(I)-33.) 314,314,315
314 I=I+1
    IF(I-J) 300,399,50
315 XLM=WT*2.
    TB(I)=33.+((Q2-Q3-SHU-XLM)/W)
    I=I+1
    IF(I-J) 300,399,50
316 IF(TB(I)-33.) 317,320,320
```

Table B.1--Continued

Computer Listing

```
317 Q2=BUT*DELT*(TE(I-1)-TB(I))
    TE(I)=TB(I)
    Q3=BFT*DELT*(TB(I)-TB(I+1))
    TB(I)=TB(I)+((Q2-Q3)/WT)
    IF(TB(I)-33.) 318,318,319
318 I=I+1
    IF(I-J) 300,399,50
319 SHL=Q2-Q3-WT*(33.-TE(I))
    TB(I)=33.+(SHL/W)
    I=I+1
    IF(I-J) 300,399,50
320 IF(TB(I+1)-33.) 322,321,321
321 TE(I)=TB(I)
    TB(I)=TB(I)+(((DB *DELT)*(TE(I-1)+TB(I+1)-2.*TB(I)))/(DELY**2))
325 I=I+1
    IF(I-J) 300,399,50
322 Q2=DELT*C*(TE(I-1)-TB(I))
    Q3=BFU*DELT*(TB(I)-TB(I+1))
    TE(I)=TB(I)
    IF(TB(I+1)-31.) 323,323,324
323 TB(I)=TB(I)+((Q2-Q3)/W)
    GO TO 325
324 Q3=Q3*(BUT/BFU)
    GO TO 323
399 TB(I+1)=TB(I)
    GO TO 300
 50 CONTINUE
    IF(THEAT) 418,418,417
417 IF(TH-THEAT)  398,418,418
418 IF(TS.GT.0.) GO TO 436
470 PRINT 810,TH,TB(1)
    PRINT 820, TB
436 IF(STALL) 419,419,420
420 IF(TS-STALL) 430,438,438
438 IF(T.GT.0.) GO TO 419
450 PRINT 814,TS,TB(1)
    PRINT 820, TB
    GO TO 419
430 TE(1) = TB(1)
    UT = U
    TBS = TB(1) +((TA -  TB(1))* UT)  / (2. * CB/ DELY)
    TB(1)=TB(1)*(1.-TZB-TOB)+TZB*TA+TOB*TB(2)+TSUN*(SR*AB-(EM*SIGMA*
   1 (TBS + 460.)**4 ))
    DELT=.0005
    TS = TS+DELT
```

Table B.1--Continued

Computer Listing

```
440 I=2
    GO TO 300
419 IF(T) 40,40,33
 330QTOP = (BI*CM/DELY)*(TM(1)-TA) +EM*SIGMA*((TM(1)+460.)**4)
   1 - SR*AB
    QBTM = V*(TD(K)-TM(K))  + CM*(TD(K-1)-TD(K))  /DELY
    PARCEL = DELT * (QTOP +QBTM)
    HEAT1 = HEAT1 + PARCEL
    TOTAL = TM(1)/2.
    DO 32 N=2,K
 32 TOTAL = TOTAL + TM(N)
    ZETAH = S* TOTAL
    HEAT2 = ALPHAH - ZETAH
    CHECK = 100. * ( HEAT2 - HEAT1 ) / HEAT2
    AVGT = TOTAL / (Y-.5)
    QUANT = TMIX(M) * THICK
 10 TIME = 60. * T
    IF (TIME - 60.) 53,53,80
 53 IF (AVGT - TEST) 70,70,60
 60 IF (TIME-A) 40,65,65
 65 PRINT 880, TIME, AVGT, QTOP, QBTM, HEAT1, HEAT2, CHECK
    PRINT 820, TM
    PRINT 820, TB
    A = A + 1.
    GO TO 40
 70 TEST = TEST - 25.
    TIMIT(L) = TIME
    TEMP(L) = AVGT
    L = L+1
    IF (TEST - 150.) 90,90,60
 80 TIMIT(L) = TIME
    TEMP(L) = AVGT
 90 PRINT 806, RUN
    PRINT 807, THICK, TMIX(M), BASE(M), TAS(M), SRS(M)
    DO 91 L=1,4
 91 PRINT 804, TEMP(L), TIMIT(L)
    PRINT 808, QUANT
    PRINT 825,VIEWFA(M), THEATB(M), TSTALL(M)
    PUNCH 840, RUN, (TIMIT(I), I = 1,3)
840 FORMAT (4F10.3)
    RUN = RUN + 1.
    M = M + 1
    GO TO 1
800 FORMAT (I2,8X,I2,8X,3F10.0)
801 FORMAT (2F10.0)
```

Table B.1--Continued

Computer Listing

```
 802 FORMAT (I2/(I2,8X,7F10.0))
 8030FORMAT (10X,18HTHICKNESS OF MAT =F6.2,2X,6HINCHES/10X,25HINITIAL M
    1IX TEMPERATURE =F6.0,2X,9HDEGREES F/10X,26HINITIAL BASE TEMPERATUR
    2E =F6.0,2X,9HDEGREES F/10X,25HATMOSPHERIC TEMPERATVRE =F6.0,2X,9HD
    3EGREES F/10X,20HSOLAR RADIANT FLUX =F6.0,2X,12HBTU/SQ FT/HR/10X,23
    4HSIZE OF MIX INCREMENT =F12.8,2X,2HFT/10X,13HBIOT NUMBER =F12.8/)
804  FORMAT (10X,23HTIME FOR MAT TO COOL TOF7.1,2X,11HDEGREES F =F8.2,2
    1X,7HMINUTES)
 805 FORMAT (//10X,23HBEGINNING OF RUN NUMBERF6.0//)
 806 FORMAT (//10X,21HSUMMARY OF RUN NUMBERF6.0//)
 8070FORMAT (10X,18HTHICKNESS OF MAT =F6.2,2X,6HINCHES/10X,25HINITIAL M
    1IX TEMPERATURE =F6.0,2X,9HDEGREES F/10X,26HINITIAL BASE TEMPERATUR
    2E =F6.0,2X,9HDEGREES F/10X,25HATMOSPHERIC TEMPERATURE =F6.0,2X,9HD
    3EGREES F/10X,20HSOLAR RADIANT FLUX =F6.0,2X,12HBTU/SQ FT/HR)
 808 FORMAT (10X,12HHEAT INDEX =,F6.0)
 820 FORMAT (10F7.1)
 880 FORMAT (7F10.1)
 810 FORMAT(19H TIME OF HEATING = F10.6,7H HOURS./25H TEMPERATURE OF NO
    1DE 1 = F10.3/)
 811 FORMAT(25H TEMPERATURE AT NODE 2 = F10.5)
 813 FORMAT(15H TIME OF MAT = F10.5)
 814 FORMAT(17H TIME OF STALL = F10.5,6H HOURS/25H TEMPERATURE AT NODE
    11 = F10.5 /)
 825 FORMAT(50H VIEW FACTOR FOR HEATING AT 4000 DEGREE F FLAME = F10.5,
    1/ 19H TIME OF HEATING = F10.5,2X,7H HOURS./49H TIME BETWEEN HEATER
    2 INPUT AND ASPHALT LAYDOWN = F10.5,2X,7H HOURS./)
 830 FORMAT(8F10.5)
 831 FORMAT(41H PHYSICAL PROPERTIES OF ASPHALT AND BASE.//  31H THERMAL
    1 CONDUCTIVITY OF MAT = F 8.3,11H OF BASE = F 8.3,  19H OF THAWING
    2BASE = F 8.3,  18H OF FROZEN BASE = F 8.3,  /24H HEAT CAPACITY OF
    3MAT = F 8.3,  11H OF BASE = F 8.3,  18H OF FROZEN BASE = F 8.3,
    436H FICTIVE CAPACITY OF THAWING BASE = F8.3/  18H DENSITY OF MAT =
    5 F8.3, 12H, OF BASE = F8.3,  20H, OF THAWING BASE = F8.3,
    6  19H, OF FROZEN BASE = F8.3)
 835 FORMAT(19H TIME OF HEATING = F9.5,  17H TIME OF STALL = F8.5/)
 836 FORMAT(I2)
837  FORMAT (1H1)
 100 CONTINUE
     PRINT 837
     STOP
     END
```

Table B.2

Computer Listing

```
 ODIMENSION TM(20), TB(41), TEMP(8), TIMIT(8),
 1 TMIX(50), BASE(50), TAS(50), SRS(50), TD(20), TE(41)
  DIMENSION VIEWFA(50), THEATB(50), TSTALL(50)
  READ 836, NOTURN
  DO 100 II = 1, NOTURN
  PRINT 837
  READ 830, VSHB
  READ 830,CM,CB, TCB,FCB,SHAM,SHB, TSHB,FSHB, RHO,RHOB, TRHO,FRHO
  PRINT 831,CM,CB,TCB,FCB,SHAM,SHB, TSHB,FSHB, RHO,RHOB, TRHO,FRHO
  PRINT 832, VSHB
; FIN FRONT OF BASE PROPERTY INDICATES FROZEN BASE
;  T IN FRONT  OF BASE PROPERTY INDICATES THAWING BASE
;  NO PREFIX INDICATES BASE IS UNFROZEN
  DELT=.0005
  TFLAM = 4000.
  HEAT1 = .0
  AB=.85
  EM=.95
  SIGMA=1.714E-09
  DM=CM/(RHO*SHAM)
  DB=CB/(RHOB*SHB)
  TDB=TCB/(TRHO*TSHB)
  FDB=FCB/(FRHO*FSHB)
  READ 800, K,J,H, HC,HB
  READ 801, THICK, RUN
  READ 802, NO, (M, TMIX(M), BASE(M), TAS(M), SRS(M), VIEWFA(M),
 1  THEATB(M), TSTALL(M), MN=1,NO)
  Y = K
  DELY = (THICK/12.) / (Y-.5)
  BI = H * DELY / CM
  P=DM*DELT/DELY**2
  O=DB*DELT/DELY**2
  R=(2.*DM*DELT)/(CM*DELY)
  S = SHAM * RHO * DELY
  V = S / DELT
  B = CM/DELY
  C = CB/DELY
  D = DELY/(2.*CM)
  E = DELY/(2.*CB)
  G = 1./(D+E)
;   W = RHO*SHB*DELY FOR UNFROZEN BASE
; WFX=RHO*SHB*DELY FOR FROZEN BASE
; WT=RHO*SHB*DELY FOR THAWING BASE
  W = RHOB * SHB * DELY
  WFX=FRHO*FSHB*DELY
```

Table B.2--Continued

Computer Listing

```
      WT=TRHO*TSHB*DELY
      BUT=1./((DELY/(2.*CB))+(DELY/(2.*TCB)))
      BFT=1./((DELY/(2.*TCB))+(DELY/(2.*FCB)))
      BFX=FCB/DELY
      BFU=1./((DELY/(2.*CB))+(DELY/(2.*FCB)))
      BTM=1./((DELY/(2.*CM))+(DELY/(2.*TCB)))
      BFM=1./((DELY/(2.*CM))+(DELY/(2.*FCB)))
      BT=TCB/DELY
      U=1./((1./HB) + (DELY/2.*CB))
      TZB = U * DELT / (RHOB * SHB * DELY)
      TOB = CB * DELT / (RHOB * SHB * DELY * DELY)
      TSUN = DELT / (RHOB * SHB * DELY)
      M = 1
    1 IF (M - NO) 2,2,100
    2 DO 3 N=1,K
      TD(N)=TMIX(M)
    3 TM(N) = TMIX(M)
      DO 4 I=1,J
      TE(I)=BASE(M)
    4 TB(I) = BASE(M)
      TA = TAS(M)
      SR = SRS(M)
      T = .0
      A = 1.
      L = 1
      TEST = 225.
      PRINT 805, RUN
      PRINT 803, THICK, TMIX(M), BASE(M), TAS(M), SRS(M), DELY, BI
      PRINT 825,VIEWFA(M), THEATB(M), TSTALL(M)
      K1 = K-1
      J1 = J-1
      HEAT1 = 0.
      TOTAL = TM(1)/2.
      DO 31 N=2,K
   31 TOTAL = TOTAL + TM(N)
      ALPHAH = S * TOTAL
      WTV = RHOB* VSHB * DELY
      TS=0.0
      TH =0.0
      THEAT = THEATB(M)
      STALL=TSTALL(M)
      TF = TFLAM / 100.
      VIEWF = VIEWFA(M)
      HT = 9999999999.
      IF(VIEWF) 40,40,398
```

Table B.2--Continued

Computer Listing

```
398 TBS = TFLAM - (UT/HT)*(TFLAM- TB(1))
    TZ = TBS/100.
    HR = ((TF* TF* TF* TF) - (TZ* TZ* TZ* TZ)) * .173*AB/(TFLAM-TBS)
    HT = HR + HC
    UT = 1./((1./HT) + ((DELY/2.) / CB))
    Q2Z = UT* (TFLAM - TB(1))
    Q2B = Q2Z * VIEWF
    TE(1) = TB(1)
    DELT=.00005
    Q2F=Q2B*DELT
    IF(TB(1)-33.) 406,400,400
400 IF(TB(1).GT.100.) GO TO 599
    Q2 = Q2F
    Q3=C*DELT*(TB(1)-TB(2))
    TE(1)=TB(1)
    IF(TB(2)-33.)  401,405,405
401 IF(TB(2)-31.) 402,403,403
402 Q3=Q3*(BFU/C)
    GO TO 405
403 Q3=Q3*(BUT/C)
405 TB(1)=TB(1)+((Q2-Q3)/W)
    I=2
    GO TO 499
406 IF(TB(1)-31.) 407,412,412
407 Q2=Q2F
    Q3=BFX*(TB(1)-TB(2))*DELT
    TE(1)=TB(1)
    TB(1)=TB(1)+((Q2-Q3)/WFX)
    IF(TB(1)-31.) 408,408,409
408 I=2
    GO TO 499
409 SHU=WFX*(31.-TE(1))
    TB(1)=31.+((Q2-Q3-SHU)/WT)
    IF(TB(1)-33.) 410,411,411
410 I=2
    GO TO 499
411 XLM=WT*2.
    TB(1)=33.+((Q2-Q3-SHU-XLM)/W)
    I=2
    GO TO 499
412 TE(1)=TB(1)
    Q2=Q2F
    Q3=BFU*DELT*(TB(1)-TB(2))
    IF(TB(2)-31.) 414,414,413
413 Q3=Q3*(BT/BFU)
```

Table B.2--Continued

Computer Listing

```
 414 TB(1)=TB(1)+((Q2-Q3)/WT)
     IF(TB(1)-33.) 415,415,416
 415 I=2
     GO TO 499
 416 SHL=Q2-Q3-(WT*(33.-TE(1)))
     TB(1)=33.+(SHL/W)
     I=2
 499 CONTINUE
     TH=TH+DELT
 480  GO TO 300
 599 IF(TB(1) - 220.) 606,600,600
 600 Q2 = Q2F
     Q3 = C*DELT*(TB(1) - TB(2))
     TE(1) = TB(1)
     IF(TB(2) - 33.) 601,604,604
 601 IF(TB(2)- 31.) 602,603,603
 602 Q3 = Q3*(BFU/C)
     GO TO 604
 603 Q3 = Q3*(BVT/C)
 604 CONTINUE
 605 TB(1) = TB(1) + ((Q2 - Q3)/W)
     I = 2
     GO TO 499
 606 IF(TB(1) - 210.) 607,612,612
 607 Q2 = Q2F
     Q3 = C*DELT*(TB(1) - TB(2))
     TE(1) = TB(1)
     IF(TB(2) - 33.) 2601,2604,2604
2601 IF(TB(2) - 31.) 2602,2603,2603
2602 Q3 = Q3*(BFU/C)
     GO TO 2604
2603 Q3 = Q3*(BUT/C)
2604 CONTINUE
     TB(1) = TB(1) + ((Q2 - Q3)/W)
     IF(TB(1) - 210.) 608,608,609
 608 I = 2
     GO TO 499
 609 SHU = W*(210. - TE(1))
     TB(1) = 210. + ((Q2 - Q3 - SHU)/WTV)
     IF(TB(1) - 220.) 610,611,611
 610 I = 2
     GO TO 499
 611 XLM = WTV*10.
     TB(1) = 220. + ((Q2 - Q3 - SHU - XLM)/W)
     I=2
```

Table B.2--Continued

Computer Listing

```
      GO TO 499
  612 TE(1) = TB(1)
      Q2 = Q2F
      Q3 = C*DELT*(TB(1) - TB(2))
  613 CONTINUE
      IF(TB(2) - 33.) 3601,3604,3604
 3601 IF(TB(2) - 31.) 3602,3603,3603
 3602 Q3 = Q3*(BFU/C)
       GO TO 3604
 3603 Q3 = Q3*(BUT/C)
 3604 CONTINUE
  614 TB(1) = TB(1) + ((Q2 - Q3)/WTV)
      IF(TB(1) - 220. ) 615,615,616
  615 I = 2
      GO TO 499
  616 SHL = Q2-Q3 - (WTV*(220. - TE(1)) )
      TB(1) = 220. + (SHL/W)
       I = 2
      GO TO 499
   40 TD(1)=TM(1)
      DELT=.0005
     OTM(1)=TM(1)*(1.-2.*P*(BI+1.))+2.*P*(TM(2)+BI*TA)+R*(SR*AB
     1 -(EM* SIGMA *(TM(1) + 460. ) **4))
      DO 30 N=2,K1
      TD(N)=TM(N)
      TM(N)=TM(N)+P*(TM(N+1)-2.*TM(N)+TD(N-1))
   30 CONTINUE
      IF(TB(1)-33.) 206,200,200
  200 Q1=B*DELT*(TD(K-1)-TM(K))
      Q2=G*DELT*(TM(K)-TB(1))
      TD(K)=TM(K)
      TM(K)=TM(K)+((Q1-Q2)/S)
      Q3=C*DELT*(TB(1)-TB(2))
      TE(1)=TB(1)
      IF(TB(2)-33.)  201,205,205
  201 IF(TB(2)-31.) 202,203,203
  202 Q3=Q3*(BFU/C)
      GO TO 205
  203 Q3=Q3*(BUT/C)
  205 TB(1)=TB(1)+((Q2-Q3)/W)
      I=2
      GO TO 299
  206 IF(TB(1)-31.) 207,212,212
  207 Q1=B*DELT*(TD(K-1)-TM(K))
      Q2=BFM*DELT*(TM(K)-TB(1))
```

Table B.2--Continued

Computer Listing

```
      TD(K)=TM(K)
      TM(K)=TM(K)+((Q1-Q2)/S)
      Q3=BFX*(TB(1)-TB(2))*DELT
      TE(1)=TB(1)
      TB(1)=TB(1)+((Q2-Q3)/WFX)
      IF(TB(1)-31.) 208,208,209
  208 I=2
      GO TO 299
  209 SHU=WFX*(31.-TE(1))
      TB(1)=31.+((Q2-Q3-SHU)/WT)
      IF(TB(1)-33.) 210,211,211
  210 I=2
      GO TO 299
  211 XLM=WT*2.
      TB(1)=33.+((Q2-Q3-SHU-XLM)/W)
      I=2
      GO TO 299
  212 TE(1)=TB(1)
      Q1=B*DELT*(TD(K-1)-TM(K))
      Q2=BTM*DELT*(TM(K)-TB(1))
      TD(K)=TM(K)
      TM(K)=TM(K)+((Q1-Q2)/S)
      Q3=BFU*DELT*(TB(1)-TB(2))
      IF(TB(2)-31.) 214,214,213
  213 Q3=Q3*(BT/BFU)
  214 TB(1)=TB(1)+((Q2-Q3)/WT)
      IF(TB(1)-33.) 215,215,216
  215 I=2
      GO TO 299
  216 SHL=Q2-Q3-(WT*(33.-TE(1)))
      TB(1)=33.+(SHL/W)
      I=2
  299 CONTINUE
      T=T+DELT
  300 IF(TB(I)-31.)301,316,316
  301 Q2=BFX*DELT*(TE(I-1)-TB(I))
      IF(TE(I-1)-31.)  302,302,303
  302 GO TO 310
  303 IF(TE(I-1)-33.) 304,305,305
  304 Q2=Q2*(BFT/BFX)
      GO TO 310
  305 Q2=Q2*(BFU/BFX)
  310 TE(I)=TB(I)
      Q3=BFX*DELT*(TB(I)-TB(I+1))
      TB(I)=TB(I)+((Q2-Q3)/WFX)
```

Table B.2--Continued

Computer Listing

```
      IF(TB(I)-31.) 311,311,313
 311  I=I+1
      IF(I-J) 300,399,50
 313  SHU=WFX*(31.-TE(I))
      TB(I)=31.+((Q2-Q3-SHV)/WT)
      IF(TB(I)-33.) 314,314,315
 314  I=I+1
      IF(I-J) 300,399,50
 315  XLM=WT*2.
      TB(I)=33.+((Q2-Q3-SHU-XLM)/W)
      I=I+1
      IF(I-J) 300,399,50
 316  IF(TB(I)-33.) 317,320,320
 317  Q2=BUT*DELT*(TE(I-1)-TB(I))
      TE(I)=TB(I)
      Q3=BFT*DELT*(TB(I)-TB(I+1))
      TB(I)=TB(I)+((Q2-Q3)/WT)
      IF(TB(I)-33.) 318,318,319
 318  I=I+1
      IF(I-J) 300,399,50
 319  SHL=Q2-Q3-WT*(33.-TE(I))
      TB(I)=33.+(SHL/W)
      I=I+1
      IF(I-J) 300,399,50
 320  IF(TB(I+1)-33.) 322,321,321
 321  TE(I) = TB(I)
      IF(TB(I) - 220.) 706,700,700
 700  TE(I) = TB(I)
      Q2 = C*DELT*(TE(I-1) - TB(I))
      Q3 = C*DELT*(TB(I) - TB(I+1))
      IF(TB(I+1) - 33.) 4601,4604,4604
4601  IF(TB(I+1) - 31.) 4602,4603,4603
4602  Q3 = Q3*(BFU/C)
      GO TO 4604
4603  Q3 = Q3*(BUT/C)
4604  CONTINUE
      TB(I) = TB(I) + ((Q2 - Q3)/W)
      IF(TB(I) - 220.) 701,705,705
 701  SHU = W*(TE(I) - 220.)                                          *
      TB(I) = 220. + ((Q2 - Q3- SHU)/WTV)                             *
 705  GO TO 325
 706  IF(TB(I) -  210.) 707,712,712
 707  TE(I) = TB(I)
      Q2 = C*DELT*(TE(I-1) - TB(I))
      Q3 = C*DELT*(TB(I) - TB(I+1))
```

Table B.2--Continued

Computer Listing

```
      IF(TB(I+1) - 33.) 5601,5604,5604
 5601 IF(TB(I+1) - 31.) 5602,5603,5603
 5602 Q3 = Q3*(BFU/C)
      GO TO 5604
 5603 Q3 = Q3*(BUT/C)
 5604 CONTINUE
      TB(I) = TB(I) + ((Q2 - Q3)/W)
      IF(TB(I) - 210.) 708,708,709
  708 GO TO 325
  709 SHU = W*(210. - TE(I))
      TB(I) = 210. + ((Q2 - Q3 - SHU)/WTV)
      IF(TB(I) - 220.) 710,711,711
  710 GO TO 325
  711 XLM = WTV*10.
      TB(I) = 220. + ((Q2 - Q3- SHU -XLM)/W)
      GO TO 325
  712 TE(I) = TB(I)
      Q2 = C*DELT*(TE(I-1) - TB(I))
      Q3 = C*DELT*(TB(I) - TB(I+1))
  713 CONTINUE
      IF(TB(I+1) - 33.) 6601,6604,6604
 6601 IF(TB(I+1) - 31.) 6602,6603,6603
 6602 Q3 = Q3*(BFU/C)
      GO TO 6604
 6603 Q3 = Q3*(BUT/C)
 6604 CONTINUE
  714 TB(I) = TB(I) + ((Q2 - Q3)/WTV)
      IF(TB(I) - 220.) 715,715,716
  715 IF(TB(I) - 210.) 717,718,718                                  *
  717 SHL = Q2 - Q3 - (WTV*(TE(I) - 210.))                          *
      TB(I) = 210. + (SHL/W)                                        *
  718 GO TO 325                                                     *
  716 SHL = Q2 - Q3 - (WTV*(220. - TE(I)))
      TB(I) = 220. + (SHL/W)
      GO TO 325
  325 I=I+1
      IF(I-J) 300,399,50
  322 IF(TB(I-1).GT.210.) GO TO 321
      Q2=DELT*C*(TE(I-1)-TB(I))
      Q3=BFU*DELT*(TB(I)-TB(I+1))
      TE(I)=TB(I)
      IF(TB(I+1)-31.) 323,323,324
  323 TB(I)=TB(I)+((Q2-Q3)/W)
      GO TO 325
  324 Q3=Q3*(BUT/BFU)
```

Table B.2--Continued

Computer Listing

```
      GO TO 323
  399 TB(I+1)=TB(I)
      GO TO 300
   50 CONTINUE
  490 IF(THEAT) 418,418,417
  417 IF(TH-THEAT)  398,418,418
  418 IF(TS.GT.0.) GO TO 436
  470 PRINT 810,TH,TB(1)
      PRINT 820, TB
  436 IF(STALL) 419,419,420
  420 IF(TS-STALL) 430,438,438
  438 IF(T.GT.0.) GO TO 419
  450 PRINT 814,TS,TB(1)
      PRINT 820, TB
      GO TO 419
  430 TE(1) = TB(1)
      UT = U
      TBS = TB(1) +((TA -  TB(1))* UT)  / (2. * CB/ DELY)
      TB(1)=TB(1)*(1.-TZB-TOB)+TZB*TA+TOB*TB(2)+TSUN*(SR*AB-(EM*SIGMA*
     1 (TBS + 460.)**4.))
      DELT=.0005
      TS = TS+DELT
  440 I=2
      GO TO 300
  419 IF(T) 40,40,33
 3300QTOP = (BI*CM/DELY)*(TM(1)-TA) +EM*SIGMA*((TM(1)+460.)**4)
     1 - SR*AB
      QBTM = V*(TD(K)-TM(K))  + CM*(TD(K-1)-TD(K))  /DELY
      PARCEL = DELT * (QTOP +QBTM)
      HEAT1 = HEAT1 + PARCEL
      TOTAL = TM(1)/2.
      DO 32 N=2,K
   32 TOTAL = TOTAL + TM(N)
      ZETAH = S* TOTAL
      HEAT2 = ALPHAH - ZETAH
      CHECK = 100. * ( HEAT2 - HEAT1 ) / HEAT2
      AVGT = TOTAL / (Y-.5)
      QUANT = TMIX(M) * THICK
   10 TIME = 60. * T
      IF (TIME - 60.) 53,53,80
   53 IF (AVGT - TEST) 70,70,60
   60 IF (TIME-A) 40,65,65
   65 PRINT 880, TIME, AVGT, QTOP, QBTM, HEAT1, HEAT2, CHECK
      PRINT 820, TM
      PRINT 820, TB
```

Table B.2--Continued

Computer Listing

```
      A = A + 1.
      GO TO 40
   70 TEST = TEST - 25.
      TIMIT(L) = TIME
      TEMP(L) = AVGT
      L = L+1
      IF (TEST - 150.) 90,90,60
   80 TIMIT(L) = TIME
      TEMP(L) = AVGT
   90 PRINT 806, RUN
      PRINT 807, THICK, TMIX(M), BASE(M), TAS(M), SRS(M)
      DO 91 L=1,4
   91 PRINT 804, TEMP(L), TIMIT(L)
      PRINT 808, QUANT
      PRINT 825,VIEWFA(M), THEATR(M), TSTALL(M)
      PUNCH 840, RUN, (TIMIT(I), I = 1,3)
  840 FORMAT (4F10.3)
      RUN = RUN + 1.
      M = M + 1
      GO TO 1
  800 FORMAT (I2,8X,I2,8X,3F10.0)
  801 FORMAT (2F10.0)
  802 FORMAT (I2/(I2,8X,7F10.0))
  8030FORMAT (10X,18HTHICKNESS OF MAT =F6.2,2X,6HINCHES/10X,25HINITIAL M
     1IX TEMPERATURE =F6.0,2X,9HDEGREES F/10X,26HINITIAL BASE TEMPERATUR
     2E =F6.0,2X,9HDEGREES F/10X,25HATMOSPHERIC TEMPERATURE =F6.0,2X,9HD
     3EGREES F/10X,20HSOLAR RADIANT FLUX =F6.0,2X,12HBTU/SQ FT/HR/10X,23
     4HSIZE OF MIX INCREMENT =F12.8,2X,2HFT/10X,13HBIOT NUMBER =F12.8/)
  804 FORMAT (10X,23HTIME FOR MAT TO COOL TOF7.1,2X,11HDEGREES F =F8.2,2
     1X,7HMINVTES)
  805 FORMAT (//10X,23HBEGINNING OF RUN NUMBERF6.0//)
  806 FORMAT (//10X,21HSUMMARY OF RUN NUMBERF6.0//)
  8070FORMAT (10X,18HTHICKNESS OF MAT =F6.2,2X,6HINCHES/10X,25HINITIAL M
     1IX TEMPERATURE =F6.0,2X,9HDEGREES F/10X,26HINITIAL BASE TEMPERATUR
     2E =F6.0,2X,9HDEGREES F/10X,25HATMOSPHERIC TEMPERATURE =F6.0,2X,9HD
     3EGREES F/10X,20HSOLAR RADIANT FLVX =F6.0,2X,12HBTV/SQ FT/HR)
  808 FORMAT (10X,12HHEAT INDEX =,F6.0)
  820 FORMAT (10F7.1)
  880 FORMAT (7F10.1)
  810 FORMAT(19H TIME OF HEATING = F10.6,7H HOURS./25H TEMPERATURE OF NO
     1DE 1 = F10.3/)
  811 FORMAT(25H TEMPERATURE AT NODE 2 = F10.5)
  813 FORMAT(15H TIME OF MAT = F10.5)
  814 FORMAT(17H TIME OF STALL = F10.5,6H HOURS/25H TEMPERATURE AT NODE
     11 = F10.5 /)
```

Table B.2--Continued

Computer Listing

```
 825 FORMAT(50H VIEW FACTOR FOR HEATING AT 4000 DEGREE F FLAME = F10.5,
    1/ 19H TIME OF HEATING = F10.5,2X,7H HOURS./49H TIME BETWEEN HEATER
    2 INPUT AND ASPHALT LAYDOWN = F10.5,2X,7H HOURS./)
 830 FORMAT(8F10.5)
 831 FORMAT(41H PHYSICAL PROPERTIES OF ASPHALT AND BASE.//  31H THERMAL
    1 CONDUCTIVITY OF MAT = F 8.3,11H OF BASE = F 8.3,  19H OF THAWING
    2BASE = F 8.3,  18H OF FROZEN BASE = F 8.3,  /24H HEAT CAPACITY OF
    3MAT = F 8.3,  11H OF BASE = F 8.3,  18H OF FROZEN BASE = F 8.3,
    436H FICTIVE CAPACITY OF THAWING BASE = F8.3/  18H DENSITY OF MAT =
    5 F8.3, 12H, OF BASE = F8.3,  20H, OF THAWING BASE = F8.3,
    6  19H, OF FROZEN BASE = F8.3)
 832 FORMAT(45H FICTIVE HEAT CAPACITY DVRING VAPORIZATION = F10.5)
 835 FORMAT(19H TIME OF HEATING = F9.5,  17H TIME OF STALL = F8.5/)
 836 FORMAT(I2)
837  FORMAT (1H1)
 100 CONTINUE
     PRINT 837
     STOP
     END
```

*Note: Table B.2 is a listing assuming only first node steam loss. To obtain results assuming complete steam loss, first remove all cards with an * at the end. Then replace card 701 with the statement

701 WTV = W

Also replace card 715 with the card

715 GO TO 325

Table B.3

How to feed data into program

*1. Read in the number of environmental conditions to be investigated as NOTURN.

2. Decide on condition of top ½-inch of base. If it is moist, use program 2 with VSHE the appropriate number. If it is dry use program 1.

3. Read in the thermal conductivity of the asphalt and base during normal, thawing, and frozen conditions, along with the specific heat of the asphalt and base during normal, thawing, and frozen conditions.

4. Read in the density of the asphalt and base during normal, thawing, and frozen conditions.

5. Read in the number of nodes in the asphalt and in the base. Read in the convective heat transfer coefficient of the asphalt, of the base during heating, and of the base during stall.

6. Read in the thickness of the base, and the run number.

7. Read in the number of combinations of temperatures, heating time, stall time, and view factor to be investigated.

8. Read in combination number, initial temperatures of the asphalt, initial base temperature, initial atmospheric temperature, solar radiant flux, view factor, time of heating and time of stall.

*Each number implies a new data card.

Table B.4

Fortran Code Used in Computer Listing

TM( )	Temperature of a point in the hot-mix asphalt concrete, ^{o}F
TB( )	Temperature of a point in the base, ^{o}F
TIME	Time, hr
A	Time, min
TA	Atmospheric temperature, ^{o}F
CM	Thermal conductivity of hot-mix asphalt concrete, Btu, hr^{-1}, ft^{-1}, $^{o}F^{-1}$
CB	Thermal conductivity of base, Btu, hr^{-1},ft^{-1},$^{o}F^{-1}$
TCB	Thawing thermal conductivity of base, Btu, hr^{-1}, ft^{-1}, $^{o}F^{-1}$
FCB	Frozen thermal conductivity of base, Btu, hr^{-1}, ft^{-1}, $^{o}F^{-1}$
DM	Thermal diffusivity of hot-mix asphalt concrete, ft^2, hr^{-1}
DB	Thermal diffusivity of base, ft^2, hr^{-1}
TDB	Thermal diffusivity of hot-mix asphalt concrete, ft^2, hr^{-1}
FDB	Frozen diffusivity of hot-mix asphalt concrete, ft^2, hr^{-1}
DELT	Incremental time, hr
DELY	Thickness of element in hot-mix asphalt concrete, ft
BI	Biot number, dimensionless
SRS( )	Solar radiant flux, Btu, ft^{-2}, hr^{-1}
AB	Total absorptance of hot-mix asphalt concrete surface, dimensionless

EM	Total emittance of hot-mix asphalt concrete surface, dimensionless
SIGMA	Stephan-Boltzmann constant, 1.714×10^{-9}, Btu, ft^{-2}, hr^{-1}, $^{o}R^{-4}$
THICK	Thickness of lift, in.
SHAME	Specific heat of hot-mix asphalt concrete, Btu, lb^{-1}, $^{o}F^{-1}$
SHB	Specific heat of unfrozen base, Btu, lb^{-1}, $^{o}F^{-1}$
TSHB	Specific heat of thawing base, Btu, lb^{-1}, $^{o}F^{-1}$
FSHB	Specific heat of frozen base, Btu, lb^{-1}, $^{o}F^{-1}$
VSHB	Specific heat of vaporizing base, Btu, lb^{-1}, $^{o}F^{-1}$
RHO	Density of hot mix asphalt concrete, lb, ft^{-3}
RHOB	Density of unfrozen base, lb, ft^{-3}
TRHO	Density of thawing base, lb, ft^{-3}
FRHO	Density of frozen base, lb, ft^{-3}
TFLAM	Flame temperature, ^{o}F
K	Number of finite-difference nodes in mix
J	Number of finite-difference nodes in base
H	Convective heat transfer coefficient for mix, Btu, ft^{-2}, hr^{-1}, $^{o}F^{-1}$
HC	Forced convective heat transfer coefficient during heating, Btu, ft^{-2}, hr^{-1}, $^{o}F^{-1}$
HB	Convective heat transfer coefficient for base, Btu, ft^{-2}, hr^{-1}, $^{o}F^{-1}$
RUN	Run number
NO	Number of separate runs within the conditions specified
NOTURN	Number of conditions specified

TMIX( )	Initial temperature of the hot-mix asphalt concrete, ^{o}F
BASE( )	Initial base temperature, ^{o}F
TAS( )	Initial atmospheric temperature, ^{o}F
VIEWFA( )	View factor
THEATB( )	Time of heating, hr
TSTALL( )	Time between heater input and asphalt laydown, hr
TBS	Surface temperature, ^{o}F
P,Q,R,S V,B,C,D, E,G,WFX, WT,BUT, BFT,BFX, BTM,BFM, BT,TZB, TOB,TSUM, WTV,TF, TZ,Q2Z, Q2F,Q2, Q3,SHU, XLM,SHL	Constants, evaluated as indicated in computer program
U	Combined overall heat transfer coefficient in the base during stall, Btu, ft^{-2}, hr^{-1}, $^{o}F^{-1}$
UT	Combined overall heat transfer coefficient in the base during heating, Btu, ft^{-2}, hr^{-1}, $^{o}F^{-1}$
QLB	Heat flux into the base, Btu, hr^{-1}
HEAT 1	Difference between initial heat content of 1 sq ft of asphalt hot-mix concrete and heat content at any particular time, T, as determined from energy fluxes and time, Btu
TOTAL	Weighted average of temperatures of all incremental elements in the hot-mix asphalt concrete, ^{o}F
ALPHAH	Initial heat content (above 0 ^{o}F) of 1 sq ft of hot-mix asphalt concrete, Btu
QTOP	Net thermal energy flux from upper surface of hot-mix asphalt concrete into atmosphere, Btu, ft^{-2}, hr^{-1}

QBTM	Thermal energy flux from lower surface of hot-mix asphalt concrete into base, Btu, ft^{-2}, hr^{-1}
PARCEL	Incremental decrease in thermal energy of 1 sq ft of hot-mix asphalt concrete as determined from thermal energy fluxes and incremental time, Btu
ZETAH	Heat content (above 0 ^{o}F) at any particular time, T, of 1 sq ft of hot-mix asphalt concrete
HEAT 2	Difference between initial heat content of 1 sq ft of asphalt hot-mix concrete and heat content at any particular time, T, determined from temperature distribution in the hot-mix asphalt concrete
CHECK	The percentage difference in the decrease in thermal energy of hot-mix asphalt concrete as determined from HEAT 1 and HEAT 2
AVGT	Average temperature of mix, ^{o}F
QUANT	Heat index
TEST	Specified temperature to cool to, ^{o}F

NOTE: In the foregoing Fortran code mention is made of the heat or thermal energy content of 1 sq ft of hot-mix asphalt concrete. This quantity is the thermal energy content of the volume of hot-mix asphalt concrete represented by 1 sq ft of surface and given thickness.

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