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METHODS FOR CALCULATING TEMPERATURE PROFILES OF HOT-MIX ASPHALT CONCRETE AS RELATED TO THE CONSTRUCTION OF ASPHALT PAVEMENTS

By

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ABSTRACT

Temperature is an important variable in the compaction of hot-mix asphalt concrete. Cooling rates differ significantly and affect the allowable time for compaction to specified density. The ability to predict mix temperature for any environment, time, and place in the mix is of considerable importance in estimating the allowable time for compaction after placement of the mix. Mathematical expressions describe the flow of heat or thermal energy from the hot-mix asphalt concrete to the upper and lower surfaces of the mix. Environmental or boundary conditions: wind velocity, initial base temperature, solar radiation, and time affect the flow of thermal energy to the upper and lower surfaces of the mix. Interaction of the conductive, radiative, and convective modes of thermal energy controls the flow of heat from the upper surface to the atmosphere, while the conductive mode of transfer alone controls the flow of heat from the lower surface to 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 mix, and various 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. Constant physical

properties for the mix and base were assumed and used directly for data input to the computer program.

A comparison of calculated temperatures with experimental temperatures in the compactive temperature range (above 200°F) shows a maximum difference of 12°F, or about 6 percent of the experimental value. This comparison is based on temperatures calculated from complete data on environmental conditions. It was found that, in general, closer agreement between calculated and experimental temperatures might be expected for points near the lower surface of the mix since temperatures in this region are less affected by variations in the boundary conditions of the upper surface.

The computer program developed in this study was used as a means of investigating the effect of environmental conditions on the cooling of hot-mix asphalt concrete. In order to demonstrate the variance of mix temperature for different environmental conditions a criterion was established: the elapsed time (after placement of the mix) for the temperature at a given place in the mix to decrease to an established level. For a range of environmental conditions that might normally be expected during construction and for a lift thickness of 2½ in., the elapsed time to reach 200°F for a point ¼ in. into the mix from the upper surface varied from 9 to 31 minutes, and the elapsed time to reach 200°F for a point ¼ in. into the mix from the lower surface varied from 5 to 33 minutes. For different thicknesses of hot-mix asphalt concrete, greater variation was found in the elapsed time to reach 200°F near the upper surface of the mix than near the lower surface of the mix.

The effect of wind velocity, solar radiation, and atmospheric temperature is greater on mix temperatures near the upper surface of the mix than on mix temperatures near the lower surface of the mix. Initial base-temperature distribution affects temperatures near the lower surface of the mix to a much greater extent than it affects temperatures near the upper surface. The results of this study indicate that, in general, temperatures of the hot-mix asphalt concrete near the lower surface decrease more rapidly than temperatures near the upper surface. Since compactive effort is less near the lower surface, temperatures near the lower surface are of particular significance in obtaining specific densities.

The numerical method of determining the temperature distribution in hot-mix asphalt concrete lends itself well to computer programing and provides a means of investigating the effect of an almost limitless number of environmental conditions on the cooling of hot-mix asphalt concrete during construction.

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INTRODUCTION

The purpose of this study is to develop methods of predicting the temperature of hot-mix asphalt concrete as a function of time and place in the mix from the moment it leaves the paver until compaction to specified density is complete. It is generally recognized that mix design, temperature (as it relates to asphalt viscosity), and compactive effort are the most important variables in compaction. For a particular mix, temperature and compactive effort are the most important factors to be considered during the paving operation. Since cooling rates differ significantly because of wide variations encountered in environmental conditions, the allowable time during which adequate compaction can be obtained is subject to considerable variance. In some instances it is believed that variance in the allowable time for compaction has led to failure of asphalt concrete because insufficient compaction eventually led to the problems generally associated with high voids content and low densities. The primary objectives in developing a method of predicting mix temperature as a function of time and place in the mix are to provide a means of investigating environmental conditions that may be marginal with respect to obtaining adequate compaction and to stimulate the development of procedures for obtaining adequate compaction under adverse environmental conditions. Hopefully, the application of such information will result in savings of both time and money by minimizing failures and guiding experimental research.

Previous Work

The importance of temperature as a variable in the compaction of hot-mix asphalt concrete has been the subject of serious technical investigation. According to Parker[1], compacting a particular mixture of asphalt and aggregate at 200°F gave an air voids content 2.4 times as large as that obtained when the mixture was compacted at 275°F. Similarly, compaction at 175°F gave air voids 4 times as large as that obtained at 275°F. Parker used the Marshall compaction procedure (50 blows on both the top and bottom of the sample) in his investigation, and the temperature range studied was 100 to 350°F. Kiefer[2], using the Hveem kneading compactor in his study of the influence of compaction temperature on density of a low-viscosity paving mixture, obtained an increase in density from 146.3 to 148.4 lb per cu ft when the compaction temperature was increased from 150 to 270°F. Kiefer's work embraced a temperature range of 150 to 350°F.

Several investigators have measured the cooling rate of hot-mix asphalt concrete experimentally. Serafin and Kole[3] measured temperature at the mid-point of the mix as a function of time and atmospheric temperature. According to their study, the temperature at the mid-point of the mix (1¼ in. total compacted mix thickness) decreased from 285 to 200°F in 9 minutes with an atmospheric temperature of 40 to 50°F. McLeod[4], also measuring the temperature at the mid-point of the mix (compacted thickness 1½ in.), investigated how rapidly an ordinary layer of paving mixture cools off behind a paver. With an ambient air temperature of 86°F, the mix cooled from 275 to 175°F in 30 minutes. Beagle[5] demonstrated experimentally the dependency of temperature on location in the mix as well as on time for single-lift construction of 2½, 5, and 7½ in. compacted thickness. According to experimental data presented by Beagle, the decrease in temperature with time was highest for the 2½-in. thickness and lowest for the 7½-in. thickness; and for the prevailing environmental conditions (subgrade temperatures 66 to 74°F and air temperature 66 to 110°F), the decrease in temperature with time for all lift thicknesses was greatest near the lower surface of the lift. Previous investigations have therefore established the importance of temperature in compaction, the dependency of temperature on time and place in the mix, and the importance of environmental conditions.

Analysis of the Problem

A simplified sketch showing the flow of heat or thermal energy from hot-mix asphalt concrete during construction is presented in Figure 1. It will be noted there is a net heat flux upward in the direction of the upper pavement surface and a heat flux downward in the direction of the structural base. As used in this study, unless otherwise noted, the word "base" refers to the in-place material on which the hot-mix asphalt concrete is placed. The heat flux in the direction of the upper pavement surface is modified by the word "net" since, as discussed later, there are other modes of thermal energy transfer that must be considered at the surface boundary condition. Because the flow of thermal energy results from a temperature gradient and since the heat content of the hot-mix asphalt concrete is transient (going from a higher energy level to a lower one), it is clear that the temperature of the mix is fundamentally a function of time and position in the mix.

Basically the problem is one of unidimensional transient flow of thermal energy in a finite-thickness slab. The rate of flow of thermal energy from the upper and lower physical boundaries of the pavement at any particular time is dependent on environmental conditions at the respective boundaries as well as the thermal properties and temperature distribution of the mix and base. Environmental conditions at the upper surface include atmospheric temperature, wind velocity, and solar radiation. The environment to be considered at the lower surface is of course the temperature distribution of 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

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

$$\frac{\partial \theta}{\partial t} = \alpha \frac{\partial^2 \theta}{\partial y^2} \qquad \text{(Eq. 1)}$$

In this equation alpha, α, is defined as the thermal diffusivity, the ability of a material to transfer or conduct thermal energy compared to the ability to store thermal energy, and is given by the relationship:

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

where k is the thermal conductivity of the material, ρ is the density, and C_p is the specific heat, Theta, θ, is a dimensionless temperature and may be defined as:

$$\theta = \frac{T - T_a}{T_o - T_a}$$

where T = unknown temperature at a particular time and place in the hot-mix asphalt concrete.

T_a = atmospheric temperature.

T_o = initial temperature of the hot-mix asphalt concrete at the time the mix is placed.

Solution to the above equation for temperature by separation of variables gives the following relationship:

$$\theta = e^{-\lambda^2 \alpha t} (A \cos \lambda y + B \sin \lambda y) \qquad \text{(Eq. 2)}$$

where e is the base of the natural logarithms, and λ, A, and B are constants to be evaluated by using the specific boundary conditions pertinent to the problem. In the evaluation of the constants λ, A, and B, it is necessary to make the boundary conditions homogeneous (where θ goes to zero), thus obtaining a solution that vanishes at one of the boundaries.

A means of making boundary conditions homogeneous is suggested by an analysis of the flow of thermal energy in Figure 1. If the two heat fluxes being considered are opposite in direction, there must be an infinitesimally thin horizontal plane where the temperature does not vary with the y coordinate, or $\frac{d\theta}{dy} = 0$. The location of the plane is a function of time, since the two heat fluxes are not necessarily equal. The problem may then be separated into two parts, as illustrated in Figure 2, divided by the imaginary infinitesimally thin horizontal plane where $\frac{d\theta_1}{dy} = 0$ and $\frac{d\theta_2}{dy} = 0$; θ_1 and θ_2 being the dimensionless temperatures for the respective parts. The upper and lower surface boundary conditions are also shown in Figure 2. The mathematical expressions shown in Figure 2 for the upper and lower surface boundary conditions simply indicate that the conductive heat flux traveling upward in the mix is equal to the combined convective and radiative transfer of thermal energy at the surface of the mix, and the conductive heat flux traveling downward in the mix is equal to the conductive heat flux traveling in the same direction into the base at the lower surface of the mix. In effect then the problem becomes a search for the dimensions of L_1 and L_2 which for any particular time will define the plane at which $\frac{d\theta}{dy} = 0$.

At time = 0, the hot-mix asphalt concrete is at some initial temperature throughout the mix or $T = T_o$; consequently $\theta_1 = \theta_2 = 1$. Applying this boundary condition on time together with the boundary conditions shown in Figure 2 gives the following equations for θ_1 and θ_2:

$$\theta_1 = 2 \sum_{n=1}^{\infty} e^{-\lambda_n^2 \alpha t} \frac{\sin \lambda_n L_1}{\sin \lambda_n L_1 \cos \lambda_n L_1 + \lambda_n L_1} \cos \lambda_n y \qquad \text{(Eq. 3)}$$

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 or the vertical distance from the point at which $\frac{d\theta_1}{dy} = 0$ to a point under consideration, ft

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

and, $$\theta_2 = 2 \sum_{n=1}^{\infty} e^{-\lambda_n^2 \alpha t} \frac{\sin \lambda_n L_2}{\sin \lambda_n L_2 \cos \lambda_n L_2 + \lambda_n L_2} \cos \lambda_n y \quad \text{(Eq. 4)}$$

where $\lambda_n = \dfrac{k_b \cot \lambda_n L_2}{k_m \sqrt{\pi \alpha t}}$

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

After determining the appropriate values L_1 and L_2 for any particular time, one can then calculate the temperature at that time for any point in the hot-mix asphalt concrete as a function of the position coordinate y.

The equations for the heat flux at the upper and lower surfaces of the mix are:

for the upper surface,

$$q_1 = -k_m \left(\frac{d\theta_1}{dy} \right)_{y=L_1} = 2 k_m \sum_{n=1}^{\infty} \frac{\lambda_n e^{-\lambda_n^2 \alpha t} \sin^2 \lambda_n L_1}{\sin \lambda_n L_1 \cos \lambda_n L_1 + \lambda_n L_1} \quad \text{(Eq. 5)}$$

and for the lower surface,

$$q_2 = -k_m \left(\frac{d\theta_2}{dy} \right)_{y=L_2} = 2 k_m \sum_{n=1}^{\infty} \frac{\lambda_n e^{-\lambda_n^2 \alpha t} \sin^2 \lambda_n L_2}{\sin \lambda_n L_2 \cos \lambda_n L_2 + \lambda_n L_2} \quad \text{(Eq. 6)}$$

It will be noted that a combined convective and radiative heat transfer coefficient, U, has been used in describing the surface boundary condition to produce a solution of θ_1. This simplification was found necessary because of insufficiently powerful mathematics to obtain an analytical solution when the surface boundary condition was rigorously described.

Interaction of the various modes of thermal energy transfer at the pavement surface is shown in Figure 3. The thermal energy flux, whose source is within the body of the hot-mix asphalt concrete, is directed upward toward the surface of the pavement and is represented in Figure 3 by the conductive heat flux, $-k_m \frac{dT}{dy}$. Next is the hemispherical radiant energy from the sun, H_s, over all the wavelengths and incident on the pavement surface. A portion of this radiant energy is absorbed by the pavement surface, aH_s, where a is the total (over all wavelengths) absorptance of the pavement surface. Part of the energy from the sun, noted on the diagram as $(1-a)H_s$, is diffusely reflected into the hemisphere. In addition there is radiant energy emitted by the asphalt surface solely as a result of its temperature and defined by the expression $\epsilon \sigma T^4$, where ϵ represents the total emmitance of the asphalt pavement surface, σ is the Stephan-Boltzmann constant, and T is the temperature of the pavement surface. One mode of transfer remains to be described, accounting for the convective transfer of thermal energy to the atmosphere. The convective mode of transfer is represented by the expression $U_c \ (T-T_a)$, where U_c is the convective heat transfer coefficient, and $(T-T_a)$ represents the temperature difference between the pavement surface and the atmosphere.

When the interaction of thermal energy transfer modes at the pavement surface is taken into consideration, the upper surface boundary condition instead of being represented by $-k_m \left(\frac{d\theta_1}{dy} \right)_{y=L_1} = U\theta$, now becomes

$$-k_m \left(\frac{dT}{dy} \right)_{y=L_1} = U_c (T-T_a) + \epsilon \sigma T^4 - aH_s \qquad \text{(Eq. 7)}$$

or in terms of a dimensionless temperature,

$$-k_m \left(\frac{d\theta_1}{dy} \right)_{y=L_1} = \frac{U_c \theta_1 + \epsilon \sigma \left[\theta_1 (T_o - T_a) + T_a \right]^4 - aH_s}{(T_o - T_a)} \qquad \text{(Eq. 8)}$$

The above equation states that the conductive transfer of thermal energy at the pavement surface is equal to the convective plus the radiative transfer of thermal energy from the surface minus the absorption of incident solar radiant energy at the surface. It is, therefore, readily apparent that if the convective and radiative transfer of thermal energy from the surface are greater than the absorption of incident solar radiant energy, there will be a net transfer of thermal energy from the pavement to the surrounding atmosphere. This is the prevailing condition from the time the hot-mix asphalt concrete leaves the paver until steady-state conditions are reached, or until such time as the absorption of incident radiation equals or exceeds the combined convective and radiative transfer of thermal energy from the surface.

A rather important observation may be made concerning the surface boundary condition. Although the hemispherical radiant energy streaming from the pavement surface in all directions is a function of the fourth power of the pavement surface temperature, the quantity, $\frac{\epsilon \sigma T^4}{(T-T_a)}$, is essentially a constant within a surface temperature range of approximately 200 to 300°F, as shown in Table 1.

Table 1

Radiant energy emitted from hot-mix asphalt concrete

T °F	T °R	$\epsilon \sigma T^4$ Btu, ft^{-2}, hr^{-1}	$T-T_a$ (1) °F	$\frac{\epsilon \sigma T^4}{T-T_a}$ Btu, ft^{-2}, hr^{-1}, °F^{-1}
300	760	543	220	2.47
275	735	475	195	2.44
250	710	414	170	2.44
225	685	358	145	2.47
200	660	309	120	2.58

(1) atmospheric temperature, T_a, assumed to be 80°F

Further, for periods of limited time duration, the change in irradiance, radiant energy from the sun incident on the pavement surface, may be such that only minor variation is encountered in the quantity $\frac{aH_s}{T-T_a}$. If the quantities $\frac{\epsilon \sigma T^4}{T-T_a}$ and $\frac{aH_s}{T-T_a}$ may be assumed substantially constant within the temperature and time intervals of interest, it is possible to use a combined over-all surface heat-transfer coefficient, U, in describing the net thermal energy leaving the pavement at the upper surface boundary. Caution should be exercised, however, in using a combined over-all surface heat-transfer coefficient, for it must be remembered that the interaction of thermal radiation with other modes of thermal energy transfer is inherently non-linear, since radiative transfer depends on the fourth power of the temperature while conduction and convection vary linearly with temperature.

Numerical Solution

The interaction of the various modes of thermal-energy transfer at the pavement surface are more readily accounted for in a numerical solution. The numerical or finite difference solution is based on dividing the hot-mix asphalt concrete as well as the base into incremental elements as shown in Figure 4. An energy balance over the finite element of hot-mix asphalt concrete next to the upper surface generates an equation for the surface temperature after an increment of time, Δt, as follows:

$$T_{1(t+\Delta t)} = T_{1(t)} \left[1 - \frac{2\alpha\Delta t}{\Delta y^2} (N_{Bi} + 1) \right] + \frac{2\alpha\Delta t}{\Delta y^2} (T_{2(t)} + N_{Bi}T_a) + \frac{2\alpha\Delta t}{k_m \Delta y} (aH_s - \epsilon\sigma T_{1(t)}^4) \quad \text{(Eq. 9)}$$

where $T_{1(t)}$ = temperature, °F, at surface of hot-mix asphalt concrete at time, t

$T_{1(t+\Delta t)}$ = temperature, °F, at surface of hot-mix asphalt concrete at time, $(t+\Delta t)$

$T_{2(t)}$ = temperature, °F, of incremental element, 2, at time, t

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

Δt = incremental time, hr

Δy = thickness of incremental element of hot-mix asphalt concrete, ft

N_{Bi} = Biot number, dimensionless

T_a = atmospheric temperature, ^oF

k_m = thermal conductivity of hot-mix asphalt concrete, Btu, hr^{-1}, ft^{-1}, $^oF^{-1}$

H_s = solar radiant energy incident on hot-mix asphalt concrete surface, Btu, ft^{-2}, hr^{-1}

a = total absorptance of hot-mix asphalt concrete surface, dimensionless

ϵ = total emittance of hot-mix asphalt concrete surface, dimensionless

σ = Stephan-Boltzmann constant, 1.714×10^{-9}, Btu, ft^{-2}, hr^{-1}, $^oR^4$

Similarly, an energy balance over an element within the hot-mix asphalt concrete (not adjacent to the upper or lower surface) generates an equation for interior temperature as follows:

$$T_{3(t+\Delta t)} = T_{3(t)} + \frac{\alpha \Delta t}{\Delta y^2} (T_{4(t)} - 2\,T_{3(t)} + T_{2(t+\Delta t)}) \qquad \text{(Eq. 10)}$$

The equation for the temperature of the incremental element of the mix adjacent to the lower surface of the mix is:

$$T_{10}(t+\Delta t) = T_{10}(t) + \frac{\alpha \Delta t}{\Delta y^2}\left(T_{b_1}(t) - 2\,T_{10}(t) + T_9(t+\Delta t)\right) \qquad \text{(Eq. 11)}$$

where α is the thermal diffusivity of the mix.

The equation for the temperature of the incremental element of the base adjacent to the lower surface of the mix is:

$$T_{b_1}(t+\Delta t) = T_{b_1}(t) + \frac{\alpha \Delta t}{\Delta y^2}\left(T_{b_2}(t) - 2\,T_{b_1}(t) + T_{10}(t+\Delta t)\right) \qquad \text{(Eq. 12)}$$

where α is the thermal diffusivity of the base.

Finally, an energy balance over an element within the base (not adjacent to the lower surface of the mix) yields an equation for the temperature of an element in the base as shown below, thus completing the set of finite difference equations to be used in determining the temperature distribution in hot-mix asphalt concrete.

$$T_{b_3}(t+\Delta t) = T_{b_3}(t) + \frac{\alpha \Delta t}{\Delta y^2}\left(T_{b_4}(t) - 2\,T_{b_3}(t) + T_{b_2}(t+\Delta t)\right) \qquad \text{(Eq. 13)}$$

It should be remembered that in the immediately foregoing equation α now represents the thermal diffusivity of the base.

The heat flux leaving the upper surface of the mix is described in the following equation:

$$q_1 = \frac{N_{Bi} k_m}{\Delta y}(T_1 - T_a) + \epsilon \sigma T_1^4 - aH_s \qquad \text{(Eq. 14)}$$

Likewise, an energy balance over the element adjacent to the lower surface yields the following equation for the heat flux leaving the lower surface

$$q_2 = \frac{\rho C_p \Delta y}{\Delta t} (T_{10(t)} - T_{10(t+\Delta t)} + k_m (T_{9(t+\Delta t)} - T_{10(t+\Delta t)}) \quad \text{(Eq. 15)}$$

The foregoing equations provide the basis for setting up the computer program included in Appendix B.

Approach

The approach used in this study was to first determine experimentally the temperature of hot-mix asphalt concrete as a function of time and place in the mix. Data were obtained during paving operations on construction projects for which various environmental conditions were encountered. A computer program was then developed from the finite difference equations governing the transfer of thermal energy during the cooling of the hot-mix asphalt concrete. Temperatures as a function of time and place in the mix were then calculated by means of the computer program using as nearly as possible the same respective environmental conditions as experienced when obtaining the experimental data. Calculated temperatures were then compared with experimental temperatures. The effects of various environmental conditions on the cooling of hot-mix asphalt concrete were then investigated by using the computer program as a means of calculating temperatures of the mix.

EXPERIMENTATION

The purpose of obtaining experimental data was to provide a means of comparing temperatures that were measured during actual paving operations to temperatures that were calculated by taking into consideration the appropriate values of the several variables pertaining to the problem. It was deemed sufficient, as a condition of the experimentation, to simply determine the values of the variables, and no effort was made to place limits or constraints on any of the variables that were measured. Consequently, the experimentation consisted of (1) measuring temperature as a function of time and place in the mix, and (2) measuring variables known to affect the rate of cooling of hot-mix asphalt concrete: wind velocity, atmospheric temperature, initial base-temperature distribution, solar radiation, and thickness of the mix.

Apparatus and Equipment

Temperatures were recorded with a Brown Electronic, 8-point recorder, Model No. 153X65P8-X-1, 0 - 500°F range, 110 - 125 volts, 60 cycle AC. A powercon Model 12D15 inverter was used to convert a 12-volt DC (automobile alternator) input to the 120-volt AC output required for operation of the temperature recorder. Thermocouples used were iron-constantan. Several types of thermocouple insulation were used, the most successful being a flexible vinyl-coated fiber-glass tubing. A 1/8-in.- diameter ceramic insulator was placed adjacent to the iron-constantan junction of each thermocouple, except those used to measure surface temperatures. The length of the ceramic insulator was determined by the depth of penetration of the thermocouple into the mix or the base.

Procedures

A masonry drill was used to drill holes of desired depth into the base, and thermocouples were installed in the base prior to placing the hot-mix asphalt concrete. Thermocouples in the mix were placed by hand from the surface of the mix downward immediately after the mix was placed.

Displacement of thermocouples during the breakdown rolling operation was the cause of erroneous temperature measurement in some instances. Means of anchoring mix thermocouples to steel pins inserted in the base were considered, but discarded because of the necessity of placing materials of substantially different thermal properties than the mix near or adjacent to the thermocouple junction. Although displacement of thermocouples could not be controlled, it was possible to determine if displacement had occurred by careful observation of the orientation of the ceramic insulator as it was removed from the mix upon completion of the test. If displacement was noted, the data from that thermocouple were discarded.

Wind velocities were measured with an anemometer for

Test No. 67-2. For Test Nos. 67-1 and 66-4, wind velocities were obtained from FAA weather-station data.

Solar altitude was determined by measuring the length of a shadow cast on the surface of the pavement by a vertical plumb line of known length. Solar altitude in degrees was calculated by means of the following relation:

$$\text{Tan } \phi = \frac{\text{length of plumb line}}{\text{length of shadow}}$$

where ϕ is the solar altitude in degrees

Data

Experimental data for 3 paving projects are presented in Appendix A. For convenience, data for each of the projects are subdivided into three classifications: general information, environmental data, and experimental temperatures.

RESULTS

The results of this study consist of (1) the computer program that was developed to predict the temperature of hot-mix asphalt concrete as a function of time and place in the mix, (2) a comparison of experimental temperatures with calculated temperatures, and (3) an investigation of the effects of various environmental conditions on the cooling of hot-mix asphalt concrete.

Computer Program

The basic computer program was developed from the finite difference equations (9 to 15 inclusive) governing the transfer of thermal energy in hot-mix asphalt concrete during the paving operation.

Listing

A listing of the computer program is presented in Table B.1, Appendix B. Data shown in the listing are for Test No. 67-2, Evanston-Lyman. Also included in Appendix B is the Fortran code used in the computer listing, Table B.2.

The computer listing is presented in a form believed to be the most easily understood, and it can be modified to save computer time.

Data Input

Some of the variables or environmental conditions that affect the transfer of thermal energy in hot-mix asphalt concrete can be used directly for data input to the computer program. Other variables, including wind velocity, solar altitude, and some physical properties, must be changed to a form that is acceptable for use in the computer program.

Wind Velocity. Wind velocity is used to determine the Biot number (a function of the convective heat-transfer coefficient), which can then be used as data input. Numerous procedures involving theoretical and/or empirical relationships for determining the convective heat-transfer coefficient are to be found in texts on heat transfer. In general these procedures include finding the Reynolds number, calculating the Nusselt number as a function of Renolds number and Prandtl number, and obtaining the convective heat-transfer coefficient as a function of Nusselt number. The procedure used in this study is simplified somewhat by use of a chart, "Influence of free-stream turbulence on heat transfer," prepared by Irving and Hartnett(6) for obtaining Nusselt number as a function of Reynolds number. Use of the chart has the advantage of being able to take into consideration the transition from laminar to turbulent flow at a lower Reynolds number when there is increased free-stream turbulence, as might be expected from the rough surface (compared to a smooth flat plate) of hot-mix asphalt concrete.

First the Reynolds number is calculated as follows:

$$N_{Re} = \frac{V\ L}{\nu_a} \qquad \text{(Eq. 16)}$$

where N_{Re} = Reynolds number, dimensionless

V = wind velocity, ft, hr^{-1}

L = characteristic length, ft

ν_a = kinematic viscosity of air (evaluated at the mean film temperature, ft^2, hr^{-1}

The characteristic length, L, is measured parallel to the surface of the pavement and in the direction of air flow from the edge of the pavement to the location at which temperatures are being evaluated.

The Nusselt number is then obtained from the chart prepared by Irving and Hartnett[6].

Next the convective transfer coefficient is calculated:

$$h_c = \frac{N_{Nu}\ k_a}{L} \qquad \text{(Eq. 17)}$$

where h_c = convective heat transfer coefficient, Btu, ft^{-2}, hr^{-1}, $^oF^{-1}$

k_a = thermal conductivity of air (evaluated at the mean film temperature), Btu, hr^{-1}, ft^{-1}, $^oF^{-1}$

L = characteristic length, ft

For the special case of zero wind velocity, Hutchinson[7] shows the following empirical equation for the convective transfer coefficient to be in good agreement with experimental data obtained for temperature differences comparable to those encountered in the study.

$$h_c = (0.38)\Delta t^{\ 0.25} \qquad \text{(Eq. 18)}$$

where Δt = temperature difference, ^oF (difference between temperature of hot-mix asphalt concrete surface and atmospheric temperature)

The convective heat transfer coefficient, h_c, is then used to claculate the Biot number for use in the finite difference equation governing the transfer of thermal energy from the surface of the hot-mix asphalt concrete.

$$N_{Bi} = \frac{h_c \Delta y}{k_m} \qquad \text{(Eq. 19)}$$

where N_{Bi} = Biot number, dimensionless

Δy = thickness of incremental element of hot-mix asphalt concrete, ft

k_m = thermal conductivity of hot-mix asphalt concrete, Btu, hr^{-1}, ft^{-1}, $^oF^{-1}$

Other methods may be used of course for determining the convective transfer coefficient. The particular method selected in this study, although less detailed than some that might be selected, appears to give results that are in good agreement with experimental data.

Solar Radiation. The solar constant, the radiant energy flux incident upon a surface normal to the sun's radiation and located outside the earth's atmosphere, varies from about 400 to 430 Btu, ft^{-2}, hr^{-1}, depending on the distance from the sun to the earth at different times of the year. The amount of solar radiation incident upon the earth's surface is significantly less than the solar constant as the result of its journey through the earth's atmosphere, and it is a function of solar altitude, elevation, absorptive components of the earth's atmosphere, cloudiness, and turbidity. Robinson[8] presents graphically for substantially sea-level conditions the variation in solar-radiant flux with altitude of the sun. According to Robinson solar-radiant flux incident on the earth's surface on a clear day may vary from about 40 to 300 Btu, ft^{-2}, hr^{-1}, depending on solar altitude. For the purposes of this study, solar-radiant flux at sea level was corrected to the desired solar-radiant flux for a particular elevation by means of Figure 5, which is based on data reported by Abetti[9] for solar-radiant flux at several different elevations. Figure 5 is also based on the assumption that the rate of change of the quantity of absorptive components per unit volume of the earth's atmosphere is greatest next to the earth's crust and decreases to substantially zero at the outer boundary of the troposphere.

<u>Physical Properties</u>. Values used for physical properties of hot-mix asphalt concrete are presented in Table 2.

Table 2

Physical properties of hot-mix asphalt concrete

Thermal conductivity	0.70	Btu, hr^{-1}, ft^{-1}, $^{o}F^{-1}$
Density	140	lb, ft^{-3}
Specific heat	0.22	Btu, lb^{-1}, $^{o}F^{-1}$
Total absorptance	0.85	dimensionless
Total emittance	0.95	dimensionless

Constant physical properties were assumed, and the foregoing values are representative of values reported in the literature. Some variation in thermal properties might be expected with temperature and degree of compaction. However, it is quite likely that thermal diffusivity remains substantially constant with changes in the degree of compaction since an increase would be expected in both thermal conductivity and density with increased compaction.

The same thermal properties were used for the asphalt base, although the computer program is designed to accept different physical properties for the base, should this be necessary or desirable.

Comparison of Experimental Temperatures with Calculated Temperatures

Comparisons of experimental temperatures with calculated temperatures are presented graphically in Figures 6 through 14 for three paving projects involving hot-mix asphalt-concrete surfacing. It was considered desirable to present comparisons that included data for a variety of environmental conditions, which are discussed in detail for each of the comparisons that follow. For the comparisons presented, best agreement between experimental temperatures and calculated temperatures was obtained for Test No. 67-2, Evanston-Lyman, for which more complete data on environmental conditions were obtained than for either of the other two earlier tests.

Test No. 67-2, Evanston-Lyman

Figures 6 and 7 illustrate a comparison of experimental data with calculated data for Wyoming Project No. I-80-1(27)26, Evanston-Lyman, Wyoming. Calculated temperatures are in good agreement with experimental temperatures. The maximum difference of 12°F between experimental and calculated temperatures is for TC-2 located ½ in. below the top surface. Better agreement between calculated and experimental values is indicated for TC-3 located ½ in. above the lower surface. It is believed that closer agreement of calculated temperatures with experimental temperatures might generally be expected for points near the lower surface of the mix, since temperatures in this region are less affected by the changing boundary conditions of the upper surface.

Test data are presented in Tables A.1, A.1A, A.1B (Appendix A). Approximately 1 hour before the test, the base-temperature distribution was uniform at about 54°F. At the start of the test, base temperatures had increased to a range of 60 to 64°F as the result of solar radiation, even though atmospheric temperature was about 50°F and wind velocities were in the range of 5 to 10 knots. As would be expected, test temperatures dropped quite rapidly as the result of the existing environmental conditions.

Although wind velocities varied considerably, an average velocity of 730 fpm was used for the test period. Wind direction was parallel to the centerline of the pavement; and normally for this situation, a large value of L, the characteristic length in the equation for Reynolds number, would be used. However, paving operations were interrupted for a period of about 15 minutes when the paver was approximately 5 ft from the test location. The surface of the hot mix that had already been placed cooled quite rapidly; therefore, a new "edge of pavement" was established with respect to the test location and wind direction. Consequently, a characteristic length, L, of 5 ft was assumed.

Test No. 67-1, North of Rock Springs

A comparison of experimental temperatures with calculated temperatures on Wyoming Project No. SMP 5854, North of Rock Springs, Wyoming, June 22, 1967, is shown in Figures 8, 9, and 10. In a period of slightly over an hour preceding the test, an approaching thunderstorm dropped the surface temperature of the asphalt base from 116 to 78°F, resulting in an inverted base-temperature distribution (surface of base at a lower temperature than temperatures at various levels next to the surface). This condition was included in the data input to the computer.

Wind direction was normal to the bearing of the highway. Wind velocity was approximately 10 knots, with gusts of 15 to 25 knots. A constant wind velocity of 15 knots was used in calculating input data for the computer program.

A substantial cloud cover sharply reduced solar-radiant flux prior and during the test as evidenced by the rapid drop of 38°F in base temperature shortly before the test, while atmospheric temperature decreased only about 5°F. Consequently, a diffuse solar-radiant flux of 40 Btu, ft^{-2}, hr^{-1} was assumed. Experimental and calculated temperatures of the mix are in good agreement in spite of the highly changing environmental conditions.

Experimental and calculated base temperatures are also in good agreement when one considers that the initial base-temperature distribution was in an unsteady state at the time the test was started. Best agreement was obtained for TC-6, while differences between calculated and experimental temperatures for TC-7 and TC-8 ranged from 1 to 9°F.

Test No. 66-4, Grand Junction Airport

Presented in Figures 11 through 14 is a comparison of experimental temperatures with calculated temperatures for a test conducted during the construction of FAA Project No. 9-05-004-C-706, Grand Junction, Colorado Airport. The test is of particular interest in that both wind velocity and direction changed during the test. Unfortunately a complete record of the change of wind velocity and direction with time during the test is not available; however, it is felt that sufficient data are available to demonstrate the adaptability of the numerical solution to changing environmental conditions.

At the start of the test, wind velocity was 14 knots and wind direction was 30 degrees. After a period of one hour, wind velocity had changed to 5 knots with a direction of 170 degrees. Thus, data recorded by the FAA station at the airport defined the initial and final conditions of wind velocity and direction for the one hour test period. Inspection of the time-temperature curve for the surface of the mix, Figure 11, reveals a nearly isothermal condition on the surface of the mix for the interval between 5 and 25 minutes of test duration. This condition simply indicates that the thermal energy being transferred by conduction from the mix to the incremental element adjacent to the surface of the mix is the same as the net thermal energy being transferred from the surface of the mix to the atmosphere by convection and radiation. The term "net" is used in referring to the thermal energy transfer from the surface of the mix to the atmosphere since the surface of the mix is concurrently absorbing solar-radiant energy.

A Nusselt number for the period of 0 to 5 minutes of test duration was calculated from the initial conditions of wind velocity and direction. For the period 5 to 25 minutes of test duration, a Nusselt number was calculated, assuming natural or free convection. For the period of 25 to 60 minutes of test duration, a Nusselt number was calculated based on the final condition of wind velocity and direction for the one-hour test period. The calculated Nusselt numbers were then used in determining the Biot numbers for computer data input. In addition, the solar-radiant flux was reduced from 280 to 250 Btu, ft^{-2}, hr^{-1} after 25 minutes test duration based on observations of the solar altitude during the test.

Referring to Figure 11, one may note that the calculated time-temperature curve for the surface of the mix is quite similar to that developed from experimental data for the period of 0 to 10 minutes test duration. It appears that if an adequate record of wind velocity and direction were available for computer data input, it would be possible to very nearly duplicate the behavior of the surface temperature of the mix. The rather large difference between calculated and experimental temperatures for the surface of the mix appears to be the result of using wind velocities lower than actual for the periods of 0 to 5 minutes and 5 to 20 minutes of test duration.

Comparisons of calculated and experimental temperatures for points within the mix are presented in Figures 12 and 13. Poorer agreement between calculated and experimental values than those obtained for the other two tests presented in this study is believed to be the result of the rather incomplete record of wind velocities during the test.

A comparison of experimental and calculated base temperatures is presented in Figure 14. It will be noted that TC-3, located ½ in. below the surface of the base, did not measure an accurate base temperature until after a period of about 14 minutes test duration, which was after breakdown rolling. Prior to this time, base material was apparently not consolidated adjacent to the thermocouple. It should be mentioned that this was one of the initial tests in the study, and the procedure for installing base thermocouples was subsequently modified to that previously described. Aside from this occurrence, calculated temperatures for points in the base are in good agreement with experimental data.

Heat fluxes from the upper and lower surfaces of the hot-mix asphalt concrete vs. time are presented in Figure 15. Data plotted in Figure 15 are from the same computer program from which temperatures were obtained for comparison with experimental data. With reference to the heat flux from the upper surface of the hot-mix asphalt concrete, a substantial decrease will be noted when wind velocity was decreased from 14 to 0 knots at the end of 5 minutes test duration. An increase will also be noted at the end of 25 minutes of test duration when the wind velocity was increased to 5 knots, although solar radiation was decreased from 280 to 250 Btu, ft^{-2}, hr^{-1}. Heat flux from the lower surface of the hot-mix asphalt concrete into the base has a substantially higher value at 1 minute test duration (1,819 Btu, ft^{-2}, hr^{-1}, not plotted) than the heat flux from the upper surface and decreases more uniformly to a value somewhat less than the heat flux from the upper surface.

Also presented in Figure 15 is a plot of the decrease with time of the heat content of one square foot of hot-mix asphalt concrete of 2¼-in. thickness. As would be expected, the rate of decrease of heat content is greatest at the initial part of the test.

Effects of Various Environmental Conditions

In order to demonstrate the change of temperature with the several environmental and geometrical variables involved; wind velocity and direction, solar radiation, atmospheric temperature, base temperature, and thickness of mix, it was necessary to establish some test or criterion to which data could be compared. Comparing numerous temperature profile curves for various locations in the mix at different times under changing environmental conditions becomes tedious at best. It was also felt that the test or criterion should be meaningful, in that it should provide pertinent information concerning the cooling of the mix. It is generally agreed that compaction of the mix should take place above a certain temperature, and some investigations, (10) (11), have indicated that the temperature should be above 200°F. It therefore seemed reasonable to use a temperature of 200°F in the criterion, but next came the question, "where in the mix?" One cannot very well consider the upper or lower surface temperature as a desirable part of the criterion since, theoretically at least, there is nothing to compact at a point on the surface of the mix. It, therefore, appeared appropriate to examine the temperature at a given distance into the mix from the upper and lower surfaces. Thus, with consideration being given to the independent variable time, the basis of a criterion or test was established: the elapsed time before the temperature at a given point in the mix decreases to an established level.

With the temperature established at 200°F, the position was established at 0.263 in., or about ¼ in. into the mix. There was nothing significant about specifying 0.263 in., except that it was convenient, since it represented the thickness of the finite element initially used in this study for the numerical solution of temperature distribution in the 2½-in.-thick compacted pavement.

As explained later in "Error Analysis," the difference in temperature between a point 0.263 in. into the mix and a point ¼ in. into the mix is only about 1°F. Therefore, for the purposes of this study, the point is described as being ¼ in. into the mix.

It is quite natural to assume that the elapsed time, if the appropriate place in the mix and minimum temperature are properly selected, could give the available time for breakdown rolling to take place, during which desired compaction could be expected with the application of an adequate compactive effort. It should be stressed, however, that for this study the particular position in the mix was selected arbitrarily and solely for the purpose of demonstrating the effect of pertinent variables on the cooling of hot-mix asphalt concrete.

Effect of Wind Velocity

In Figure 16 wind velocity is plotted against elapsed time before reaching 200°F for points approximately ¼ in. into the mix from the upper and lower surfaces. Atmospheric temperature, initial base temperature, solar-radiant flux, and thickness of mix are held constant at the values indicated. As might be expected, change in wind velocity has a greater effect on the temperature near the upper surface of the mix than near the lower surface. For the particular environmental conditions shown, the elapsed time is the same for a wind velocity of about 12.5 knots. At velocities higher than 12.5 knots, the upper part of the mix cools more rapidly; and for velocities lower than 12.5 knots, the lower part of the mix cools more rapidly. For a point ¼ in. into the mix from the upper surface, the elapsed time to reach 200°F decreases from about 31 minutes at a wind velocity of 0 knots to about 9 minutes for a wind velocity of 25 knots. For a point ¼ in. into the mix from the lower surface, the respective elapsed times are 17 and 13 minutes.

Figure 17 shows the effect of wind velocity on the temperature profile of the mix at a time of 15 minutes after placement of the mix. For the environmental conditions indicated and for a wind velocity of 5 knots, about 10 percent of the mix has cooled to a temperature below 200°F. For a wind velocity of 15 knots, approximately 25 percent of the mix has cooled to a temperature below 200°F. Temperature profiles for lesser elapsed time after placement of the mix would of course give greater percentages of the mix at a temperature above 200°F.

Effect of Atmospheric Temperature and Base Temperature

In Figure 18 is presented the variation of elapsed time with atmospheric temperature and base temperature. In this instance both atmospheric and base temperature were concurrently varied in such a manner as might reasonably be expected with a solar-radiant flux of 250 Btu, ft^{-2}, hr^{-1} and a wind velocity of 5 knots. The effect of low initial base temperature on the elapsed time curve for the lower part of the mix is considerably greater than the effect of low atmospheric temperature on the upper part of the mix.

Although atmospheric temperature and base temperature are interacting with respect to temperatures near the upper and lower surfaces, base temperature is controlling for temperatures near the lower surface, and atmospheric temperature is controlling for temperatures near the upper surface. In the discussion that follows, initial base temperature will be referred to as the highest temperature of the base for any particular base-temperature distribution. A decrease in base temperature from 140 to 20°F produces a decrease in elapsed time to reach 200°F from about 33 minutes to 5 minutes for a point ¼ in. into the mix from the lower surface. On the other hand a decrease in atmospheric temperature from 100 to 20°F gives a corresponding decrease in elapsed time from 28 minutes to 17 minutes.

From Figure 19 an impression can be gained as to the relative effect of atmospheric and base temperatures on the percentage of the mix remaining above 200°F. For an atmospheric temperature of 100°F and corresponding base temperature of 140°F, a total of 100 percent of the mix remains above 200°F. With an atmospheric temperature of 20°F and a corresponding base temperature of 35°F, a total of 33 percent of the mix has cooled to 200°F or below, 28 percent of which is adjacent to the base. It will be noted that the higher temperature gradients, and consequently the higher cooling rates, are to be found at the lower part of the mix. The temperature profiles shown in Figure 19 are for a time of 15 minutes after placement of the mix, and shorter time intervals yield higher temperature profiles.

Effect of Solar-Radiant Flux

The elapsed time before reaching 200°F is plotted against solar-radiant flux in Figure 20. Atmospheric temperature, initial base temperature, wind velocity, and thickness of the mix are held constant at the values indicated, while solar-radiant flux is varied from 0 to 350 Btu, ft^{-2}, hr^{-1}. The radiant energy from the sun has a decidedly more pronounced effect on the temperature of the mix next to the upper surface than on the temperature of the mix next to the lower surface. A decrease in solar radiation from 350 to 0 Btu, ft^{-2}, hr^{-1} decreases the elapsed time to reach 200°F from about 25 minutes to about 16 minutes for a point ¼ in. into the mix from the upper surface. A like change in solar radiation produces a respective change in elapsed time of 16 minutes down to 15 minutes for a point ¼ in. into the mix from the lower surface. The greater effect of solar-radiant flux on temperatures near the upper surface of the mix is also shown in Figure 21, in which temperature profiles of the mix are presented with various solar-radiant fluxes incident upon the upper surface of the mix.

Reference to Figures 20 and 21 might give one the impression that solar-radiant flux plays only a minor role in the cooling of hot-mix asphalt concrete, but it should be kept in mind that the overall effect of solar radiation is two-fold. It affects the rate of cooling on the upper surface of the mix, and it affects the initial base-temperature distribution prior to the time that the mix is placed. The effect of solar radiation on initial base-temperature distribution is undoubtedly of much greater consequence than its effect after the mix is placed.

Effect of Thickness of Lift

The effect of thickness of lift on elapsed time is shown in Figure 22. The elapsed time to reach 200°F for a point ¼ in. into the mix from the upper surface is affected to a much greater extent by thickness of lift than for a point the same distance into the mix from the lower surface.

Temperature profiles calculated for a time of 10 minutes after placement of the mix are shown in Figure 23 for various mix thicknesses and for the particular set of environmental conditions shown. It will be noted that 100 percent of the 1½-in. lift has cooled to a temperature below 200°F. About 85 percent of the 2½-in. lift is above 200°F, and still larger percentages, 92 and 95, remain above 200°F for the 4-and 6-in. lifts, respectively. The highest temperature gradients, and consequently the greatest heat losses, occur at the lower surface of the lift. This is essentially the same result as found experimentally by Beagle[12].

> It was found that the greatest heat loss was caused by transmission to the subgrade. ... This was found to be true regardless of the depth of mix applied. The losses were consistent for the 2½ inch, 5 inch and 7½ inch lifts.

Calculated heat fluxes from the upper and lower surfaces of the mix for a time of 10 minutes after placement of the mix are presented in Table 3.

Table 3

Heat flux from upper and lower surfaces of hot-mix asphalt concrete 10 minutes after placement of mix

Thickness of lift, in.	Heat flux from upper surface, Btu, ft^{-2}, hr^{-1}	Heat flux from lower surface, Btu, ft^{-2}, hr^{-1}
1½	532	577
2½	650	710
4	669	748
6	675	780

As was found by Beagle[12], the heat loss is greater at the lower surface of the mix, even though environmental conditions for this example are substantially different from those encountered in his study. It is believed that greater heat loss at the lower surface of the mix would be the case for most actual paving operations. It should be mentioned, however, that there are environmental conditions (high wind velocity, low solar radiation) for which the reverse might be true. With reference to Table 3, the differences in heat flux from the upper and lower surfaces are the result of the differences in temperature gradients shown in Figure 23.

Error Analysis

As applied to this study, error analysis consists of an investigation of experimental and calculative errors. The experimental errors encountered are those peculiar to the particular experimental methods that were employed. The analysis of calculative error is worthy of careful consideration, because one can strike a balance between the accuracy desired and the time required to perform the calculations.

Experimental Error

The greatest source of error in the experimental data is probably in the accurate positioning of the thermocouple in the hot mix. The magnitude of the error introduced from this source is dependent on the other variables of the problem: time, initial temperature of the mix, and environmental conditions. An analysis of the computer data from this study indicates a possible error in the range of 0 to 10°F for a 1/8 in. difference in vertical placement of the thermocouple junction and for an elapsed time of 30 minutes after the placement of the mix. The magnitude of the error is greatest near the upper and lower surfaces of the hot mix, where temperature gradients are highest.

During the rolling operation, thermocouples are pressed deeper into the mix. The amount of vertical displacement caused by rolling depends on the difference between the initial and final compaction of the mix. The possible error caused by this displacement is a function of the magnitude of the displacement and the temperature gradient between the initial and final positions of the thermocouple. Errors from this source are, therefore, greatest for thermocouples located near the upper and lower surfaces of the mix.

Other experimental errors known to exist but not evaluated include errors in the temperature-measuring system itself. Included are errors introduced by conduction in the thermocouple lead wires as well as in the ceramic insulator. Errors in the temperature-measuring system are considered to be of only minor significance insofar as the practical use of the results from this study is concerned.

Calculative Error

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

The magnitude of an error in calculated temperature caused by an error in the measurement or estimation of data used in the calculations is not only a function of time and place in the mix for which the temperatures is obtained but also a function of other data as well. It is possible, however, to gain some appreciation of errors that may be involved by referring to the temperature profiles shown in Figures 17, 19, 21, and 23. For example with reference to Figure 17, temperature profiles for various wind velocities, it may be seen that an assumed wind velocity of 15 knots compared to an actual velocity of 10 knots produces an error of about 14°F in the temperature predicted at or near the upper surface 15 minutes after placement of the mix. The resulting error for a temperature at or near the lower surface of the mix is less than 1°F. Other such comparisons can be made for atmospheric and base-temperature distribution, thickness of mix, and solar radiation; however, one should be mindful that the errors indicated are applicable only to the particular environmental conditions shown.

As pointed out by Dusinberre[13], there are several methods for determining the stability of finite difference equations.

> ...More sophisticated criteria have been devised for systems to which differential equations are applicable and can be solved. But as a practical matter we can lay down the simple rule: avoid negative coefficients.

Applying this rule to equations 9 through 15 for this study gives

$$1 - \frac{2\alpha \Delta t}{\Delta y^2} (N_{Bi} + 1) \geqslant 0 \qquad \text{(Eq. 20)}$$

and

$$\frac{(\Delta y)^2}{\alpha \Delta t} \geqslant 2 \qquad \text{(Eq. 21)}$$

In addition to the foregoing criteria, a thermal energy balance was included in the basic computer program to establish an adequate level of confidence in the calculations. Briefly this balance consisted of (1) calculating the thermal energy fluxes from the upper and lower surface of the mix for each time increment, (2) using the thermal energy fluxes to find the total cumulative heat lost from the mix, and (3) comparing the 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 at the identical time for which the total cumulative heat loss was calculated. Significant variance in the two quantities indicates possible errors in calculated temperatures. In Table 4 are shown the relationships found to exist between the size of the incremental time and thickness elements, the percentage difference in the thermal energy balance, and the difference in calculated temperatures.

Table 4

Calculative error analysis

Incremental thickness element Δy, ft	Incremental time element Δt, hr	Ratio $\frac{\Delta t}{(\Delta y)^2}$	Variance in energy balance, %	Difference in calculated temperatures °F (1)
0.02193	0.00104	2.16	3.7	0
0.02193	0.00208	4.32	7.6	2
0.01097	0.00052	4.32	7.6	2
0.01097	0.00104	8.64	15.3	6
0.01097	0.00208	17.28	30.8	20

(1) Temperature at a point ¼ in. into the mix from the upper surface (obtained with the 3.7 percent variance in energy balance) minus the temperature at the same point for any particular energy balance.

As might be expected from an inspection of equation 9, the variance in energy balance was found to be in direct proportion to the ratio $\Delta t/(\Delta y)^2$. The particular environmental conditions used in this error study were purposely selected to give high gradients at the upper and lower surfaces. Temperatures calculated for a time of 30 minutes after placement of the mix were used for comparison. The respective differences in calculated temperatures for a point the same distance into the mix from the lower surface were somewhat less than for the upper surface. In the interest of minimizing computer time, a variance in energy balance of 7 percent was considered acceptable for the purpose of this study.

SUMMARY AND CONCLUSIONS

Calculation of the time-and-space dependent temperature distribution in hot-mix asphalt concrete during compaction has been presented. The analytical solution to the one-dimensional partial differential equation completely describes, in a manner that is mathematically exact, the flow of thermal energy encountered in the cooling of hot-mix asphalt concrete. Its usefulness is limited by the necessary assumption of constant physical properties and simplified boundary conditions. The numerical solution displays greater versatility in handling the rather complex boundary conditions peculiar to this problem. It is limited to the extent that stability criteria must be met in order to avoid absurd results. The numerical solution lends itself well to computer programing, with its attendant advantages.

Results of this study indicate that, in general, the heat flux into the base is initially greater than the heat flux into the atmosphere. For this reason, temperatures of the hot-mix asphalt concrete near the lower surface decrease more rapidly than temperatures near the upper surface. 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.

A criterion or test, the elapsed time before the temperature at a given point decreases to an established level, has been suggested for the purpose of comparing the investigative results of various environmental or boundary conditions. With the proper selection of temperature and place in the mix, it appears that this same criterion might be used in predicting the available time for breakdown rolling to take place, during which adequate compaction can be expected.

The problem and its solution have been presented to enhance understanding and appreciation of the various modes of thermal-energy transfer and to provide a means of investigating the effect of an almost limitless number of environmental conditions on the cooling of hot-mix asphalt concrete.

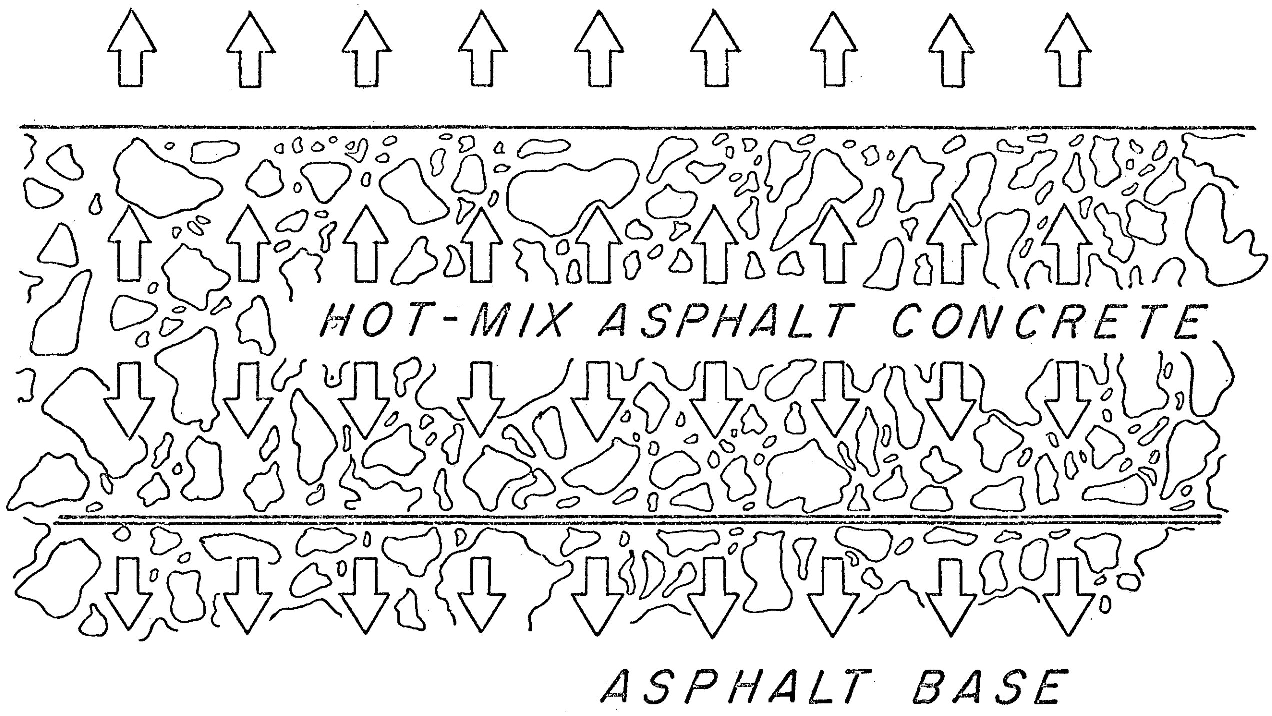


Figure 1. Cross Section of Hot-mix Asphalt Concrete Indicating Directional Flow of Thermal Energy.

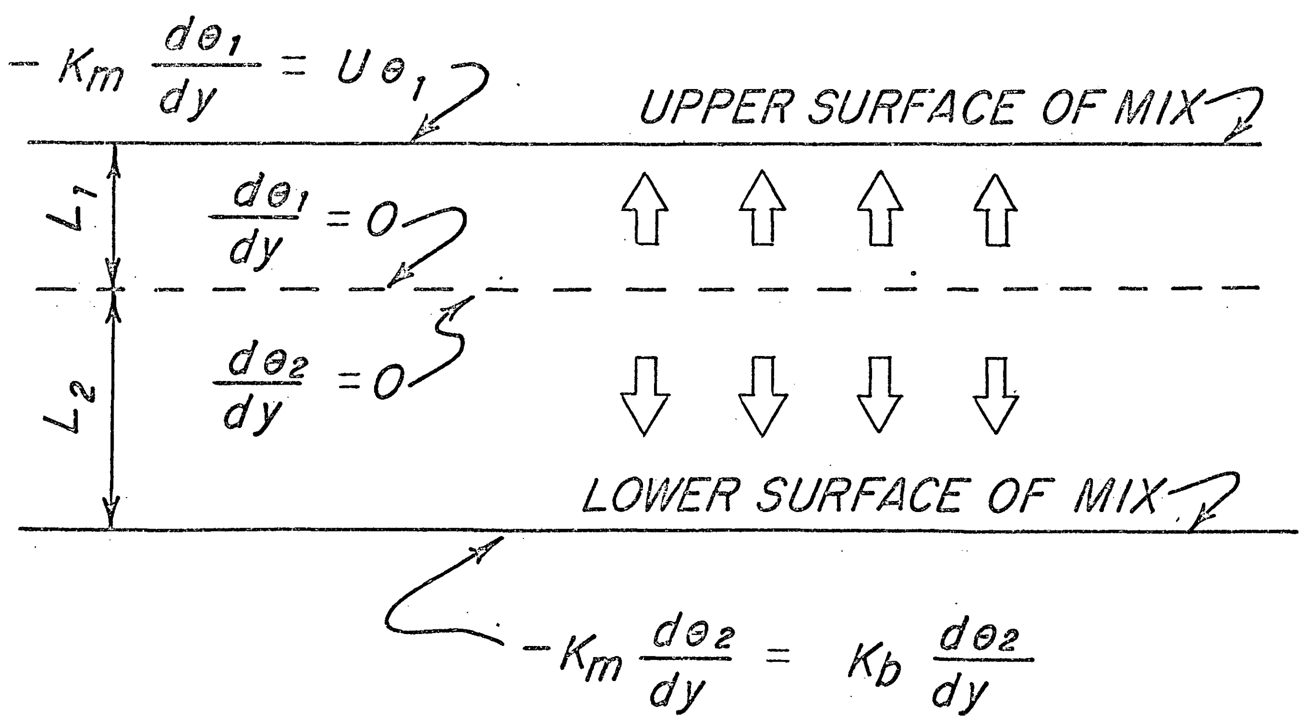


Figure 2. Boundary Conditions for Analytical Solution.

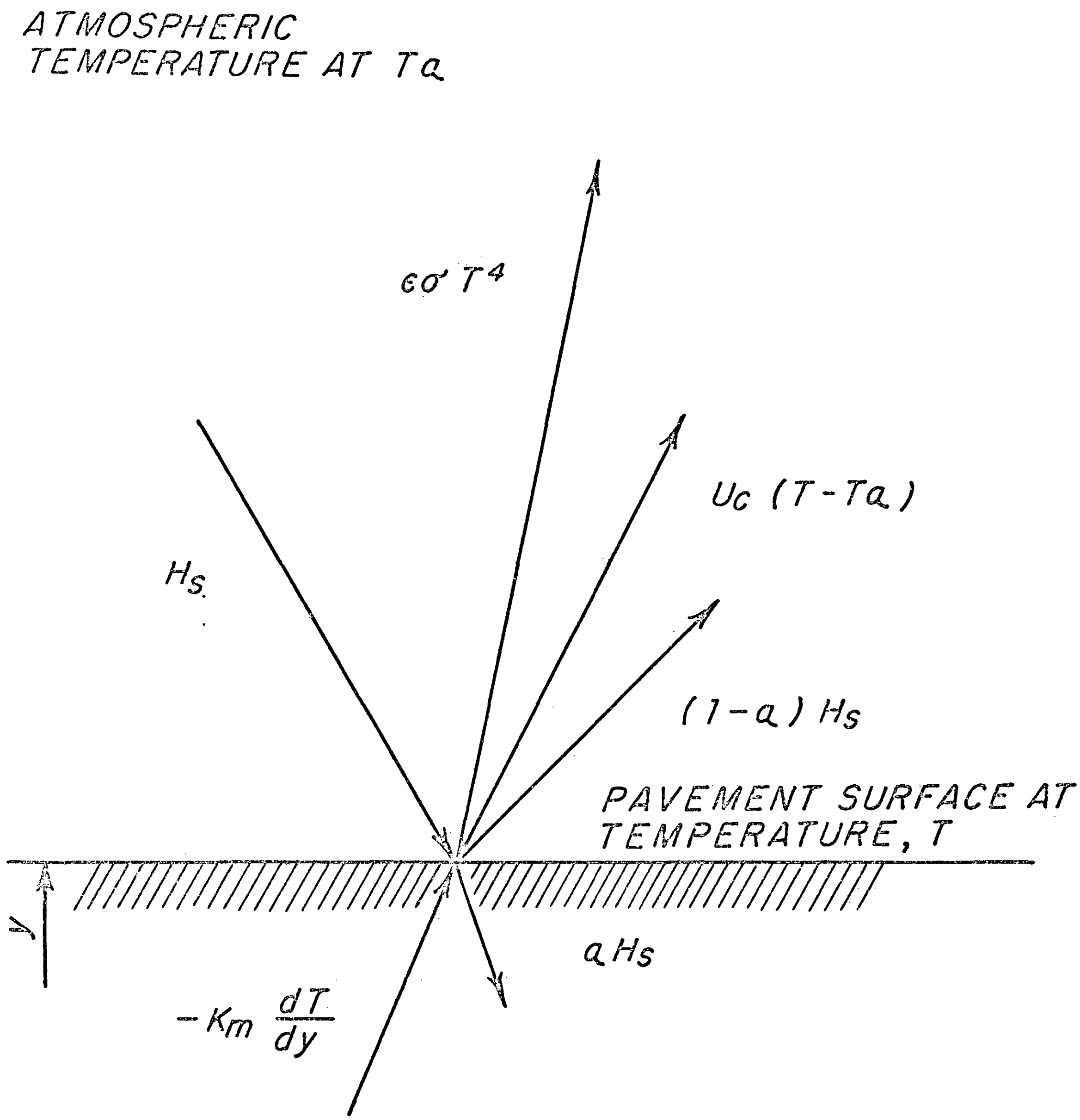


Figure 3. Interaction of Various Modes of Thermal Energy Transfer at the Pavement Surface.

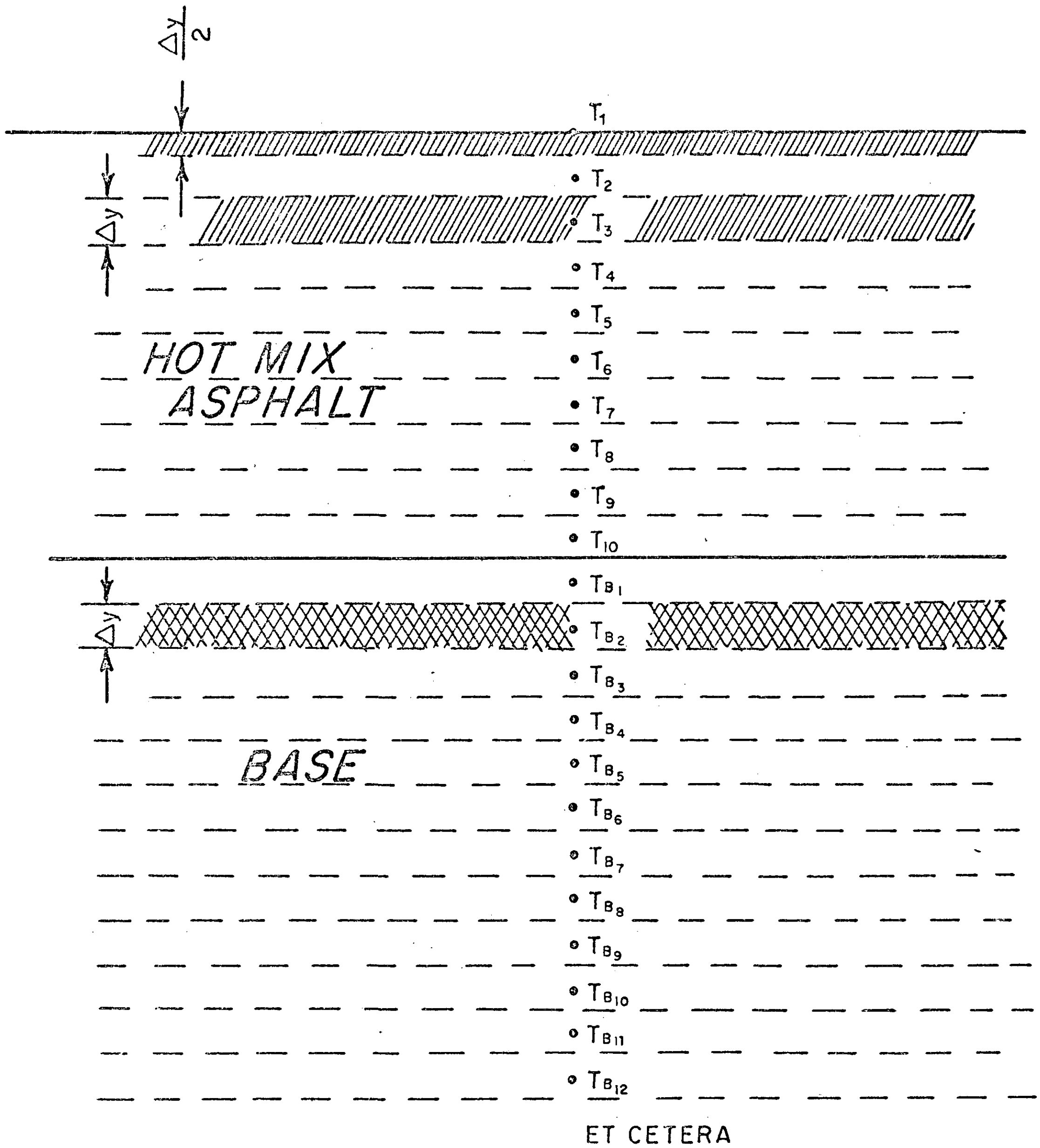


Figure 4. Typical Incremental Elements of Hot-mix Asphalt Concrete and Base Used in Numerical Solution.

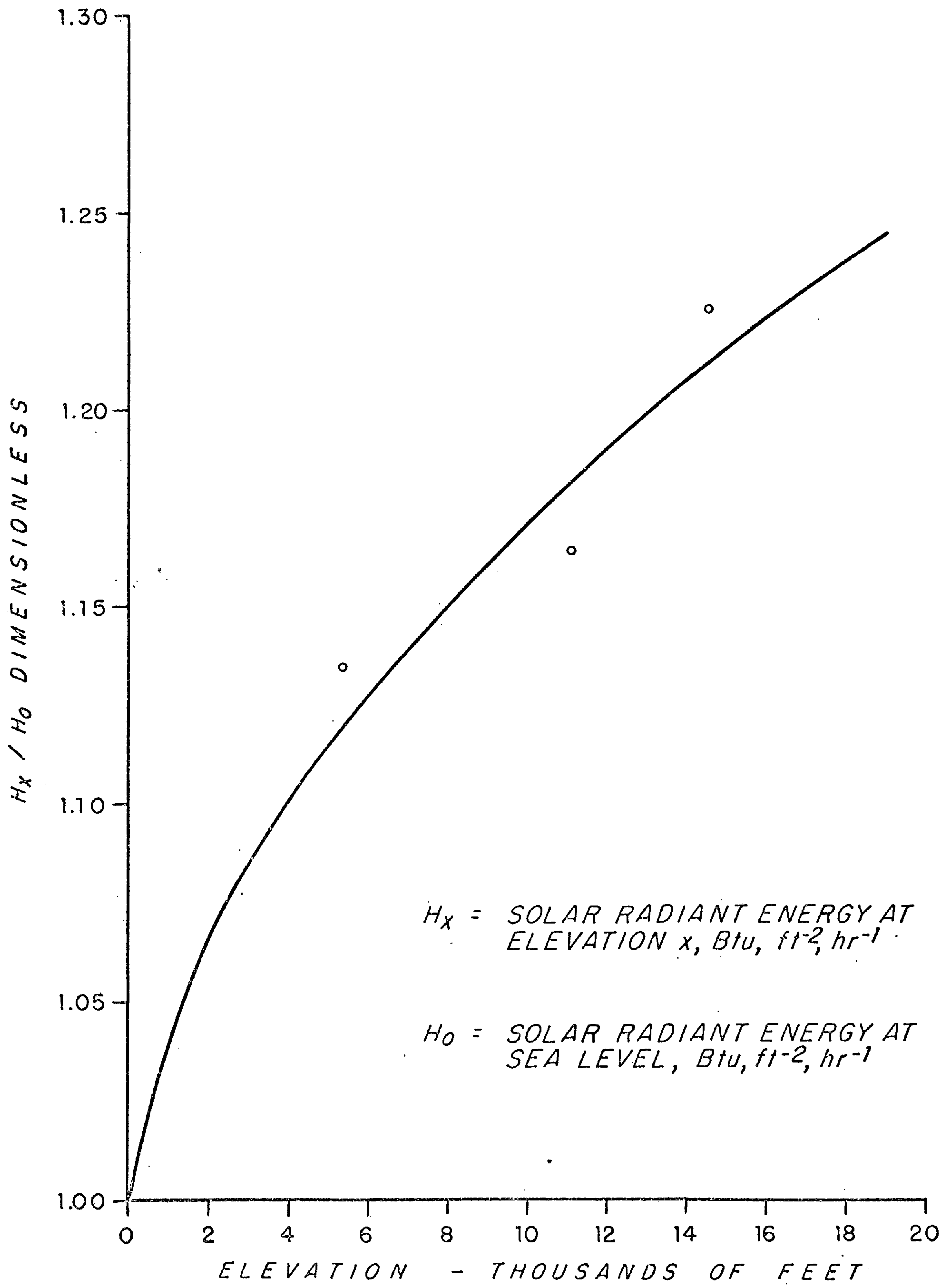


Figure 5. Variation of Solar Radiant Flux with Elevation.

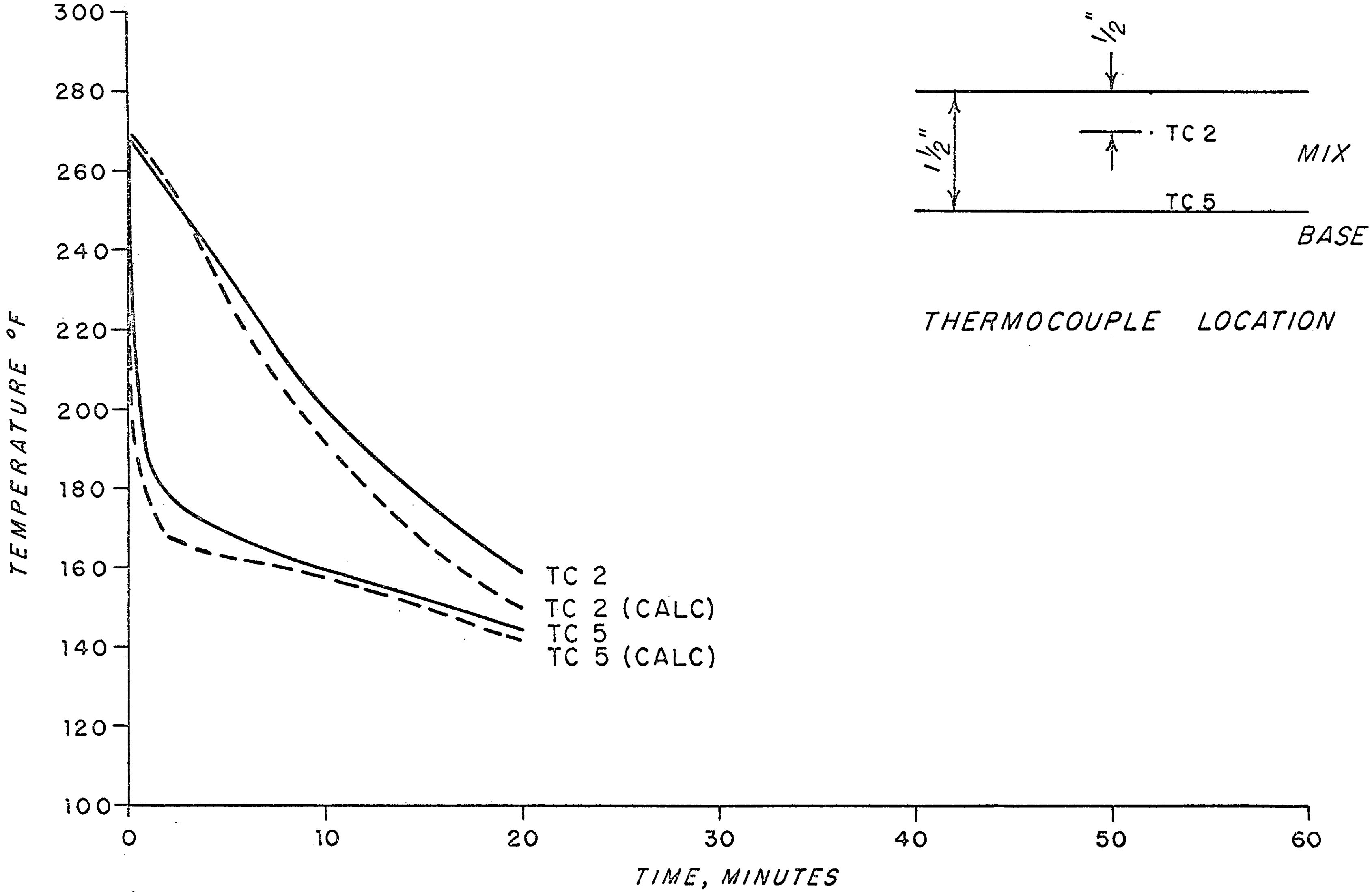


Figure 6. Comparison of Experimental Temperatures with Calculated Temperatures, Test No. 67-2, Evanston, Lyman.

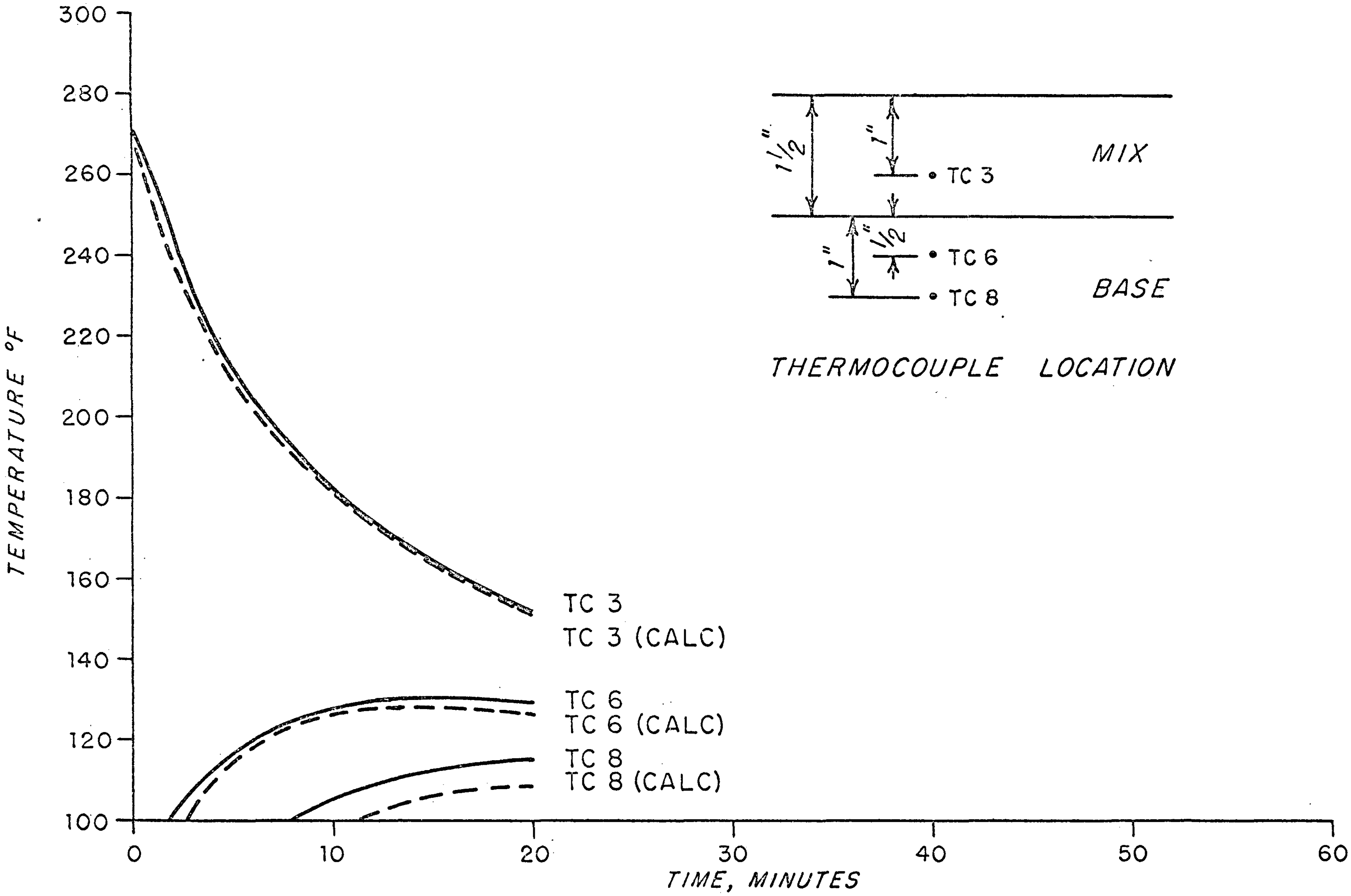


Figure 7. Comparison of Experimental Temperatures with Calculated Temperatures, Test No. 67-2, Evanston, Lyman.

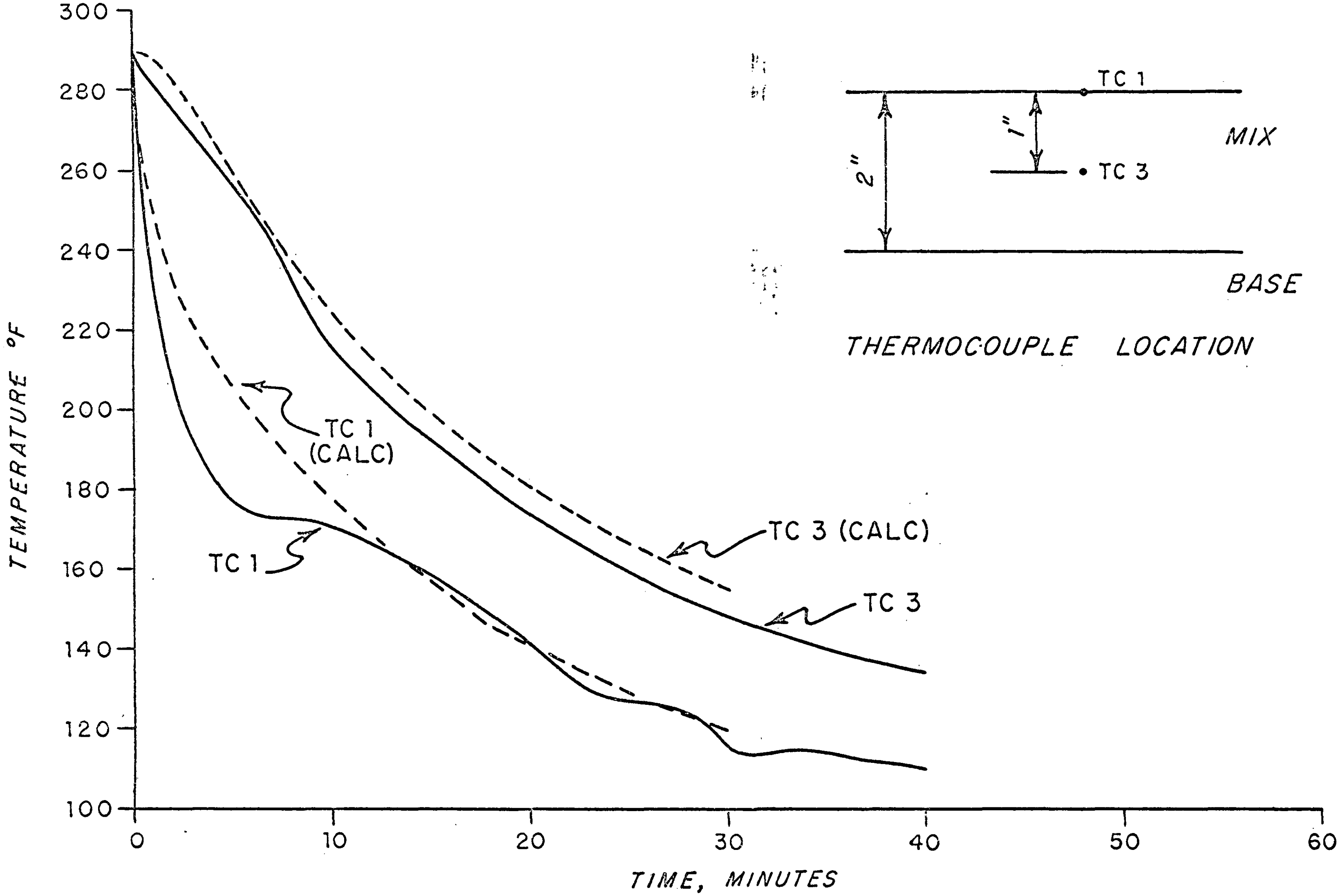


Figure 8. Comparison of Experimental Temperatures with Calculated Temperatures, Test No. 67-1, North of Rock Springs.

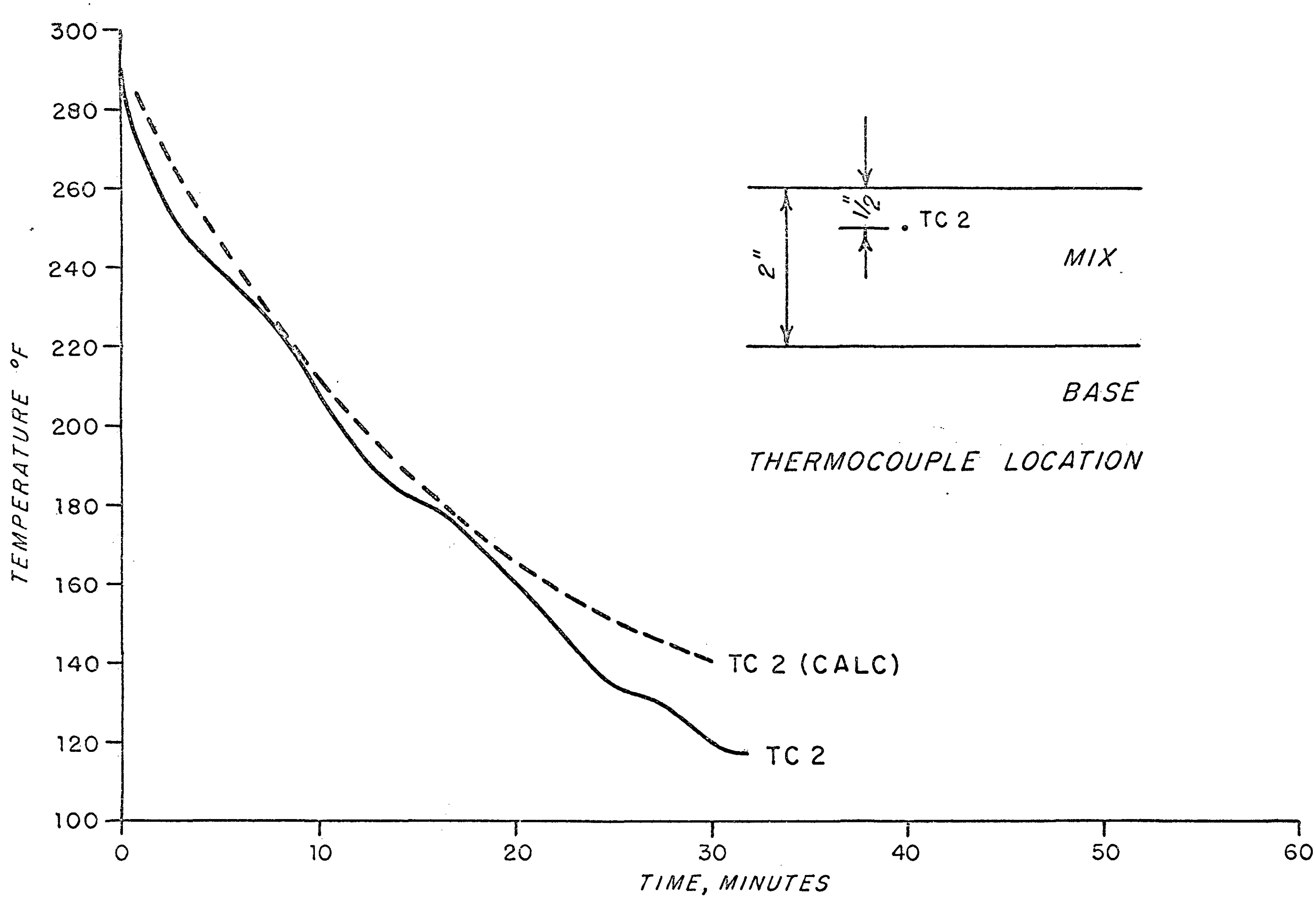


Figure 9. Comparison of Experimental Temperatures with Calculated Temperatures, Test No. 67-1, North of Rock Springs.

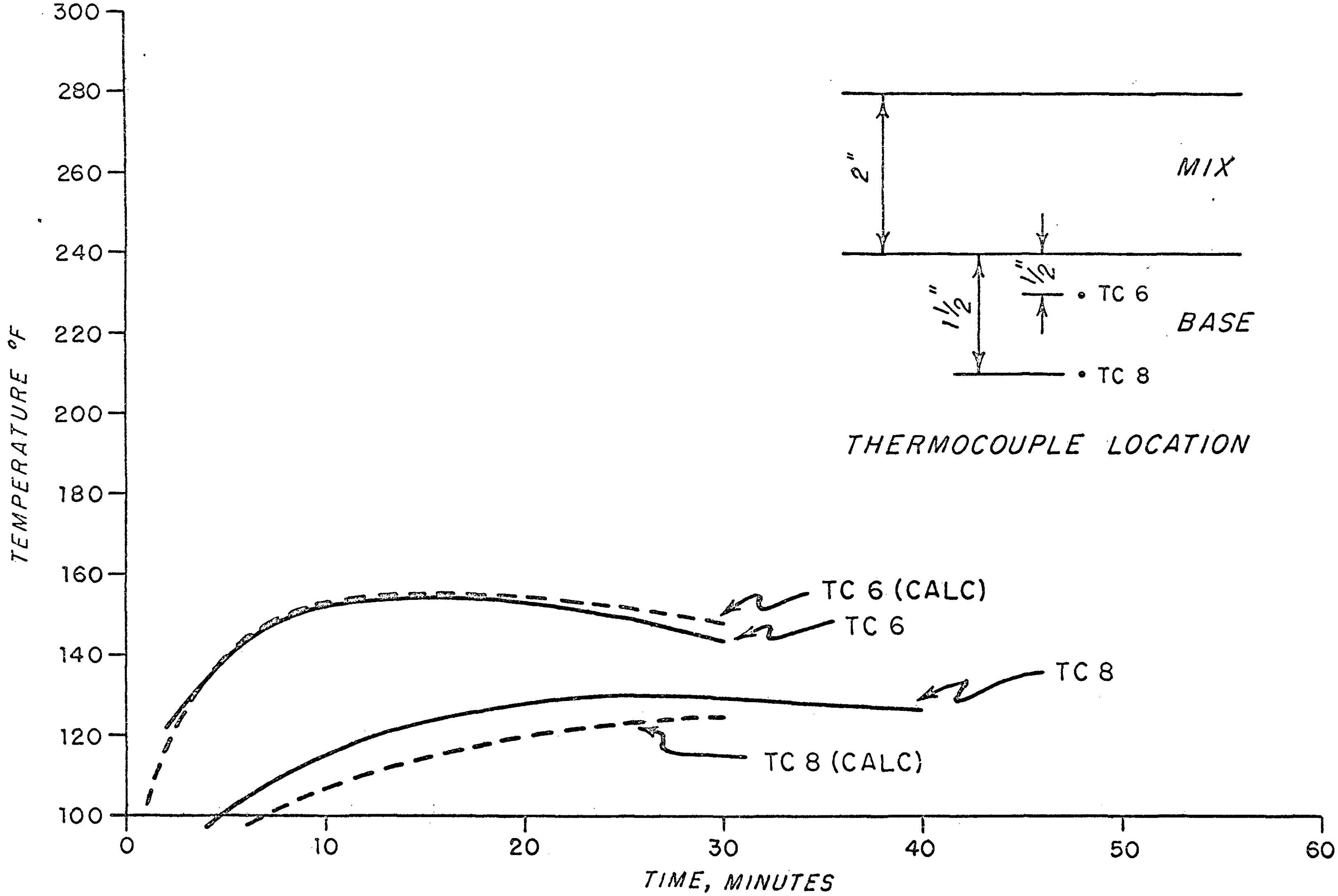


Figure 10. Comparison of Experimental Temperatures with Calculated Temperatures, Test No. 67-1, North of Rock Springs.

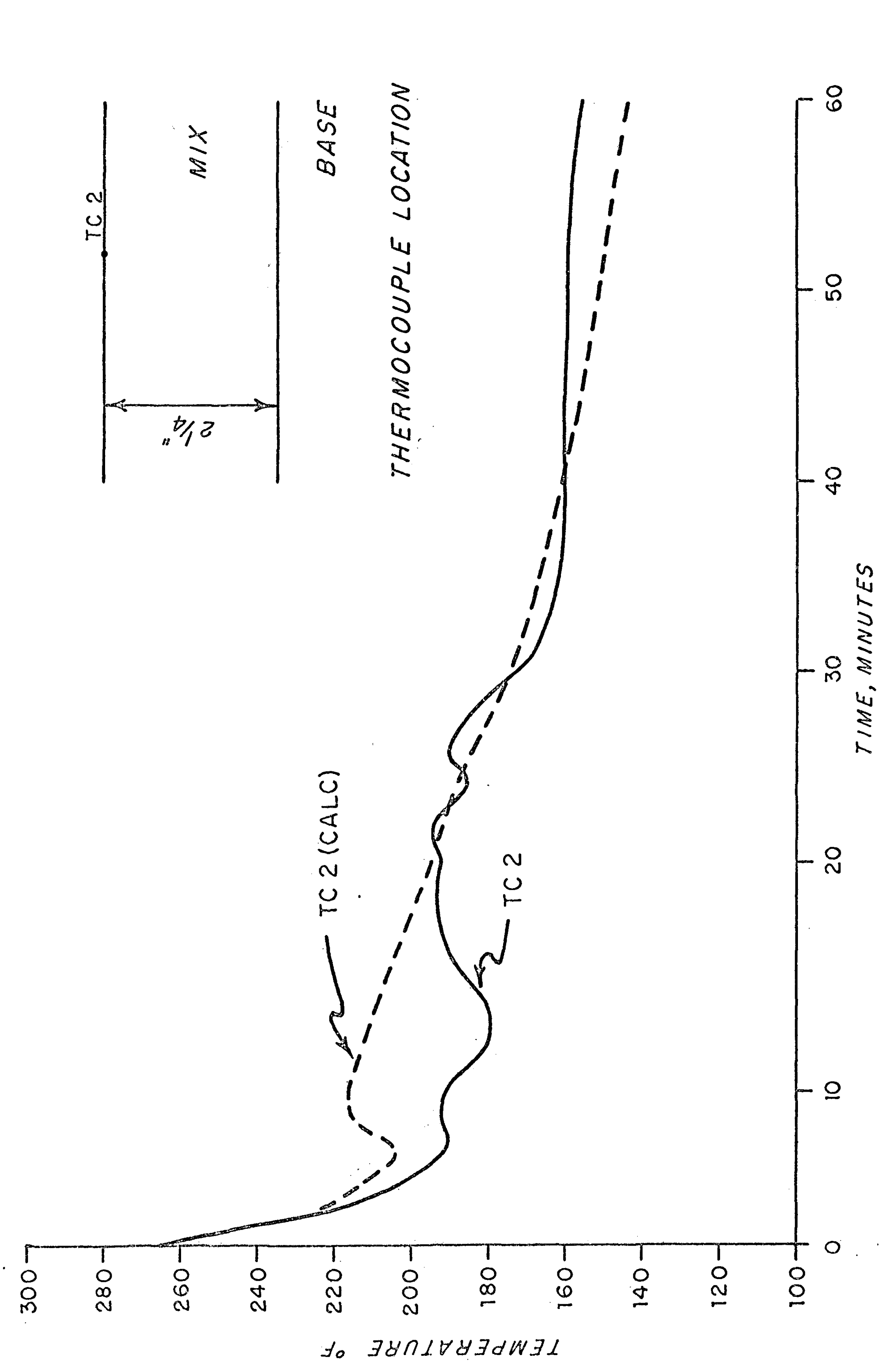


Figure 11. Comparison of Experimental Temperatures with Calculated Temperatures, Test No. 66-4, Grand Junction, Colorado Airport.

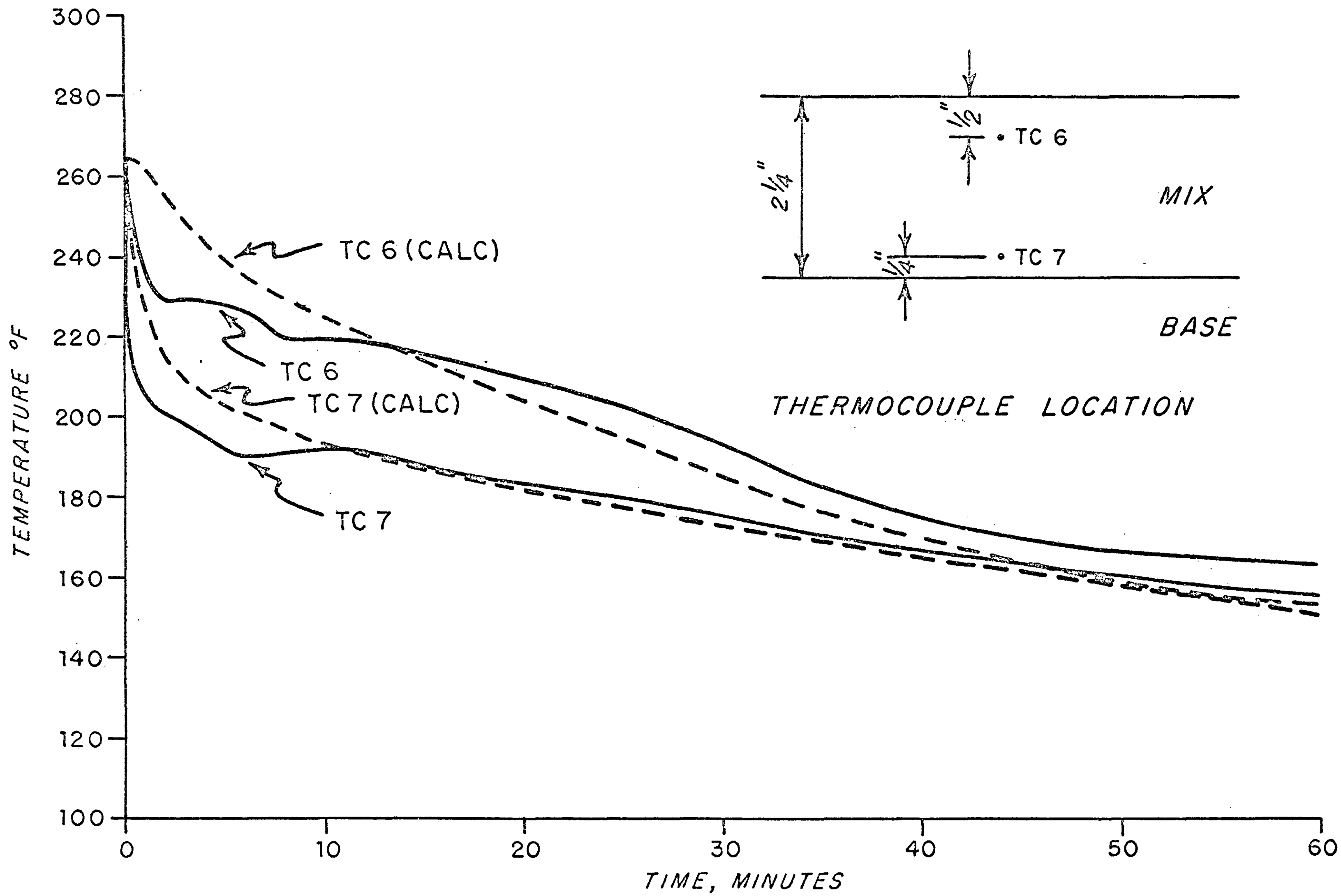


Figure 12. Comparison of Experimental Temperatures with Calculated Temperatures, Test No. 66-4, Grand Junction, Colorado Airport.

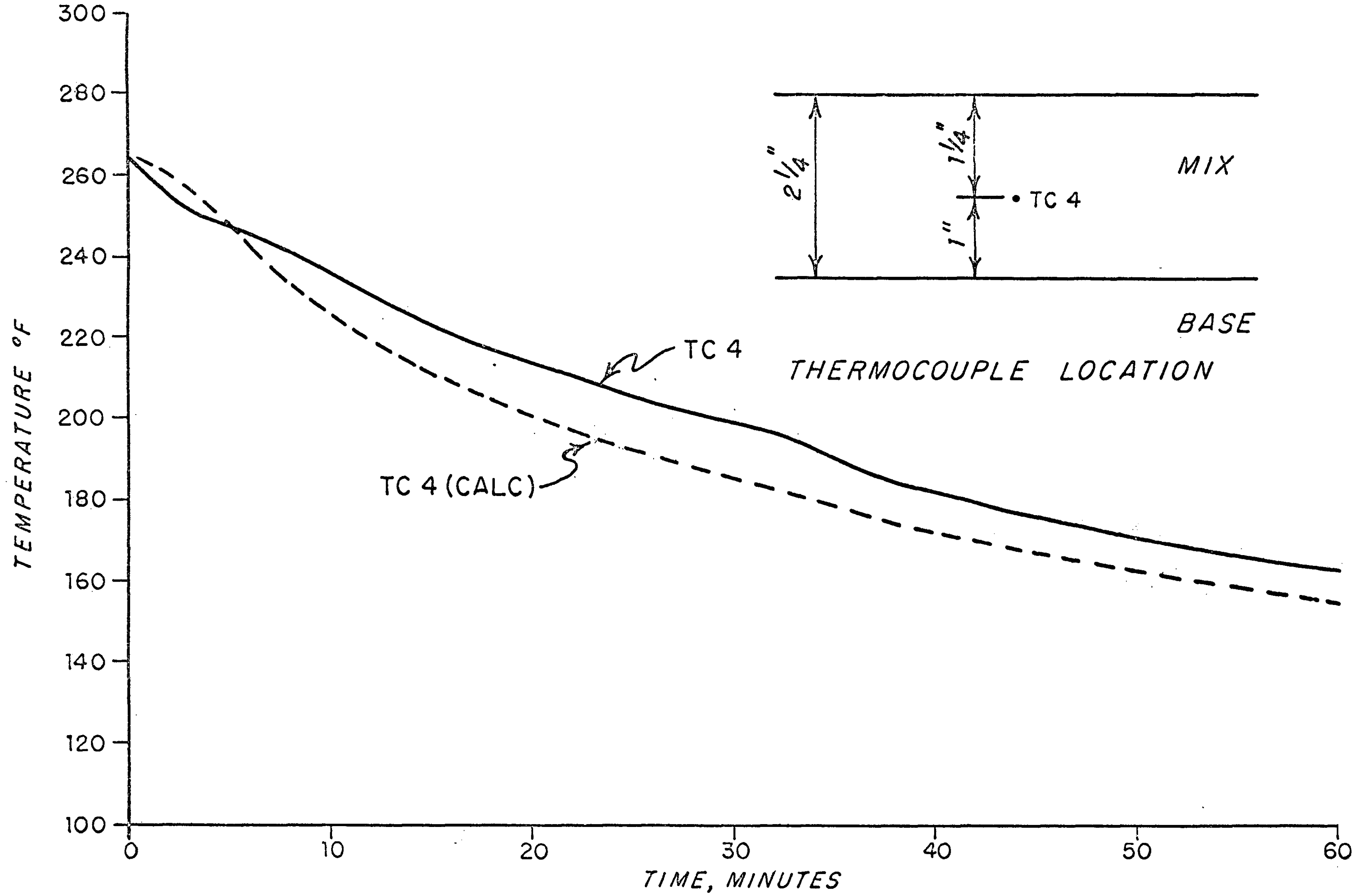


Figure 13. Comparison of Experimental Temperatures with Calculated Temperatures, Test No. 66-4, Grand Junction, Colorado, Airport.

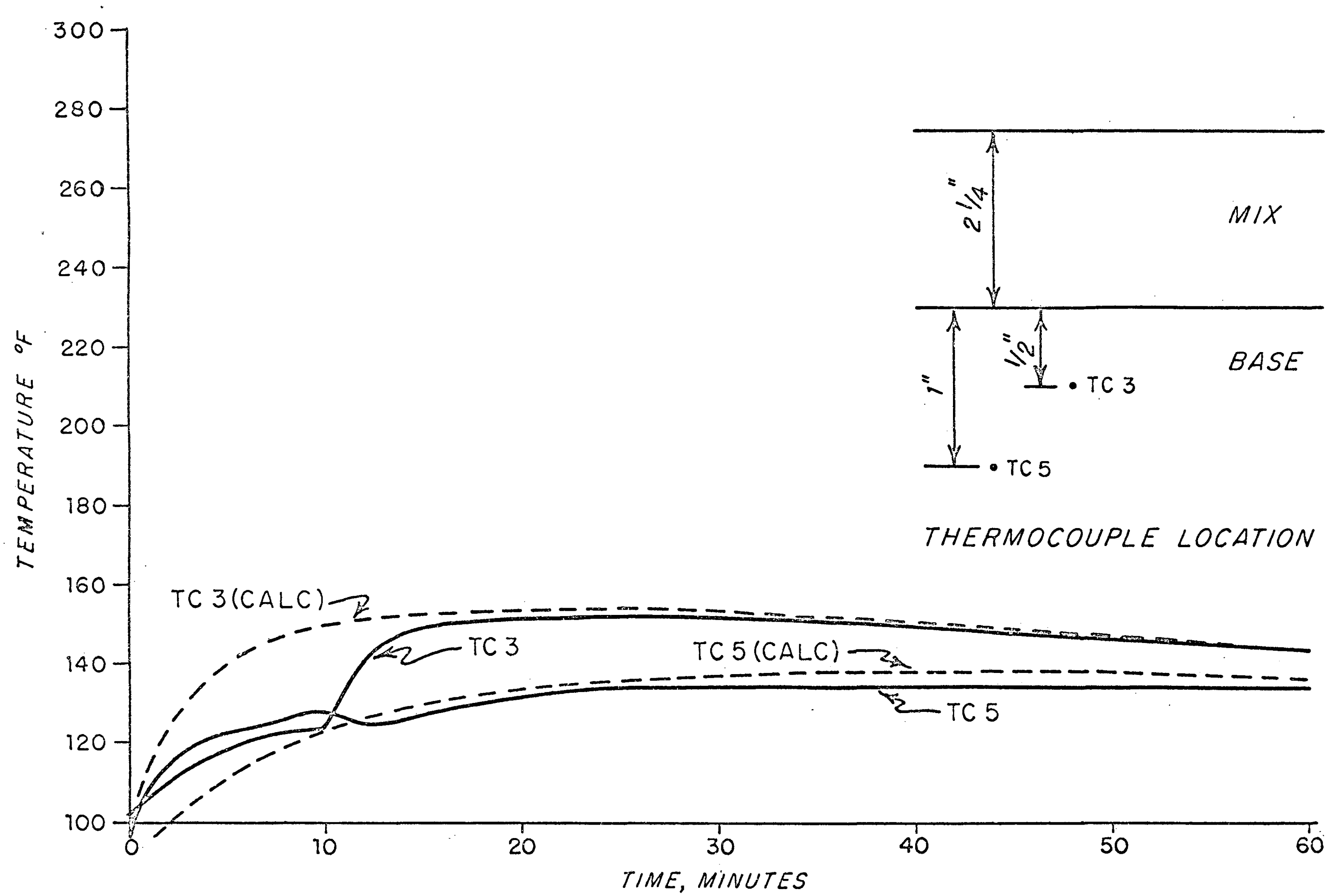


Figure 14. Comparison of Experimental Temperatures with Calculated Temperatures, Test No. 66-4, Grand Junction, Colorado, Airport.

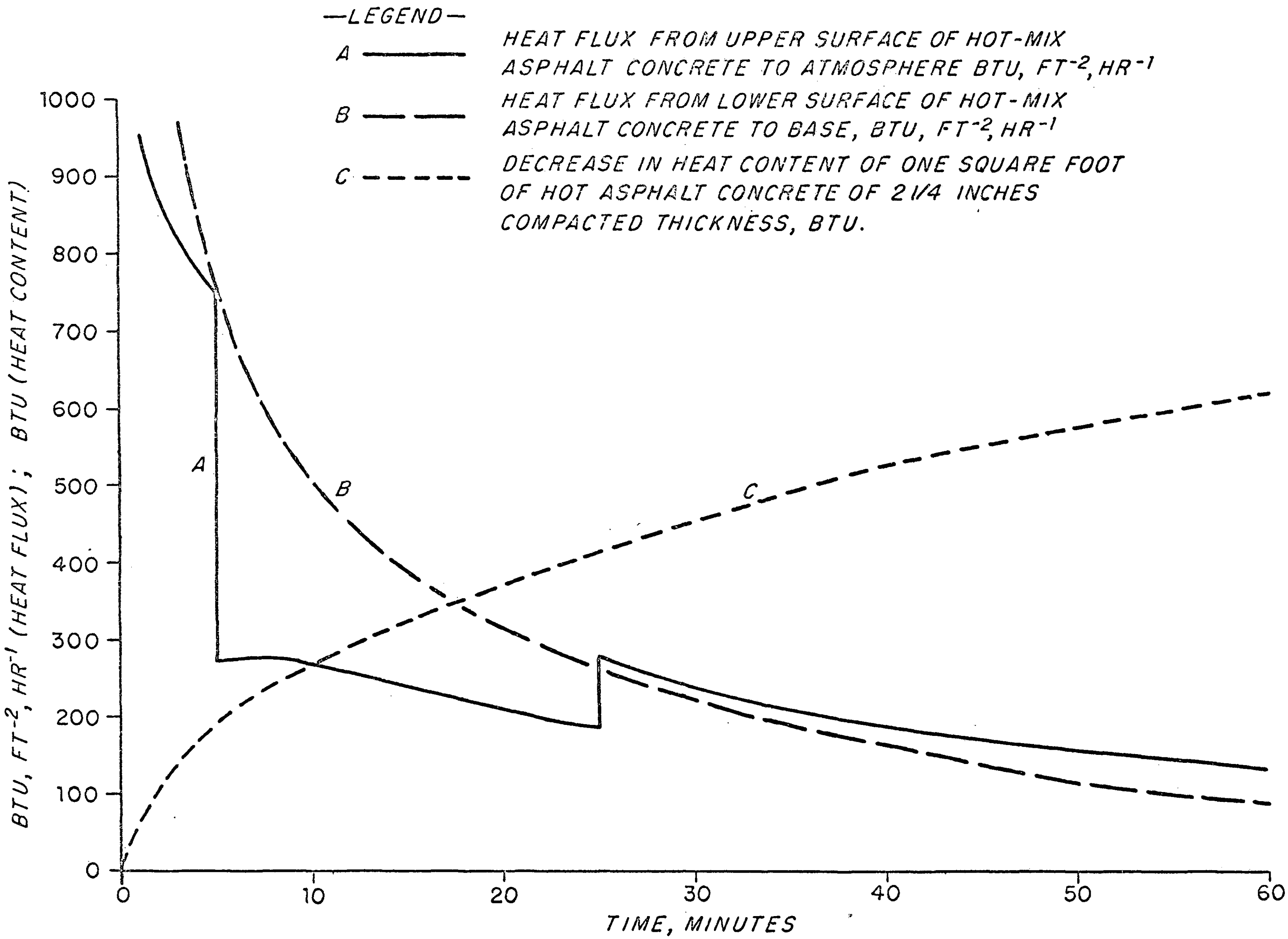


Figure 15. Flux and Heat Content vs. Time: Test No. 66-4, Grand Junction, Colorado Airport.

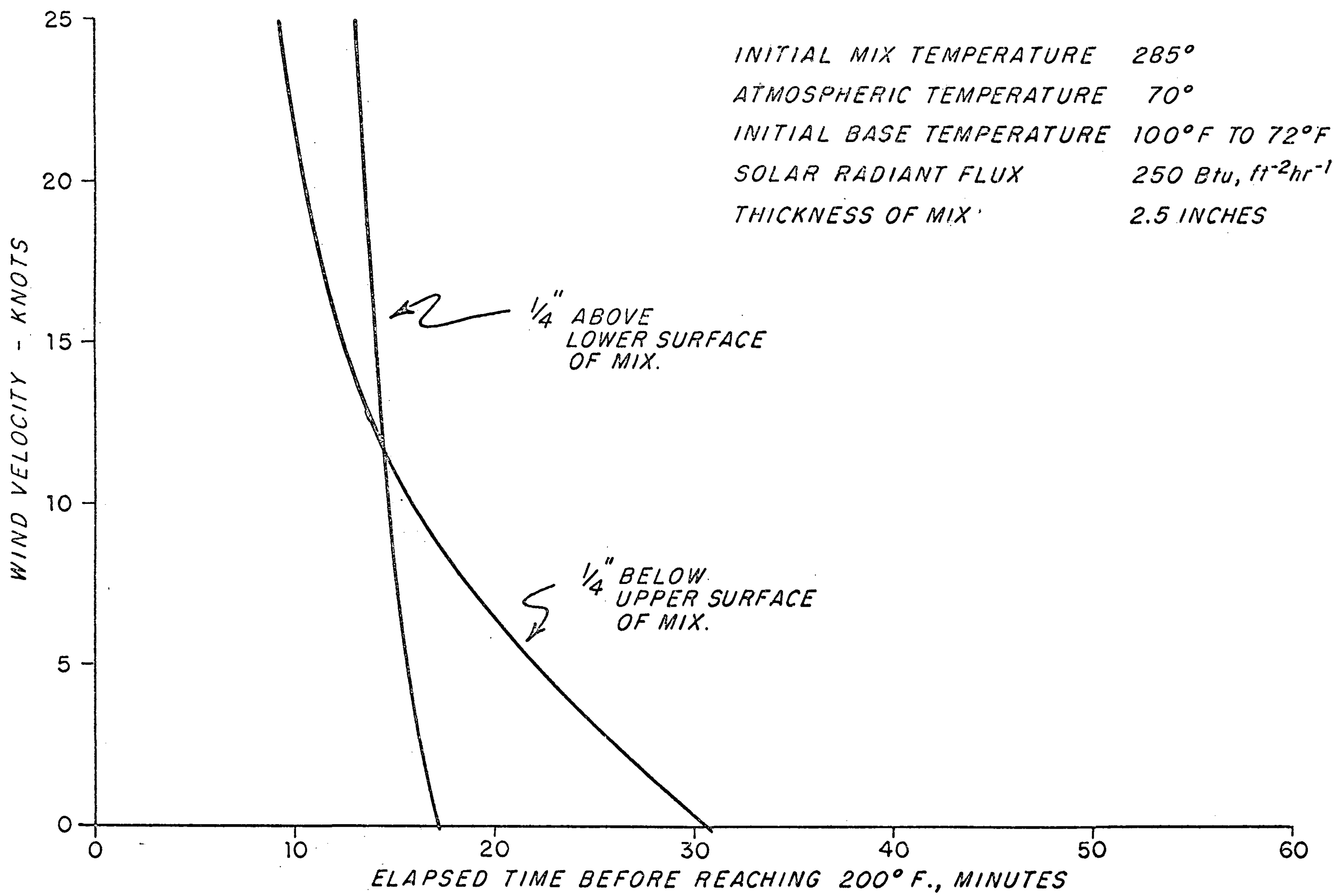


Figure 16. Elapsed Time Before Reaching 200° F. vs Wind Velocity.

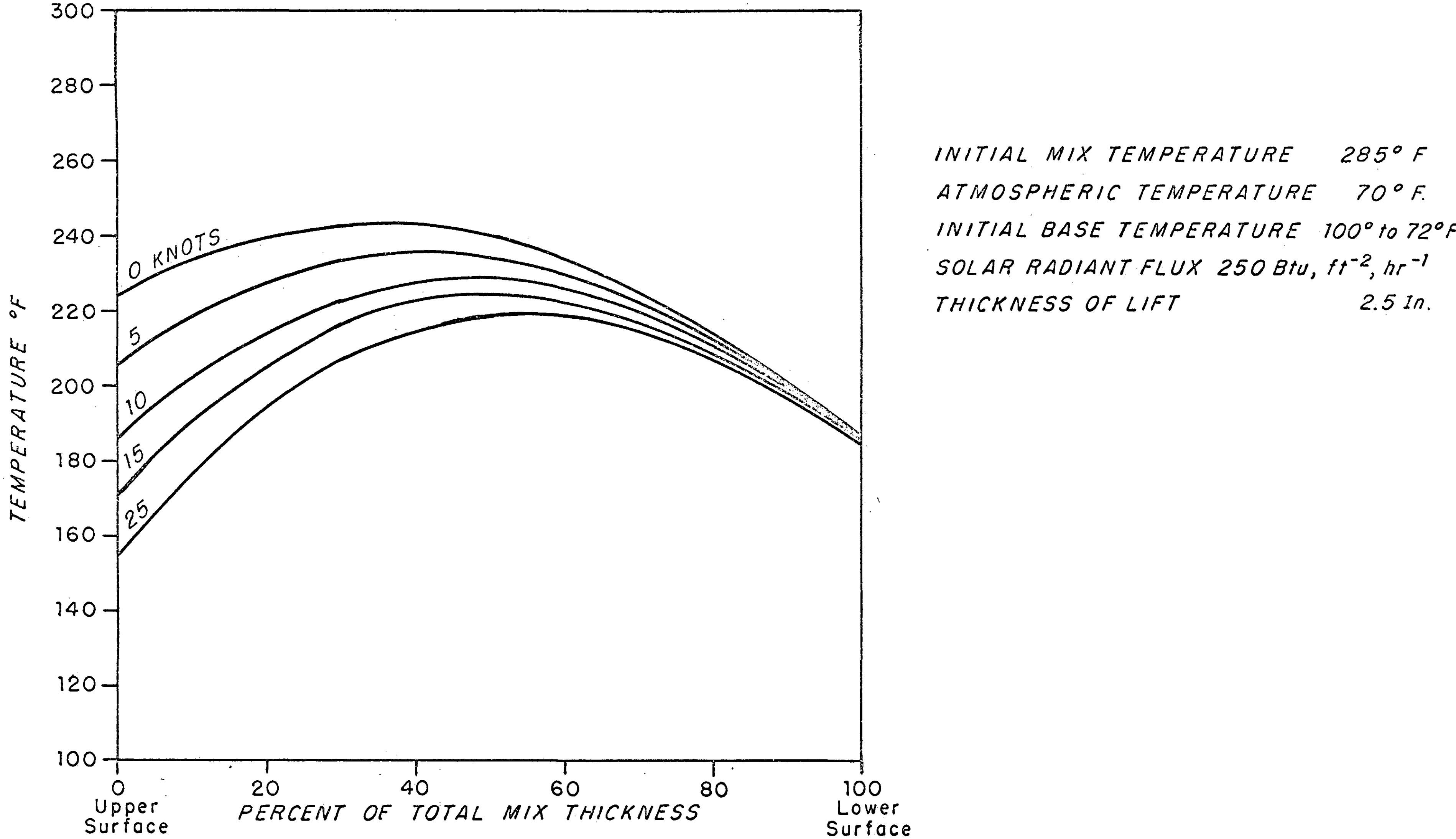


Figure 17. Effect of Wind Velocity on Temperature of Mix 15 Minutes after Placement of Mix.

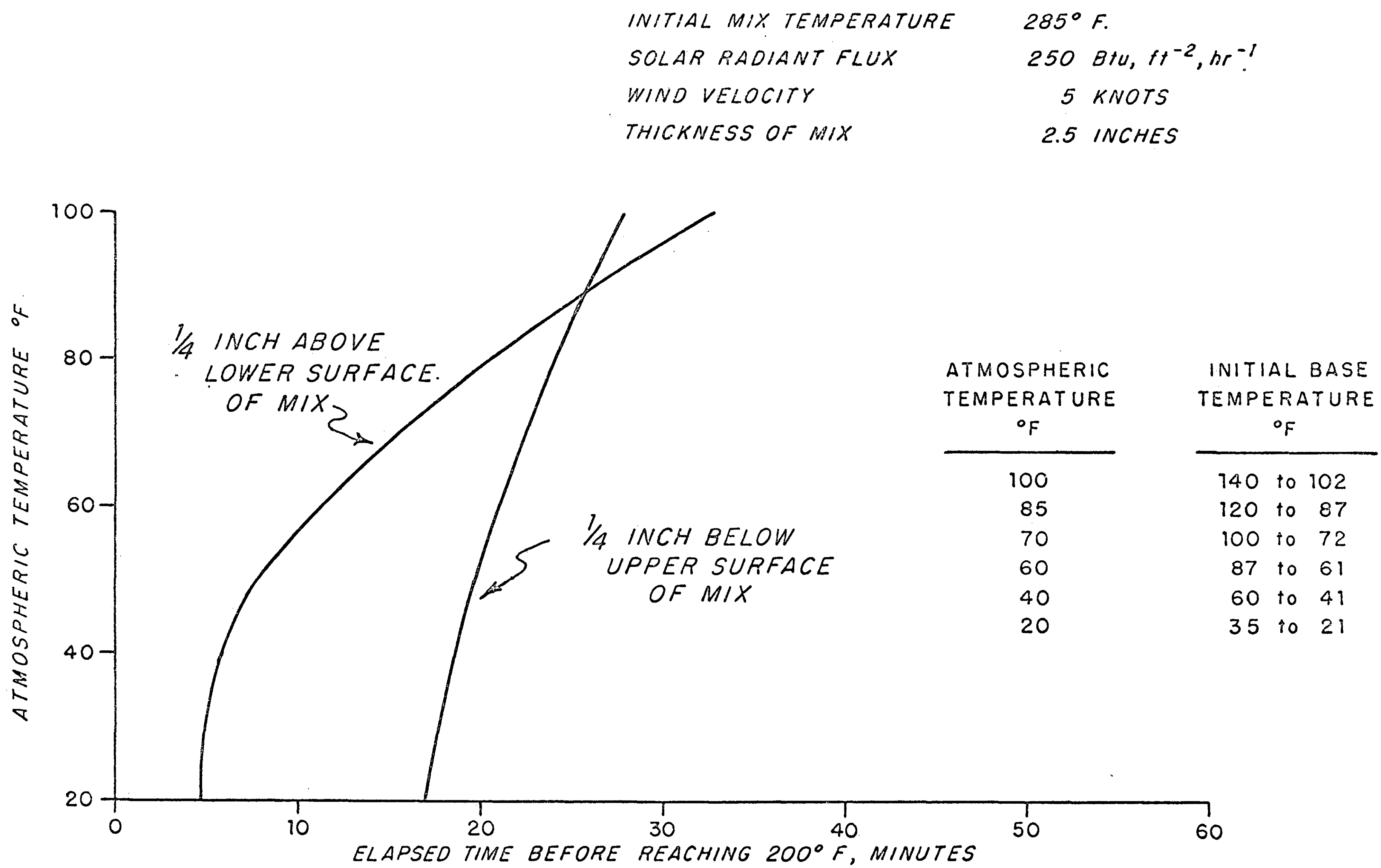
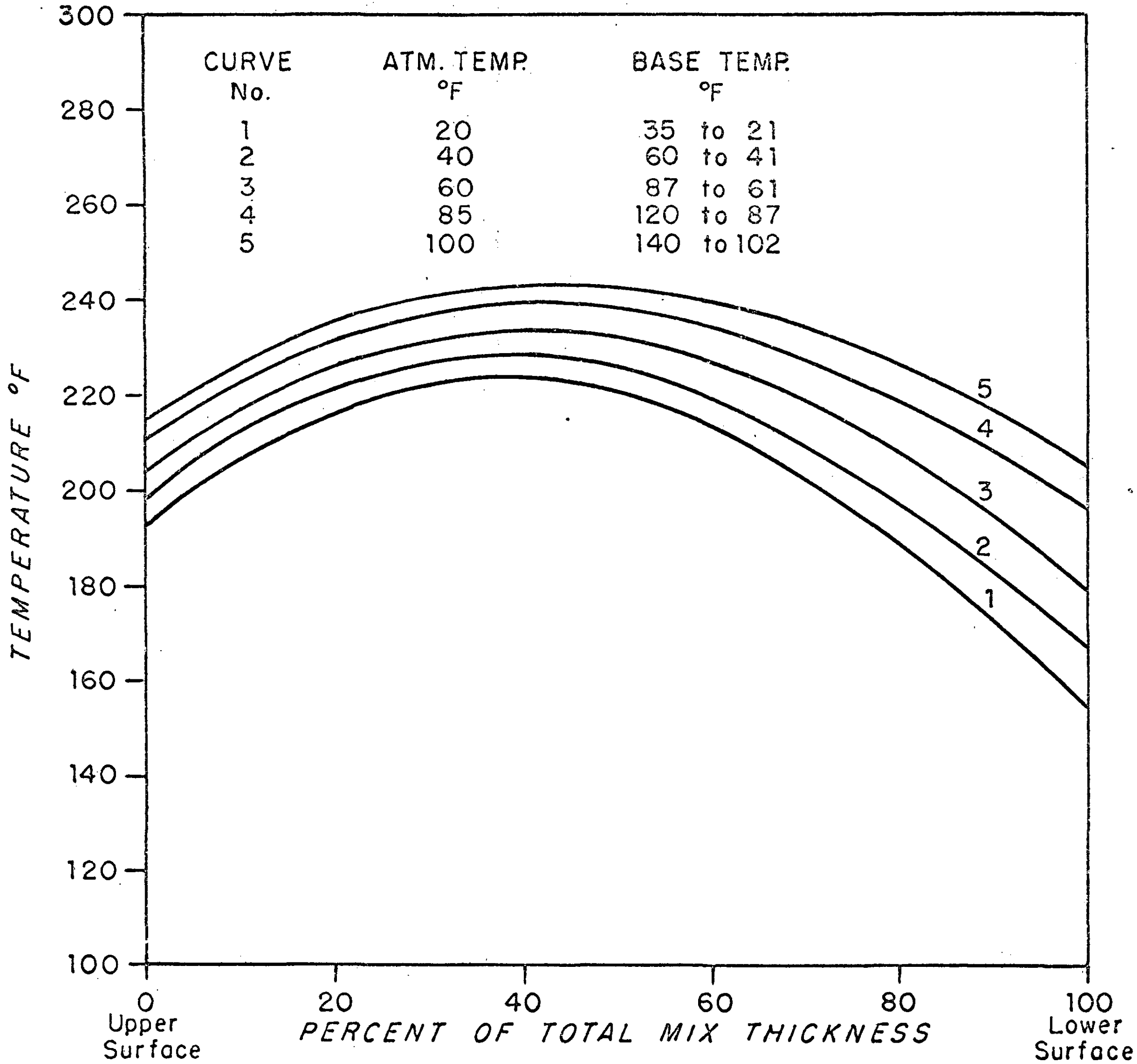


Figure 18. Elapsed Time Before Reaching 200° F vs. Atmospheric Temperature and Base Temperature.



INITIAL MIX TEMPERATURE 285° F

SOLAR RADIANT FLUX 250 Btu, ft^{-2}, hr^{-1}

WIND VELOCITY 5 KNOTS

THICKNESS OF MIX 2.5 INCHES

Figure 19. Effect of Atmospheric and Base Temperatures on Temperature of Mix 15 Minutes after Placement of Mix.

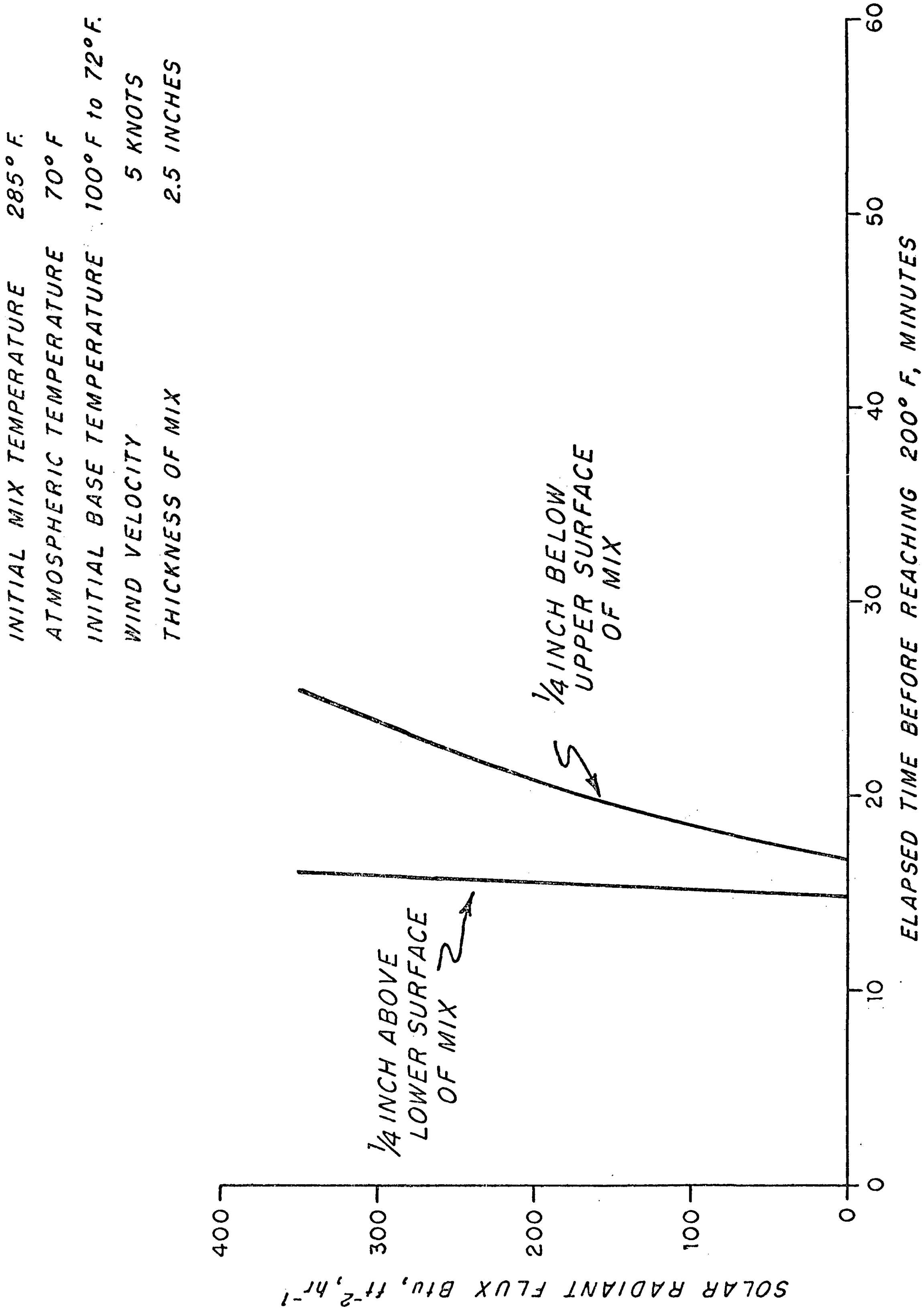


Figure 20. Elapsed Time Before Reaching 200° F vs. Solar Radiant Flux.

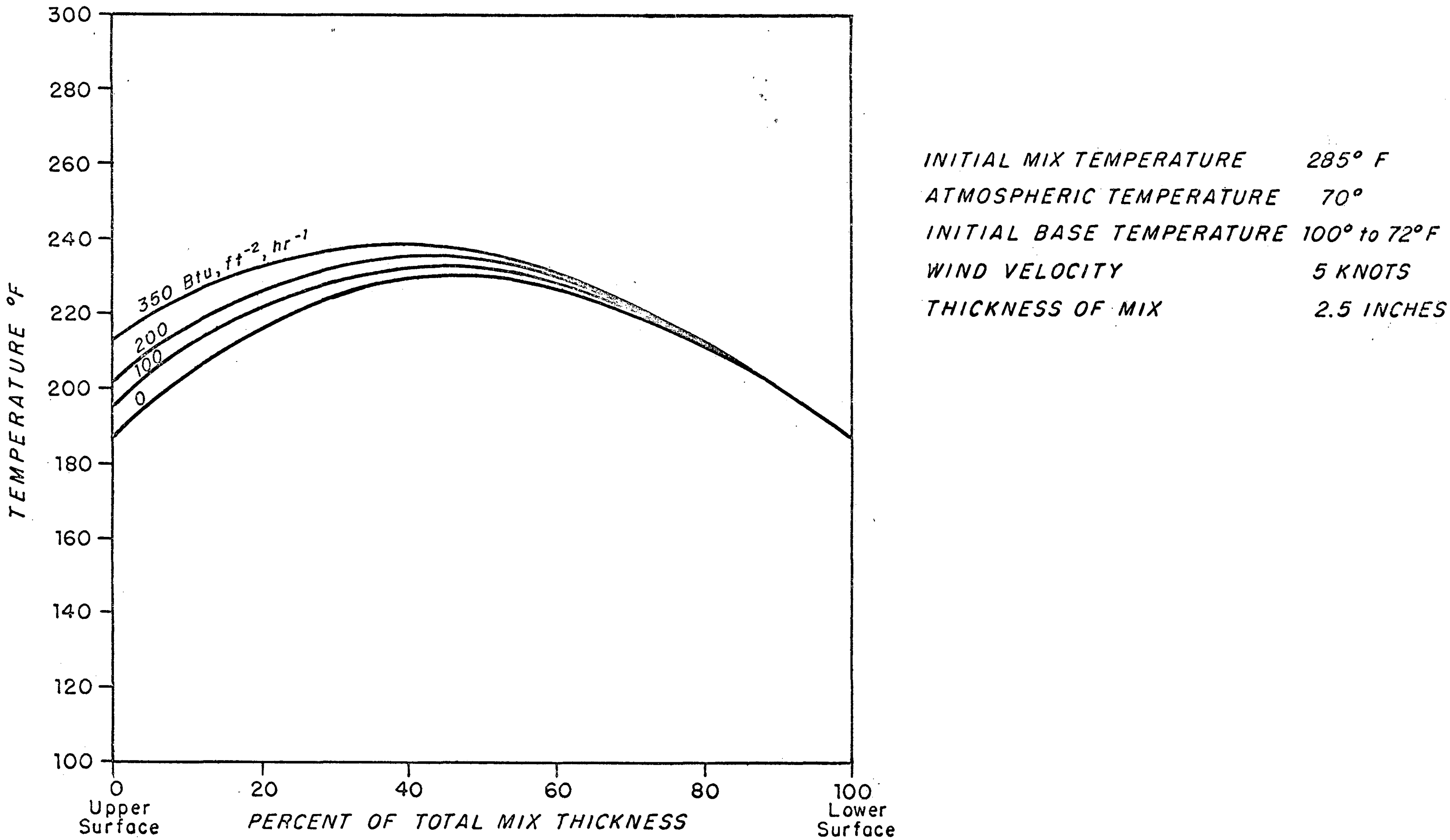


Figure 21: Effect of Solar Radiation on Temperature 15 Minutes after Placement of Mix.

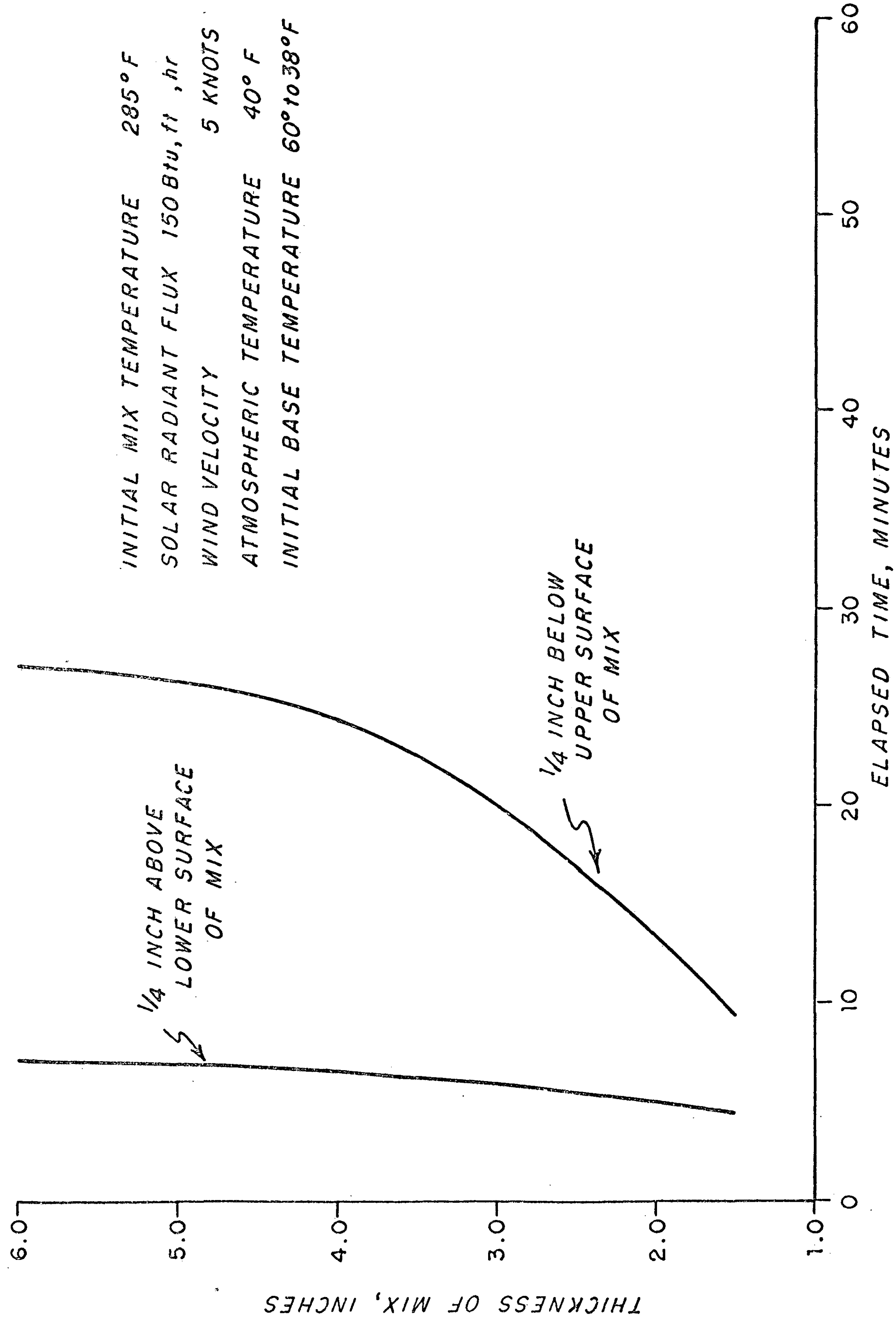


Figure 22. Elapsed Time Before Reaching 200° F vs. Thickness of Mix.

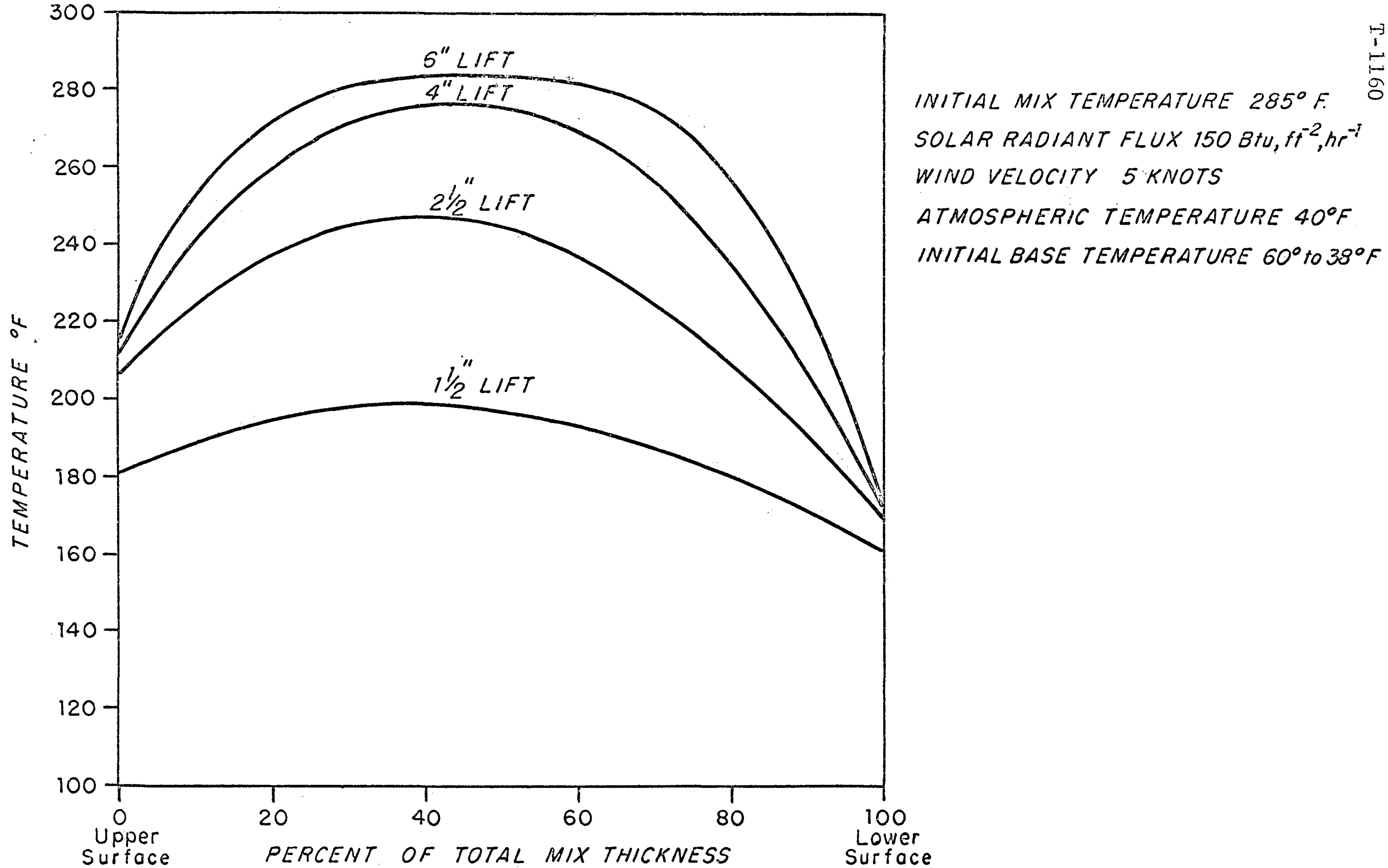


Figure 23. Temperature Profiles of Various Lift Thicknesses 10 Minutes after Placement of the Mix.

APPENDIX A

Table A.1

Test No. 67-2, Evanston-Lyman,
General Information

Date	Sept. 13, 1967
Project No.	Wyoming I-80-1 (27) 26
Location	Evanston-Lyman
Station No. at test location	5240 + 00
Elevation at test location, ft.	6930
Bearing of highway at test location	S 80° 40' W
Thickness of lift, in.	1.5
Thickness of in-place asphalt concrete	
Leveling Course, in.	1.5
Plant Mixed Surface, in.	1.5
Type of base	Cement Treated
Thickness of base, in.	6.0
Thermocouple location	
Distance from edge of pavement, in.	48
Distance from upper surface of lift	
TC-1, in. (surface)	0
TC-2, in.	0.5
TC-3, in.	1.0
TC-4, in. (displaced during test)	1.5
TC-5, in. (top of previous lifts)	1.5
TC-6, in.	2.0
TC-7, in.	3.5
TC-8, in.	2.5

Table A.1A

Test No. 67-2, Evanston-Lyman,
Environmental Data

Time	Wind Velocity fpm	Wind Direction deg.	Atmospheric Temperature °F	Solar Altitude deg.	Remarks
9:38 a.m.	1000	270	46	-	
9:45	965	270	-	-	
9:55	975	270	-	-	
10:00	-	-	-	32	
10:10	710	270	47	-	
10:20	-	-	-	-	Start of test
10:22	527	270	53	-	
10:27	799	270	54	-	
10:29	781	270	-	-	
10:32	570	270	56	-	
10:37	-	-	-	39	
10:40	618	270	53	-	
10:45	933	270	53	-	
10:47	647	270	54	-	
10:50	930	270	53	-	End of test
11:00	-	-	-	44	

Table A.1B

Test No. 67-2, Evanston-Lyman,
Experimental Temperatures

Time	TC-1 °F	TC-2 °F	TC-3 °F	TC-5 °F	TC-6 °F	TC-8 °F	TC-7 °F
10:20 a.m.	(270)	(270)	(270)	64	63	62	60
10:22	-	256	248	178	102	77	63
10:24	194	242	220	172	113	89	69
10:26	168	227	206	168	120	96	72
10:28	155	213	192	163	125	101	77
10:30	148	200	183	160	128	106	82
10:32	156	190	174	157	130	110	86
10:34	150	181	168	154	130	112	90
10:36	148	174	162	151	130	114	92
10:38	141	167	157	148	130	114	94
10:40	131	158	152	145	129	115	96
10:42	132	154	148	142	128	116	98
10:44	130	150	114	141	126	116	99
10:46	-	146	141	137	124	115	100
10:48	-	142	138	134	124	115	100
10:50	-	138	135	132	123	114	100

( ) Indicates initial temperature of hot-mix asphalt concrete

Table A.2

Test No. 67-1, North of Rock Springs, General Information

Date	June 26, 1967
Project No.	Wyoming SMP 5854
Location	North of Rock Springs, Wyoming
Station No. at test location	677 + 00
Elevation at test location, ft.	6643
Bearing of highway at test location	N 66° 09' W
Thickness of lift, in.	2.0
Thickness of in-place asphalt concrete Surfacing, in.	2.0
Type of base	Untreated Crushed
Thickness of base, in.	3.5
Thermocouple location	
Distance from edge of pavement, in.	48
Distance from upper surface of lift	
TC-1, in. (surface)	0
TC-2, in.	0.5
TC-3, in.	1.0
TC-4, in.	1.5
TC-5, in.	2.0
TC-6, in.	2.5
TC-7, in.	3.0
TC-8, in.	3.5

Table A.2A

Test No. 67-1, North of Rock Springs, Environmental Data

Time		Wind Velocity Knots (1)	Wind Direction deg. (1)	Atmospheric Temperature °F	Solar Altitude deg.	Remarks
1:00 p.m.		12	230	68	Cloudy	
1:30		-	-	70	do	
2:00	(2)	10	180	60	do	
2:10		-	-	72	do	
2:18		-	(3)	-	do	Start of test
2:35		-	-	65	do	
2:45		-	-	65	do	
2:55		-	-	65	do	
3:00	(2)	10	170	65	do	End of test

Notes: (1) Wind velocity and direction from FAA station at Rock Springs, Wyoming.

(2) Velocity reported as 10 knots with gusts of 15 to 25 knots.

(3) Wind direction at test location was perpindicular to highway or 200 degrees.

Table A.2B

Test No. 67-1, North of Rock Springs, Experimental Temperatures

Time	TC-1 °F	TC-2 °F	TC-3 °F	TC-6 °F	TC-7 °F	TC-8 °F
2:18 p.m.	(290)	(290)	(290)	90	92	92
2:20	-	-	276	120	102	93
2:22	182	243	263	134	112	98
2:24	175	236	248	142	122	104
2:26	172	224	232	149	130	110
2:28	169	210	216	152	134	116
2:30	168	196	208	153	137	118
2:32	161	184	198	154	139	122
2:34	159	180	189	155	140	124
2:36	149	171	182	154	142	126
2:38	140	161	174	152	142	128
2:40	132	150	168	152	142	129
2:42	128	138	162	151	142	130
2:44	128	133	158	150	141	130
2:46	126	128	153	148	140	130
2:48	114	120	148	145	138	130
2:50	114	118	145	143	136	129
2:52	114	118	142	142	135	129
2:54	112	118	140	140	134	129
2:56	112	118	137	138	132	128
2:58	110	119	135	136	130	127

( ) Indicates initial temperature of hot-mix asphalt concrete

Table A.3

Test No. 66-4, Grand Junction Airport,
General Information

Date	September 30, 1966
Project No.	FAA 9-05-004-C706
Location	Grand Junction, Colorado
Test Location	SE End of Runway
Elevation at Test Location, ft.	4858
Bearing of Runway	N 54° 54' W
Thickness of lift, in.	2.25
Thickness of in-place asphalt concrete Plant Mixed Surface, in.	2
Type of base	Untreated Granular
Thickness of base, in.	7
Thermocouple location	
Distance from edge of pavement, in.	36
Distance from upper surface of lift	
TC-6, in.	0.5
TC-4, in.	1.25
TC-7, in.	2.0
TC-3, in.	2.75
TC-5, in.	3.25

Table A.3A

Test No. 66-4, Grand Junction Airport, Environmental Data

Time	Wind Velocity Knots	Wind Direction deg.	Atmospheric Temperature °F	Solar Altitude deg.	Remarks
11:00 a.m.	15	60	70		
12:00 noon	16	30	71		
1:00 p.m.	14	30	74	50	Start of test
2:00	5	170	74	45	End of test
3:00	10	310	76		

Table A.3B

Test No. 66-4, Grand Junction Airport
Experimental Temperatures

Time	TC-2 °F	TC-6 °F	TC-4 °F	TC-7 °F	TC-3 °F	TC-5 °F
1:00 p.m.	(265)	(265)	(265)	(265)	102	96
1:02	-	230	254	200	108	114
1:04	195	229	250	194	116	120
1:06	191	226	246	190	120	124
1:08	191	220	240	192	123	126
1:10	182	220	236	192	124	128
1:12	180	219	230	191	142	125
1:14	185	216	225	189	148	126
1:16	191	214	222	187	150	128
1:18	193	212	217	186	151	130
1:20	192	210	214	184	152	132
1:22	193	208	210	182	152	133
1:24	185	205	207	180	152	134
1:26	190	201	204	179	152	134
1:28	184	196	202	178	152	134
1:30	174	194	200	176	152	134
1:32	166	188	196	174	152	134
1:34	162	185	192	172	151	134
1:36	160	181	189	170	150	134
1:38	160	178	186	168	150	135
1:40	159	174	182	167	150	135
1:42	159	172	180	166	149	135
1:44	159	171	178	164	148	135
1:46	160	170	175	164	147	135
1:48	160	168	174	162	146	135
1:50	160	168	172	160	146	135
1:52	160	166	170	160	146	134
1:54	159	166	169	158	145	134
1:56	158	164	167	157	144	134
1:58	156	164	165	156	144	134
2:00	155	163	164	155	143	134

( ) Indicates initial temperature of hot-mix asphalt concrete

APPENDIX B

Table B.1

Computer Listing

```
*FORTRAN       LISTING          5701        CORLEW J
      COMPARISON OF FIELD DATA WITH CALCULATED DATA
      RUN 102 EVANSTON LYMAN TEST NO 67-2

      DIMENSION TM(10),TB(20)
      READ 810, TM, TB
      PRINT 820, TM, TB
      T = .0
      A = 1.
      TA = 54.
      CM = .70
      CB = .70
      DM = .0227
      DB = .0227
      DELT = .00052085
      DELY = .01318
      BI = .0625
      SR = 200.
      AB=.85
      EM=.95
      SIGMA=1.714E-09
      HEAT1 = .0
      RHO = 140.
      SHAM = .22
      P=DM*DELT/DELY**2
      Q=DB*DELT/DELY**2
      R=(2.*DM*DELT)/(CM*DELY)
      S = SHAM * RHO * DELY
      V = S / DELT
     0TOTAL=(TM(1)/2.+TM(2)+TM(3)+TM(4)+TM(5)+TM(6)+TM(7)+TM(8)
     1+ TM(9) + TM(10))
      ALPHAH = S * TOTAL
  400TM(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=2,9
      TM(N) = TM(N) + P*(TM(N+1) - 2.*TM(N) + TM(N-1))
   30 CONTINUE
```

Table B.1--Continued

Computer Listing

```
      TAB = TM(10)
      TM(10)=TM(10) +P*(TB(1)-2.*TM(10)+TM(9))
      TB(1) = TB(1) + O*(TB(2) - 2.*TB(1) + TM(10))
      DO 50 I=2,19
      TB(I) =TB(I) +O*(TB(I+1)-2.*TB(I) +TB(I-1))
   50 CONTINUE
     0QTOP = (BI*CM/DELY)*(TM(1)-TA) +EM*SIGMA*((TM(1)+460.)**4)
     1 - SR*AB
      OBTM = V*(TAB-TM(10))+CM*(TM(9)-TM(10))/DELY
      PARCEL = DELT * (OTOP +OBTM)
      HEAT1 = HEAT1 + PARCEL
     OTOTAL=(TM(1)/2.+TM(2)+TM(3)+TM(4)+TM(5)+TM(6)+TM(7)+TM(8)
     1+ TM(9) + TM(10))
      ZETAH = S* TOTAL
      HEAT2 = ALPHAH - ZETAH
      T=T+DELT
   10 TIME = 60. * T
      IF (TIME - A) 40,60,60
   60 CHECK = 100. * ( HEAT2 - HEAT1 ) / HEAT2
      PRINT 880, TIME, OTOP, OBTM, HEAT1, HEAT2, CHECK
      PRINT 820, TM, TB
      A = A + 1.
      IF ( T - 1. ) 40, 40, 100
      IF ( TM ) 40, 100, 40
  810 FORMAT (8F10.0)
  820 FORMAT (10F7.1)
  880 FORMAT (/5X, 6F10.1 )
  100 I=XEXITF (0)
      END
```

Table B.2

Fortran code used in computer listing

TM ( )....	Temperature of a point in the hot-mix asphalt concrete, °F
TB ( )....	Temperature of a point in the base, °F
T..........	Time, hr
A..........	Time, min
TA.........	Atmospheric temperature, °F
CM.........	Thermal conductivity of hot-mix asphalt concrete, Btu, hr^{-1}, ft^{-1}, $°F^{-1}$
CB.........	Thermal conductivity of base, Btu, hr^{-1}, ft^{-1}, $°F^{-1}$
DM.........	Thermal diffusivity of hot-mix asphalt concrete, ft^2, hr^{-1}
DB.........	Thermal diffusivity of base, ft^2, hr^{-1}
DELT.......	Incremental time, hr
DELY.......	Thickness of element in hot-mix asphalt concrete, ft
BI.........	Biot number, dimensionless
SR.........	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}, $°R^{-4}$

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

RHO........ Density of hot-mix asphalt concrete, lb, ft^{-3}

SHAM....... Specific heat of hot-mix asphalt concrete, Btu, lb^{-1}, $^{o}F^{-1}$

P, Q, R, S,
and V...... Constants, evaluated as indicated in computer program

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

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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