THERMAL CONDUCTIVITY AND THERMAL DIFFUSIVITY OF FLAKEBOARDS

By

JOE PETER ZEEBEN

A thesis submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN

MECHANICAL ENGINEERING

WASHINGTON STATE UNIVERSITY

1960

To the Resident Instructional Staff:

The members of the Committee appointed to examine the thesis of JOE PETER ZEEBEN find it satisfactory and recommend that it be accepted.

Harry C. Sorensen
Chairman

George M. Marra

George Snyder

ACKNOWLEDGEMENTS

The writer wishes to express his gratitude to Dr. George G. Marra and the staff of the Wood Products Laboratory for their guidance and assistance, and use of materials and equipment during the entire performance of the experimental work.

Thanks are due to Lloyd B. Craine and the staff of the Engineering Experiment Station for the helpful assistance in instrumentation and for the use of their equipment.

The author also wishes to thank Dr. Harry A. Sorensen for his guidance and advice in writing this thesis, and Dr. George T. Austin for use of his equipment and continued interest in the performance of the experimental work.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

INTRODUCTION

Flakeboards are manufactured by spraying wood flakes with resin, laying the flakes to form a mat, and then pressing the mat to a desired thickness and curing the resin with heat. In order to cure the resin at the center of the board a temperature of more than 200°F for two minutes is required. Since the maximum temperature that may be applied to the surface of the mat is determined by the point at which damage to the flakes and resin occurs, usually 350°F, the time required to reach 200 F at the center of the board is determined by thermal properties of the flake mat.

The rate at which heat is transferred to the center of the board is determined by two properties of the flake mat: the thermal conductivity and the thermal diffusivity. To conduct a study of the heat transfer rates one must know how these properties vary with mat density, moisture content, resin content and its chemical composition, and the wood species of the flakes.

It was decided that a fundamental step in determining the heat transfer rates in flakeboard manufacture would be to determine the thermal conductivity and thermal diffusivity of flakeboards, and how these are affected by specific gravity, moisture content, and the species of the wood from which the board is constructed. The resin content should be kept constant to eliminate one of the variables and therefore decrease the number of tests required.

The determination of thermal conductivity of solids and insulating materials is most commonly accomplished by the guarded hot plate apparatus. A calorimetric measurement will yield the specific heat of the material, and the thermal diffusivity may then be calculated, if the density of the material is known.

Although these methods could be applied to measure the thermal properties of flakeboards it would be extremely difficult to do so as two identical samples, 20 inches in diameter, are required for each test in a guarded hot plate apparatus. Also samples of this size would have random density differences that would affect the accuracy of results. A separate test would be necessary for the determination of thermal diffusivity, and at least two sets of samples would be required to determine thermal conductivity as wood is an anisotropic material. The most important objection to using a guarded hot plate apparatus is that it could not be used on samples containing moisture. Moisture migration would cause errors in the determination of thermal conductivity.

It appeared, after conducting a literature survey, that the probe method of determining thermal conductivity could be used more advantageously, and could be adapted to measure thermal diffusivity at the same time.

A thermal conductivity probe is a slender rod with a heating element on the periphery and a temperature sensing element in the center. By applying a known quantity of energy to the heating element and noting the temperature rise with respect to time one is able to determine the thermal properties of the material in which the probe is inserted.

THEORY

The general theory of heat conduction in an anisotropic material states:[1]

$$-f_x = K_{11}\frac{\partial\theta}{\partial x} + K_{12}\frac{\partial\theta}{\partial y} + K_{13}\frac{\partial\theta}{\partial z}$$

$$-f_y = K_{21}\frac{\partial\theta}{\partial x} + K_{22}\frac{\partial\theta}{\partial y} + K_{23}\frac{\partial\theta}{\partial z}$$

$$-f_z = K_{31}\frac{\partial\theta}{\partial x} + K_{32}\frac{\partial\theta}{\partial y} + K_{33}\frac{\partial\theta}{\partial z}$$

where f_i represents the flux vectors of heat in any particular direction, and the quantities K_{rs} are called the conductivity coefficients which are the components of a second-order tensor. This generalization is necessary because it is not usually true that the direction of the flux vector at a point is normal to the isothermal through the point.

If the above values of heat flux are substituted into the general equation of heat conduction

$$c_p\frac{\partial\theta}{\partial t} = -\left[\frac{\partial f_x}{\partial x} + \frac{\partial f_y}{\partial y} + \frac{\partial f_z}{\partial z}\right]$$

the resulting equation will be

$$c_p\frac{\partial\theta}{\partial t} = K_{11}\frac{\partial^2\theta}{\partial x^2} + K_{22}\frac{\partial^2\theta}{\partial y^2} + K_{33}\frac{\partial^2\theta}{\partial z^2} + (K_{23} + K_{32})\frac{\partial^2\theta}{\partial y\partial z}$$

$$+(K_{31} + K_{13})\frac{\partial^2\theta}{\partial z\partial x} + (K_{12} + K_{21})\frac{\partial^2\theta}{\partial x\partial y}$$

There is a transformation which will reduce the quadratic

$$K_{11}x^2 + K_{22}y^2 + \cdots\cdots\cdots + (K_{12} + K_{21})\,xy$$

to a sum of squares

$$K_1\xi^2 + K_2\eta^2 + K_3\zeta^2$$

with a new system of coordinates ξ, η, and ζ. In terms of the above variables the general equation of heat conduction becomes

$$\rho c \frac{\partial \theta}{\partial t} = K_1 \frac{\partial^2 \theta}{\partial \xi^2} + K_2 \frac{\partial^2 \theta}{\partial \eta^2} + K_3 \frac{\partial^2 \theta}{\partial \zeta^2}$$

where the new axes are "principal axes" and the coefficients K_1, K_2, and K_3 are the "principal conductivities."

If an additional transformation is made,

$$\xi_1 = \xi \left(\frac{K}{K_1} \right)^{\frac{1}{2}}, \quad \eta_1 = \eta \left(\frac{K}{K_2} \right)^{\frac{1}{2}}, \quad \zeta_1 = \zeta \left(\frac{K}{K_3} \right)^{\frac{1}{2}}$$

where K is chosen arbitrarily then

$$\frac{\partial \theta}{\partial t} = \frac{K}{\rho c} \left(\frac{\partial^2 \theta}{\partial \xi_1^2} + \frac{\partial^2 \theta}{\partial \eta_1^2} + \frac{\partial^2 \theta}{\partial \zeta_1^2} \right)$$

It may be seen that the equation for an anisotropic material can be reduced to the same form as equations for isotropic materials, but with tilted axes.

Thus the previous transformations reduce anisotropic problems to solutions of similar problems on isotropic solids when the solid is infinite, or when it is bounded by planes perpendicular to the principal axes of conductivity. The later case would apply to probe testing of flakeboard samples.

To apply the equations above to physical situations there exist certain boundary conditions for the solution of the problem. The probe method of determining thermal conductivity was first suggested by E. F. M. Van der Held and developed by F. C. Hooper and F. R. Lepper.[2] The method involves the solution of the equations of heat flux for a line source of heat in an infinite medium.

The following derivation is given by Ingersoll and Zobel:[3]

If, at a point, Q units of heat are suddenly developed, radial flow of

heat results and the temperature at any point for any subsequent time may be found in terms of distance from the center. A line source may be thought of as a continuous series of points in an infinite line. The magnitude of each point would be Qdz and the strength would be Sdz, where Q is the heat released per unit length per unit time. If the line source of heat is permanent starting at time zero, the temperature is given by:

$$\theta = \frac{S}{4\pi\alpha}\int_0^t e^{-\frac{r^2}{4\alpha(t-\tau)}} (t-\tau)^{-1}\, d\tau$$

putting

$$\beta = \frac{r}{2\sqrt{\alpha(t-\tau)}}$$

then

$$\theta = \frac{S}{2\pi\alpha}\int_{r\eta}^{\infty} \beta^{-1} e^{-\beta^2} d\beta = \frac{Q}{2\pi k} I(r\eta)$$

where θ = temperature

Q = heat input per unit time per unit length

k = thermal conductivity

$S = \frac{Q}{\rho c}$

$$I(r\eta) = \int_{r\eta}^{\infty} \beta^{-1} e^{-\beta^2} d\beta$$

$$\eta = \frac{1}{2\sqrt{\alpha t}}$$

r = distance from line source at which the temperature is measured

α = thermal diffusivity

t = time

if $r\eta = x$

$$I(x) = \ln\frac{1}{x} + \frac{x^2}{2} - \frac{x^4}{8} - 0.2886$$

If the temperature rise is measured along an electrically heated wire and plotted with respect to time, the value of the preceding integral may be solved for the thermal conductivity of the medium in which the heat is being released by the line source.

$$k = \frac{Q}{4\pi} \frac{\ln t_2/t_1}{\theta_2 - \theta_1} \tag{1}$$

Although the thermal diffusivity constant was included in the solution of the equation, the resulting error function integral for a "long-time" solution $(r\eta) < 0.2$ becomes a logarithmic function and both it and the radius cancel out.

In subsequent work on probe methods F. C. Hooper and S. C. Chang employed a graphical solution of the error integral $I(r\ )$ realizing the previous equation was a simplification and only applied when the temperature rise became asymptotic to the line $\frac{Q}{k} \ln t$.

The equation

$$\theta = \frac{Q}{2\pi k} I(r\eta) \tag{2}$$

may be solved by constructing three sets of graphs on which the temperature rise versus time may be imposed. To do this, one constructs a family of curves $\frac{Q}{k}$ on the ordinate θ and abscissa $I(r\eta)$; a family of curves of $\frac{r}{\sqrt{\alpha}}$ on the ordinate $(r\eta)$ and abscissa t; and the function $I(r\eta)$ versus $(r\eta)$ is plotted.

Each axis of graphs has one variable which is common to the next graph, and by assuming a value of $\frac{Q}{k}$ and joining the corresponding variable of time and temperature to fit your experimental data a series of points results on the graph of $(r\eta)$ versus t. If this series of points parallels an existing $\frac{r}{\sqrt{\alpha}}$ value then the assumption of $\frac{Q}{k}$ was correct and k may be determined providing that Q is known. This method

also establishes a value of $\frac{r}{\sqrt{\alpha}}$ but Hooper and Chang found that this constant had no relationship to some empirical probe radius and the thermal diffusivity value of the material being tested.

In the derivation just completed the boundary conditions can only be realized ideally. In the actual case, however, one must consider the effects of inserting the probe in a sample of finite size and the effects of the probe having a certain heat capacity. In addition to the conditions mentioned above there is at the surface of the probe a film of air which presents a resistance to heat flow, and the effects of this contact resistance must also be considered to reach a satisfactory solution of the differential equations which define the transient heat flow phenomenon.

The addition of probe finite radius, probe heat capacity, and contact conductivity to the boundary conditions of a line source of heat results in a solution involving Laplace Transformations and asymptotic expansion of Bessel functions. Carslaw and Jaeger consider problems of the cylinder and sphere and discuss probe methods of determining thermal conductivity.[4] They present the following:

If a cylinder of radius a, of thermal conductivity much greater than its surrounding infinite medium is heated at the rate Q per unit length per unit time, the temperature of the cylinder at any time t is given as

$$\theta = \frac{Q}{k} G\,(h, \alpha_1, \infty, \tau)$$

if there is contact resistance R per unit length between the probe and the surrounding medium.

In the equation above,

$$h = 2\pi Rk,\ \alpha_1 = 2\pi a^2 \rho c / S_1,\ \tau = \frac{\chi t}{a^2}$$

where ∞ signifies infinite heat capacity in the external medium as the probe heat capacity is α_1, and

R = thermal resistance per unit length

k = thermal conductivity of the medium

ρ = density of the medium

c = specific heat of the medium

$\varkappa$ = thermal diffusivity of the medium

S_1 = thermal capacity of the probe per unit length

a = probe radius

t = time

The solution of the problem for small values of τ, less than 0.02 then becomes

$$\theta = \frac{Q\alpha_1}{2\pi k}\left[\tau - \frac{\alpha_1\tau^2}{2h} + O(\tau^{5/2})\right], \quad h \neq 0 \tag{3}$$

or

$$\theta = \frac{Q\alpha_1}{2\pi k}\left[\tau - \frac{4\alpha_1\tau^{3/2}}{3\pi^{\frac{1}{2}}} + O(\tau^2)\right], \quad h = 0 \tag{4}$$

For large values of τ,

$$0 = \frac{Q}{4\pi k}\left[2h + \ln\frac{4}{\theta} - \frac{4h-\alpha_1}{2\alpha_1} + \frac{\alpha_1 - 2}{2\alpha_1\tau}\ln\frac{4}{C} + \cdots\right] \tag{5}$$

where $C = 1.7811 = \exp\gamma$, and $\gamma = 0.5772\ldots$ is Eulers constant.

To apply the small time solutions of the preceding equation the time has to be such the $\tau \leq 0.02$, one considers the material which is being used and the dimensions of the probe:

$$\tau = \frac{\varkappa t}{a^2} = 0.02$$

if $\varkappa = 0.006$ ft^2/hr and a = 0.00225 ft.

then $t = 6.048 \times 10^{-2}$ seconds

One would apply the time-temperature relation in the following manner:

Since the equation may be reduced to

$$\theta = Xt + Yt^2 + Zt^{5/2} \qquad (6)$$

where

$$X = \frac{Q\alpha_1\varkappa}{2\pi ka^2} \qquad Y = \frac{Q\alpha_1^2\varkappa^2}{4\pi^2Rk^2a^4}$$

and Z is a remainder term because the solution is not exact.

Equation (5) may be reduced as equation (3).

$$\theta = A' \ln t + B' + \frac{1}{t}(C' \ln t + D')$$

where $A' = \frac{Q}{4\pi k}$

and $B' = A'(\ln \varkappa + \ln 4 - \ln C - 2 \ln a + 2\pi Rk)$

By fitting equation (7) to a time-temperature curve, the thermal conductivity value may be obtained from A' if Q is known. The thermal diffusivity enters in constant B and could be determined if R were known or if it were so small as not to affect the summation of the constant terms. The value of R may be determined from coefficient of equation (6) since

$$Y = \frac{Q\alpha_1^2\varkappa^2}{4\pi^2Rk^2a^4} = Q\left(\frac{2\pi\rho ca^2}{S_1}\right)^2 \left(\frac{k}{\rho c}\right)^2 \frac{1}{4\pi^2Rk^2a^4}$$

$$= \frac{Q}{S_1^2R}$$

and $$X = \frac{Q\alpha_1\varkappa}{2\pi ka^2} = Q\left(\frac{2\pi a^2\rho c}{S_1}\right)\left(\frac{k}{\rho c}\right)\frac{1}{2\pi ka^2}$$

Substituting R into the expression of B' will give a value for thermal diffusivity since all other values were previously determined.

J. H. Blackwell uses Carslaw and Jaeger as one of his principal references and presents a derivation which will yield values of thermal conductivity, thermal diffusivity, and contact resistance. A brief summary of his work follows:[5]

The parameters involved in the solutions of probe temperature are listed below.

$\theta_1(t)$ = temperature of the probe

M_1 = probe mass per unit length

C_1 = probe specific heat

b = external radius of probe

$\theta(\rho t)$ = temperature of external medium

K_2 = thermal conductivity of external medium

t = time

h_2^2 = thermal diffusivity of external medium

H = contact or outer conductivity

Q = heat supplied per unit length per unit time

$$Q' = \frac{Q}{2\pi b}$$

$$\alpha = \frac{M_1 c_1}{b}$$

$$T = \frac{h_2^2 t}{b^2}$$

$$\gamma = 0.5772 \ldots$$

To solve the equation of temperature all the parameters, as listed, must be known and it is assumed that the probe conductivity is very high—infinite in comparison with the material being tested. The approximate "long-time" solution for temperature is:

$$\theta_1(t) = \frac{bQ'}{2K_2}\left[\ln 4T - \; + \frac{2K_2}{bH} + \frac{1}{2T}\left\{\ln 4T - \gamma + 1 - \frac{\alpha h_2^2}{bK_2}\left(\ln 4T - \gamma + \frac{2K_2}{bH}\right)\right\} + O\left(\frac{1}{T^2}\right)\right]$$

In the references previously cited the term $O(\frac{1}{T^2})$ was omitted. Blackwell solved the above equation by the method of least squares and performed a numerical integration of the exact integral (not presented here). The two results agreed very closely. Unless T is very large, the omission of $O(\frac{1}{T^2})$ can cause serious error in the solution for thermal conductivity.

To apply the above equation it may be reduced to the form:

$$\theta_1(t) = A \ln t + B + \frac{1}{t}(C \ln t + D) \qquad (8)$$

where $$A = \frac{Q}{4\pi K_2}$$

$$B = A\left[\ln h_2^2 - 2 \ln b + \ln 4 - \gamma + \frac{2K_2}{bH}\right]$$

By fitting the equation of the curve to suitable experimental data the constant A will yield the value of K_2 provided that Q is known. To determine the thermal diffusivity from the constant B the value of H must be known or be very large so as not to affect the solution.

Blackwell combines a "long-time" solution for the probe and a "small-time" solution for the external medium so that if:

$$\frac{b^2}{h_1^2} < t < \frac{b^2}{h_2^2}$$

and $b - a \ll b$ were b is the external radius of the probe, and a is the radius of the core. Thus $b - a$ is the heater element sheath thickness, then

$$\Delta_2 \approx \frac{(b-a)^2}{6h_1^2}$$

and $$\theta(at) \approx \frac{2Q'}{\alpha}\left[-\Delta_2 + t - \frac{H}{\alpha}t + \frac{16H^2h_2}{15K_2}t^{5/2} + O(t^3)\right]$$

To evaluate the value of h_2^2, the above equation may be written:

$$Y = \frac{\alpha}{t^2}\left(t - \Delta_2 - \frac{\alpha\theta_1}{2Q'}\right) \approx H - \frac{16H^2 h_2}{15\sqrt{\pi}K_2}\, t^{\frac{1}{2}} + O(t^3) \qquad (9)$$

If Y is plotted against $t^{\frac{1}{2}}$ for small t, H is the intercept on the Y axis when t = 0. If H is not small, additional terms must be added to the right side of the equation to make it exact. Large values of H affect the values of K_2 and h_2^2 slightly, therefore, only an approximate value is required to determine h_2^2 from the constant B.

In the radial flow of heat from a point source isothermal lines will be circular in any plane whose thermal conductivity values in the x and y directions are equal. If the thermal conductivity values are not equal then the isothermal lines assume an elliptical shape.[6] Wood is an anisotropic material, but when it is flaked and felted to make a mat, random orientation of wood grain occurs in the x and y (width and length) plane. It is then reasonable to assume that the thermal conductivity values in the x and y directions would be equal. If the thermal conductivity in the z direction is different, it would be impossible to insert the probe into the sample and obtain a value of k_z without involving k_x or k_y. Before a probe could satisfactorily be used to determine k_{xy} and k_z an expression for the interrelation must be derived.

A line source is a series of points. Consider the simplest case of an instantaneous point source where the differential equation of heat conduction in isotropic material is

$$\frac{\rho c}{k}\frac{\partial\theta}{\partial t} = \frac{\partial^2\theta}{\partial x^2} + \frac{\partial^2\theta}{\partial y^2} + \frac{\partial^2\theta}{\partial z^2}$$

and is satisfied by the expression

$$\theta = \frac{Q(\rho c)^{3/2}}{8(\pi kt)^{3/2}}\, e^{-\frac{\rho c}{4kt}\left[(x-x')^2 + (y-y')^2 + (z-z')^2\right]} \qquad (10)$$

In an anisotropic material with principle conductivity values k_1 , k_2, k_3 in the x, y, and z directions the differential equation of heat conduction is satisfied by

$$\theta = \frac{Q(\rho c)^{3/2}}{8(\pi^3 k_1 k_2 k_3 t^3)^{3/2}} e^{-\frac{\rho c}{4t}\left[\frac{(x-x')^2}{k_1} + \frac{(y-y')^2}{k_2} + \frac{(z-z')^2}{k_3}\right]} \quad (11)$$

For an instantaneous line source inaan isotropic material the temperature, obtained by integrating equation (10) is

$$\theta = \frac{Q(\rho c)^{3/2}}{8(\pi kt)^{3/2}} \int_{-}^{+} dz' e^{-\frac{\rho c}{4kt}\left[(x-x')^2 + (y-y')^2 + (z-z')^2\right]}$$

$$= \frac{Q(\rho c)}{4\pi kt} e^{-\frac{\rho c}{k4t}\left[(x-x')^2 + (y-y')^2\right]} \quad (12)$$

as given by Carslaw and Jaeger.[7]

If equation (12) is written for an anisotropic material as was equation (11), then

$$\theta = \frac{Q(\rho c)}{4\pi (k' k'')^{\frac{1}{2}} t} e^{-\frac{\rho c}{4t}\left[\frac{(x-x')^2}{k'} + \frac{(y-y')^2}{k''}\right]}$$

and k' is the thermal conductivity in the xy directions and k'' is in the z direction then

$$(k' k'')^{\frac{1}{2}} = k'''$$

The thermal conductivity in the xy directions may be obtained by orienting the probe with its axis in the z direction. Moving the probe axis to any other angle with respect to the xy plane involves k_z and the value of thermal conductivity obtained will be k''' , therefore,

$$k_z = (k''')^2 / k_{xy} \quad (14)$$

It is interesting to note that equation (14) may be derived from a steady state solution given by Carslaw and Jaeger for a point source in a thin crystal plate.[8]

$$Q = 4\pi m (k_1' k_2')^{\frac{1}{2}}$$

or

$$m = \frac{Q}{4\pi (k_1'' k_2'')^{\frac{1}{2}}}$$

and the expression for m is similar to the expression for A or A' in equations (8) and (7).

If $k_1' = k_2'$ then

$$m = \frac{Q}{4\pi k_{1,2}} = \frac{Q}{4\pi (k_1'' k_2'')^{\frac{1}{2}}}$$

and $k_{12}^2 = k_1'' k_2''$, where k_{12} is the thermal conductivity determined by the probe when its axis is oriented in any direction other than z, and $k_1'' = k_{xy}$ and $k_2'' = k_z$.

All the preceding derivations were subject to the boundary conditions of an infinite line source in an infinite medium. For a probe of finite length there is at each end a flow of heat in the axial direction. Blackwell gives the minimum probe length to diameter ratio required to reduce the axial flow error to ½%,[9]

$$\frac{L}{d} > \left(\frac{T}{0.0632}\right)^{\frac{1}{2}}$$

where $T = \frac{h_2^2 t}{b^2}$ and t = time

In a later publication Blackwell shows in a specific calculation for a probe with an L/b ratio of 30 that the error in thermal conductivity would be 0.051% for a hollow probe, and 0.12% for a solid probe.[10]

F. A. Joy conducted a study of moistrue content in insulating material and its effect on thermal conductivity values.[11]

He considered four hypothetical moisture arrangements:

1. Parallel Arrangement--In this system, the water is arranged in continuous shafts parallel to the direction of heat flow.
2. Series Arrangement--In this system the water is in layers perpendicular to the direction of heat flow.
3. Bead Arrangement--In this system, the water is in the form of small beads throughout the sample.
4. Foam Arrangement--In this system, the water films surround the insulation fibers to form a honeycomb structure.

For the series arrangement,

$$k = \frac{k_n k_w}{k_w - X}$$

For the parallel arrangement,

$$k = k_n + X$$

where:

k = average conductivity of the sample

k_n = conductivity of the dry sample

k_w = conductivity of the water modified by the soluble material in the sample

W = volume fraction of water in the sample

A = volume fraction of air space within the sample

$$X = \frac{W}{A} (k_w - k_n)$$

Bead and foam arrangements may be considered as two phase aggregates.

For these arrangements,

$$k = \frac{1 + 2VY}{1 - VY}$$

where:

k = average conductivity of aggregate

k_c = conductivity of the continuous phase

k_d = conductivity of dispersed phase

V = volume fraction of dispersed phase

$Z = k_c/k_d$ and,

$$Y = \frac{1 - Z}{1 + 2Z}$$

INSTRUMENTATION

A thermal conductivity probe is usually constructed by taking a slender tube of suitable length to diameter ratio, and inserting a temperature sensing element and a heating element in the center. The heating element is constructed of either manganin or constantan wire as it has a very low temperature coefficient of resistance. A low temperature coefficient is necessary to provide constant I^2R heating. The constant current which is in the order of milliamperes is easily obtained from a storage battery.

The temperature sensing element used most commonly is a thermocouple.[12, 13, 14] A resistance temperature sensing element has also been used.[15]

In thermal conductivity determination, when the sample has a moisture content, the temperature rise must not exceed one or two degrees Fahrenheit. Excessive temperature rise will cause errors due to moisture migration. For a total temperature rise of one degree Fahrenheit for flakeboards, the change in temperature between the fourth and fifteenth minute will be approximately $0.10^{\circ}F$. An error in measurement of $0.001^{\circ}F$ will cause a one percent error in the thermal conductivity determination.

When using thermocouples, accurate recording of temperature differences of $0.01^{\circ}F$ requires a mirror galvanometer and photo sensitive paper mounted on vibration-free tables. This type of apparatus is extremely difficult to use and the accuracy is limited. Therefore, no

attempt was made to use a similar apparatus in this research.

In the first probes that were constructed an attempt was made to use a thermocouple as the temperature sensing element. A copper constantan thermocouple produces an emf of approximately 22 microvolts at room temperature. An amplification of 1000 or more is necessary to make the signal strong enough to record. A good quality electronic d-c microvolt meter will measure voltages as low as 0.1 microvolts. The output of the amplifier that actuates the meter may be used to supply a signal to a recorder, but the noise level is about five percent of the total signal strength.

An uncertainty of five percent would result in 0.05°F temperature error. Thermocouples were, therefore, unsatisfactory for this work.

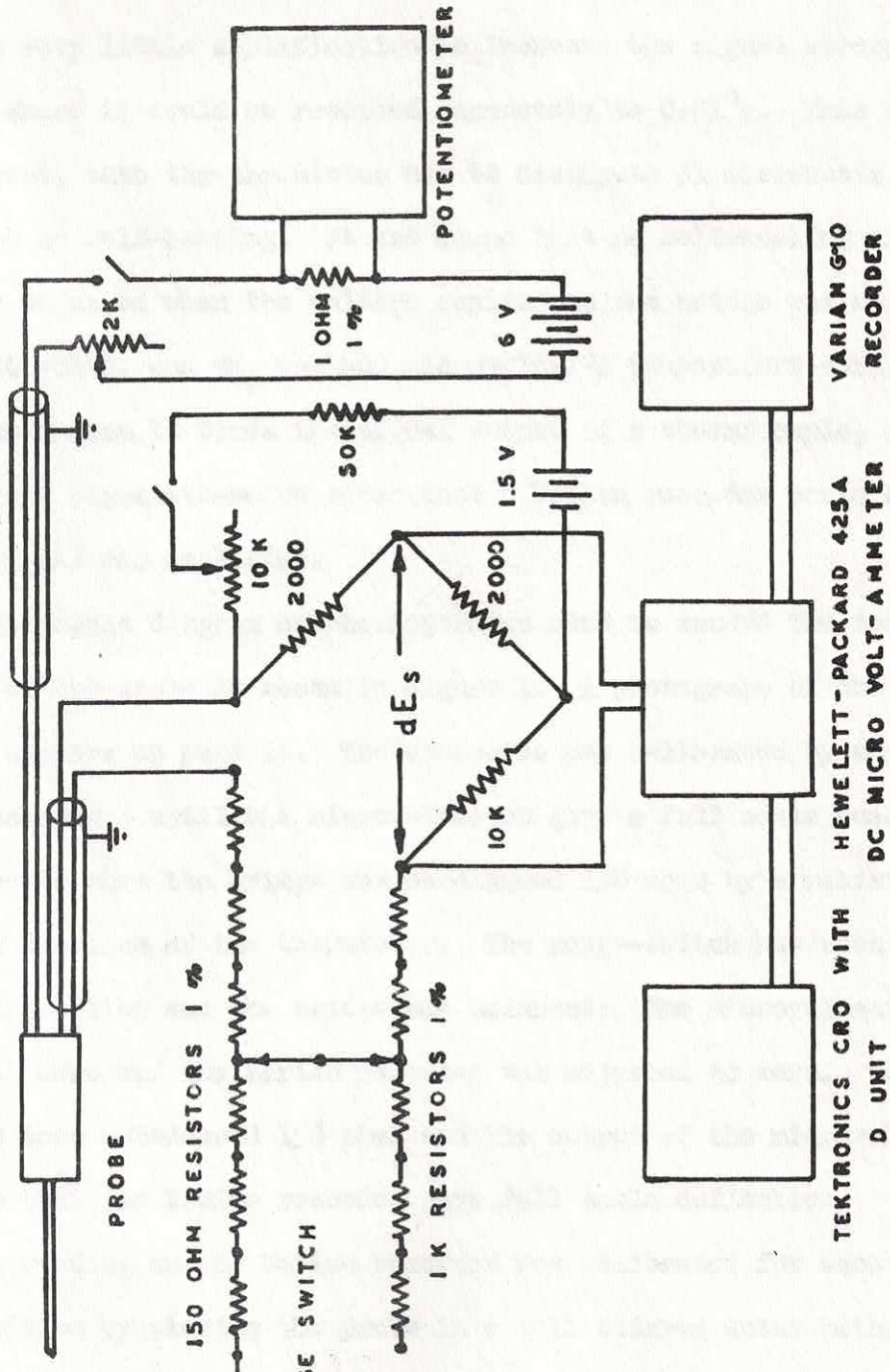
A thermistor has the property of decreasing in resistance with an increase in temperature. This characteristic has been used successfully to measure temperature changes as small as 0.001°F without difficulty. At 70°F an 8000 ohm thermistor has a negative resistance change of approximately 150 ohms/°F. The major difficulty involved in using a thermistor for accurate temperature measurement is that the electrical current flowing through it does not cause the thermistor to heat itself. If a thermistor is used in a bridge-circuit, similar to the one shown in Figure 1, the signal output is proportional to the voltage applied across the bridge. The relationship is given by

$$\frac{dE_s}{E} = \frac{R_4}{(R_t + R_4)^2} \, dR_t$$

where E is the applied voltage, dE_s is the voltage unbalance of the bridge, and dR_t is the change in resistance of the thermistor to give

Fig. 1

CIRCUIT DIAGRAM FOR THERMISTOR PROBE TEST



dE_s. If all legs of the bridge were originally balanced in resistance and one volt was applied to the bridge, then for a 150 ohm change in thermistor resistance, the signal strength would be 4.7 millivolts. It would take very little amplification to increase the signal strength to the point where it could be recorded accurately to 0.01°F. This would mean, however, that the thermistor has to dissipate 31 microwatts of energy with no self-heating. It was found that no self-heating of the thermistor occurred when the voltage applied on the bridge was approximately 0.10 volts, and dE_s was 400 microvolts/°F temperature change. This was more than 18 times the signal output of a thermocouple, and was of sufficient signal-to-noise ratio that a Varian recorder could be used when the signal was amplified.

A schematic diagram of the apparatus used to record the temperature rise of the probe is shown in Figure 1. A photograph of the apparatus appears on page 26. The apparatus was calibrated by adjusting the 10K resistance until the microvoltmeter gave a full scale reading of 300 microvolts when the bridge was unbalanced 150 ohms by a resistance decade box in place of the thermistor. The range-switch was then placed in the 1-1 position and the bridge was balanced; the microvoltmeter was adjusted to zero and the Varian recorder was adjusted to zero. The bridge was then unbalanced 150 ohms and the output of the microvoltmeter was set so that the Varian recorder gave full scale deflection.

The reading on the Varian recorder was calibrated for each range-switch position by placing the probe in a well stirred water bath. The temperature of the bath was determined by a thermometer with temperature divisions of 0.05°F. The thermometer had been calibrated by the U. S. Bureau of Standards.

TABLE 1

PROBE PHYSICAL CHARACTERISTICS

Probe shield color	Red	Blue	White
Total probe length (in)	4.5	4	4
Total heating element length (in)	4.30	3.47	3.47
Weight of probe/ft(lb)	0.006167	0.003527	0.003520
Ohms/ft	333.00	224.10	209.96
Tube diameter - O.D. (in) - I.D.	0.058 0.044	0.0355 0.0230	0.0355 0.0230
Probe diameter (in)	0.073 $\pm$ .001	0.054 $\pm$ .001	0.054 $\pm$ 0.0005
Thermistor descriptions	8000 ohms 0.020" dia. bead Ratio = 7.3	8000 ohms 0.014" dia. bead Ratio = 7.3	8000 ohms 0.014" dia. bead Ratio = 7.3

A full-scale reading on the Varian recorder represented approximately 0.75°F temperature change. The chart paper had 100 divisions, therefore, the maximum accuracy of reading the temperature change was 0.0075°F. The temperature of the bath would not remain constant for this amount of accuracy, so it was heated intermittently and the maximum reading on the thermometer was matched with a maximum reading on the recorder. By this procedure a constant temperature was obtained for two minutes. Calibration was carried out from 68°F to 72°F.

Although a thermistor does not have a linear resistance temperature relationship, for the small range of temperatures employed, it was found that the recorder reading was linear with respect to temperature change.

Three probes were constructed, and their physical characteristics are listed in Table 1. To determine the rate of probe heating, a one-ohm 1% resistor was placed in series with the probe heating element. The voltage drop across the resistor was measured with a potentiometer, and this gave a direct reading of heating element current to 0.01 milliamperes.

EXPERIMENTAL PROCEDURE

Since it was originally assumed that flakeboard thermal conductivity and thermal diffusivity values would change with board density, the first step in the experimental procedure was to construct a board with no layer density variation. It was found that this could be done by using a urea formaldehyde resin (AMRES 7501) and catalyst (SP10) manufactured by the American Marietta Company. This resin polymerizes at room temperature in about eight hours, but best results were obtained if the boards were left in the press for approximately 24 hours. Boards 0.75 inches thick and 15 inches square were constructed so that their moisture content would be approximately nine percent, and their dry specific gravity would be 0.50, 0.70, and 0.90. Boards were constructed from Redwood, Cedar, Ponderosa Pine, and Birch flakes. The Birch boards had extremely poor quality at the lower density levels, so they were discarded and more were made at specific gravity 0.80 and 1.00.

After each board was removed from the press it was trimmed to 13 inches on each side, and placed in a conditioning room at 65°F and 50% relative humidity. In three or four days the boards were removed from the conditioning room and cut into three-inch squares. Each square was measured and then segregated by specific gravity level. At least three squares were required for a sample to be tested by a probe 0.073 inches in diameter and two squares for a sample to be tested by a probe .054 inches in diameter. This was done so that the sample size exceeded the minimum length determined by the probe L/d ratio.

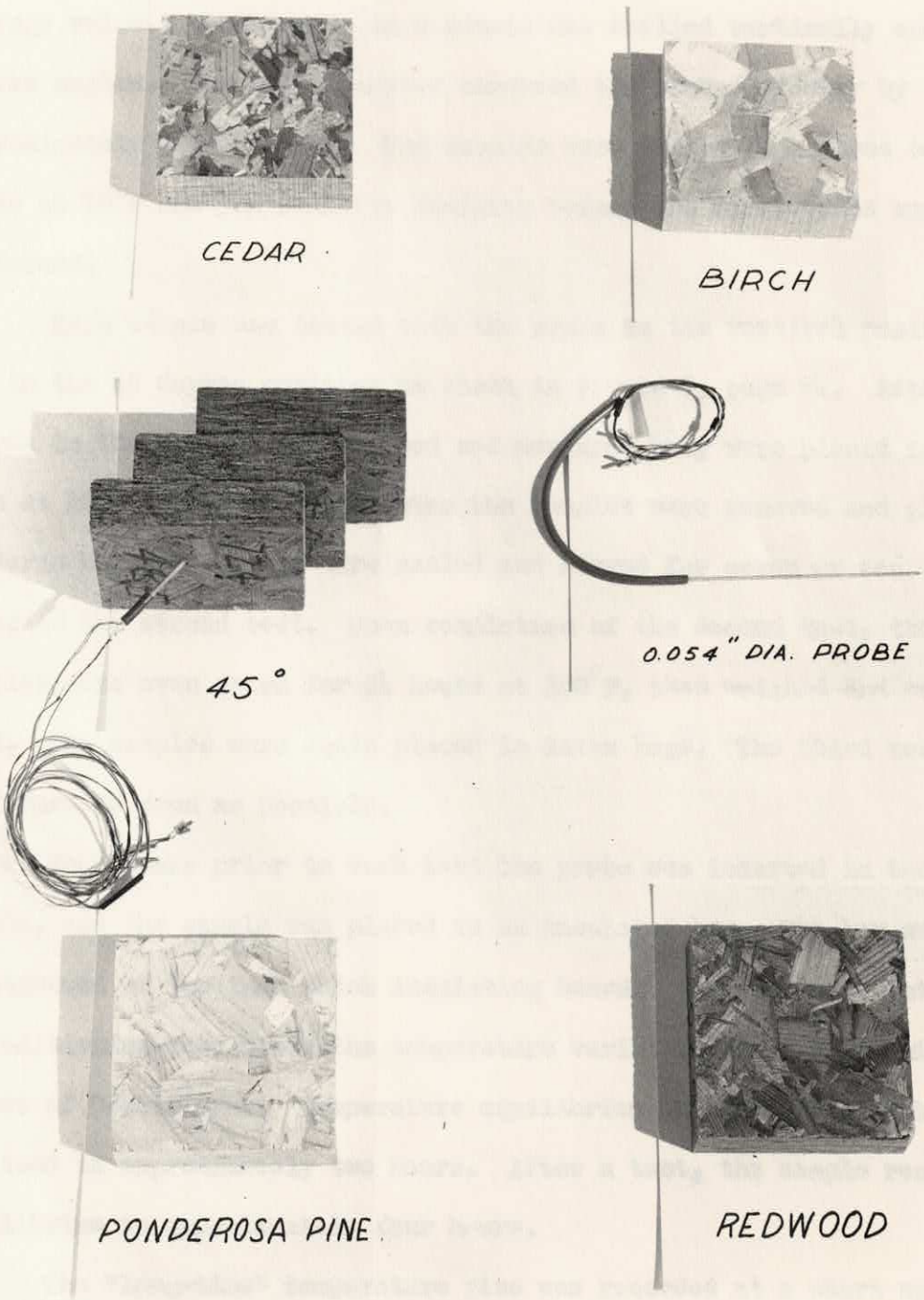


Fig. 2—Test Samples and Probe

The specific gravity of each board in a sample was ± 3% of the average value. Each square in a sample was drilled vertically and at 45 degree angles. The hole diameter exceeded the probe diameter by approximately 0.005 inches. The samples were stored from three to five weeks at 70°F and 50% relative humidity before the first tests were performed.

Each sample was tested with the probe in the vertical position, and in the 45 degree position as shown in Figure 2, page 24. After boards in the sample were weighed and measured they were placed in an oven at 100°F. Twelve hours later the samples were removed and placed in Saran bags. The bags were sealed and stored for seven or ten days prior to the second test. Upon completion of the second test, the samples were oven dried for 24 hours at 220°F, then weighed and measured. The samples were again placed in Saran bags. The third test was performed as soon as possible.

Four hours prior to each test the probe was inserted in the sample, and the sample was placed in an insulated box. The box was constructed of two-inch thick insulating board. The box was located in a conditioning room where the temperature variation was ± 0.10°F with an offset of 0.0008°F/hr. Temperature equilibrium in the insulated box was attained in approximately two hours. After a test, the sample reached equilibrium in approximately four hours.

The "long-time" temperature rise was recorded at a chart speed of 40 inches/hr, and the "short-time" was recorded with an eight second time exposure of a Polaroid camera on the oscilliscope.

The sweep time on the oscilliscope was one centimeter per second, and the vertical deflection was five millivolts per centimeter.

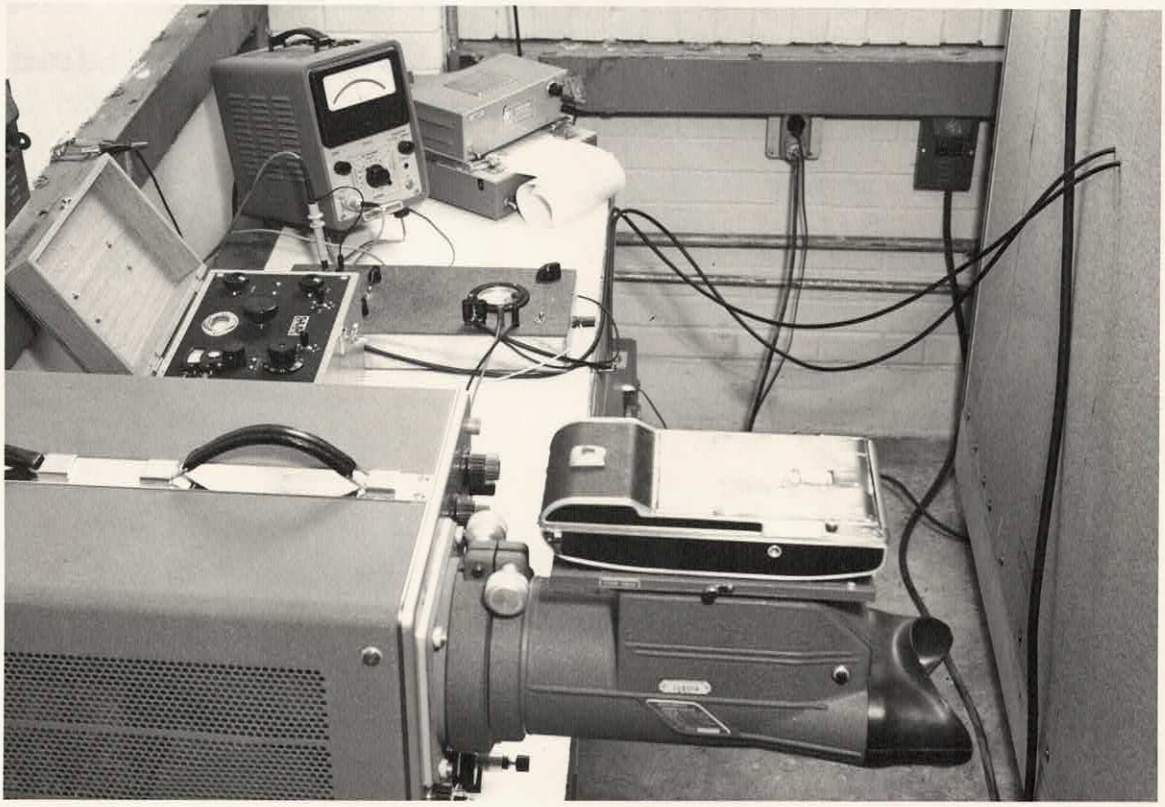


Fig. 3—Temperature Recording Equipment

When the probe heating rate was from 0.20 to 0.25 BTU/hr-ft, the temperature rise was not more than 1.75°F and not less than 0.09°F in fifteen minutes.

Figure 3 shows the equipment arrangement. At the right the probe leads pass through the wall of the conditioning room where the insulated box was placed.

CALCULATIONS

It was found that the time-temperature relationship, when plotted on semi-log paper, became linear after 0.10 hours. The thermal conductivity value could then be calculated by equation (1). To simplify calculations, equation (1) was reduced so that

$$k = \frac{Q}{12.56} \frac{\ln 10/4}{\theta_{10} - \theta_4}$$

$$k = \frac{5.5577 \times 10^{-5} \ (ma)^2}{\theta_{10} - \theta_4} \quad \ldots \text{"blue" probe}$$

$$k = \frac{5.225 \times 10^{-5} \ (ma)^2}{\theta_{10} - \theta_4} \quad \ldots \text{"white" probe}$$

$$k = \frac{8.2662 \times 10^{-5} \ (ma)^2}{\theta_{10} - \theta_4} \quad \ldots \text{"red" probe}$$

where θ_{10} is the temperature rise at the tenth inch and θ_4 is the temperature rise at the fourth inch of chart paper after heating began. The time in hours at each point is 0.25 and 0.10 respectively.

To calculate the thermal diffusivity of the flakeboard, constant B of equation (8) must be determined. It was found that the method of least squares did not give a reasonable solution for the thermal conductivity and thermal diffusivity values. No attempt to solve equation (5) was made, because it is similar to equation (8). If the test was continued for one hour, rather than fifteen minutes the temperature rise

should equal the value of B + D. Since D is a remainder term included to make the solution exact for smaller time, its value would be negligible compared to B.

In the region where the temperature rise becomes linear with ln t, equation (8) may be applied by reducing it to the form:

$$\theta = A \ln t + B$$

$$\theta_{10} = -1.38629\ A + B$$

$$\theta_{4} = -2.3026\ A + B$$

$$\theta_{10} - \theta_{4} = 0.9136A$$

The value of k calculated in this manner agrees with the value calculated by equation (1), and the value of B agrees with the value of temperature obtained when a straight line is extended to one hour on the ln t vs θ plot. By substituting a value of probe radius into the expression for B the value of ln h^2 may be determined by

$$\ln h_2^2 = \frac{B}{A} - 12.40 - 657.53\ \frac{k_2}{H} \quad \text{for the "red" probe}$$

and

$$\ln h_2^2 = \frac{B}{A} - 13.00 - 889.00\ \frac{k_2}{H} \quad \text{for the "blue" and}$$

"white" probes.

The value of H may be determined from equation (9) providing that α_1 and α_2 are known. For the purpose of a first approximation it was decided that a value of c_1 could be estimated. Since the stainless steel tube of the probe constitutes 75% of the total weight, and the specific heat values of the manganin and stainless steel are within 10% of 0.11 BTU/ $lb^{\circ}F$, little error would be incurred by estimating the probe specific heat. The same situation exists in estimation of h_1^2 .

The probe weight/ft is known, thus its density may be calculated. The thermal conductivity values for manganin and stainless steel are 12.6 and 15 BTU-ft/hr ft^2 °F respectively. The left-hand side of equation (9) then may be reduced to the form

$$Y = 258.6/t - 0.1806/t^2 - 639\theta_1/t^2Q \text{ for the "red" probe}$$

and

$$Y = 197.39/t - 0.1215/t^2 - 521.3\ \theta_1/t^2Q$$

for the "blue" and "white" probes. The time is in seconds rather than hours, because small whole numbers are more convenient to use. If Y is plotted against value of $t^{\frac{1}{2}}$, near time zero the resulting curve should become a straight line. The intercept at time zero is H.

To solve for the thermal diffusivity value from B' of equation (7) the value of R must first be determined. Equation (6) may be solved for X and Y by a set of simultaneous equations for values of time and temperature at two seconds, three seconds, and four seconds. The resulting expression may be reduced so that

$$0.7488X = 3.124\ \theta_2 - 3.166\ \theta_3 + \theta_4$$

$$-0.1224Y = 2.752\ \theta_2 - 3.429\ \theta_3 + 1.196\ \theta_4$$

then $R = X^2/QY$

If Q has the dimensions of BTU/hr-ft then the dimensions of R will be hr-ft^2 °F/BTU-ft and may be substituted directly into the expression for B', thus

$$\ln = \frac{B'}{A'} - 12.40 - 6.2832\ Rk \quad \text{for the "red" probe}$$

and

$$\ln = \frac{B'}{A'} - 13.00 - 6.2832\ Rk \quad \text{for the "blue" and}$$

"white" probes.

RESULTS AND CORRELATIONS

All the thermal conductivity values were calculated to three significant figures, but are reported in Tables 2 and 6 in two significant figures since it is possible that the maximum error could be as much as ten percent. This assumption is verified by the scatter of points shown on the graphs (Figures 4 through 12) of thermal conductivity versus specific gravity. The scatter of points is believed not to be a result of instrumentation, but is probably caused by sample density and moisture variation.

Since the solid portions of wood are primarily composed of approximately the same materials; cellulose, lignin, and various resins, it was originally believed that the thermal conductivity and thermal diffusivity values of flakeboards at any given density would be the same regardless of the species from which the board was constructed. This appears to be partially true at zero moisture content. At dry specific gravity 0.45 the thermal conductivity values in the xy and z directions are listed below:

Specimen	Redwood Control	Cedar	Ponderosa Pine	Redwood
k_{xy}	0.090	0.088	0.088	0.089
k_z	0.073	0.084	0.092	0.075

At dry specific gravity 0.80 the thermal conductivity values in the xy and z directions are:

Specimen	Redwood Control	Cedar	Ponderosa Pine	Redwood
k_{xy}	0.170	0.150	0.170	0.170
k_z	-	0.102	0.130	0.115

Considering the exceedingly small number of samples tested any broad generalizations would be hazardous, but the graphs do definitely show a general trend.

For the purpose of correlations the experimental procedure followed would have given values of thermal conductivity between zero and nine percent if the samples did not have any dimensional change when they were dried. The samples, however, generally decreased in thickness when dried, and the dry specific gravity value changed throughout the tests. The original plan was that each sample of a given density would have a plot of thermal conductivity versus moisture content: Since the specific gravity of each sample changed this type of correlation would not have any significance. The samples were not uniformly dried to some intermediate level of moisture content, therefore; a graph of thermal conductivity versus dry specific gravity could not be constructed. The Birch specimens had very low internal bonding, and delamination occurred when they were dried. The specimens were not tested at zero or intermediate moisture content.

For the dry specimens, the k_{xy} and k_z values diverged as specific gravity increased, but the opposite was true for specimens at equilibrium moisture content. This behavior may be explained by the distribution of moisture within the board, and by the physical structure of the flakeboard as density increased. The relation between thermal conductivity and moisture distribution is discussed in the theory

section of this thesis.

Since an increase in the amount of water displaces air within the sample, the foam and parallel arrangement would have a maximum effect for any change in sample moisture content. The flakeboard samples that were tested were all below the fiber saturation point. It is reasonable to assume that the foam arrangement prevailed.

Consider a flakeboard of low specific gravity: the conductivity of the dispersed phase is determined by the ratio of water to air within the flakeboard. When the sample gains moisture, for a low density board, the volume fraction does not change appreciably because there is still considerable amounts of air in the sample. At low densities, then, the conductivity does not change rapidly. For flakeboards of high specific gravity there is little air space left within the sample, consequently its effect on the conductivity of the dispersed phase is limited. The volume fraction then changes rapidly as does the value of Z. The effect on k at high density levels is considerably more pronounced and it increases rapidly with moisture content.

The k_{xy} values, for the sample tested, decrease approximately 10% from equilibrium to zero moisture content, but the slope of the curve does not change noticeably. This is logical since for flakeboards the percentage of the linear dimension change due to water absorption is negligible in comparison to the percentage of thickness change.

The small number of k_z values that are shown on the graph of Redwood Control specimens were obtained from samples that were originally tested by the guarded hot plate apparatus. When tested by the guarded hot plate apparatus the value of k_z was 0.063 whereas the

graph shows 0.070. A sample was tested in the k_z direction because it was not known whether probe methods had been previously used to test anisotropic material. In a publication obtained later, it was found that F. A. Joy had also used the form $k = \frac{k_2^2}{k_1}$ to relate conductivity values in different planes.[16]

The results of several thermal diffusivity calculations are shown in Tables 7 and 8. For the thermal diffusivity values calculated, the specific heat values of flakeboards would be approximately one-tenth of the specific heat values of natural wood. This is unreasonable since the thermal conductivity values were within the range of values for natural wood, and a specific heat one-tenth the value of wood is the general range for metals.

It is characteristic of transient radial heat flow, that after the initial temperature rise, the change is very gradual and is controlled by the thermal conductivity rather than thermal diffusivity. The maximum temperature rise is partially controlled by the probe diameter. Consider the expressions for B and B': In determining the thermal diffusivity value, the variables are B, A, and H or R. If R and H are of such value as not to affect h_2^2, then ln h_2^2 is a function of the probe diameter and the value of B/A. When the probe radius is decreased and the thermal properties of the sample being tested are the same, the value of B must increase.

Because of the logarithmic nature of the thermal diffusivity solution, slight changes in thermal conductivity values produce large changes in the calculated thermal diffusivity value. Blackwell states that for a specific set of values, if there is a 1% error in thermal conductivity determination, the resulting error in thermal diffusivity

is 12%. In a specific test performed on a flakeboard sample where the value of thermal conductivity differed by $\frac{1}{2}$%, the difference in the calculated thermal diffusivity value was 9.5%.

Since the scatter in thermal diffusivity values was large and results were not reasonable, that portion of the testing and calculation was discontinued in the remainder of the tests.

SUMMARY AND RECOMMENDATIONS

In general, the method of determining thermal conductivity values with a probe is well established and is known to give as good or better results than the guarded hot plate apparatus. No references have been found, to research with probes, where the temperature sensing elements were thermistors.

When thermistors are used properly, the accuracy of temperature measurement is greater than that obtained by thermocouples and the associated apparatus required to record temperature rise is readily available and simple to use.

This work was primarily conducted to determine the general characteristics of flakeboard thermal properties. No attempt was made to obtain a large number of tests on one particular species so that the exact values of the thermal properties could be reported. To establish a general trend of values, the greatest number of tests were conducted on Redwood flakeboards, because flakes were readily available. Redwood was a poor choice because it takes a long time for samples to reach equilibrium moisture content, and the moisture content is not uniform between successive samples. An equilibrium moisture content of nine percent was used since the humidity room at the Wood Products Laboratory was set to give this value. Nine percent is also approximately, the value at which flake mats enter a press. Considerably less scatter could have been obtained if the flakeboards constructed were sanded so that they were uniform in thickness before they were cut into samples.

It is time consuming, but better density uniformity in each sample could have been obtained if the boards were oven dried before density segregation was performed.

It was believed that for any given moisture content and density the flakeboards would have equal values of thermal conductivity, but tests proved that this is not the case. The differences of the dispersed moisture phase for boards constructed of high density wood is considerably different from that of boards constructed from low density wood. The thermal conductivity values conform to the theory of foam arrangement when the moisture content is below fiber saturation.

The thermal diffusivity determinations by probe methods proved inadequate in this work. Blackwell's work on the application of his equations was not published.[17] It is believed that the solutions to the differential equations adequately represent the physical characteristics of transient heat flow, but instrumentation and experimental procedure were not properly designed to obtain accuracy and response necessary to measure temperature rise. It may be that the time necessary for a "small-time" solution is longer than six seconds as Blackwell's equations indicate, and perhaps it may have to be less than 0.006 seconds as calculated on page 8 of this thesis. It seems reasonable that, with care, thermal diffusivity could be reproduced to the useful limit of the equation. The useful limit is 10 or 20 percent for low values of thermal diffusivity because the slope of a logarithmic curve is very steep in this region. The reproducibility of the thermal conductivity test is usually one percent in homogeneous material. If the errors are random in nature, statistical analysis might give better values.

The maximum accuracy of the thermal conductivity tests performed in this work was approximately 5%. This is due to an accuracy of 1% in measurement of current flow in the heating element, and 0.05% dwell of the recording pen when the temperature change is gradual.

Unless specifically stated other wise, the units of all results reported in this work are in the fph system.

LITERATURE CITED

1. Carslaw, H. S. and Jaeger, J. C., Conduction of Heat in Solids, (second edition; Oxford at the Claredon Press: Oxford University Press, Amen House, Amen House, 1959), pp. 8-49.

2. Hooper, F. C. and Lepper, F. R., "Transient Heat Flow Apparatus for Determination of Thermal Conductivity," Heating, Piping, and Air Conditioning, (August, 1950), pp. 129-134.

3. Ingersoll, L. R. and Zobel, O. J., Heat Conduction, (first edition: International Series in Pure and Applied Physics; New York: McGraw-Hill Book Co., Inc., 1950), pp. 143-146.

4. Carslaw and Jaeger, loc. cit. p. 345.

5. Blackwell, J. H., "A Transient-Flow Method for Determination of Insulating Materials in Bulk," Journal of Applied Physics, Vol.XXV, No. 2 (February, 1954), pp. 137-144.

6. Carslaw and Jaeger, loc. cit. pp. 41-49.

7. Ibid., pp. 256-258.

8. Ibid, p.45.

9. Blackwell, loc. cit.

10. Blackwell, J. H., "Axial Flow Error in the Thermal Conductivity Probe," Canadian Journal of Applied Physics, Vol. XXXIV, (1956), pp. 412-417.

11. Joy, F. A., "Thermal Conductivity of Insulations Containing Moisture," American Society for Testing Materials, Special Technical Publication, No. 217, pp. 49-80.

12. Hooper and Lepper, loc. cit.

13. Hooper, F. C. and Chang, S. C., "Development of Thermal Conductivity Probe", Heating, Piping, and Air Conditioning, (October, 1952) pp. 125-129.

14. D'Eustachio, D. and Schreiner, R. E., "A Study of a Transient Heat Method for Measuring Thermal Conductivity," Heating, Piping, and Air Conditioning, (American Society of Heating and Ventilating Engineers, Journal Section), (June, 1952), pp. 113-117.

15. Joy, loc. cit.

16. Joy, loc. cit. p. 74

17. Letter from Blackwell, J. H., Professor of Physics, University of Western Ontario, Department of Physics, London, Ontario, Canada (March 21, 1960)

18. Ibid.

APPENDIX

Fig.4

THERMAL CONDUCTIVITY vs DRY SPECIFIC GRAVITY
RED WOOD CONTROL SPECIMENS

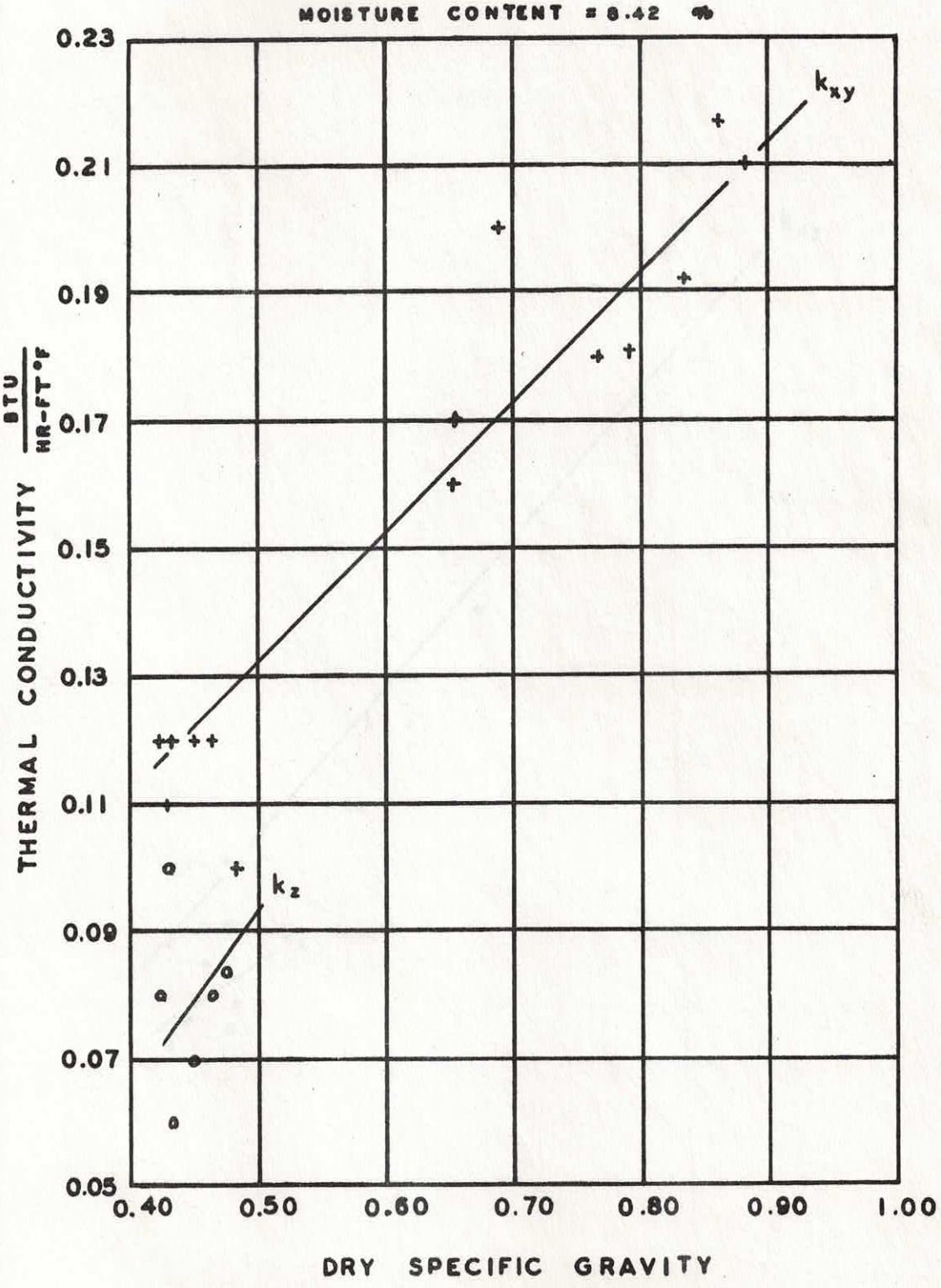


Fig.5

THERMAL CONDUCTIVITY vs DRY SPECIFIC GRAVITY
REDWOOD CONTROL SPECIMENS

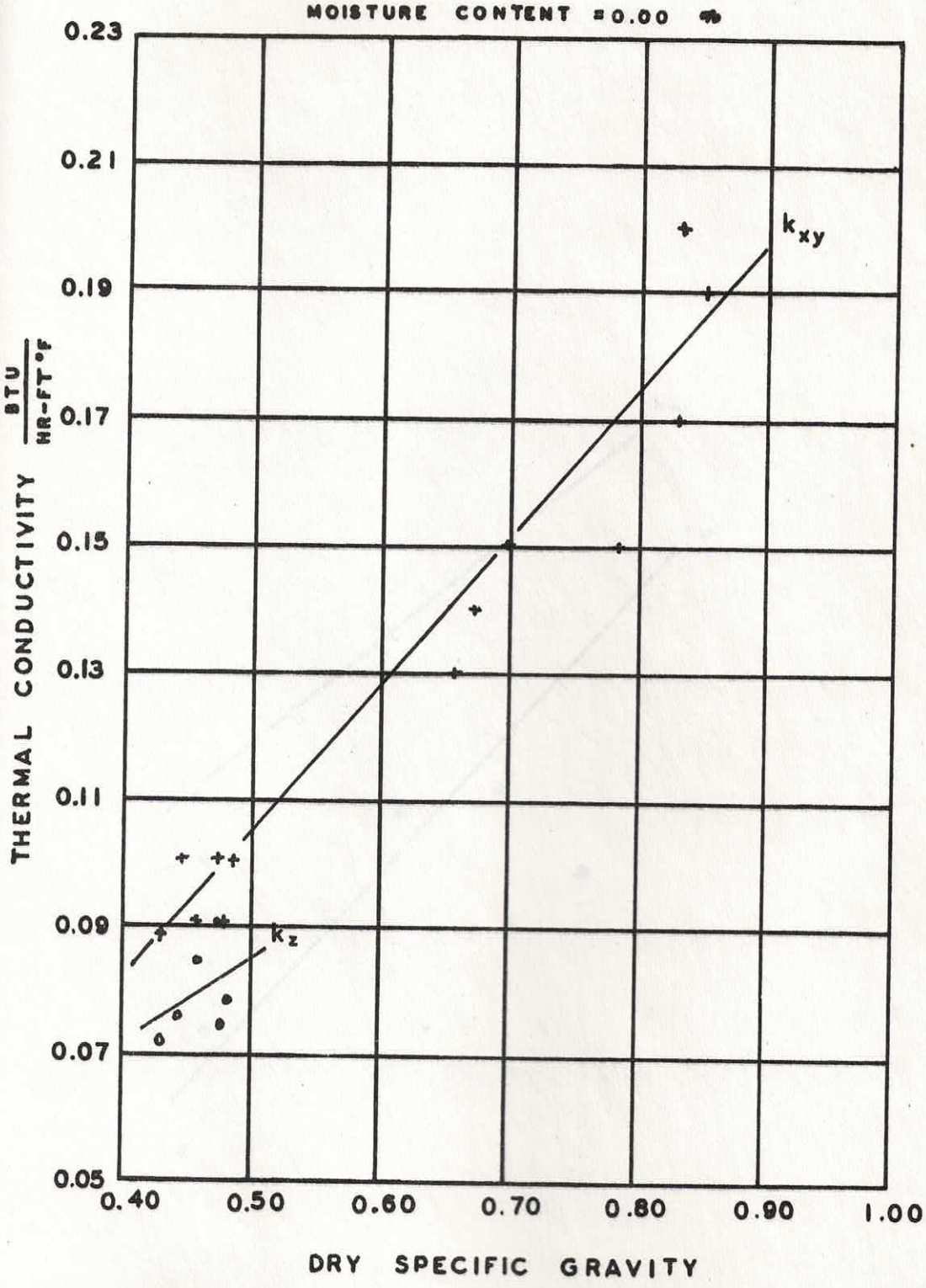


Fig.6

THERMAL CONDUCTIVITY vs DRY SPECIFIC GRAVITY
CEDAR SPECIMENS

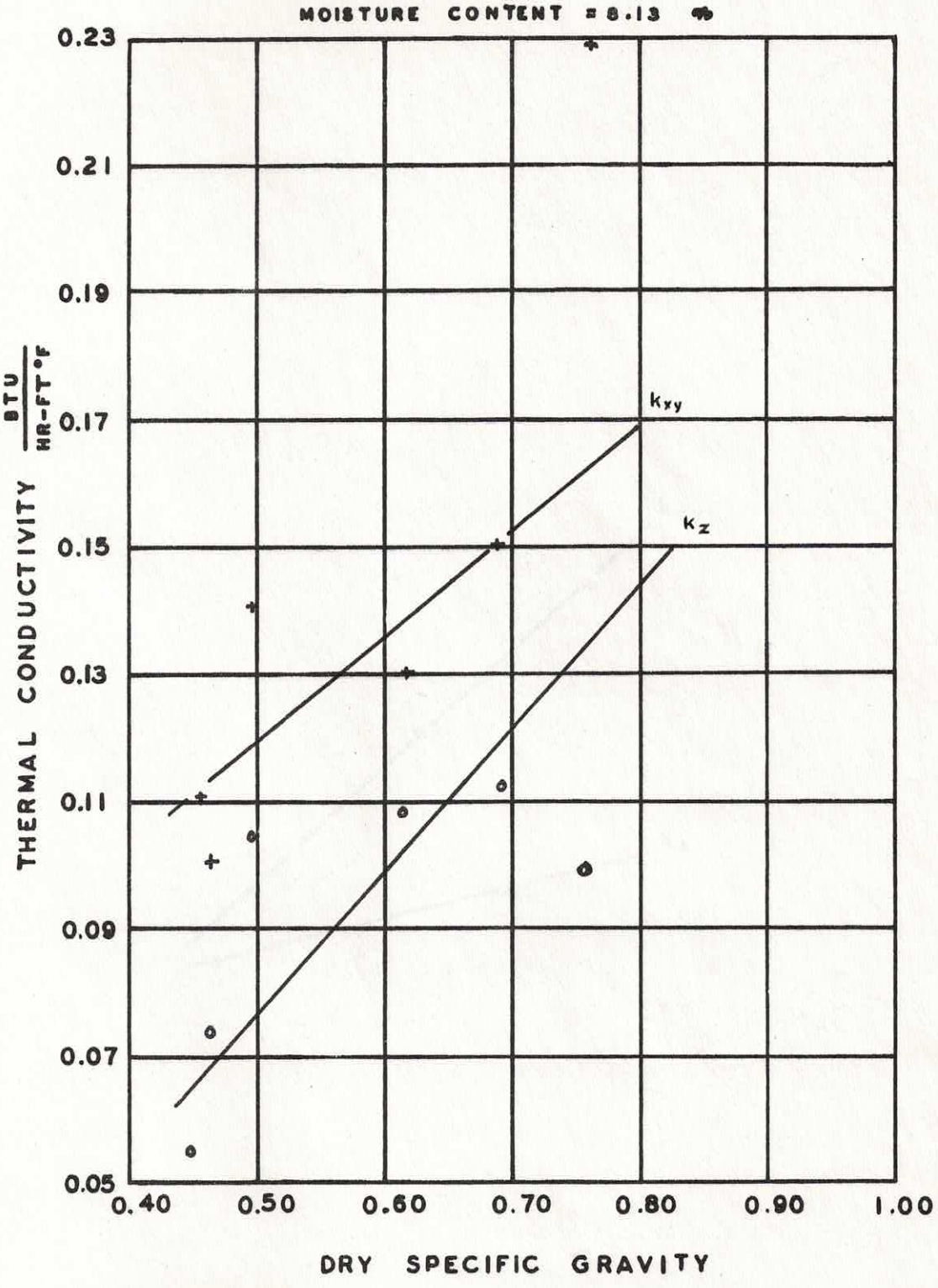


Fig.7

THERMAL CONDUCTIVITY vs DRY SPECIFIC GRAVITY
CEDAR SPECIMENS

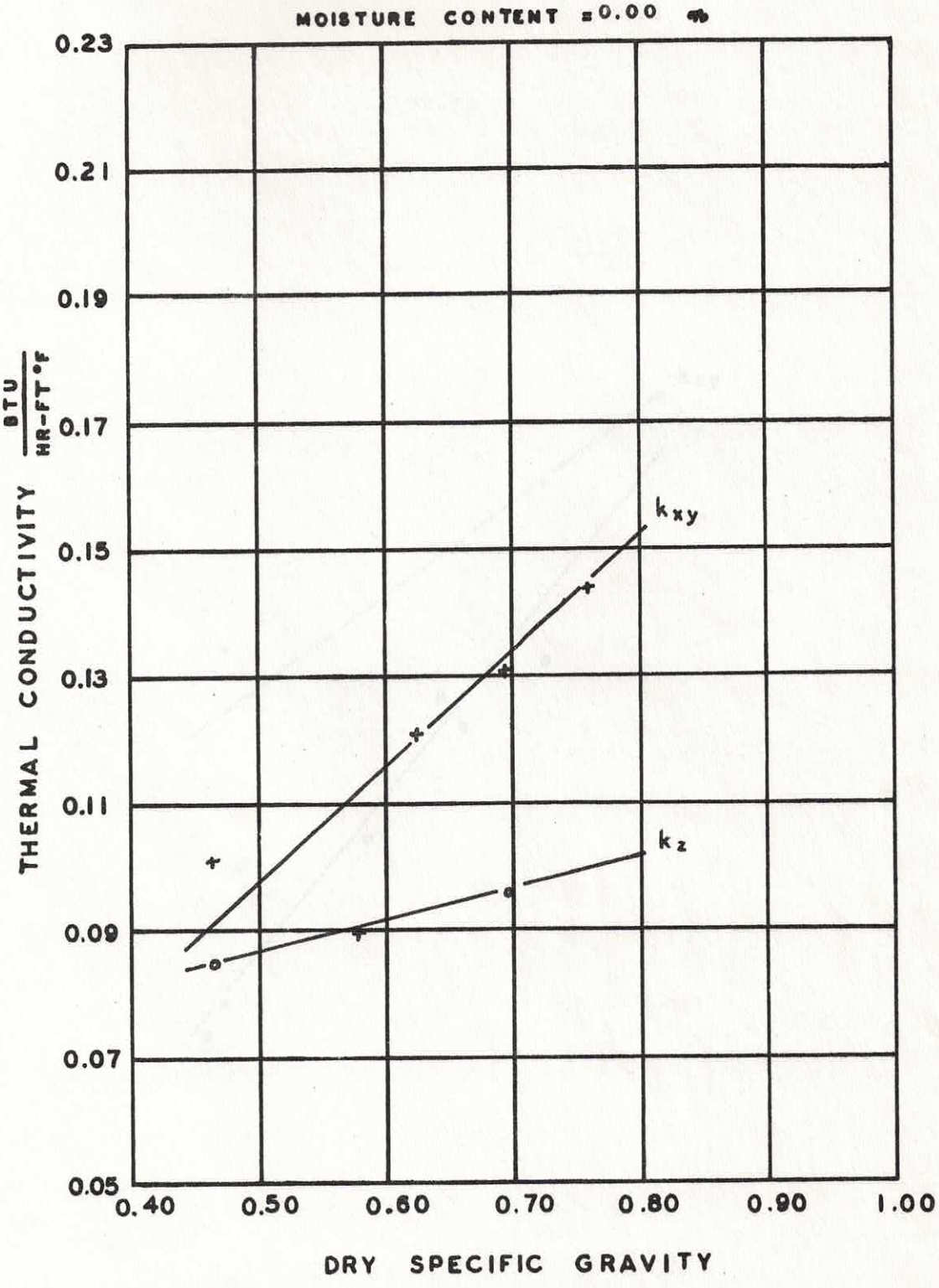


Fig. 8

THERMAL CONDUCTIVITY vs DRY SPECIFIC GRAVITY
PONDEROSA PINE SPECIMENS

MOISTURE CONTENT = 9.72 %

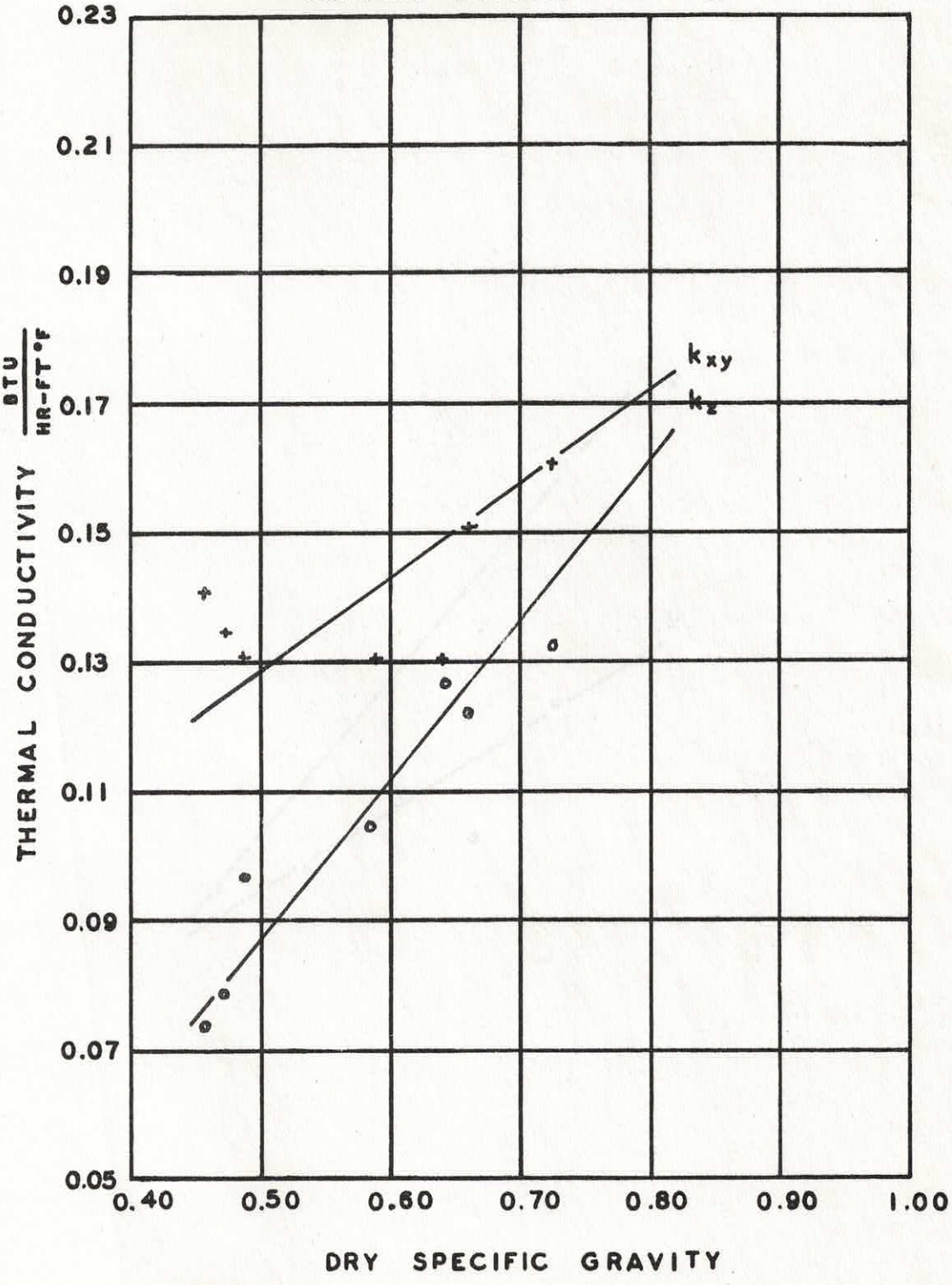


Fig. 9

THERMAL CONDUCTIVITY vs DRY SPECIFIC GRAVITY
PONDEROSA PINE SPECIMENS

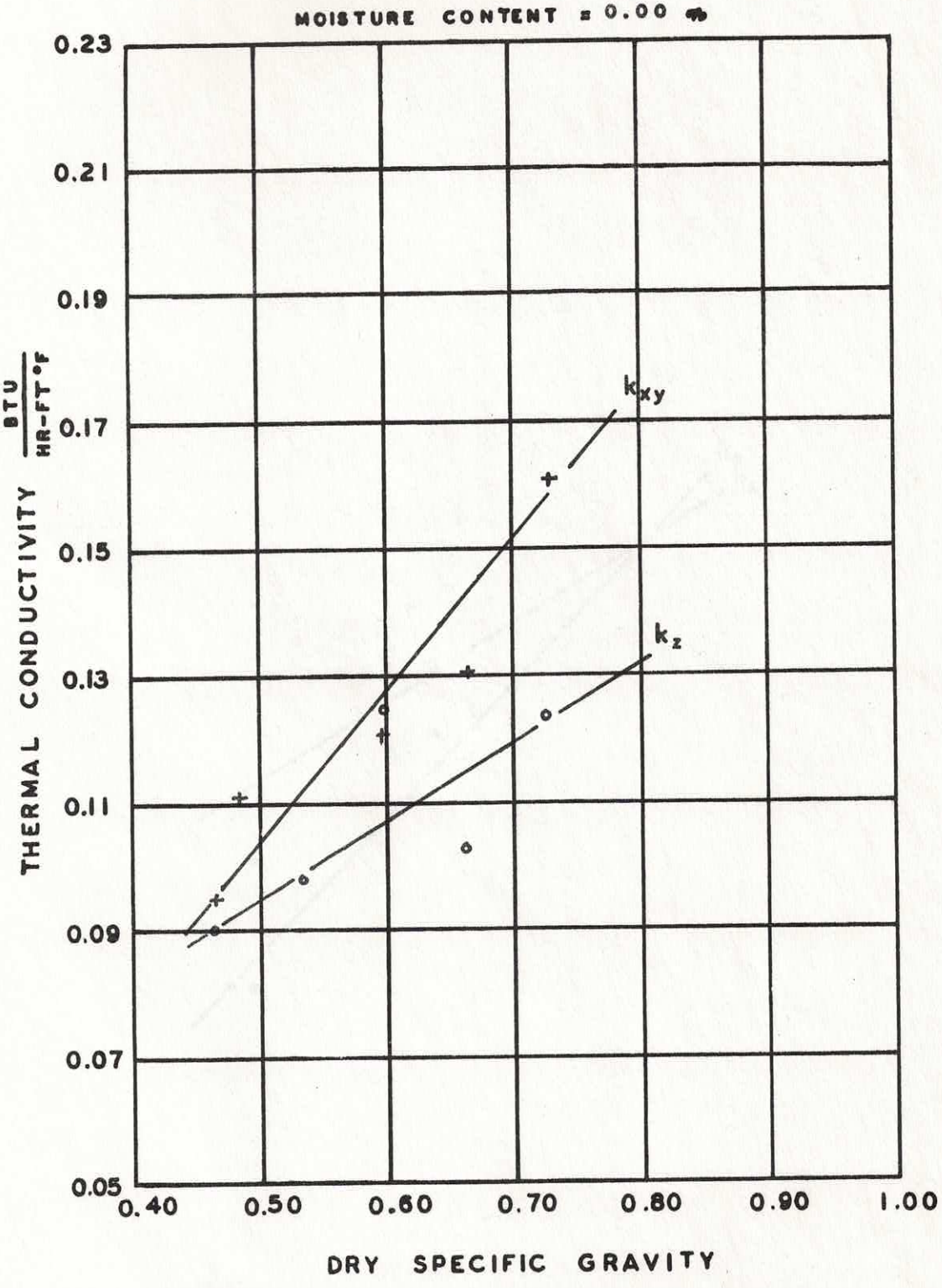


Fig. 10

THERMAL CONDUCTIVITY vs DRY SPECIFIC GRAVITY
REDWOOD SPECIMENS

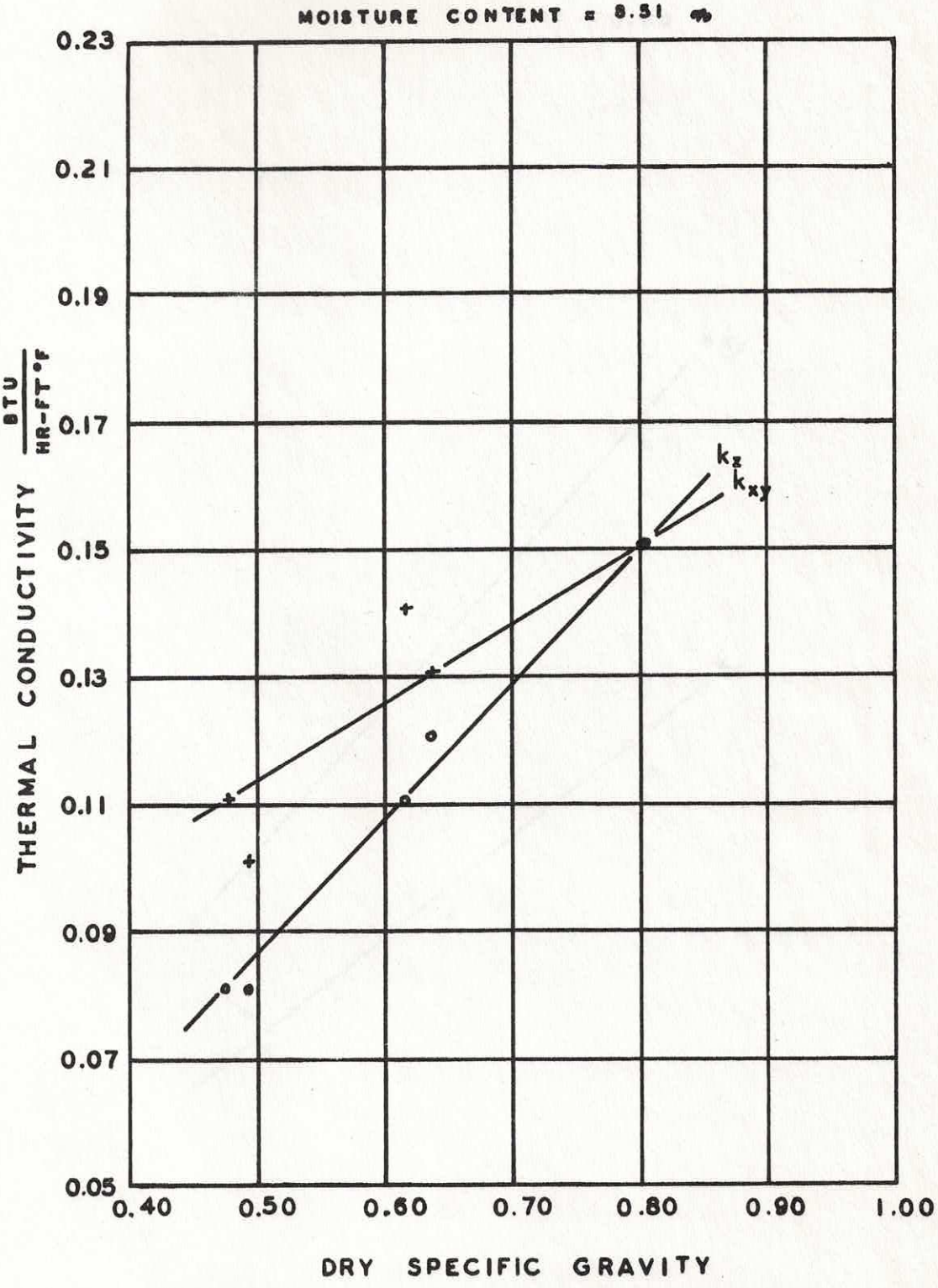


Fig. 11

THERMAL CONDUCTIVITY vs DRY SPECIFIC GRAVITY
REDWOOD SPECIMENS

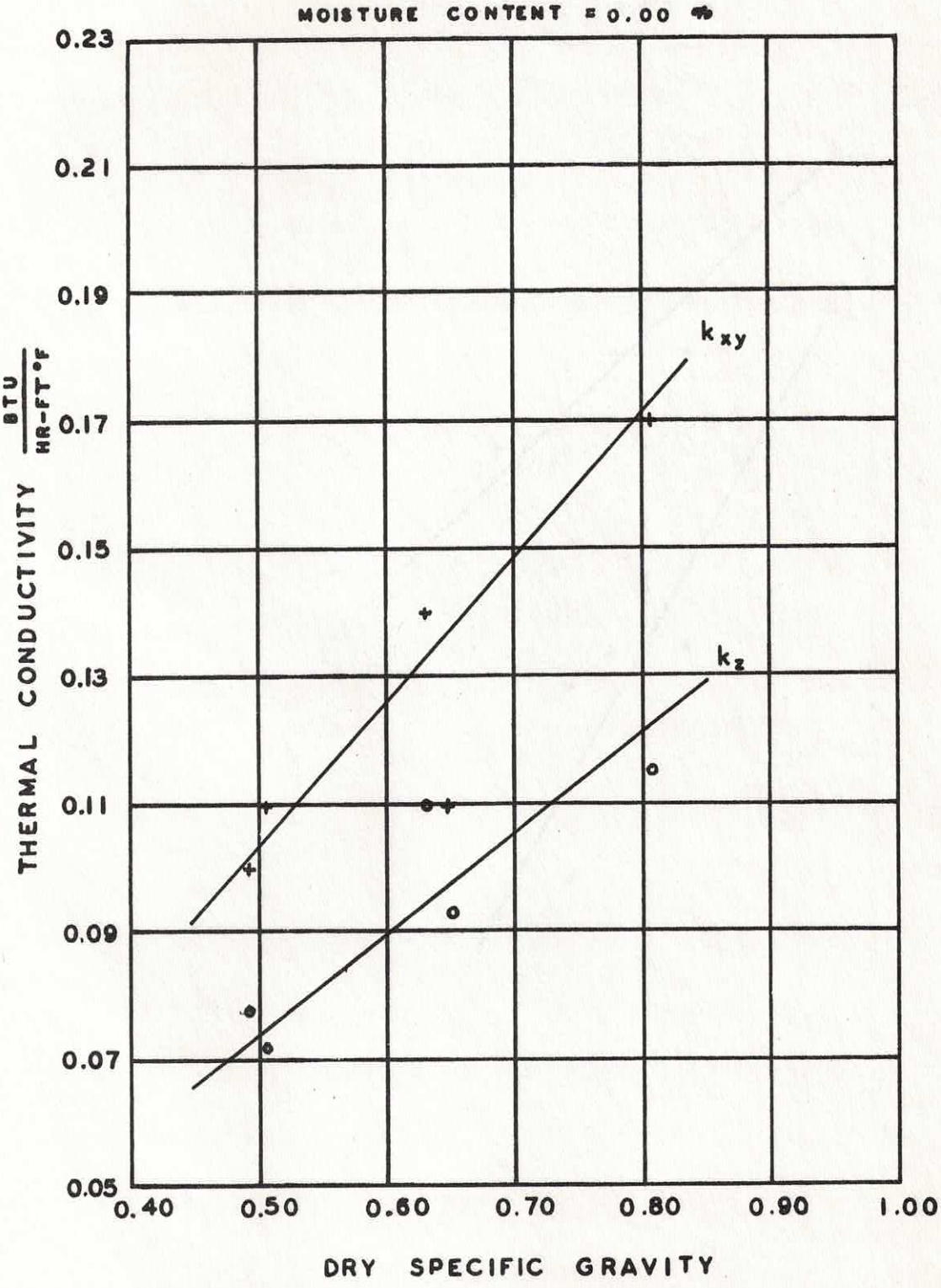


Fig. 12

THERMAL CONDUCTIVITY vs DRY SPECIFIC GRAVITY

BIRCH SPECIMENS

MOISTURE CONTENT = 8.98 %

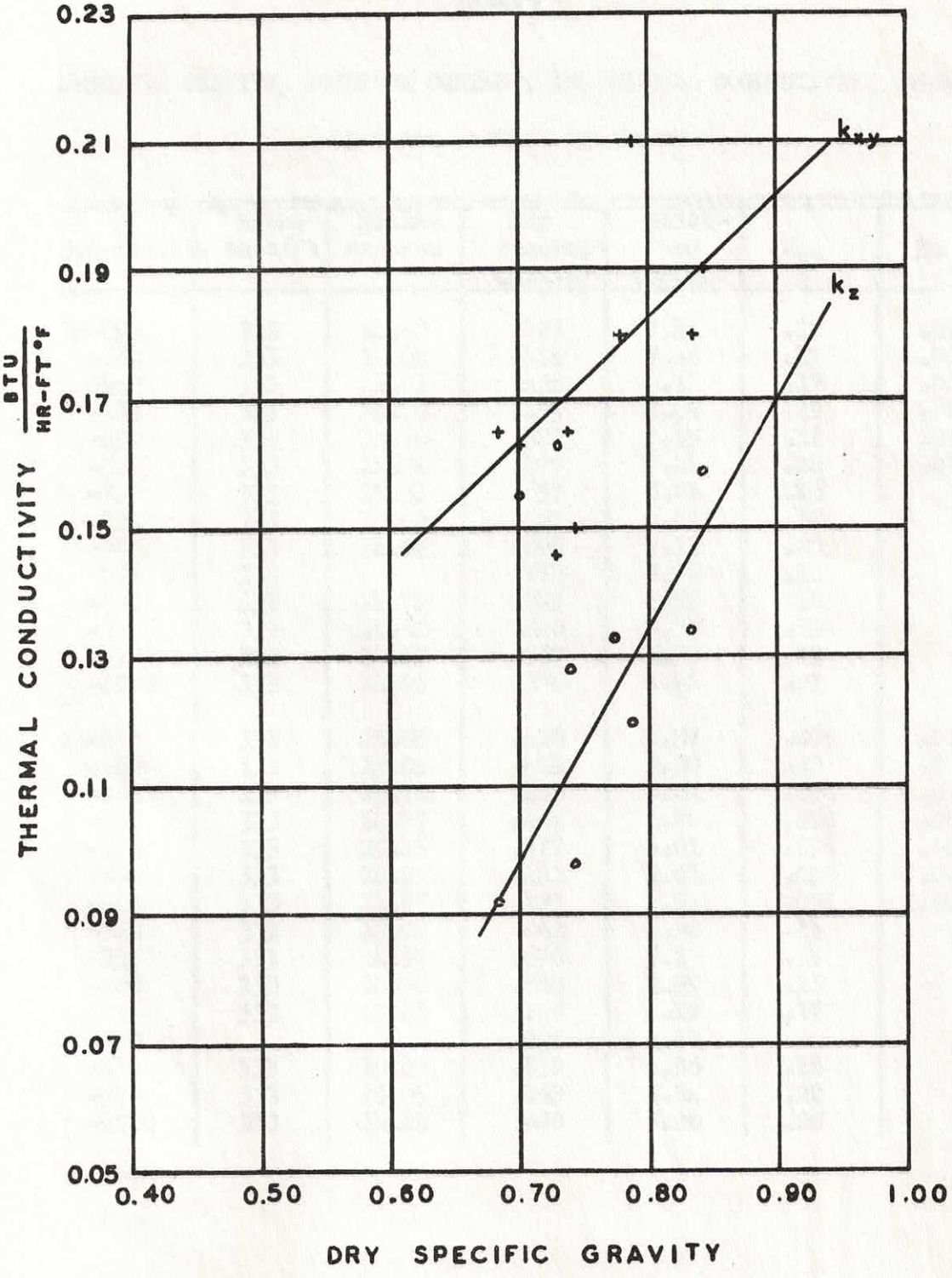


TABLE 2

SPECIFIC GRAVITY, MOISTURE CONTENT, AND THERMAL CONDUCTIVITY VALUES

Redwood Control Specimens

Specimens	Probe ohms/ft	Milli-amperes	Dry Specific Gravity	Moist-ure Content	K_{xy}	Kz
1R-453	333	14.60	.427	7.41	.12	.079
-460	333	14.62	.434	7.16	.11	.096
-462	333	14.42	.438	8.11	.12	.062
-480	333	14.70	.455	8.04	.12	.066
-490	333	14.70	.470	7.85	.12	.076
-503	333	14.70	.479	7.44	.10	.077
-720	333	15.51	.657	8.21	.16	
-735	333	14.62	.667	8.81	.17	
-768	333	14.62	.695	9.11	.20	
-856	333		.778	8.54	.18	
-890	333	14.79	.929	8.52	.18	
-945	333	14.66	.840	8.70	.19	
-970	333	14.77	.867	8.37	.22	
-1000	333	14.95	.886	8.42	.21	
2R-453	333	15.05	.436	3.57	.096	.072
-460	333	15.05	.445	2.30	.10	.072
-462	333	14.72	.448	3.61	.094	.078
-480	333	14.77	.462	3.90	.090	.087
-490	333	15.15	.477	4.01	.098	.081
-500	333	14.99	.482	3.61	.098	.069
-503	333	14.85	.493	2.51	.091	.079
-720	333	15.05	.661	5.20	.14	
-735	333	14.95	.676	5.13	.14	
-768	333	14.98	.708	2.99	.18	
-856	333	15.06	.793	4.19	.17	
-890			.930	4.66		
-942	333	15.03	.839	4.96	.18	
-970	333	15.05	.869	4.84	.22	
-1000	333	14.80	.888	5.20	.20	

TABLE 2 --Continued

Specimens	Probe ohms/ft	Milli-amperes	Dry Specific Gravity	Moist-ure Content	K_{xy}	K_z
3R-453	333	15.05	.443	0	.088	.071
-460	333	15.05	.451	0	.13	
-462	333	15.05	.456	0	.10	.075
-480	333	15.04	.470	0	.09	.084
-490	333	15.05	.486	0	.10	.090
-500	333	15.05	.490	0	.09	.074
-503	333	15.05	.498	0	.10	.068
-720	333	15.04	.668	0	.13	
-735	333	14.78	.683	0	.14	
-768	333	15.05	.709	0	.15	
-856	333	14.73	.797	0	.17	
-890	333	15.05	.934	0	.17	
-942	333	15.05	.840	0	.20	
-970	333	15.05	.861	0	.19	
-1000	333	15.05	.883	0	.20	

TABLE 3

SPECIFIC GRAVITY, MOISTURE CONTENT, AND THERMAL CONDUCTIVITY VALUES

Redwood Specimens

Specimens	Probe ohms/ft	Milli-amperes	Dry Specific Gravity	Moist-ure Content	K_{xy}	K_z
1R-535	224	19.08	.485	8.35	.11	.080
-554	224	17.75	.500	8.70	.10	.079
-695	209	19.36	.627	8.11	.14	.11
-715	224	17.49	.644	8.65	.13	.12
-900	209	17.76	.809	8.74	.15	.15
2R-535	209	17.84	.493	2.92	.11	.081
-554	224	17.58	.507	3.66	.098	.074
-695	209	17.83	.632	3.43	.13	.099
-715	224	17.60	.648	4.12	.12	.10
-900	209	17.83	.808	4.82	.17	.14
3R-535	209	17.82	.495	0	.10	.078
-554	209	17.81	.509	0	.11	.072
-695	224	17.62	.634	0	.14	.11
-715	224	17.34	.651	0	.11	.093
-900	224	17.60	.812	0	.17	.12

TABLE 4

SPECIFIC GRAVITY, MOISTURE CONTENT, AND THERMAL CONDUCTIVITY VALUES

Ponderosa Pine Specimens

Specimens	Probe ohms/ft	Milli-amperes	Dry Specific Gravity	Moist-ure Content	K_{xy}	K_z
1P-520	209	17.99	.460	9.64	.14	.073
-535	209	17.52	.476	9.83	.13	.078
-545	224	17.42	.484	9.92	.13	.096
-669	224	17.34	.594	9.78	.13	.10
-725	224	17.26	.644	9.7	.13	.13
-751	209	17.48	.664	9.56	.15	.12
-800	209	17.49	.727	9.61	.16	.13
2P-520	224	17.60	.470	3.83	.086	.084
-535	209	17.81	.484	3.65	.096	.089
-545	224	17.60	.488	4.66	.11	.066
-669	224	17.60	.597	4.13	.11	.11
-725	209	17.85	.647	4.49	.17	.074
-751	209	17.82	.665	4.41	.14	.10
-800	224	17.61	.725	4.88	.17	.12
3P-520	209	17.84	.473	0	.094	.089
-535			.484	0		
-545	207	17.90	.493	0	.11	.097
-669	207	17.90	.603	0	.12	.12
-725			.653	0		
-751	209	17.80	.674	0	.13	.10
-800	209	17.81	.735	0	.16	.12

TABLE 5

SPECIFIC GRAVITY, MOISTURE CONTENT, AND THERMAL CONDUCTIVITY VALUES

Cedar Specimens

Specimens	Probe ohms/ft	Milli-amperes	Dry Specific Gravity	Moist-ure Content	K_{xy}	K_z
1C-515	209	17.83	.467	7.97	.11	.053
-525	224	17.61	.475	8.10	.10	.073
-646	209	17.85	.585	8.40	.14	.104
-694	224	17.61	.628	8.01	.13	.108
-770	209	17.85	.699	7.95	.15	.112
-855	224	17.60	.768	8.35	.23	.098
2C-515	209	17.82	.471	3.05	.10	.096
-525	224	17.60	.480	2.77	.087	.079
-646	209	17.90	.588	3.65	.13	.089
3C-515	209	17.81	.471	0	.10	.084
-525			.480	0		
-646	207	16.58	.587	0	.089	
-694	209	17.75	.633	0	.12	
-770	209	17.84	.702	0	.13	.095
-885	209	17.82	.767	0	.14	

TABLE 6

SPECIFIC GRAVITY, MOISTURE CONTENT, AND THERMAL CONDUCTIVITY VALUES

Yellow Birch Specimens

Specimens	Probe ohms/ft	Milli-amperes	Dry Specific Gravity	Moist-ure Content	K_{xy}	K_z
1B-760	224	17.26	.688	9.07	.17	.092
-780	209	17.42	.705	8.54	.16	.155
-815	224	17.06	.734	9.54	.15	.163
-826	209	17.32	.742	9.00	.17	.128
-856	224	17.22	.748	9.14	.15	.098
-880	224	17.26	.778	9.00	.18	.133
-900	209	17.45	.791	8.70	.21	.120
-930	209	17.49	.839	8.90	.18	.134
-955	224	17.61	.848	8.90	.19	.159

TABLE 7

THERMAL DIFFUSIVITY

Calculated by Use of Equations (6) and (7)

Specimens	Probe ohms/ft	Q	K	$\frac{B}{A}$	R	h_2^2
1R-715 V	224	0.2339	0.1259	9.925	0.2764	0.041
-715 45	224	0.2345	0.1208	9.535	0.07475	0.0134
-995 V	333	0.25335	0.2052	10.350	8×10^{-4}	0.129
-900 V	209	0.2260	0.1525	9.581	0	0.036
-900 45	209	0.22985	0.1524	9.675	2.458	0.0035
-535 V	224	0.2784	0.1069	9.992	0.0227	0.050
-695 V	209	0.26857	0.135	9.93	0.0332	0.047
-890 V	333	0.24796	0.181	10.090	0.13	0.0865
1P-535 V	209	0.21995	0.1336	11.386	0.034	0.189

TABLE 8

THERMAL DIFFUSIVITY

Calculated by Use of Equations (8) and (9)

Specimens	Probe ohms/ft	Q	K	$\frac{B}{A}$	H	h_2^2
1R-695 V	209	0.2686	0.135	9.937	515	0.0398
-538 V	224	0.2784	0.106	9.993	660	0.460
-995 V	333	0.2533	0.2052	10.340	510	0.100
-900 V	209	0.2261	0.1525	9.581	595	0.026
-715 V	224	0.2339	0.1259	9.925	600	0.0385
-715 45	224	0.2345	0.1208	9.535	320	0.0228
2R-500 V	333	0.2547	0.0978	11.030	385	0.216
-856 V	333	0.2571	0.1200	11.140	515	0.230
-735 V	333	0.2533	0.1420	10.154	505	0.088
1P-520 45	209	0.2311	0.0991	10.010	700	0.0445