4-1978

Thermal Conductivity Measurements of Wet Paper

Keith S. Kearcher
Western Michigan University

THERMAL CONDUCTIVITY MEASUREMENTS
OF WET PAPER

by

Keith S. Kearcher

A Thesis submitted
in partial fulfillment of
the course requirements for
The Bachelor of Science Degree

Western Michigan University
Kalamazoo, Michigan

April, 1978

ABSTRACT

The thermal conductivity of wet paper mats was studied as a function of moisture content and porosity. The conductivity measurements were conducted with a steady-state hot plate apparatus. Results show the relationship of conductivity and moisture content to be non-linear in an increasing fashion. Large variability in results obtained is largely attributed to experimental apparatus design and engineering. Solid cellulose conductivities were calculated using experimental results and the average value was found to be 0.317 ± 0.188 BTU/hr-ft-°F. Close correlation of data using different pulp furnishes indicate type of furnish is not a major variable in conductivity determinations.

TABLE OF CONTENTS

INTRODUCTION

The theory of contact drying has been developed by several investigators whose analyses are in general agreement. However, this work has found little application in the design of dryer systems or in dryer performance evaluation. This lack of application of appropriate analytical work appears to result from the wide variation of physical properties of the web and the equally wide variation of machine variables which make it difficult to develop generally applicable design and performance evaluating methods. As a result, dryer system design is based to a large extent on experience, and performance improvements come slowly. Nevertheless, the industry is very much concerned with improvements in drying system performance, in terms of better drying uniformity and of higher drying rates. Here we will review the available analytical and experimental information dealing with thermal conductivity, and the closely related heat and mass transfer characteristics of paper during contact drying. It is hoped that the following study will provide some of the needed information concerning the fundamental properties of paper to achieve a more thorough quantitative look at the mechanism of hot surface drying of paper.

HEAT TRANSFER

Conduction defined (1) is the transfer of heat through a stationary medium by transfer of heat between adjacent molecules. The basic equation for one directional steady state conduction is:

$$Q = \frac{kA}{t}\Delta T$$

OR

$$Q = U \cdot A \cdot \Delta T$$

Where: Q= Heat transfer rate (BTU/hr)

k= Thermal conductivity $\left(\frac{BTU}{hr.ft.°F}\right)$

A= Heat transfer area (ft^2)

ΔT= Temperature difference (°F)

t= Thickness (ft.)

And $\frac{k}{t}$ the so called heat transfer coefficient (U) has the dimensions BTU/hr.ft^2°F. This overall coefficient is often used in heat transfer calculations for paper machines, usually being determined experimentally with readily available instruments. Unfortunately, this is an oversimplification of the process and is of little aid in process design.

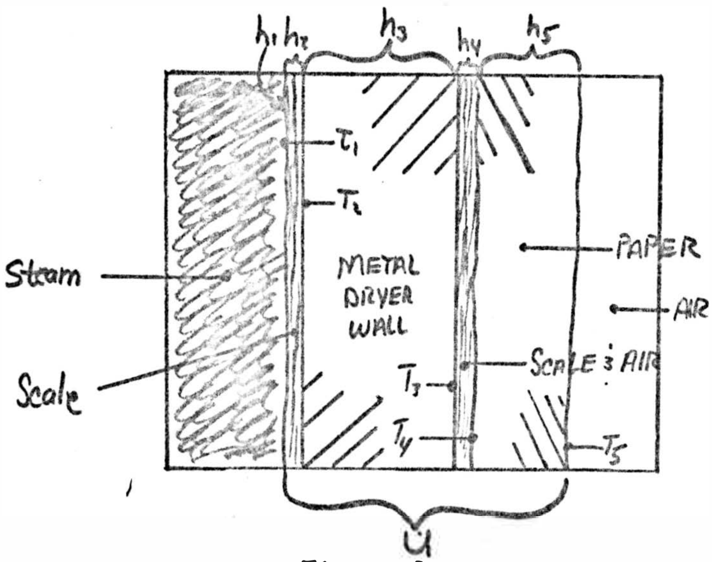


Figure 1

$$U = \frac{1}{\frac{1}{h_1} + \frac{1}{h_2} + \frac{1}{h_3} + \frac{1}{h_4} + \frac{1}{h_5}}$$

where:

$h_1 = \frac{k_1}{T_1}$ of condensed steam

$h_2 = \frac{k_2}{T_2}$ of inside scale & dirt film

$h_3 = \frac{k_3}{T_3}$ of metal dryer shell

$h_4 = \frac{k_4}{T_4}$ of outside scale & air film

$h_5 = \frac{k_5}{T_5}$ of paper web

Figure 3 represents a schematic breakdown of the overall conductance coefficient (U). Compared to the other conductivities, the low conductivity observed of the air layer (h_5) is one of the most significant factors influencing drying rate. Here dryer felt tension plays an important role in determining the degree of resistance put forth by the air film. However, with Yankee dryer systems it has been found that this air film is no longer the primary resistive factor. It is the conductance through the drier shell that has the greatest effect. This can be accounted for by the improved paper-cylinder contact experienced with Yankee driers limiting the air resistive film between shell and paper.

THE DRYING PROCESS

In helping to understand the significant roll thermal conductance of paper plays in the drying of a web of paper a brief description of the drying process is required. This process may be broken down into four basic phases:

1) The sheet enters the dryer with a quite uniform temperature and moisture distribution.

2) In the initial part of the dryer, a substantial amount of moisture is evaporated from the surfaces of the sheet. Some of this vapor is transferred by diffusion into the sheet, where it condenses, raising the temperature and the moisture content of the center of the sheet. Additional heat is transferred to the center of the sheet by conduction. Since the sheet is heated from alternate sides by succesive drums, the temperature and

moisture distributions are approximately symmetrical about the center of the sheet.

3) After the initial phase in which temperature and moisture gradients are established, a period of near constant drying rate occurs. In this period, heat is transferred within the sheet by conduction and by diffusion of vapor. Mass transfer occurs from the center toward the surface by diffusion of vapor and by capillary movement of water as a result of the moisture gradient. Throughout the process, the temperature is lower and the moisture ratio higher at the center of the sheet than at the surfaces. However, as drying proceeds, the moisture ratio at the center, and therefore the total moisture content, decreases.

4) As the sheet becomes dryer, the thermal conductivity of the sheet decreases and below a moisture ratio of approximately 0.2 the vapor pressure of the water-fiber mixture decreases. The drying rate therefore decreases and continues to decrease until the sheet leaves the dryer.

Figure 2

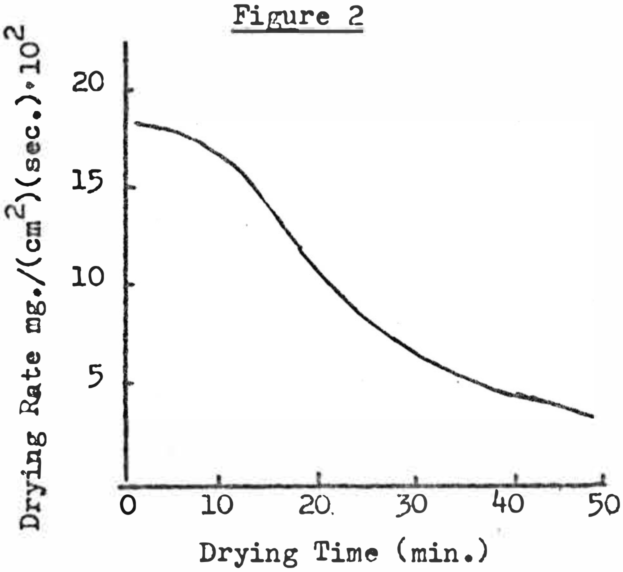
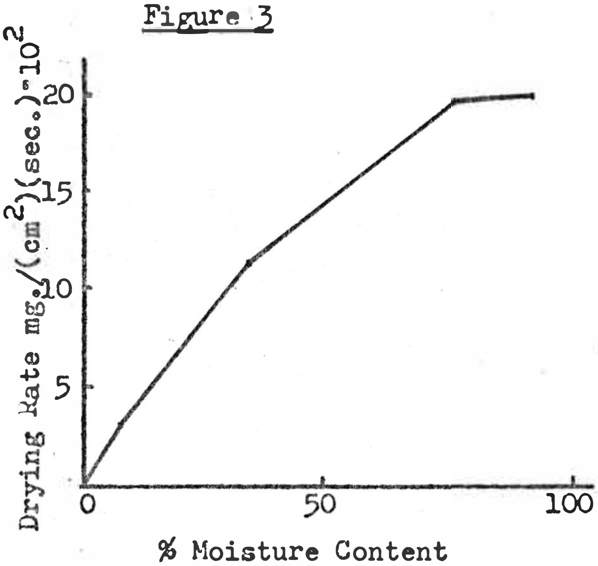


Figure 3



This varying conductivity of the sheet and methods of measurement are of prime concern when detailed analysis for dryer systems design and process efficiencies are undertaken.

FLUID TRANSFER AND VAPOR MOVEMENT

As is well known, heat may be transferred by conduction, convection, and radiation. Radiation in a fibre mat is generally negligible, but convection in the pores may constitute a significant part of heat transfer. From all available evidence, water migrates in a fibre mat as soon as drying is initiated. In a relatively wet state, both water and air are distributed continuously in the interconnected pores. At any point across the water-air curved interface, a pressure difference exists which is called capillary pressure.

$$P_{cap.} = P_{air} - P_{water}$$

Water moves in response to pressure gradients, which are in turn dependent on saturation and temperature. By virtue of the increase in pressure due to temperature, the vapor due to evaporation, migrates from the contacting surface to the exposed surface. As the vapor passes through the web, it also passes through the temperature gradient of the sheet and a certain amount of condensation occurs which, in turn, releases latent heat into the web. The latent heat released helps to raise the temperature in the layers away from the contacting surface and there to increase the distance from the contacting surface at which evaporation occurs. In this way, it is shown that this convected heat transfer can also contribute substantially to the effective conductivity of the web.

As evaporation at the contacting surface of the web and migration of vapor from this surface into the web proceeds, a gradual capillary movement of water within the web occurs, leading to a migration of liquid water towards the hot cylinder surface. When the web separates from the cylinder, vapor entrapped between the cylinder and the web is immediately released and rapid evaporation from the hot surface of the web occurs, accompanied by rapid cooling of the web. Less rapid evaporation also occurs from the cooler previously exposed surface. Finally, the sheet contacts the next cylinder, the surface which before was exposed becomes the contacting surface, is rapidly heated, and the cycle begins again. It is estimated (1) that capillary flow accounts for no more than 30% of fluid movement, vapor diffusion providing the balance. Of the internal heat flow, conduction accounts for only 30 to 40 percent, while vapor diffusion and condensation (convection) provide the major proportion. Even after the overall moisture is reduced to 60 percent dryness, the level of moisture in the core is still only slightly below that of the sheet as it leaves the press section. This mechanism suggests that drying could be speeded by preheating the whole web to high temperatures at the beginning of drying to minimize internal condensation.

THERMAL CONDUCTIVITY

Heat transfer through a sheet of paper is obviously measured by thermal conductivity. In view of the complex drying mechanism mentioned before with respect to the moisture and vapor movement, and the possible existance of condensation-vaporization cycles, it is extreemly difficult to make a detailed heat transfer analysis which would satisfy all the local conditions

in the present course of drying.

During the entire drying process, the thermal conductivity is determined by moisture content, the temperature, the porosity of the web, and the conductivity of the solids.

CONDUCTIVITY WITHOUT CONVECTION (NON-VOLATILE COMPONENT)

True thermal conductivity excludes convection and radiation. The contribution of radiation to heat transfer in fibre mats is negligible provided the porosity is less than 0.99 and the temperature below the normal boiling point of water (4). The convection of fluids in the pores, however, may not often be ignored and will be considered later.

A wet paper web may be characterized as being three phased in nature, i.e. fiber-water-air. Consequently, the mechanisms of heat transfer in the compressible system is taken to be:

1. Conduction in the voids
2. Conduction in the fibers
3. Conduction in the contact region between fibers

The contact region includes the fluid filament adjacent to the contact as well as the solid-solid contact area.

By assuming the heat flow in the voids is parallel with the heat flow in the solid structure and their cross-section areas are proportional to the void and solid fractions, and that the fibre lengths are the same as the mat thickness, a prediction equation has been developed.

$$ka = (1-\epsilon)\, ks + \epsilon S k_{\ell} + \epsilon(1-S) kg$$

k_a = Apparent conductivity of water

k_ℓ = Thermal conductivity of liquid phase

k_g = Thermal conductivity of gas or fluid phase

ϵ = Void fraction or porosity, void volume/total bed volume

S = Average bed saturation, liquid volume/void volume

k_s = Thermal conductivity of solid phase

This model represents the limiting case of maximum conductivity of a porous structure. As the conductivities of the fluid and solid phases come close to each other, the model becomes a reasonable one.

For a solid-fluid conductivity ratio as high as 10, the parallel model holds quite well and also agrees with experimental data at a porosity as low as 0.75$\frac{cc}{}$/cc. When a mat of deformable fibres is compressed, its porosity decreases, the fibres are brought into more contacts more intimately either by an increase in macroscopic area or in microscopic proximity, probably both, causing more heat flow through the contact areas. The reduction of contact resistance results in a higher conductivity at a lower porosity. Thus the range of porosity in which the parallel model is applicable will vary with the deformability and surface nature of the fibres.

CONDUCTIVITY WITH CONVECTION (VOLATILE COMPONENT, i.e. PAPER)

NOMENCLATURE

C_f = specific heat of fiber (0.32), cal./(g.)(°C)

C_w = specific heat of water, cal./(g)(°C)

k = apparent thermal conductivity, cal./(sec.)(sq.cm.)(°C/cm)

L = thickness of the whole sheet, cm.

m = basis weight (from open surface to the plane under consideration) g./sq.cm.

$\bar{m}$ = location as defined by the ration m/M, dimensionless

M = basis weight of the whole sheet, g/sq.cm.

Q = heat transferred across a unit area of the hot surface, cal./sq.cm.

Q_f = heat absorbed by fiber per unit area, cal./sq.cm.

Q_v = heat for evaporation of moisture per unit area, cal./sq.cm.

Q_w = heat absorbed by water per unit area, cal./sq.cm.

t = temperature, °C.

w = cumulative moisture content (from open surface to the plane under consideration), g./sq.cm.

$\bar{w}$ = cumulative moisture content as defined by the ratio w/M, dimensionless

W = cumulative moisture content of the whole sheet, g./sq.cm.

x = distance from open surface, cm.

λ = latent heat of vaporization of water, cal./g.

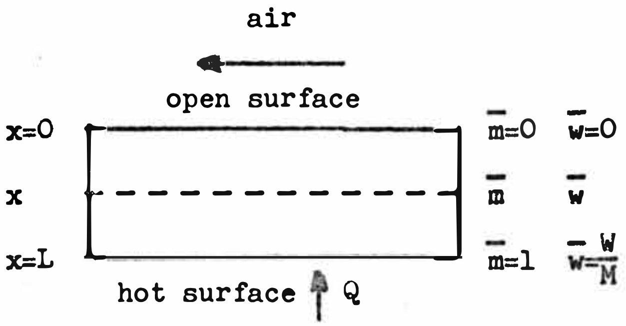
ρ_f = apparent density of fiber in sheet as defined by the derivative dm/dx, g./cc.

ρ_w = apparent density of water in sheet as defined by the partial derivative w/ x, g./cc.

θ = drying time, sec.

Considering a deformable fibrous system one would expect a good prediction of the conduction contribution to heat flow to be acquired from the parallel phase distribution equation. The solid-fluid conductivity ratios in the wood fiber-water-air system are low, but more importantly, the fiber-fiber contact areas are significant and would greatly enhance the heat flow in the fiber network. The internal geometry of both the fiber and the fiber network are complex but the use of the phase distribution equation may pro-

vide an adequate estimate of the conductivity.



Relative Bwt., $\bar{m} = \frac{m}{M} = \frac{x}{L}$

Cumulative Moisture, $\bar{w} = \frac{w}{M}$

L = thickness of whole sheet

x = distance from open surface

Figure 4

Other work done in the area of heat transfer during drying by Han and Ulmanen has led to calculations of the thermal conductivity through evaluation of local conditions on the course of drying.

From a simple viewpoint, we may consider that a quantity of heat transferred across the hot surface during time θ is used up in three ways. A major part of heat is consumed as the latent heat of vaporization. A second part is absorbed by fiber and a third part by water as sensible heat. A very small amount of heat lost to the air stream by conduction and radiation is neglected. Using the boundary conditions specified in Figure 4 and taking a unit area perpendicular to the heat flow we have:

Heat conducted across the hot surface:

$$Q = \int_{\theta_1}^{\theta_2} k \left.\frac{dt}{dx}\right|_{\text{at } x=L} d\theta = \int_{\theta_1}^{\theta_2} \frac{k}{L} \left.\frac{dt}{dm}\right|_{\text{at } \bar{m}=1} d\theta$$

Heat of vaporization:

$$Q_v = \int_{\theta_1}^{\theta_2} - \left.\frac{dw}{d\theta}\right|_{\text{at } \bar{m}=1} d\theta = \int_{\theta_1}^{\theta_2} -\lambda M \left.\frac{d\bar{w}}{d\theta}\right|_{\text{at } \bar{m}=1} d\theta$$

Heat absorbed by fiber:

$$Qf = \int_0^L C_f \rho_f (t\theta_2 - t\theta_1)dx = \int_0^1 C_f M(t\theta_2 - t\theta_1)d\bar{m}$$

Heat absorbed by water:

$$Qw = \int_0^L C_w \rho_w (t\theta_2 - t\theta_1)dx = \int_0^{w/m} C_w M(t\theta_2 - t\theta_1)d\bar{w}$$

Where ρf and ρw are apparent densities defined by:

$$\rho f = \frac{dm}{dx} \quad \rho w = \frac{\partial w}{\partial x}$$

since Q = Qv + Qf + Qw we abstain a heat balance expressed in terms of the heat transfer variables.

eq. 2)

$$\int_{\theta_1}^{\theta_2} \frac{k}{L} \frac{dt}{d\bar{m}}_{\bar{m}=1} d\theta = \int_{\theta_1}^{\theta_2} -\lambda M \frac{d\bar{w}}{d\theta}_{at\ \bar{m}=1} d\theta + \int_0^1 Cfm$$

$$(t\theta_2 - t\theta_1)\ d\bar{m} + \int_0^{W/M} CwM(t\theta_2 - t\theta_1)\ d\bar{w}$$

The left-hand integral cannot be evaluated because we do not have a knowledge of apparent thermal conductivity k as a function of drying time θ. By taking partial derivatives of equation (2) with respect to θ_2, we transform it into a rate equation:

eq. 3)

$$\frac{k}{LM} \frac{dt}{d\bar{m}} \text{ at } \bar{m} = 1 = -\lambda\left(\frac{d\bar{w}}{d\theta}\right)_{at\ \bar{m}=1} = Cf \int_0^1 \left(\frac{\partial t}{\partial \theta}\right)_{\bar{m}} d\bar{m} + Cw \int_0^{W/M}$$

$$\left(\frac{\partial t}{\partial \theta}\right)_{\bar{w}} d\bar{w} + Cw\ (t\theta_2 - t\theta_1)\left(\frac{d\bar{w}}{d\theta}\right)_{at\ \bar{m}=1}$$

It will be noted that the upper limit of W/M of the last integral of

equation (2) is a function of Θ, and its partial derivative results in the last term of equation (3).

In the final equation, all quantities except k can be evaluated from experimental data. At each chosen time (Θ_2), we can determine a value for k which corresponds to a definate moisture content at the hot surface of the sheet. In this way a relationship between apparent thermal conductivity and moisture content is established for the particular sheet. The results obtained by Han and Ulmanen are shown in Figure 5.

The curve is of an "S" shape. In the high moisture region the apparent conductivity is of the order of magnitude as that of water which has a k value of 0.0016 cal/(sec)(cm^2) or 0.39 BTU/(hr)(ft)(°F) at a temperature of 80°C or 176°F. In the intermediate range of moisture, k drops sharply. This may be attributed to the entrance of air into the sheet. When moisture removal exceeds sheet shrinkage, an increase in air voids in the sheet is expected along with a decrease in conductivity. Finally, in the very low moisture range, the conductivity approaches a fixed value of approximately 0.039 BTU/(hr)(ft)(°F). According to literature (2), the conductivity of paper is about).075 and a lap of wood pulp about 0.028. Since this experimental data used lightly beaten sulphite pulp the results seem to correlate well.

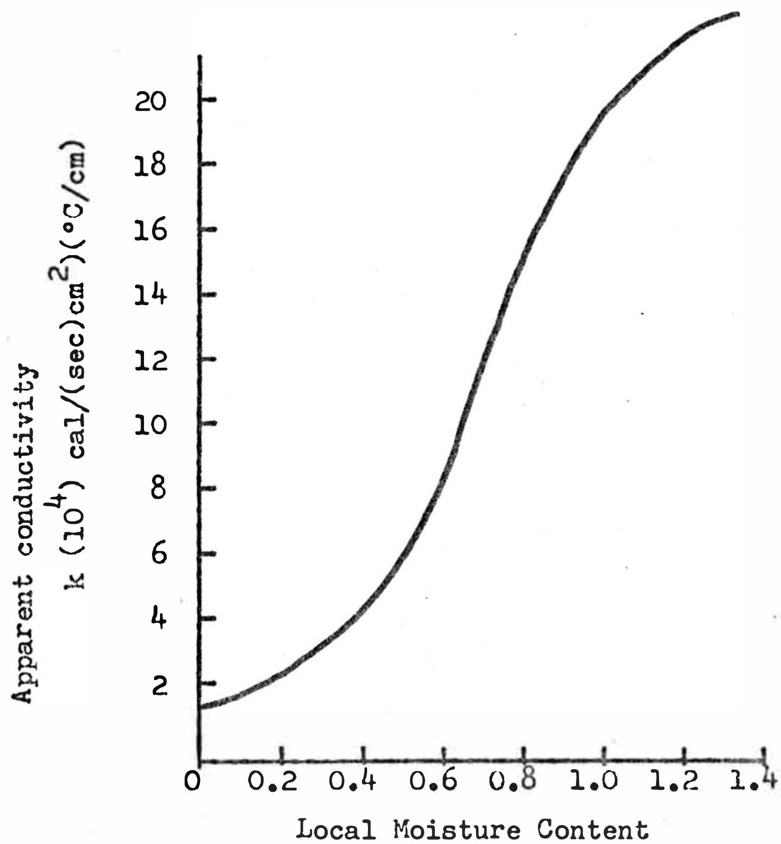


Figure 5

EXPERIMENTAL OBJECTIVES

Experimental proceedings were directed towards construction of an instrumental device to determine experimentally the conductivity of paper as a function of moisture content.

Two drastically different pulp runs were made to determine the effects of pulp type and fibre lenght on conductivity. Also, porosity measurements were attempted to enable the calculation of the thermal conductivity of solid pure cellulose using Equation 1, the model representing the maximum conductivity of pourous structures.

EXPERIMENTAL PROCEDURE

MATERIALS -

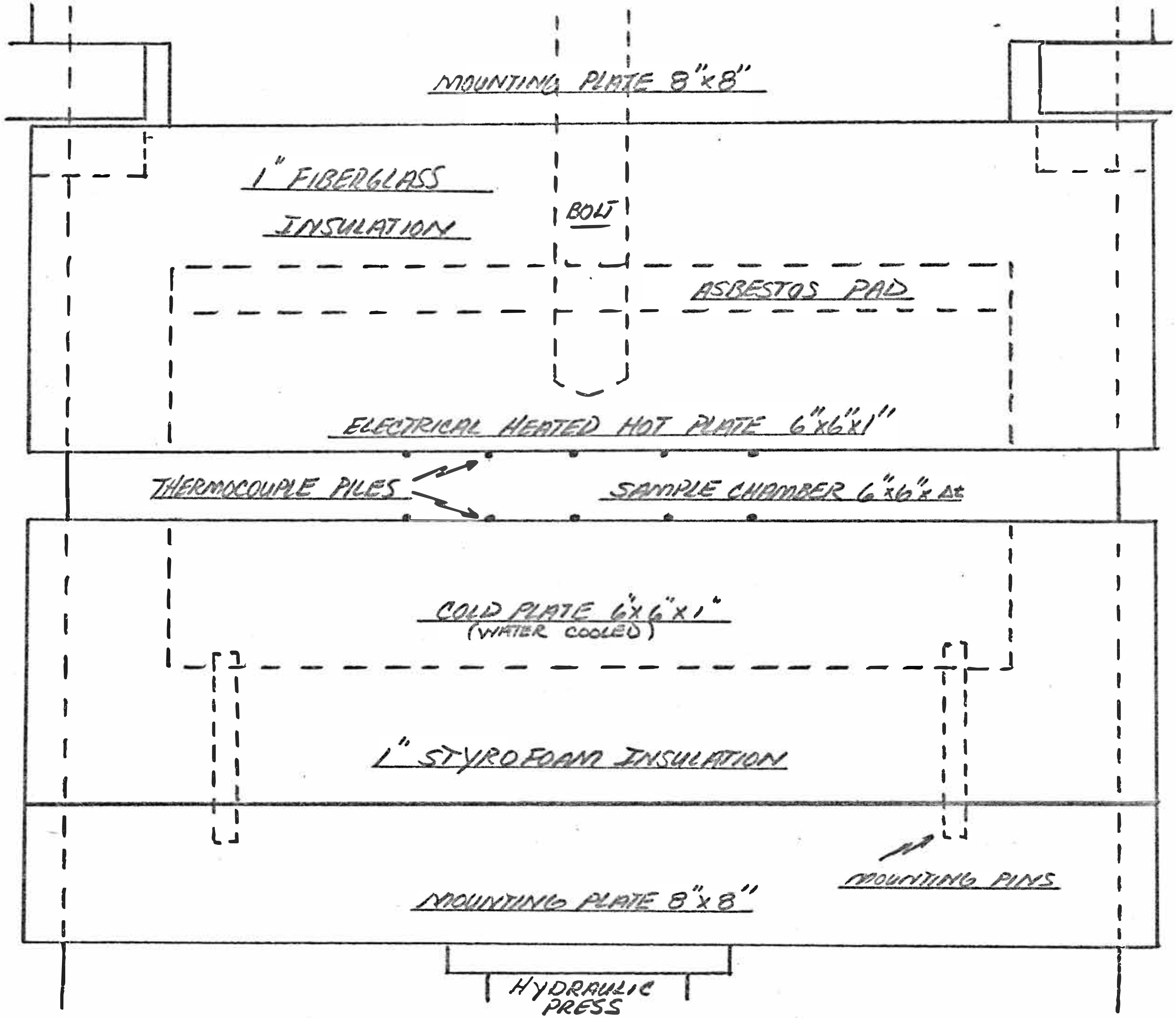
- Softwood Kraft pulp lap produced by the Rayonier Co. (Virginia)
- Hardwood Kraft pulp lap produced by the Weyerhaeuser Company. (West coast)
- Styrofoam and glass wool insulation.
- Chromel-Alumel thermocouple wire.

EQUIPMENT -

- Leeds & Northrup mili-volt potentiomenter.
- Two (0-100° ± 0.05°) centrigrade mercury thermoters.
- Water bath tray and bottle.
- Hydraulic laminating press equipped with "Meehanite" plates capable of being electrically heated or circulatorily liquid cooled, (produced by the Fred S. Carver Co.).
- Voltage regulator for constant (non-cyclic) voltage input to heating plate.
- Noble & Wood hand sheet mould and press.

APPARATUS DESCRIPTION -

The apparatus is composed of two parallel plates, the upper plate being heated electrically and the lower being cooled by constant water flow. Temperature measurements were made using chromel-alumel thermocouple piles with five sensing elements each. Heat loss due to radiation and convection will be reduced by using insulation around the plates and by directing the heat



MOUNTING PLATE 8"x8"
1" FIBERGLASS INSULATION
BOLT
ASBESTOS PAD
ELECTRICAL HEATED HOT PLATE 6"x6"x1"
THERMOCOUPLE PILES
SAMPLE CHAMBER 6"x6"x Δt
COLD PLATE 6"x6"x1"
(WATER COOLED)
1" STYROFOAM INSULATION
MOUNTING PINS
MOUNTING PLATE 8"x8"
HYDRAULIC PRESS

flow in a downward direction. Thermocouple readout was made with the use of a potentiometer. A constant pressure of approximately 1 psi is applied to the sample by the hot plate.

PROCEDURE

SAMPLE PREPARATION - heat samples were formed on a Noble & Wood sheet mold. Dry lapped pulp was dispersed in water with a mixer. Maximum thickness sheets, which still provide adequate drainage, were formed and pressed. The sample was then cut down to 6" x 6".

The potentiometer was referenced to the cold plate after 10 minutes of constant water flow. The sample was placed between the hot and cold plates. The cold plate is raised until the hot plate is raised off its stops. The volgage regulator is used to apply power to the heating elements of the hot plate. The temperature was raised to approximately 100°F, measured by the potentiometer, and then is leveled off by adjustment of the regulator to obtain a constant temperature and thus a constant heat flow. Average time to reach equilbrium was approximately 30 minutes. At equilibrium, hot and cold plate temperature measurements were recorded along with cooling water temperatures into and out of the cooling plate. The cooling water temperatures were used to calculate the heat flow through the sample using the equation: $Q = mC_p \Delta T$. The sample was then weighed and dried. A second weighing was performed for moisture calculations and the caliper of the sheet measured.

A special sample preparation technique was used when making porosity measurements. As before, the sample was formed and pressed and then rewetted to a fully saturated condition. It was then weighed, pressed again, reweighed and cut to size.

EXPERIMENTAL RESULTS

Hardwood Kraft

Twenty trials were run using Weyerhaeuser (West coast) hardwood Kraft pulp. The resulting conductivity values are plotted as a function of moisture content as shown in Figure 7. Raw data are tabulated in Table I.

Statistical analysis of the results are presented in Table II with a brief explanation of the analysis.

Softwood Kraft

Twenty trials were run using Rayonier (Virginia) softwood Kraft pulp. The resulting conductivity values are plotted as a function of moisture content as shown in Fibure 8. Raw data are tabulated in Table I.

Statistical analysis of the results are presented in Table II with a brief explanation of the analysis.

Softwood Kraft (Porosity Runs)

Eight trials were run using Rayonier softwood Kraft pulp. The resulting conductivity values are plotted as a function of moisture content as shown in Figure 8 being represented by triangles. Raw data are tabulated in Table I. Thermal conductivity as a function of porosity is presented in Figure 9.

Calculation of ks, the conductivity of solid pure cellulose from the three phase conduction model Table I,

$$ka = (1-\epsilon)ks + \epsilon S k_{\ell} + \epsilon(1-S)kg$$

where: ka = apparent conductivity of system

ks = thermal conductivity of solid phase

k_{ℓ} = thermal conductivity of liquid phase = 0.36" @ 110°F

kg = thermal conductivity of gas phase = 0.157 BTU/hr @ 110°F

ϵ = void fraction or porosity

S = average bed saturation, moisture content

is presented in Table I.

TABLE I

MOISTURE	(k)	MOISTURE	(k)	MOISTURE	(k)	POROSITY	(k)
48	0.098	26	0.080	51	0.097	0.77	0.265
76	0.300	40	0.103	41	0.065	0.81	0.498
71	0.220	43	0.073	36	0.057	0.82	0.576
78	0.350	43	0.191	74	0.288	0.48	0.226
82	0.265	29	0.089	52	0.076	0.69	0.133
52	0.050	41	0.128	32	0.049	0.81	0.579
73	0.155	49	0.133	69	0.136	0.63	0.110
45	0.041	11	0.042	65	0.128	0.65	0.049
78	0.290	7	0.033				
76	0.259	48	0.141				
49	0.128	53	0.175				
43	0.122	56	0.249				
56	0.166	55	0.166				
37	0.110	66	0.205				
40	0.105	79	0.373				
8	0.039	64	0.267				
21	0.046	78	0.317				
35	0.092	42	0.105				
25	0.058	80	0.318				
37	0.071	43	0.097				

WHERE:

$$\text{MOISTURE} = \%\ \text{moisture} = \frac{\text{wet weight} - \text{dry weight}}{\text{wet weight}} \times 100$$

k = THERMAL CONDUCTIVITY = BTU/hr - ft - °F

$$\text{POROSITY} = \frac{\text{void volume}}{\text{total volume}} = \frac{\text{total mass} - \text{pressed mass}}{\text{total mass}}$$

FIGURE 7

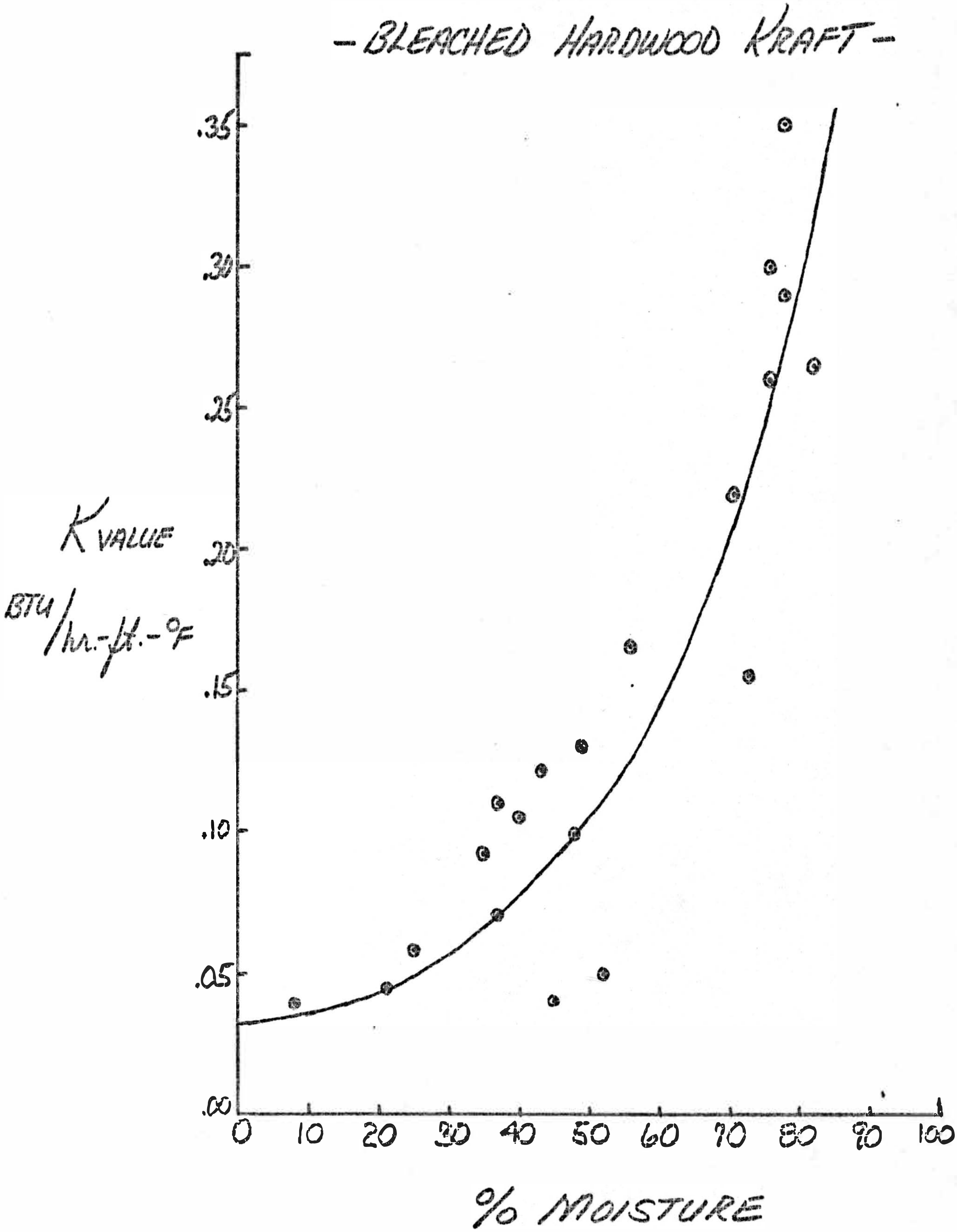
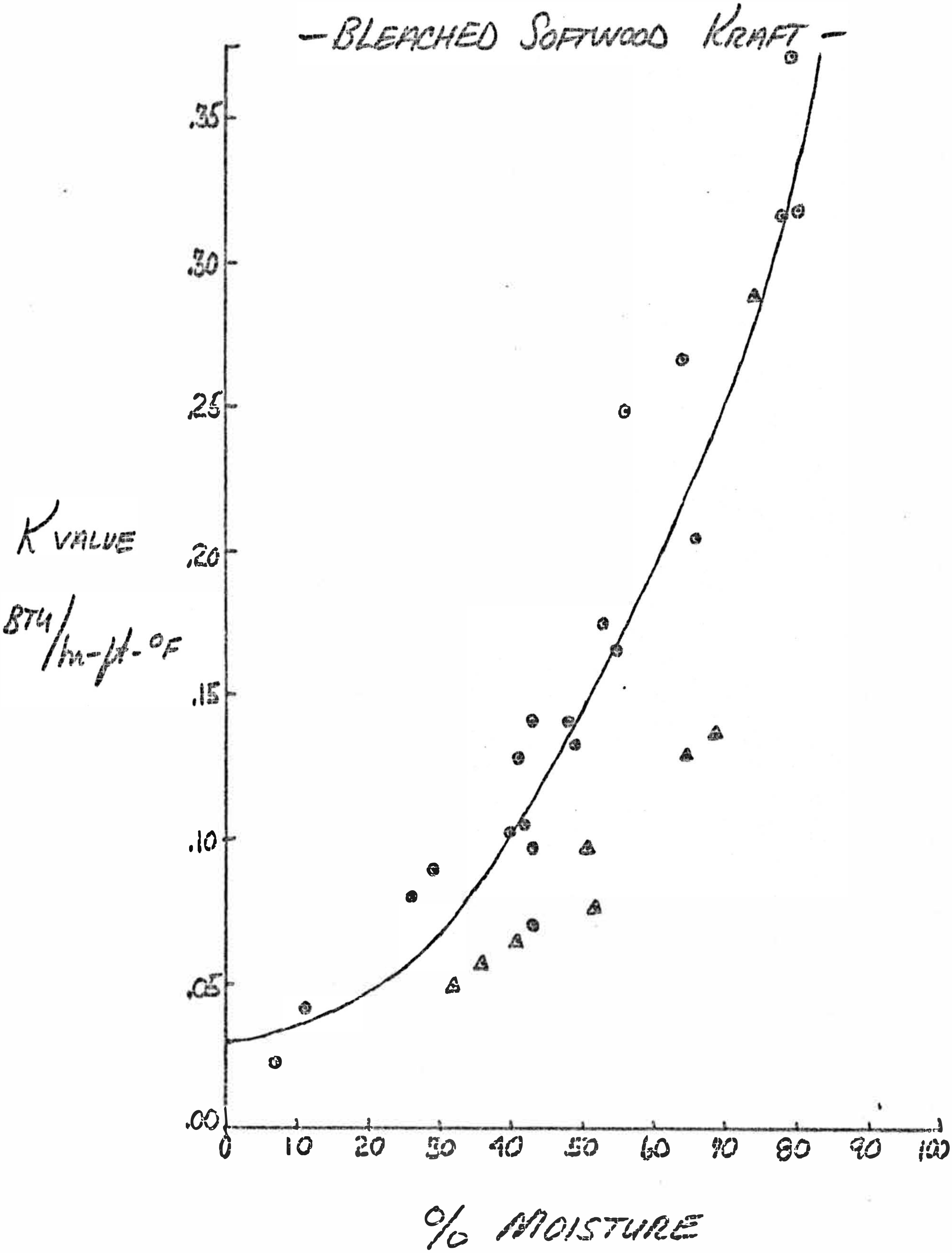
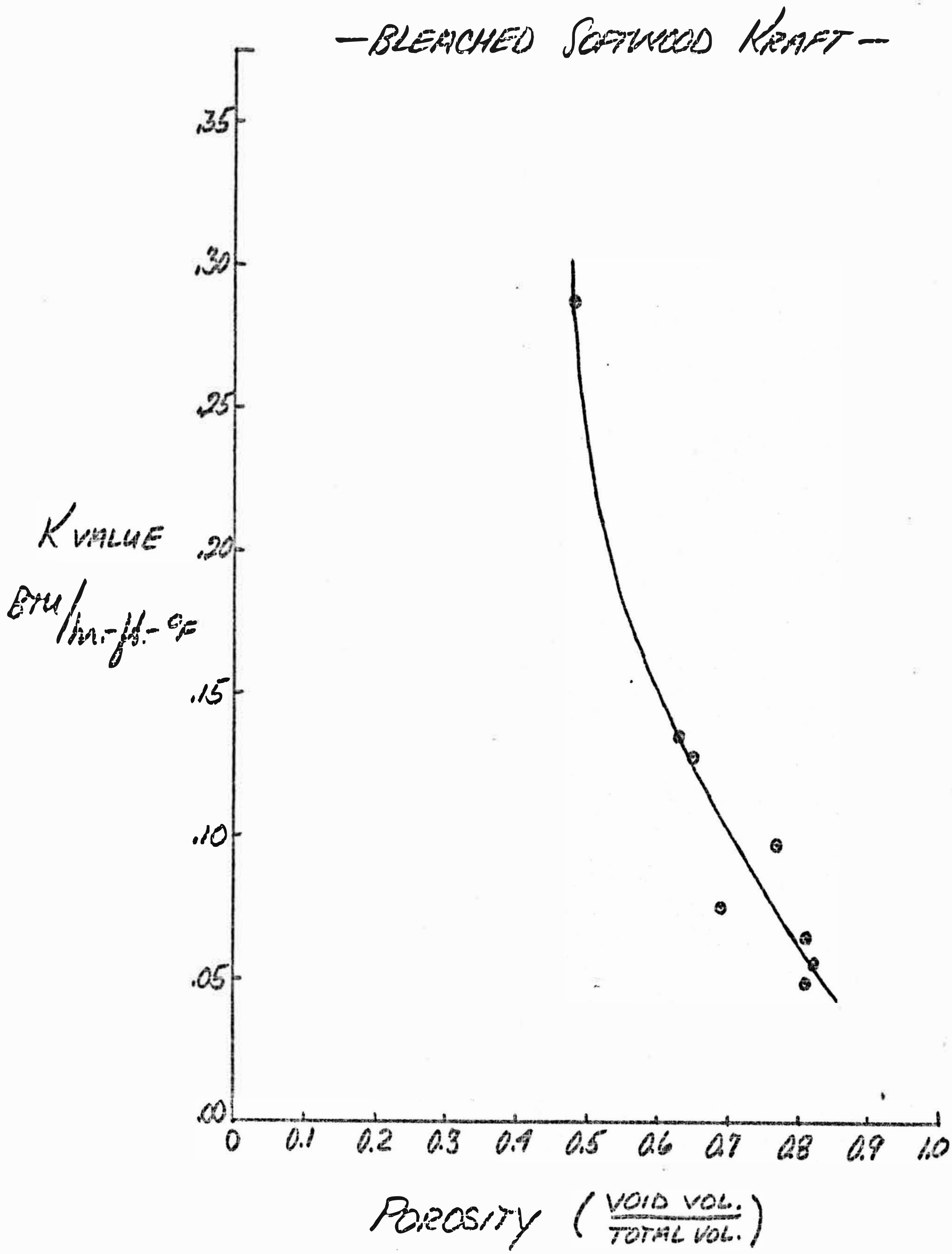

- BLEACHED HARDWOOD KRAFT -
K VALUE
BTU/hr.-ft.-°F
.35
.30
.25
.20
.15
.10
.05
.00
0
10
20
30
40
50
60
70
80
90
100
% MOISTURE

FIGURE 8



-BLEACHED SOFTWOOD KRAFT-
K VALUE
BTU/hr-ft-°F
.35
.30
.25
.20
.15
.10
.05
.00
0
10
20
30
40
50
60
70
80
90
100
% MOISTURE

FIGURE 9



—BLEACHED SOFTWOOD KRAFT—
K VALUE
BTU/hr.-ft.-°F
.35
.30
.25
.20
.15
.10
.05
.00
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
POROSITY (VOID VOL. / TOTAL VOL.)

TABLE II

A multiple linear regression was performed on the moisture-vs-lnk value to prove the non-linear relationship of the data. The k value was transformed into the lnk state to provide a type of curve fitting process. Linear equations were obtained from the analysis and were plotted along with a 95% confidence interval about them. The estimated constant term refers to the Y axis intercept and the regression coefficient refers to the slope of the line.

The coefficient of determination indicates what proportion of the total variation in the response Y (k) is explained by the fitted regression model. The higher the value, usually expressed in percent data explained by the model, the more satisfactory the model becomes.

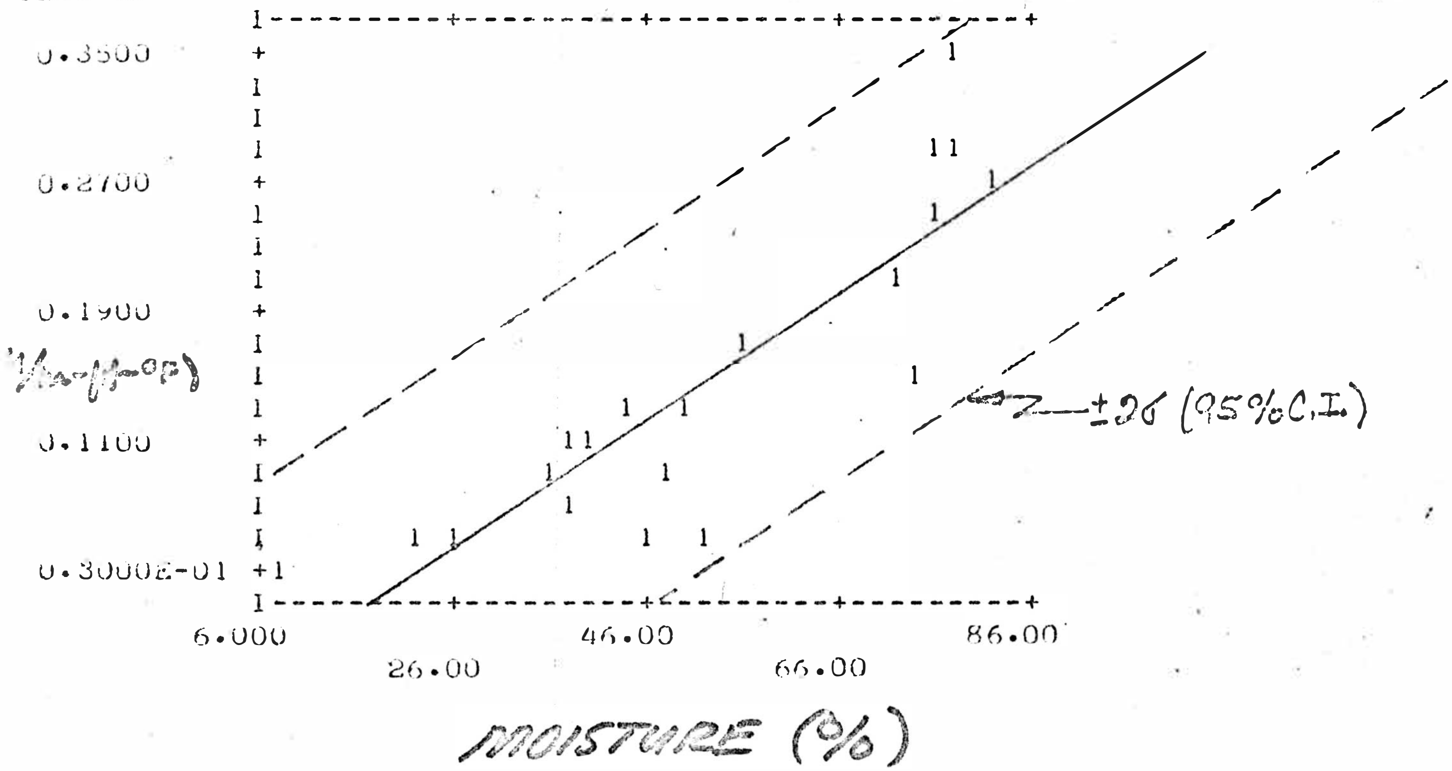
The F value or the regression sum of squares is used to give some indication concerning whether or not the model is an adequate explanation of the true situation. The larger the F value, the more adequate the model becomes.

In looking at the regression analysis performed on the hardwood Kraft, an increase is observed in both the determination coefficient and the F value when going from the standard k value to the transformed (lnk) state. This meaning that the transformed state better fits the regression model, or in other words, yield a less deviant straight line, proving that the data is more non-linear than linear in its standard state. This in turn confirms previous results of k values lending to non-linear data when plotted as a function of moisture content.

The same results are also obtained with the softwood regression, only the increase is much greater, meaning the model is better satisfied.

HARDWOOD KRAFT

PLOT OF VARIABLE: 1 (HORIZ.) VS VARIABLE: 2 (VERT.)



***** MULTIPLE LINEAR REGRESSION *****

SAMPLE SIZE 20
DEPENDENT VARIABLE: 2
INDEPENDENT VARIABLES: 1

COEFFICIENT OF DETERMINATION 0.76145
MULTIPLE CORR COEFF. 0.87261

$K = 0.004 \cdot MOIST. - 0.056$

ESTIMATED CONSTANT TERM -0.55752287E-01
STANDARD ERROR OF ESTIMATE = 0.49247886E-01

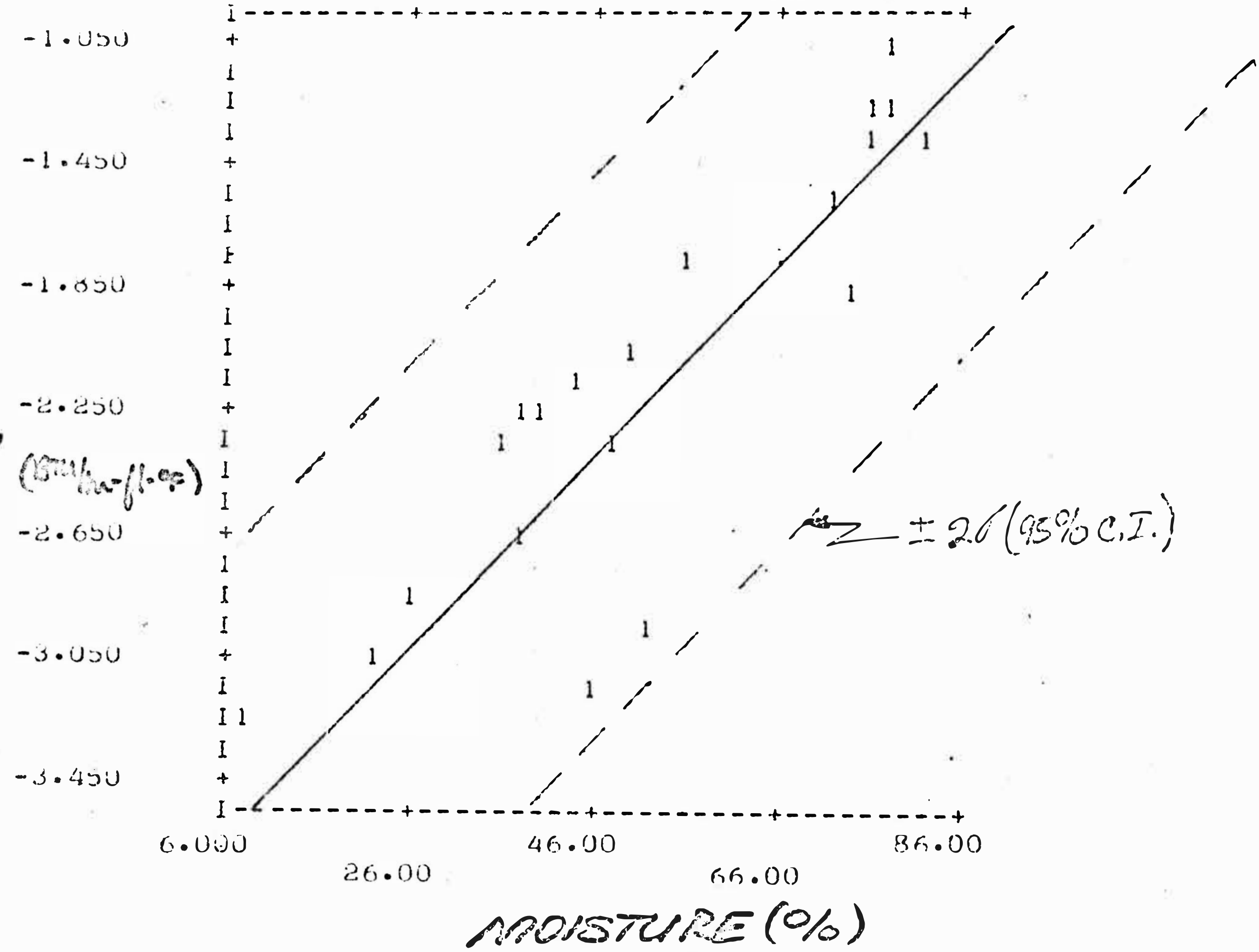
ANALYSIS OF VARIANCE
FOR THE REGRESSION

SOURCE OF VARIATION	DF	S. SQ.	M.S.	F	PROB
REGRESSION	1	0.139353	.139353	57.46	0.0000
RESIDUALS	18	0.436564E-01	.242535E-02		
TOTAL	19	0.183010			

VAR.	REGRESSION COEFFICIENT	S. E. OF REG. COEF.	F-VALUE DF (1, 18)	PROB	CORR.COEF. WITH 2
1	0.3961209E-02	.5226E-03	57.46	0.0000	0.8726

HARDWOOD KRAFT

PLOT OF VARIABLE: 1 (HORIZ.) VS VARIABLE: LOG2 (VERT.)



***** MULTIPLE LINEAR REGRESSION *****

SAMPLE SIZE 20
DEPENDENT VARIABLE: LOG2
INDEPENDENT VARIABLES: 1

COEFFICIENT OF DETERMINATION 0.76624
MULTIPLE CORR COEFF. 0.87535

ESTIMATED CONSTANT TERM -3.6135010
STANDARD ERROR OF ESTIMATE 0.35246358

$\ln K = 0.029 \cdot \text{MOIST.} - 3.61$

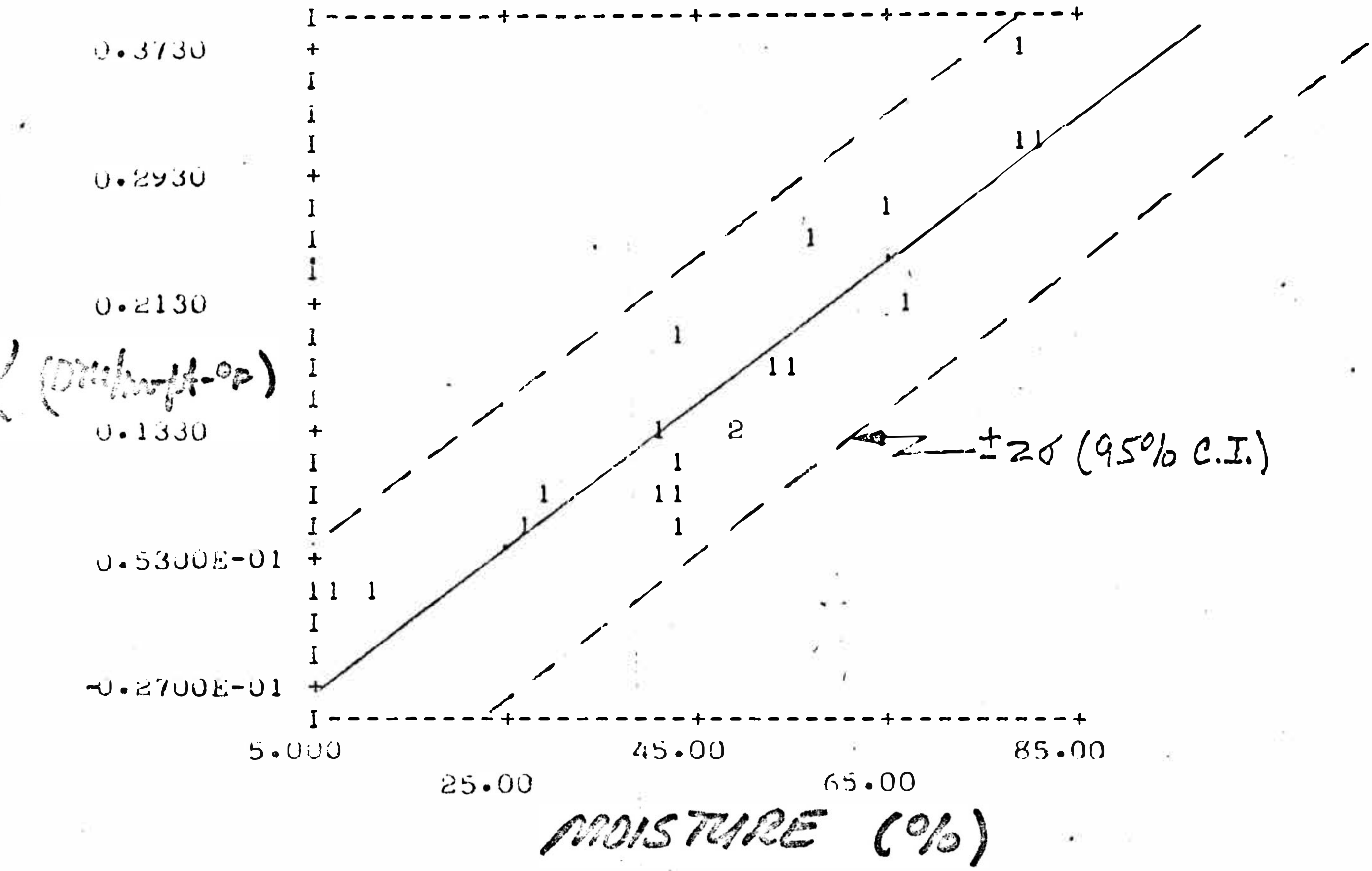
ANALYSIS OF VARIANCE
FOR THE REGRESSION

SOURCE OF VARIATION	DF	S. SQ.	M.S.	F	PROB
REGRESSION	1	7.32969	7.32969	59.00	0.0000
RESIDUALS	18	2.23615	.124231		
TOTAL	19	9.56584			

NO.	REGRESSION COEFFICIENT	S. E. OF REG. COEF.	F-VALUE DF (1, 18)	PROB	CORR.COEF. WITH LOG2
1	0.28726413E-01	.3740E-02	59.00	0.0000	0.8753

SOFTWOOD KRAFT

PLOT OF VARIABLE: 3 (HORIZ.) VS VARIABLE: 4 (VERT.)



***** MULTIPLE LINEAR REGRESSION *****

SAMPLE SIZE 20
DEPENDENT VARIABLE: 4
INDEPENDENT VARIABLES: 3

COEFFICIENT OF DETERMINATION 0.83857
MULTIPLE CORR COEFF. 0.91573

K = 0.0044·MOIST.−0.046

ESTIMATED CONSTANT TERM -0.45652755E-01
STANDARD ERROR OF ESTIMATE = 0.40028870E-01

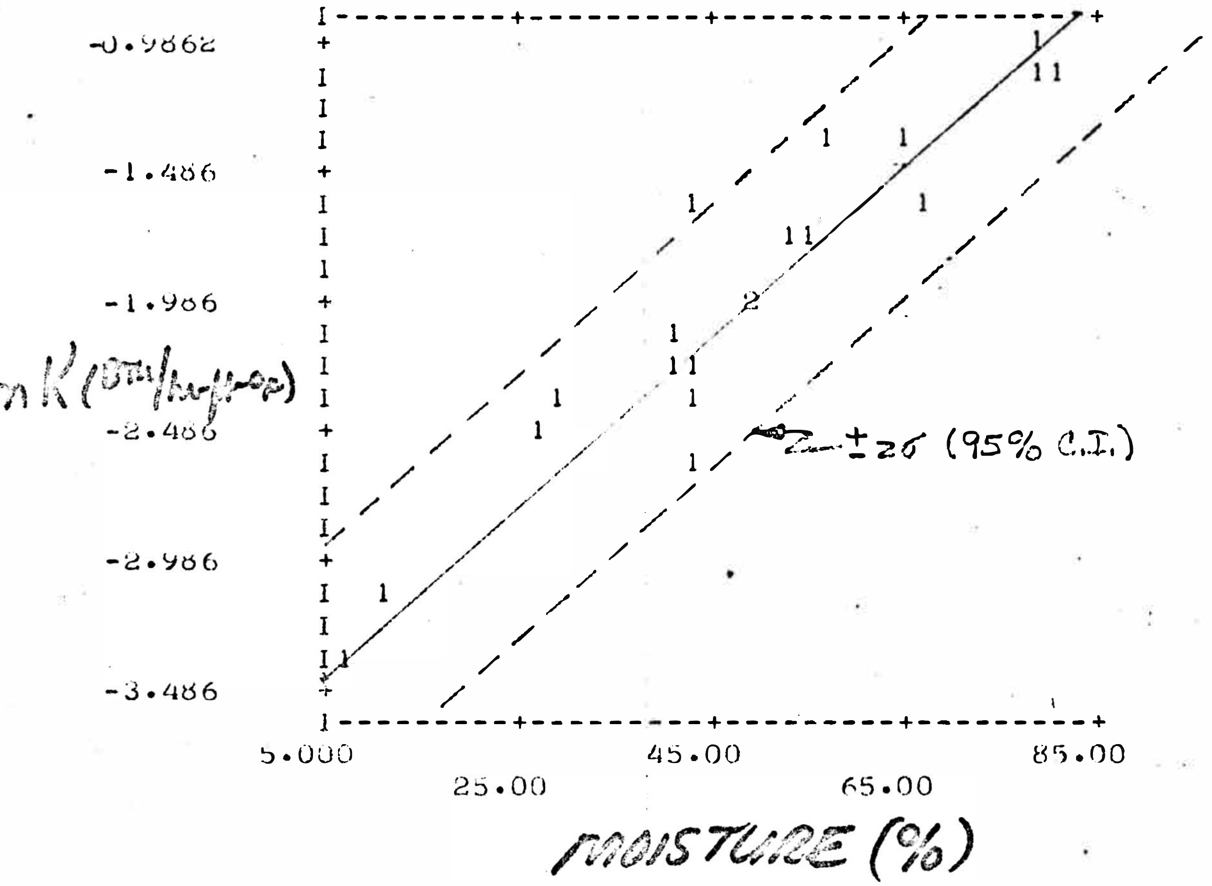
ANALYSIS OF VARIANCE
FOR THE REGRESSION

SOURCE OF VARIATION	DF	S. SQ.	M.S.	F	PROB
REGRESSION	1	0.149816	.149816	93.50	0.0000
RESIDUALS	18	0.288416E-01	.160231E-02		
TOTAL	19	0.178658			

NO.	REGRESSION COEFFICIENT	S. E. OF REG. COEF.	F-VALUE DF (1, 18)	PROB	CORR.COEF. WITH 4
3	0.44050945E-02	.4556E-03	93.50	0.0000	0.9157

SOFTWOOD KRAFT

PLOT OF VARIABLE: 3 (HORIZ.) VS VARIABLE: LOG4 (VERT.)



***** MULTIPLE LINEAR REGRESSION *****

SAMPLE SIZE 20
DEPENDENT VARIABLE: LOG4
INDEPENDENT VARIABLES: 3

COEFFICIENT OF DETERMINATION 0.89972
MULTIPLE CORR COEFF. 0.94853

ESTIMATED CONSTANT TERM -3.4598111
STANDARD ERROR OF ESTIMATE 0.21323472

ln K = 0.031·MOIST. − 3.46

ANALYSIS OF VARIANCE
FOR THE REGRESSION

SOURCE OF VARIATION	DF	S. SQ.	M.S.	F	PROB
REGRESSION	1	7.34292	7.34292	161.5	0.0000
RESIDUALS	18	0.818443	.454690E-01		
TOTAL	19	8.16136			

VAR.	REGRESSION COEFFICIENT	S. E. OF REG. COEF.	F-VALUE DF (1, 18)	PROB	CORR.COEF. WITH LOG4
3	0.30839?1E-01	.8427E-02	161.5	0.0000	0.9485

DISCUSSION OF RESULTS

Data obtained in all cases was scattered somewhat more than expected. However, the non-linear trend can clearly be seen by the sketched curve on the graphs. Points taken from these curves correlate well to the previously obtained results by Han & Ulmanen and by Lau & Pratte.

Kearcher (Hardwood Kraft)		Lau & Pratte (Newsprint)	
MOISTURE	k value	MOISTURE	k value
20	0.045	20	0.040
40	0.075	40	0.070
60	0.145	60	0.012
80	0.350	80	0.280

There was little difference in the data obtained from the hardwood Kraft versus the softwood Kraft pulps. The softwood Kraft k values were somewhat higher in the mid moisture regions. Also, the close correlation with Lau & Pratte's newsprint data show that the pulp furnish is not a significant variable in the conductivity of the wet paper mat.

The k_s (conductivity of solid fraction) value calculated using McMaster's three-phase parallel prediction equation show that the conductivity of a pure cellulose solid may be in the area of 0.317 BTU/hr-ft-°F with a standard deviation of $\pm$.188. This would be in the same region, for example, as that of brick, pyrex and fused quartz. The large standard deviation also indicates the variability in the data obtained.

CONCLUSIONS

As metioned earlier, data obtained was scattered more than expected. This is believed to be the result of inadequate engineering in the design of the experimental apparatus. Also despite all precautions and sophistication in the design of an apparatus, it is never possible to completely suppress some sources of error that require corrections to measured quantities. Two such sources of error, namely radiation and convection, are inseparably associated with all measurements on fluid and fluid containing substances, irrespective of the type of apparatus employed. Both phenomena effect the energy transfer through the fluid film.

Analysis of tabulated results show that the type of furnish used in the paper mat is not a prime variable in its conductivity behavior. Prime variables would include, moisture content, applied pressure and sheet porosity.

RECOMMENDATIONS

Areas of further study should include:

1) Design aspects of the experimental apparatus and how to minimize experimental error.

2) Further study into the drying machanism and how vapor diffusivity and water migration effect experimental results.

3) Further study into the effects of film length and species on conductive properties.

4) Further investigation into dryer length prediction models based on conductivity parameters.

LITERATURE CITED

1) Gunnar, G.N. "Drying of Paper and Paperboard", New York, Lockwood, pp. 24-27 & 50.

2) Han, S.T., and Ulmanen, T., TAPPI 41: 185 (April, 1958)

3) McMaster, D.G., TAPPI 47: 796 (Dec., 1964)

4) Han, S.T., Pulp and Paper Mag. of Canada 65, No.11: p.537 (Dec., 1964)

5) Montgomery, A.E., Technical Assoc. Papers 29th series: p. 525 (1946)

6) Lau, Y.L., and Pratte, B.D., "Measurements of Thermal Conductivity of Wet Paper", National Research Council of Canada, Div. Mech. Eng. Hydraulics Sect. Rep. LTR HY8: (Dec., 1969)

7) McCabe, W.L., and Smith, J.C., "Unit Operations of Chemical Engineering" 3rd ed., McGraw Hill, 1976

8) Tye, R.P., "Thermal Conductivities", Academic Press Inc., New York 1969

9) Ho, C.Y., "Thermal Conductivity", Plenum Press, New York, 1969