THE UNIVERSITY OF MANITOBA

THERMAL CONDUCTIVITY OF SPRING WHEAT AT LOW TEMPERATURES

by

SUBHASH CHANDRA

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF

MASTER OF SCIENCE

DEPARTMENT OF AGRICULTURAL ENGINEERING

WINNIPEG, MANITOBA

MAY 1971

A B S T R A C T

THERMAL CONDUCTIVITY OF SPRING WHEAT AT LOW TEMPERATURES

By Subhash Chandra

Thermal conductivities of different varieties of wheat have been determined by various methods but the reported information is usually limited to a narrow range of temperature. Although most surplus spring wheat in Canada and northern United States is stored under temperate climatic conditions where winter temperatures may be as low as -40C, thermal conductivities have not been determined below +20C. A knowledge of thermal conductivity is necessary to predict grain temperatures in grain storages. Predicted grain temperatures can be used to design improved storage structures to maintain the quality of grain. Thermal conductivity of grain is also important in the analysis of other heat transfer processes, such as drying, aeration and cooling of the grain. The purpose of this research project was to measure the thermal conductivity of hard red spring wheat containing 4 to 23% moisture within the temperature range -27C to +20C.

A transient heat flow method with a line heat source was used to determine the thermal conductivity of wheat. The transient heat flow method of determining thermal conductivity minimizes the problem of moisture migration in the grain and the time required for a test is also small.

The thermalconductivity of wheat can be expressed as a function of moisture content. The coefficients of correlation were considerably less at temperatures below -8C than at higher temperatures indicating that the linear relationship between thermal conductivity and moisture content is not as strong at temperatures below -8C. Moisture present in

the wheat appeared to be affecting thermal conductivity less at low temperatures than at high temperatures. Thermal conductivity for a moisture content range of 4.4% to 22.5% varied from 0.000344 to 0.000407 cal C^{-1} cm^{-1} sec^{-1} at 20C, 0.000352 to 0.000391 cal C^{-1} cm^{-1} sec^{-1} at 5C, 0.000336 to 0.000396 cal C^{-1} cm^{-1} sec^{-1} at 1C, 0.000334 to 0.000397 cal C^{-1} cm^{-1} sec^{-1} at -6C, 0.000329 to 0.000389 cal C^{-1} cm^{-1} sec^{-1} at -17C and 0.000330 to 0.000385 cal C^{-1} cm^{-1} sec^{-1} at -27C. It was also found that the thermal conductivity of mouldy wheat at 19.3% moisture content was as much as 15% below that of uninfected wheat at the same moisture content. The density of wheat was found to be more at -6C than at +20C and the increase in the density was more at higher moisture contents than at lower moisture levels.

ACKNOWLEDGEMENTS

The author wishes to express his deep appreciation to Dr. W.E. Muir, Agricultural Engineering Department, for the advice, assistance and encouragement he has offered throughout the term of this research project. It is to Dr. W.E. Muir as well that the author is indebted for the original suggestion of this topic and for various suggestions on problems that arose in the experimental part of this project.

The author is also very grateful to Dr. G.E. Sims, Mechanical Engineering Department and Dr. J.S. Townsend, Agricultural Engineering Department for many fruitful discussions. Acknowledgement is extended to Dr. G.E. Laliberte, Head of the Agricultural Engineering Department, for his interest and encouragement.

The assistance of the technical staff of the Agricultural Engineering Department is gratefully acknowledged.

The author also wishes to acknowledge the financial support of the National Research Council of Canada and the Canada Department of Agriculture.

Last but not least, the author is particularly appreciative of the tireless efforts of Miss A. M. Korol for careful and cheerful typing of this manuscript.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

α	thermal diffusivity of the material, $cm^2\ sec^{-1}$
e	base of natural logarithm
k	thermal conductivity of the material, cal $C^{-1}\ cm^{-1}\ sec^{-1}$
M	moisture content, % wet basis
n	$1/2\ (\alpha\theta)^{-1/2}$, cm^{-1}
Q	heat input per unit time and length of heat source, cal $cm^{-1}\ sec^{-1}$
R	radius from the heat source, cm
r	correlation coefficient
s	standard deviation
t	temperature at radius R,C
t_1	temperature at time θ_1, C
t_2	temperature at time θ_2, C
θ	time, sec
v	voltage output, mv

I. INTRODUCTION

Wheat is stored for long periods of time in Canada, northern United States and other countries. The rate of deterioration of this grain is controlled by many factors, of which grain temperature is one of the more important. To rationally design grain storages to maintain grain quality, grain temperatures must be predictable. Temperature changes in a grain bin due to external or internal temperature changes may be calculated by the use of heat transfer equations. The use of these equations necessitates a knowledge of many physical factors. One of the physical factors required is the thermal conductivity of grain. The thermal conductivity of grain is also important for the analysis of other heat transfer processes, such as aeration, drying and cooling of the grain.

Thermal properties of hygroscopic materials are affected by temperature and moisture content. The thermal conductivity of cereal grains is a linear function of moisture content within the moisture range of 0 to 30% and the temperature range of 20 to 48C (Bakke and Stiles, 1935; Moote, 1953; Kazarian and Hall, 1965; Dua and Ojha, 1969; Wratten et al., 1969). Although most surplus spring wheat is stored under temperate climatic conditions where environmental temperatures may be as low as -40C, thermal conductivities have not been determined below +20C. Therefore, the objective of this investigation was to determine the effect of moisture content on thermal conductivity of hard red spring wheat at low temperatures. The wheat used, had a moisture content of 4 to 23% wet basis. The tests were conducted in the temperature range -27C to +20C.

2. REVIEW OF LITERATURE

Many earlier investigators have determined the thermal properties of grain using a number of different methods. The values vary considerably. This apparent disagreement could be due not only to instrumental errors but to the methods used.

2.1 Methods of determining thermal conductivity

There are two general methods of determing the thermal conductivity:

1) Steady-state methods - these are the methods which are based on steady flow of heat. In a steady-state system, temperature and rate of heat flow at any point in the system do not change with time. The time required to reach a steady-state varies from a few hours to many days, depending on the thermal properties of material being tested.

2) Transient heat flow methods - these are the methods which are based on unsteady flow of heat. In the unsteady or transient state, temperature and rate of heat flow change with time.

2.2 Steady-state methods used by earlier investigators

Oxley (1944) determined the thermal conductivity of wheat, corn and oats by a concentric spheres steady-state apparatus. The grain samples were placed between the two spheres. The inner sphere was equipped with an electrical heating element to provide the heat flow across the grain. The spheres were placed in a constant temperature box. When the temperature of the inner sphere became constant and was equal to that of air in the constant temperature box, the electrical current to the heater was switched on. The temperature difference across the grain, when the steady-state condition was reached, was used to calculate the thermal conductivity of the grain.

The thermal conductivity of wheat was measured by Babbitt (1945) and Moote (1953) using a steady-state method. The wheat was enclosed in a metal cylinder which was equipped with an electrical heating wire at its axis. After reaching the steady-state condition the temperature distribution along a radius was used to calculate the thermal conductivity.

2.3 Objections to steady-state methods

The two main objections to steady-state methods are:

1) the long time required to achieve steady-state conditions (Moote, 1953; obtained steady-state after 100 hours of heating) and,

2) the large amount of moisture migration along the temperature gradient during the long test period. Moote (1953) reported that the moisture distribution in wheat having an initial moisture content of 10.85% wet basis*, was 5.4% near the axis and 11.6% near the outside of the 1 ft. diameter cylinder after the test.

Both of these factors are minimized in transient heat flow methods in which the test period is reduced considerably.

2.4 Transient heat flow method

Reidy and Rippen (1969), in their discussion of transient heat flow methods of determining thermal conductivities, concluded that the

---

* All reference to moisture content is given on wet basis

most suitable method for grain is one in which a line heat source of infinite length and constant strength is stretched in an infinite homogeneous body intially at uniform temperature. The basic equation for one-dimensional heat flow from a line heat source is:

$$\frac{\partial t}{\partial \theta} = \alpha\left[\frac{\partial^2 t}{\partial R^2} + \frac{1}{R}\frac{\partial t}{\partial R}\right] \qquad (2.1)$$

where:

t = temperature at radius R,

θ = time,

R = radius from the heat source, and

α = thermal diffusivity of the material.

The solution for the temperature is given by Hooper and Lepper (1950) as:

$$t = \frac{Q}{2\pi k}\, I(Rn) \qquad (2.2)$$

where:

Q = heat input,

k = thermal conductivity of the material,

$n = \frac{1}{2}(\alpha\theta)^{-\frac{1}{2}}$.

and the series I is given by

$$I(Rn) = A - \log_e(Rn) + \frac{(Rn)^2}{2} - \frac{(Rn)^4}{8} + \ldots\ldots \qquad (2.3)$$

where:

A = a constant

If (Rn) is sufficiently small, then all the terms of the I series except the first two may be dropped. Then

$$I(Rn) = A - \log_e(Rn) \qquad (2.4)$$

and the temperature is given by:

$$t = \frac{Q}{2\pi k} [A - \log_e (Rn)] \qquad (2.5)$$

The solution for thermal conductivity is also given by Hooper and Lepper (1950) as:

$$k = \frac{Q \log_e(\theta_2/\theta_1)}{4\pi (t_2 - t_1)} \qquad (2.6)$$

where:

t_1 = temperature at time θ_1,

t_2 = temperature at time θ_2.

The temperatures t_1 and t_2 are measured at radius R from the heat source. The thermal conductivity is then calculated from the measured quantities of Q, θ_1, θ_2, t_1 and t_2. Since a plot of temperature and $\log_e$ (time) should show a straight line with a slope of $Q/4\pi k$, the use of Equation (2.6) is limited only to the straight line portion of the plot.

2.5 Transient heat flow method used by earlier investigators

Based on the transient heat flow method Hooper and Lepper (1950) developed a thermal conductivity probe to determine the thermal conductivities of various materials. An electrical heating wire was enclosed in a metal tube of small diameter. The thermal conductivity probe could be inserted in to a homogeneous body. Temperature near the mid point of the heater was measured to calculate the thermal conductivity.

D'Eustachio and Schriener (1952) used the thermal conductivity probe to determine the thermal conductivity of cellular glass and silica gel. Their results were the same as those obtained using a guarded hot plate apparatus. Hooper and Chang (1953) used the thermal conductivity probe to determine the thermal conductivity of various materials including wheat.

Both Kazarian and Hall (1965), and Wratten et al. (1969) studied the effect of moisture content on thermal conductivity of grains using the transient heat flow method. The grain was enclosed in a hollow metal cylinder, which was heated by a heating wire stretched along the axis of the cylinder. The temperature rise near the heating wire was measured by a thermocouple. The only difference in methods used by Kazarian and Hall, and Wratten et al. was the different ways of attaching the thermocouple to the heating wire. Kazarian and Hall attached the thermocouple to the heating wire by a single layer of plastic electrical tape. The electrical tape insulated the thermocouple and separated it from the heating wire by approximately 0.04 cm at the point of attachment. This method of attaching the thermocouple to the heating wire most likely caused the following problems:

1) the joint of thermocouple and heating wire will not be very strong, so the repeated process of filling and emptying the cylinder will change the location of the thermocouple ;
2) insulation of the joint by electrical tape will restrict the flow of heat from heater to grain at the point of attachment.

Wratten et al. (1969) soldered the thermocouple at the center of heating wire. The solder and thermocouple probably increased the cross-sectional area of the joint, which will increase the rate of heat transfer from the joint. But the increase in area at the joint will decrease the resistance thereby decreasing heat production in the joint. These factors can be reduced considerably by using a thermocouple of higher gauge and by keeping the size of the joint small.

2.6 Errors in using transient heat flow method

There are two sources of errors in using the transient heat flow method of determining thermal conductivity:

1) The effect of dropping the terms of I-series in Equation (2.3). Both Hooper and Lepper (1950) and Kazarian and Hall (1965) have shown that for small (Rn) the error caused by dropping the other terms of I-series in Equation (2.3) is negligible. In this present study of determining the thermal conductivity of spring wheat at low temperatures, the temperature was measured at the center of heater. Therefore, R, the radius from the heat source is zero. Since all the terms dropped in Equation (2.3) are a function of R, no error is involved in dropping these terms.

2) The effect of finite diameter and length of heat source. The length of the heat source is chosen long enough to ensure radial heat flow at the test section. A method to compensate for the finite diameter of the heat source, which in effect replaces a small core of grain, has been discussed by Hooper and Lepper (1950). The difference in heat absorption between the heater and the displaced core can be considered as heat production before the start of measured time, that

is a time correction, θ_o, is subtracted from each observed time. The time correction, θ_o, is obtained by plotting the values of $\frac{d\theta}{dt}$ against time and reading the value of time at $\frac{d\theta}{dt} = 0$. The corrected equation for thermal conductivity thus becomes:

$$k = \frac{Q}{4\pi(t_2 - t_1)} \log_e \left[\frac{\theta_2 - \theta_0}{\theta_1 - \theta_0}\right] \qquad (2.7)$$

2.7 Reported values of thermal conductivity of wheat

Thermal conductivity is a function of both moisture content and temperature. Many studies have been conducted with different methods to determine the effect of moisture content on thermal conductivities of various grains and of different varieties (Table 1).

Oxley (1944) reported the thermal conductivity of No. 1 Manitoba wheat to be 0.00036 cal C^{-1} cm^{-1} sec^{-1} at 11.7% moisture content and 0.00041 cal C^{-1} cm^{-1} sec^{-1} at 12.5% moisture content. These results show that the thermal conductivity increases with increasing moisture content. Also the thermal conductivity of English wheat was 0.00039 cal C^{-1} cm^{-1} sec^{-1} at 17.8% moisture content. The thermal conductivity of English wheat at 17.8% moisture was lower than No. 1 Manitoba wheat at 12.5% moisture content. This difference in thermal conductivities could possibly be due to the difference in variety of the wheat.

Oxley also found that the thermal conductivity of damp mouldy No. 1 Manitoba wheat at 19.5% moisture content was 0.00037 cal C^{-1} cm^{-1} sec^{-1}. He stated that the reason for lower value of thermal conductivity of No. 1 Manitoba wheat at a higher moisture content was the growth of fungi which might have tended to insulate adjacent grains from each other.

Table 1 Reported values of thermal conductivity of wheat

Material	M.C. % w.b.	Temperature C	Density g cm^{-3}	Thermal conductivity cal C^{-1} cm^{-1} sec^{-1}
Oxley (1944)				
No. 1 Manitoba	11.7			0.00036
wheat	12.5			0.00041
English wheat	17.8			0.00039
Mouldy No. 1				
Manitoba	19.5			0.00037
Babbitt (1945)				
hard wheat	9.2	26-48	0.85	0.00036
Hooper and Chang (1953)				
wheat				0.000318
Moote (1953)				
hard red spring wheat	1.38		0.842	0.000312
	2.15		0.846	0.000324
	2.54		0.825	0.000329
	2.91		0.822	0.000329
	3.48		0.822	0.000332
	4.58		0.859	0.000336
	5.32		0.828	0.000328
	6.45		0.858	0.000355
	6.9		0.881	0.000361
	6.9		0.831	0.000345
	7.32		0.860	0.000364
	7.67		0.828	0.000358
	9.85		0.831	0.000364
	10.88		0.821	0.000379
	13.75		0.821	0.000400
Kazarian and Hall (1965)				
soft white winter wheat	0.68	21-44	0.772	0.000280
	5.45		0.774	0.000292
	10.3		0.775	0.000309
	14.4		0.766	0.000324
	20.3		0.743	0.000330

Babbitt (1945) reported only one value of thermal conductivity of hard wheat for temperature range of 26 to 48C. The moisture content of the wheat was 9.2% and the bulk density 0.85 g cm^{-3}. His reported value of thermal conductivity of 0.00036 cal C^{-1} cm^{-1} sec^{-1} is equal to the thermal conductivity of No. 1 Manitoba wheat at 11.7% moisture reported by Oxley (1944). The equality of thermal conductivity values for different moisture contents could be due to the different methods used.

The thermal conductivity of two samples of hard red spring wheat was determined by Moote (1953) using the same method as Babbitt (1945). The moisture content of sample A was varied from 1.38% to 7.35% by adding water to the wheat. The moisture content of sample B was varied from 13.75% to 5.3% by intermittently drying at 105C. The thermal conductivity varied linearly with moisture content, sample B having slightly lower values than sample A. The conductivity values of sample A ranged from 0.000312 cal C^{-1} cm^{-1} sec^{-1} at 1.38% moisture content to 0.000361 cal C^{-1} cm^{-1} sec^{-1} at 7.35% moisture content. The thermal conductivity values for sample B varied from 0.000328 cal C^{-1} cm^{-1} sec^{-1} at 5.3% moisture content to 0.000400 cal C^{-1} cm^{-1} sec^{-1} at 13.75% moisture content. No explanation was given for the variation in the thermal conductivities of different samples.

The thermal conductivity of wheat reported by Moote for 9.85% moisture which is the nearest value of moisture content to that of Babbitt was 0.000364 cal C^{-1} cm^{-1} sec^{-1}. This small variation in thermal conductivities reported by Moote and Babbitt could be expected due to the difference in moisture content.

Hooper and Chang (1953) reported that the thermal conductivity of wheat was 0.000318 cal C^{-1} cm^{-1} sec^{-1}. The moisture content and the variety of the wheat was not specified.

Kazarian and Hall (1965) studied the effect of moisture content on thermal conductivity of soft white wheat using a transient heat flow method. The temperature of wheat during the test varied from 21 to 44C. The wheat at 0.68% moisture content had a thermal conductivity value of 0.000280 cal C^{-1} cm^{-1} sec^{-1} and at 20.3% moisture content a value of 0.000330 cal C^{-1} cm^{-1} sec^{-1}. Thermal conductivity increased linearly with increasing moisture content. Their linear regression equation is discussed in section 4. In general, the thermal conductivities reported for soft white wheat were less than those for hard red spring wheat reported by Moote (1953). This difference could be expected due to variation in the variety of wheat and the methods used.

3. METHODS AND MATERIALS

3.1 Apparatus

The apparatus used for measuring the thermal conductivity of wheat was similar to one used by Kazarian and Hall (1965). The apparatus consisted of a hollow aluminum cylinder 30 cm high and 15 cm in diameter. The cylinder wall was 0.16 cm thick. Both ends of the cylinder were plugged with 1.9 cm thick pieces of wood. The line heat source was a 25 cm long 0.0361 cm in diameter (27 gauge B & S) chromel wire, having resistance of 0.0985 ohms per cm, which was stretched between copper leads on the axis of the cylinder (Figure 1).

The chromel wire was heated by electric power supplied by a 6 volt storage battery. Current flow through the heater wire was controlled with a 0 to 35 ohms variable resistor. A 0.0 to 0.6 amp direct current ammeter, minimum graduation 0.01 amp, accuracy ±1% full span, was used to measure the current. Temperature was measured at the center of the heating wire with a 0.0127 cm diameter (36 gauge B & S) copper-constantan thermocouple soldered to the chromel wire. The size of the soldered joint was kept as small as possible to reduce the effect of extended surface on the heat transfer from the joint. The thermocouple reference junction was maintained at 0 C ±0.01C. Electrical potential of the thermocouple circuit was measured with a potentiometer strip chart recorder, minimum graduation 1 μV, overall accuracy ±2 μV (Figure 2). The aluminum cylinder was enclosed in an insulated wooden box (Figure 3), which was placed in a controlled temperature chamber (Figure 4a). The insulated wooden box reduced temperature changes and the effect of air currents around the test cylinder. Temperature at the center of the wooden box varied less than ± 0.027C with time. Battery, ammeter and potentiometer

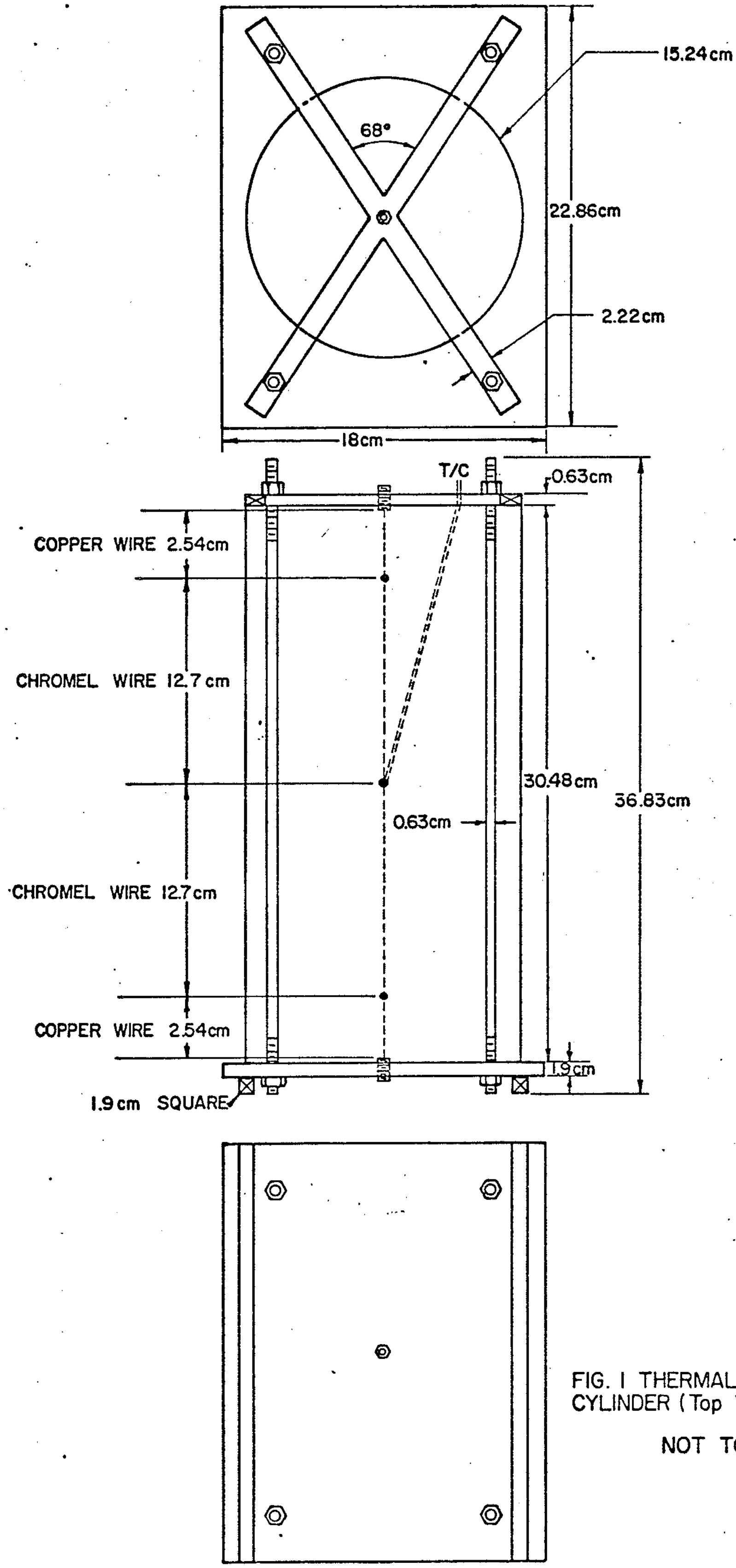

FIG. 1 THERMAL CONDUCTIVITY TEST CYLINDER (Top Wooden Plank Removed)

NOT TO SCALE

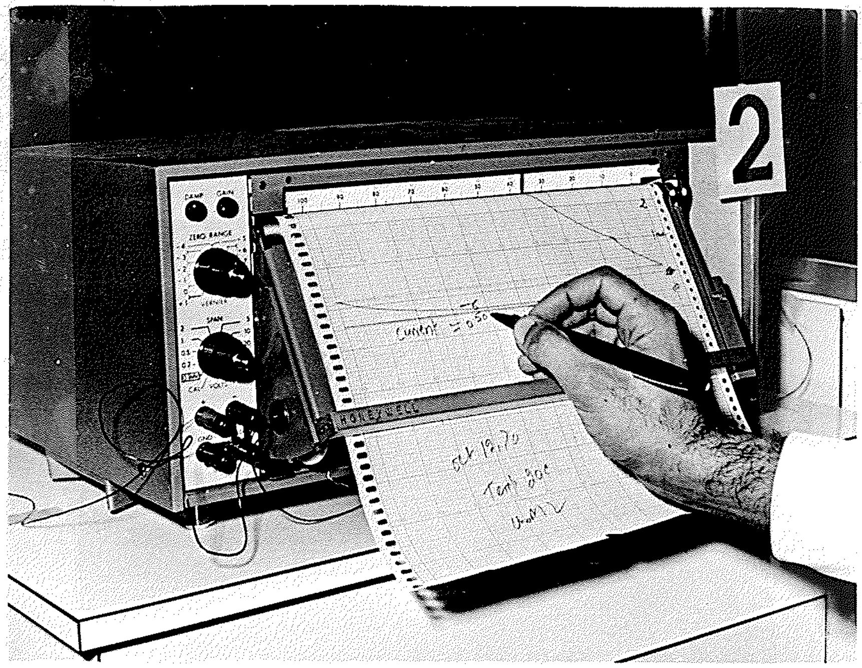

Fig. 2 Potentiometer strip chart recorder

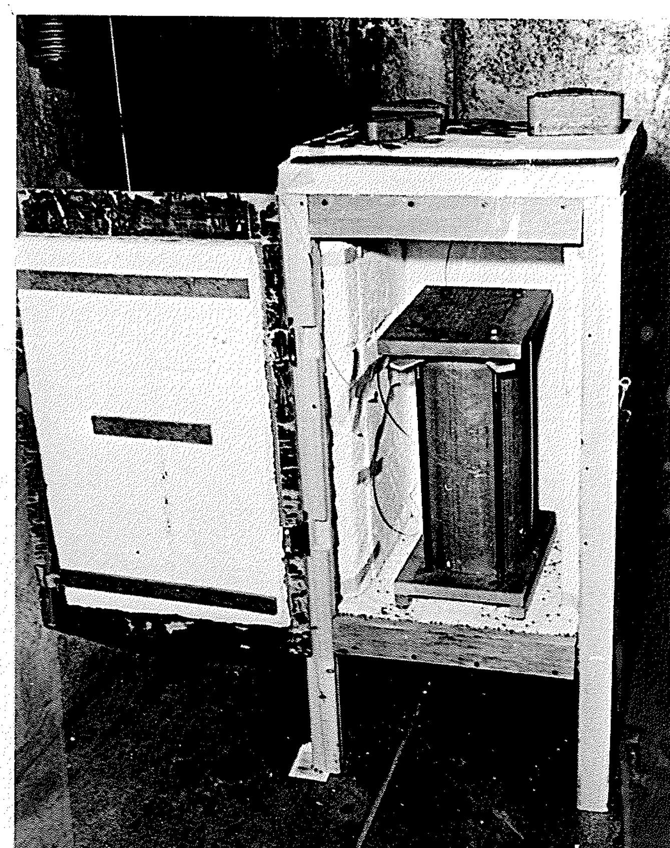

Fig. 3 Test cylinder and the insulated wooden box

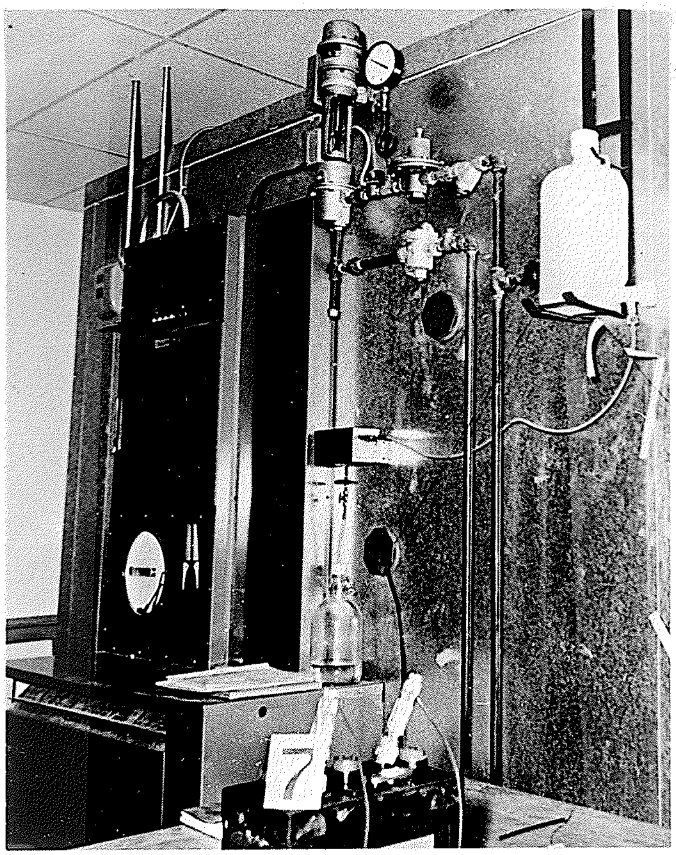

Fig. 4a Controlled temperature chamber

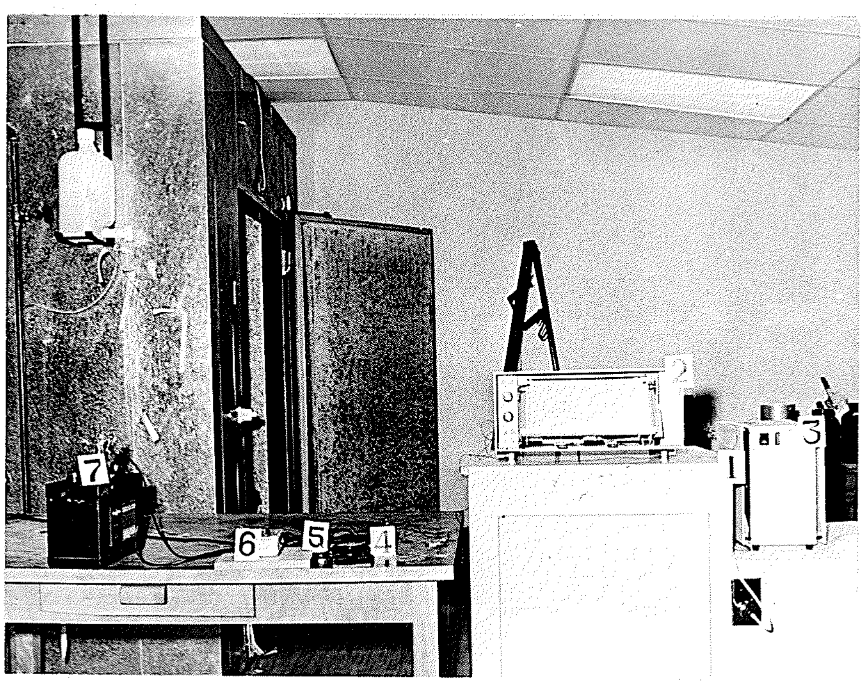

Fig. 4b Electrical and measuring circuit equipment

1. Stand 2. Potentiometer strip chart recorder
3. Ice point reference unit 4. Ammeter
5. variable resistor 6. Switch 7. Storage battery

recorder were at room temperature located outside the controlled temperature chamber (Figure 4b).

3.2 Calibration of thermocouple

The thermocouple used for measuring the temperature of the heater was calibrated against a constant temperature bath in the temperature range -26.3C to +48.9C. Temperature of the bath was controlled by a platinum resistance sensor. Manufacturers of the bath indicate that the accuracy of temperature control is more than $\pm$0.004C at an operating temperature of +37C. The temperature of the bath was measured by a mercury thermometer having a minimum graduation of 0.1C. The temperature-millivolt data for 0.0 to 48.9C and for -26.3 to 0.0C were analysed separately. The millivolt output was recorded for 48 settings of temperature in the temperature range 0.0 to 48.9C and for 21 settings in the temperature range -26.3 to 0.0C. The regression equations expressing the relationship between temperature and millivolt for each range of temperature are:

Temperature range 0.0 to 48.9C

$$T = 0.401 + 2.47 \times 10^3 v \tag{3.1}$$

$r = 0.9999; \quad s = 0.253$

Temperature range -26.3 to 0.0C

$$T = -0.319 + 2.53 \times 10^3 v \tag{3.2}$$

$r = 0.998; \quad s = 0.489$

where:

T = temperature, C

v = voltage output, mv

s = standard deviation, C

r = correlation coefficient.

3.3 Grain sample

Manitou, a hard red spring wheat, harvested during the fall of 1969, graded No. 2 Manitoba Northern was used in the tests. The original moisture content of the wheat was 10.8% and protein content was 13.3% on the basis of 13.5% moisture content.

The wheat was divided into seven lots which were conditioned to moisture contents ranging from 4.4 to 22.5%. Samples to have a moisture content above 10.8% were conditioned by adding water. Pixton and Warburton (1968) reported that the re-distribution of moisture within the wetted grain usually takes at least seven days. Therefore, lots conditioned by adding water were held after the addition of water for at least 12 days, to allow the moisture to become completely uniform throughout the lot. A temperature of 2C was maintained during this period to avoid fungal growth in the wheat. Lots to have moisture content below 10.8% were dried at temperatures not greater than 60C to reduce the chemical changes in the wheat at high temperatures. Wheat at any moisture content, when not being used, was kept in plastic cans at the temperature the tests were being conducted. To determine the moisture content, four 20 to 25 g samples from lot were dried in an oven at 100C for 96 hours. The samples, before and after drying, were weighed by an electric single pan balance indicating weight up to 0.0001 g. The moisture content was calculated on wet basis.

3.4 Density

Grain density was determined by weighing the amount of wheat required to fill the thermal conductivity test cylinder and dividing by its volume. A consistent filling procedure was used to avoid variation in compaction. The density was measured for each replication of thermal conductivity at two temperatures, 20C and -6C.

3.5 Preliminary tests

To determine the amount of current flow to be used in the experiments, 10-tests were run, 5 each with current flows of 0.500 amp and 0.528 amp. These tests were conducted at 20C using wheat containing 10.8% moisture. A curve between temperature and $\log_e$(time) was plotted for three different heating tests with a current of 0.500 amp. The plot of temperature and $\log_e$(time) resulted in a straight line only after 0.6 minutes of heating. Since Equation (2.6) is applicable to only straight line portion, the θ_1 was chosen to be 1 minute . θ_2 was arbitrarily chosen to be 8 minutes.

It was found that a current of 0.500 amp would give a temperature rise of approximately 12.6C after 8 minutes of heating. The temperature change between 1 and 8 minutes was approximately 2.7C. The temperature rise with a current of 0.528 amp after a heating time of 8 minutes was approximately 13.6C and between 1 and 8 minutes was approximately 3.0C. These results were used to calculate the thermal conductivity of wheat with two different levels of currents. Slightly higher values of thermal conductivities were obtained for the tests with a current of 0.528 amp due to greater increase in temperature (Table 2), but were not significantly different at the 5% level from those obtained with a current of 0.500 amp. A similar conclusion with currents of 0.490 amp and 0.560 amp and a heating time of 1 to 10 minutes was reported for corn by Kazarian and Hall (1965). Hooper and Lepper (1950) reported that while a wide range of currents and temperature rise can be used, in general lower currents are suited to lower thermal conductivities. Therefore, a current of 0.500 amp was used for the thermal conductivity tests. The current varied less

Table 2 Effect of current on thermal conductivity

Moisture content = 10.8% w.b.

Temperature = 20C

	Thermal conductivity, cal C^{-1} cm^{-1} sec^{-1}	
Current	0.500 amp	0.528 amp
	0.000362	0.000387
	0.000359	0.000389
	0.000379	0.000413
	0.000344	0.000352
	0.000356	0.000457
Average	0.000360	0.000399
Standard deviation	1.26×10^{-5}	3.87×10^{-5}

Table 3 Effect of heating time on thermal conductivity

Moisture content = 10.8% w.b.

Temperature = 20C Current = 0.500 amp

	Thermal Conductivity, cal C^{-1} cm^{-1} sec^{-1}		
Heating time	7 minutes	8 minutes	9 minutes
	0.000363	0.000362	0.000360
	0.000363	0.000358	0.000359
	0.000370	0.000367	0.000367
	0.000356	0.000354	0.000355
	0.000349	0.000347	0.000347
Average	0.000360	0.000358	0.000358
Standard deviation	7.98×10^{-6}	7.64×10^{-6}	7.33×10^{-6}

than $\pm 0.8\%$ during a test.

To determine if using different heating times had any effect on thermal conductivity, 5 additional tests were run with a current of 0.500 amp. Wheat was heated for 9 minutes and the thermal conductivity was calculated after a heating period of 7, 8, and 9 minutes for each test with θ_1 equal to 1 minute. There were insignificant differences in thermal conductivities determined after 7, 8 and 9 minutes of heating (Table 3). Therefore, thermal conductivities determined for the heating periods of 1 to 7, 1 to 8 and 1 to 9 minutes were averaged for each test.

3.6 Thermal conductivity

After determining the current and heating time to be used, plastic cans with wheat were kept in the controlled temperature chamber to bring the wheat to equilibrium with the temperature of the controlled temperature chamber. When the temperature of wheat in cans became constant, the thermal conductivity cylinder was filled with the wheat. The test was started, when the temperature of wheat in the cylinder varied less than 0.027C over a time period of at least 10 to 15 minutes. The recorder was started 1 to 3 minutes before power was applied. This served as a check of the initial temperature of wheat. Then the electrical circuit was closed and the temperature rise recorded. After each test the grain was removed from the cylinder. For 20C and -6C the weight of the sample in the cylinder was recorded. A fresh sample was used to fill the cylinder for the next test and the grain from the previous test was kept in the chamber to bring the temperature of wheat back down to the chamber temperature. Care was taken to fill the cylinder in the same way so that the density would not vary greatly between tests.

The time correction, θ_o, was found by the procedure discussed in section 2.6. A time-temperature curve was plotted for 2 tests of thermal conductivity. A typical curve is shown in Figure 5. The values of $d\theta/dt$ were obtained by drawing tangents to the time-temperature curve. Then the values of $d\theta/dt$ were plotted to obtain the desired time correction (Figure 6). The time correction, θ_o, was found to be 3 seconds for both the tests. Hooper and Lepper (1950) also reported that the time correction for most materials, and for a particular apparatus is nearly constant.

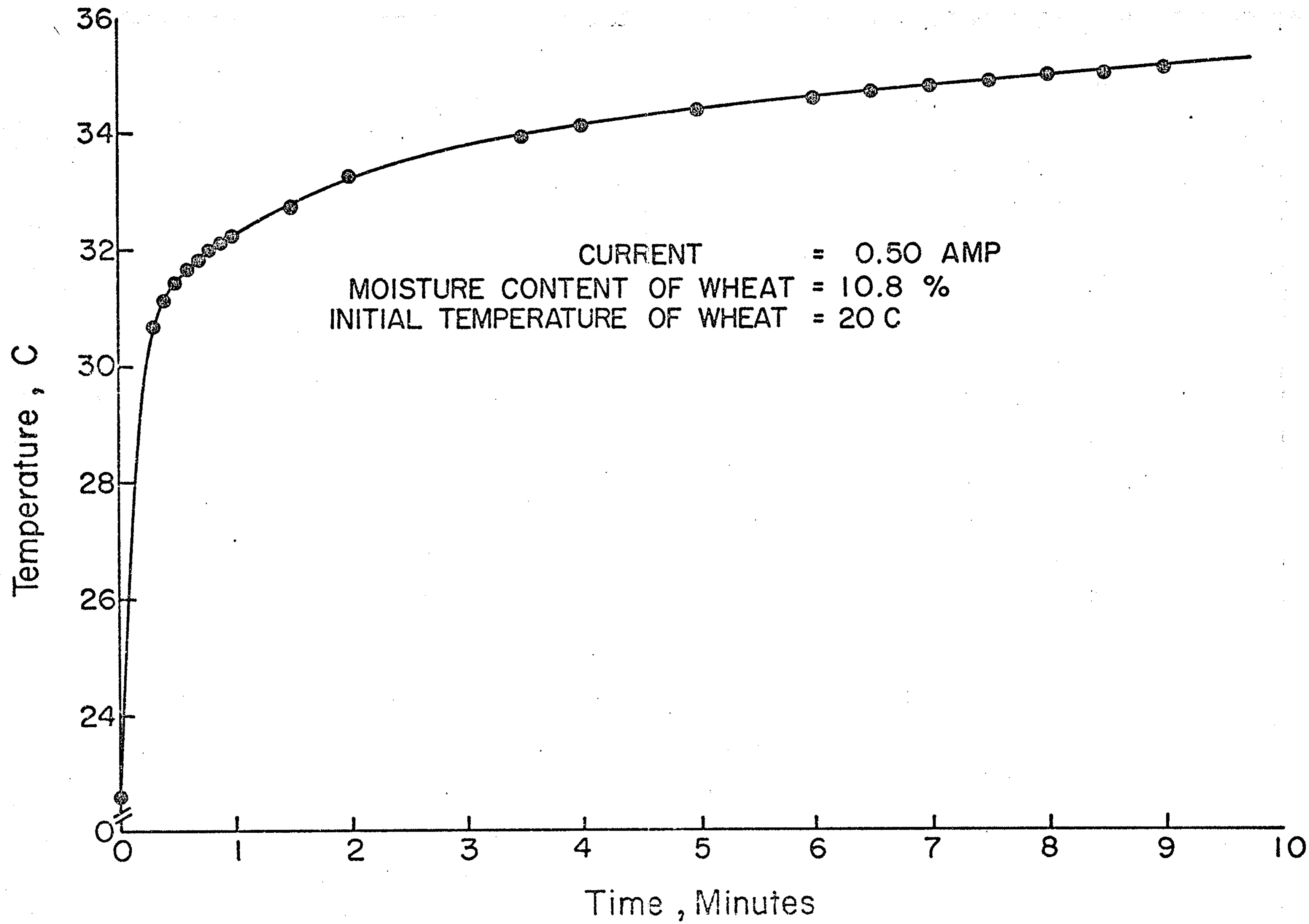

FIG. 5 TIME TEMPERATURE CURVE

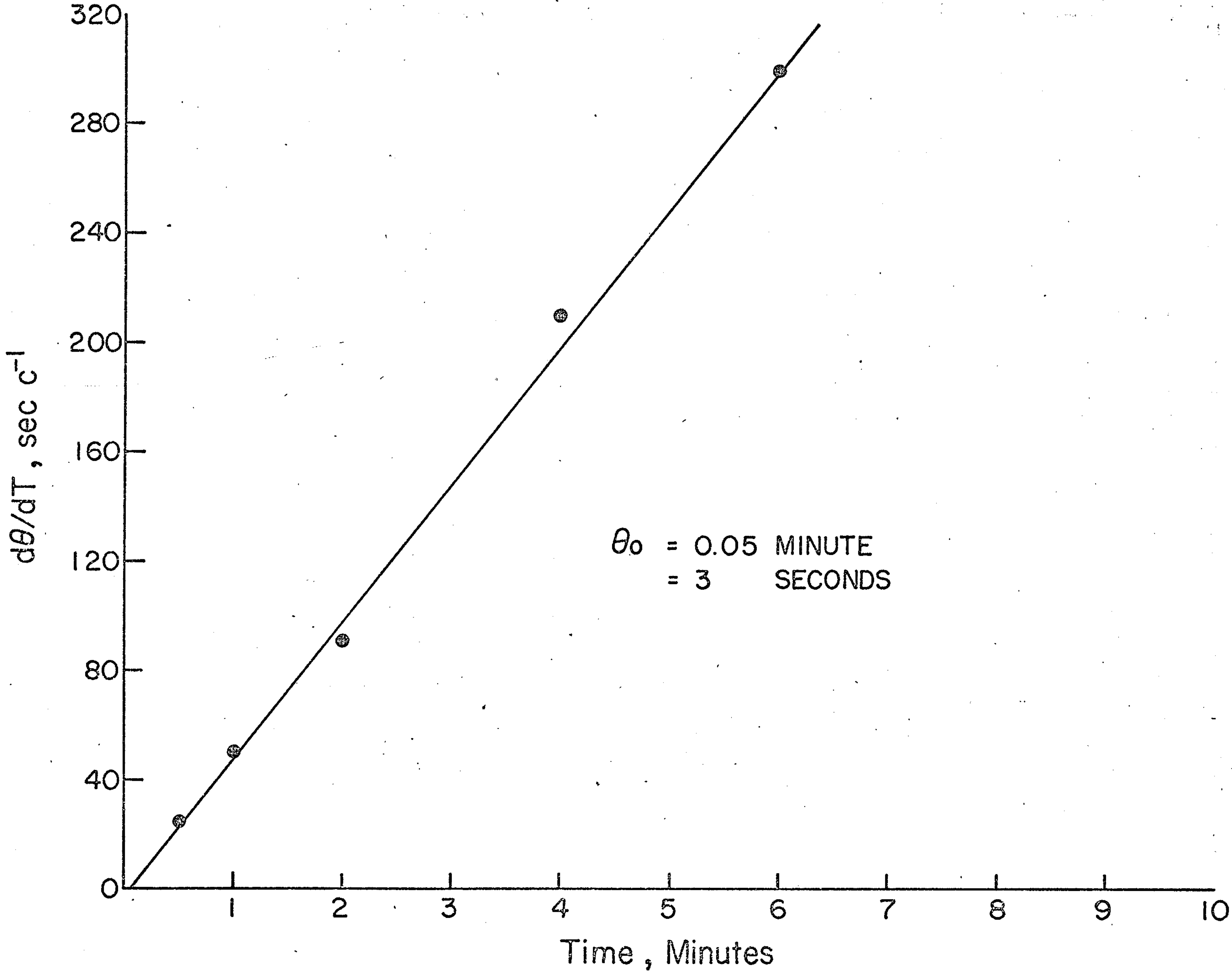

FIG. 6 DETERMINATION OF TIME CORRECTION , θ_0

4. RESULTS AND DISCUSSION

The effect of moisture on thermal conductivity at test temperatures is shown in Figures 7 to 12. The thermal conductivity of spring wheat increased linearly with increasing moisture content at each temperature. The linear regression equations for different temperatures are:

Temperature = 20C

$$k = 3.34 \times 10^{-4} + 3.37 \times 10^{-6} M \quad (4.1)$$

$$r = 0.80, \qquad s = 1.62 \times 10^{-5}$$

Temperature = 5C

$$k = 3.44 \times 10^{-4} + 2.28 \times 10^{-6} M \quad (4.2)$$

$$r = 0.73, \qquad s = 1.37 \times 10^{-5}$$

Temperature = 1C

$$k = 3.26 \times 10^{-4} + 3.25 \times 10^{-6} M \quad (4.3)$$

$$r = 0.94, \qquad s = 7.73 \times 10^{-6}$$

Temperature = -6C

$$k = 3.17 \times 10^{-4} + 3.67 \times 10^{-6} M \quad (4.4)$$

$$r = 0.91, \qquad s = 1.08 \times 10^{-5}$$

Temperature = -17C

$$k = 3.36 \times 10^{-4} + 2.24 \times 10^{-6} M \quad (4.5)$$

$$r = 0.67, \qquad s = 1.63 \times 10^{-5}$$

Temperature = -27C

$$k = 3.43 \times 10^{-4} + 2.28 \times 10^{-6} M \quad (4.6)$$

$$r = 0.67, \qquad s = 1.62 \times 10^{-5}$$

The linear regression equation based on the 210 thermal conductivity determinations at all six test temperatures is:

$$k = 3.33 \times 10^{-4} + 2.86 \times 10^{-6} M \quad (4.7)$$

$$r = 0.77, \qquad s = 1.48 \times 10^{-5}$$

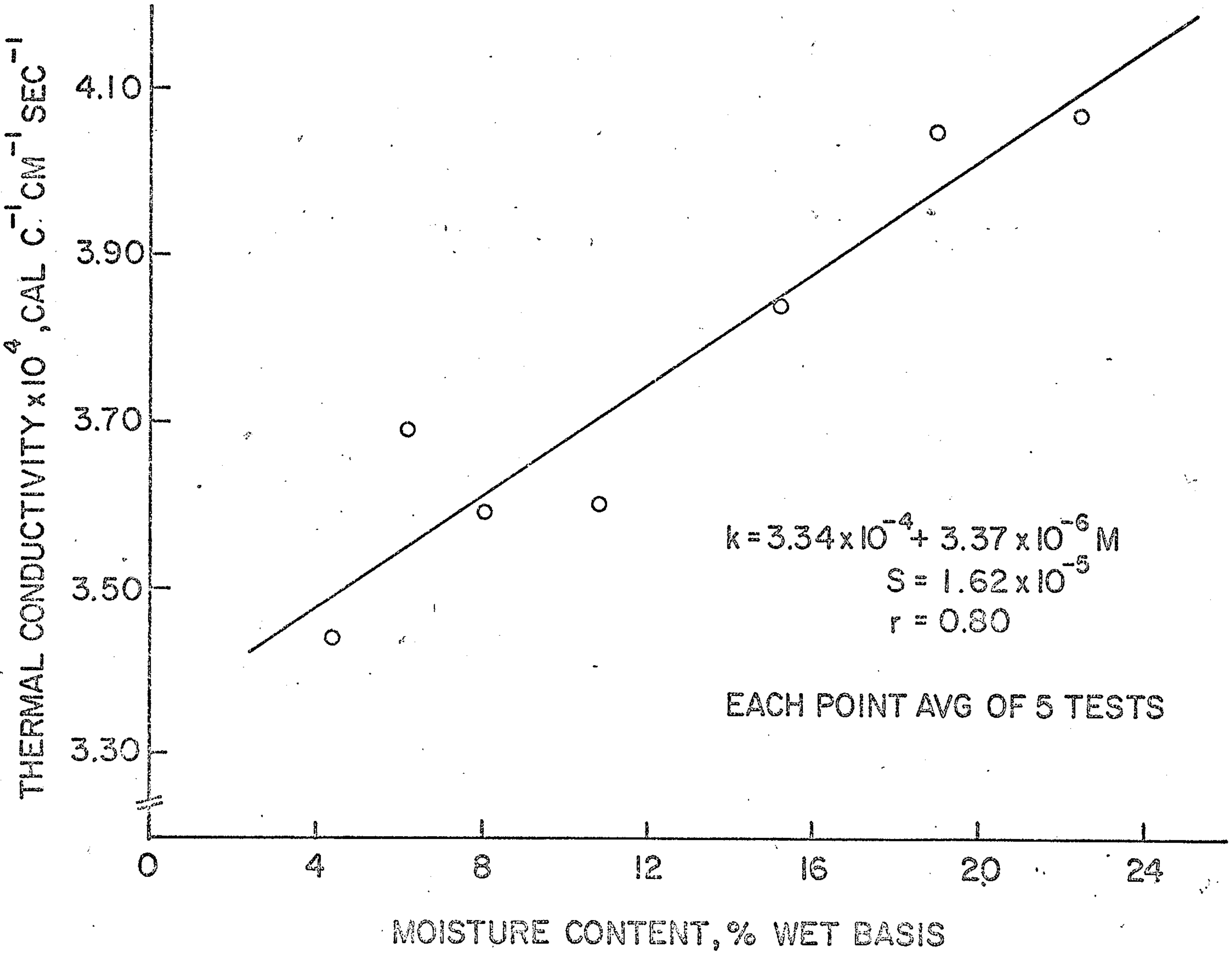

FIG. 7 THERMAL CONDUCTIVITY OF SPRING WHEAT AT 20°C

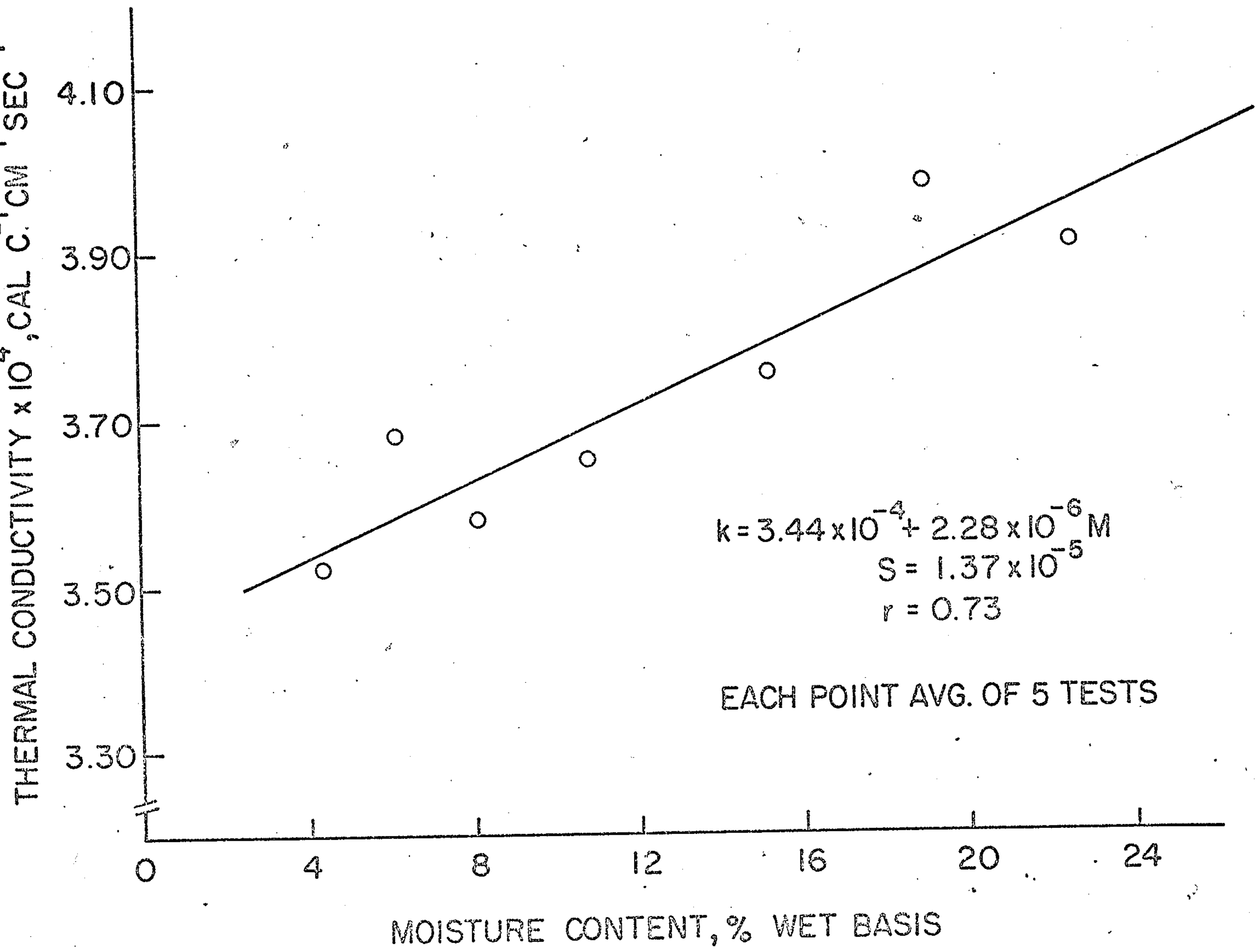

FIG. 8 THERMAL CONDUCTIVITY OF SPRING WHEAT AT 5°C

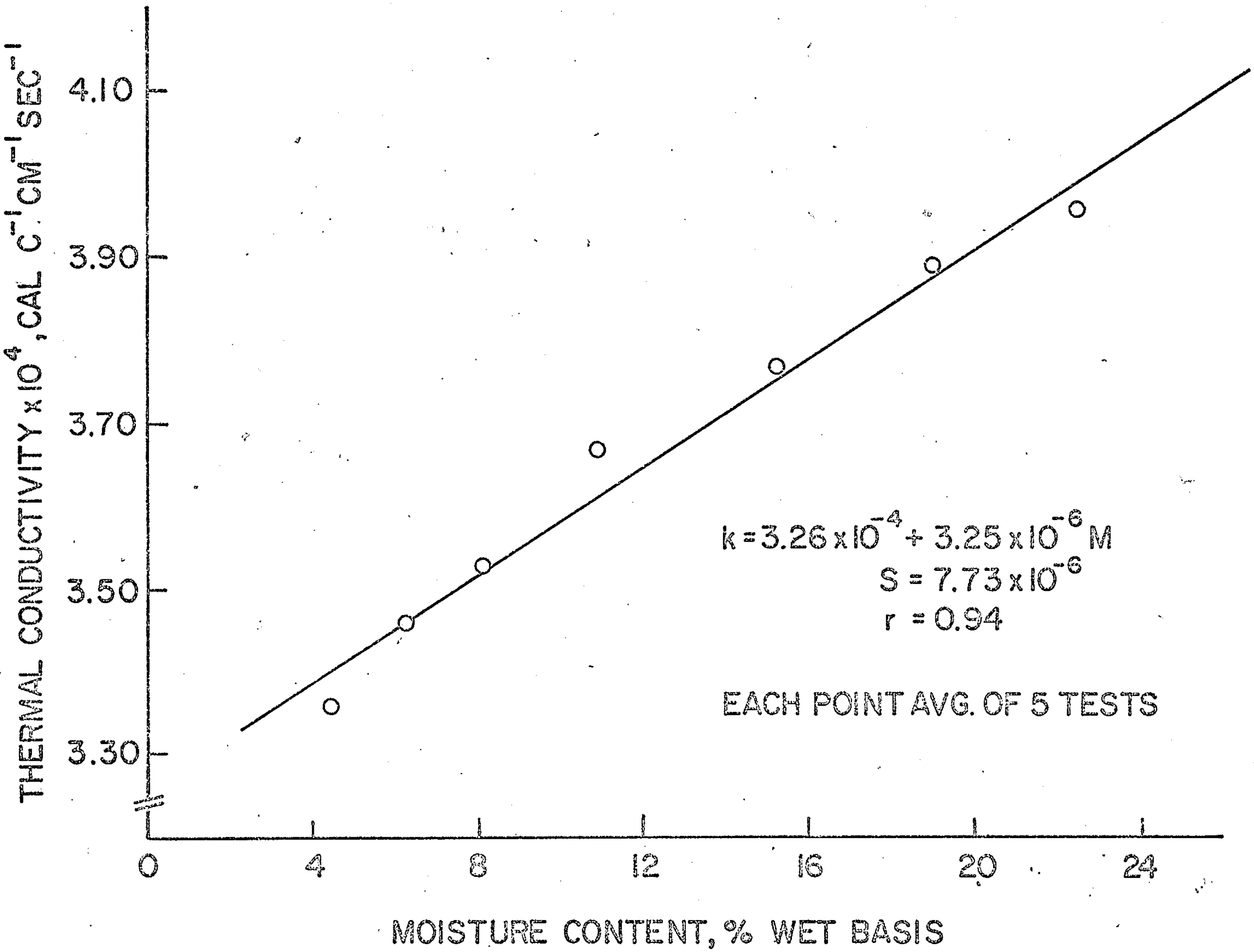

FIG. 9 THERMAL CONDUCTIVITY OF SPRING WHEAT AT 1°C

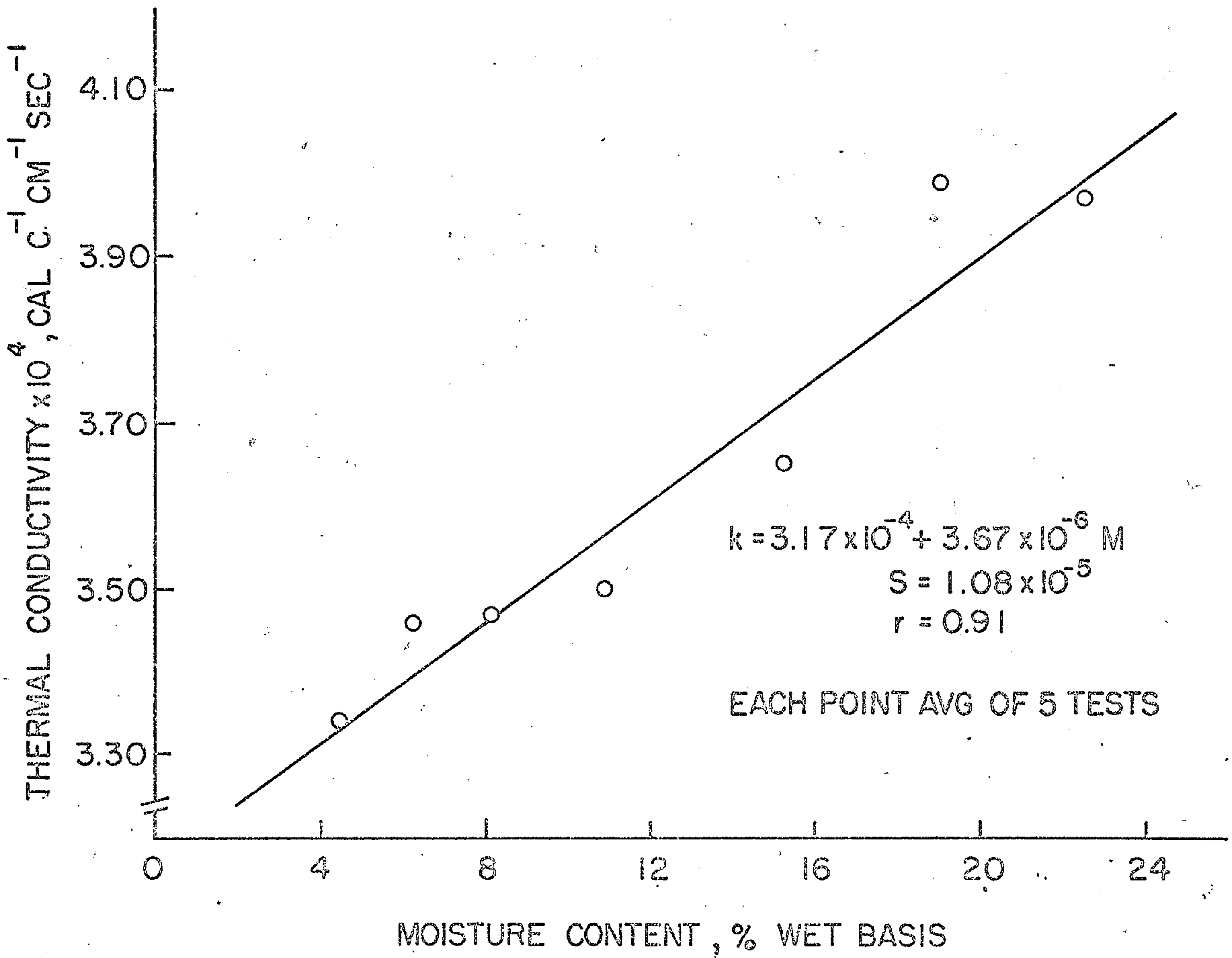

FIG. 10 THERMAL CONDUCTIVITY OF SPRING WHEAT AT −6°C

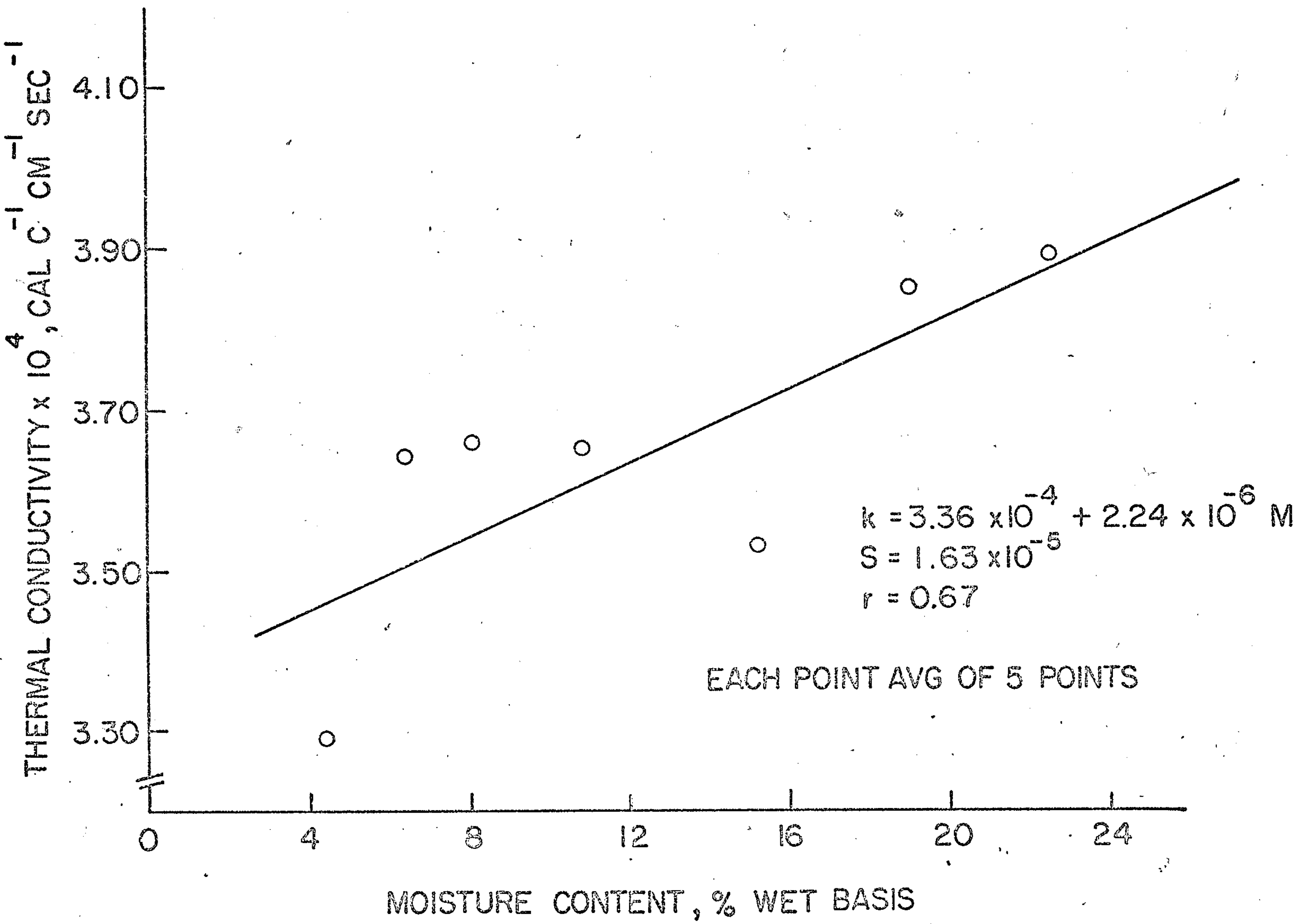

FIG. 11 THERMAL CONDUCTIVITY OF SPRING WHEAT AT −17°C

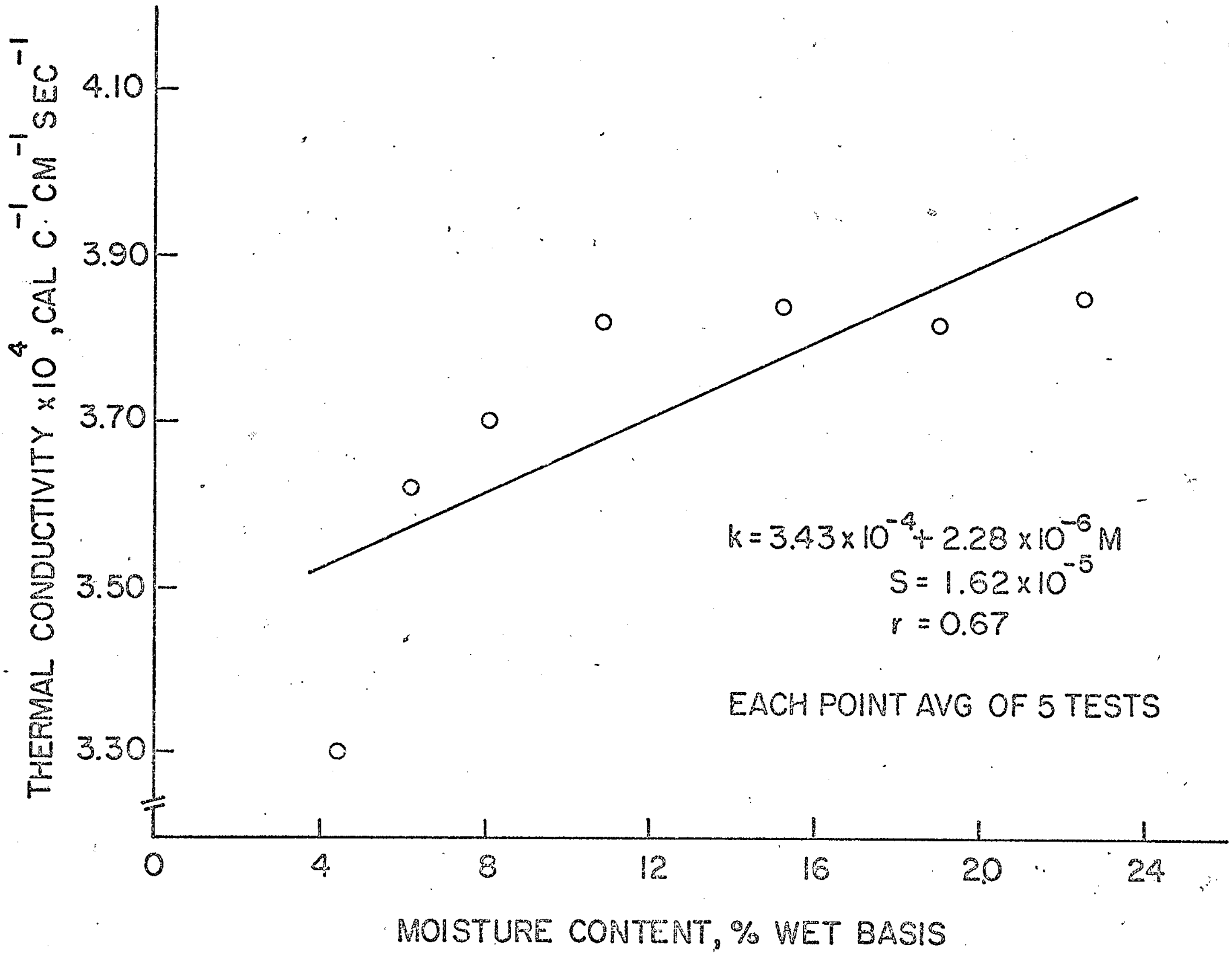

FIG. 12 THERMAL CONDUCTIVITY OF SPRING WHEAT AT $-27°C$

where:

k = thermal conductivity, cal C^{-1} cm^{-1} sec^{-1},

M = moisture content, % wet basis

s = standard deviation of regression equation, cal C^{-1} cm^{-1} sec^{-1}

r = correlation coefficient.

The standard deviations of regression equations are based on all individual test determinations and not on means at each moisture content. The slopes of the curves at -17C and -27C are less than those for higher temperatures. Though there is not much evidence , there seems to be a trend of moisture content affecting thermal conductivity less at low temperatures than at high temperatures. Coefficients of correlation are considerably less at -17C and -27C than at higher temperatures. Only 45% (r = 0.67) of the variation in thermal conductivity is explained by linear regression equations for -17C and -27C. The reason for the low values of correlation coefficients at -17C and -27C was not established. But thermal conductivity appears to be a linear function of moisture content at the higher temperatures as was also shown by Moote (1953) and Kazarian and Hall (1965).

A similar statistical analysis of the data presented by Moote (1953) for hard red spring wheat, temperature range 32 to 60C, moisture content 1.38 to 13.75% results in the following equation:

$$k = 3.08 \times 10^{-4} + 6.54 \times 10^{-6} M \qquad (4.8)$$

$$r = 0.96, \qquad s = 6.59 \times 10^{-6}$$

The slope and intercept of Equation (4.8) were compared against those of Equation (4.1) for 20C. The standard deviation of the regression Equation (4.1) was used for the comparison. The slope and intercept of Equation (4.8) were statistically different at the 5% level from those of Equation (4.1). The difference in slopes could be expected since the effect of moisture content appears to increase with temperature. The difference between the equations could also be due to larger moisture migration in the steady-state method used by Moote than in the transient state method used in this study.

Kazarian and Hall (1965) presented the following regression equation for soft white winter wheat, moisture content 0.68 to 20.3%, temperature range 21C to 44C:

$$k = 2.79 \times 10^{-4} + 2.70 \times 10^{-6} M \qquad (4.9)$$

The effect of moisture content on thermal conductivity of soft wheat, i.e. the slope of the equation, is not significantly different at the 5% level from that found for hard red spring wheat at 20C. But the differences in dry matter and kernel size and shape do affect the thermal conductivity since the thermal conductivities at 0.0% moisture content i.e. intercepts of both equations of the two wheat varieties are significantly different. Two samples of the same variety wheat grown under different environmental conditions may be different in quality from each other. This difference in quality of wheat may also affect the thermal conductivity.

Wheat containing 19.3% moisture which had been allowed to remain at room temperature for a short period of time was found to be badly infected with mould. At all tested temperatures the thermal conductivity of this mouldy wheat was less than that of uninfected wheat at the same moisture content (Table 4). Oxley (1944) made similar observations. Therefore, in measuring or applying thermal conductivities of grain, care must be taken to determine the extent of fungal growth.

Table 4 Effect of fungi growth on thermal conductivity*

Temperature C	Thermal conductivity, cal C^{-1} cm^{-1} sec^{-1}		% decrease from uninfected wheat at 19.0%
	M.C. 19.27%, wheat infected with fungi	M.C. 19.0%, uninfected wheat	
20	0.000348	0.000405	14.07
5	0.000367	0.000398	7.97
1	0.000376	0.000389	3.34
-6	0.000339	0.000399	15.04
-17	0.000335	0.000385	12.99
-27	0.000363	0.000382	4.97

* The thermal conductivity of infected wheat at different temperatures was determined in the following order: 20C, 5C, 1C, -6C, -17C and -27C; and that of uninfected wheat was determined in the order of 5C, 1C, -6C, -17C, -27C and 20C.

Figure 13, in which each point is the average of 35 thermal conductivity determinations at each temperature in the moisture content range of 4.4 to 22.5% shows that the thermal conductivity was minimum at about -8C. A similar pattern of increasing thermal conductivity above and below a certain temperature has been found for ice and meats (Lentz, 1961). The minimum occurs at 0C for ice and around -2C for meats. For these materials there is a discontinuity in thermal conductivity at this temperature when freezing occurs, but the curve for wheat appears to be continuous. Therefore, the moisture in wheat, containing up to 23% moisture, does not appear to undergo a sharp change in phase. There does not appear to be consistent effect of temperature on thermal conductivity, but Figures 14 to 20 show that the temperature at which the thermal conductivity is minimum depends on the amount of water present in the wheat.

The thermal conductivity is a consequence of the following modes of heat transfer which may exist in bulk grain:

1. Conduction within each kernel,
2. Conduction across kernel contact points,
3. Conduction across the pore spaces,
4. Convection across the pore spaces,
5. Radiation between kernels,
6. Moisture migration.

The relative importance of each of these factors must depend largely on the conditions of the temperature gradients set up, their rate of change, the size and shape of masses involved, and the resistance to air movement between the grains (Oxley, 1944). Oxley (1944) and Babbitt (1945) have shown that the effect of convection currents in the

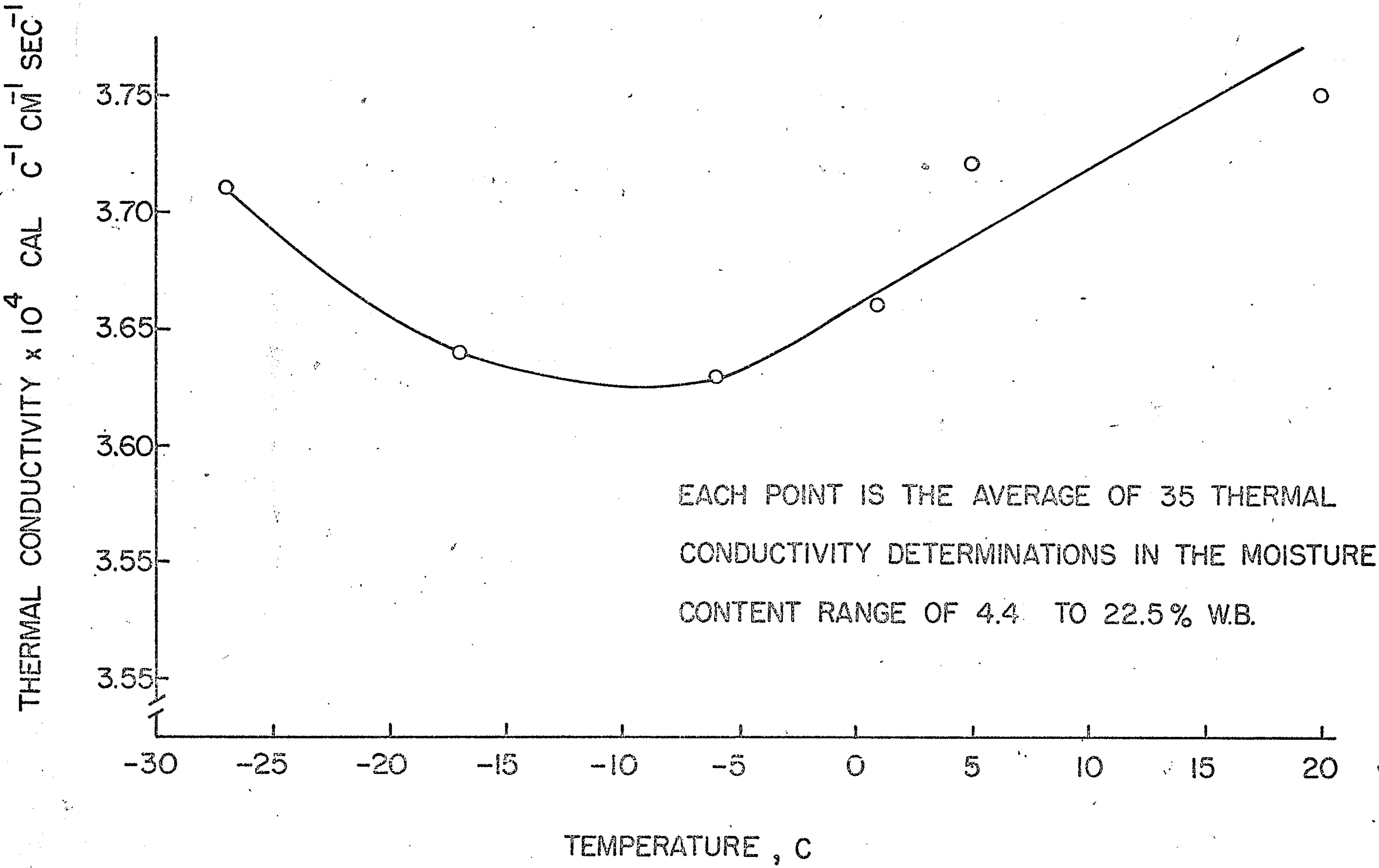

FIG. 13 EFFECT OF TEMPERATURE ON THERMAL CONDUCTIVITY OF SPRING WHEAT

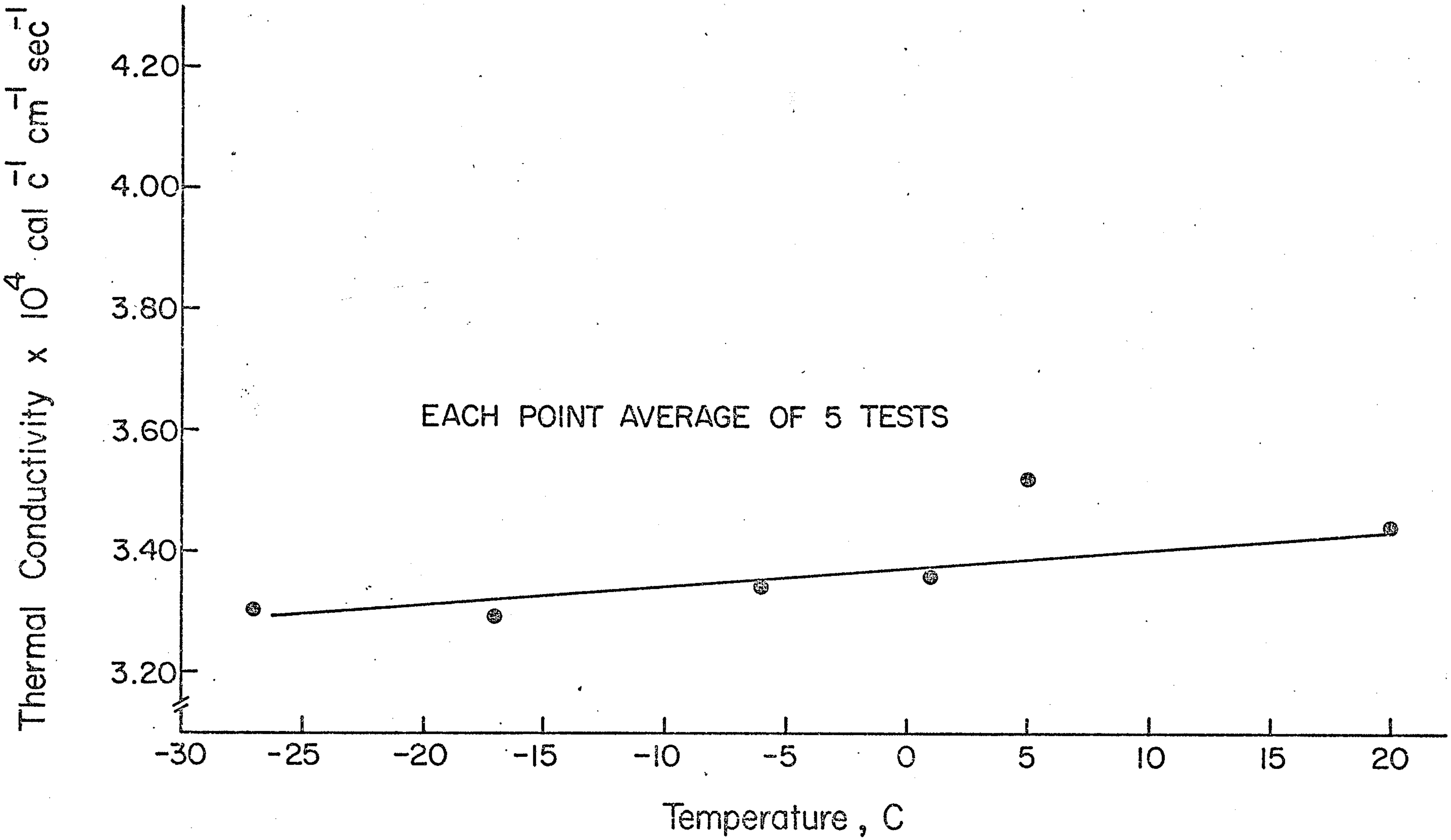

FIG. 14 THERMAL CONDUCTIVITY OF SPRING WHEAT AT 4.4 % MOISTURE CONTENT

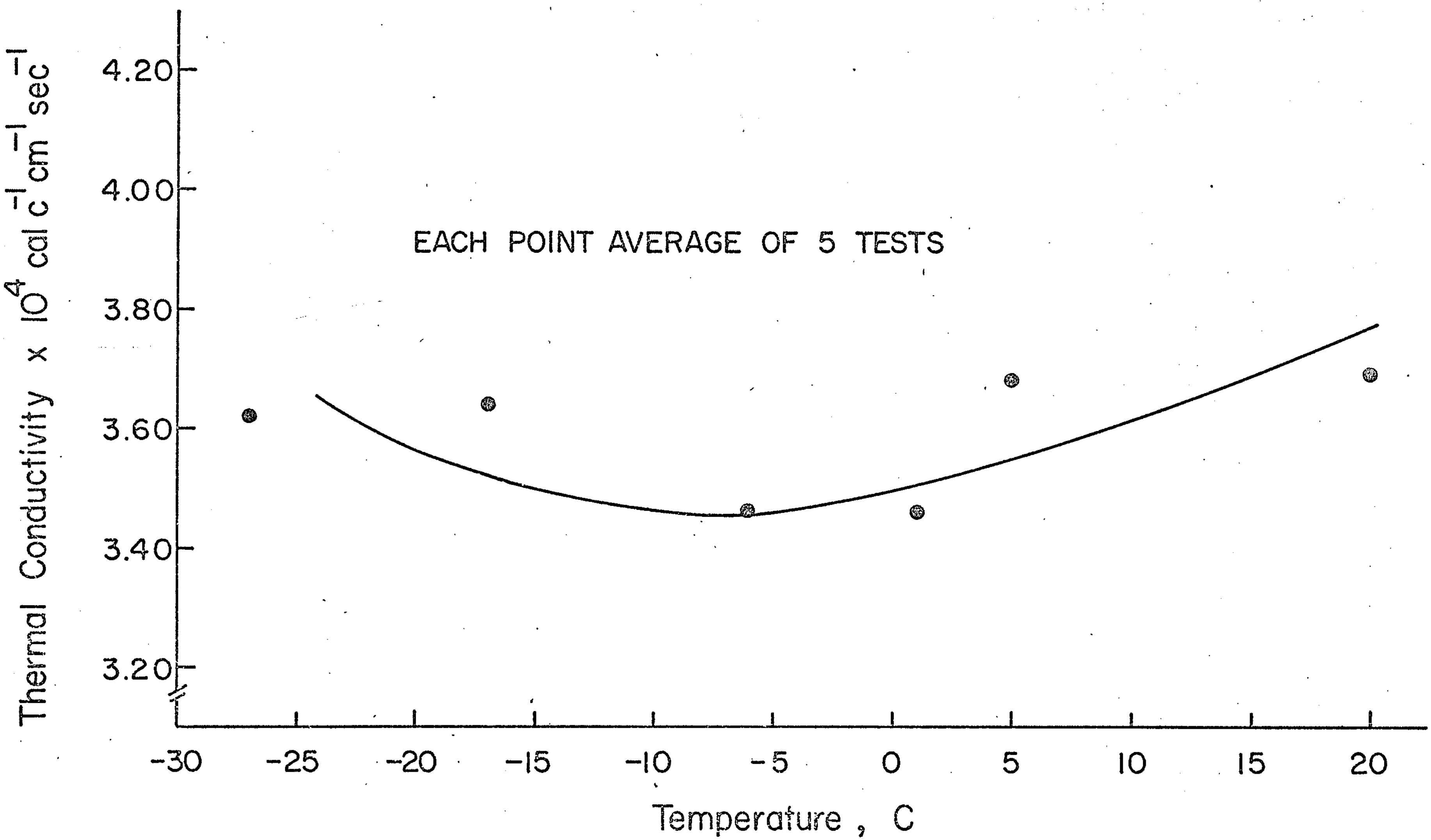

FIG. 15 THERMAL CONDUCTIVITY OF SPRING WHEAT AT 6.2% MOISTURE CONTENT

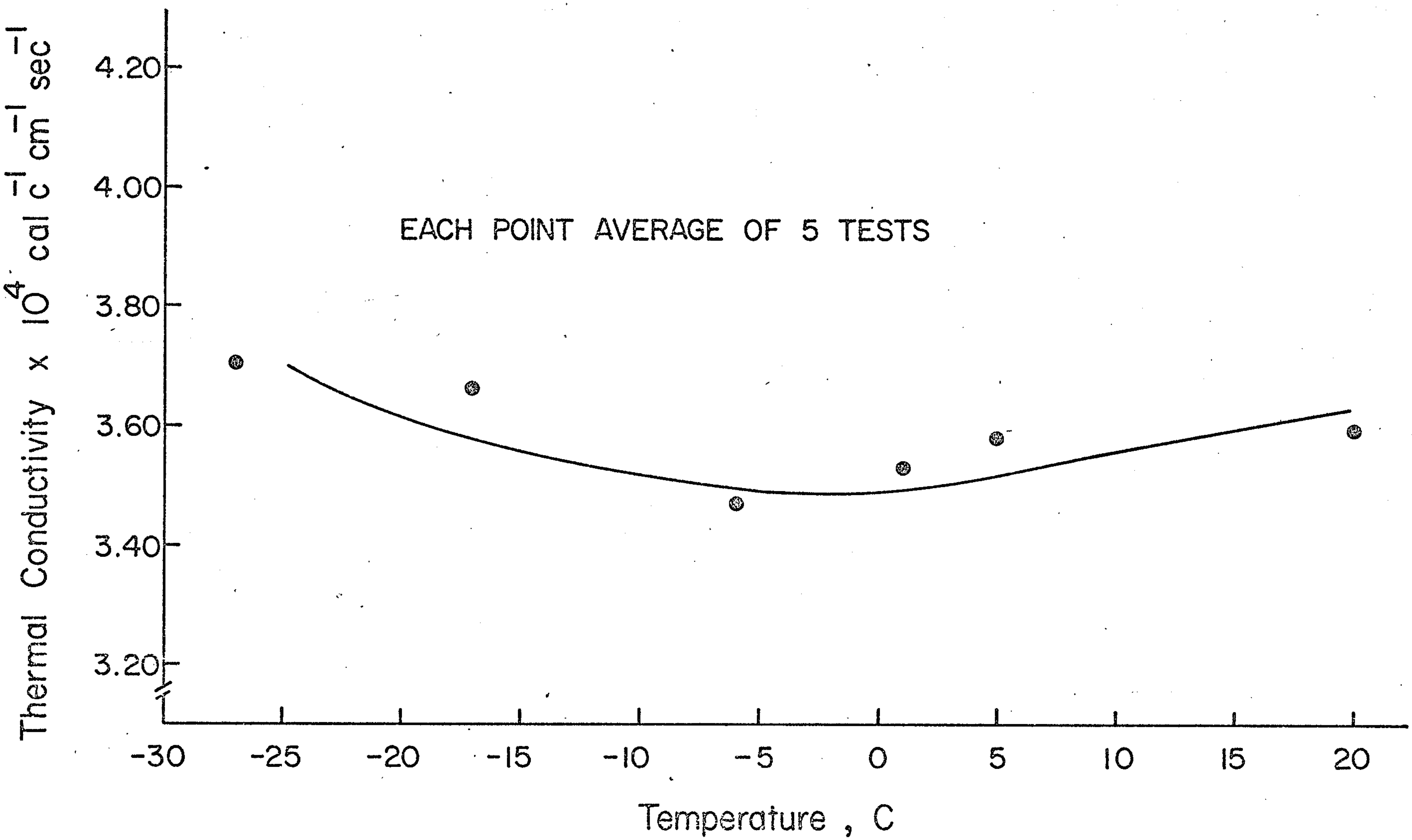

FIG. 16 THERMAL CONDUCTIVITY OF SPRING WHEAT AT 8.1% MOISTURE CONTENT

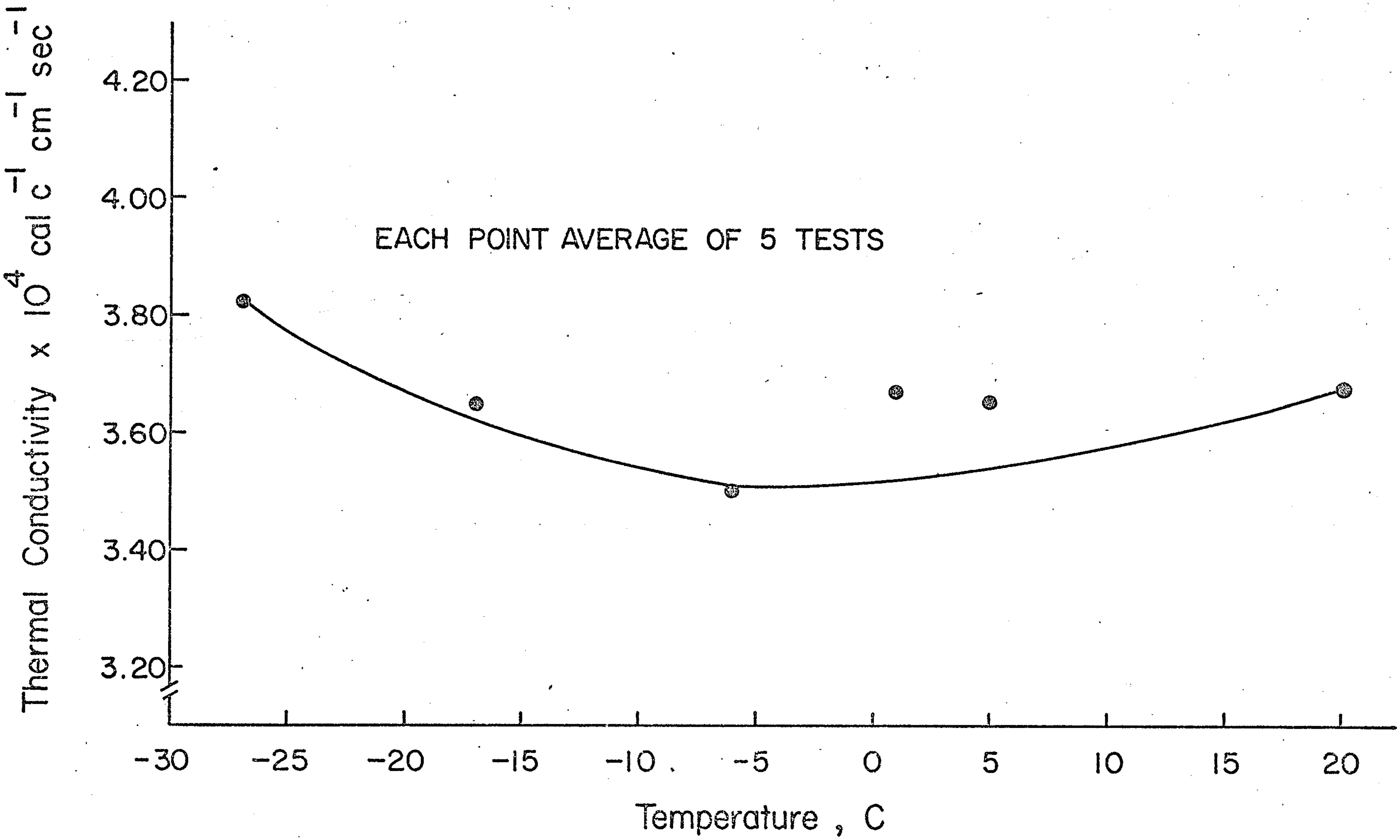

FIG. 17 THERMAL CONDUCTIVITY OF SPRING WHEAT AT 10.8 % MOISTURE CONTENT

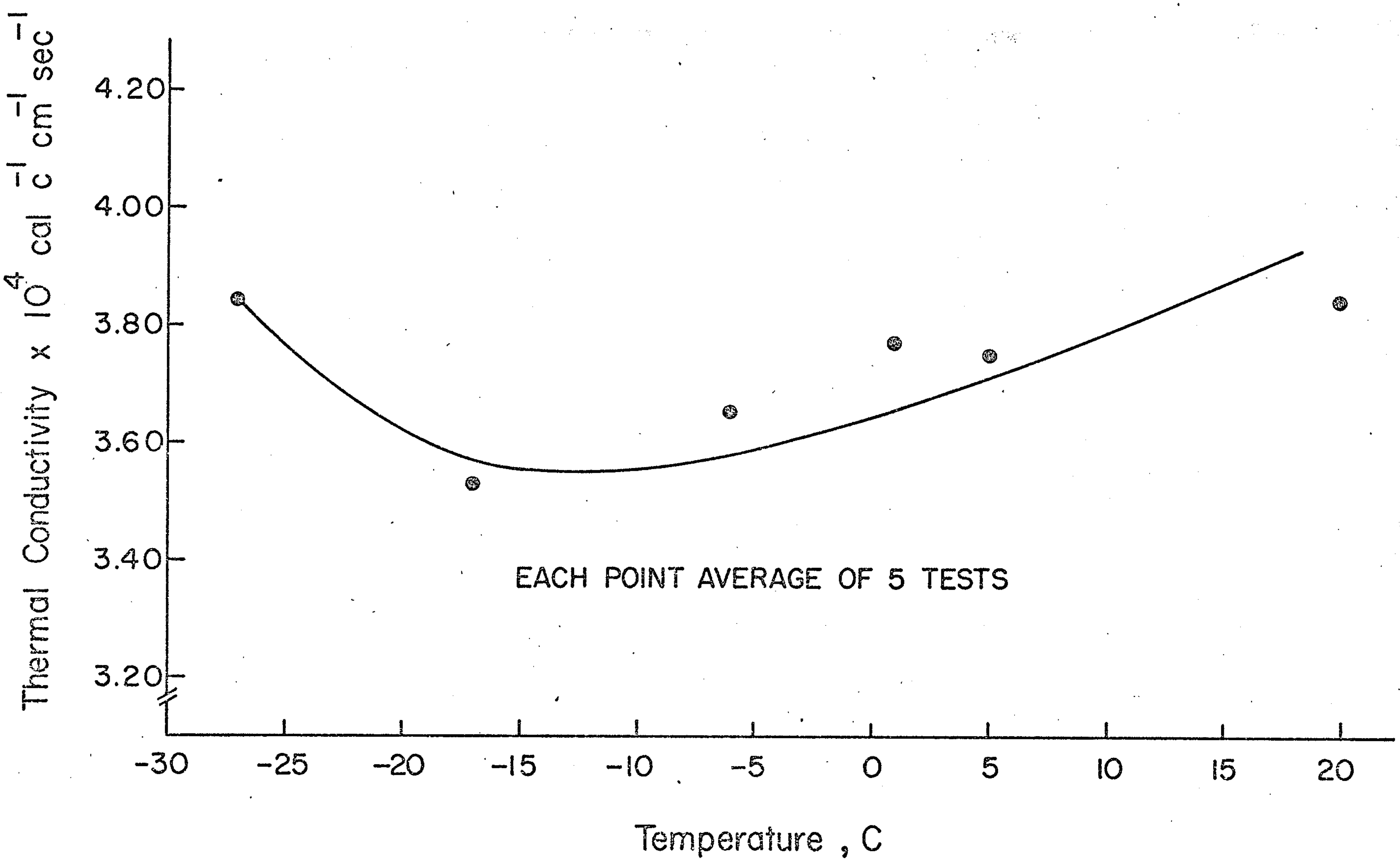

FIG. 18 THERMAL CONDUCTIVITY OF SPRING WHEAT AT 15.2 % MOISTURE CONTENT

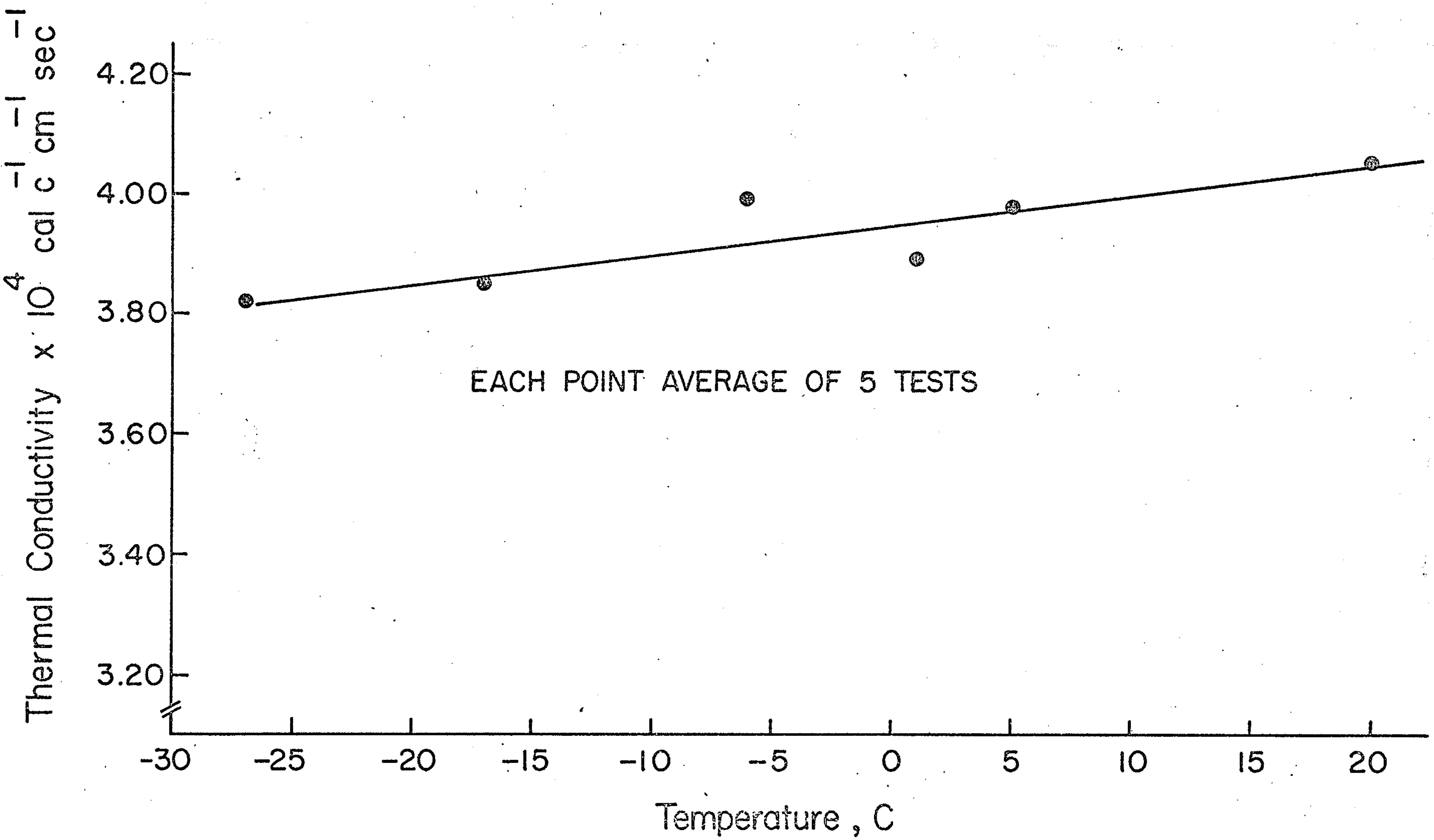

FIG. 19 THERMAL CONDUCTIVITY OF SPRING WHEAT AT 19.0 % MOISTURE CONTENT

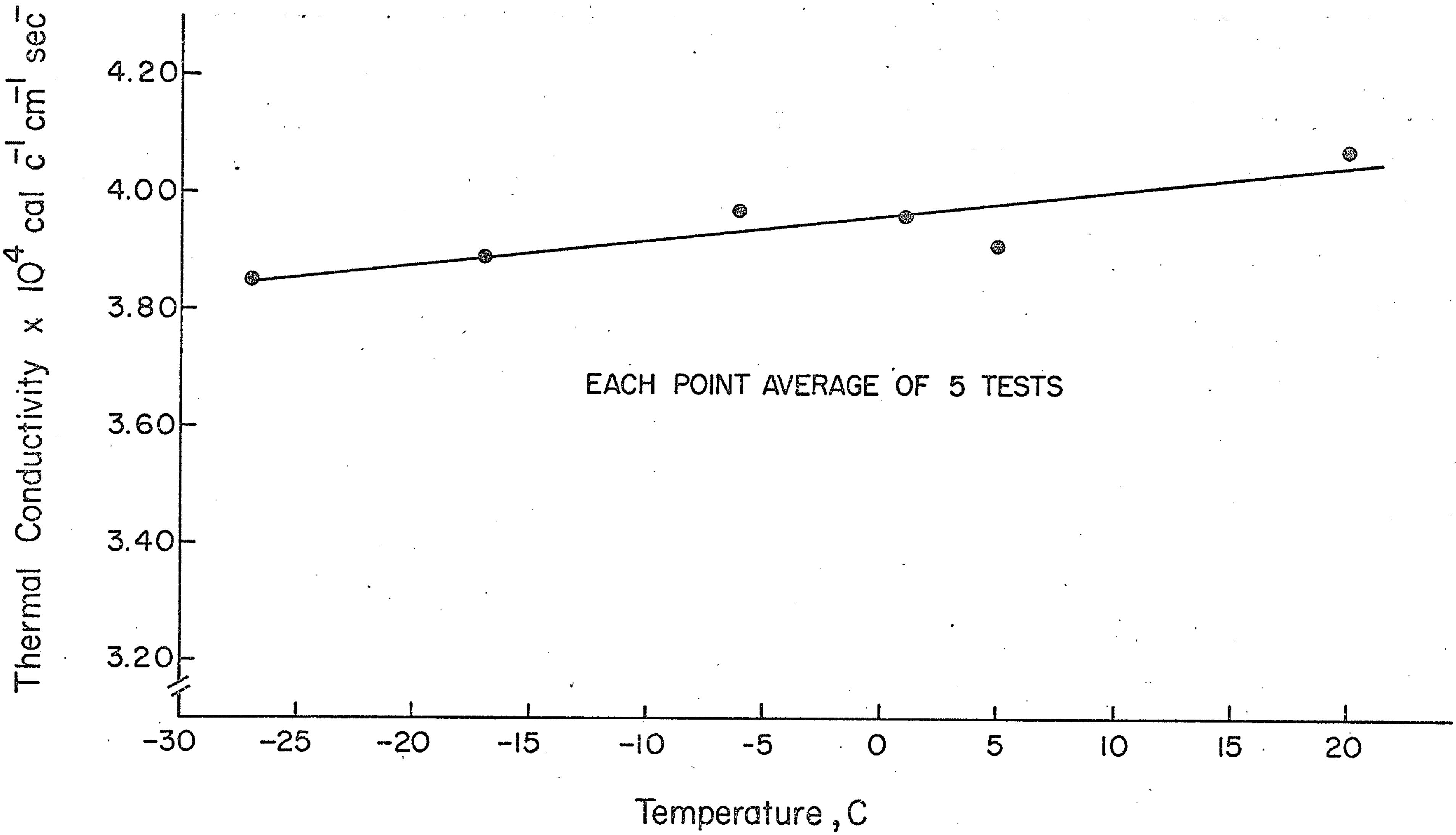

FIG. 20 THERMAL CONDUCTIVITY OF SPRING WHEAT AT 22.5 % MOISTURE CONTENT

bulk grain is negligible in steady-state apparatus. Since the temperature gradient across the small pore spaces in the wheat with transient state method used in this study is expected to be small, the effect of radiation and convection across the pore spaces can be considered to be negligible. As discussed earlier, total moisture migration in the transient state method can also be considered negligible. It would, therefore, appear that the heat transfer was mainly by conduction under the test conditions.

Since there appears to be no sharp change in the phase of water in the grain it would, therefore, be expected that the thermal conductivity of the grain kernel will decrease with decreasing temperatures. Also, decreasing temperatures cause a decrease in thermal conductivity of the air in the pore spaces (Kreith, 1965). The combined effect of these two factors is a decrease in thermal conductivity of wheat with decreasing temperatures. Dua and Ojha (1969) reported that the thermal conductivity of grains increases with increase in density. The increase in density could result in increased kernel to kernel contact and thereby causing an increase in conduction between kernels. Therefore, the only factor that could cause an increase in thermal conductivity as the temperature decreases below the temperature at which the thermal conductivity is minimum is an increase in conduction from kernel to kernel due to increase in bulk density. Such an increase in bulk density was found between +20C and -6C (Figure 21). The increase in bulk density will also decrease the size of pore spaces, which might decrease the effect of pore spaces on lowering the thermal conductivity at lower temperatures. So the increasing bulk density may become the dominate factor affecting thermal conductivity as the temperature drops below the temperature at

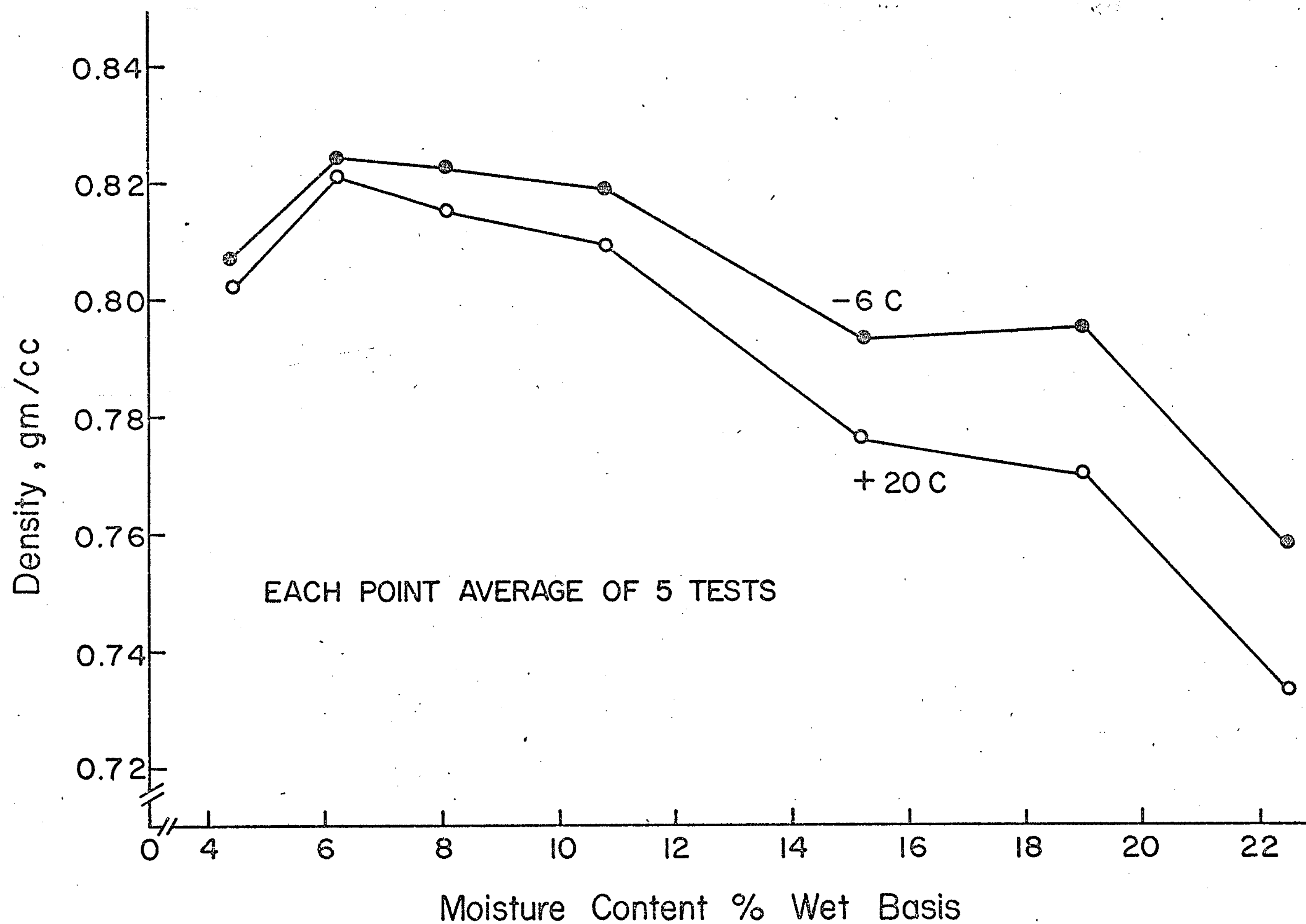

FIG. 21 DENSITY OF SPRING WHEAT AT 20 C AND −6 C

which the thermal conductivity is minimum causing the increase in thermal conductivity.

The effect of moisture content in increasing the thermal conductivity of grain is twofold:

1) Since the thermal conductivity of water is more than that of dry grain, it increases the thermal conductivity of grain,

2) there is more increase in density with lowering of temperature at higher moisture content than low moisture content (Figure 21), which increases the kernel to kernel contact thereby increasing the thermal conductivity

Due to increase in density, with lowering of temperature at the same moisture content, size of pore spaces may be reduced, which might decrease the effect of pore spaces on lowering thermal conductivity of wheat. But at high moisture contents the density of grain is greatly reduced, and the overall effect of moisture on density at low temperatures is still a decrease in density (Figure 21). Also, the thermal conductivity of water below 121C decreases with decreasing temperatures (Kreith, 1965). This decrease in thermal conductivity will be greater at higher moisture contents. Therefore, the overall effect of moisture contents on thermal conductivity at low temperatures will be a small increase in thermal conductivity with increasing moisture contents. This might be the reason for smaller slopes in regression Equation (4.5) and (4.6) at -17C and -27C respectively.

5. CONCLUSIONS

The general conclusions of this study of measuring thermal conductivity of spring wheat at low temperatures are:

1) The thermal conductivity of spring wheat for a moisture content range of 4.4% to 22.5% varied from 0.000329 to 0.000407 cal C^{-1} cm^{-1} sec^{-1} within the temperature range of -27C to +20C.

2) Thermal conductivity was a linear function of moisture content above a temperature of -8C. The relationship below this temperature was not as strong.

3) Thermal conductivity was minimum at about -8C and increased with both increasing temperatures above this and with decreasing temperatures below this temperature.

4) Moisture content appears to be affecting thermal conductivity less at low temperatures than at high temperatures.

5) Thermal conductivity of mouldy wheat was less than that of uninfected wheat at the same moisture content for all temperatures.

6) Density of wheat was more at -6C than at +20C. The effect of temperature on density was more at higher moisture contents than at lower moisture contents.

7) There does not appear to be any change in phase of water present in wheat containing 4.4% to 22.5% moisture down to temperature of -27C.

6. SUGGESTIONS FOR FUTURE STUDY

1) The effect of density of grain on thermal conductivity should be investigated.
2) The effect of temperature on density of grains should be studied more thoroughly.
3) The effect of adsorption and desorption of moisture on thermal conductivity should be investigated.
4) The effect of different type and extent of fungal growth on thermal conductivity should be studied.
5) The temperature gradients within pore spaces and their effect on heat movement should be investigated.
6) The effect of thermal expansion of grain should be studied.
7) The rate of heat transfer across the kernel contact surfaces should also be determined.

7. REFERENCES

Babbitt, J.D. 1945: The thermal properties of wheat in bulk. Can. J. of Res., 23: 300-401.

Bakke, A.L. and Stiles, H. 1935. Thermal conductivity of stored oats with different moisture content. Plant Physiology 10: 521-524.

D'Eustachio, D. and Schreiner, R.E. 1952. A study of a transient heat method for measuring thermal conductivity. Amer. Soc. Heat. and vent. Eng. Trans. 58: 331-342.

Dua, K.K. and Ojha, T.P. 1969. Measurement of thermal conductivity of paddy grains and its by-products. J. Agri. Engr. Res. 14(1): 11-17.

Hooper, F.C. and Lepper, F.R. 1950. Transient heat flow apparatus for the determination of thermal conductivity. Amer. Soc. Heat. and Vent. Eng. Trans. 56: 309 - 322.

Hooper, F.C. and Chang, S.C. 1953. Developement of the thermal conductivity probe. Amer. Soc. Heat. and Vent. Eng. Trans. 59: 463 - 472.

Kazarian, E.A. and Hall C.W. 1956. Thermal properties of grain. Trans. ASAE 8(1): 33 - 48.

Kreith, F. 1965. Principles of heat transfer. International Textbook Company. Scranton, Pennsylvania. 595 - 597.

Lentz, C.P. 1961. Thermal conductivity of meats, fats gelatin, gels and ice. Food Tech. 15: 243-247.

Moote, I. 1953. The effect of moisture on the thermal properties of wheat. Can. J. of Tech. 31: 57-69.

Oxley, T.A. 1944. The properties of grain in bulk. Soc. Chem. Indus. J. Trans. 63: 53-57.

Pixton, S.W. and Warburton, S. 1968. The time required for conditioning grain to equilibrium with specific relative humidities. J. Stored Prod. Res. 4: 261-265.

Reidy, G.A. and Rippen, A.L. 1969. Methods for determining thermal conductivity of foods. ASAE Paper No. 69-383.

Wratten, F.T., Poole, W.D., Chesness, J.L., Bal, S. and Ramarao, R. 1969. Physical and thermal properties of rough rice. Trans. ASAE. 12(6): 801-803.

Other references not cited in the text

Allen, P.H., 1959. Fluid thermal conductivity by a transient method. Symposium on thermal properties. Purdue University, Amer. Soc. Mech. Engrs. 350-357.

Bard, F.F. and Keppler,R.A. 1969. A method of predicitng the thermal properties of frozen sucrose - corn syrup solid solutions. ASAE paper No. 69-384.

Bhilotra, K.R.K. 1964. Measurements of the thermal conductivity of some organic liquids and a study of methods employed for such measurements. An unpublished Master of Science thesis. Department of Mechanical Engineering, University of Manitoba.

DeVries, D.A. 1952. Non-stationary method for determining thermal conductivity of soil in situ. soil science 73: 83-89.

Frechette, R.J. and Zahradnik, J.W. 1960. Thermal properties of McIntosh Apple. Trans. ASAE. 11(1): 21-27

Gaffney, J.J. and Stephenson,K.Q. 1960. Apparent thermal conductivity during freeze drying of a food model. Trans. ASAE 11(6): 874-880.

Hall, C.W. 1957. Drying farm crops. Edwards brothers, Inc. Ann Arbor, Michigan.

Hoel, P.G. 1967. Elementary statistics, second edition. John Wiley & Sons. Inc. New York.

Kazarian, E.A. 1962. Thermal properties of grain. An unpublished Master of Science thesis. Agricultural Engineering Department. Michigan State University.

Lentz, C.P. 1952. A transient heat flow method of determining thermal conductivity: Application to insulating materials, Can. J. of Tech. 30: 153-166.

Muir, W.E. 1970. Temperatures in grain bins. Can. Agr. Engr. 12(1): 21-24.

Skaggs, R.W. and Smith, E.M. 1968. Apparant thermal conductivity of soil as related to soil porosity. Trans. ASAE 11(4): 504-507.

Smith, R.E. and Nelson, G.L. 1969. Transient heat transfer in solids-theory versus experiment. Trans. ASAE. 12(6): 833-836.

Swindells, J.F. 1968. Precision measurement and calibration. National Bureau of Standards. United States department of Commerce. Special publication No. 300-vol. 2.

Van Der Held, E.F.M. and Van Drunen, F.G. 1949. A methof of measuring the thermal conductivity of liquids. Physicia. 15(10): 865-881.

APPENDIX A

Temperature-time relationship

This appendix includes figures A-1 and A-2 which show the relationship between temperature and log (time). The time θ_1 was determined from these figures.

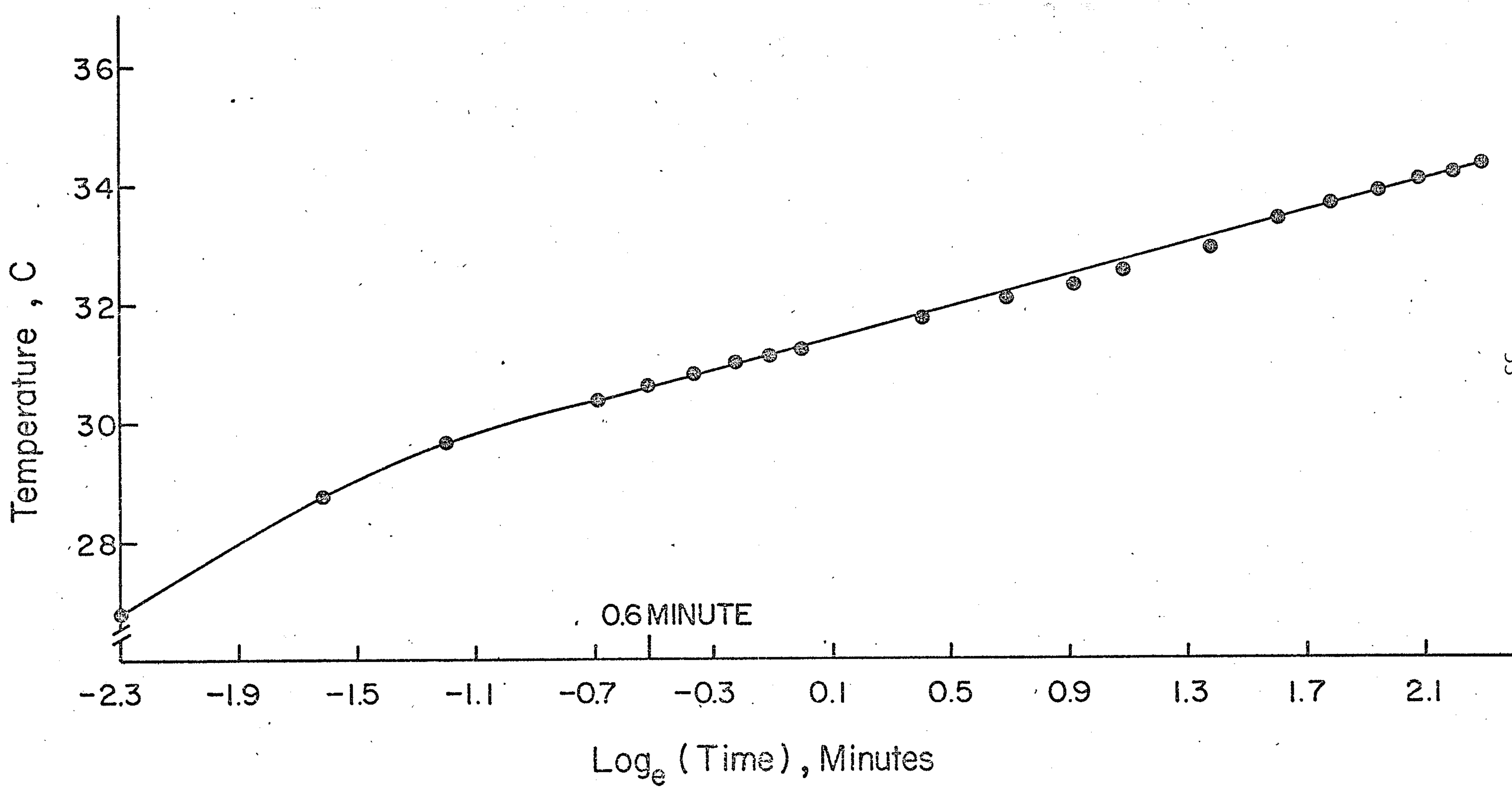

FIG. A-1 TEMPERATURE VS LOG$_e$ (TIME) PLOT

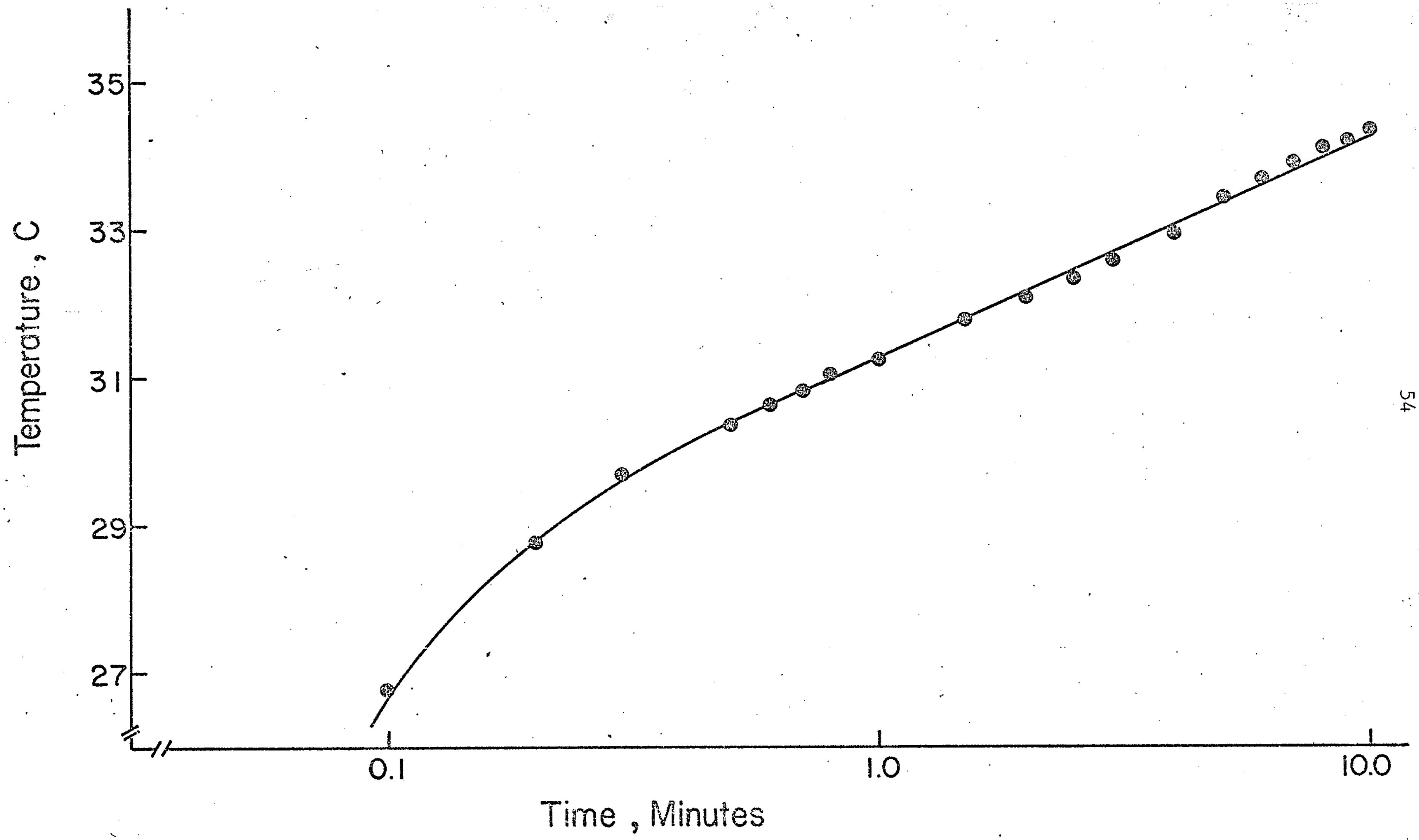

FIG. A-2 TEMPERATURE VS LOG_{10} (TIME) PLOT

APPENDIX B

SAMPLE CALCULATIONS

This section includes a typical calculation procedure used to calculate the thermal conductivity for each test determination. The equation for thermal conductivity is:

$$k = \frac{Q}{4\pi(t_2 - t_1)} \log_e \left[\frac{\theta_2 - \theta_0}{\theta_1 - \theta_0}\right] \qquad (B.1)$$

where:

k = thermal conductivity,

t_1 = temperature at time θ_1,

t_2 = temperature at time θ_2,

Q = heat in put per unit length of line heat source,

θ_o = time correction.

To calculate the thermal conductivity, k, in metric units the equation is modified as:

$$k = \frac{i^2 R_e 4.3}{72\pi(t_2 - t_1)} \log_e \left[\frac{\theta_2 - \theta_1}{\theta_1 - \theta_0}\right] \qquad (B.2)$$

where:

k = thermal conductivity, cal C^{-1} cm^{-1} sec^{-1},

i = current, amperes

R_e = electrical resistance of the heater, ohms per cm,

t = temperature, C.

For wheat having 10.8% moisture content:

i = 0.502 amperes,

R_e = 0.0985 ohms per cm,

θ_o = 3 seconds,

Initial temperature = 5.9C,

Temperature after 1 minute of heating = 14.78C,

Temperature after 7 minutes of heating = 17.38C,

Temperature after 8 minutes of heating = 17.55C,

Temperature after 9 minutes of heating = 17.70C.

Substituting these values into Equation (B.2) yields:

1) For 1 and 7 minutes,

$$k = 0.000361 \text{ cal } C^{-1} \text{ cm}^{-1} \text{ sec}^{-1};$$

2) For 1 and 8 minutes,

$$k = 0.000362 \text{ cal } C^{-1} \text{ cm}^{-1} \text{ sec}^{-1};$$

3) For 1 and 9 minutes,

$$k = 0.000363 \text{ cal } C^{-1} \text{ cm}^{-1} \text{ sec}^{-1};$$

Average of three is,

$$k = 0.000362 \text{ cal } C^{-1} \text{ cm}^{-1} \text{ sec}^{-1}.$$

APPENDIX C

Tables of data

In this section, different values of thermal conductivity and density determined at different moisture contents and temperatures are reported. Tables C-1 to C-6 are for thermal conductivity and tables C-7 and C-8 are for density.

Table C-1 Thermal conductivity of spring wheat at 20C

Moisture content, percent	Thermal conductivity, 10^{-4} cal C^{-1} cm^{-1} sec^{-1}						
	4.4	6.2	8.1	10.8	15.2	19.0	22.5
	3.38	3.84	3.35	3.70	4.08	4.14	4.15
	3.54	3.53	3.46	3.65	3.74	3.94	4.13
	3.62	3.75	3.70	3.89	3.93	4.07	3.90
	3.34	3.81	3.92	3.52	3.64	3.91	4.10
	3.32	3.52	3.50	3.64	3.82	4.21	4.09
Average	3.44	3.69	3.59	3.68	3.84	4.05	4.07
Standard deviation	0.133	0.154	0.225	0.135	0.170	0.128	0.100

Table C-2 Thermal conductivity of spring wheat at 5C

Moisture content, percent	Thermal conductivity, 10^{-4} cal C^{-1} cm^{-1} sec^{-1}						
	4.4	6.2	8.1	10.8	15.2	19.0	22.5
	3.66	3.59	3.40	3.74	3.88	4.05	3.91
	3.42	3.70	3.70	3.57	3.81	4.07	4.05
	3.42	3.80	3.68	3.62	3.68	4.00	3.64
	3.57	3.62	3.60	3.96	3.76	3.90	3.98
	3.55	3.68	3.54	3.38	3.62	3.90	3.99
Average	3.52	3.68	3.58	3.65	3.75	3.98	3.91
Standard deviation	0.103	0.081	0.121	0.214	0.103	0.081	0.161

Table C-3 Thermal conductivity of spring wheat at 1C

Moisture content, percent	Thermal conductivity, 10^{-4} cal C^{-1} cm^{-1} sec^{-1}						
	4.4	6.2	8.1	10.8	15.2	19.0	22.5
	3.41	3.44	3.63	3.69	3.86	3.88	3.90
	3.24	3.48	3.40	3.69	3.70	3.91	3.92
	3.42	3.52	3.44	3.77	3.73	3.85	4.01
	3.45	3.47	3.58	3.63	3.88	3.89	3.96
	3.28	3.41	3.62	3.56	3.66	3.92	4.01
Average	3.36	3.46	3.53	3.67	3.77	3.89	3.96
Standard deviation	0.094	0.042	0.107	0.078	0.098	0.027	0.051

Table C-4 Thermal conductivity of spring wheat at -6C

Moisture content, percent	Thermal conductivity, 10^{-4} cal C^{-1} cm^{-1} sec^{-1}						
	4.4	6.2	8.1	10.8	15.2	19.0	22.5
	3.33	3.29	3.39	3.61	3.55	3.98	4.02
	3.35	3.49	3.46	3.50	3.57	4.04	3.97
	3.28	3.46	3.67	3.41	3.77	4.08	4.07
	3.35	3.59	3.44	3.50	3.64	3.94	4.01
	3.40	3.45	3.37	3.49	3.73	3.91	3.78
Average	3.34	3.46	3.47	3.50	3.65	3.99	3.97
Standard deviation	0.043	0.108	0.120	0.071	0.096	0.070	0.112

Table C-5 Thermal conductivity of spring wheat at -17C

Moisture content, percent	Thermal conductivity, 10^{-4} cal C^{-1} cm^{-1} sec^{-1}						
	4.4	6.2	8.1	10.8	15.2	19.0	22.5
	3.34	3.46	3.61	3.59	3.48	3.79	4.06
	3.31	3.68	3.65	3.63	3.31	3.91	3.85
	3.23	3.68	3.71	3.65	3.69	3.93	4.07
	3.32	3.71	3.62	3.63	3.47	3.92	3.89
	3.24	3.68	3.71	3.76	3.69	3.71	3.59
Average	3.29	3.64	3.66	3.65	3.53	3.85	3.89
Standard deviation	0.050	0.103	0.048	0.064	0.162	0.098	0.195

Table C-6 Thermal conductivity of spring wheat at -27C

Moisture content, percent	Thermal conductivity, 10^{-4} cal C^{-1} cm^{-1} sec^{-1}						
	4.4	6.2	8.1	10.8	15.2	19.0	22.5
	3.30	3.51	3.66	3.83	3.78	3.90	3.96
	3.26	3.63	3.71	3.63	3.90	3.88	3.81
	3.32	3.64	3.65	3.82	3.69	3.73	4.16
	3.40	3.70	3.80	3.94	3.84	3.82	3.55
	3.22	3.60	3.69	3.87	4.00	3.78	3.79
Average	3.30	3.62	3.70	3.82	3.84	3.82	3.85
Standard deviation	0.068	0.069	0.060	0.115	0.117	0.070	0.225

Table C-7 Density of spring wheat at 20C

Moisture content, percent	4.4	6.2	8.1	10.8	15.2	19.0	22.5
	Density, g cm^{-3}						
	0.800	0.821	0.799	0.809	0.770	0.774	0.731
	0.803	0.819	0.822	0.815	0.765	0.772	0.732
	0.805	0.821	0.826	0.805	0.779	0.772	0.732
	0.799	0.821	0.815	0.805	0.776	0.767	0.736
	0.803	0.821	0.815	0.812	0.790	0.763	0.736
Average	0.802	0.821	0.815	0.809	0.776	0.770	0.733

Table C-8 Density of spring wheat at -6C

Moisture content, percent	4.4	6.2	8.1	10.8	15.2	19.0	22.5
	Density, g cm^{-3}						
	0.806	0.826	0.826	0.822	0.786	0.797	0.756
	0.808	0.825	0.815	0.820	0.797	0.795	0.756
	0.803	0.825	0.826	0.820	0.795	0.795	0.758
	0.803	0.819	0.821	0.820	0.794	0.793	0.758
	0.815		0.825	0.815	0.792	0.797	0.761
Average	0.807	0.824	0.823	0.819	0.793	0.795	0.758

APPENDIX D

Calculated values of Thermal Conductivity

This appendix consists of table D-1, which shows the values of thermal conductivity for a moisture content range of 4% to 23%. These values were calculated by Equations 4.1 to 4.6 for each temperature.

TABLE C-1 CALCULATED VALUES OF THERMAL CONDUCTIVITY, cal C^{-1} cm^{-1} sec^{-1}

% M.C.	TEMPERATURES, C					
	20C	5C	1C	-6C	-17C	-27C
4.00	0.0003475	0.0003531	0.0003390	0.0003317	0.0003450	0.0003521
5.00	0.0003508	0.0003554	0.0003422	0.0003353	0.0003472	0.0003544
6.00	0.0003542	0.0003577	0.0003455	0.0003390	0.0003494	0.0003567
7.00	0.0003576	0.0003600	0.0003487	0.0003427	0.0003517	0.0003590
8.00	0.0003610	0.0003622	0.0003520	0.0003464	0.0003539	0.0003612
9.00	0.0003643	0.0003645	0.0003552	0.0003500	0.0003562	0.0003635
10.00	0.0003677	0.0003668	0.0003585	0.0003537	0.0003584	0.0003658
11.00	0.0003711	0.0003691	0.0003617	0.0003574	0.0003606	0.0003681
12.00	0.0003744	0.0003714	0.0003650	0.0003610	0.0003629	0.0003704
13.00	0.0003778	0.0003736	0.0003682	0.0003647	0.0003651	0.0003726
14.00	0.0003812	0.0003759	0.0003715	0.0003684	0.0003674	0.0003749
15.00	0.0003845	0.0003782	0.0003747	0.0003720	0.0003696	0.0003772
16.00	0.0003879	0.0003805	0.0003780	0.0003757	0.0003718	0.0003795
17.00	0.0003913	0.0003828	0.0003812	0.0003794	0.0003741	0.0003818
18.00	0.0003947	0.0003850	0.0003845	0.0003831	0.0003763	0.0003840
19.00	0.0003980	0.0003873	0.0003877	0.0003867	0.0003786	0.0003863
20.00	0.0004014	0.0003896	0.0003910	0.0003904	0.0003808	0.0003886
21.00	0.0004048	0.0003919	0.0003942	0.0003941	0.0003830	0.0003909
22.00	0.0004081	0.0003942	0.0003975	0.0003977	0.0003853	0.0003932
23.00	0.0004115	0.0003964	0.0004007	0.0004014	0.0003875	0.0003954