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THERMAL CONDUCTIVITY AND THERMAL DIFFUSIVITY OF NORTH DAKOTA AND MONTANA LIGNITE

by

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This Thesis submitted by Julio F. Duarte in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

ABSTRACT

The objective of this experiment was to determine the thermal conductivity and thermal diffusivity of lignite from five mines in North Dakota and Montana with full bed moisture.

The values of the thermal conductivity and thermal diffusivity found in the present work do not show a significant difference between samples. The thermal conductivity ranges from 0.152 to 0.170 Btu hr^{-1} ft^{-1} $°F^{-1}$. The thermal diffusivity was from 0.0051 to 0.0058 sq ft hr^{-1}. No significant difference was found due to the cut of the samples with the long axis parallel or perpendicular to the bedding plane.

Specific heat and density determinations for each sample of lignite were made. These values ranged from 0.33 to 0.43 Btu lb^{-1} $°F^{-1}$ and from 74.3 to 82.9 lb ft^{-3} respectively.

INTRODUCTION

The primary objective of this investigation was to determine the thermal conductivity and thermal diffusivity of lignite with full bed moisture content from different mines in North Dakota and Montana.

Lignite is essentially an organic material, the product of the degradation of cellulose and other plant tissues and contains, like many other materials of vegetable origin, some water in a state of physical or chemical combination, as well as inherent and extraneous ash. When exposed to air of average humidity, lignite does not dry completely, but assumes rather a state of moisture equilibrium at which there remains in the lignite from 12 to 20 percent of moisture depending on the kind of lignite and the humidity of the air.

Lignite is a conglomerate of varying composition, and is unstable, tending to shrink with loss of moisture and to slack on exposure. Consequently physical characteristics can vary depending on initial composition and history of the sample.

The method used for thermal conductivity and for thermal diffusivity of lignite required the determination of certain other properties of the system including the heat transfer coefficient at the solid-fluid interface, the specific heat, and the density of the lignite.

A simple unsteady state method with a graphical solution, as outlined by Newman,[1] was used to determine the thermal conductivity and thermal diffusivity of lignite. Temperature was determined as a function of time at the center of single pieces of lignite cut in the shape of a rectangular parallelopiped. The thermal conductivity and thermal diffusivity were calculated from the unsteady state temperature history and the physical properties of the lignite.

REVIEW OF PERTINENT LITERATURE

Numerous experimental techniques have been devised for the determination of thermal conductivity and thermal diffusivity of solids, some involving steady state and some, unsteady state measurements of temperature. In steady state methods, the conditions of the experiment are maintained for a sufficient time to allow the temperature throughout the sample to reach a steady value. In unsteady state methods, the temperature is measured as a function of time.

The first reference to the unsteady state method of determining the thermal conductivity of solids was the work of Angstroem.[2,3,4] He produced periodic changes of temperature by alternately heating and cooling metal rods in air. Neumann[5] in 1862 showed how to determine the thermal diffusivity by air cooling of rods and tubes which had been previously heated at one end. Since then numerous modifications of the unsteady state method have been applied.

In 1923 Gurney and Lurie[6] presented a set of charts for solution of the unsteady state heat transfer of heat in a slab, an infinite cylinder, sphere and semi-infinite solid. By the use of the appropriate chart, it is possible to calculate the thermal conductivity and thermal diffusivity from the temperature history of the sample given the boundary values for a specific case.

In 1947 Heisler[7] presented similar charts for different geometries. These are the most complete charts in this field and were used in the present work to determine the thermal conductivity and thermal diffusivity of lignite.

Kegel and Mastchak[8] determined the thermal conductivity of German brown coals using the moisture content as a variable. Fritz and Diemke[9,10] also made many determinations of the thermal conductivity of German coals. Results show a range of thermal conductivity from 0.112 to 0.210 Btu ft^{-1} hr^{-1} $^{o}F^{-1}$ at 86° F. Zubilin[11,12] determined the thermal diffusivity and thermal conductivity of Russian coals ground and compacted to different densities. The experimental apparatus used by Zubilin was similar to the one used in the present research. His results are summarized in Table 1. Margit[13] in Hungary and Badzioch, Gregory and Field[14] in England determined the thermal properties of various coals by a hot wire method. A straight-wire heat source was inserted in the coal samples, and the temperature history at a point in the sample was determined. This information was used to calculate thermal conductivity and thermal diffusivity. Originally the hot-wire method was developed by Van der Held and Van Drunen[15] for determining the thermal conductivity and thermal diffusivity of poor conductors.

TABLE 1

THERMAL CONDUCTIVITY AND THERMAL DIFFUSIVITY OF COAL[a]

Coal Grade	C[b]			K[c]			OS[d]			Mixed Charge		
Bulk density lb ft^{-3}	50.0	56.2	62.4	50.0	56.2	62.4	50.0	56.2	62.4	50.0	56.2	62.4
Thermal conductivity Btu ft^{-1} hr^{-1} °F^{-1}	0.063	0.070	0.078	0.064	0.072	0.081	0.057	0.067	0.077	0.063	0.072	0.080
Thermal diffusivity sq ft hr^{-1}	0.0063	0.0037	0.0036	0.0040	0.0041	0.0042	0.0041	0.0043	0.0045	0.0040	0.0040	0.0041

[a] I. G. Zubilin, "Determination of the Thermal Constants of Coals at Different Bulk Densities," Zavodskaya Laboratorlya, 27, 431-433, 1961.

[b] Volatile matter: 37.4%

[c] Volatile matter: 26.3%

[d] Volatile matter: 15.2%

Badzioch, Gregory and Field[14] also used another method, the slab method, to determine the thermal diffusivity of coals. A slab of coal was heated in a furnace and temperatures were taken at different points. The thermal diffusivity was calculated using the solution of the conduction equation in one dimension. These results are summarized for Hungarian coals in Table 2 and for British coals in Table 3.

TABLE 2

THERMAL CONDUCTIVITY OF HUNGARIAN COALS[a]

Samples	Density lb ft^{-3}		Initial Temperature °F	Final Temperature °F	Average Temperature °F	Thermal Conductivity Btu hr^{-1} ft^{-1} °F^{-1}
	Wet	Dry				
Tatai, washed coal, 12.3% moisture	43.7	38.4	81	223	152	0.161
			88	289	188	0.162
			102	453	278	0.176
			162	793	483	0.237
Borsodi, regular briquets, 8.0% moisture	38.6	35.4	81	176	128	0.233
			86	217	152	0.241
			100	329	215	0.260
			117	417	267	0.280
Szentgali, lignite, 6.0% moisture	42.3	39.8	77	221	149	0.136
			79	344	207	0.137

---

[a] W. Margit, "Determination of the Specific Heat and the Heat Conductivity Factor of Hungarian Coals and Cokes," *Nehezvegyipari Kutato Intezet*, *1*, 27-37, 1958.

TABLE 3

THERMAL CONDUCTIVITY AND THERMAL DIFFUSIVITY OF BITUMINOUS AND ANTHRACITE BRITISH COALS[a]

	Hot Wire Method				Slab Method	
Temperature $^{\circ}$F	Thermal Conductivity Btu ft^{-1} hr^{-1} $^{\circ}$F^{-1}		Thermal Diffusivity sq ft hr^{-1}		Thermal Diffusivity sq ft hr^{-1}	
	Mean	Range	Mean	Range	Mean	Range
68	0.160	0.133 - 0.194	0.0062	0.0039 - 0.0077	0.0066	0.0047 - 0.0082
212	0.133	0.109 - 0.194	0.0050	0.0031 - 0.0077	0.0058	0.0039 - 0.0074
302	0.133	0.109 - 0.194	0.0047	0.0031 - 0.0077	0.0054	0.0031 - 0.0070
392	0.136	0.109 - 0.194	0.0043	0.0031 - 0.0077	0.0047	0.0031 - 0.0066
482	0.136	0.109 - 0.194	0.0047	0.0031 - 0.0077	0.0043	0.0031 - 0.0058
572	0.138	0.109 - 0.194	0.0043	0.0031 - 0.0077	0.0043	0.0031 - 0.0054
662	0.136	0.109 - 0.194	0.0050	0.0031 - 0.0077	0.0047	0.0031 - 0.0054
752	0.124	0.109 - 0.194	0.0055	0.0031 - 0.0077	0.0047	0.0031 - 0.0054
842	0.155	0.121 - 0.290	0.0070	0.0039 - 0.0135	0.0051	0.0031 - 0.0054
932	0.194	0.145 - 0.290	0.0110	0.0058 - 0.0155	0.0062	0.0035 - 0.0058
1022	0.238	0.169 - 0.363	0.0120	0.0077 - 0.0023	0.0082	0.0039 - 0.0062

---

[a] S. Badzioch, D. R. Gregory, and M. A. Field, "Investigation of the Temperature Variation of the Thermal Conductivity and Thermal Diffusivity of Coals," Fuel, 43, 267-280, 1964.

MATHEMATICAL ANALYSIS

An unsteady state method involving a graphical solution was used to determine the thermal conductivity and thermal diffusivity of lignite. Table 4 summarizes the nomenclature used in the present work.

The thermal diffusivity and thermal conductivity are two property values that appear in the solution of the heat conduction equation. Strictly speaking, the thermal conductivity and diffusivity are not constants even for the same substance, but are functions of temperature. However, when the range of temperature is limited, this variation in the thermal conductivity and thermal diffusivity may be neglected.

Various experimental methods have been used for determining thermal conductivity and thermal diffusivity; some of these are obsolete, but the mathematical treatment, presented as follows, is the same for all of them.[16]

An example of a steady state determination can be a solid bounded by two infinite parallel planes at different temperatures, when heat has been flowing for a time sufficient to establish uniform conditions. The results of experiments show that:

TABLE 4

NOMENCLATURE

q = Rate of heat flow, Btu hr^{-1} ft^{-2}

t = Temperature at time θ at a point in the solid, ^{o}F

t_o = Initial uniform temperature of solid, ^{o}F

t_s = Constant temperature of the fluid medium, ^{o}F

$\frac{t_s - t}{t_s - t_o}$ = Dimensionless temperature at a given x, y

x, y = Distance from center of solid, ft

θ = Time, hr

k = Thermal conductivity, Btu hr^{-1} ft^{-1} ^{o}F^{-1}

Cp = Specific heat, Btu lb^{-1} ^{o}F^{-1}

ρ = Density, lb ft^{-3}

α = Thermal diffusivity, sq ft hr^{-1}

h = Heat transfer coefficient, Btu ft^{-2} ^{o}F^{-1} hr^{-1}

a, b = Half thickness of rectangular solid in x and y direction respectively, ft

$X(x)$ = Solution of the heat conduction equation in the x direction

$Y(y)$ = Solution of the heat conduction equation in the y direction

$$q = k\frac{t_1 - t_2}{x} \qquad t_1 > t_2 \qquad (1)$$

where q is the rate of heat flow, x is the thickness of the solid between the two planes, t_1 and t_2 are the temperatures at the parallel planes 1 and 2 respectively, and k is the thermal conductivity, which can be determined if the pertinent data are available.

In the past the unsteady state methods have been used less often than steady state methods, as it is difficult to know how nearly the actual boundary conditions in an experiment agree with those postulated in theory. However, unsteady state methods allow for rapid measurements and involve only small changes in temperature.

The time necessary for the temperature at any particular point within an object to reach a particular value is dependent upon physical properties, dimensions and geometry of the object. Convenient geometries for test specimens are a rectangular parallelopiped of finite cross-section or a cylinder of finite diameter with the length in both cases being such that heat transfer along the long axis is negligible. Convenient initial temperature conditions would be a uniform temperature for the object and a uniform but different temperature for the surroundings.

The general partial differential equation for heat flow in rectangular coordinates is:

$$\frac{\partial t}{\partial \theta} = \alpha \left\{ \frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2} \right\} \tag{2}$$

If heat is permitted to flow only in the x direction there is no temperature gradient in the y or z directions, and the equation reduces to that of the slab (see Figure 1).

$$\frac{\partial t}{\partial \theta} = \alpha \frac{\partial^2 t}{\partial x^2} \tag{3}$$

For a slab of thickness $2a$ the central plane being at $x = 0$, the case of heating or cooling by convection at the surfaces $x \pm a$ is represented by the above partial differential equation and by the following boundary conditions:[1]

$$\pm k \frac{\partial t}{\partial x} = h\,(t_s - t) \qquad \text{at} \quad x \mp a$$

each side of the above equation represents the heat quantity passing across unit surface area in unit time, and

$$k \frac{\partial t}{\partial x} = 0 \qquad \text{at} \quad x = 0$$

represents the condition where there is no heat flow across the central plane of the slab because of symmetry. The condition

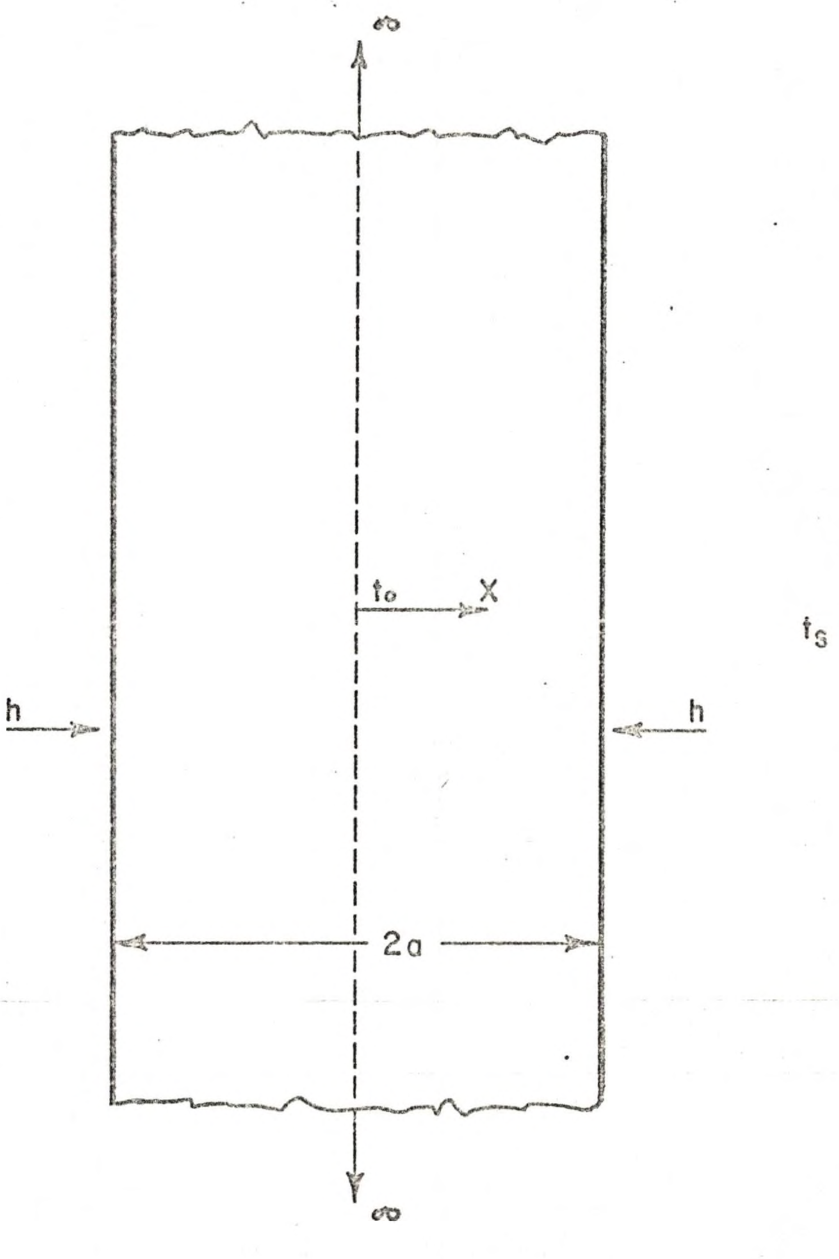

Fig. 1.--Heat flow in a slab of finite thickness.

$$t = t_o \qquad \text{when } \theta = 0$$

indicates uniformity of temperature at the beginning of heating or cooling, and

$$t = t_s \qquad \text{when } \theta = 0$$

$\theta = \infty$?

indicates that eventually the whole slab will be heated or cooled to the temperature of the surroundings.

An equation, in dimensionless form, satisfying the differential equation and the above boundary conditions is:[17]

$$\frac{t_s - t}{t_s - t_o} = 2 \sum_{n=1}^{\infty} \frac{\exp\left[-\beta_n^2\left(\frac{\alpha\theta}{a^2}\right)\right]\left(\frac{ah}{k}\right) \sec \beta_n \cos\left(\beta_n \frac{x}{a}\right)}{\frac{ah}{k}\left(\frac{ah}{k} + 1\right) + \beta_n^2} = X(x) \qquad (4)$$

β_n is defined by $\cot \beta = \left(\frac{k}{ha}\right)\beta$ and the values for β_1 , β_2 , etc., being the first, second, etc., roots of this equation. Tabulated values of β_n were published by Newman and Green.[18]

If it were desired to set up the condition for heat flow in the y direction only, then the partial differential equation would be

$$\frac{\partial t}{\partial \theta} = \alpha \frac{\partial^2 t}{\partial y^2} \qquad (5)$$

and the solution would be identical to the solution obtained for heat flow in the x direction.

If heat were permitted to flow in the x direction and y direction but not in the z direction the differential equation would be:

$$\frac{\partial t}{\partial \theta} = \alpha \left[\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} \right]$$

This is the case in the present research; the length of the lignite samples is very great as compared with the dimension of the cross-section. The thickness of the sample in the x direction is $2a$ and in the y direction is $2b$. It can be proved that a solution satisfying the conditions for this case is:[1]

$$\frac{t_s - t}{t_s - t_o} = X(x) \cdot Y(y)$$

Taking as variables the four dimensionless quantities

$$\frac{\alpha \theta}{a^2}, \quad \frac{k}{ha}, \quad \frac{x}{a}, \quad \frac{t_s - t}{t_s - t_o}.$$

equation 4 has been reduced to a set of tables which are used to plot the curves of Figures 5 and 6 of Appendices D and E. Plots were prepared by Heisler.[7]

In the present research the determinations were made at the center of the samples so that $\frac{x}{a}$ is equal to zero, leaving only three dimensionless parameters. With the curves of Figure 6 the thermal conductivity and diffusivity of lignite can be calculated using a trial and error method explained in Appendix E. To use this method of calculation, the specific heat and density of lignite, and the heat transfer coefficient at the solid-liquid interface must be known.

APPARATUS AND MATERIALS

A thermal conductivity apparatus, manufactured by Engineering Laboratory Design, Inc. of Minnetonka, Minnesota, was used (see Figure 2). The apparatus had the following components:

1. A constant temperature bath with automatic control.
2. A circulation chamber for controlled contact of the samples with the water from the constant temperature bath.
3. A pump to transfer water from the constant temperature bath to the circulation chamber.

To record the temperature history of the samples a SPEEDOMAX W recorder with an adjustable-zero, adjustable range (AZAR) control unit fabricated by Leeds and Northrup Co., of Philadelphia, Pennsylvania, was used.

For the specific heat determination of lignite, a Parr calorimeter manufactured by Parr Instrument Company, Moline, Illinois was used. The calorimeter consisted of a cromium-plated brass water container, 2 liters capacity, supported within a double walled bakelite insulating jacket. A stirrer extended into the water container for agitation. A support rod with bracket was attached to the cover to support a 0.1

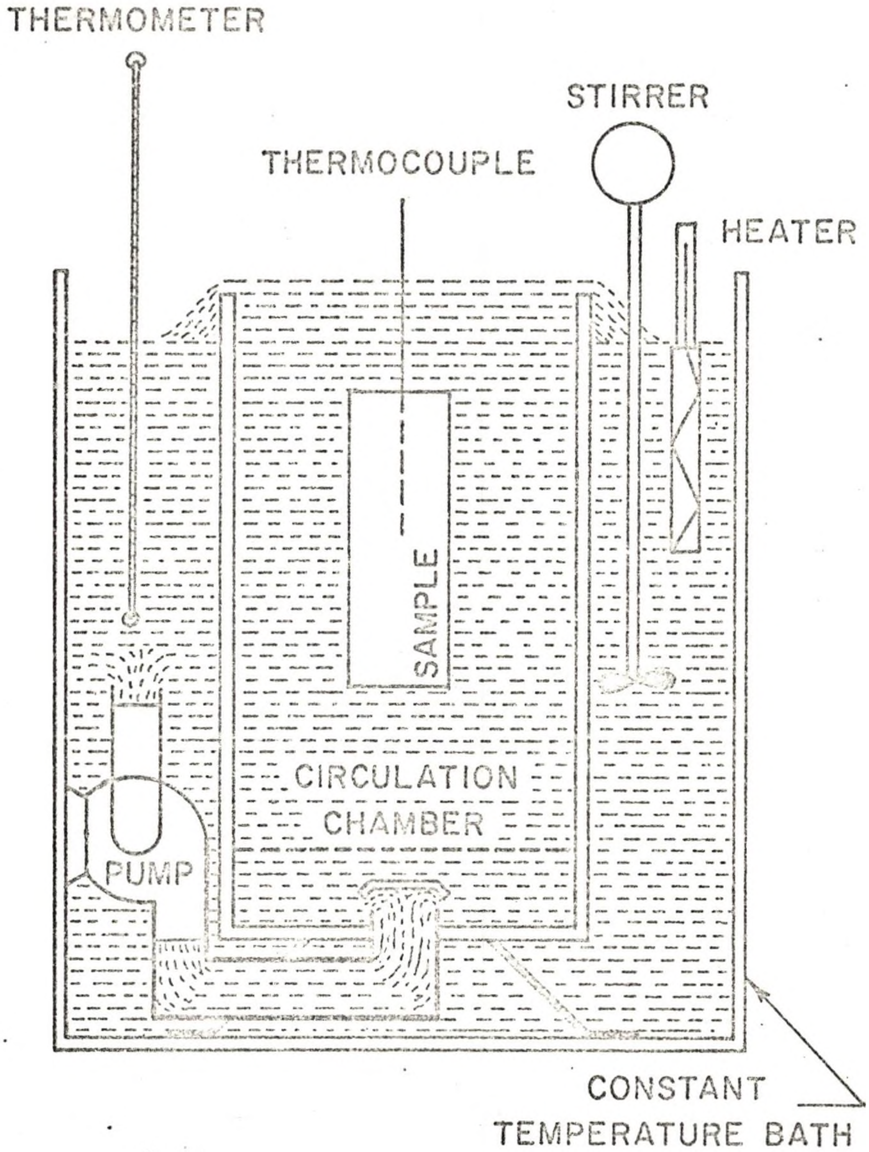

Fig. 2.--Diagram of the thermal conductivity apparatus.

degree thermometer.

A pycnometer with a capacity of 25 ml containing a thermometer was used to determine the density of lignite. The thermometer had a range of 14° to 37° C in 0.2 degree divisions.

The thermocouples used to measure the temperatures were made of copper and constantan wire 0.004 in diameter with a measuring junction 0.001 in thick. The reference junction was maintained at 32° F with an ice water bath.

Samples of acrylic plastic, 1 percent carbon steel, pure aluminum, and 10 percent Sn bronze, all cylindrically shaped, were used for the heat transfer coefficient determinations. Three reference samples were 2 in diameter and 6 in long with the exception of the acrylic plastic sample which was 1 in diameter and 6 in long. Each sample had a copper-constantan thermocouple located at its center (see Figure 3).

The samples of lignite were rectangular parallelopipeds with copper-constantan thermocouples located at their centers. See Figure 4 and Appendix A for additional details concerning the lignite samples.

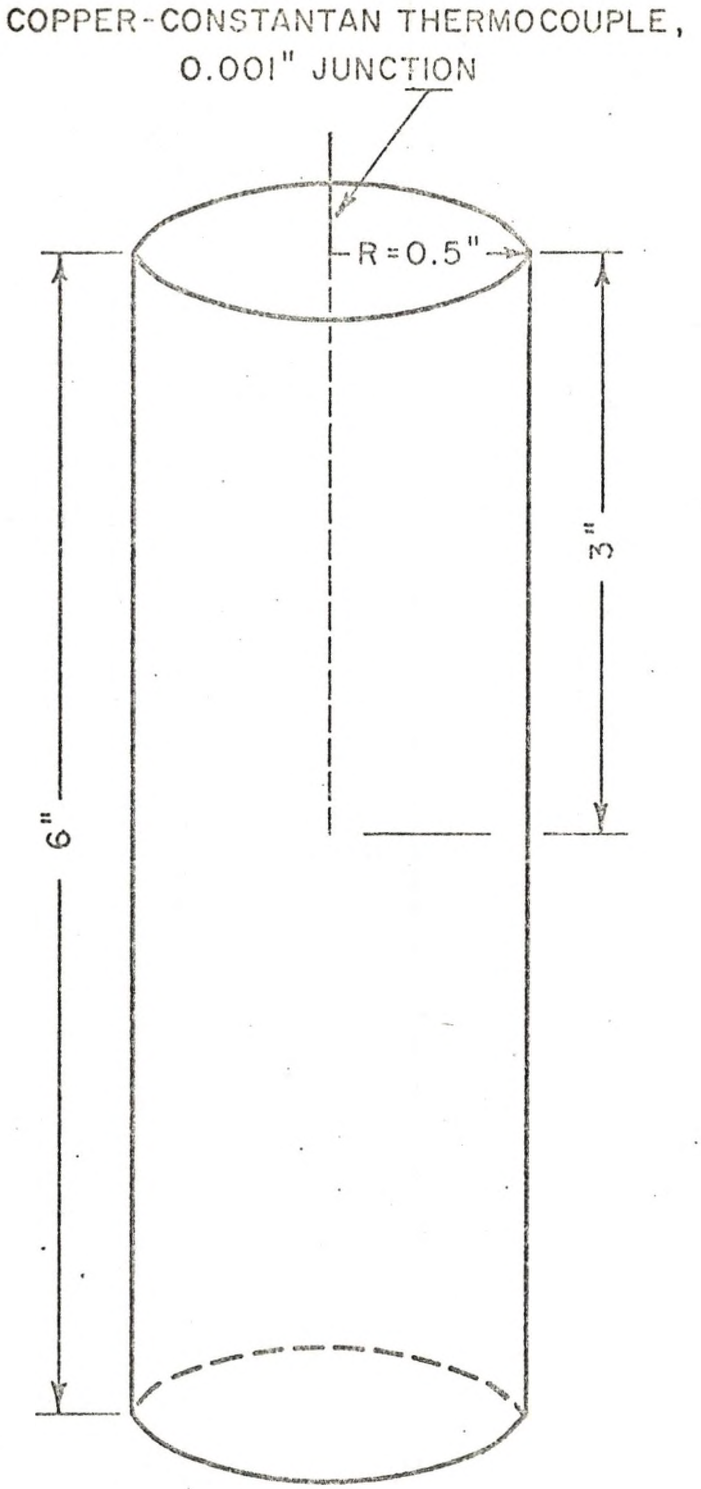

Fig. 3.--Reference sample for the heat transfer coefficient. Cylindrical shape, radius = 0.5" length = 6".

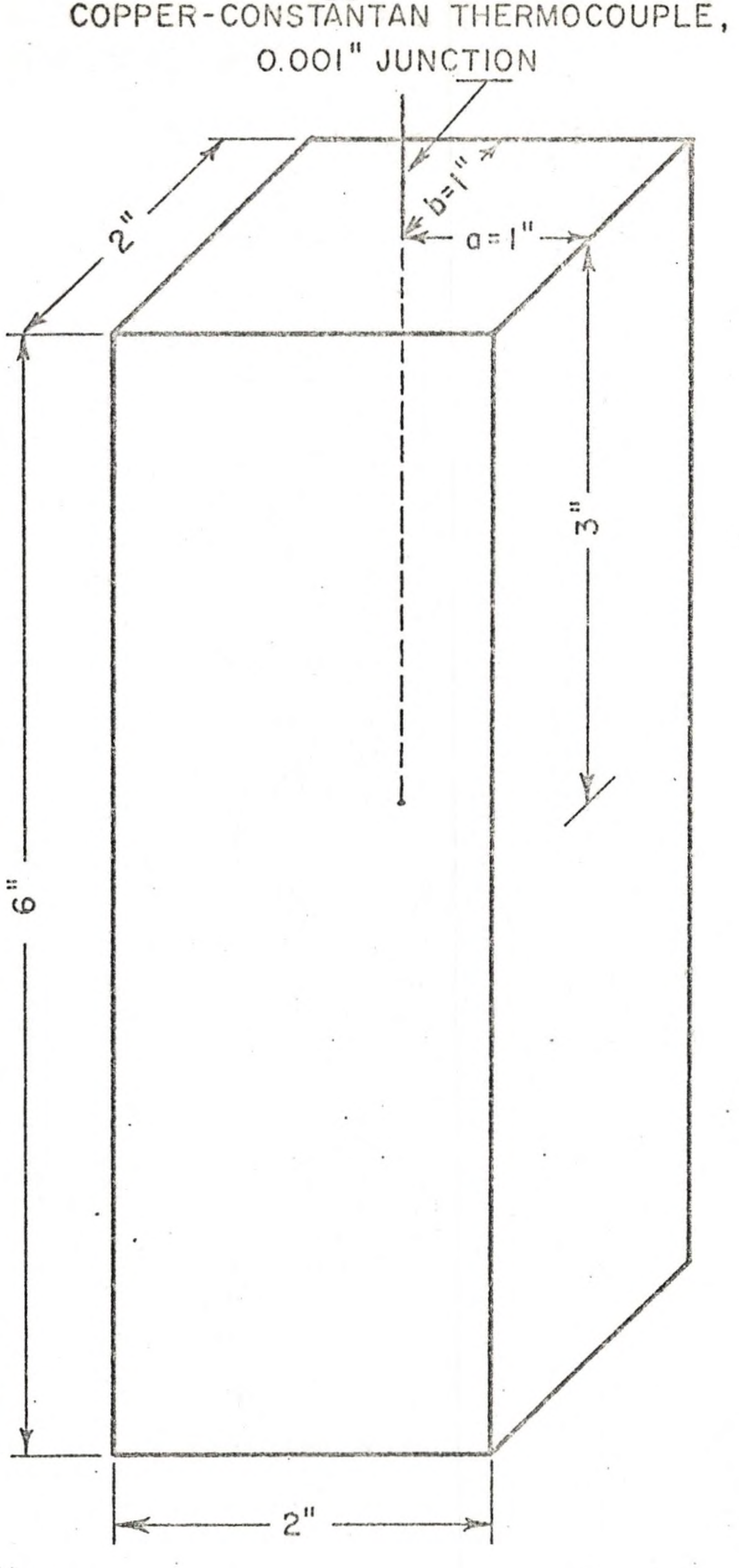

Fig. 4.--Sample of lignite, rectangular parallelopiped shape of 2" x 2" x 6" dimension.

EXPERIMENTAL PROCEDURE

For the determination of the thermal conductivity and thermal diffusivity the following procedure was employed:

1. The water bath was brought to the predetermined temperature and controlled using the automatic temperature control. The circulation pump was in operation.
2. The SPEEDOMAX recorder was set adjusting the span to the 5 millivolt scale.
3. Before placing the sample in the circulation chamber the bath temperature was measured with a copper-constantan thermocouple. The reference junction was at 32° F.
4. The sample was placed in the circulation chamber and the temperature history at the center of the sample was recorded until a steady value was achieved.
5. The bath temperature was measured again using the copper-constantan thermocouple.
6. The thermal conductivity and thermal diffusivity were calculated using the temperature history of the sample and the plots of Figure 6. See Appendix E for details of the calculation.

For the heat transfer coefficient at the solid-fluid interface the experimental procedure was similar to the one followed for the thermal diffusivity and the thermal conductivity, but the method of calculation used was different from the one above (see Appendix D).

The specific heat of lignite was determined using a Parr calorimeter. Samples of lignite weighing about 70 g were wrapped in polyethylene bags and left overnight in a bath of ice water in a Dewar flask to insure equilibrium temperature of 0° C. The polyethylene was used to avoid any contact of lignite and water. The sample was dropped, without the wrapping, into the Parr calorimeter containing water at room temperature. The change in temperature was recorded until the equilibrium was reached. The specific heat was calculated from the heat balance (see Appendix C for details). To obtain the heat capacity of the calorimeter the above procedure was followed using pure copper of known specific heat.

A pycnometer, with a capacity of 25 ml, was used for the density determinations. Samples of lignite weighing approximately 1 g were used. The density was obtained by dividing the weight of the sample by the volume of water displaced by the sample in the pycnometer. A sample calculation is shown in Appendix A.

The F-test for analysis of variance for the thermal conductivity, heat capacity, density and thermal diffusivity was used for the statistical interpretation of the results. The 90 percent confidence limits for these values were also calculated (see Appendix F).

EXPERIMENTAL RESULTS

Thirteen thermal conductivity and thermal diffusivity determinations covering five different lignites were made. The temperature range of each determination was approximately from 70° to 140° F. All the samples, except one, were cut with the long axis parallel to the bedding plane. The cut of the remaining sample was with the long axis perpendicular to the bedding plane. The thermocouple was always placed parallel to the long axis.

The proximate analyses of the lignites used are shown in Table 5. The analyses are of lumps of lignites, as closely representative as possible, taken from the same batch as those used in the tests.

In Table 6 the results of the specific heat, density, thermal conductivity and thermal diffusivity measurements are shown. Detailed calculations of these physical constants are shown in Appendices B, C and E.

The results for the heat transfer coefficient at the solid-fluid interface are presented in Table 7. Details for calculations are given in Appendix D. Several materials were tested, but the acrylic plastic was chosen as the reference sample because its thermal properties are similar to those of lignite.

TABLE 5

PROXIMATE ANALYSIS OF LIGNITE (as received)

Mines	Moisture Percent	Ash Percent	Volatile Matter Percent	Fixed Carbon Percent
Larson Mine (Baukol-Noonan Mining Co. Burke County, N. Dak.)	35.0	6.1	24.5	34.4
South Beulah Mine (Knife River Coal Mining Co., Mercer County, N. Dak.)	32.9	4.8	28.6	33.7
Gascoyne Mine (Knife River Coal Mining Co., Bowman County, N. Dak.)	44.9	6.4	23.2	25.5
Velva Mine (Truax Traer Coal Mining Co., Ward County, N. Dak.)	36.2	3.4	28.6	31.8
Savage Mine (Knife River Coal Mining Co., Richland County, Mont.)	32.3	4.2	27.9	35.6

TABLE 6

THERMAL PROPERTIES OF VARIOUS LIGNITES[a]

Mines	Initial Sample Temperature °F	Bath Temperature °F	Specific Heat Btu lb^{-1} $°F^{-1}$	Density lb ft^{-3}	Thermal Conductivity Btu hr^{-1} ft^{-1} $°F^{-1}$	Thermal Diffusivity sq ft hr^{-1}
Larson	79	123	0.35	82.9	0.156	0.0055
do	72	128	0.34	81.8	0.152	0.0053
do	73	141	0.35	80.6	0.155	0.0055
do	70	137	0.33	81.3	0.154	0.0058
(Long axis perpendicular to the bedding plane)	72	133	0.34	82.8	0.158	0.0056
South Beulah	74	137	0.43	76.8	0.162	0.0052
do	78	126	0.40	76.6	0.170	0.0054
Gascoyne	75	122	0.39	76.8	0.158	0.0053
do	70	144	0.37	77.9	0.156	0.0051
Velva	73	142	0.37	79.5	0.158	0.0054
do	74	132	0.36	80.2	0.157	0.0054
Savage	71	132	0.38	74.9	0.162	0.0054
do	73	123	0.40	74.3	0.162	0.0053
90% Confidence Limits			0.019	1.56	0.0043	0.00014

[a] All samples, except as noted, cut with the long axis parallel to the bedding plane.

TABLE 7

THERMAL PROPERTIES OF THE REFERENCE SAMPLES

Material	Density lb ft^{-3}	Thermal Conductivity Btu ft^{-1} hr^{-1} $^{o}F^{-1}$	Thermal Diffusivity sq ft hr^{-1}	Heat Capacity Btu lb^{-1} $^{o}F^{-1}$	Heat Transfer Coefficient Btu ft^{-2} hr^{-1} $^{o}F^{-1}$
10% Sn Bronze[a]	553	40	0.803	0.091	155
100% Aluminum[b]	169	132	3.650	0.214	153
1% Carbon steel[c]	487	25	0.452	0.113	130
Acrylic plastic[d]	73.7	0.108	0.0042	0.350	74

[a] J. H. Perry, ed., Chemical Engineering Handbook, 4th ed., New York: McGraw-Hill, 1963, pp. 23-47.

[b] A. J. Chapman, Heat Transfer, New York: Macmillan Co., 1960, p. 402.

[c] *Ibid*.

[d] From literature provided by the manufacturer. Catalog PL-693a, Rohm and Haas Co., Philadelphia, Pennsylvania.

DISCUSSION OF THE RESULTS

The measured values of both the thermal conductivity and thermal diffusivity for all the lignites investigated in the present research fall within a range of 0.152 to 0.170 Btu hr^{-1} ft^{-1} ^{o}F^{-1} and 0.0051 to 0.005 sq ft hr^{-1} respectively. The 90 percent confidence intervals for determined conductivity and diffusivity are 0.0043 and 0.00014. The values of thermal conductivity and thermal diffusivity are average values for the range of temperatures employed, 70^{o} to 140^{o} F.

Knowledge of the numerical values of the thermal conductivity and thermal diffusivity permits calculation of the temperature profile within a lump of lignite during heating.

It was thought that the thermal conductivity and thermal diffusivit would depend to some extent upon the cut of the sample, long axis parallel or perpendicular to the bedding plane. No significant differenc was found between the two different cuts. The different values of the thermal conductivity between any two samples can be attributed to differences in the extent to which these particular samples form cracks. This variability in crack formation entirely obscures any variation which may exist between the thermal conductivity and the direction of the cut of the sample. This is also true of the thermal diffusivity.

The results obtained in the present research are in the range of results found in the literature for other coals. Badzioch, Gregory and Field,[14] reported a range of 0.133 to 0.194 Btu ft^{-1} hr^{-1} $^{o}F^{-1}$ for the thermal conductivity and 0.0047 to 0.0082 sq ft hr^{-1} for the thermal diffusivity. Margit[13] found that the thermal conductivity for Hungarian coals ranges from 0.136 to 0.280 Btu ft^{-1} hr^{-1} $^{o}F^{-1}$.

The values for surface heat transfer coefficient of different reference materials of known thermal conductivity and thermal diffusivity ranged from 74.3 to 155 Btu ft^{-2} hr^{-1} $^{o}F^{-1}$. The value for the acrylic plastic was used because its thermal properties are similar to those of lignite. The parameter $\frac{k}{ha}$ expresses the relative resistance of the interior of the solid to that of the film at the boundary. It can be shown that the value of the surface heat transfer coefficient does not have a great effect in this determination because lignite is a poor conductor and has a low thermal conductivity. From the samples tested the value of the parameter $\frac{k}{ha}$ was close to zero (see Figure 6).

The F-test for analysis of variance for the values of thermal conductivity, thermal diffusivity, density and specific heat as determined in the present work shows that there is no significant difference betwee the mines at the 0.01 level.

APPENDIX A

PREPARATION OF THE SAMPLE

The lignite used in this project was supplied from the Savage mine in Montana, and from Larson, Beulah, Gascoyne and Velva mines in North Dakota. The large pieces of lignite were stored in polyethylene bags to avoid moisture loss.

For the determination of the specific heat the samples were wrapped in polyethylene bags and left overnight in a bath of ice water in a Dewar flask. The polyethylene was used to avoid any contact of lignite and water. For density determinations a small lump of lignite weighing approximately 1 g was used.

For the determination of the thermal conductivity and thermal diffusivity large lumps of lignite were cut with a Doall band saw at a speed of 1500 ft min^{-1}; cutting had to be done carefully because lignite breaks very easily. The samples were rectangular parallelopipeds of 2 in x 2 in x 6 in. The samples were kept in polyethylene bags to avoid moisture loss until the determination was carried out.

A 3 in hole of 2 mm diameter was drilled centrally at the top of the sample, parallel to the long axis, and in it was placed a copper-constantan thermocouple with a 0.001 in measuring junction. The hole at the top of the sample was sealed with rubber cement after the thermocouple was inserted in order to avoid an influx of water during the determination.

APPENDIX B

SAMPLE CALCULATION OF DENSITY

For the density determinations, a 25 ml pycnometer, with a thermometer attached to the cover, was used. A sample calculation for lignite from the Larson mine is shown below:

Weight of Pycnometer + sample:	29.1876 g
Pycnometer:	27.9677
Sample:	1.2199 g

Temperature of water: 26° C

Density of water at 26° C: 0.99682 g/cc

Pycnometer filled with water:	52.8390
Pycnometer:	27.9677
Weight of H_2O:	24.8733

Pycnometer + water + sample:	53.1458
Pycnometer + sample:	29.1876
Water:	23.9582

Weight of H_2O:	24.8733
Water:	23.9582
Water displaced by lignite sample:	0.9151 g

Volume of water in cc: $\frac{0.9151}{0.99682} = 0.9180$ cc

Density $\frac{1.2199}{0.9188} \frac{g}{cc} = 1.3289$ g/cc $= 82.9$ lb ft^{-3}

APPENDIX C

SAMPLE CALCULATION OF THE SPECIFIC HEAT

For the specific heat determinations a Parr calorimeter was used. Samples of lignite weighing around 70 grams were wrapped in polyethylene bags and left overnight in an ice water bath to insure equilibrium temperature of 0° C. Temperatures in the calorimeter were taken until the equilibrium was reached. Once the equilibrium was attained the sample was dropped, without the wrapping, quickly in the calorimeter and the change in temperature was recorded until the equilibrium was obtained. The following data were recorded for a sample of lignite from the Larson mine:

Weight of water in the calorimeter:	2000 g
Weight of the calorimeter:	715.5 g
Weight of the lignite sample:	70.102 g
Heat capacity of water at 26° C	0.9989 cal g^{-1} $^{o}C^{-1}$
Heat capacity of calorimeter:	0.150 cal g^{-1} $^{o}C^{-1}$
Temperature change in the water:	0.300 ^{o}C
Temperature change in the lignite sample:	25.620 ^{o}C

$$Cp \times 70.1 \times 25.62 = 2000 \times 0.9989 \times 0.300 \underset{\uparrow\,+}{\times} 715.5 \times 0.300 \times 0.150$$

$$Cp = 0.352 \text{ cal } g^{-1}\ {}^{o}C^{-1}$$

APPENDIX D

SAMPLE CALCULATION OF THE HEAT TRANSFER COEFFICIENT

For the determination of the heat transfer coefficient, at the solid-fluid interface, the same experimental procedure used in the thermal conductivity and thermal diffusivity, was followed:

The following data were obtained for Bronze 10 percent Sn cylindrically shaped, 1 in radius and 6 in long.

$t_s = 159.68^{\circ}$ F

$t_o = 77.55^{\circ}$ F

$\rho = 553.2$ lb cu ft^{-1}; Cp = 0.091 Btu lb^{-1} ^{o}F^{-1};

k = 40 Btu ft^{-1} ^{o}F^{-1} hr^{-1}; $\alpha = .8032$ ft^{2} hr^{-1}

Time (sec)	Temp. ^{o}F	$\dfrac{t_s - t}{t_s - t_o}$	$\dfrac{\alpha\theta}{R^2}$
0	77.55	1.0000	0.0000
6	77.55	1.0000	0.1928
12	78.13	0.9912	0.3856
18	86.48	0.8908	0.5784
24	95.83	0.7770	0.7712
30	104.22	0.6749	0.9640
36	111.67	0.5843	1.1566
42	117.58	0.5124	1.3496
48	123.46	0.4407	1.5424
54	128.08	0.3846	1.7352
60	132.25	0.3334	1.9280
66	136.00	0.2884	2.1208

Time (sec)	Temp. ^{o}F	$\frac{t_s - t}{t_s - t_o}$	$\frac{\alpha \theta}{R^2}$
72	138.68	0.2557	2.3136
78	141.36	0.2229	2.5064
84	143.25	0.1999	2.6922
90	145.48	0.1728	2.8920
96	146.28	0.1631	3.0848
102	148.71	0.1359	3.2776
108	150.16	0.1158	3.4704
114	151.17	0.1035	3.6632
120	152.20	0.9103 0.09103	3.8500
.	.	.	.
.	.	.	.
∞	159.68	0.0000	∞

From the plot of the dimensionless temperature versus the inverse of the Biot modulus $\frac{k}{hR}$ the heat transfer coefficient can be calculated (see Figure 5).

Using a number of pairs of experimentally determined dimensionless temperatures and dimensionless times, the inverse of the Biot modulus can be found for 10 percent Sn bronze whose thermal conductivity and thermal diffusivity is known. For example:

$\frac{t_s - t}{t_s - t_o}$	$\frac{\alpha \theta}{R^2}$
0.2557	2.3136
0.2229	2.5064

Plotting these values in Figure 5 and drawing a vertical line, until it reaches the horizontal axis, a value for $\frac{k}{hR}$ can be found. This value is 3.1.

$$\frac{k}{hR} = 3.1$$

$$h = \frac{k}{3.1R} = \frac{40}{3.1 \times \frac{1}{12}} = 155 \text{ Btu ft}^{-2}\text{ hr}^{-1}\,{}^{\circ}\text{F}^{-1}$$

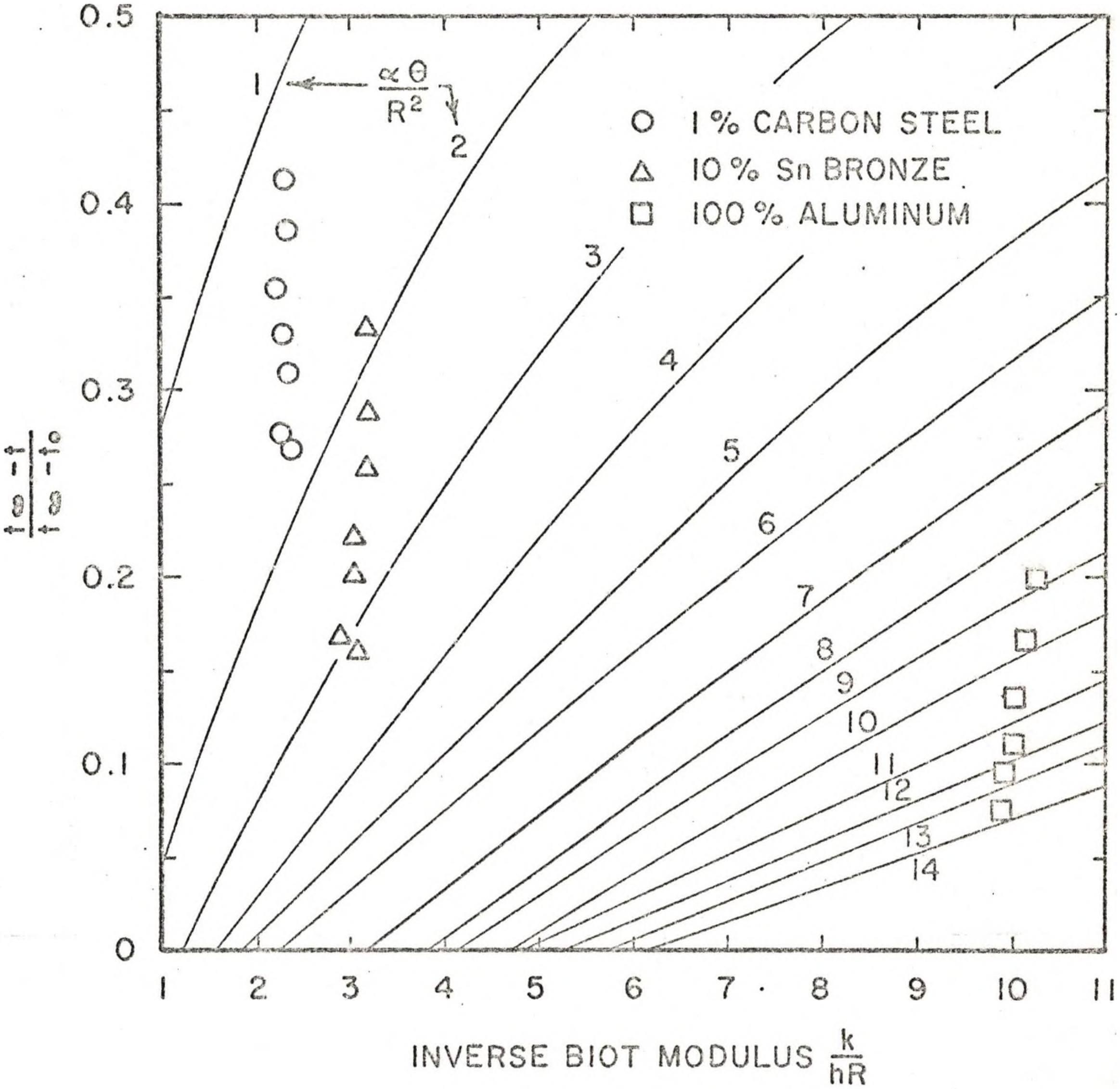

Fig. 5.--Graph for determining the heat transfer coefficient. 1 % carbon steel, 100 % aluminum and 10 % Sn bronze as reference samples. $\frac{r}{R} = 0$

APPENDIX E

SAMPLE CALCULATION OF THE THERMAL CONDUCTIVITY AND THERMAL DIFFUSIVITY

For lignite, whose thermal conductivity and diffusivity are unknown, it is not possible to calculate either the dimensionless time $\frac{\alpha\theta}{a^2}$, or the inverse of the Biot modulus $\frac{k}{ha}$. However, a trial and error determination can be made using Figure 6.

The following data were collected for a sample of lignite from the Larson mine:

$\rho = 83.0$ lb cu ft^{-1}; Cp = 0.35 Btu lb^{-1} ^{o}F^{-1}; $a = 1/12$ ft;

$t_s = 123.40^{o}$ F; $t_o = 79.00^{o}$ F.

tabulated values

Time (min)	Temp. ^{o}F	$\frac{t_s - t}{t_s - t_o}$	$\sqrt{\frac{t_s - t}{t_s - t_o}}$	$\frac{k\theta}{PC\rho a^2}$
0	79.00	1.000	1.000	0.000
1	79.00	1.000	1.000	0.838
2	79.00	1.000	1.000	0.168
3	79.23	0.995	0.998	0.252
4	80.00	0.978	0.989	0.335
5	80.78	0.960	0.980	0.419
6	82.30	0.926	0.962	0.503
7	84.00	0.887	0.942	0.587
8	86.00	0.842	0.918	0.671
9	88.00	0.797	0.898	0.755
10	89.74	0.758	0.871	0.838
11	92.00	0.707	0.841	0.922

– this should be $\frac{\theta}{\rho C_p a^2}$ or K after each value in column

Time (min)	Temp. ^{o}F	$\frac{t_s - t}{t_s - t_o}$	$\sqrt{\frac{t_s - t}{t_s - t_o}}$	$\frac{k\theta}{PC\rho a^2}$
12	94.00	0.662	0.813	1.006
13	95.50	0.628	0.793	1.089
14	97.00	0.595	0.771	1.174
15	99.00	0.549	0.742	1.257
16	100.50	0.516	0.718	1.343
17	102.00	0.482	0.694	1.425
18	103.30	0.453	0.673	1.509
19	105.00	0.414	0.643	1.593
20	106.00	0.392	0.626	1.677
21	107.00	0.369	0.607	1.760
22	108.20	0.342	0.585	1.842
23	109.00	0.324	0.569	1.928
24	110.50	0.291	0.539	2.011
25	111.50	0.268	0.518	2.096
26	112.00	0.257	0.507	2.179
27	113.00	0.234	0.484	2.263
28	113.80	0.216	0.468	2.347
29	114.66	0.197	0.444	2.431
30	115.25	0.183	0.428	2.515
31	115.98	0.167	0.409	2.599
32	116.75	0.149	0.387	2.682
33	117.25	0.138	0.372	2.766
34	117.80	0.126	0.355	2.850
35	118.32	0.114	0.338	2.934
36	119.00	0.099	0.315	3.018
37	119.30	0.092	0.303	3.102
38	120.00	0.077	0.278	3.185
40	121.50	0.043	0.207	3.353
45	123.00	0.009	0.095	3.772
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
∞	123.46	0.000	0.000	∞

At any particular time in the experimentally determined temperature-history of the sample of lignite there is a corresponding value of

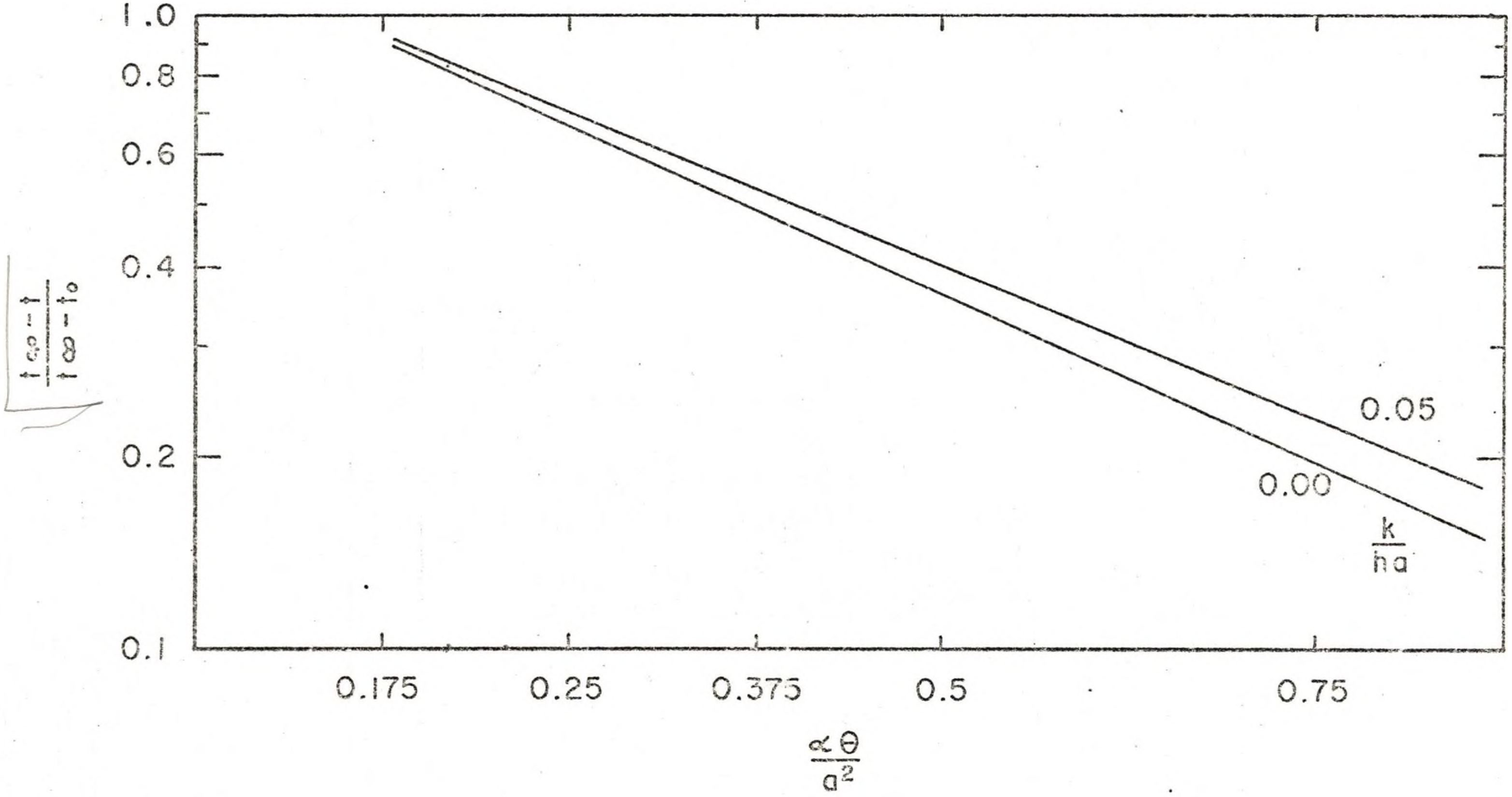

Fig. 6.--Dimensionless temperature distribution in a slab.

dimensionless temperature. For this value of the dimensionless temperature there corresponds a pair of values of dimensionless time, $\frac{\alpha\theta}{a^2}$, and the reciprocal of the Biot modulus, $\frac{k}{ha}$, which satisfy the plot of Figure 6. A trial and error procedure was followed for the calculation of the thermal conductivity.

For example: Let us assume $k = 0.156$ Btu ft^{-1} hr^{-1} ${}^{o}F^{-1}$

So: $\frac{k}{ha} = 0.025$

From the table above:

$\sqrt{\frac{t_s - t}{t_s - t_o}}$	$\frac{k\theta}{PC_\rho a^2}$
0.694	1.425 k
0.643	1.593 k
0.608	1.760 k

Same

From Figure 6 the corresponding values for $\frac{\alpha\theta}{a^2}$ are:

0.225
0.250
0.275

The k calculated will be:

0.158
0.157
0.156

These values of k agree with the assumed value.

The thermal diffusivity is calculated dividing the thermal conductivity by the heat capacity and the density.

APPENDIX F

STATISTICAL INTERPRETATION OF RESULTS

The F-test for analysis of variance for the thermal conductivity, heat capacity, density and thermal diffusivity was used for the statistical interpretation of the results. The F values from the tables correspond to 0.01 significance level. The F-test for the thermal conductivity, thermal diffusivity, heat capacity and density, indicates that there is no significant difference among the mines at the 0.01 level. The 90 percent confidence intervals for these property values were calculated too.

ANALYSIS OF VARIANCE FOR THERMAL CONDUCTIVITY

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	Calculated F	Critical F
Between (mines)	1.78×10^{-4}	4	0.44×10^{-4}	5.22	11.4
Within (error)	0.43×10^{-4}	5	0.09×10^{-4}		
Total	2.21×10^{-4}	9			

NINETY PERCENT CONFIDENCE INTERVAL FOR THERMAL CONDUCTIVITY: 0.0043 Btu hr^{-1} ft^{-1} $^{o}F^{-1}$

ANALYSIS OF VARIANCE FOR THERMAL DIFFUSIVITY

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	Calculated F	Critical F
Between (mines)	7.83×10^{-8}	4	1.96×10^{-8}	2.05	11.4
Within (error)	4.79×10^{-8}	5	0.96×10^{-8}		
Total	12.62×10^{-8}	9			

NINETY PERCENT CONFIDENCE INTERVAL FOR THERMAL DIFFUSIVITY: 0.00014 sq ft hr^{-1}

ANALYSIS OF VARIANCE FOR DENSITY

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	Calculated F	Critical F
Between (mines)	46.64	4	11.66	9.8	11.4
Within (error)	5.95	5	1.19		
Total	52.59	9			

NINETY PERCENT CONFIDENCE INTERVAL FOR DENSITY: 1.56 lb ft^{-3}

ANALYSIS OF VARIANCE FOR SPECIFIC HEAT

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	Calculated F	Critical F
Between (mines)	6.27×10^{-3}	4	1.56×10^{-3}	8.22	11.4
Within (error)	0.95×10^{-3}	5	0.19×10^{-3}		
Total	7.22×10^{-3}	9			

NINETY PERCENT CONFIDENCE INTERVAL FOR SPECIFIC HEAT: 0.019

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