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A STUDY OF THE HEAT TRANSMISSION OF BUILDING MATERIALS

BY
A. C. WILLARD
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ENGINEERING EXPERIMENT STATION,
URBANA, ILLINOIS.
A STUDY OF THE HEAT TRANSMISSION
OF BUILDING MATERIALS

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A STUDY OF THE HEAT TRANSMISSION
OF BUILDING MATERIALS*

I. INTRODUCTION

1. Purpose of Investigation.—The object of this investigation is to determine the coefficients of heat transmission of standard building materials for exterior building walls under conditions similar to those commonly found in practice. In applying these coefficients to actual problems it is necessary to take account of the temperature of the air inside and outside the building; therefore the data must be determined under similar or comparable conditions. Since it is impossible to test all types and combinations of exterior wall construction, some method must be devised for applying the data obtained from the tests of a relatively small number of simple walls. This method should permit, by a simple calculation, the determination of the coefficient of transmission in the case of the various compounds and special walls. It is necessary, therefore, only to apply the simple principles underlying the transfer of heat to, through, and from a building wall, and to determine the basic coefficients required in making the calculations of the actual transmission coefficient. In order to explain this procedure for the general case it is necessary to analyze the process by which heat transmission through a wall takes place.

2. Acknowledgments.—The writers acknowledge their indebtedness to PROFESSOR L. A. HARDING, formerly in charge of the work in Experimental Mechanical Engineering at the University of Illinois, and to DEAN C. R. RICHARDS, Dean of the College of Engineering and formerly head of the Department of Mechanical Engineering at the University of Illinois. This investigation was begun under Professor Harding’s supervision, and a large part of the test data was secured before his resignation. Dean Richards contributed valuable suggestions during the progress of the tests.

*The results here reported do not constitute results of a complete series of experiments. It is the present purpose to continue the study of heat transmission of building materials and to release results for publication from time to time as the work proceeds.
II. PRINCIPLES OF HEAT TRANSMISSION

3. Conduction.—Heat passes through a wall by conduction provided the temperature on one side of the wall is higher than that on the other. The amount of heat (H) passing through the wall depends upon the following factors:

1. The coefficient of conductivity (C) which varies with the material of the wall. This coefficient is practically constant* for any given wall for the ranges of surface temperatures found in heating buildings; it is not constant, however, at high temperatures if there is much variation in the mean temperature of the wall.†

2. The thickness of the wall in inches (x).

3. The difference in temperature in degrees F. between the two surfaces \((t_1 - t_2)\).

4. The time in hours \((D)\).

5. The mean area of the cross section in square feet through which the heat passes \((A)\).

The nature of the two surfaces is of no consequence provided the faces are parallel. The amount of heat transferred is also independent of the actual temperatures of the two surfaces but it depends upon the difference in temperatures between the two surfaces; thus the heat transmitted by conduction is, in B. t. u.,

\[
H = \frac{C}{x} (t_1 - t_2) D A. \quad (1)
\]

It is at once apparent that all these factors except the surface temperatures are easily ascertainable, and it should be noted that the inside and outside air temperatures are of no value in determining the amount of heat transmitted by conduction.

Heat reaches the surface of a wall both by radiation and by convection provided the objects and the air are at a higher temperature than the surface of the wall. By a reverse process § of radiation and convection, the heat which has been received by the inner surface of a wall and transmitted through it by conduction may be given off

by the outer surface. In refrigeration, the direction of flow is reversed, but the coefficient is the same for ordinary ranges of temperature. The air and objects on the cooler side of the wall must, of course, remain at a lower temperature than the surface of the wall.

4. Radiation.—Newton seems to have been the first to consider the "law of cooling" of a body by radiation, and, as stated by Preston, "he supposed that the rate of cooling was proportional to the excess of the temperature of the body above that of the medium in which it was immersed." The same authority expresses the heat lost by radiation in a unit of time as the difference between the total heat given off by radiation from the body and the total heat gained by radiation to the body or \((ft - ft_1)\), in which

\[
ft = \text{the total heat loss per second by radiation when the body is at the temperature } (t), \text{ and}
\]

\[
ft_1 = \text{the total heat received per second by radiation when the surroundings are at the temperature } (t_1).
\]

This is equivalent to assuming that for the absolute scale of temperature the function \(ft = R(t - t)\) so that \(ft - ft_1 = R(t - t_1)\) and the heat lost by radiation is

\[
H_R = R(t - t_1)DA \text{ in B. t. u., } \ldots \ldots (2)
\]

in which \(R\) is the coefficient of radiation for the surface of the material under consideration, \(t\) and \(t_1\) are Fahrenheit temperature readings, \(D\) is the time in hours, and \(A\) is the area in square feet. Preston says, "This formula has been found to represent the facts fairly well for small differences of temperature. For differences exceeding 40 or 50 degrees C. this law was found to deviate seriously from the truth."

Where the differences in temperature become large and when "black bodies," which are perfect radiators and perfect absorbers of heat, are used, the total energy transferred by radiation has been shown by Stefan† and Boltzmann‡ to depend: first, upon a factor called coefficient of radiation \((R)\), and secondly, upon the difference

---

†Joseph Stefan, physicist, was born in Austria-Hungary in 1835 and died in 1893. He was Professor of Higher Mathematics and Physics at the University of Vienna, and carried on extensive investigations on the transmission of light, heat and sound, and the diffusion of gases.
‡Ludwig Boltzmann, physicist, was born in Vienna, Austria, in 1844 and died in 1906. He was Professor of Experimental and Theoretical Physics at the Universities of Graz and Vienna, and made many valuable researches in the field of thermodynamics. He published a great many books and papers on various physical subjects and problems, including "Der Zweite Hauptsatz der Mechanischen Wärmetheorie."
between the fourth powers of the absolute temperatures of the surfaces between which the transfer takes place. For English units, therefore, the heat transmitted by radiation is, in B. t. u.,

\[ H_R = R (T_1^4 - T_2^4) D A. \]  

(2a)

in which, as previously, \( D \) is the time in hours, and \( A \) is the area of the surface in square feet, \( T_1 \) and \( T_2 \) are degrees F. on the absolute scale and in the case of sooted surfaces with the cooler entirely surrounding the warmer surface, which must not “see” anything but the cooler surface, \( R = 1.6 \times 10^{-9} \). The experimental determination of values of \( R \) for either small or great temperature differences for commercial building materials would require rather elaborate equipment.

It is evident, from equation (2a) that for large temperature differences, a most rapid increase in radiation will occur: first, with an increase in the temperature of the warmer body; and secondly, if, for the same temperature differences, both temperatures \( T_1 \) and \( T_2 \) are increased.* It should be noted that the energy transferred by radiation must first be transformed at the surface of the warmer body from the form of sensible heat or kinetic energy into radiant energy, so that it may pass, like light,† through space to the surface of the cooler body, and there be retransformed into heat energy.‡

5. Convection.—The amount of heat transferred by convection, or air movement, over the surface of a body has been shown by Peclet¶ to depend upon:

(1) A factor, coefficient of convection \( (N) \), which varies with the form and arrangement of the surface.

(2) Some power of the velocity of flow across the surface in feet per second \( V^{1/2} \).

(3) The difference in temperature between the surface and the surrounding air \( (t_1 - t_2) \) in degrees F.

The heat transferred by convection is independent of the nature of the surface, and the absolute temperature of the surface and the surrounding air; consequently for English units, the heat transferred from or to a wall by convection is, in B. t. u.,

\[ H_N = N V^{1/2} (t_1 - t_2) D A. \]  

(3)

---

in which $D$ is the time in hours and $A$ is the area of the surface in square feet. The values of $N$ and $n$ must be determined experimentally. Elaborate testing equipment is required for the determination of these values.

6. Heat Transmission to, through, and from a Simple Wall.—In view of the foregoing analysis, it will be apparent from the diagram, Fig. 1, that the temperature gradient through a wall, which separates air at a higher temperature ($t$) from air at a lower temperature ($t_0$), can be represented by the line $t, t_1, t_2, t_0$, provided it is recognized that the surface temperature of the wall and the air in contact with it are not the same. This difference in temperature occurs within a thin layer or film of air very close to the surface. That the wall surface must be at a lower or at a higher temperature than the surrounding air and the objects is evident; otherwise there would be no "flow" or transfer of heat to or from the wall.

It has also been suggested by Dalby* that there is probably a further drop of temperature head, represented by the distance between $t_1$ and $t_0$, which is required to force the flow across the surface where the gas film is in contact with the wall, corresponding to a po-
potential difference at a joint in an electric circuit. This is usually referred to as contact resistance. Contact resistance cannot be measured by thickness, but requires an appreciable amount of potential difference, whether the potential difference be in volts or degrees, and whether the current flow be in amperes or thermal units.

If the air and surface temperatures are known, it is possible, for small temperature differences, to express the amount of heat entering the wall per square foot per hour in terms of equations (2) and (3), in which $D$ and $A$ become unity, as:

$$H_R + H_N = R \left[ (t+460) - (t_1+460) \right] + N \times V^t (t-t_1) \quad . \quad \text{(4)}$$

For walls of fixed height, possibly from nine to ten feet, standing in still air so that only natural or gravity convection currents exist, the factor \( V^t \), moreover, becomes a constant and can be included in $N$ making it $N_1$, so that the combined or total heat transfer at the surface of the wall can be expressed as:

$$H_R + N_1 = R \left( t - t_1 \right) + N_1 \left( t - t_{11} \right), \quad \text{(5)}$$

or, letting $K_1 = (R + N_1)$,

$$H_R + N_1 = K_1 \left( t - t_1 \right) \quad \text{. \quad \text{(6)}}$$

The heat passing through the wall per square foot per hour can be expressed by equation (1) as:

$$H_c = \frac{C}{X} (t_1 - t_2), \quad \text{. \quad \text{(7)}}$$

if the two wall surface temperatures are known.

The heat leaving the wall for the limited range of temperatures found in practice can be expressed, furthermore, by equations (2) and (3) simplified to read as follows:

$$H_R + N_2 = K_2 \left( t_2 - t_0 \right), \quad \text{. \quad \text{(8)}}$$

in which \((R + N_2) = K_2\) are new coefficients determined under outside conditions of temperature and average wind movement.

Finally, if the overall transmission coefficient from air inside to air outside is $U$, in B. t. u. per square foot per hour, the heat transmitted is

$$H_u = U \left( t - t_0 \right), \quad \text{. \quad \text{(9)}}$$

Since the heat $H$ transmitted in B. t. u. per square foot per hour is the same in each of the above cases,

---

*Refrigerating World, p. 29, September, 1914.
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\[ H = K_1 (t - t_1) \]
\[ = \frac{C}{X} (t_1 - t_2) \]
\[ = K_2 (t_2 - t_0) \]
\[ = U (t - t_0) \]

and \[
\frac{1}{K_1} + \frac{X}{C} + \frac{1}{K_2} = \frac{t - t_1}{H} + \frac{(t_1 - t_2)}{H} + \frac{(t_2 - t_0)}{H} = \frac{t - t_0}{H}
\]

But \[
\frac{1}{U} = \frac{t - t_0}{H}
\]

hence \[
\frac{1}{U} = \frac{1}{K_1} + \frac{1}{K_2} + \frac{X}{C}
\]

and \[
U = \frac{1}{K_1 + \frac{1}{K_2} + \frac{X}{C}}
\]

In the case of compound walls (See Fig. 2 A, B, and C) with no air spaces and with a variety of materials of different conductivities, \(C_1, C_2, C_3,\) etc., and of various thicknesses, \(X_1, X_2, X_3,\) etc., the equation assumes the form,

\[
U = \frac{1}{K_1 + \frac{1}{K_2} + \frac{X_1}{C_1} + \frac{X_2}{C_2} + \frac{X_3}{C_3} + \ldots}
\]

If the compound wall contains air spaces, (See Fig. 2 D) the value of \[
U = \frac{1}{K_1 + \frac{1}{K_2} + \frac{1}{K_4} + \frac{1}{K_5} + \frac{X_1}{C_1} + \frac{X_2}{C_2} + \frac{X_3}{C_3} + \ldots}
\]
in which the proper surface coefficients for each material and for each surface must be used. All coefficients will be taken for "still air" conditions, except that for the outside wall the surface coefficient must be increased, as indicated under "Applications" (Fig. 2 D), to correspond with the average wind movement.

It must, therefore, be apparent that, if values of the combined surface coefficients \((K_1)\) and \((K_2)\) and of the coefficient of conductivity \((C)\) can be determined experimentally by measuring the heat transmitted through typical wall materials, the very practical and useful coefficient of transmission \((U)\) can be readily calculated by equation (10) for a wall of any given thickness \(x\). As will be shown later under methods of testing, it is a fairly simple matter to determine the surface coefficients of walls standing in still air and the coefficients of conductivity at the same time that the actual determination of the coefficient of transmission \((U)\) is being made.
FIG. 2. APPLICATION OF TEST DATA TO SIMPLE AND COMPOUND WALLS,
EXAMPLES IN THE CALCULATION OF U
III. Methods of Testing for Heat Transmission of Building Materials

7. General Conditions.—There are two general cases to be considered in determining the value of the coefficient \( U \) for walls: first, the case of walls standing in perfectly still air, except for the vertical convection currents set up by the wall itself, and secondly, that of walls standing in moving air where the velocities cover the range found in atmospheric air during the average heating season. Both cases have been investigated in these tests so that the data reported are divided into two parts, one for “still air tests” and the other for “moving air tests.”

8. Investigations.—Heat transmission tests previously made have in many cases been confined to small specimens so that the data secured have proved unsatisfactory when applied to walls of practical proportions. All investigators in this field have profited by the pioneer experimental work of the French physicist, Peclet.* His work was followed by investigations (which included the work of Rietschel† and Grashof‡), conducted under the auspices of the German and Austrian governments. The results of this work have been translated in part by J. H. Kinealy¶ and still form the basis for many transmission coefficients in use to-day.

The most prominent American investigator has been Prof. C. L. Norton§ of the Massachusetts Institute of Technology. The best

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* Jean Claude Eugene Peclet was born at Besançon, France, in 1793 and died in Paris in 1857. He was Professor of Industrial Physics at the Central School of Arts and Manufacturers in Paris. Among his most important works is his “Traité de la Chaleur et de son Application aux Arts et aux Manufactures,” published in two volumes in 1829, a second edition being issued in 1843 and translated into German.

† Herman Iman Rietschel was born at Dresden, Germany, in 1847. He was a professor in the Königliche Technische Hochschule, Berlin. He wrote “Leitfaden zum Berechnen und Entwerfen von Luftungs- und Heizungs-Anlagen. Ein Hand und Lehrbuch für Ingenieure und Architekten,” which was published in 1894 (second edition). He also wrote “Theorie und Praxis der Bestimmung der Rohrweiten von Warmwasserheizungen,” published in 1897.

‡ Franz Grashof was born at Düsseldorf, Germany, in 1826 and died in 1893. He was one of the founders of the Verein Deutscher Ingenieure and was president of this society for thirty-five years. He was Professor of Applied Mechanics and Director of the Department of Machine Construction in the Polytechnical High School, Karlsruhe. His writings are very numerous and include the “Resultate der Mechanischen Wärmetheorie,” published in 1870.

¶ John Henry Kinealy was born at Hannibal, Missouri, in 1864. Among his other works is the translation of the Prussian tables for heat transmission. This translation was published in 1899 and is known as “Formulas and Tables for Heating.”

§ Charles Ladd Norton was born at Springfield, Massachusetts, in 1870. He is Professor of Heat Measurements in the Massachusetts Institute of Technology. His investigations have included the transmission of heat through various building materials as well as the thermal conductivity of earthy materials and cold storage insulation.
equipped thermal-transmission testing plant in this country has been erected by the Armstrong Cork Company, at Beaver Falls, Pennsylvania. A similar plant is located at the Pennsylvania State College at State College, Pennsylvania. In the tests run at the former plant little attention has been given to surface temperatures, since only actual or overall transmission air to air coefficients were desired. In the plant at Pennsylvania State College both air and surface temperatures are measured by means of platinum resistance pyrometers, and the Engineering Experiment Station at State College has been studying the effect produced on the heat transmission by varying the relative humidity and velocity of the air passing over the outside surface of a building wall.

The Worcester Polytechnic Institute* has recently conducted a series of tests on the heat transmission of various types of ice house construction. Prof. J. R. Allen,† University of Michigan, has recently reported the results of tests on transmission coefficients for glass made under a variety of conditions.

The latest heat transmission tests of importance are those of L. B. McMillan made at the University of Wisconsin.‡ Steam pipe coverings were investigated to determine their heat insulating properties. For determining the temperature of the air in the test room, high grade mercury thermometers were used, and after considerable experimenting it was decided to use constantan-copper thermocouples for the pipe temperatures. In this connection the potentiometer method of measuring the electro motive force of the couples was used. To imbed the thermocouple junction in the pipe, a chip was raised on the surface of the pipe, the thermocouple junction was held underneath, and the chip was forced down; thus the couple was held in contact with the metal pipe.

Similar work is also in progress at the Mellon Institute.

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*Refrigerating World, June, 1915.
IV. TESTING METHODS AND EQUIPMENT

9. Methods.—The equipment or apparatus for making heat transmission tests in building materials varies according to the method of testing and the data desired. Some excellent laboratory plants have been designed for making heat transmission tests, and some of the most elaborate of these have been used abroad.* The methods most commonly employed in this country may be classified, according to principle at least, as follows:

1. Ice Box method.
2. Oil Box method.
3. Cold Air Box method.
4. Hot Air Box method.
5. Flat or Hot Plate method.

**Fig. 3. The Ice Box Method of Testing Heat Transmission**

10. The Ice Box Method.—This method, illustrated by Fig. 3, is the simplest one employed in making heat transmission tests. Ice is placed inside a metal box, or cube, and the material to be tested is placed outside. If the rate at which the ice melts, the temperature of the melting ice, and the outside air temperature are known, the heat transmission is readily obtainable.

This method may prove unsatisfactory in the following respects:

---

(a) The melting of ice in pockets and its retention in the box after melting cause low results.

(b) Frequent additions of ice must be made to keep the box as full as possible.

(c) The inside temperature reading is not the true inside temperature because of the temperature gradient through the walls of the metal box, which results in low coefficients.

(d) The range of temperature drop, through which the material is to be tested, is fixed unless some means are employed for regulating the outside air temperature.
11. **The Oil Box Method.**—In this method, illustrated by Fig. 4, a metal box is covered with the material to be tested. Oil is placed inside the box and is kept at the desired temperature by means of an electrical heater immersed in the oil. A stirring device keeps the oil at uniform temperature. The amount of heat transmitted through the material under test is determined from the electrical input.

![Fig. 6. The Hot Air Box Method of Testing Heat Transmission](image)

In this method the range of temperature through which the tests may be run is much larger than in the ice box method, and it is not necessary to add to the material in the metal box. In other respects, however, this method presents the same disadvantages as the ice-box method.

12. **The Cold Air Box Method.**—In this method, illustrated by Fig. 5, a box of cracked ice, hung near the top on the center line of the testing box, is substituted for the electrical heating element. The melting of the ice maintains the temperature of the air in the box at a lower degree than the air outside. The suspension of the ice box near the top of the test box supposedly causes natural circulation to maintain the inside air temperature nearly uniform. The heat transmitted is determined by weighing the amount of ice melted. Since it is not possible to control satisfactorily the temperature inside the box, this method is generally inferior to the hot air box method.

13. **The Hot Air Box Method.**—The test box for the hot air box method (Fig. 6) is made entirely of the material to be tested, unless the material is such that a skeleton frame work is necessary to provide
strength for the structure. The heat is supplied by electrical means, a resistance coil or a bank of lamps being used. A fan is usually employed inside the test box to circulate the air and maintain a uniform air temperature throughout the interior of the box. The amount of heat transmitted through the material is determined from the combined electrical input to the heater and to the fan motor.

This method, or a modification of it, is considered, according to Prof. C. L. Norton, the best to employ in testing materials for heat transmission. The use of the fan, however, is objectionable if a determination of the inside coefficient \( K_i \) is to be made, since the velocity of the air over the inside surface tends to increase the value of \( K_i \). In test specimens of large dimensions the fan is necessary if the interior air is to be maintained at a uniform temperature throughout.

14. The Flat or Hot Plate Method.—In this method (Fig. 7), the heating element consists of an electric grid, which is made of resistance wire placed between asbestos sheets. The material to be tested is placed on both sides of the grid and in contact with it. Outside the test material are placed two hollow flat plates, which are kept at constant temperature by means of water circulation through the plates. All the heat, except that lost from the edges in some plates, goes through the test material into the water-cooled outside plates. In some hot plates no water-cooled outside plates are used, the edges being covered with the test material; thus the heat passes through only the test material. The heat lost is measured by the
electrical input, and the temperature difference between the inside and outside surfaces is usually determined by electrical means. Given the dimensions of the plate, the conductivity of the specimen may be readily determined.

The amount of the heat loss from the edges, in the one case, is unknown. According to one authority, this loss is not only considerable but varies in amount, the variation depending upon the nature and the thickness of the material being tested. A correction, the accuracy of which is rather uncertain, for this edge loss must be made. When the water-cooled plates are used, only the conductivity can be determined; without them the outside surface coefficient may also be obtained. In neither case can the transmission coefficient (air to air) be obtained.

15. The Determination of the Heat Transmission Coefficient under the Foregoing Methods.—In any of the box methods of testing, the determination of the heat transmission coefficient \( U \) is a comparatively simple matter, but in order to obtain any of the other coefficients an accurate determination of surface temperatures must be made. Various means of temperature measurement have been employed for this purpose. Oil wells for mercury thermometers have been sunk in the surface of the material, the center line of the oil well lying in the plane of the material being tested. Mercury thermometers have been fully imbedded in the material, half-way imbedded, or fastened on the surface in attempts to determine the true surface temperature. Experiments show that the accuracy with which mercury thermometer determinations of surface temperatures can be made depends almost entirely upon the dimensions and the nature of the test specimen; the temperature gradient through the material being the governing factor. If the material being tested is thick with a correspondingly small temperature drop per inch through the material, the displacement of the center line of the thermometer with regard to the surface of the material is much less important than with a comparatively thin test specimen and its correspondingly steeper temperature gradient.

Dalby further complicates the matter by his suggestion, previously mentioned, that there is probably a further drop of temperature head occurring just at the surface of the material which is required to force the flow of heat across the surface. The temperature head required to cause the flow of heat through the material,
however, is the difference between the temperatures at each end of the temperature gradient through the material itself.

The temperature gradient through the material is usually assumed to be a straight line. This assumption suggests the possibility of determining the surface temperatures at two different points along this gradient and then solving graphically or analytically for the surface temperatures, but most building materials are not homogeneous enough to warrant the straight line assumption. The density of the material must be considered in determining the homogeneity of the material.

Attempts to determine surface temperatures by means of platinum discs held against the surface of the material have been made at the Engineering Experiment Station of Pennsylvania State College.
V. DESCRIPTION OF SPECIMENS, TESTING APPARATUS, AND METHOD
OF CONDUCTING TESTS

16. The Testing Plant.—Since practically full size specimens
were to be used in determining the heat transmission of all the walls
investigated and in ascertaining the values of the surface and con-
ductivity coefficients, the hot air box method of testing was chosen.
The box was built of the material to be tested except where means of
support were needed. In order to get convection conditions similar
to those in actual practice, the boxes were built about the height of
a room and were supported on small piers; thus air was allowed to
circulate around practically all parts of the box.

The heating element was composed of "Yankee Silver" resistance wire,* helically wound with increasing pitch from bottom to
top upon a wooden frame support placed inside the box. With this
method of heating it was found after considerable experimenting
that the same variation in air temperature was maintained as is
found in the average room, that is, the air was warmer near the ceil-
ing than at the floor line.

A voltmeter across the terminals of the resistance heating coil,
an ammeter in the line, and a water resistance box, or rheostat, to
control the current constituted the apparatus necessary to control
and determine the heat input into the box. All electrical instru-
ments were accurately calibrated against standard meters of the Elec-
trical Engineering Department.

Air and surface temperatures were measured with mercury ther-
nometers and thermocouples or with thermocouples alone. All mer-
ccury thermometers were carefully calibrated against a standard Cen-
tigrade thermometer of known accuracy.

A diagrammatic sketch of the apparatus used for determining
the various coefficients is presented as Fig. 8. Only one thermo-
couple circuit is shown in the diagram.

For the moving air tests, in addition to the apparatus illustrated
by Fig. 8, a hood shown in Fig. 9 was placed over the column. This
hood, placed so that the column was centrally located inside, was
connected to a No. 4 Sirocco multivane fan by means of a 24-inch
duct about thirty feet long. A variable speed direct-current motor,

* The wire used for the resistance coil is known as a "Yankee Silver" No. 16 B. and S.
gage, a patented alloy manufactured by Driver-Harris Company, Harrison, New Jersey.
The resistance per mil foot is 200 ohms at 75 degrees F. The temperature coefficient is
0.000086 per degree. The specific gravity is 8.6. The weight per cubic inch is 0.31 pounds.
Fig. 9. Diagram of Apparatus Used in Moving Air Tests
belt-connected to the Sirocco fan, furnished the means for varying the velocities of air flow over the surface of the column being tested. By means of dampers in the hood the velocity of the air was kept uniform over the four sides.

A Pitot tube and a piezometer ring were used to determine the quantity of air discharged by the fan; consequently the velocity of the air over the surface of the test column was readily calculated.

Photograph views of the test apparatus are presented in Figs. 10, 11, and 12.

17. Calibration of Thermocouples.—The thermocouple has been found to be better suited to the determination of surface temperatures than the thermometer. The junction, when embedded just in the surface of the material, indicates the surface temperature as nearly as it is possible, at the present time, to make such measurements. The accuracy of the temperatures determined in this manner is also dependent upon the temperature gradient through the material, but owing to the difference in dimensions between a thermocouple junction and the thickness of the material to be tested, this factor is not significant.

The thermocouples used in these tests were made of copper and a nickel alloy of copper called constantan, No. 25 B. and S. gage, double silk covered wire being used. The junctions were made by fusing the ends of the two different wires together in the flame of a blast lamp. Each junction was placed in a glass tube closed at one end and filled with oil, and the two wires were insulated from each other by a small glass tube slipped around one of the wires.

Calibrations were made with a cold junction temperature of 70 degrees F., the hot junction temperature being controlled by means of a hot-water bath. In series with each couple, by means of switches, were placed a resistance and a Leeds and Northrup Type H D'Arsonval galvanometer for indicating by angular deflections the current generated and therefore the temperature in each thermocouple circuit. The deflection method of measuring the temperature difference between the cold and hot junctions was used. In order to make this method as accurate as possible, all calibrations were made with the galvanometer balanced and set in position on a concrete pier; in this position it remained without any change through the set of tests on any specimen with which a given set of thermocouples was connected. The deflection method is considered entirely reliable, if proper care
Fig. 10. View of test columns showing brick column in place and other columns as made ready for testing.
This view also shows the rheostat and the electrical instruments for controlling and measuring the heating current supplied to the column in the right foreground. The concrete pier and leads to thermocouples are shown at the left. 

Note—Small galvanometer shown on pier was not used during the tests reported.
is taken, and has been used by other investigators in this field. The Babcock and Wilcox Company have recently applied this method in a series of tests run at Bayonne, N. J., on the rate of heat transfer through boiler tubes.

In calibrating thermocouples it is customary to hold the temperature of the cold junction constant at a predetermined point, to vary the hot junction temperature, and to note the deflection of the galvanometer. Owing to the slight inconvenience of keeping the cold junction at the temperature at which it was calibrated, some experimenters prefer to run a series of calibrations with the temperature of the cold junction varying over the range expected during the test.

Another method of procedure is to calibrate, as in the first case, by holding the cold junction at a certain temperature and then, with a fixed hot junction temperature, the cold junction temperature is changed to a point above and to a point below the original temperature during the calibration. The three readings or deflections are plotted, the equation of the curve determined, and the correction for the cold junction temperature is readily made.

The first method was followed during these experiments. A typical set of thermocouple calibration curves is presented in Fig. 13. It will be noted that the curve A, of the lower temperature differences, is obtained with 300 ohms external resistance in the circuit while 1,300 ohms were used to obtain the curve of higher temperature differences. This method gives a larger deflection for the lower temperatures than would otherwise be obtained with a single fixed resistance in the circuit, yet the deflection, corresponding to the highest temperature to be measured, remains within the range of the galvanometer.

After calibration, the so-called hot junctions were removed from the glass containers and fastened in position on the surface of the material to be tested or in the air about one inch from the surface. All thermocouples and mercury thermometers used for determining air temperatures were shielded against direct radiation by means of paper shields.

Thermocouples for determining surface temperatures were attached to the surfaces in the manner described in the following: For wood, a thin shaving was glued over the junction, the junction being somewhat imbedded in the surface of the material before the application of the thin shaving; for the materials composed of asbestos, the junction was covered by a thin sheet of asbestos or held against the
DARSONVAL GALVANOMETER DEFLECTION

EXTERNAL RESISTANCE
CURVE A- 300 OHMS
CURVE B- 1,300 OHMS

FIG. 13. TYPICAL THERMOCOUPLE CALIBRATION CURVES
surface with a mixture of powdered asbestos and water; for the vitreous materials, the junction was fastened to the surface with a thin layer of plaster of Paris.

In determining surface temperatures with mercury thermometers, it was found that if the thermometer was imbedded in a trench just deep enough to permit the thermometer to lie entirely below the surface of the material, the temperature recorded was higher than that given by the thermocouple, the difference being dependent upon the thickness of the material. If the thermometer were placed against the surface, all the thermometer being out of the surface, yet covered, and stuck to the surface, as previously described, it was found that the temperature recorded was somewhat lower than that recorded by the thermocouple. With comparatively thick materials the temperatures indicated by the thermometers and the thermocouples were practically the same when the thermometers were so imbedded that their axes lay in the plane of the surface of the material.

18. The Method of Conducting Tests.—The temperature of the air inside the test column was brought to the desired point by allowing a relatively large current to flow through the heating coil. As the rising air temperature approached the desired point, the current was decreased until the right amount was flowing to maintain the required temperature. In all cases sufficient time, ranging from twenty-four to seventy-two hours, according to the material and its thickness, was then allowed to elapse in order to insure constant heat flow. Readings of thermometers, thermocouples, and electrical instruments were then taken at intervals of thirty minutes. From five to seven readings were taken during each test, local conditions determining the duration of the tests. Usually three or four tests were run on each material, various air temperature differences being maintained for each test. In most cases both mercury thermometers and thermocouples were installed for each test. This installation made it possible to run both tests at the same time, and provided the data for a direct comparison.

The moving air tests were conducted in a manner similar to that described in the preceding paragraph, and in addition a traverse of the air duct was made during each test, the fan speed was recorded, and the exit velocity of the air over the four sides of the column was checked with an anemometer at the regular 30-minute intervals. The relative humidity of the air was also determined for each test.
In the combined moving air and humidity tests, the humidity of the air as it left the air washer was also recorded. The air washer made it possible to supply air at practically one hundred per cent relative humidity for the combined moving air and humidity tests.

19. Calculations for Finding Coefficients.—The readings, taken during a test, for each thermometer, thermocouple, or electrical meter were averaged and then corrected according to the calibration curves. The corrected averages for any one section, such as the outside surface temperatures, were then averaged, the result being the outside surface temperature in the case mentioned. From these final temperatures the various drops, air to air, wall to wall, air to wall, and wall to air, were determined.

The heat transmitted was determined from the electrical input by means of the following relation:

\[ \text{Volts} \times \text{Amperes} \times 3.412 = \text{B. t. u. loss per hour.} \]

Since the heat input was known, the various coefficients were determined from the following equations:

\[
U = \frac{H}{S_m (t_1 - t_4)} \\
K_1 = \frac{H}{S_1 (t_1 - t_2)} \\
K_2 = \frac{H}{S_2 (t_3 - t_4)} \\
C = \frac{H_x}{S_m (t_2 - t_3)}
\]

In which,

- \( S_m \) is the mean area of the inside and outside surfaces in square feet and is taken as the arithmetical mean of \( S_1 \) and \( S_2 \).
- \( S_1 \) is the inside area of the test box in square feet.
- \( S_2 \) is the outside area of the test box in square feet.
- \( H \) is the total heat transmission of the box in B. t. u. per hour.
- \( t_1 \) is the inside air temperature.
- \( t_2 \) is the inside wall temperature.
- \( t_3 \) is the outside wall temperature.
- \( t_4 \) is the outside air temperature.

In the moving air tests, flow of air occurred over the four sides.
of the test box only; thus it is necessary to make a correction to allow for the difference in loss of heat from the ends and sides. It is assumed that the loss of heat from the ends is the same during the moving air tests as during the still air tests, and the correction is accordingly made in the following manner:

\[ H_s = H_t - u S_e (t_1 - t_4) \]

in which,
- \( H_s \) is the heat loss through the sides in B. t. u.
- \( H_t \) is the total heat loss from the test box in B. t. u.
- \( u \) is the unit transmission of the test box, obtained from the still air tests.
- \( S_e \) is the mean area of the ends of the box in square feet.
- \( t_1 \) is the inside air temperature in degrees F.
- \( t_4 \) is the outside air temperature in degrees F.

In determining the coefficients for the moving air tests, the relations given on page 32 are used; \( H_s \) is substituted for the heat loss, and the respective areas of the sides are used instead of those in the entire box.

In making a traverse to determine the quantity of air flowing, the duct was divided into five concentric zones of equal area, and readings were taken on the circle which equally divided the area of each zone. The traverse was made across on one diameter only, thus giving ten readings in inches of water, which will be called \( h \). To calculate the mean velocity, these values of \( h \) were substituted in the following equation:

\[ V_m = \frac{18.27}{d^{\frac{1}{2}}} \left[ \left( \sqrt{h_1} + \sqrt{h_2} + \sqrt{h_3} + \text{etc.} \right) \right] \]

in which,
- \( V_m \) is the mean velocity in feet per second.
- \( d \) is the density of the air at the mean temperature pounds per cubic foot.
- \( h \) is the velocity pressure in inches of water.
- \( n \) is the number of readings taken.

Knowing the mean velocity of the air in the duct, the relative areas of the duct, and the space between the test column and the surrounding hood, the air velocity over the surface of the test column can readily be determined.

The space between the hood and the test column was changed in going from the low to the high velocity tests in order to run the velocities as high as desired.
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<tr>
<th>Material</th>
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<th>Density</th>
<th>Area</th>
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<td>36.06 Sq. Ft.</td>
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**TABLE I**

Heat Transmission Tests—Still Air
A STUDY OF THE HEAT TRANSMISSION OF BUILDING MATERIALS

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<thead>
<tr>
<th>Material</th>
<th>Density</th>
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<th>Mean</th>
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<th>Outside</th>
<th>Areas</th>
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<td>1½-in. Magnesia Board</td>
<td>13.5 Lb. / Cu. Ft.</td>
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<td>45.12 Sq. Ft.</td>
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<td>2-in. Cork Board (Nonpareil)</td>
<td>9.74 Lb. / Cu. Ft.</td>
<td>2.03&quot;</td>
<td>39.34 Sq. Ft.</td>
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<td>46.04 Sq. Ft.</td>
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<td>1-in. Wood (Fir)</td>
<td>33.37 Lb. / Cu. Ft.</td>
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<td>97.07</td>
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<td>2.86</td>
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<tr>
<td>100.07</td>
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<td>2.86</td>
<td>0.27</td>
<td>0.27</td>
<td>0.27</td>
<td></td>
</tr>
</tbody>
</table>

Thermocouple and Thermometer values are shown in the table. The table also includes Mean Inside and Outside values along with the Areas for each material. The Air Test Temperature Differences are also listed.
<table>
<thead>
<tr>
<th>Material</th>
<th>Coverage</th>
<th>Inside Mean</th>
<th>Outside Mean</th>
<th>Heat Loss</th>
<th>Air</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-in. Concrete</td>
<td>Covered</td>
<td>139.7 Lb./Cu. Ft.</td>
<td>1.34 Lb./Sq. Ft.</td>
<td>3.34'</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-Course Brick</td>
<td>Covered</td>
<td>131.9 Lb./Cu. Ft.</td>
<td>1.34 Lb./Sq. Ft.</td>
<td>3.34'</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE I (Continued)**

**HEAT TRANSMISSION TESTS—STILL AIR**

<table>
<thead>
<tr>
<th>Material</th>
<th>Coverage</th>
<th>Inside Mean</th>
<th>Outside Mean</th>
<th>Heat Loss</th>
<th>Air</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-in. Concrete</td>
<td>Covered</td>
<td>139.7 Lb./Cu. Ft.</td>
<td>1.34 Lb./Sq. Ft.</td>
<td>3.34'</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-Course Brick</td>
<td>Covered</td>
<td>131.9 Lb./Cu. Ft.</td>
<td>1.34 Lb./Sq. Ft.</td>
<td>3.34'</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Panes Glass 1/4&quot; Air Space</td>
<td>Single Strength Glass 76.3% Glass</td>
<td>Sheet Asbestos 60 Sheets 1-64-in. Thick</td>
<td>1-in. Asbestos Board (Corrugated Interior)</td>
<td>Material Density Per Square Foot</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------------</td>
<td>----------------------------------</td>
<td>------------------------------------------</td>
<td>---------------------------------------------</td>
<td>----------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>141.1 Lb. / Cu. Ft.</td>
<td>0.088&quot; and 0.127&quot;</td>
<td>48.25 Lb. / Cu. Ft.</td>
<td>20.42 Lb. / Cu. Ft.</td>
<td>50.10 Sq. Ft.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>45.46 Sq. Ft.</td>
<td>43.23 Sq. Ft.</td>
<td>30.96 Sq. Ft.</td>
<td>46.58 Sq. Ft.</td>
<td>1.286 Lb.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17.90</td>
<td>43.33 Sq. Ft.</td>
<td>48.75 Sq. Ft.</td>
<td>53.61 Sq. Ft.</td>
<td>1.10 Lb.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermocouple</td>
<td>Thermocouple</td>
<td>Thermometer</td>
<td>Thermometer</td>
<td>Mean Inside Temperature Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>73.1</td>
<td>1194.0</td>
<td>3740.5</td>
<td>789.6</td>
<td>Mean Outside Temperature Area</td>
<td></td>
<td></td>
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<tr>
<td>146.40</td>
<td>1300.0</td>
<td>5109.7</td>
<td>809.2</td>
<td>Mean Inside Temperature Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28.5</td>
<td>48.04</td>
<td>69.19</td>
<td>77.83</td>
<td>Mean Outside Temperature Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>52.2</td>
<td>44.40</td>
<td>63.00</td>
<td>32.02</td>
<td>Mean Inside Temperature Area</td>
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<td></td>
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<td>9.38</td>
<td>25.55</td>
<td>13.46</td>
<td>33.12</td>
<td>Mean Outside Temperature Area</td>
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<td></td>
</tr>
<tr>
<td>14.97</td>
<td>15.42</td>
<td>9.39</td>
<td>31.23</td>
<td>Mean Inside Temperature Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.90</td>
<td>2.22</td>
<td>1.09</td>
<td>2.17</td>
<td>Mean Outside Temperature Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.61</td>
<td>0.86</td>
<td>0.05</td>
<td>0.32</td>
<td>Mean Inside Temperature Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.96</td>
<td>1.78</td>
<td>1.30</td>
<td>1.35</td>
<td>Mean Outside Temperature Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>C</td>
<td>K1</td>
<td>K2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.78</td>
<td>1.04</td>
<td>1.47</td>
<td>1.32</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.34</td>
<td>0.88</td>
<td>1.34</td>
<td>1.86</td>
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<td></td>
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<tr>
<td>0.31</td>
<td>0.86</td>
<td>1.44</td>
<td>1.95</td>
<td></td>
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</tbody>
</table>

Table 1 (Continued)
<table>
<thead>
<tr>
<th>Material</th>
<th>Density</th>
<th>Thickness</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tile 119.86 Lb./Cu. Ft.</td>
<td>141.1 Lb./Cu. Ft.</td>
<td>0.085'</td>
<td>0.15'</td>
</tr>
<tr>
<td>Roofing 0.83 Lb./Sq. Ft.</td>
<td>1.34 Lb./Sq. Ft.</td>
<td>3.79'</td>
<td>119.86 Lb.</td>
</tr>
<tr>
<td>Gravel 0.83 Lb./Sq. Ft.</td>
<td>0.83 Lb./Sq. Ft.</td>
<td>1.34</td>
<td>3.79'</td>
</tr>
</tbody>
</table>

**Table 1** (Concluded)

**Heat Transmission Tests—Still Air**

<table>
<thead>
<tr>
<th>Thermocouple</th>
<th>Thermometer</th>
<th>Thermo-</th>
<th>Thermo-</th>
<th>Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1039.0</td>
<td>5</td>
<td>147.1</td>
<td>441.0</td>
<td>1038.0</td>
</tr>
<tr>
<td>5.00</td>
<td>48.04</td>
<td>28.39</td>
<td>72.85</td>
<td>5.00</td>
</tr>
<tr>
<td>51.13</td>
<td>26.07</td>
<td>28.39</td>
<td>72.85</td>
<td>5.00</td>
</tr>
<tr>
<td>10.05</td>
<td>11.70</td>
<td>28.39</td>
<td>72.85</td>
<td>5.00</td>
</tr>
<tr>
<td>10.05</td>
<td>13.81</td>
<td>28.39</td>
<td>72.85</td>
<td>5.00</td>
</tr>
<tr>
<td>13.81</td>
<td>28.39</td>
<td>28.39</td>
<td>72.85</td>
<td>5.00</td>
</tr>
<tr>
<td>2.71</td>
<td>4.00</td>
<td>28.39</td>
<td>72.85</td>
<td>5.00</td>
</tr>
<tr>
<td>1.82</td>
<td>4.00</td>
<td>28.39</td>
<td>72.85</td>
<td>5.00</td>
</tr>
<tr>
<td>1.82</td>
<td>4.00</td>
<td>28.39</td>
<td>72.85</td>
<td>5.00</td>
</tr>
<tr>
<td>1.82</td>
<td>4.00</td>
<td>28.39</td>
<td>72.85</td>
<td>5.00</td>
</tr>
<tr>
<td>1.82</td>
<td>4.00</td>
<td>28.39</td>
<td>72.85</td>
<td>5.00</td>
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<tr>
<td>1.82</td>
<td>4.00</td>
<td>28.39</td>
<td>72.85</td>
<td>5.00</td>
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<tr>
<td>1.82</td>
<td>4.00</td>
<td>28.39</td>
<td>72.85</td>
<td>5.00</td>
</tr>
</tbody>
</table>

**Coefficients**

- U
- Κ1
- K2
VI. RESULTS AND TEST DATA

20. Still Air Tests.—The material, density, thickness, and heat transmitting areas of the various walls investigated are given in Table 1. This table also presents the average test data for heat transmitted and temperature differences which are required in calculating the coefficients $U$, $C$, $K_1$, and $K_2$. The calculated values for each coefficient are given in the last four columns of the table. In most cases there are two separate sets of tests for each material, the first being the mercury thermometer tests, and the second the thermocouple tests. For every thermometer test there is a corresponding thermocouple test, the two having been run at the same time.

21. Coefficients of Heat Transmission.—In each case, $U$ is the heat, in B. t. u., transmitted by one square foot of wall surface per hour, per degree of difference in air temperature, inside to outside, for the thickness of wall actually tested. For the solid walls, such as brick, concrete, or cork, $C$ is the conductivity of one square foot of wall surface per hour, per degree of difference in the surface temperatures, per inch in thickness of the material tested. For walls made of other than solid materials, such as the tile walls, the value of $C$ is given for the thickness of wall actually tested. The surface coefficient $K_1$ is the heat received by one square foot of wall surface per hour, per degree difference in temperature between the inside air and inside wall surface. $K_2$ is the heat emitted by one square foot of wall surface per hour, per degree of difference in temperature between the outside wall surface and the outside air. The thickness or nature of the wall does not affect the determination of surface coefficients.

22. Discussion of Results.—The values of the transmission coefficients, $U$, have undoubtedly been affected by the abnormally high values of inside surface coefficients, $K_1$, when based on thermocouple readings. The radiation from the heating coil to the inside wall of the test column was apparently great enough to make the inside surface coefficient larger than the outside one. It was thought that with this method of heating, that is, eliminating the fan inside the box (See Hot Air Box method of testing), that surface coefficients corresponding approximately to still air conditions would be obtained for both the inside and outside surfaces. In this case, the air-to-air heat
transmission of the walls would have corresponded to still air conditions.

It will be noted from the result sheets, Table 1, that the $K_1$ values of each set of tests roughly check each other; this agreement indicates that mercury thermometers imbedded half-way in the material give fairly close readings of the outside surface temperatures.

The values of the transmission coefficients, $U$, show that for the air-to-air coefficient mercury thermometers give fairly accurate results. For the inside surface temperatures, however, where oil wells imbedded in the surface were used, the results from the mercury thermometer tests are far from correct; thus there is no checking of the $K_1$ and $C$ values of the two sets of tests. Only the thermocouple temperatures are to be relied upon for inside wall temperatures.

For calculating heat transmission coefficients of simple or compound walls, it is, fortunately, only necessary to have the coefficients

### Table 2

**Coefficients Based on Heat Transmission Tests**

(See "Applications of Test Data to Typical Walls")

<table>
<thead>
<tr>
<th>No.</th>
<th>Material</th>
<th>$C$ per 1&quot; Thickness per Sq. Ft. per 1° F.</th>
<th>$K$ Still Air per 1° F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Brick Wall (Mortar Bond &amp; Dry Conditions)</td>
<td>4.00</td>
<td>1.40</td>
</tr>
<tr>
<td>2</td>
<td>Concrete, 1-2-4 Mixture</td>
<td>8.30</td>
<td>1.30</td>
</tr>
<tr>
<td>3</td>
<td>Wood (Fir, one surface finished)</td>
<td>1.00</td>
<td>1.40</td>
</tr>
<tr>
<td>4</td>
<td>Corkboard</td>
<td>0.32</td>
<td>1.25</td>
</tr>
<tr>
<td>5</td>
<td>Magnesia Board</td>
<td>0.50</td>
<td>1.45</td>
</tr>
<tr>
<td>6</td>
<td>Glass (actual glass 91.4% of total area)</td>
<td>2.063</td>
<td>2.00</td>
</tr>
<tr>
<td>7</td>
<td>2-in. Tile, 1/4-in. plaster on both surfaces</td>
<td>1.004</td>
<td>1.10</td>
</tr>
<tr>
<td>8</td>
<td>4-in. Tile, 1/4-in. plaster on both surfaces</td>
<td>0.604</td>
<td>1.10</td>
</tr>
<tr>
<td>9</td>
<td>6-in. Tile, 1/4-in. plaster on both surfaces</td>
<td>0.474</td>
<td>1.10</td>
</tr>
<tr>
<td>10</td>
<td>2-in. Tile, plastered as above and roofing covered</td>
<td>0.84</td>
<td>1.25</td>
</tr>
<tr>
<td>11</td>
<td>Asbestos Board</td>
<td>0.50</td>
<td>1.00</td>
</tr>
<tr>
<td>12</td>
<td>Sheet Asbestos</td>
<td>0.30</td>
<td>1.40</td>
</tr>
<tr>
<td>13</td>
<td>Double Glass, 1/4-in. air space (glass 69.3% of total area)</td>
<td>1.5034</td>
<td>2.00</td>
</tr>
<tr>
<td>14</td>
<td>Roofing $^1$</td>
<td>5.304</td>
<td>1.25</td>
</tr>
<tr>
<td>15</td>
<td>Air Space $^2$</td>
<td>1.00-1.704</td>
<td>....</td>
</tr>
</tbody>
</table>

1 Calculated from values of $C$ for 2-in tile with and without roofing. \( \left( \frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} \right) \)

2 See "Air Spaces."

3 Per sq. ft. of actual glass set in wood frame but based on total heat transmitted.

4 For thickness and construction stated, not per 1" of thickness.

Note: These values are selected from Table 1 and are based on the tests run under most satisfactory conditions.
of conductivity and the surface coefficients of the materials composing the wall; consequently, in selecting the coefficients for Table 2 only the outside surface coefficients were considered in getting the values found under the column headed $K$. These values are the surface coefficients for still air conditions, and are in B. t. u. per square foot of surface per hour, per degree difference between the surface temperature and the temperature of the air in contact with it. Values of $C$ are in B. t. u. per one square foot of surface per hour per degree difference between the inside and outside surface temperatures, per inch in thickness for solid walls, and for the actual thickness of hollow walls of simple or compound construction. In selecting these coefficients, the greatest significance has been attached to the values obtained from the tests of greatest air temperature differences, and only the tests in which thermocouples were used were considered.

Attention is called to the value of $C$ for roofing, deduced from the values of $C$ obtained in the 2-inch tile tests with and without roofing. This value was calculated from the relation:

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$$

where $C_1$ and $C_2$ are the conductivities of the tile and the roofing respectively. In the table of coefficients values will also be found for the so-called conductivity of air spaces, an explanation of which will be found under the section on air spaces.

23. Moving Air Tests.—Results of the moving air tests on brick are presented in Table 3.

Curves showing the effect of the velocity of air on the various coefficients for a 4-inch brick wall are given in Figs. 14 and 15. Just why $K_1$, the inside surface coefficient, should increase with an increasing air velocity over the outside of the box is difficult to explain. Air moving over the outside surface causes the outside surface temperatures to approach that of the outside air with an increase in velocity. The loss of heat being practically the same in all but a few of the tests, the temperature of the inside surface would have to drop until the temperature gradient through the material was the same as in the still air tests. On account of the lowering of the inside wall temperature, a drop of the inside air temperature, of such magnitude that the coefficient for the inside surface would be the same as under still air conditions, would be expected. According to the tests, however, the temperature difference is less than this amount, resulting in
### TABLE 3

**RESULTS OF THE MOVING AIR TESTS ON BRICK**

**PARTLY SATURATED AIR**

<table>
<thead>
<tr>
<th>No.</th>
<th>Total Heat Loss</th>
<th>Corrected Heat Loss</th>
<th>Air Temperature Difference</th>
<th>Wall Temperature Difference</th>
<th>Air to Wall Difference</th>
<th>U</th>
<th>C</th>
<th>K₁</th>
<th>K₂</th>
<th>Air Velocity</th>
<th>Relative Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1278.0</td>
<td>1117.2</td>
<td>73.96</td>
<td>47.40</td>
<td>19.05</td>
<td>7.51</td>
<td>0.70</td>
<td>4.15</td>
<td>3.89</td>
<td>5.30</td>
<td>1563</td>
</tr>
<tr>
<td>2</td>
<td>1227.5</td>
<td>1061.0</td>
<td>76.55</td>
<td>49.15</td>
<td>19.45</td>
<td>7.95</td>
<td>0.64</td>
<td>3.98</td>
<td>3.63</td>
<td>4.76</td>
<td>985</td>
</tr>
<tr>
<td>3</td>
<td>1126.5</td>
<td>967.2</td>
<td>73.25</td>
<td>45.55</td>
<td>17.80</td>
<td>9.90</td>
<td>0.61</td>
<td>3.91</td>
<td>3.61</td>
<td>3.48</td>
<td>461</td>
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<tr>
<td>4</td>
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<td>1019.3</td>
<td>71.81</td>
<td>46.70</td>
<td>17.95</td>
<td>7.16</td>
<td>0.66</td>
<td>4.02</td>
<td>3.77</td>
<td>5.07</td>
<td>1955</td>
</tr>
<tr>
<td>5</td>
<td>1413.0</td>
<td>1244.2</td>
<td>77.62</td>
<td>53.95</td>
<td>18.95</td>
<td>4.72</td>
<td>0.74</td>
<td>4.25</td>
<td>4.36</td>
<td>9.40</td>
<td>3100</td>
</tr>
<tr>
<td>6</td>
<td>1434.5</td>
<td>1241.5</td>
<td>88.73</td>
<td>56.00</td>
<td>19.25</td>
<td>5.48</td>
<td>0.65</td>
<td>4.09</td>
<td>4.29</td>
<td>8.08</td>
<td>4378</td>
</tr>
<tr>
<td>7</td>
<td>1485.0</td>
<td>1317.0</td>
<td>77.23</td>
<td>55.60</td>
<td>16.40</td>
<td>5.23</td>
<td>0.79</td>
<td>4.37</td>
<td>5.34</td>
<td>9.16</td>
<td>5200</td>
</tr>
<tr>
<td>8</td>
<td>1191.0</td>
<td>1039.5</td>
<td>69.54</td>
<td>48.55</td>
<td>16.50</td>
<td>4.49</td>
<td>0.69</td>
<td>3.95</td>
<td>4.19</td>
<td>8.26</td>
<td>3135</td>
</tr>
<tr>
<td>9</td>
<td>1171.5</td>
<td>1024.4</td>
<td>67.66</td>
<td>45.95</td>
<td>17.40</td>
<td>4.31</td>
<td>0.70</td>
<td>4.11</td>
<td>3.91</td>
<td>8.47</td>
<td>2570</td>
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</tr>
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<td>9.05</td>
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<td>989</td>
</tr>
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<td>46.65</td>
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<td>7.50</td>
<td>0.62</td>
<td>3.75</td>
<td>3.40</td>
<td>4.71</td>
<td>1175</td>
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</tbody>
</table>
an increase of $K_1$, with the velocity of the air. The conductivity curve is practically horizontal, as would be expected, since the mean temperature of the material was about the same for all the tests. The transmission curve increases with the air velocity in a manner similar to the increase of the outside surface coefficient.

**Fig. 14.** $K_1$ and $K_2$ Curves, Brick Box Moving Air Test (Average Relative Humidity, see Table 3)

**Fig. 15.** $U$ and $C$ Curves, Brick Box Moving Air Test (Average Relative Humidity, see Table 3)
### Table 4

**Results of the Moving Air Tests on Wood**

**Partly Saturated Air**

<table>
<thead>
<tr>
<th>No.</th>
<th>Total Heat Loss</th>
<th>Corrected Heat Loss</th>
<th>Air Temperature Difference</th>
<th>Wall Temperature Difference</th>
<th>Air to Wall Difference</th>
<th>Wall to Air Difference</th>
<th>U</th>
<th>C</th>
<th>K1</th>
<th>K2</th>
<th>Air Velocity</th>
<th>Humidity</th>
</tr>
</thead>
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<td>9.73</td>
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<td>2322</td>
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<td>0.84</td>
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<td>5.40</td>
<td>3138</td>
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<tr>
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<td>8.88</td>
<td>0.70</td>
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<td>4015</td>
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<td>...</td>
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<td>4.69</td>
<td>3.21</td>
<td>41</td>
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</table>
24. Discussion of Results.—Results of the moving air tests on wood are presented in Table 4. These data are plotted on the curve sheets, Figs. 16 and 17, and show the rate of change of the various coefficients with air velocity. The remarks regarding \( K_1 \) for the brick box tests apply equally well to the \( K_1 \) values for the wood box tests. In the still air tests the value of \( K_1 \) for wood is evidently incorrect and has been disregarded in drawing the \( K_1 \) curve for this material.

![Fig. 16. \( K_1 \) and \( K_2 \) Curves, Wood Box Moving Air Test (Average relative humidity, see Table 4)](image1)

![Fig. 17. \( U \) and \( K_2 \) Curves, for Wood Box Moving Air Test (Average relative humidity, see Table 4)](image2)
### Table 5

**RESULTS OF THE SATURATED AIR TESTS ON THE BRICK BOX**

<table>
<thead>
<tr>
<th>No.</th>
<th>Total Heat Loss</th>
<th>Corrected Heat Loss</th>
<th>Air Temperature Difference</th>
<th>Wall Temperature Difference</th>
<th>Air to Wall Difference</th>
<th>Wall to Air Difference</th>
<th>U</th>
<th>C</th>
<th>K1</th>
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</table>

### Table 6

**RESULTS OF THE SATURATED AIR TESTS ON THE WOOD BOX**

<table>
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<th>No.</th>
<th>Total Heat Loss</th>
<th>Corrected Heat Loss</th>
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<th>Wall Temperature Difference</th>
<th>Air to Wall Difference</th>
<th>Wall to Air Difference</th>
<th>U</th>
<th>C</th>
<th>K1</th>
<th>K2</th>
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<td>5.94</td>
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<td>2.55</td>
<td>6.53</td>
<td>4510</td>
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</table>
25. The Effect of Variations in Relative Humidity on Surface Coefficients.—Results of the saturated air tests on the brick box are presented in Table 5, and those on the wood box in Table 6. Curves of the various coefficients determined from the saturated air tests on the wood box are shown in Fig. 18.

The three curves shown in Fig. 19, which are taken from the \( K_z \) curves in Figs. 14 and 16, at the lower velocities, and the four points plotted, which are obtained from the data of the saturated air tests
on the brick box in Table 5, show the effect of humidity on the outside surface coefficients. The conclusion is that the increase in humidity has no appreciable effect on the outside surface coefficient for brick, while in the case of wood an increase is apparent. The practical importance of this conclusion is doubtful, since the increase would be negligible in making a calculation for the heat transmission through a wall.

![U Curves, Air Velocity Below 2000 Feet Per Minute](image)

The three curves shown in Fig. 20, taken from the \( u \) curves in Figs. 15, 17, and 18, at the lower velocities, and the four points plotted, which are obtained from the results of the saturated air tests on the brick box Table 5, show the effect of humidity on the heat transmission coefficient. The plotted points lie close enough to the curve for brick with partially saturated air to justify the conclusion that increasing the relative humidity from an average of 51.6 per cent to an average of 95.9 per cent does not increase the heat transmission through a brick wall four inches thick. In the case of the wood box, the effect of increasing the relative humidity of the air from an average of 71.3 per cent to an average of 96.9 per cent is also practically negligible.

26. The Value of Air Spaces.—Heat is transferred across an air space by means of all three methods of heat transfer, radiation, convection, and conduction.

With a large drop in temperature across the air space the circulation of the air will obviously be more rapid, and the convection
loss will therefore be greater than with a small drop. Removing the air from the space has no appreciable effect until a very high vacuum is reached, as Nüsselt* found that a 29.96-inch vacuum (referred to a 30-inch barometer) had little effect on the loss by convection. In order, therefore, to reduce the loss by convection to an appreciable amount a very high vacuum is necessary. Convection loss, then, depends on the velocity of circulation of the air, which varies with the temperature difference of the two containing walls.

Air is a poor conductor of heat, and this fact accounts for the general belief that no matter what the structure air spaces built into walls will reduce the loss of heat to a great extent. The double glass box with a half-inch air space between the panes illustrates the value of an air space in constructions of this nature. A comparison of the brick and tile tests shows favorable results for the air space.

When higher temperatures than those met in ordinary building wall construction are encountered, however, the transfer of heat across an air space assumes a different aspect. For the lower temperature differences the radiation factor is not of very great importance. But since the quantity of heat which passes across an air space by means of radiation is proportional to the difference of the fourth powers of the absolute temperatures of the surfaces† enclosing the air space, it is evident that the radiation loss will increase rapidly with the temperatures of the two surfaces, although the difference between these surfaces remains constant. On the other hand, if a solid material such as used in building walls should be used instead of the air space, the heat would be transferred through it by means of conduction alone. The amount of heat lost by conduction, moreover, would increase only slightly with an increase in temperature if the temperature difference between the two surfaces remained constant.

An air space may thus be as effective a heat insulator as a solid insulating material, at the lower temperatures and with the same temperature difference, but with a higher mean temperature and the same temperature difference, the air space would prove to be very inefficient.

Ray and Kreisinger‡ state that the amount of heat passing through furnace walls would be much reduced if the air spaces were

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* Wilhelm Nüsselt, a private lecturer at the University of Dresden in Mechanical and Electrical Engineering. He has written on the subject of heat.
† This is exactly true only for perfect radiators and perfect absorbers.
filled with brick or preferably with materials of poor conductivity, such as ash, sand, or mineral wool. In other words, because of the radiation factor, when heat at low temperatures is to be insulated, use air spaces; when heat is at high temperatures as in the case of furnace walls, use solids of poor conductivity.

From the results of the single glass and the double glass box tests, the so-called conductivity of the \( \frac{1}{2} \)-inch air space, meaning by "so-called conductivity" the B. t. u. loss per square foot per hour per degree of difference in the surface temperatures of the two containing walls, is found to be 1.77.

Prof. L. A. Harding, in a Pennsylvania State College Experiment Station Bulletin, gives a value of 1.66 for the so-called conductivity of air spaces ranging from one to six inches in thickness. From tests reported in Ice and Refrigeration* a value of 1.25 is deduced for a 1-inch air space. From tests on a steel mail-car side, reported by Prof. A. C. Willard,† a value of 1.59 is deduced for a 4-inch air space. Nüsselt states that air spaces greater than \( \frac{3}{4} \) inch in thickness give no additional value for heat insulating purposes, a statement substantiated by the foregoing data. An average of the previously mentioned values gives a value of 1.57 for the "so-called conductivity" of an air space.

From the data already presented, the temperature drop across the air space was calculated, and a curve was plotted with air-temperature differences as abscissae and the so-called conductivity of air spaces as ordinates. The curve, indicating the variation of the so-called conductivity with the temperature difference across the space, is shown in Fig. 21.

In making calculations for heat transmission coefficients of compound walls, an air space may be treated in either of the following ways: the air space may be regarded as a solid insulating material through which the heat passes according to the so-called conductivity theory or considering the transfer by the three methods, radiation, convection, and conduction, the radiation and convection action may be combined into a single surface coefficient and the true conductivity of the air neglected. For every air space two surface coefficients, accordingly, would be considered. If different surfaces enclosed the air space, different surface coefficients would be used for the two walls.

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*Refrigerating World, October, 1914.
†Railway Age Gazette, Vol. 56 n. s., p. 1572, June 26, 1914.
It has been customary to assume still air conditions inside the air space, and consequently to use the surface coefficients corresponding to this condition. This assumption gives values for $U$, when calculated which are generally in accord with the actual transmission values obtained in tests of hollow building walls. It would probably not prove true for air spaces at high temperatures, as in furnace work.
VII. APPLICATIONS OF DATA TO TYPICAL SIMPLE AND COMPOUND WALLS

27. Types of Wall Construction.—Reference has already been made to the fact that it is manifestly impossible to test all types and combinations of building materials used in actual wall construction. It will, therefore, generally be necessary to calculate from test data, similar to those given in this bulletin and amplified by further tests, the values of the overall or heat transmission coefficients ($U$) for many walls. Two cases exist, one involving solid walls of one or more materials and the other including hollow walls of simple or compound construction with one or more air spaces.

28. Solid Wall Construction.—In a simple wall or a compound wall without air spaces there are two surfaces which enter into the calculations for the heat transmission coefficient. For the inside surface a coefficient corresponding to still air conditions is used. This is obtained from the list of coefficients, Table 2. For the outside surface a coefficient of three times that corresponding to still air conditions is used; this allows for a wind velocity of practically fifteen miles per hour. The conductivity values for the materials involved are obtained from the same table of coefficients. With these values substituted in the heat transmission formula, the heat loss in B. t. u., per square foot, per hour, per degree of difference in air temperatures is obtained and the total loss through the walls of a building for any given air temperature difference may be readily calculated, as shown by Fig. 2.

The walls shown involve materials for which tests have already been run to determine $K_1$, $K_2$ and $C$. Additional tests will furnish data for a variety of materials which are not so generally used as those listed in Table 2.

29. Air Space Construction.—For walls containing an air space or spaces, the accepted method of determining the heat transmission of the wall is the same as that for a simple or compound wall with the addition of two surface coefficients for each space included in the construction. The surface coefficients used for air spaces are those used for still air conditions. As mentioned before, however, this assump-
tion of still air conditions in an air space is probably not true in all cases.

To determine the heat transmission of a wall containing an air space according to this alternate method, the following tentative solution may be adopted: The temperature drop across the air space is assumed, the so-called conductivity value is determined from the curve, Fig. 21, calculation for the transmission coefficient is made, and the loss for the overall air temperature difference determined. Dividing this value by the conductivity value used for the air space gives the

![Fig. 21. The so-called conductivity curve for air space construction, based on temperature difference between enclosing walls](image)
temperature drop across the air space. This result should check the assumed temperature drop if the assumption is correct. If the resulting temperature is greater than the assumed one, an assumption of temperature drop larger than the previous one is made, and calculations are made again, and so on until the calculated drop checks the assumed one.
VIII. CONCLUSIONS

The following summary includes the more important conclusions which have been drawn from the results of the investigation:

(1) For determining the transmission coefficient, air to air, and the outside surface coefficient, mercury thermometers may be used and if properly installed will give results of practically the same accuracy as those determined with the thermocouples. Mercury thermometer wells were shown to be of no value in determining surface temperatures. The method finally adopted was to imbed the thermometer in the surface so that its center line would lie in the plane of the surface of the material being tested. Thermocouples are to be preferred for determining temperatures in this work.

(2) A variation in the air velocity over the surface affects both the air-to-air coefficient and the outside surface coefficient. The outside surface coefficients of brick and wood surfaces are affected in practically the same manner at the lower air velocities, while the coefficient for brick gradually rises above that of wood for the higher velocities.

(3) The coefficient of transmission, $U$, for a simple or compound wall, floor, or roof can be readily computed provided the surface coefficients for the building materials used in the surfaces are known for both still and moving air conditions. It is also necessary to know the coefficients of conductivity for all the materials used in the wall. These coefficients should be determined on full size walls for the temperature ranges usually encountered. (See Applications Fig. 2). The effect of moving air is to increase the value of the outside surface coefficient, and this increase involves the combined action of heat transfer by radiation and convection. While this effect is variable, according to the velocity of wind, it seems evident that it can always be expressed as some function of the still air coefficient for the same wall; thus where the average wind movement during the heating season is approximately fifteen miles per hour, a value of $K_2 = 3K_1$ is recommended. In any case, the test data presented herewith indicate the manner and degree in which the factor varies for different velocities so that the value of $K_2$ can be modified to conform with the conditions of wind movement ex-
isting in the locality where the heat transmission data are to be applied.

(4) The effect of the relative humidity of the air on the heat transmission of an ordinary building wall is so small that it can safely be neglected in determining the total heat loss from a building. An increase in the relative humidity of the air causes a slight increase in the value of the surface coefficient; hence the overall transmission coefficient becomes larger. If the walls are actually wet so that they absorb moisture, the coefficient of conduction, $C$, may be seriously affected, as in the case of brick work where an increase of at least twenty-five per cent may easily occur.

(5) Air space construction is of value at low temperatures, but not at high temperatures. In all cases the heat transmission across an air space will rapidly increase not only with an increase in the temperature difference in the enclosing walls but also with the same difference of temperature, if the absolute values of the enclosing wall temperatures are increased.
LIST OF PUBLICATIONS OF THE ENGINEERING EXPERIMENT STATION


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