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The Thermal Conductivity of Refractories

BY

BOYD DUDLEY, Jr.

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THE THERMAL CONDUCTIVITY OF REFRACTORIES.

By Boyd Dudley, Jr.

The usefulness of correct data in regard to the thermal conductivity of refractories and other materials used in the construction of metallurgical and industrial furnaces is quite generally recognized. Numerous investigations of this property of refractories have been conducted, and in many cases the published data of different investigators are somewhat conflicting. This is particularly true of figures pertaining to materials intended for use at high temperatures, and it is with such materials that the metallurgist is most interested. The difficulties in the way of precise determinations of thermal conductivities at elevated temperatures are numerous, and it is not particularly surprising that there exists a set of data for each method of determination, the figures of which fail to agree closely with those obtained by other methods. However, it should be remembered that the variations in the figures of different observers are doubtless due to variations in the materials tested as well as to differences between, or inaccuracies of, the methods employed. The present paper deals with the methods and results of an investigation designed to develop a practical and reasonably accurate means of determining the thermal conductivity of regular kinds of brick, under conditions approaching those of practice, and without the necessity of preparing special shapes or samples of the materials being tested.

In reviewing the methods that have been used and proposed for determining the conductivity of refractory materials, they fall naturally into three general classes, calorimeter methods, measured heat-input methods, and comparison methods.

The calorimetric measurement of conductivity consists of heating the substance to be tested on one side while the other side is in contact with a water-jacket or other cooling device. The rate of heat flow is determined by measuring the rise in temperature of the water flowing through the jacket together with the rate of flow. Temperatures are measured at various points in the test piece, and from these data, together with a consideration of the size and shape of the body under test, the conductivity may be calculated. This method was used by Wologdine[1] in an extended research involving the determination of porosity as well as of conductivity of a number of refractories. In these experiments the specially prepared round test piece was inserted into a hole in the top of a small gas furnace. The test piece was heated on the lower side and the calorimeter was applied to the upper side. Temperatures were measured by means of thermocouples at various points within the test piece. From the description of the method it would appear that the precautions taken against heat transfer from the surroundings to the water in the calorimeter were inadequate, and apparently this point was not considered in calculating the conductivity of the test pieces. The calorimeter method was used by C. P. Randolph[2] in determining the conductivities of compressible materials and powders such as lamp-black, magnesia, asbestos, etc. In this case the material being tested was pressed between an electrically heated copper plate and the calorimeter, which was round in shape and constructed in two compartments, one surrounding the other. Both compartments were maintained at the same temperature; the outer compartment thus constituted a guard ring or insulator, which protected the inner compartment from gain of heat through its sides. A modification of the calorimeter method was used by Hutton and Beard[3] in a study of the conductivity of finely powdered fire clays and similar materials. Instead of a water calorimeter they employed a brass disk in contact with the cool side of the material being tested, and estimated the rate of heat flow by heating the disk to the temperature that it attained in the experiments and allowing it to cool in air. By noting the rate of cooling, the rate of heat loss was calculated from this and from the weight and specific heat of the disk.

The measured heat-input method involves the construction of

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[1] Electrochem. and Met. Ind., **7**, 383 (1909).

[2] General Electric Review, **16**, Feb. (1913); Trans. American Electrochem. Soc., **21**, 545 (1912); Met. and Chem. Eng., **10**, 287 (1912).

[3] Electrochem. and Met. Ind., **3**, 291 (1905).

a furnace or hollow test piece of the material to be tested, on the inside of which heat is generated at a measured rate by means of an electric current. When thermal equilibrium has been established, temperature measurements are made at various points on the walls of the furnace or test piece. From these data the thermal conductivity of the material may be calculated, taking into account, of course, the size and shape of the furnace. This method was employed by Clement and Egy,[4] who used specially prepared cylinders of fire-clay heated internally by means of a resistance coil of nickel wire. Hering[5] proposed the use of a hollow sphere of the refractory material filled with and surrounded by suitable liquids, or, as a substitute for the sphere, a cylindrical cup with hemispherical ends. The liquid on the inside of the container is to be heated by electricity. FitzGerald[6] compared the conductivities of various refractories by constructing a small cubical furnace of each and heating it internally with a resistance of nichrome wire. The comparison was obtained by determining the maximum temperatures attained by each furnace at various rates of heat generation. Richards[7] compared the conductivities of electrode carbon and electrode graphite by heating a small cubical furnace constructed of each material by means of an electric arc, the comparisons being effected by measuring the energy input and the internal and external temperatures of the furnaces. As a means of comparing the thermal conductivities of refractory materials the measured heat-input method possesses the advantages of simplicity and ease of operation. But the satisfactory calculation of the conductivity from data thus secured is usually a difficult matter, owing to the facts that the more or less complicated and uncertain shape factor[8] of the test piece must be considered and that the conductivity is rarely constant over any great range of temperature.

A comparison method differing from all of the above has been suggested by Northrup,[9] who proposes placing the body, the

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[4] Bull. 36, Eng. Experiment Sta., Univ. of Ill., Urbana, Ill.; Met. and Chem. Eng., **8**, 414 (1910).

[5] Trans. Am. Electrochem. Soc., **18**, 213 (1910); Met. and Chem. Eng., **8**, 627 (1910).

[6] Trans. Am. Electrochem. Soc., **21**, 535 (1912); Met. and Chem. Eng., **10**, 286 (1912); Met. and Chem. Eng., **10**, 129 (1912).

[7] Trans. Am. Electrochem. Soc., **24**, 109 (1913); Met. and Chem. Eng., **21**, 575 (1913).

[8] Langmuir, Trans. Am. Electrochem. Soc., **24**, 53 (1913); Met. and Chem. Eng., **11**, 574 (1913).

[9] Met. and Chem. Eng., **11**, 572 (1913); Trans. Am. Electrochem. Soc., **24**, 85 (1913).

conductivity of which is to be measured, in contact with another body, the conductivity of which is known, and then passing heat through the two in series. By measuring the temperatures at the surfaces of the two materials the temperature drop through each may be found and thus a comparison of their conductivities may be obtained. If the conductivity of one is known, that of the other may be calculated. It is of course necessary to know the conductivity of the standard body at various temperatures, and the practicability of the method depends upon the possession of this knowledge.

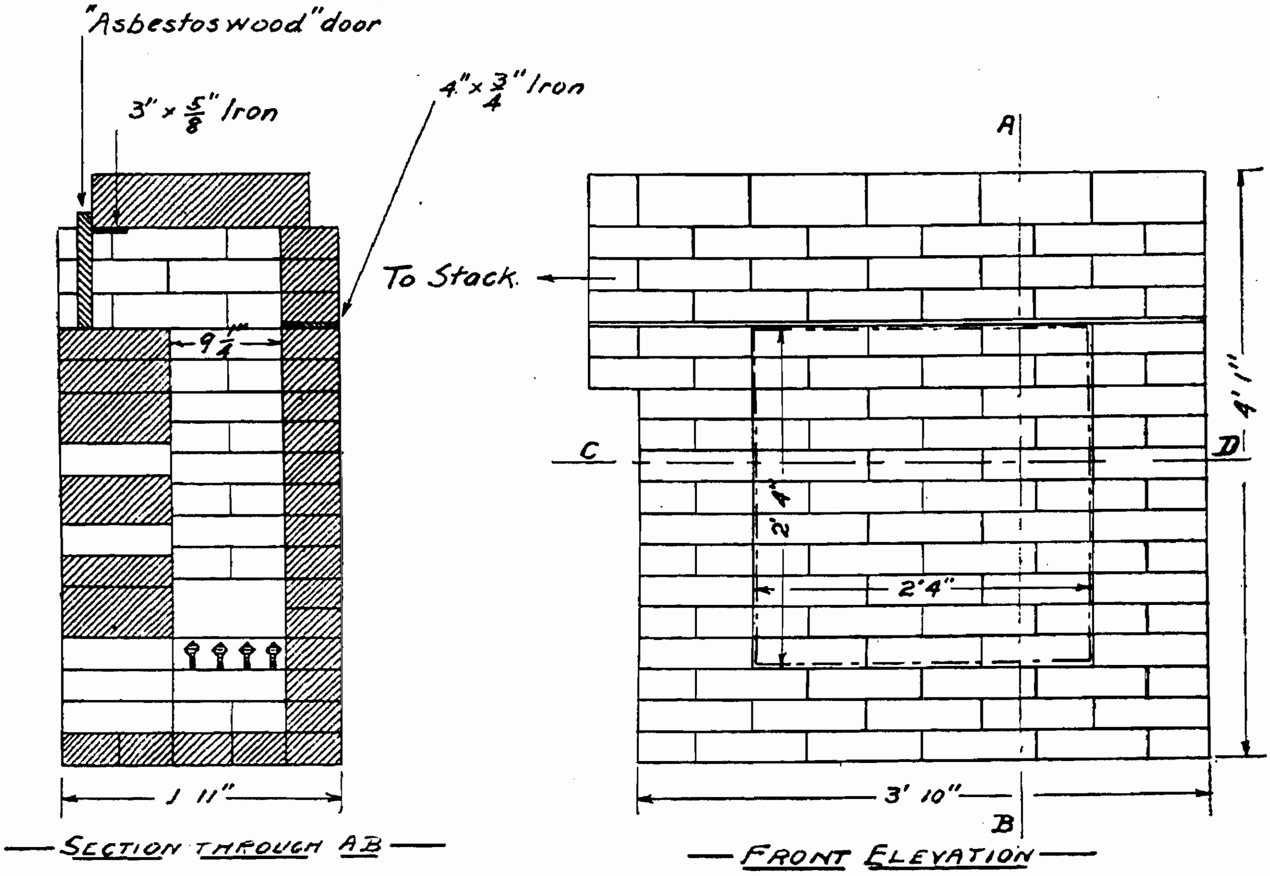


Fig. 1.

The method of determining thermal conductivities employed by the writer consists of heating a wall of the brick being tested with a specially constructed coke-fired furnace, and measuring the rate of heat flow through a certain area of the wall by means of a water jacket applied to the cold side. Temperature measurements are made at various points in the brick, and from the data thus secured the conductivity of the material constituting the wall is calculated. The advantages of the method are these: Special shapes or test pieces of the refractory are not needed, the tests being made on samples of commercial brick. The conductivity is readily calculated from the observed data without recourse to complicated factors involving the shape of the conducting body. Variation of the conductivity with temperature is made apparent by graphic representation of the temperature gradient through the brick.

The construction of the furnace is shown in Fig. 1 and Fig. 2. It consists of three permanent walls, one side and two ends, provided with a permanent roof and stack connection. These three walls are constructed of fire brick and tile, and are each nine inches thick. The roof of the furnace and the stack connection are supported from the end walls on iron bars placed as shown. The third wall, outlined in Fig. 1 by a dot and dash line, is one brick (4½ inches, 11.3 cm.) thick and is independent of the other parts of the furnace. This is the part of the furnace used for the determinations, the wall being built of the brick

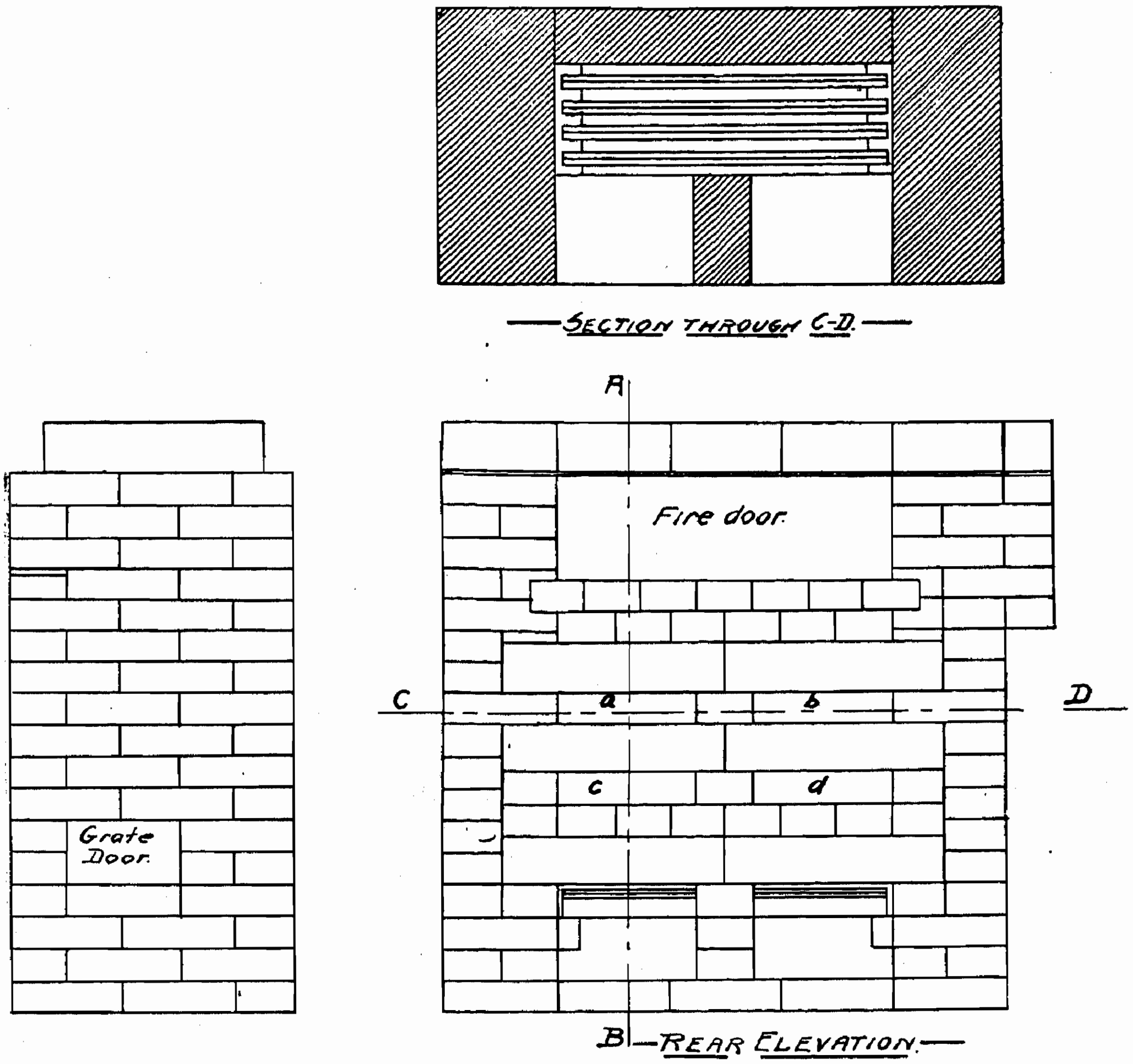


FIG. 2.

to be tested. The fuel used is sized by-product coke, which is charged through the fire door at the top of the back side of the furnace. The grate consists of four iron bars placed as shown. Air enters under the grate, and additional air is drawn through the openings *a, b, c, d,* (Fig. 2) in the back side of the furnace.

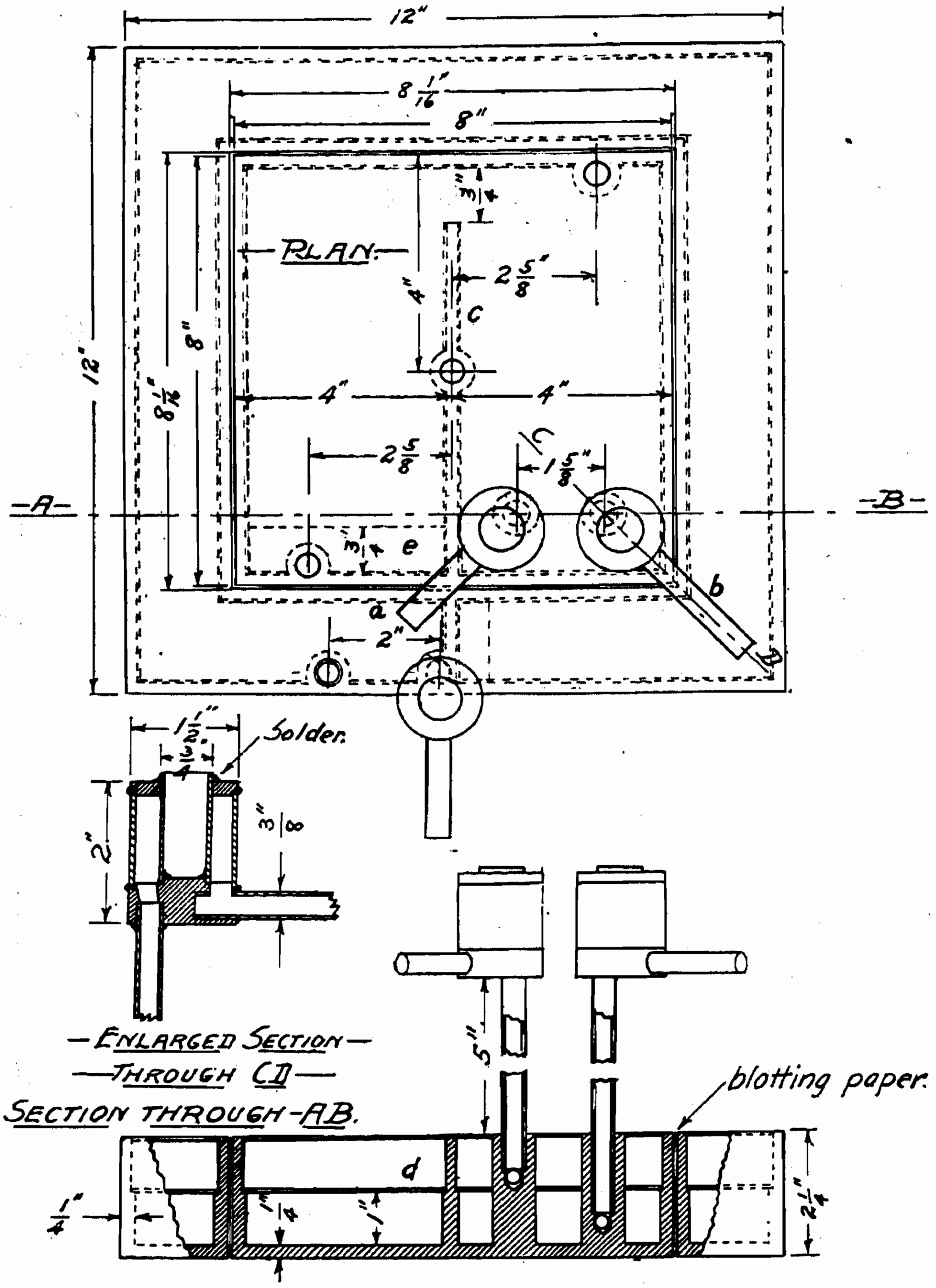


FIG. 3.

These openings may be closed or left open as is necessary; it is found that by regulating the amount of air entering the furnace at the various points it is possible to secure rapid combustion of the coke from the top of the bed of fuel to the grate, a depth of about 26 inches. In this manner a sufficiently large area of the test wall is heated to a uniform temperature to render permissible the use of a calorimeter one foot square. The test furnace was constructed at the back of a large coal-fired assay furnace, and was connected to it so that the products of combustion entered the latter through its fire door and then passed to the stack. A general view of the furnace with the calorimeter in position is shown in Fig. 4.

As indicated in the preceding paragraph, the front wall of the furnace is constructed of the brick to be tested. Thirty standard nine-inch brick are needed. They are specially selected with reference to regularity of size and shape, perfection of edges and corners, and good workmanship in general. The brick are first laid out on the floor in the exact position that they will occupy on the wall. They are thus arranged in the manner best suited to give a wall of smooth surface and thin joints. Each brick is then numbered and marked so that it may be placed in the wall in the position determined upon. Three of the brick are notched in their under surface in such a manner that when the wall is laid there will be three holes extending into the brick

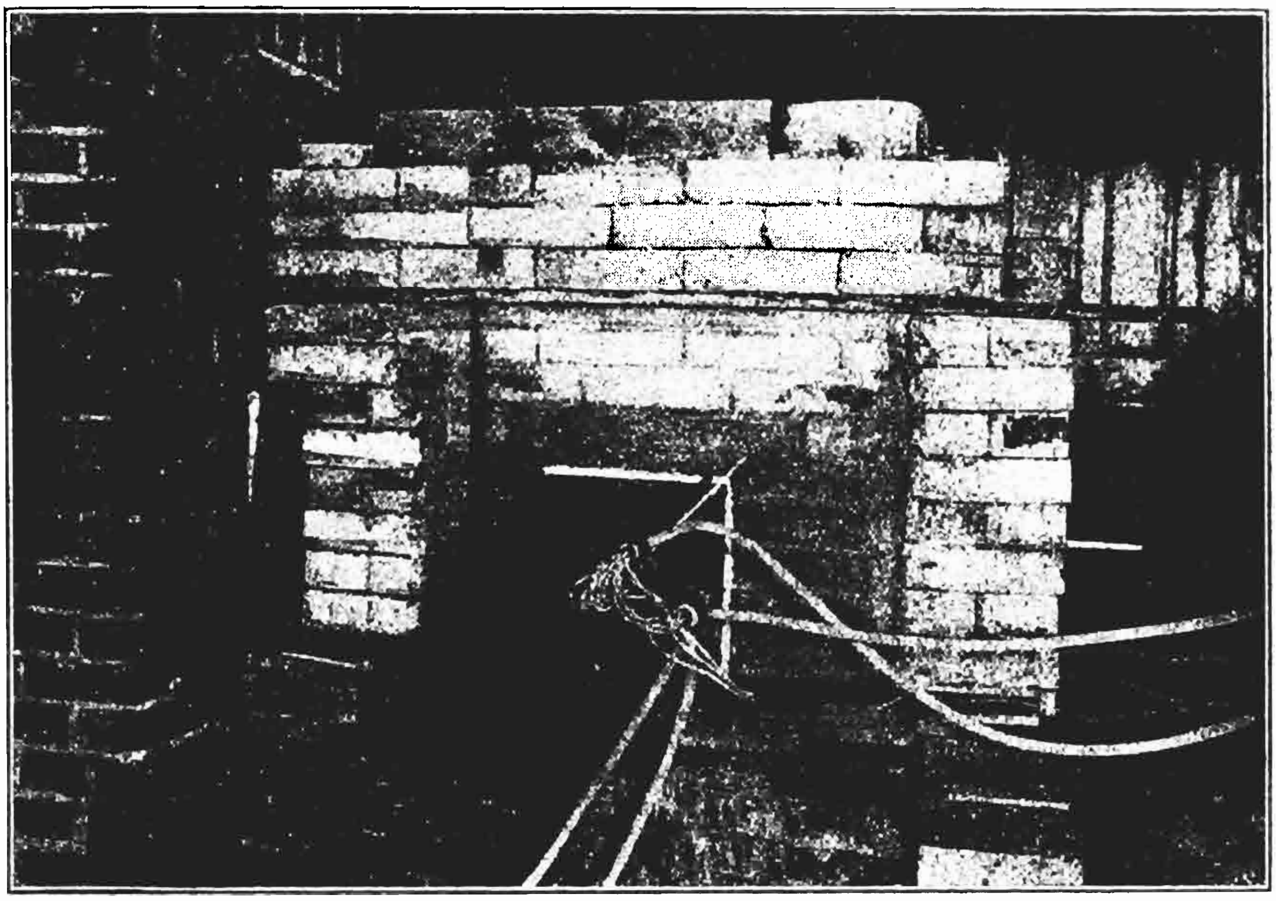


FIG. 4.

to a depth of 4¼ inches (10.6 cm.). The position of these notches is such that the holes in the finished wall will coincide with the three holes through the inner compartment of the calorimeter; see Fig. 3. The notches are carefully cut in order to make them of uniform cross-section and exact length. The depth of the notch is about ⅛ inch (0.3 cm.), the width at the top being about the same. The length of the notch is 4¼ inches (10.6 cm.), which makes the hole in the finished wall the same in depth. Since the thickness of the wall is 4½ inches (11.3 cm.), that being the width of the standard brick used, ¼ inch (0.7 cm.) of brick is left at the back of the hole. The brick are laid with great care to secure a wall with smooth face and joints of the least possible thickness; a thin mixture of finely ground fire-clay and water is used in the joints. When the notched brick are laid a piece of copper wire ⅛ inch (0.3 cm.) in diameter is first placed in the notch, then the notched surface of the brick and the ends are covered with the fire-clay and water mixture, after which the brick is pressed and tapped into its place. At the end of about an hour the copper wire is withdrawn from the brick with a rotary motion, which leaves a smooth hole slightly greater than ⅛ inch in diameter and extending 4¼ inches into the wall. The position of the three holes in the finished wall coincides, as was explained above, with the three holes through the inner compartment of the calorimeter; they are spaced one layer of brick (2½ inches, 6.3 cm.) apart in vertical distance and approximately 3½ inches (8.8 cm.) apart in horizontal distance. Thus the temperature of the wall is taken during a test at three points, one being at the center of the inner compartment of the calorimeter, the others being at the upper left-hand corner and the lower right-hand corner of this compartment, respectively. After the test wall is completed the three pyrometer holes are plugged with tightly fitting pieces of wood, all lumps on the face of the wall are carefully dressed down, and the entire surface is painted with a mixture of neat Portland cement and water. In this manner a smooth and practically plane surface is produced, against which the calorimeter may be snugly fitted. The back or fire side of the wall is covered with a thin layer of cement and fire clay, which is well troweled to a smooth surface. The completed wall is thoroughly dried by heating it for several days with an electric resistance heater consuming about 1.5 kw., which is placed in the bottom of the furnace.

The construction of the calorimeter, with which the rate of heat flow through the wall is measured, is shown in Fig. 3. It consists of two independent compartments, one of which is surrounded by the other. The inner compartment is 8 inches (20.3 cm.) square, and consists of a brass casting finished on the sides and base, to which is soldered a cover of sheet brass. The water connections and interior partitions are so arranged as to provide for thorough circulation of the water within the calorimeter. Water enters through the tube marked *a* (Fig. 3) and passes out through the tube marked *b*. It circulates within the compartment by passing around the end of the interior partition *c*, while on the side of the diaphragm marked *d*; at the point *e* it passes to the opposite side of the diaphragm, and then by passing around the end of the partition *c* it reaches the exit pipe *b*. The outer compartment is 8-1/16 by 8-1/16 inches (20.5 cm.) inside and 12 by 12 inches (30.5 cm.) outside. It consists of a brass casting finished on the base and on the four inner sides, *i. e.,* those sides that face the inner compartment. The arrangement of this compartment for securing thorough circulation of the water is similar to that of the other. The inlet and outlet tubes of the inner compartment and the outlet tube of the outer compartment are each provided with a small double-walled cylindrical water-jacket through which the water has to pass; the construction of these cylinders is shown by the sectional drawing through C-D, Fig. 3. The materials used are sections of brass tubing and brass disks turned as shown. The rise in temperature of the water flowing through the inner compartment and the difference in temperature of the outflows from the two compartments are determined by means of thermocouples carried by rubber stoppers, which are inserted into the open tubes of these cylindrical water-jackets. To provide an outlet for air that is trapped by both compartments of the calorimeter in the spaces above the water outlets, small copper tubes are attached at the top edge of each compartment. When the calorimeter is placed in position against the wall the tubes are allowed to remain open until all of the air is expelled, as indicated by the passage of a continuous stream of water through each; then they are closed by pinching the ends with a pair of pliers. At intervals of a half hour during a test one or more of the tubes are opened in order to release any air that may have collected. The outer compartment carries four tubes, two on each side of the diaphragm. Only one tube is attached to the inner compartment, the space on the opposite side of the diaphragm being vented by means of a small hole 1/32 inch (0.8 mm.) in diameter drilled through the diaphragm. This hole allows the escape of air from the back side of the diaphragm without seriously interfering with the circulation of the water. The space between the two compartments of the calorimeter, amounting to 1/32 inch (0.8 mm.) is filled with a layer of blotting paper or with three layers of heavy detail paper. When in use the entire face of both compartments is covered with a layer of cork linoleum ¼ inch (0.6 cm.) thick, and the sections of the copper tubing leading from the calorimeter to the temperature jackets are covered with two thicknesses of rubber

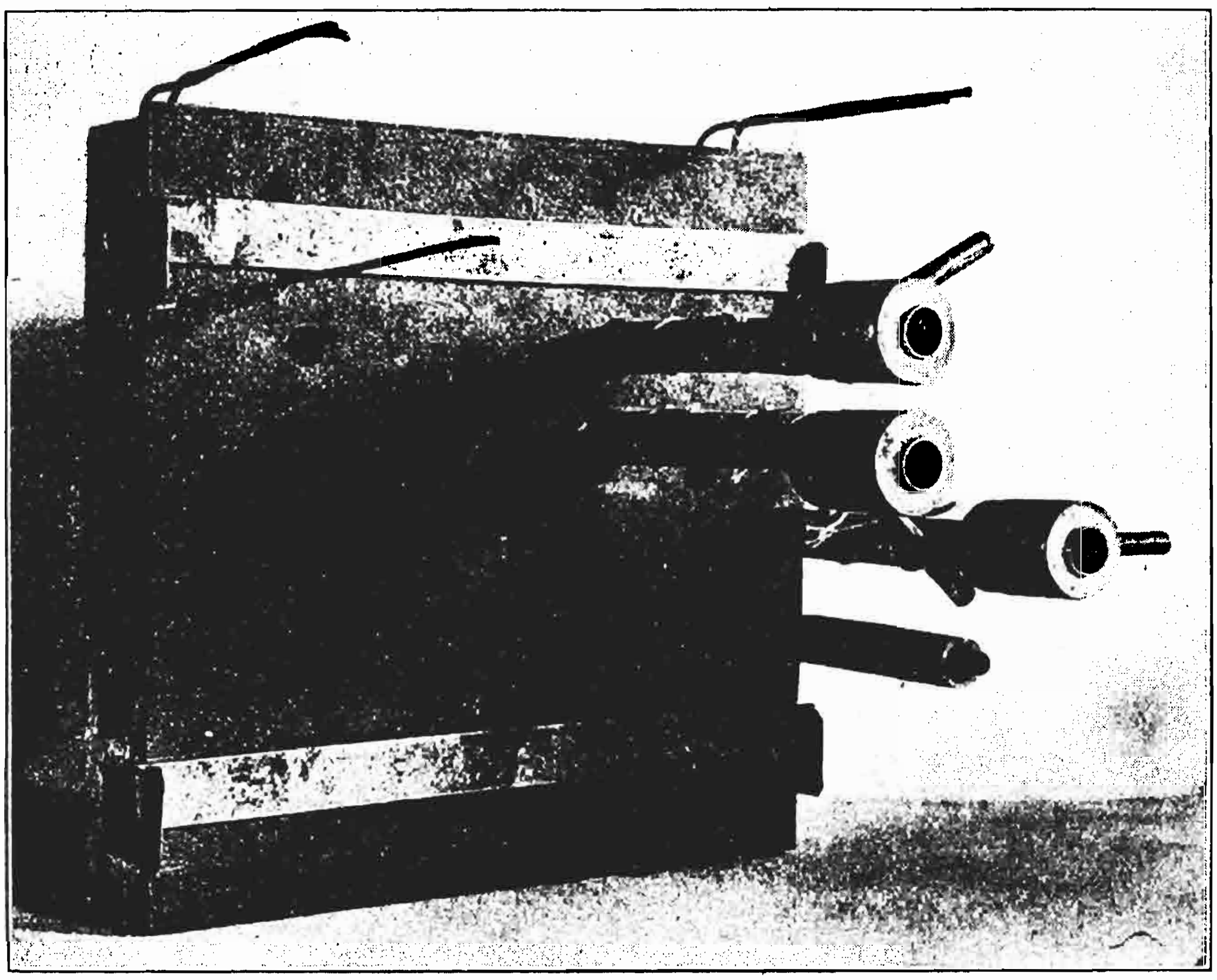


Fig. 5.

tubing. Reference to Figs. 4, 5, and 6, will make clear the construction of the calorimeter and the arrangement of its various parts. Water is delivered to the inlet tubes of each compartment through a rubber tube, which is connected to a ¼-inch (0.6 cm.) pet-cock. Since all of the work described herein was done during the summer vacation, when the water supply of the building was not being used for any other purpose, it was unnecessary to adopt special means for maintaining a constant head of water in the inlet tubes of the calorimeter. The pet-cocks were therefore connected directly to the laboratory supply pipe.

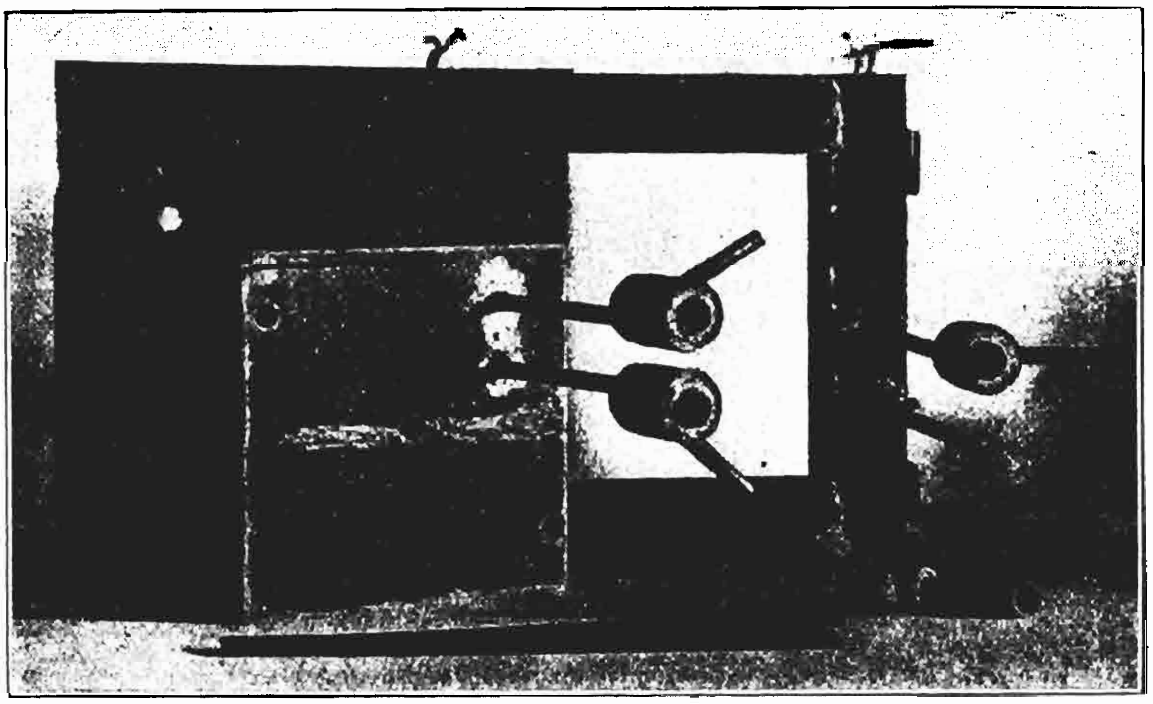
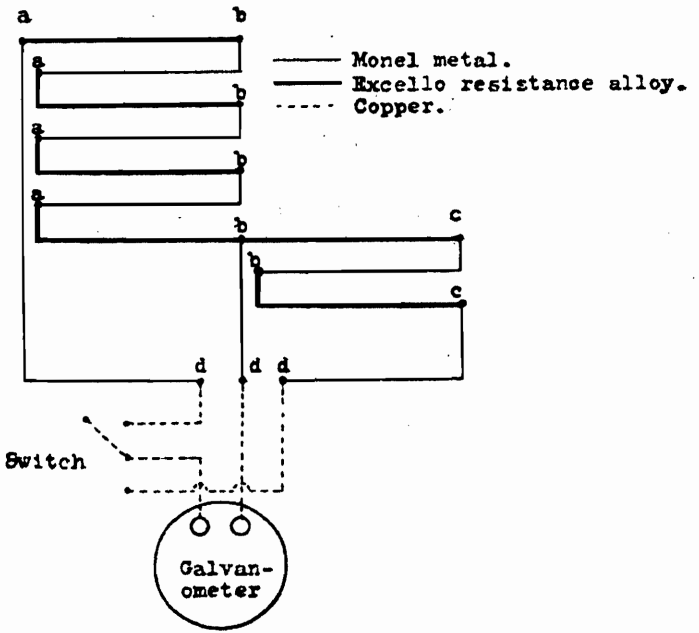


FIG. 6.

Aside from the consideration of heat exchange between the sides of an unprotected calorimeter and the surroundings, is it necessary to recognize the fact that when a cold water-jacket is applied to a heated surface, the area of which is greater than that of the jacket, the temperature of the part of the surface in contact with the jacket becomes lower than that of the surrounding surface, which remains exposed to the air. Consequently the lines of heat-flow are deflected, and heat flows to the margin of the area in contact with the jacket from the surrounding material as well as from the points within the wall that are directly opposite the jacket. The outside compartment of a calorimeter constructed as above described is the one that receives this heat from the surrounding portions of the wall, while all of the heat received from the wall by the inner compartment flows through the brick in lines normal to the surface of the wall. Such, at any rate, is the assumption made in these experiments. In other words, it is assumed that all of the heat that leaves the wall through the 64 square inches (413 sq. cm.) of surface in contact with the inner compartment of the calorimeter enters the wall at the other side through an equal and opposite area. By operating both compartments of the calorimeter under the same temperature conditions, which is accomplished by regulating the flow of water through the outer compartment so that the temperature of the outflows from both are the same, the sides of the inner compartment are effectively protected against heat exchange with the surroundings. The water enters both compartments at the same temperature since it comes to each from the same source, and it is possible to maintain the temperature of the outflows practically equal. During a test the difference is not permitted to become greater than 0.2° C. When the inner compartment is thus protected it is safe to assume that it receives heat from two sources only, from the heated brick surface and from the air in contact with the linoleum cover. The conductivity of the linoleum under these conditions is readily determined and may be allowed for, as will be explained later. The considerations stated above are chief among those that caused the selection of the double compartment type of calorimeter for use in these experiments.



NOTE: Junctions marked *a* passed through one rubber stopper, which was inserted in the temperature-jacket on the inlet tube of the inner compartment.

Junctions marked *b* were inserted into the temperature jacket on the outlet tube of the inner compartment.

Junctions marked *c* were inserted into the temperature jacket on the outlet tube of the outer compartment.

Junctions marked *d* were carried in small glass tubes bound closely together, thus insuring that differences in temperature did not arise between these junctions.

FIG. 7.

The rise in temperature of the water flowing through the inner compartment and the difference in temperature of the outflows from the two compartments are measured by means of thermocouples and a sensitive galvanometer. The arrangement of the thermocouples and galvanometer is shown by the diagram, Fig. 7. The thermocouples consist of wires of Monel metal and "Excello" resistance alloy. The galvanometer used is a Leeds and Northrup instrument of the mirror type with a curved scale, and having an internal resistance of 609 ohms. Each group of junctions is carried by a rubber stopper through which the wires pass, being insulated from each other by the rubber and by small glass tubes. The rubber stoppers are inserted in the open tubes of the small cylindrical water-jackets to such a depth that the junctions are within ¼ inch (0.6 cm.) of the bottom of the tube. The volume of air space surrounding the junctions is thus reduced to a cylinder ⅝ inch in diameter by ½ inch (1.6 x 1.3 cm.) in length. The galvanometer will respond to a change in temperature of the water flowing through the temperature jackets within 15 seconds after the change occurs, and will give a constant reading within one minute. The method of calibrating these thermocouples was as follows: Two thermos bottles of one pint capacity were filled with water at slightly differing temperatures. The temperature of the water in each was determined to within 0.1° C. with a Beckmann thermometer graduated to 0.01° C. Then two sets of the junctions, each carried by its rubber stopper and protected by a test tube, were inserted into the necks of the bottles, one set of junctions being at the bottom of its test tube and at the center of each bottle. The terminals of the thermocouple circuit were connected with the galvanometer as shown in Fig. 7, and the couples were allowed to assume the temperature of the water in which they were immersed.

The difference in temperature between the water in the two bottles was registered by the galvanometer deflection. When the galvanometer reading became constant, the test tubes and couples were removed from the bottles and the temperature of the water in each was quickly determined with the Beckmann thermometer, the instrument being read to the nearest 0.01° C. Before inserting the thermometer into the bottle the temperature of bulb and stem of the instrument was brought to within 0.1° C. of that of the water in the bottle by immersing the thermometer in mixtures of warm and cold water previously prepared. The temperature of the water in the thermos bottle could be predicted with certainty from the preliminary measurement. In this manner the error introduced into the final temperature measurements due to the heating or cooling of the bulb and stem of the thermometer by the water in the bottles was reduced to a minimum. Table I gives the calibration figures obtained by this method; the points are graphically represented in Fig. 8. These figures show the deflections produced by the two sets of junctions marked *a* and *b* in Fig. 7, when the junctions at *b* are at higher temperature than those at *a*. This is the condition under which the junctions are used in connection with the calorimeter.

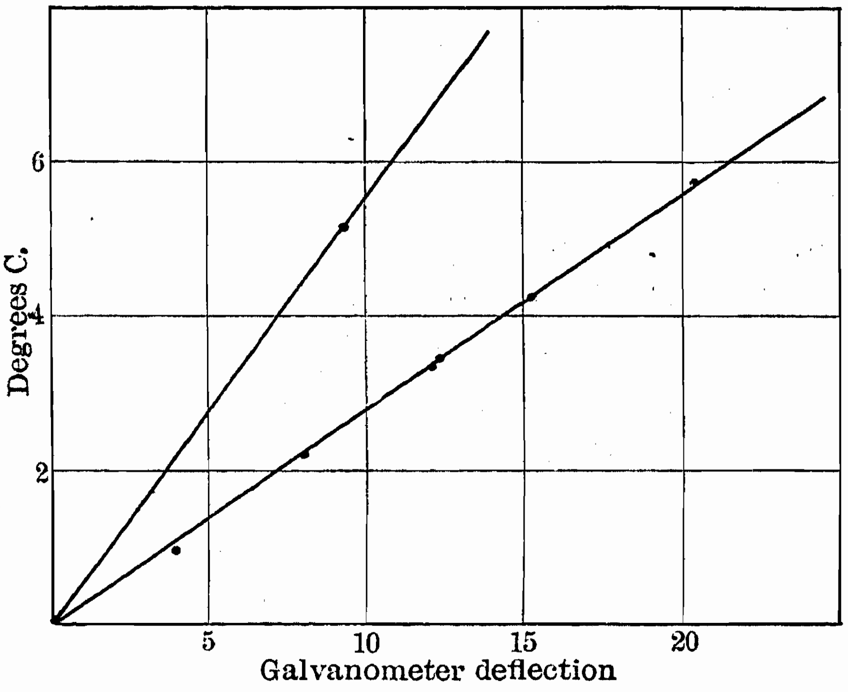


FIG. 8.

TABLE I.

Temperature Difference Degrees C.	Galvanometer Deflections in Cm. on the Red Scale
0.99	3.8
2.20	8.0
3.38	12.2
3.46	12.3
4.27	15.2
5.73	20.3

Since the junction circuit *b-c* (Fig. 7) is used only to compare the temperature of the outflows from the calorimeter compartments, accurate calibration was not considered necessary and only one point was taken. With 5.17 degrees difference in temperature this combination produced a deflection of 9.3 cm., which agrees well with the deflections produced by the other combination. The number of junctions in the second series being one half as great as in the first, the deflections produced should be one half for equal differences in temperature; the two straight lines shown in Fig. 8 illustrate this point. The relation between the galvanometer deflections and temperature differences is linear and may be expressed as follows:

For circuit *a-b*, 1 cm. galv. deflection = 0.279° C.
For circuit *b-c*, 1 cm. galv. deflection = 0.558° C.

These are the constants used in determining the rate of heat absorption by the calorimeter.

In the course of a conductivity determination the rate of flow of the water through the inner compartment of the calorimeter and the rise in temperature of this water during its passage through the compartment are measured. The product of the rate of flow expressed in grams per second into the rise in temperature expressed in degrees C. gives the rate of heat absorption by this compartment of the calorimeter expressed in gram calories per second. The heat thus determined comes from two sources, namely, the wall in contact with the calorimeter and the air in contact with the linoleum that covers the opposite face of the calorimeter. The air at this point is always at a higher temperature than the water within, and the amount of heat reaching the water from this source must be deducted from the total in order to find the true rate of heat flow through the wall. To determine the magnitude of this correction it was necessary to determine the thermal conductivity of the linoleum cover by means of such measurements as can be readily duplicated in the course of a regular conductivity test. It was found that, when the calorimeter was in its place in contact with the wall, the temperature of the air a short distance away from the surface of the linoleum was practically constnat from top to bottom of the calorimeter. The temperature variation between these points was not more than 2° C., when the temperatures were measured by a mercury thermometer placed with the bulb parallel to the surface and with the center of the bulb one inch distant from the surface.

The distance of the bulb from the surface affected the reading of the thermometer at the rate of about 0.5 degree for each ¼ inch (0.6 cm.), the temperature rising with increasing distance from the linoleum. From these figures it is apparent that if the temperature of the air in contact with the surface of the linoleum is determined with a mercury thermometer held near the center of the surface and at a distance of one inch from it, such a measurement can be duplicated with sufficient accuracy and without difficulty. The average temperature of the water within the calorimeter is readily obtained by deducting half the temperature rise from the actual temperature of the outflow, as indicated by a mercury thermometer. Therefore the conductivity of the cover of the calorimeter was determined in terms of the difference between the temperature of the air on the outside and the average temperature of the water on the inside, each of these temperatures being determined as above described.

To determine the conductivity of the linoleum the calorimeter was assembled as for a test, but in addition to the layer of linoleum over the face of the calorimeter a cover of the same material was placed in contact with the back side, it being held in position by two pieces of strap iron as was the cover on the opposite side. The entire apparatus was then mounted in a vertical position inside of a wooden box, the dimensions of which were 4 ft. high by 3 ft. by 3 ft. The position of the calorimeter was with its top edge about one inch below the top or lid of the box, while it was centrally placed with reference to the sides of the box. The interior of the box was accessible through one side, which was provided with a cover of corrugated paper. Holes were bored through the top of the box to admit two thermometers, one of which was suspended on each side of the calorimeter, the bulb being opposite the center of the side and one inch from the surface. An electric resistance heater was placed in the box, and by regulating the current through the heater by means of an external resistance any desired air temperature could be maintained within the box. The temperature rise of the water and the rate of flow through the inner compartment gave the rate of heat flow through the two linoleum-covered surfaces of this compartment. The temperature of the outflow from the outer compartment was kept within 0.2 degree of that from the inner compartment. With a given current through the heating coil, the box was closed and the air temperature was allowed to rise until the maximum was attained. When the air temperature became constant, as measured by the two thermometers, and when the rise in temperature of the water became constant, the two were recorded together with the temperature of the outflowing water. The rate of flow of the water through the inner compartment was determined by catching the discharge in a tub and weighing it at the end of 15 minutes. The total heat flow thus determined

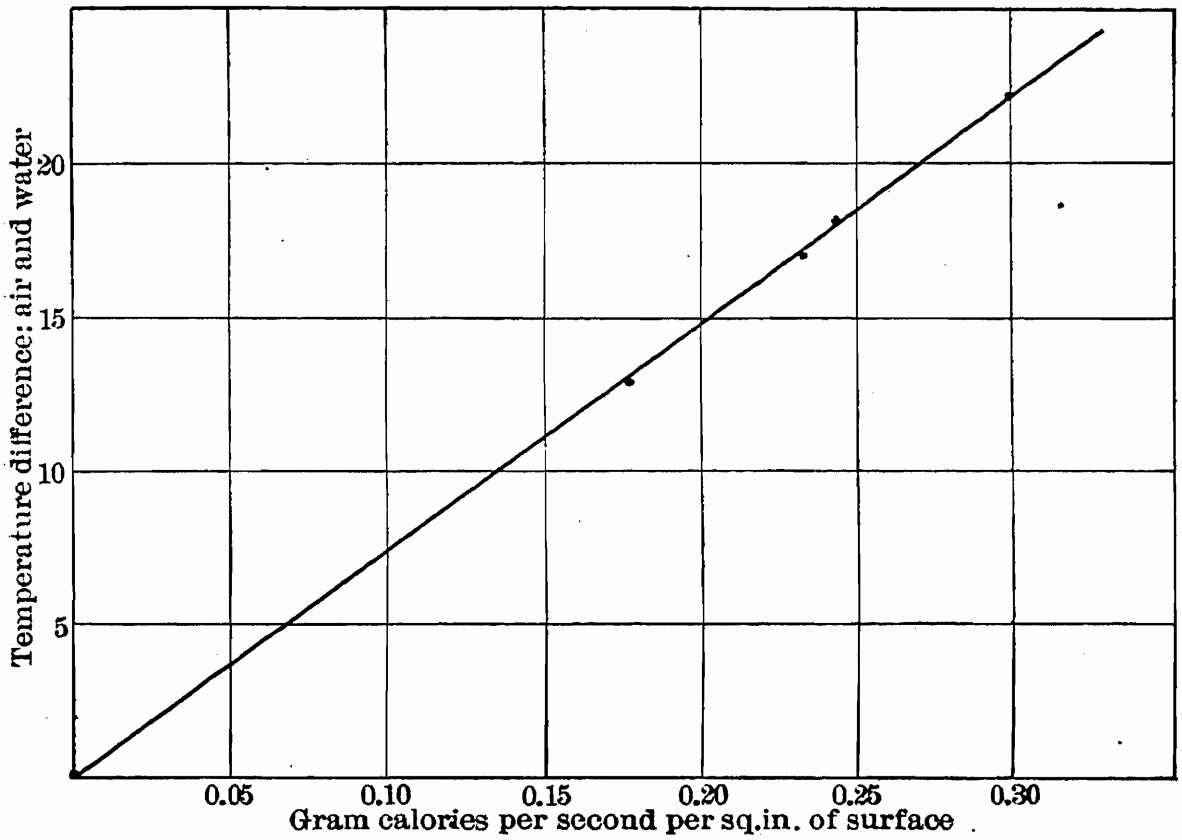


FIG. 9.

was that which passed through the two linoleum-covered faces of the inner compartment; the area of each of these is 64 square inches (413 sq. cm.). Hence the total rate of heat flow determined by such a test divided by 128 gives the rate of heat flow through one square inch of the linoleum-covered surface. In this method of interpreting the results the heat flow through the rubber covers of the copper tubes leading from the temperature jackets to the calorimeter is neglected. Table II gives the results of these tests; in Fig. 9 the results are graphically represented. It will be noted that the points fall practically on a straight line, which has been drawn through the origin. Theoretically this line should cross the axis of abscissas slightly to the right of the origin on account of the heat generated by frictional resistance to the passage of the water through the calorimeter and its connections. The heat thus generated could be calculated from the rate of flow of the water and the loss of head in passing through the calorimeter. However, no attempt was made to measure the latter quantity, because the heat resulting from friction is necessarily small, and it is considered sufficiently accurate to draw the line through the origin as has been done in Fig. 9.

TABLE II.

Temp. Air		Temp. W.	Temp. Rise W.		Water Flow		Temp. Diff.	Calories per Sec.	
A	B	Out	Galv.	Deg. C.	lb. min.	g. sec.	Air-Water	Total	Sq. In.
31.0	32.0	19.0	2.80	0.778	3.82	28.8	12.9	22.5	0.176
35.0	36.0	19.0	3.80	1.06	3.70	28.0	17.0	29.6	0.232
37.0	37.0	19.5	4.00	1.11	3.70	28.0	18.1	31.1	0.243
41.0	41.0	19.5	4.90	1.36	3.70	28.0	22.2	38.1	0.298

In order to make clear the method of conducting a test to determine the conductivity of a refractory, a complete description of the operations involved will be given. Assuming that the wall has been constructed and dried as previously described, a fire is started in the furnace at about 6:00 A. M. As rapidly as possible the furnace is filled with the sized by-product coke that is used as a fuel. By 9:00 A. M. the bed of coke should be ignited from bottom to top, and the wall should be completely warmed through. At about 10:00 A. M. the calorimeter is placed in its position against the wall, and the corner made by the outer sides of the calorimeter and the surface of the wall is filled with asbestos fibre pulp, made by soaking scraps of asbestos paper in water. The purpose of filling this corner is to prevent the formation of air currents between the calorimeter and the brick in places where their contact is not sufficiently close. After the application of the calorimeter to the wall several hours are required to bring about uniform conditions. During this time the fire is urged, and the rate of flow of the water through the outer compartment is regulated in order to equalize the temperatures of the outflows. When the wall is so uniformly heated that the pyrometer inserted to the full depth of each of the three holes shows a variation of only 20 to 30 degrees in temperature from one hole to the next, the quantitative part of the test is started. To produce this condition careful firing is required, and it is usually not possible to begin the quantitative part of the determination before 2:00 or 3:00 P. M.; in some cases the test cannot be started before 5:00 P. M. When uniform temperature conditions are obtained, the water from the inner compartment of the calorimeter is deflected into a galvanized iron tub, and readings are taken at five-minute intervals as follows: The temperature rise of the water flowing through the inner compartment is determined by reading the galvanometer deflection produced by the thermocouple circuit that measures this difference in temperature. In the same manner the difference in temperature between the two outflows is determined. The temperature of the air one inch from the face of the calorimeter is noted, as is the temperature of the outflow from the calorimeter. If, at the time of several successive readings, the outflows differ in temperature by more than 0.2 degree, a change is made in the rate of flow through the outer compartment in order to correct this condition. In the intervals of time between these readings the temperature gradients from the back to the front of the wall are taken. The thermocouple is inserted into one of the holes to its full depth and allowed to remain there until the galvanometer reading becomes constant; the reading is then recorded and the couple is pulled out of the hole a distance of ½ inch (1.3 cm.) where it is allowed to remain until the galvanometer reading again becomes constant. Subsequent readings are taken after the junction has been moved back ½ inch (1.3 cm.) each time, until nine readings are taken in each hole, the first and last readings of each set being ¼ inch (0.6 cm.) from the hot side and ¼ inch (0.6 cm.) from the cold side of the wall, respectively. About thirty minutes time is usually required for taking the readings through each hole, and on this account the readings taken at five minute intervals are conducted over a period of 1½ hours. When all of the temperature gradients have been taken, the temperature of the deepest part of each hole is redetermined. If these temperatures have not changed by more than 20 or 30 degrees, the test is considered finished. If the temperature at the back of any hole has changed more than 30 degrees, the test is continued until these temperatures remain constant or practically so for a sufficient time to allow the taking of three complete temperature gradients.

All of the temperature measurements within the brick are made with a thermocouple of Pt and Pt with 10 percent Rh, which is connected through a resistance of 4,000 ohms to the Leeds and Northrup galvanometer. One wire of the couple passes through a small silica tube, while the other is bare. The couple was calibrated by comparing it with a carefully standardized junction at a number of temperatures. The temperature of the cold junction was maintained at 32.5 degrees during the comparison, that being the average temperature of the cold junction when the couple is in use at the furnace.

The method employed in determining the temperatures at various points within the brick is open to question, because, after the first or innermost temperature has been taken, the subsequent positions of the thermocouple are such as to expose it to radiation from the hot end of the hole. Heat is not only radiated from the hot end of the hole but also is conducted from this point by the air that fills the hole. Hence a point on the wall of one of these holes may be at a higher temperature than that of the body of the brick at the same depth from the surface and at some distance from the hole, and the thermo-junction placed at this point may record a temperature higher than that of the brick at the same depth, where there is no hole. While it was thought that the error from this source would be slight or even inappreciable on account of the small diameter of the hole, nevertheless a test was made to determine the effect of the open hole upon the pyrometer readings. Five pieces were cut from a clay crucible and carefully filed until each was ½ inch long by ⅛ inch in diameter (1.3 x 0.3 cm.) Then at the completion of a conductivity test on a fire-clay brick and while the calorimeter was still in contact with the wall, six temperature determinations were made in the center hole; the first measurement was taken at the back of the hole and the others were taken at intervals of ½ inch (1.3 cm). Following this, one of the clay pieces was inserted into the hole and pushed to the back, and the couple was inserted with the junction in contact with the end of the clay. It was allowed to remain in this position until the galvanometer deflection became constant, indicating that the clay and the thermocouple had been heated to the temperature of the brick. The reading was recorded, and the process was repeated until all of the clay pieces had been inserted into the hole. This test gave the temperatures of six points in the hole spaced ½ inch (1.3 cm.) apart as indicated by the pyrometer when the space between the junction and the end of the hole was open, and the temperatures of the same points as indicated by the pyrometer when the space between the junction and the end of the hole was filled with tightly fitting pieces of burnt fire-clay. The results are shown in Table III. The readings with the clay pieces in front of the junction and those without them show no consistent variation, and in view of this fact it seems safe to conclude that the course of the temperature gradient through the brick is determined by the method employed with as great exactness as is warranted by the heterogeneous composition of nearly all brick.

TABLE III.

Distance in Brick Inches	Open Hole Galv. Def'n	Open Hole Temp. C.	Hole Closed with Pieces of Clay Galv. Def'n	Hole Closed with Pieces of Clay Temp. C.
4.25	21.3	945	21.3	945
3.75	19.0	875	18.8	870
3.25	16.8	800	16.8	800
2.75	14.5	720	14.7	725
2.25	12.1	625	12.1	625
1.75	9.6	520	9.5	515

The time consumed in making the above measurements was about 25 minutes, and during this time the temperatures at the backs of the two adjacent holes did not vary more than 10 degrees, indicating that the temperature conditions throughout the wall were constant.

The results of tests on four types of refractories are given below. The kinds of brick tested were first quality fire-clay brick, silica brick with clay bond, silica brick with lime bond, and magnesite brick. All of the above were manufactured by the Harbison-Walker Refractories Co., Pittsburgh, Pa., and the writer wishes to acknowledge the kindness of the manufacturers in providing the samples used in these tests. Table IV gives the names under which these types of brick are supplied to the trade together with other information concerning their properties. The analyses were kindly provided by the manufacturer; they represent the average compositions of the various materials. The apparent densities were determined by the writer on the lots of brick submitted for these tests.

TABLE IV.

Percent	Woodland	Quartzite	Star Silica	Magnesite
SiO_2	52.93	73.91	95.85	2.50
Al_2O_3	42.69	22.87	0.88	0.50
Fe_2O_3	1.98	1.48	0.79	7.00
CaO	0.33	0.29	1.80	2.75
MgO	0.38	0.31	0.14	86.50
Alkalies	1.55	1.20	0.39	....
Loss on ignition	....	....	....	0.10
Apparent density	1.91	1.91	1.56	2.46

The Woodland brick is made entirely of fire-clay from the conglomerate vein of clay in Pennsylvania, which at the point of manufacture contains both flint clay and the plastic clay necessary for bond. This brick is used largely in malleable furnaces, heating furnaces, and in general mill work where refractory fire-clay brick are required.

The Quartzite brick is made from a mixture of ganister rock with Pennsylvania flint and bond clays. This type of brick was formerly much used in by-product coke oven construction, but during the past few years the amount so used has greatly diminished, on account of the increased use of the lime-bond silica brick for this purpose.

The Star Silica brick are made from high grade Pennsylvania ganister rock, lime being used as a bonding agent. This type of brick is commonly used in open-hearth steel furnaces, for the roofs of copper reverberatory furnaces, for by-product coke ovens, in the construction of glass tanks, etc.

The Magnesite brick are made from the dead-burned material. They are dense and hard, and are representative of the type that is commonly used for the construction of open-hearth bottoms, for the lining of copper converters, and for lining other types of metallurgical furnaces where basic material is needed.

CONDUCTIVITY OF FIRST QUALITY WOODLAND FIRE-CLAY BRICK.

Test No. 1. Fire was started in the furnace at 7:00 A. M. The calorimeter was attached to the wall at 2:00 P. M. Readings were taken from 4:25 to 5:25 P. M.

Temperature rise of the water flowing through the inner compartment: Galvanometer readings were taken at five-minute intervals beginning at 4.25; the deflections noted were as follows: 19.1, 19.8, 20.3, 20.1, 20.0, 20.2, 20.7, 20.7, 20.6, 20.3, 21.3, 20.9, 20.6.

Average of these readings = 20.4.

Average temperature rise of water = 20.4 x 0.279 = 5.69° C.

Amount of water through inner compartment of calorimeter: Water during 1 hr. = 143.0 — 12.5 (weight of tub) = 130.5 lb.

Temperature of water leaving both compartments: A mercury thermometer with its bulb held in the outflow from the outer compartment was read at five-minute intervals during the test. The average of the temperatures recorded is 25.5° C.

Temperature of the air one inch from the linoleum cover of the calorimeter: Readings were taken at five-minute intervals during the test. The average of the temperatures recorded is 37.0° C.

Temperature gradients through the brick wall: The temperature of the cold junction of the pyrometer was 31 to 34° C.

Distance in brick, inches	*a* Upper hole	*b* Center hole	*c* Lower hole	Ave. Galv. Reading	Temperature deg. C.
0.25	2.3	2.3	2.5	2.4	175
0.75	4.5	4.7	5.2	4.6	285
1.25	6.3	6.7	7.5	6.8	390
1.75	8.6	8.9	9.5	9.0	490
2.25	10.8	11.2	11.5	11.2	590
2.75	13.2	13.4	13.9	13.5	680
3.25	15.5	15.9	16.6	16.0	775
3.75	18.0	18.4	18.9	18.4	855
4.25	20.5	20.6	21.0	20.7	925

Time of taking the above readings: Those under *a* were taken between 4: 15 and 4: 35 P. M.; those under *b* were taken between 4:40 and 5:00 P. M.; those under *c* were taken between 5: 10 and 5: 25 P. M. At 5:30 the temperatures at the backs of all of the holes were measured with the following results: *a*, galvanometer deflection = 20.7; *b*, galvanometer deflection = 20.5; *c*, galvanometer deflection = 20.8. These measurements show practically no change in temperature at the backs of the holes.

The mean conductivity of the brick between the two temperature extremes is calculated from the above data as follows:

The rate of total heat absorption by the inner compartment of the calorimeter =

$$\frac{131 \text{ lb. of water} \times 454 \text{ g.} \times 5.69 \text{ deg.}}{1 \text{ hr.} \times 3{,}600 \text{ sec.} \times 64 \text{ sq. in. (area of cal. surface)}} = 1.47 \text{ g. cal.}$$

per sq. in. per second. This figure represents the total heat that enters the calorimeter each second from one square inch of the wall and through one square inch of the linoleum-covered surface exposed to the air. The heat from the wall is found by

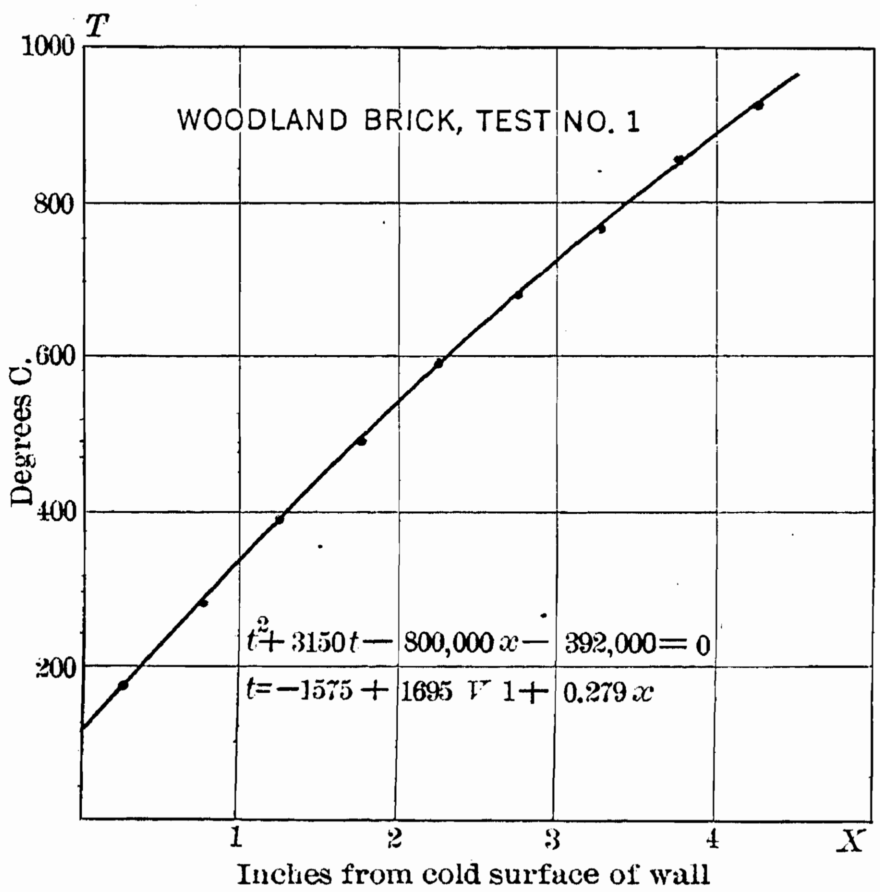


FIG. 10 (V in above cut should be $\sqrt{\quad}$)

deducting from the total heat that heat which enters through the linoleum cover, the latter being estimated as follows: The temperature of the outflowing water during the test was 25.5° C. (average). Deduct from this one-half the temperature rise of the water flowing through the calorimeter, 25.5 — 2.9 = 22.6° C., which is the average temperature of the water inside the calorimeter. The average temperature of the air one inch from the surface of the linoleum cover during the test was 37.0° C. The difference in temperature between the air outside and the water inside is 37.0 — 22.6 = 14.4° C. Fig. 9 shows the rate of heat flow through the linoleum cover of the calorimeter under these conditions to be 0.20 g. cal. per sec. per sq. in. The heat from each square inch of the wall is therefore 1.47 — 0.20 = 1.27 g. cal. per sec. The temperature gradient through the wall during this test is graphically shown in Fig. 10, distances from the cool side of the wall being plotted as abscissas, temperatures as ordinates. Extending the line of determined temperatures at each end as has been done in the figure, shows the temperature of the surfaces to have been 120° and 965° C., on the cool and hot sides respectively. The mean conductivity between these extremes of temperature is given by the equation

$$\text{conductivity} = \frac{(\text{heat flow per sq. in. per sec.}) \times (\text{thickness of wall, inches})}{(\text{difference in temperature between faces of wall})}$$

or

$$K = \frac{H\,x}{T_2 - T_1}$$

in which the conductivity is expressed in g. cal. per sec. through a cube with one-inch edge when the difference in temperature between opposite faces is 1° C. In the case under consideration

$$K = \frac{1.27 \times 4.5}{965 - 120} = 0.00676$$

which is the mean conductivity of this material between the temperatures 120° and 965° C.

The record given above and the explanation of the method of calculation will serve to illustrate the procedure followed in each case. Records of subsequent tests will be given in briefer form, and the calculation in each case will be made without further explanation.

Test No. 2. Fire was started in furnace at 6:00 A. M. Calorimeter was attached to wall at 10:00 A. M. Readings were taken from 1:40 P. M. to 3:10 P. M. Total time of test = 1.5 hr.

Temperature rise of water flowing through inner compartment: Average galvanometer deflection from 19 readings at five-minute intervals = 21.3. Temp. rise = 21.3 × 0.279 = 5.94° C.

Amount of water through inner compartment: During first half hour 67.25 lb., second half hour 67.75, third half hour 67.75. Total water in 1.5 hours = 202.75 lb.

Temperature of water leaving both compartments: Average of 19 determinations = 24.5° C.

Temperature of air one inch from face of calorimeter: Average of 19 determinations = 38.0° C.

Temperature gradients through the brick wall: The temperature of the cold junction was 30° to 33° C.

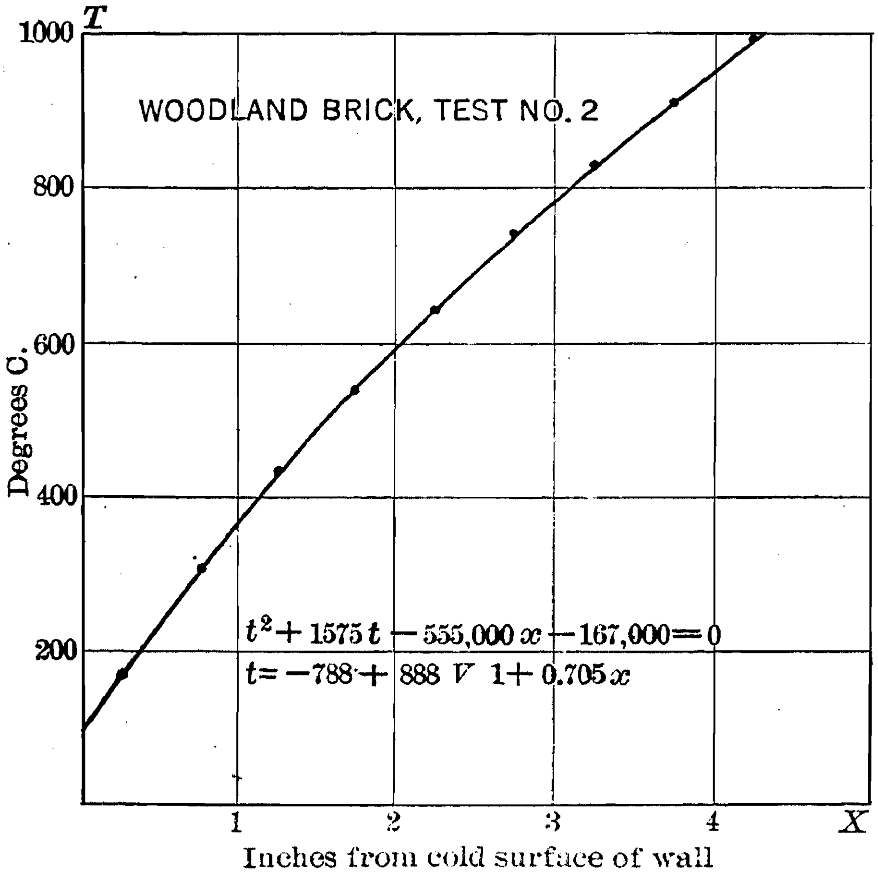


FIG. 11 (V in above cut should be $\sqrt{\quad}$)

Distance in brick, inches	*a* Upper hole	*b* Center hole	*c* Lower hole	Ave. Galv. Reading	Temperature deg. C.
0.25	2.2	2.4	2.4	2.3	170
0.75	4.7	5.0	5.3	5.0	305
1.25	7.6	7.6	7.8	7.7	435
1.75	10.0	10.0	10.2	10.1	540
2.25	12.5	12.2	12.6	12.4	640
2.75	15.1	14.7	15.3	15.0	740
3.25	17.8	17.2	17.8	17.6	830
3.75	20.6	19.7	20.4	20.2	910
4.25	23.1	22.2	23.3	22.9	995

Time at which the above readings were taken: *a* from 1:45 to 2:05, *b* from 2:10 to 2:30, *c* from 2:30 to 2:50. At 3:05 the galvanometer deflections with the junction at the backs of the holes were, $a = 23.4$, $b = 22.6$, and $c = 23.3$.

The above figures have been plotted to scale in Fig. 11. The temperatures of the surfaces of the brick are 100° and 1025° C.

Rate of heat flow into the inner compartment of the calorimeter from 1 sq. in. of wall surface and through 1 sq. in. of the linoleum cover

$$\frac{203 \text{ lb.} \times 454 \text{ g.} \times 5.94 \text{ deg.}}{1.5 \text{ hr.} \times 3600 \text{ sec.} \times 64 \text{ sq. in.}} = 1.59 \text{ g. cal. per sec.}$$

Rate of heat flow through linoleum cover: Temperature difference between air outside of calorimeter and water inside = 38.0 — (24.5 — 3.0) = 16.5° C. Fig. 9 shows the rate to be 0.22 g. cal. per sec. per sq. in.

Heat flow from wall to calorimeter = 1.59 — 0.22 = 1.37 g. cal. per sec. per sq. in.

Mean conductivity of brick between 100° and 1025° C.:

$$K = \frac{H x}{T_2 - T_1} = \frac{1.37 \times 4.5}{1025 - 100} =$$

0.00666 g. cal. per sec. per inch cube per C. degree.

Test No. 3. In this test the wall was covered with a slab of asbestos wood 24 inches square by 1½ inches thick (61 x 61 x 3.8 cm.), which was held in close contact with the surface of the test wall and to the outer side of which the calorimeter was attached. By covering the wall in this manner the mean temperature of the brick during the test was increased, and the third test was thus made under conditions somewhat different from those existing during the two previous determinations.

Fire was started in the furnace at 6:00 A. M. Calorimeter and asbestos wood were attached to wall at 10:00 A. M. Readings were taken from 4:30 to 6:00 P. M. Total time of test = 1.5 hr.

Temperature rise of water flowing through inner compartment: Average galvanometer deflection from 19 readings at five-minute intervals = 15.9. Temp. rise = 15.9 x 0.279 = 4.44° C.

Amount of water through inner compartment: During first half hour 65.75 lb., second half hour 64.0 lb., third half hour 62.5 lb. Total water in 1.5 hours = 192.25 lb.

Temperature of water leaving both compartments: Average of 19 determinations = 25.5° C.

Temperature of air one inch from face of calorimeter: Average of 19 determinations = 37.0° C.

Temperature gradients through the brick wall. Cold junction temperature was 31° to 34° C.

Distance in brick, inches	*a* Upper hole	*b* Center hole	*c* Lower hole	Ave. Galv. Reading	Temperature deg. C.
0.25	7.7	7.7	8.2	7.9	440
0.75	9.6	9.6	10.1	9.8	530
1.25	11.6	11.4	11.9	11.6	605
1.75	13.2	13.0	13.5	13.2	670
2.25	15.0	14.9	14.9	14.9	735
2.75	16.8	16.5	16.8	16.7	795
3.25	18.7	18.2	18.8	18.6	860
3.75	20.5	20.0	20.6	20.4	920
4.25	22.2	21.4	22.6	22.1	970

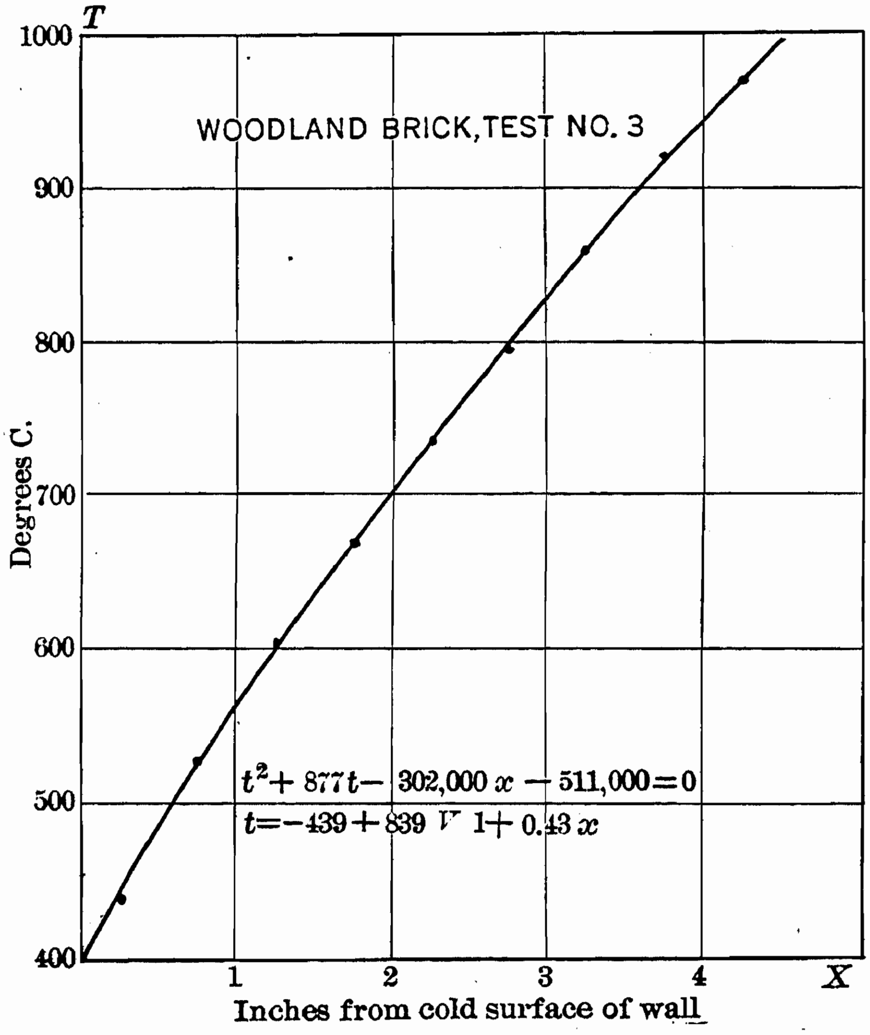


FIG. 12 (V in above cut should be $\sqrt{\quad}$)

Time at which the above readings were taken: *a* from 4:30 to 4:50, *b* from 5:00 to 5:35, *c* from 5:45 to 6:10. At 6:15 the galvanometer deflections with the junctions at the backs of the holes were, *a* = 22.4, *b* = 21.8, *c* = 22.5.

The above figures have been plotted to scale in Fig. 12. The temperatures of the surfaces of the brick are 400° and 995° C.

Rate of heat flow into the inner compartment of the calorimeter from 1 sq. in. of wall surface and through 1 sq. in. of the linoleum cover =

$$\frac{192 \text{ lb.} \times 454 \text{ g.} \times 4.44° \text{ C.}}{1.5 \text{ hr.} \times 3600 \text{ sec.} \times 64 \text{ sq. in.}} = 1.12 \text{ g. cal. per sec.}$$

Rate of heat flow through linoleum cover: Temperature difference between air outside of calorimeter and water inside = 37.0 — (25.5 — 2.2) = 13.7. Fig. 9 shows the rate to be 0.19 g. cal. per sec. per sq. in.

Heat flow from wall to calorimeter = 1.12 — 0.19 = 0.93 g. cal. per sec. per sq. in.

Mean heat conductivity of the brick between 400° and 995° C.

$$K = \frac{H x}{T_2 - T_1} = \frac{0.93 \times 4.5}{995 - 400} =$$

0.00704 g. cal. per sec. per inch cube per C. degree.

CONDUCTIVITY OF QUARTZITE BRICK.

Test No. 1. Fire was started in furnace at 6:00 A. M. Calorimeter was attached to wall at 10:00 A. M. Readings were taken from 2:05 to 4:05 P. M. Total time of test = 2.0 hr.

Temperature rise of water flowing through inner compartment: Average galvanometer deflection from 25 readings taken at five-minute intervals = 19.8. Temp. rise = 19.8 x 0.279 = 5.52° C.

Amount of water through inner compartment: During first half hour 65.5 lb., second half hour 65.5 lb., third half hour 67.5 lb., fourth half hour 67.5 lb. Total water in 2.0 hours = 265.5 lb.

Temperature of water leaving both compartments: Average of 25 determinations = 22.5° C.

Temperature of air one inch from face of calorimeter: Average of 25 determinations = 34.0° C.

Temperature gradients through the brick wall. Cold junction temperature was 30° to 34° C.

Distance in brick, inches	*a* Upper hole	*b* Center hole	*c* Lower hole	Ave. Galv. Reading	Temperature deg. C.
0.25	2.1	2.0	2.0	2.0	155
0.75	4.3	4.3	4.2	4.3	270
1.25	6.5	6.5	6.3	6.4	373
1.75	8.6	8.5	8.6	8.6	475
2.25	10.8	10.7	10.9	10.8	573
2.75	13.0	13.0	13.0	13.0	663
3.25	15.3	15.0	15.2	15.2	745
3.75	17.6	17.3	17.3	17.4	823
4.25	19.6	19.5	19.3	19.5	890

Time at which the above readings were taken: *a* from 3:00 to 3:25, *b* from 2:30 to 3:00, *c* from 2:05 to 2:25. Between 3:45 and 4:00 the galvanometer deflections with the junctions at the backs of the holes were, $a = 19.1$, $b = 19.2$, $c = 19.4$.

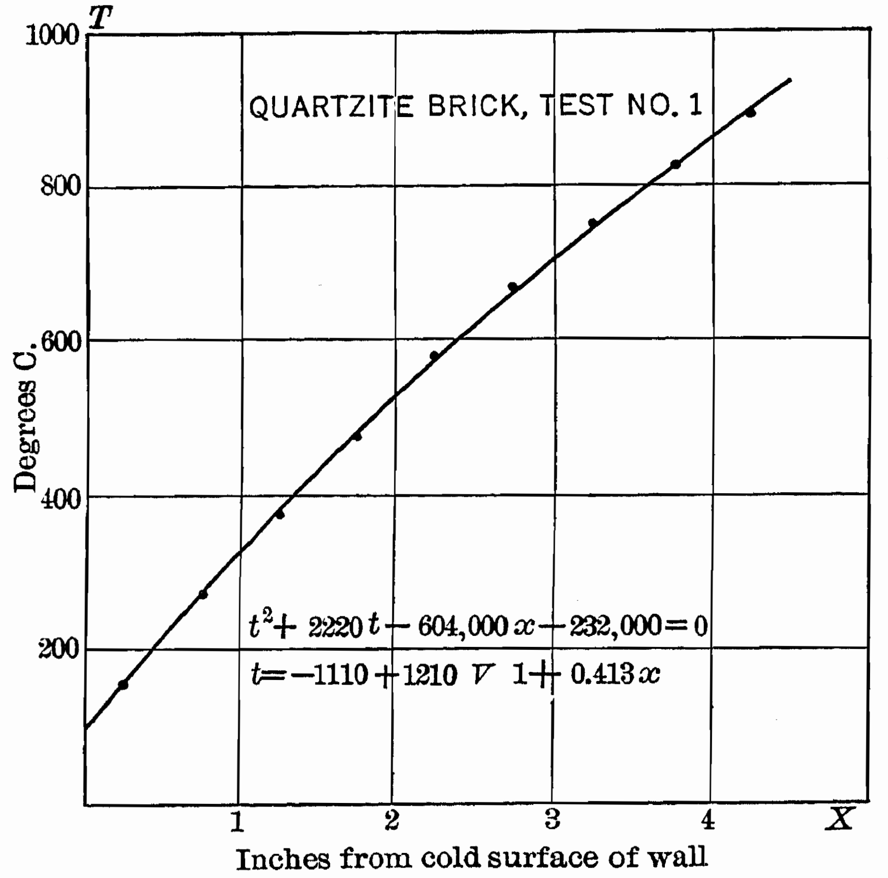


FIG. 13 (V in above cut should be $\sqrt{}$)

The above figures have been plotted to scale in Fig. 13. The temperatures of the surfaces of the brick are 100° and 935° C.

Rate of heat flow into the inner compartment of the calorimeter from 1 sq. in. of wall surface and through 1 sq. in. of the linoleum cover =

$$\frac{266 \text{ lb.} \times 454 \text{ g.} \times 5.52 \text{ deg.}}{2.0 \text{ hr.} \times 3600 \text{ sec.} \times 64 \text{ sq. in.}} = 1.45 \text{ g. cal. per sec.}$$

Rate of heat flow through linoleum cover: Temperature difference between air outside of calorimeter and water inside = 34.0 — (22.5 — 2.8) = 14.3° C. Fig. 9 shows the rate of flow to be 0.19 g. cal. per sec. per sq. in.

Heat flow from wall to calorimeter = 1.45 — 0.19 = 1.26 g. cal. per sec. per sq. in.

Mean heat conductivity of the brick between 100° and 935°,

$$K = \frac{H x}{T_2 - T_1} = \frac{1.26 \times 4.5}{935 - 100} =$$

0.00679 g. cal. per sec. per inch cube per C. degree.

Test No. 2. At the completion of test No. 1 the furnace fire was urged and additional air was supplied by directing the blast from a 16-inch electric fan into the draft holes at the back of the furnace. After two hours a second set of readings was taken from 6:00 to 6:30 P. M. Total time of test = 0.5 hr.

Temperature rise of water flowing through inner compartment of the calorimeter: Average galvanometer deflection from seven readings taken at five-minute intervals = 20.4.

Temp. rise = 20.4 × 0.279 = 5.69° C.

Amount of water through inner compartment: Total in 0.5 hr. = 67.0 lb.

Temperature of water leaving both compartments: Average of seven determinations = 22.5° C.

Temperature of air one inch from face of calorimeter. Average of seven determinations = 36.0° C.

Temperature gradients through the brick wall. Cold junction temperature was 32° to 35° C.

Distance in brick, inches	*a* Upper hole	*b* Center hole	*c* Lower hole	Ave. Galv. Reading	Temperature deg. C.
0.25	2.0	2.1	2.2	2.1	160
1.25	6.6	6.5	6.6	6.6	380
2.25	11.1	10.9	11.0	11.0	580
3.25	15.7	15.5	15.6	15.6	760
4.25	20.6	20.2	20.5	20.4	920

All of the above readings were taken during the test, *i. e.*, between 6:00 and 6:30 P. M.

The above figures have been plotted to scale in Fig. 14. The temperatures at the surfaces of the brick are 100° and 960° C.

Rate of heat flow into inner compartment of calorimeter from 1 sq. in of wall surface and through 1 sq. in. of the linoleum cover =

$$\frac{67.0 \text{ lb.} \times 454 \text{ g.} \times 5.69 \text{ deg.}}{0.5 \text{ hr.} \times 3600 \text{ sec.} \times 64. \text{ sq. in.}} = 1.50 \text{ g. cal. per sec.}$$

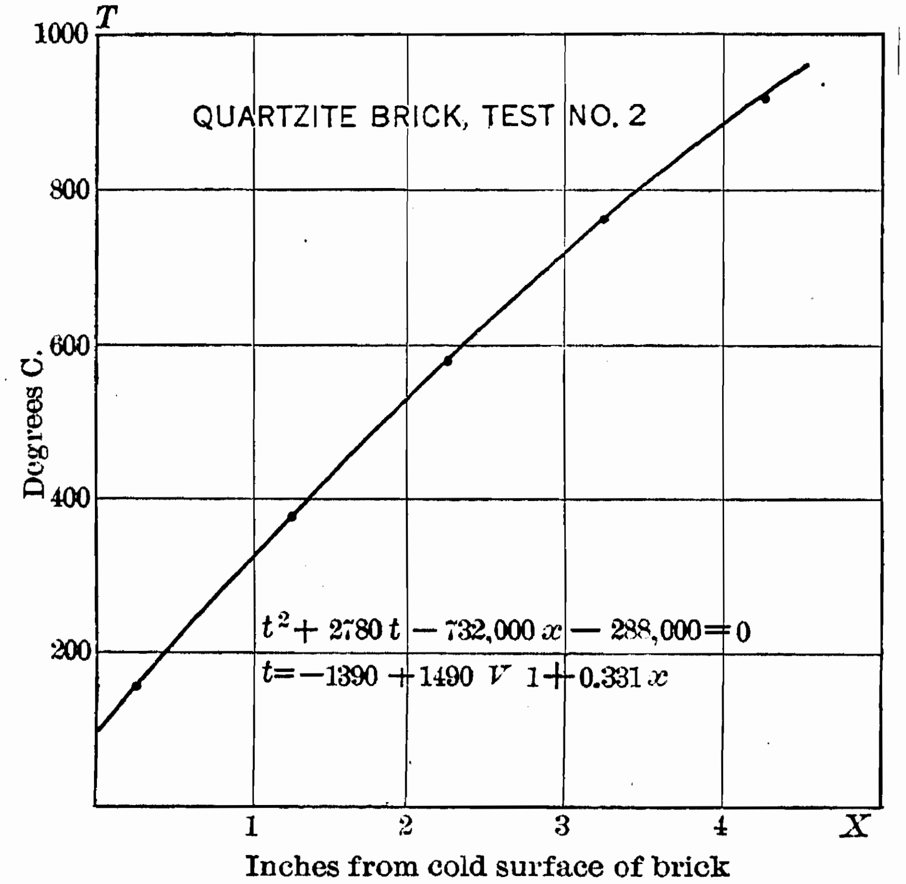


FIG. 14 (V in above cut should be $\sqrt{\quad}$)

Rate of heat flow through linoleum cover: Temperature difference between air outside of calorimeter and water inside = 36.0 — (22.5 —2.8) = 16.3° C. Fig. 9 shows the rate to be 0.22 g. cal. per sec. per sq. in.

Rate of heat flow from wall to calorimeter = 1.50 — 0.22 = 1.28 g. cal. per sec. per sq. in.

Mean heat conductivity of the brick between 100° and 960° C,

$$K = \frac{H\,x}{T_2 - T_1} = \frac{1.28 \times 4.5}{960 - 100} =$$

0.00670 g. cal. per sec. per inch cube per C. degree.

CONDUCTIVITY OF STAR SILICA BRICK.

Owing to the fact that the furnace was fired too soon after the construction of the test wall the brick cracked badly on account of insufficient preliminary drying and it was found impossible to make more than one test on this material.

Fire was started in furnace at 6:00 A. M. Calorimeter was attached to wall at 10:00 A. M. Readings were taken from 3:20 to 4:50 P. M. Total time of test = 1.5 hr.

Temperature rise of water flowing through inner compartment: Average galvanometer deflection from 19 readings taken at five-minute intervals = 17.6. Temp. rise = 17.6 × 0.279 = 4.91° C.

Amount of water through inner compartment: During the first half hour 86.0 lb., second half hour 86.0 lb., third half hour 84.0 lb. Total water in 1.5 hr. = 256.0 lb.

Temperature of water leaving both compartments: Average of 19 determinations = 25.0° C.

Temperature of air one inch from face of calorimeter: Average of 19 determinations = 39.0° C.

Temperature gradients through brick wall. Cold junction temperature was 33° to 34° C.

Distance in brick, inches	*a* Upper hole	*b* Center hole	*c* Lower hole	Ave. Galv. Reading	Temperature deg. C.
0.25	2.2	2.2	2.0	2.1	160
0.75	4.6	4.6	4.5	4.6	285
1.25	6.7	6.5	6.5	6.6	380
1.75	8.6	8.6	8.7	8.6	475
2.25	10.6	10.6	10.6	10.6	565
2.75	12.6	12.7	12.6	12.6	645
3.25	14.7	14.7	14.8	14.7	725
3.75	17.1	16.9	17.0	17.0	800
4.25	19.1	19.0	19.1	19.1	875

Time at which the above readings were taken: *a* from 3:20 to 3:50, *b* from 3:50 to 4:10, *c* from 4:10 to 4:30. Between 4:35 and 4:50 the galvanometer deflections with the junction at the backs of the holes were, *a* = 19.2, *b* = 18.9, *c* = 19.0.

The above figures have been plotted to scale in Fig. 15. The temperatures at the surfaces of the brick are 100° and 910° C.

Rate of heat flow into the inner compartment of calorimeter from 1 sq. in. of wall surface and through 1 sq. in. of the linoleum cover =

$$\frac{256 \text{ lb.} \times 454 \text{ g.} \times 4.91 \text{ deg.}}{1.5 \text{ hr.} \times 3600 \text{ sec.} \times 64 \text{ sq. in.}} = 1.65 \text{ g. cal. per sec.}$$

Rate of heat flow through linoleum cover: Temperature difference between air outside of calorimeter and water inside =

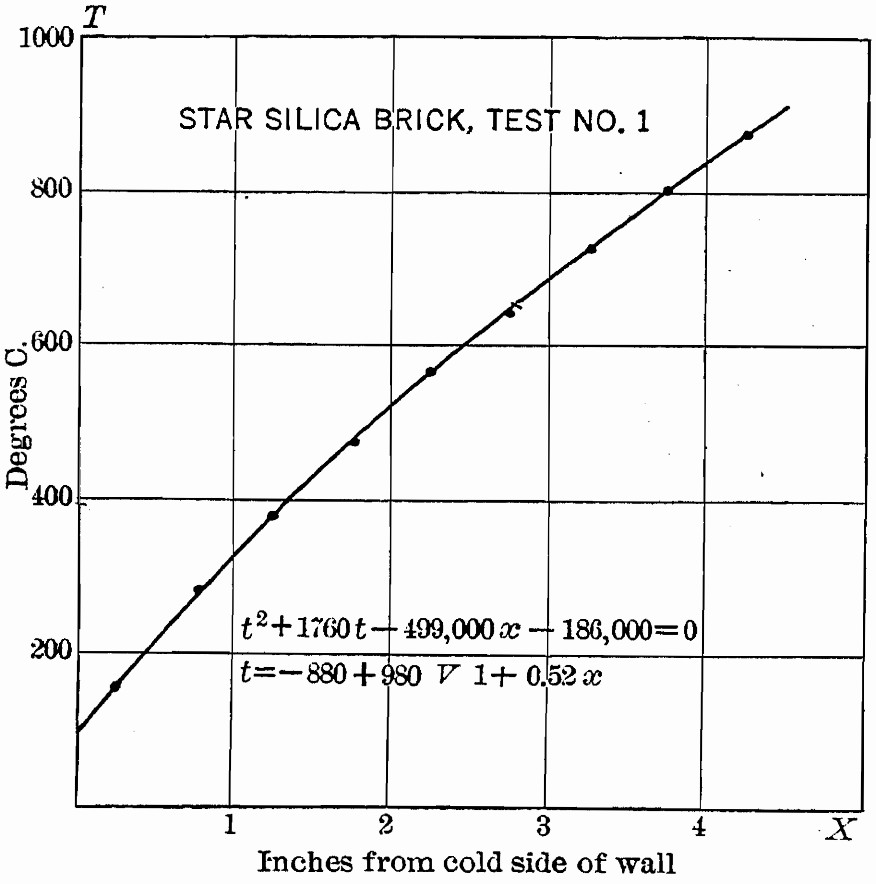


FIG. 15 (V in above cut should be $\sqrt{\quad}$)

39.0 — (25.0 — 2.5) = 16.5° C. Fig. 9 shows the rate of heat flow to be 0.22 g. cal. per sec. per sq. in.

Rate of heat flow from wall to calorimeter = 1.65 — 0.22 = 1.43 g. cal. per sec. per sq. in.

Mean heat conductivity of the brick between 100° and 910° C.,

$$K = \frac{H\,x}{T_2 - T_1} = \frac{1.43 \times 4.5}{910 - 100} =$$

0.00794 g. cal. per sec. per inch cube per C. degree.

CONDUCTIVITY OF MAGNESITE BRICK.

Fire was started in furnace at 6:00 A. M. Calorimeter was attached to wall at 10:00 A. M. Owing to the high conductivity of the brick considerable difficulty was experienced in securing even a moderately high temperature on the hot side of the wall. By the use of forced draft from the electric fan it was possible to secure a temperature of about 850° C. at this point. Readings were taken from 5:00 to 6:30 P. M. Total time of test = 1.5 hr.

Temperature rise of water flowing through inner compartment: Average galvanometer deflection from 19 readings at five-minute intervals = 19.6. Temp. rise = 19.6 × 0.279 = 5.47° C.

Amount of water through inner compartment: During first quarter hour of test 88.0 lb., during third quarter hour 88.0 lb., fifth quarter hour 88.0 lb. Total water in 1.5 hr. = 528 lb.

Temperature of water leaving both compartments: Average of 19 determinations = 22.5° C.

Temperature of air one inch from face of calorimeter: Average of 19 determinations = 40.0° C.

Temperature gradients through brick wall. Cold junction temperature was 32° to 35° C.

Distance in brick, inches	*a* Upper hole	*b* Center hole	*c* Lower hole	Ave. Galv. Reading	Temperature deg. C.
0.25	5.4	5.0	5.5	5.3	320
0.75	8.0	8.0	7.8	7.9	445
1.25	9.2	9.1	9.0	9.1	495
1.75	10.4	10.3	10.1	10.3	550
2.25	11.3	11.5	11.2	11.3	595
2.75	12.5	12.6	12.4	12.5	645
3.25	14.1	14.0	13.9	14.0	700
3.75	15.4	15.6	15.2	15.4	750
4.25	16.9	16.8	16.6	16.8	800

Time at which the above readings were taken: *a* from 5:00 to 5:25, *b* from 5:25 to 5:45, *c* from 5:50 to 6:15. Between 6:20 and 6:30 the galvanometer deflections at the backs of the holes were, *a* = 17.1, *b* = 17.0, *c* = 16.9.

The above figures have been plotted to scale in Fig. 16. The temperature gradient in this case is unlike those obtained from the tests of the three other types of brick. From 800 deg. to 445 deg. the line is practically straight, indicating constant conductivity between these points. Below the latter temperature the curve makes a sharp bend downward, which, if the figures at hand show the true temperature conditions within the brick, indicates a considerable and an abrupt change in the conductivity at this point. The reason for such a change in conductivity, assuming its existence, is not clear to the writer. On the other hand there appear no good reasons for doubting the accuracy of the temperature measurements that indicate this state of affairs. The agreement among the three sets of observations is good, and furthermore, by comparing this test with the others, it is possible to calculate approximately the temperature of the outer surface of the magnesite brick during the test, which calculated figure is in close agreement with the observations. The calculation is based on the following: The resistance to heat flow between the surface of the brick and the water in the calorimeter is the sum of the following component resistances: brick to air, air film, air to brass, brass, and brass to water. Of these the first two are the only ones that are likely to vary from one test to another, and, since the brick surface was in all cases painted with cement and the fit of the calorimeter to the wall was as close as possible in each case, it may be reasonably assumed that these two components of the total resistance were practically the same in all of the tests. Therefore it may be said that the total resistance to heat flow between the brick surface and the water in the calorimeter was the same in all of the tests, assuming of course that the component resistances do not vary to any great extent with the temperature. It follows that the temperature difference between the brick surface and the water is directly proportional

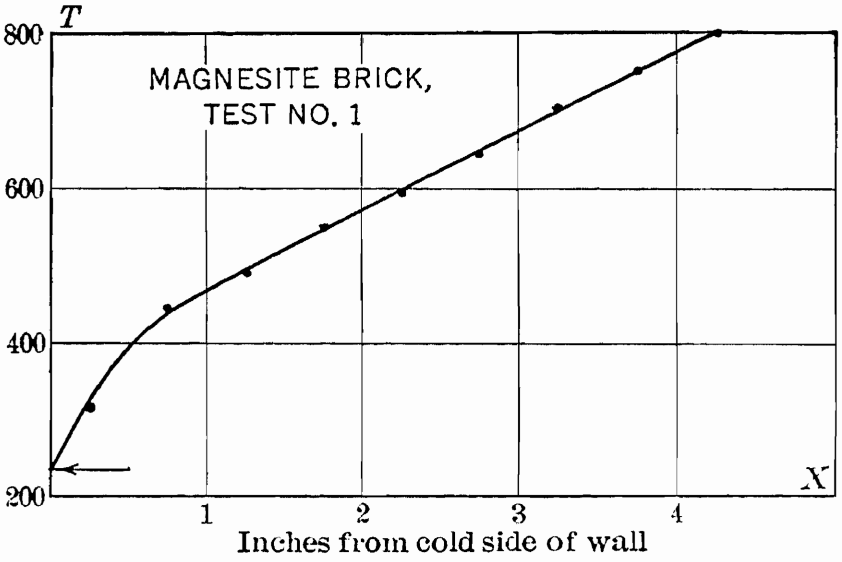


FIG. 16.

to the rate of heat flow from the one to the other. Considering the tests on the three other types of brick, with the exception of the Woodland test No. 3, the average rate of heat flow from the walls to the calorimeter was 1.32 g. cal. per sec. per sq. in., and the average temperature difference between the brick surfaces and the water in the calorimeter was 83° C. In the test on the magnesite brick the rate of heat flow from the wall to the calorimeter was 3.52 g. cal. per sec. per sq. in. (see below) while the average temperature of the water in the calorimeter was approximately 19° C. According to the above reasoning the temperature of the outer surface of the brick should have been

$$\frac{83 \text{ deg.} \times 3.52 \text{ cal.}}{1.32 \text{ cal.}} = 221^\circ \text{ C.}$$

above that of the water, making the temperature of the surface $221 + 19 = 240^\circ$ C. In Fig. 16 the calculated surface temperature is indicated by the point at the tip of the arrow.

Owing to the change in the direction of the temperature gradient the conductivity of the magnesite brick has been calculated for the range of temperature from 445° to 830° C., between which temperatures it is apparently constant.

Resuming the calculation, the rate of heat flow into the inner compartment of the calorimeter from 1 sq. in. of wall surface and through 1 sq. in. of the linoleum cover =

$$\frac{528 \text{ lb.} \times 454 \text{ g.} \times 5.47 \text{ deg.}}{1.5 \text{ hr.} \times 3600 \text{ sec.} \times 64 \text{ sq. in.}} = 3.79 \text{ g. cal. per sec. per sq. in.}$$

Rate of heat flow through linoleum cover: Temperature difference between air outside of calorimeter and water inside $= 40.0 - (22.5 - 2.7) = 20.2^\circ$ C. Fig. 9 shows the rate of heat flow to be 0.27 g. cal. per sec. per sq. in.

Rate of heat flow from wall to calorimeter $= 3.79 - 0.27 =$ 3.52 g. cal. per sec. per sq. in.

Mean heat conductivity of the brick between 445° and 830° C.,

$$K = \frac{H\,x}{T_2 - T_1} \quad \frac{3.52 \times 3.75}{830 - 445} =$$

0.0343 g. cal. per sec. per inch cube per C. degree.

The mean conductivities and resistivities of the materials tested are collected in Table V. Conductivities are expressed in gram calories per second per inch cube per degree C.; resistivities are expressed in thermal ohms per inch cube.

TABLE V.

Kind of Brick	Test No.	Mean Conductivity	Mean Resistivity	Temperature Ran
Woodland	1	0.00676	35.3	120° to 965° C.
Woodland	2	0.00666	35.8	100° to 1025° C.
Woodland	3	0.00704	33.9	400° to 995° C.
Quartzite	1	0.00679	35.2	100° to 935° C.
Quartzite	2	0.00670	35.6	100° to 960° C.
Star Silica	1	0.00794	30.1	100° to 910° C.
Magnesite	1	0.0343	6.96	445° to 830° C.

Aside from the above results, which indicate only the mean conductivities over the specified temperature ranges, the data secured in these experiments indicate the relationship between the conductivity of each of the materials and the temperature, and from them may be calculated the conductivity of each material at any given temperature and the mean conductivity over any range of temperature. These relationships are derived as follows:

When heat flows through a conductor bounded by two planes that are parallel to each other and perpendicular to the direction of heat flow, if H is the rate of heat flow expressed in gram calories per second through a section of the conductor having an area of A square inches, then

$$H = k \frac{A}{x} (T_2 - T_1)$$

wherein k is the mean conductivity of the material over the temperature range T_1 to T_2 in gram calories per second per inch cube per degree C.; x is the thickness of the conductor, *i. e.*, the distance in inches between the bounding planes; T_2 and T_1 are the temperatures C. of the hot side and cold side of the conductor, respectively. This equation holds not only for heat flow through the entire thickness of the conductor, but in the form

$$H = k\,A\,\frac{T_2 - T_1}{x_2 - x_1}$$

it is also applicable to the consideration of the heat flow between any two planes perpendicular to the direction of the flow and lying within the body of the conductor. In this case x_2 and x_1 are the respective distances of the two planes under consideration from a point of reference; in the following discussion the distances are measured from the cold surface of the conductor. T_2 and T_1 are the temperatures of the planes, and k is the mean conductivity of the material of the conductor over the temperature range from T_1 to T_2. Considering two planes that are close together, the ratio

$$\frac{T_2 - T_1}{x_2 - x_1}$$

expresses the slope of the temperature gradient between these planes, i. e., the temperature drop per unit of distance. The form of the equation just given shows that if the conductivity of the material changes with the temperature then the ratio

$$\frac{T_2 - T_1}{x_2 - x_1}$$

will also change, becoming smaller as the conductivity increases and larger as the conductivity decreases. In other words when heat flows at a uniform rate through a conductor bounded by two parallel planes that are perpendicular to the direction of heat flow, i. e., when the heat entering a unit area of the conductor on the hot side passes directly through to an equal area on the cold side without lateral loss and without being absorbed by the conductor, then the slope of the temperature gradient—the temperature-distance curve—decreases with increasing conductivity of the conducting material. The conditions of uniform heat flow, as thus defined, were practically realized in the case of the tests described above. Therefore the form of the temperature gradient determined during the course of each experiment furnishes the means whereby the relationship between the conductivity of the material and the temperature may be determined. It will be seen that all of the temperature gradients shown in Figures 10 to 15 possess the same general form; each is a smooth curve with its concave side toward the axis of abscissas, distances from the cold surface of the brick being plotted as abscissas in all cases. The slope of each curve decreases with increasing temperature or with increasing distance into the brick, and this characteristic points to the generally known fact that the conductivity of such materials increases with the temperature.

In order to determine the actual relationship between the conductivity and the temperature the heat flow equation may be expressed in a slightly more convenient form, as follows: Imagine a plane passed through the brick of the test wall parallel to the hot and cold surfaces and perpendicular to the lines of heat flow. If H equals the amount of heat passing across A square inches of this plane in gram calories per second, then

$$H = A\ k\ \frac{dt}{dx},$$

in which k is the conductivity of the material at the temperature of that region of the wall through which the plane is passed; and $\frac{dt}{dx}$ is the slope of the temperature gradient at this point. From this equation,

$$k = \frac{H}{A} \Big/ \frac{dt}{dx}$$

in which the quantity $\frac{H}{A}$, the rate of heat flow through the wall in gram calories per second per square inch, is determined by the calorimeter during the conductivity test; while $\frac{dt}{dx}$ for any temperature may be estimated from the plotted curve of the temperature gradient, or, better, the equation of the plotted curve may be determined and its slope at any point may be obtained from the first derivative of the equation. The equations of the temperature gradients shown in Figures 10 to 15 have been determined, assuming that the curves are segments of parabolas with axes parallel to the axis of abscissas; on the plot of each curve the corresponding equation is given in two forms. The general form of equation for curves of this type may be written

$$t^2 + mt + nx + p = O.$$

In which t and x are the variables, temperature and distance, respectively, and m, n, and p are constants. The method of determining the values of the constants that apply to the individual case consists simply of taking three sets of values for t and x, substituting these in the general equation, and solving the three simultaneous equations for m, n, and p. In each case the temperatures corresponding to the distances 0.5 inch, 2.0 inches, and 4.0 inches were substituted in the general equation.

It is evident that, with the constants of the temperature-distance equation known, the conductivity at any temperature may be calculated by substituting the value of $\frac{dt}{dx}$ for the given temperature together with the determined value of $\frac{H}{A}$ in the heat flow equation. The slope of the temperature gradient at any temperature is found by differentiating the equation of the curve and obtaining the first derivative. Differentiation of the general equation gives

$$2t\,dt + m\,dt + n\,dx = 0.$$

The derivative is $\frac{dt}{dx} = \frac{-n}{2t + m} = \frac{-0.5\,n}{t + 0.5\,m}$.

Substituting this value for $\frac{dt}{dx}$ in the heat flow equation gives the general formula for the calculation of the conductivity at any temperature

$$k_t = \frac{H}{A} \cdot \frac{t + 0.5\,m}{-0.5\,n}$$

in which k_t is the conductivity at the temperature t. This method of interpreting the results makes the conductivity a lineal function of the temperature, and for convenience the conductivity of each material may be calculated at two temperatures; then by plotting these sets of conductivities against their corresponding temperatures on rectangular co-ordinates straight lines representing the conductivities of the materials at any temperature will be determined. Consider, for example, the conductivity of the Star Silica brick as determined by the experiment performed on it. The conductivity at 100 deg. C. is obtained by substituting in the foregoing equation the following quantities:

$\frac{H}{A}$ = 1.43 g. cal. per sec., t = 100° C., $0.5m = 880$, — $0.5n = 250{,}000$. Hence $k_{100} = 1.43 \cdot \frac{100 + 880}{250{,}000} = 0.00560$ g. cal. per sec. per cu. in. per degree C. Similarly $k_{1000} = 1.43 \cdot \frac{1000 + 880}{250{,}000} = 0.0108$ g. cal. per sec. per cu. in. per degree C. The fact that the temperature of the hot side of the wall during the experiment was only 910° C. does not invalidate the calculation of the conductivity of 1000°; such a calculation is simply extrapolation of the observed data, the temperature of 1000° being assumed for convenience. By this method the conductivity of the materials may be calculated for temperatures considerably higher than were attained experimentally; the conductivities thus calculated are, of course, open to question, but in the absence of actual measurements the figures thus provided will be of some use at least. It was stated above, by plotting on rectangular co-ordinates two calculated values for the conductivity of one of the materials against their corresponding temperatures a straight line is determined, each point of which represents the conductivity of

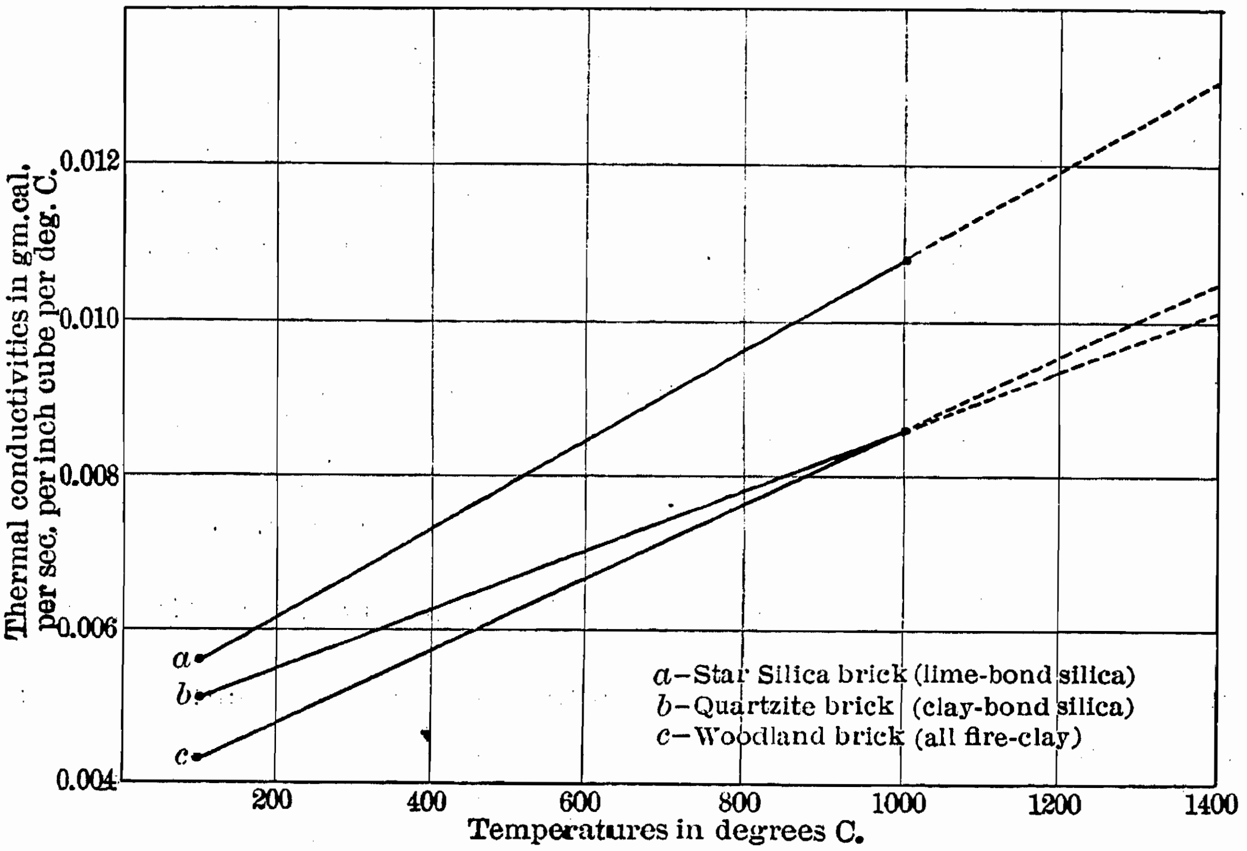


FIG. 17.

the material at a definite temperature. To obtain the mean conductivity over a range of temperature the conductivities at the extremes of the given range are averaged. By extending the line beyond the maximum experimental temperature the conductivities at higher temperatures may be estimated with some degree of accuracy.

This method of calculating the conductivities of the materials at various temperatures has been applied to the figures secured in each test, and the calculated conductivities at 100° and 1000° C. together with the mean conductivities over the experimental temperature ranges are shown in Table VI. Conductivities are expressed in gram calories per second per inch cube per degree C.

Table VI.

Material	Test No.	Exp. Temp. Range	Mean *k* Over Exp. Range	Calc. *k* at 100°	Calc. *k* at 1000°
Woodland	1	120 to 965	0.00676	0.00532	0.00816
Woodland	2	100 to 1025	0.00666	0.00438	0.00880
Woodland	3	400 to 995	0.00704	0.00332	0.00886
Quartzite	1	100 to 935	0.00679	0.00504	0.00880
Quartzite	2	100 to 960	0.00670	0.00521	0.00836
Star Silica	1	100 to 910	0.00794	0.00561	0.0108
Magnesite	1	445 to 830	0.0343	......	0.0343

While the calculated conductivities are in some cases not in close agreement, in general they are consistent in indicating the relative conductivities of the various materials. Taking the averages of the figures applying to each material the conductivities at 100° and 1000° C. are given in Table VII.

Table VII.

Material	Average *k* at 100°	Average *k* at 1000°
Woodland	0.0043	0.0086
Quartzite	0.0051	0.0086
Star Silica	0.0056	0.0108

The reasons for not including the magnesite brick in the above table are outlined in the description of the test made upon that material. It was found that between 445° and 830° C. the conductivity of the magnesite brick was practically constant, the value being 0.0343 gram calories per second per inch cube per degree C. Since further work on this material was not attempted, this is the only figure that can be offered. The figures given in Table VII have been plotted to scale in Fig. 17, in which the straight lines that join the plotted points have been extended to 1400° C.

Taking all factors into consideration, it is estimated that the precision of the figures representing mean conductivities is within 5 percent. The precision of the average figures representing the conductivities at definite temperatures is difficult to estimate, because these values not only depend upon the values assigned to the mean conductivities but also upon the accuracy with which the points on the temperature gradients were determined.

In conclusion it may be remarked that there are other methods that may be used in interpreting the data secured in this set of experiments, but the one that was adopted appears to be as rational as any. The figures thus provided, particularly those applying to the higher temperatures, will perhaps find use as a basis for conductivity calculations until by more and better work the conductivities of the commonly used refractories are actually measured over the higher ranges of temperature.

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DISCUSSION.

CARL HERING: Measurements of this kind are always welcome and of considerable value to those dealing with furnaces, because our knowledge of such conductivities, or resistivities as I prefer to call them, is very vague and uncertain.

There is no question that by the author's way of measuring the conductivity or resistivity he gets the true values for the material itself, separated and divorced entirely from another factor, namely the resistivity at the two surfaces, which may also be a very important factor. He has obtained what are doubtless very good figures for the conductivity of the material itself, perhaps the best on record so far.

In a furnace for which these figures would be used there is an additional surface resistivity which may at times be even more important than this resistivity of the material itself. In a metal coffee pot, for instance, this surface resistance constitutes virtually the entire heat insulation. In a steam boiler in which the heat travels from the flame to the water through the metal pipe, it was found a great many years ago that it did not make any practical difference whether copper or iron was used for the boiler tubes, because the heat resistance resided almost entirely at the surface. One can show this high surface resistance very nicely by pasting a postage stamp on the fire side of a boiler tube and it will be found to not even be charred; this shows that there is a very large heat gradient in the few thousandths of an inch on the surface of these tubes. Hence, the figures which Mr. Dudley gives, while of interest and of value, do not include all the figures which we need in designing furnaces; those representing the surface resistance are still wanting. Mr. Dudley has eliminated something in his calculations which other observers have not been so careful to eliminate, namely the heat insulating effect of joints. He has made his wall one brick thick, thereby avoiding the joints. In many other published tests the wall was sometimes made of two or three bricks thickness, in which case the resistivity of the joint was included, and this may be so great, in comparison to the other, as to seriously mask results.

In general, such a method of measuring as that used by this author involves a rather large error, because the temperature rise of the water is not great and when there is such a small rise the temperature must be read very precisely to give accurate results. I have seen experiments in which this rise of temperature was represented by not more than one-eighth or three-sixteenths of an inch on the scale, hence an error of only 1-32 inch (0.8 mm.) in the reading would be a very large percentage error in the temperature.

It should be noted that Mr. Dudley gets his final temperatures by extrapolation, not by measurement. He plots his curve for temperatures and then extends it to the outside surface, hence gets the outside temperature of the surface by extrapolation alone, which is sometimes a dangerous thing to do.

Another feature which may be criticized is that he paints both surfaces with Portland cement, therefore he does not get the true surface conductivity of the fire-bricks; the surface conductivity which he gets may be different from that of the brick. But this does not matter in his test, because he measured only the conductivity of the material itself, and divorced it entirely from the surface conductivity.

The paper unfortunately is extremely long. It seems to me that if it had been cut down to one-half or one-quarter of its present length, it would have been still more interesting.

FRANK THORNTON, JR. (*Communicated, read by C. G. Schluederberg*): There is a great deal of merit in the paper under discussion, as it describes a method of determining heat conductivity along lines somewhat different from those usually followed. We will all agree that there is great need for more reliable information as to the exact thermal conductivities of the heat insulating materials, and that improvement in thermal insulation is highly desirable. That is especially true when electricity is the source of heat.

The author has made careful and painstaking efforts to avoid errors in measurement, but it seems to the writer that there is a great source of possible error in the construction of the calorimeter itself. That such an error may exist is shown by the fact that the author's results average higher than those obtained by other investigators of the same class of materials. For a test wall four and one-half inches (11.5 cm.) thick, he has chosen to measure the heat arriving at the surface over an area 8 x 8 in. (20 x 20 cm.), and for protection and insurance of uniform and parallel flow of heat perpendicular to the surface he has used a guard ring only two inches (5 cm.) wide. That means that the width of the guard ring is less than one-half the thickness of the wall of the material being measured. Since the surface of the wall outside the calorimeter would be at a higher temperature than that under the calorimeter, there would be a flow of heat from that portion of the wall toward the calorimeter. It is very doubtful whether such a narrow guard ring can be relied upon to absorb it all, or to prevent a distortion of the flow of heat from parallel paths. This ring should certainly have been made at least 9 inches (22.5 cm.) wide, and preferably greater.

An electric heater would have been much more convenient than the coke fire used and would have made it possible to have obtained a more uniform distribution of the heat over the hot surface of the wall.

The variation of the thermal conductivity with the temperature is often overlooked, but the author has brought it out quite clearly. For this reason great care must be exercised in using average values.

Mr. Dudley should be commended for the thoroughness with which he has performed these tests and the completeness of his report.

H. K. HITCHCOCK: I have been very much interested in the paper which Secretary Richards has abstracted, and I think it is one of the subjects in which engineers generally are interested. In regard to Dr. Hering laying so much emphasis upon the surface resistance, he has forgotten that a furnace wall is not the shell of a boiler, and that the primary function of the furnace is to keep the heat in the furnace, and not to transmit it. In selecting material for the design of a furnace, the first thing the engineer wants to know is its thermal conductivity or resistivity. The next things desired are the way it behaves under the influence of heat, the amount of pressure it will stand structurally under the heat treatment, and the way it will behave when alternately heated and cooled, whether it will disintegrate or spall off or whether it will not, under these conditions.

I do not think that the method employed here could be greatly improved upon, nor the general character of the curves submitted. They verify data obtained by me in two very elaborate series of experiments made many years ago.

As regards the protecting ring around the calorimeter, my own judgment is that the depth and size of the ring are ample to insure accurate work, and any errors, even if present, would be negligible.

CARL HERING: Mr. Hitchcock has misunderstood me. I of course know the difference between a boiler and a furnace; the function of a boiler is to transmit heat, while that of a furnace wall is to keep it from being transmitted. I simply cited the boiler as an extreme, well known and striking case, in which that surface resistance is exceptionally great. I do not agree with Mr. Hitchcock that the surface conductivity can be neglected in the case of furnaces, though of course it will be much smaller than in boilers. Some of you may recall that Secretary Richards and I had quite a long discussion of this subject in a technical journal. In my opinion, this surface resistance may be a very important element, and one which I hope will receive attention from some one who can make as careful and accurate experiments as Dr. Dudley did in measuring the internal conductivity of the material itself. I do not wish to reflect in the least on his experiments; on the contrary, I am inclined to believe that his results for the solid material are probably very reliable, perhaps the best so far on record; but those who build the furnace need the other figure too, because it may be quite great. Foundrymen tell us that by merely whitewashing the outside of furnaces the heat from them is much less oppressive; this shows that the surface resistance must have been quite low, if a mere change of the surface makes so great a difference. It is also well known that a polished coffee pot will keep the coffee hotter than one that is dull. Dr. Langmuir has shown us in a recent paper that silver plating a surface increases its surface resistance.

H. K. HITCHCOCK: As a matter of fact, I know a little something about this, and think that the contrary is the case. For instance, if I were to plot curves for a 4.5 inch brick wall, the ordinates representing the degrees of temperature and the abscissæ representing the B. T. U.'s passing through that wall, the character of the curves would look very much like those shown in Fig. A. Curve (1) would be the temperature of the gases under the crown or against the side wall of the furnace. Curve (2) would be the temperature of the inside surface of the arch or wall, and curve (3) would be the temperature of the outside surface of the wall. Now, at any particular point here, as at X, the lengths of these vertical lines A, B and C cutting these curves, represent the resistances of the various elements to which Dr. Hering has referred. A equals the resistance capacity of the outside surface of the wall. B represents the resistance to flow through the wall, and the little line (C) represents the resistance of the surface on the inside of the wall. Now, on the other hand, if we have a nine inch (23 cm.) wall, or crown, and we will use the same temperature for the outside of the wall,

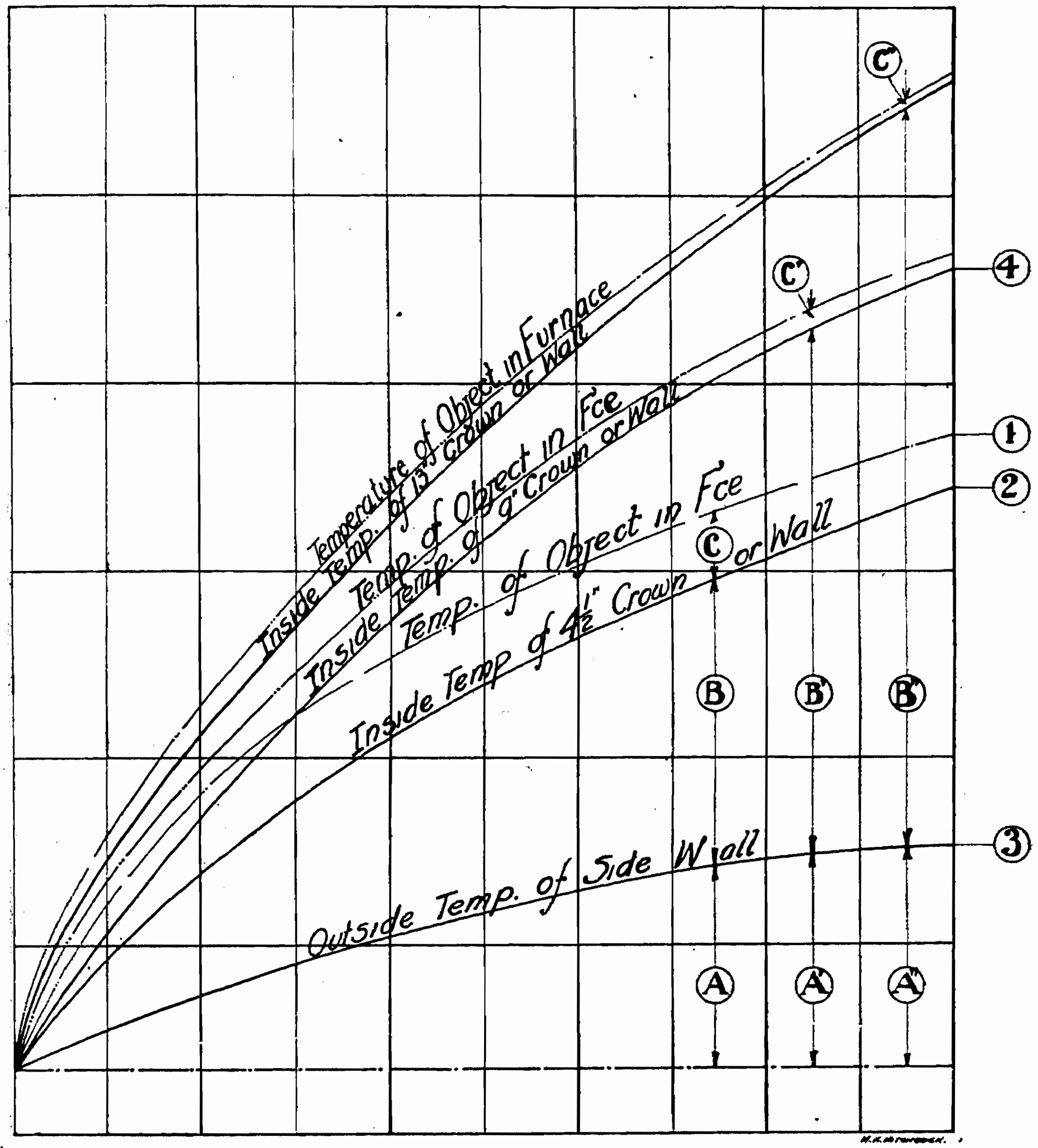

FIG. A.

this curve (4) will go higher up somewhere here, and if it is a 13 inch (33 cm.) wall it will go still higher up and with the same temperature of the furnace, the heat dissipated will be reduced accordingly while the surface resistance will remain the same in each case. Increasing the resistivity of the wall is equivalent to increasing the thickness, and is what we are all aiming at.

Carl Hering: The surface resistivity may often be far greater than that shown in Mr. Hitchcock's diagram. I fear he greatly underestimates its importance, at least in some cases.

H. C. Chapin: It seems to me that Mr. Dudley's data serve very well so far as they go, and that they could be made to serve Dr. Hering's requirements simply by addition of supplementary data on surface conductivity.

Carl Hering: Mr. Dudley does not give the true flame temperature in the inside; he merely extrapolates the temperature of the hot side of the wall and gets 900°. We know that the coke fire must have been considerably over 900°. The drop of temperature between the flame and the inside surface must have been several hundred degrees, in a space of probably a few thousandths of an inch, showing an extremely high surface resistance. There is a second surface resistance on the outside, though this is probably much less.

H. C. Chapin: I believe that I can make my contention clearer through the more familiar analogy of an electrical conductor, for example, a carbon electrode, the conductivity of which we measure by voltage drop for a given electrical current just as Mr. Dudley measures thermal conductivity by temperature gradient for a given thermal current. In one case we have a contact resistance between source of electrical current and carbon, in the other a contact resistance between flame and brick, but in neither instance does this affect the results for the conductivity of the material in question. It is quite true, as Dr. Hering states, that data on the thermal conductivity of a brick unsupplemented by data on temperature gradient between brick and source of heat does not represent the complete insulating value of the brick; but it represents the only factor in this value which is wholly characteristic of the brick itself. Once determined, this can be applied to numerous observations of total insulating value for calculation and classification of thermal contact resistances, which vary greatly with nature of surface and source of heat.

E. F. Northrup: I wish to make a few remarks in favor of a high type of altruist. I refer to the man who goes into the laboratory and makes careful, painstaking measurements. The data which he gathers and the measurements which he makes, if they have any value at all, are of value chiefly to others rather than to himself. He seldom receives any money for his work, and as the data are of chief value to others, he is certainly an altruist. The author of this paper evidently has spent a great deal of time in taking a large number of observations.

I have not analyzed the paper under discussion with sufficient care to know if the data collected are praiseworthy or not, but judging from the discussion of the paper it seems to me that they are. Heat measurements are the most difficult kind of measurements which are made in the laboratory. The movement of heat is so extremely slow that very tedious, painstaking work has to be done in order to get measurements which are at all accurate. One must wait for temperature equilibrium and if one has patience to carry through a series of heat measurements and get anything at all which is an advance on previous knowledge, he deserves the commendation and thanks of engineers.

FRANCIS C. FRARY: It seems to me that probably the difference of opinion between Mr. Hitchcock and Mr. Hering is due to the difference in the relative resistance of what they had behind their surface film. It is like putting a resistance of one ohm in series with a resistance of one-hundredth of an ohm, and saying that the one ohm is practically the whole thing, then putting one ohm in series with one hundred ohms, and still considering that the one ohm is the important thing.

JOS. W. RICHARDS: Mr. Dudley's results would be more useful to engineers if he expressed the conductivities of the materials as a constant, at 0° C., plus a function of the temperature, such that $K_t = \alpha + 2\beta t$. Outside of magnesite, all Mr. Dudley's results can be thus expressed, meaning simply that the conductivities are straight lines increasing with the temperature. A simple derivation from this gives the mean conductivity from 0° C. to t° as

$$K_m = \alpha + \beta t.$$

while the mean conductivity between any two temperatures, t′ and t″, is

$$K_m = \alpha + \beta (t' + t'')$$

I have calculated these expressions for the materials tested, and find the constant to be:

	α			β		
	Cal. per inch cube	Cal. per cm. cube	Reciprocal thermal ohms	Cal. per inch cube	Cal. per cm. cube	Reciprocal thermal ohms.
Woodland Brick	0.0038	0.0015	0.0040	0.0000024	0.0000010	0.0000025
Quartzite "	0.0047	0.0019	0.0049	0.00000195	0.0000008	0.00000205
Star Silica "	0.0050	0.0020	0.0052	0.0000029	0.0000016	0.0000030

I further believe that results should always be expressed in all such papers in calories/deg/sec/ cm. cube and also in reciprocal thermal ohms.

BOYD DUDLEY, JR. (*Communicated*): The question of surface resistance to the flow of heat seems to have been the point about which much of the discussion of my paper centered. My failure to make a study of this factor was not due to a lack of interest in it nor to a lack of appreciation of its importance, but rather to a lack of the knowledge as to just how such a study could be properly made.

Contact or surface resistances to heat flow are very difficult to study and correlate, because of the exceedingly great influence of changing conditions upon them. For example, the resistance of the surface of contact between a solid and a gas depends to a great extent upon the rate of motion of the gas. While a knowledge of such resistances is extremely useful and frequently necessary, I believe with Mr. Hitchcock that in most cases of furnace construction such resistances are of secondary importance. Let it be expressly understood, however, that I am advancing no arguments against whitewashing the outside of a foundryman's furnace or polishing the outside of a coffee pot. Such practices, without doubt, are good; they serve to restrain heat flow across the respective surfaces. Furthermore, the whitewashed furnace (so long as it remains white) improves the appearance of the foundry, and the burnished coffee pot lends an air of distinction to the breakfast table. But, as measures in the interest of heat conservation, I believe it will not be denied that an extra course of brick on the furnace and a flannel jacket on the coffee pot would be more effective.

It appears to me that in the extensive work of Dr. Langmuir,[1] on the radiation and convection of heat from surfaces, we already have a fund of information that may be applied to problems of heat flow across gas-to-solid contacts. The only factor that is needed in applying his data directly in cases involving smooth brick walls is the emissitivity of the brick, and by making reasonable assumptions in regard to this point we have information available that should be of great use to those who are particularly interested in this phase of the subject.

In regard to the width of the guard ring of the calorimeter, referred to by Mr. Thornton, this point was made the subject of a fairly thorough preliminary investigation and numerous calculations, and two inches (5 cm.) was determined upon as a safe figure for the width of the guard around the inner compartment. As evidence supporting the view that this width is sufficient, I wish to call attention to the fact that in each test three sets of temperature measurements were made through the test-wall. One pyrometer hole was in the wall at the center of the inner compartment of the calorimeter. A second hole was at the left-hand edge of this compartment and near the upper edge, while the third hole was on the right-hand edge and near lower edge. Had there been a lateral influx of heat to that portion of the wall covered by the inner compartment of the calorimeter, then the temperature gradients obtained by measurements in the marginal holes would have differed from that obtained by measurements in the center hole in such a manner as to make this influx apparent. An examination of the records of the tests will show that no such differences existed between the temperature gradients of the outside holes and that of the inside hole.

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[1] Trans. Amer. Electrochem. Soc. 23, 299. (1913),