Minnesota

ENGINEERING EXPERIMENT STATION

Samuel C. Lind, Director

BULLETIN NO. 12

THERMAL CONDUCTIVITY OF BUILDING MATERIALS

By

FRANK B. ROWLEY, M.E.
Professor of Mechanical Engineering

and

AXEL B. ALGREN, M.S. (M.E.)
Assistant Professor of Mechanical Engineering

UNIVERSITY OF MINNESOTA
Minneapolis

Printed in the United States of America

PREFACE

The data presented in this bulletin are the results of research in the field of heat transmission conducted in the Engineering Experiment Station and Bureau of Technological Research at the University of Minnesota. Various stages of the work have been in progress since 1920. At first the work was directed to the development of test methods and apparatus for determining the thermal conductivity of homogeneous materials and built-up wall sections. Later the test methods and apparatus were used to study the thermal conductivity of various types of materials and combinations of materials as used in building construction; also to analyze the heat flow through built-up wall construction and to determine the laws governing such factors as surface conductance, air space conductance, and the thermal properties of homogeneous materials. From time to time substantial contributions have been received from the industries and for several years the American Society of Heating and Ventilating Engineers through their research laboratory contributed liberally to the advancement of the work. Those manufacturing companies who in the past have contributed unrestricted research funds are the Flaxlinum Insulation Company, St. Paul, (now closed); the Insulite Company, Minneapolis; and the Wood Conversion Company, Cloquet.

Two bulletins have been published by the University of Minnesota Engineering Experiment Station—the first, Bulletin No. 3 in 1923, and the second, Bulletin No. 8 in 1932, both covering the results revised to date of publication. As the supply of Bulletin No. 8 has been exhausted and several parts of the work have been completed since its publication, it seems desirable to issue a revised summary of the work. In the present bulletin the essential parts of previous publications together with the results of new work will be co-ordinated to give a complete picture of the heat transmission work which has been conducted to date at the University of Minnesota. The publications which will be drawn upon and which may be referred to for more complete information on various parts of the work are as follows:

Transmission of Heat through Building Materials, F. B. Rowley. University of Minnesota Engineering Experiment Station Bulletin No. 3. 1923.

Heat Transmission through Building Materials, F. B. Rowley and A. B. Algren. University of Minnesota Engineering Experiment Station Bulletin No. 8. 1932.

Heat Transmission Research, F. B. Rowley, F. A. Morris, and A. B. Algren. *Journal, A. S. H. and V. E.,* Vol. 34, No. 7, pp. 517-41. July, 1928; *Transactions, A. S. H. and V. E.,* Vol. 34, pp. 439-74. 1928.

Thermal Resistance of Air Spaces, F. B. Rowley and A. B. Algren. *Journal, A. S. H. and V. E.,* Vol. 35, No. 1, pp. 17-26. January, 1929; *Transactions, A. S. H. and V. E.,* Vol. 35, pp. 165-81. 1929.

Over-all Heat Transmission Coefficients Obtained by Tests and by Calculation, F. B. Rowley, A. B. Algren, and J. L. Blackshaw. *Journal, A. S. H. and V. E.,* Vol. 35, No. 5, pp. 49-54. May, 1929; *Transactions, A. S. H. and V. E.,* Vol. 35, pp. 443-56. 1929.

Effects of Air Velocities on Surface Coefficients, F. B. Rowley, A. B. Algren, and J. L. Blackshaw. *Journal, A. S. H. and V. E.,* Vol. 1, No. 8, pp. 673-76. December, 1929.

Surface Conductances As Affected by Air Velocity, Temperature, and Character of Surface, F. B. Rowley, A. B. Algren, and J. L. Blackshaw. *Journal, A. S. H. and V. E.,* Vol. 2, No. 6, pp. 501-508. June, 1930.

Surface Coefficients As Affected by Direction of Wind, F. B. Rowley and W. A. Eckley. *Journal, A. S. H. and V. E.,* Vol. 3, No. 10, pp. 870-74. October, 1931.

Thermal Properties of Building Materials, F. B. Rowley and A. B. Algren. *H. P. and A. C.,* A. S. H. and V. E. Section, Vol. 4, No. 5, p. 363-69. May, 1932.

Heat Conductivity of Wood at Climatic Temperature Differences, F. B. Rowley. *Journal, A. S. H. and V. E.,* Vol. 1, No. 1, pp. 313-23. June, 1933; *Transactions, A. S. H. and V. E.,* Vol. 39, pp. 329-55. 1933.

Insulating Value of Bright Metallic Surfaces, Frank B. Rowley. *Journal, A. S. H. and V. E.,* Vol. 40, No. 6, pp. 263-66. June, 1934; *Transactions, A. S. H. and V. E.,* Vol. 40, pp. 413-26. 1934.

Thermal Properties of Concrete Construction, Part I, F. B. Rowley, A. B. Algren, and C. Carlson. *Journal, A. S. H. and V. E.,* Vol. 42, No. 1, pp. 53-64. January, 1936.

Thermal Properties of Concrete Construction, Part II, F. B. Rowley, A. B. Algren, and R. Lander. *Journal, A. S. H. and V. E.,* Vol. 8, No. 11, pp. 621-31. November, 1936.

The authors wish to acknowledge the assistance of the various co-authors of papers mentioned as well as the director of the American Society of Heating and Ventilating Engineers Research Laboratory and the director of the Engineering Experiment Station for their valuable assistance and co-operation in making the different phases of research work possible.

CONTENTS

TABLES

ILLUSTRATIONS

THERMAL CONDUCTIVITY OF BUILDING MATERIALS

INTRODUCTION

It is difficult to find in engineering practice a process which has a more general application than that of the flow of heat through materials or combinations of materials. In many cases, such as boilers, condensers, heat exchangers, and refrigerating machinery the object is to get a rapid transfer of heat with as little resistance as possible. In other cases, such as cold storage houses, refrigerator cars, and many types of building construction the object is to obstruct the flow of heat, or to build into the structure definite heat resistance. In general, the laws governing the heat flow are fairly well known and apply in the same manner to either of the above problems. Often, however, the structure of the materials or the combination of the materials when assembled on a job is such that it is difficult to apply the simple laws and obtain reliable calculated results. For instance, the flow of heat across an air space, common to many types of wall construction, may be reduced to a simple calculation if suitable coefficients are available. These coefficients, however, depend upon several factors, such as the area and width of the air space, the surface finish, and the mean temperature. Since the transfer is by the combined methods of conduction, convection, and radiation, an analysis of the problem to determine the coefficients is complicated. The method of calculating the flow in such cases is simple, but the selection of the proper coefficient requires an extended knowledge of the thermal properties of the materials and surfaces, and their arrangement. Likewise in tile and concrete walls in which various cored out air spaces are provided, the heat flow through the wall is a combination of that transferred through solid material and across the air spaces, and the construction is usually such that calculated results are not reliable. Even homogeneous materials possess such a wide range of characteristics in so far as their heat transfer is concerned that a wide knowledge of their thermal properties is necessary for reliable calculated results. In the final analysis the problem has become long and complicated and as the work has progressed some changes in methods and apparatus have been made. However, the general test methods for homogeneous materials and built-up wall sections have been maintained throughout the work.

Various phases of the work have been carried out as specific research projects. Thus, the thermal conductance of surfaces for various types of materials and wind velocities was a separate project. The thermal conductance of air spaces was separated into two parts—first, that for average materials, and second, that for bright metallic surfaces. The thermal conductance of various types of wood was a specific project, and, as will be noted, the over-all thermal conductivity of built-up wall sections is reported in two parts, the first including frame wall construction and a part of tile and masonary walls, and the second including a more complete program on different types of concrete construction.

Part of the material is taken directly from Bulletin No. 8 of the Engineering Experiment Station (now out of print) and part of it is additional material in the same field completed since the publication of the bulletin. The reason for this procedure is that in order to present a complete and intelligent picture of the work as a whole it is necessary to combine the principal features of the work given in Bulletin No. 8 with later research results. Many details of individual parts have been omitted due to lack of space, but in most cases they may be found in the publications listed in the Preface.

In general the objects of the researches were:

1. To develop test methods and build reliable apparatus for determining the thermal conductivity of insulating materials and the over-all heat transmission coefficients for built-up wall construction.
2. To determine reliable thermal coefficients for the surfaces of materials, for air spaces of various construction, and for homogeneous materials, in order that these coefficients may be used in the accepted methods of calculation to obtain reliable over-all heat transmission coefficients for built-up wall sections.
3. To compare the results obtained by tests and by calculations for over-all heat transmission coefficients, and to determine the accuracy of calculated results when using corrected coefficients.
4. To determine the practicability of different types of construction and the effect of mean temperature, density, and moisture on the thermal conductivity of materials.

NOMENCLATURE AND DEFINITIONS

The symbols used in this bulletin are those recommended by the Committee on Heat Transmission of the National Research Council, and will, therefore, be different from those used in some of the earlier papers referred to in the Preface. The following are the most important symbols and definitions used:

U = thermal transmittance or the over-all coefficient of heat transmission for a complete wall. It represents the number of British thermal units transmitted through one square foot of wall area per hour per degree difference in temperature, Fahrenheit, between the air on the inside and the air on the outside of the wall.

k = the thermal conductivity. It represents the amount of heat, expressed in British thermal units, transmitted per hour through one square foot surface area of homogeneous material one inch thick per degree temperature difference between the two surfaces of the material.

C = the thermal conductance. It represents the amount of heat expressed in British thermal units, transmitted through one square foot of material per hour per degree difference in temperature between the two surfaces. (It will be noted that C is different from k in that it represents the flow of heat through the material as built and not per one inch thick.)

f = film or surface conductance. It represents the amount of heat expressed in British thermal units, transmitted between the air and the surface of the material per square foot of surface area per hour per degree difference in temperature between the air and the surface. To differentiate between the two surfaces, f_1 is used for the inside surface and f_0 for the outside surface conductance.

a = the thermal conductance of an air space. It represents the amount of heat expressed in British thermal units transmitted from surface to surface of an air space per hour per square foot of surface area per degree Fahrenheit difference in temperature between the two surfaces.

The resistance to the heat flow through any path equals the reciprocal of its conductivity over the same path. Numerically the resistance is equal to the temperature drop in degrees required to force one British thermal unit through the given path.

Thus $\frac{1}{U}$ = over-all resistance from air to air

$\frac{1}{k}$ = the internal resistance per inch of material

$\frac{1}{C}$ = the internal resistance of the material in thickness as constructed

$\frac{1}{f}$ = the surface or film resistance

$\frac{1}{a}$ = air space resistance

HEAT FLOW DISCUSSION

An extended discussion of the formulae which are commonly used in heat transmission calculations is not necessary. However, since this bulletin deals with the various coefficients, the relation between them will be briefly considered. The fundamental formula by which the over-all heat transmission coefficient *U* is generally calculated is as follows:

$$(1) \quad U = \frac{1}{\frac{1}{f_1} + \frac{x_1}{k_1} + \frac{1}{a} + \frac{x_2}{k_2} + \frac{1}{f_0}}$$

This represents a wall with air space as shown in Figure 1.

In the above formula, x_1 and x_2 are the thicknesses and k_1 and k_2 are the conductivities of the two materials making up the wall structure.

While the foregoing formula represents the relation between the over-all heat transmission coefficient of the wall and the coefficients of the component parts, it is less confusing to consider the relation between the resistances. The over-all thermal resistance of a wall is equal to the sum of the resistances of the component parts, and this holds true regardless of the structure. Thus Equation 1 might be rewritten as follows:

$$(2) \quad \frac{1}{U} = \frac{1}{f_1} + \frac{x_1}{k_1} + \frac{1}{a} + \frac{x_2}{k_2} + \frac{1}{f_0} \text{ in which}$$

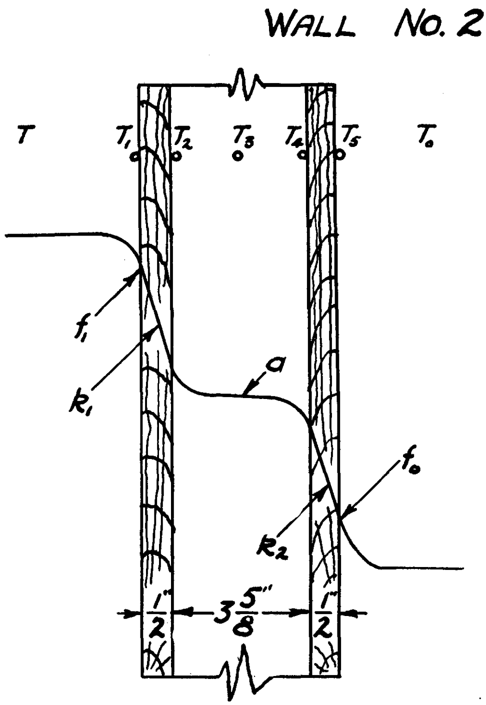
$\frac{1}{U}$ = the thermal resistance of the complete structure

$\frac{1}{f_1}$ = the inside surface resistance

$\frac{x_1}{k_1}$ = the resistance of the inside lining, etc.

In the above the reciprocals of the conductivities represent numerically the number of degrees of temperature drop required to force one British thermal unit through a given path one square foot in area.

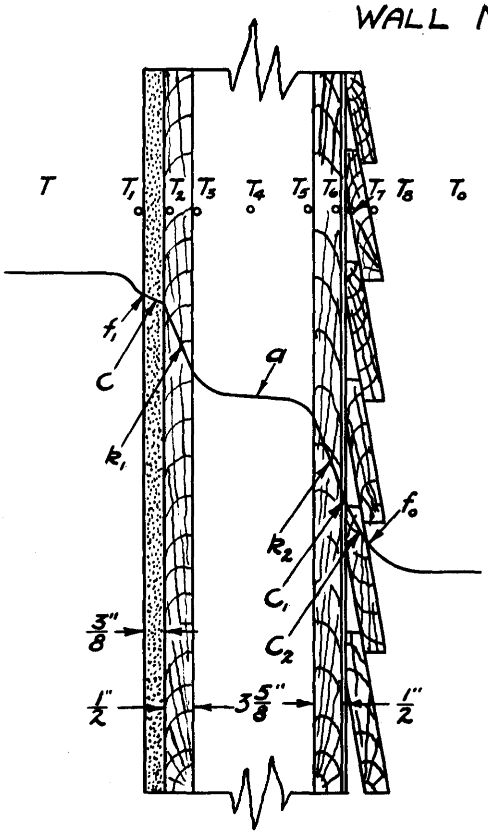
Thus, if we consider one British thermal unit as traveling through one square foot of wall area from air on one side to air on the other side, then $\frac{1}{U}$ is equal to the number of degrees temperature drop or heat head required to force this heat from air on the inside to air on the outside of the wall, $\frac{1}{f_1}$ is the number of degrees required to force the same amount of heat from air on the inside to the inside surface of the wall, $\frac{x_1}{k_1}$ is the number of degrees required to carry it through the inside surface material, etc. throughout the wall construction. The sum of the individual temperature drop, $\frac{1}{f_1} + \frac{x_1}{k_1} + \ldots$ etc. $= \frac{1}{U}$. This conception of the heat flow process is convenient and gives a ready method of calculating the temperature at any point in a wall if the characteristics of the materials and other parts of the wall are known.



RESULTS OF TESTS				
	COND. CONST. RUN 1	M T DEG.	COND. CONST. RUN 2	M T DEG.
U	.184	40.2	.185	40.5
k_1	.356	60.0	.358	61.0
k_2	.339	23.3	.341	23.2
f_1	1.80		1.82	
f_0	1.25		1.28	
a	.979		1.01	
TEMPERATURES °F				
T	80.5		80.5	
T_1	72.3		72.3	
T_2	49.7		49.6	
T_3	42.0		41.9	
T_4	34.8		34.8	
T_5	11.8		11.7	
T_6	0		+0.05	

FIGURE 1. TEMPERATURE GRADIENT THROUGH WALL SECTION CONSTRUCTED WITH TWO ½-INCH INSULATING BOARDS AND ONE 3⅝-INCH AIR SPACE

WALL No. 30



RESULTS OF TESTS

	COND. CONST. RUN 1	M T DEG.	COND. CONST. RUN 2	M T DEG.
U	.154	.400	.156	40.2
C	8.80	72.7	8.89	72.5
k_1	.357	62.4	.362	62.4
k_2	.344	32.2	.347	32.3
C_1	2.57	20.4	2.76	20.6
C_2	1.24	13.0	1.26	13.4
f_1	1.78		1.80	
f_o	1.54		1.52	
a	1.09		1.36	

TEMPERATURES °F

T	80.1	80.1
T_1	73.2	73.2
T_2	71.8	71.8
T_3	53.0	53.1
T_4	46.6	46.8
T_5	41.7	41.8
T_6	22.8	22.9
T_7	18.0	18.4
T_8	8.1	8.5
T_o	0	+0.3

FIGURE 2. TEMPERATURE GRADIENT THROUGH WALL SECTION WITH INSULATING MATERIALS BUILT INTO EACH SURFACE

Figures 1 and 2 show graphically the temperature drop throughout various sections of two walls as determined experimentally. Referring specifically to Figure 1, this represents a sectional view of a wall which was built up with 2 × 4-inch studs covered on each side with an insulating board ½ inch thick. This wall was maintained under constant conditions between air temperatures of 80.5° F. on the high side and 0° F. on the low side. Under this condition temperatures were taken at points throughout the wall as indicated by the points T_1, T_2, T_3, etc. as shown in the top part of Figure 1. The heavy curved line passing from left to right downward through the wall represents graphically to vertical scale the temperature drop throughout the wall taken at the various points. The temperature drop from point to point represents the heat head required for the passage of heat through the particular section of the wall and is, therefore, a direct measure of the heat resistance of that section of the wall. If the total heat flow per square foot area is known, the coefficient of conduction may be calculated. In this case the temperatures were determined experimentally. If, however, the coefficients were known throughout the wall, the temperatures at any point within the wall could be calculated providing the initial temperatures T and T_0 were established. Thus if the resistance of the inner surface, $\frac{1}{f_1}$ was .1 of the total resistance $\frac{1}{U}$, then the drop in temperature $T - T_1$ would be one tenth of the drop from T to T_0, and likewise the drop for other points in the wall could be calculated. The lines joining T to T_1, T_2 to T_4, and T_5 to T_0 are curved lines as the resistance is not uniform throughout these sections. The lines T_1 to T_2 and T_4 to T_5 are straight lines as the materials used for these sections are homogeneous insulating materials of uniform resistance. In Figure 2 additional inside and outside surface finishes have been applied to the wall, and since these finished materials have different thermal resistances the slopes of the line through them are different. The total drop in temperature, however, from T to T_0 is divided up between the various parts proportional to the heat resistance of these parts.

TYPES OF TEST APPARATUS

Two general types of apparatus are used for determining the thermal conductivity of materials. The first is most commonly used for determining the thermal conductivity from surface to surface of the material and is often referred to as the hot plate apparatus. This is more specifically adapted to homogeneous materials, the surfaces of which are smooth enough to give reasonably good contact between the test plates and the material. The second type is that employed for determining the over-all heat transmission coefficient from air on one side to air on the other side of the material and is particularly adapted to testing built-up wall sections or structures whose surfaces are too rough for good contact with the plate as used in the hot plate method of tests. Several individual designs of the second type have been used. A common method has been that of building a box either completely of the material to be tested or with one side constructed of the material and the remainder of the box accurately calibrated. Another method has been to use a thermal conductivity meter placed in contact with one side of the wall to be tested. The Nicholls heat meter is undoubtedly the best known apparatus of this type. The apparatus devised and used in these tests consists of a double or guarded box arrangement which will be described later.

The fundamental difference between the two types of apparatus is that, in the hot plate method, the conductance is determined from surface to surface of the material under test, thus eliminating the surface resistances, while in the hot box method, the conductance is determined from air to air, which includes the surface resistances. The conductance from surface to surface may be obtained by the hot box method, provided that thermocouples are properly placed on the surfaces of the material under test, or the over-all heat transmission coefficient may be calculated from the results obtained from the hot plate test, if the surface coefficients are known. The main objection to using the hot plate method for large wall sections is the difficulty experienced in getting contact between the plate and the surface of the wall. At present, the hot plate method is generally accepted for determining the thermal conductivity coefficients of homogeneous materials. A single method, however, of determining over-all coefficients has not been so generally accepted. In any type of apparatus, the principal object is to get accurate results. This can only be done by giving special attention to temperature measurements and to the path of heat flow through the material. Special precautions must be taken to prevent heat losses from the test section and to insure that the lines of heat flow are perpendicular to the test surfaces.

HOT PLATE APPARATUS

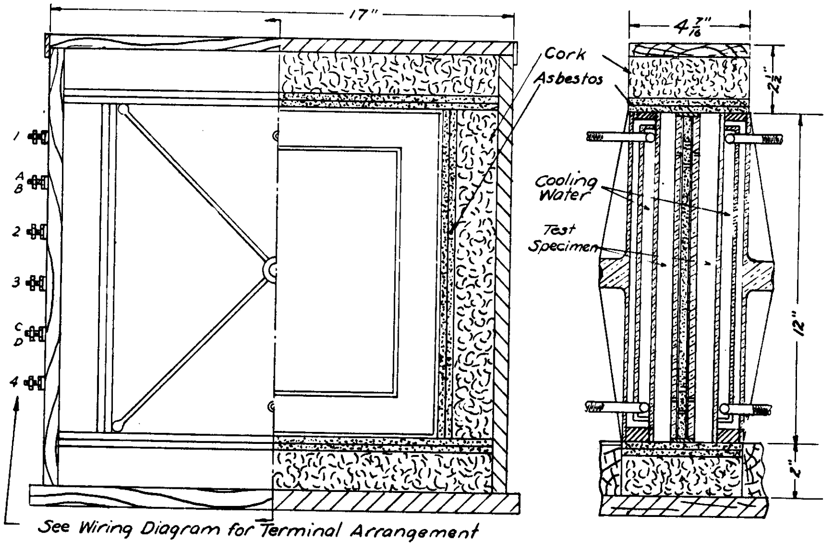
The general design of the hot plate apparatus used in this series of tests is shown in Figures 3 to 6, inclusive. This design conforms to the generally accepted standard for this type of apparatus and differs from those previously used at Minnesota in that special precautions were taken to eliminate all paths for heat flow between heating plate and guard ring, and, also, to reduce condensation on the outside of the cooling plate.

Figure 3 shows two views, part in section, of the complete apparatus. Referring to the right-hand view, the construction of the plate is as follows: The central or heating portion is 12 inches square, 7/8 inch thick, and lined on each side with a copper plate 1/4 inch thick. The copper plates are divided into two parts—an inner section 9 inches square and a band or guard ring 1½ inches wide surrounding this section. These two sections are completely separated by a 1/8-inch air gap which completely eliminates any metallic connection between the inner and outer portions of the heating plate. The inner or 9-inch section is the test section proper and the outer portion is the guard ring provided to eliminate heat losses through the edges of the material.

Heat is supplied to the plate by electric heating elements wound on 1/4-inch transite board and placed between the two 1/4-inch copper plates. The arrangements for these windings are shown in Figure 4. The heating element supplying the inner test section is completely separated from that supplying the guard ring section by a 1-inch air gap. The inner or test section of the plate is kept in line with the outer or guard section by the four insulating blocks designated by *A*. These constitute the only positive connection between the inner and outer portions of the heating plate. The only other paths for heat flow between these two sections are along the wires which are necessary to connect the heating elements and thermocouples to the apparatus outside of the plate.

The test specimens are placed one on each side of the heating plate and each covered by a cooling plate which is clamped sufficiently tight to hold the specimen in close contact with the surface of the heating and cooling plates. The assembled apparatus is surrounded by an insulating guard which serves as an additional precaution against heat losses from the edges of the test specimen.

The plates are provided with copper constantan thermocouples for measuring the surface temperatures of the copper plates which are taken as the surface temperatures of the materials under test. Two of these couples are provided in each face of the test section and two in each face of the cooling plates. A differential couple is provided across



See Wiring Diagram for Terminal Arrangement

FIGURE 3. SECTIONAL VIEW OF HOT PLATE, SHOWING INSULATED GUARD

Measure Wire bcfore and after winding to get exact length.

Bring leads for guard and heating plate out at back as shown.

Terminals to extend thru 2" of insulation.

Use 28'-7" of No.33 Advance Constant Resistance Wire on heating plate and No. 25 Nichrome Wire on guard.

Notches 1/8" deep.

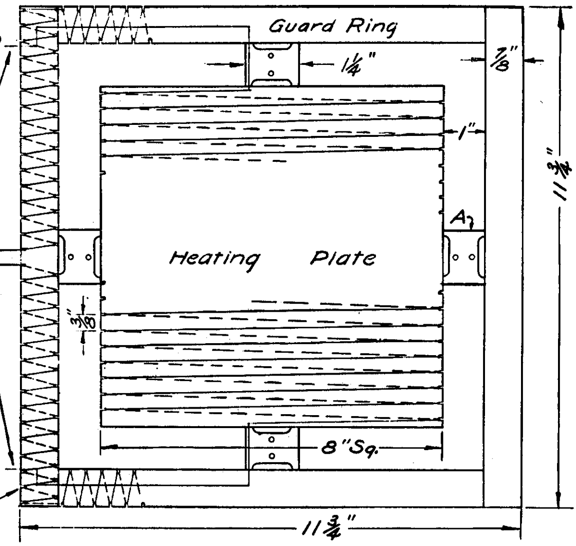


FIGURE. 4. HEATING ELEMENT FOR HOT PLATE

the air gap between the inner and outer portions of the hot plate in order to determine when a balanced temperature has been reached.

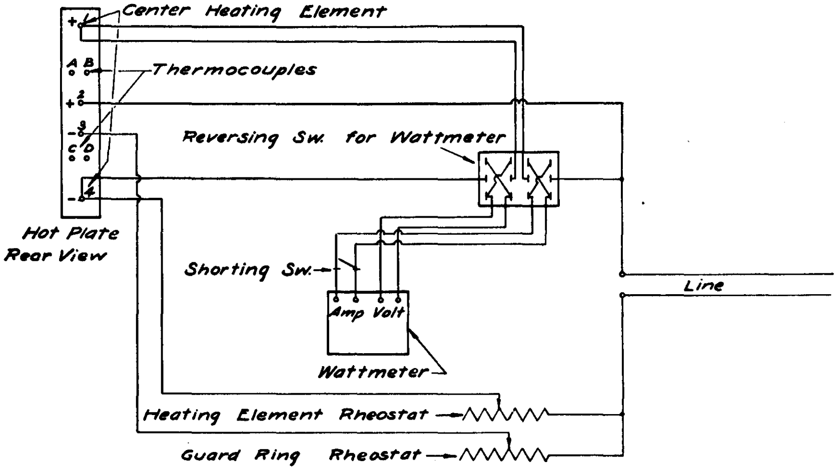


FIGURE 5. WIRING DIAGRAM FOR HOT PLATE

The heating plate is supported in a frame, the top and front portions of which are removable. All of the thermocouple and electric wires are brought out through the stationary portion of the frame (Figs. 3 and 6).

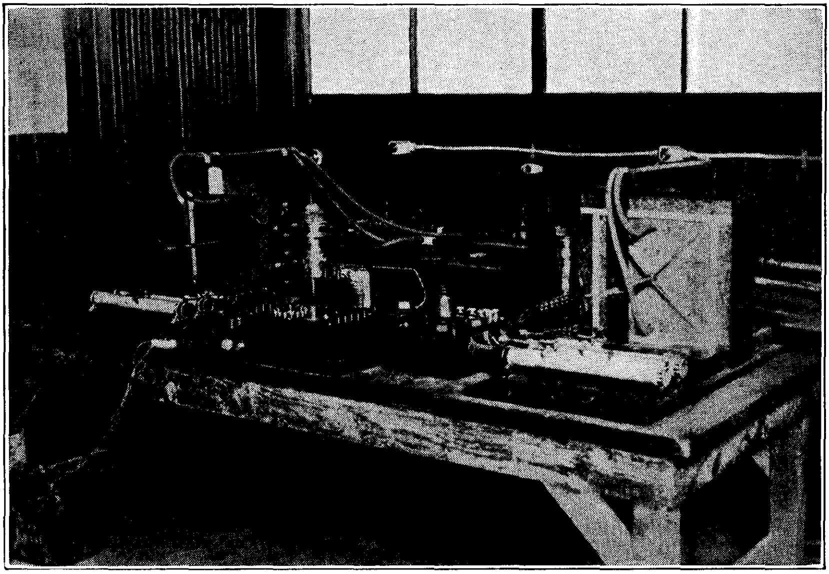


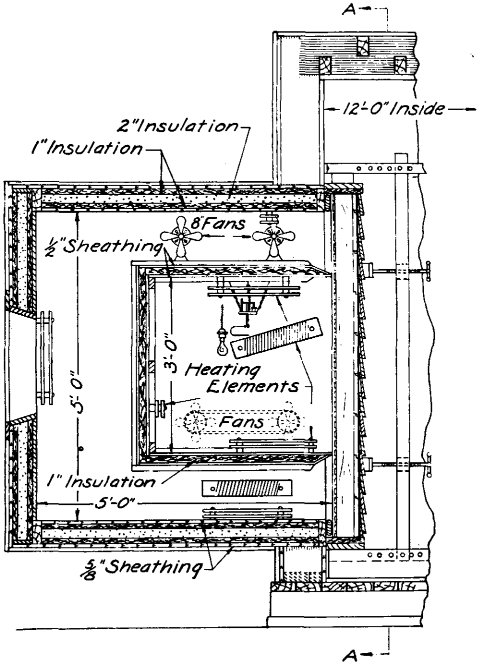
FIGURE 6. PLATES AS SET UP FOR USE

The cooling plates are provided with water-circulating channels and are protected on the outside by an air gap to prevent condensation on the outer surfaces which are in contact with the air.

HOT BOX APPARATUS

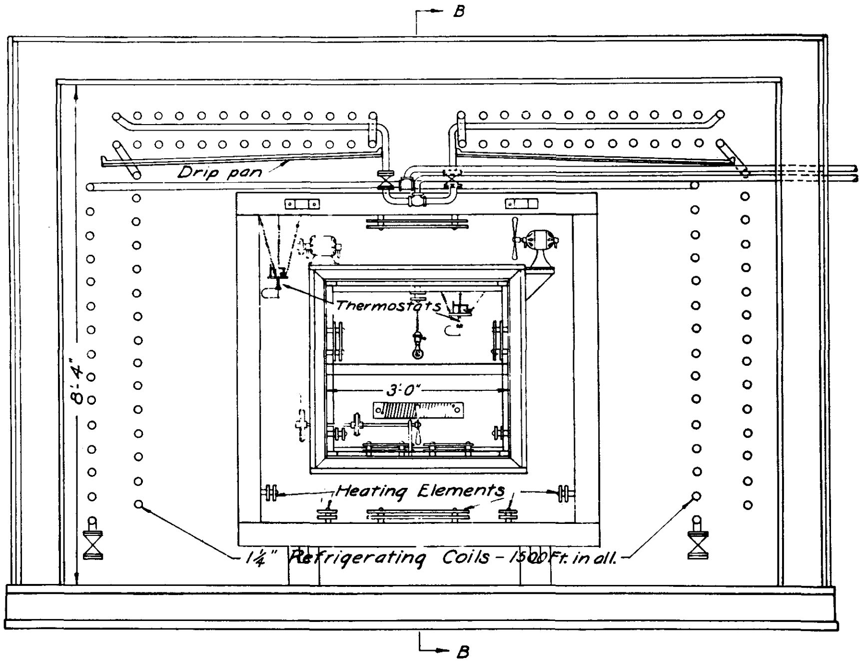
The apparatus used for determining the over-all heat transmission coefficients of built-up wall sections was designed at the beginning of the test program and consists of a double box construction built into one of the side walls of the cold storage room. This construction, together with heating elements, thermocouples, and instruments, is shown by Figures 7 to 13, inclusive. Figure 7 shows a vertical cross-sectional view of the double walled test box placed in the wall of the cold storage room with a test wall in place. Figure 8 shows a vertical cross section of the cold storage room, looking into the open end of the test boxes with the wall section removed. As shown by these two figures, both the inner and outer test boxes have one side omitted, and the boxes are so arranged that these two open faces will be in the same plane, parallel, and slightly inside of the inner surface of one of the walls of the cold room. The wall under test is placed over the open side of the two boxes and thus completely cuts off the passage of air between the inner and outer test boxes. The air temperatures of both boxes are maintained equal and at a higher level than that of the cold room. Since the air temperatures on both sides of the walls of the inner box are equal, heat supplied to this box can only pass out through the test wall into the cold room. Heat must flow in lines perpendicular to the test surface, as the area of the wall outside of the inner box is in contact with air equal in temperature to that of the inner box. Thus if the amount of heat supplied to the inner box is definitely measured and the temperatures of the air on the two sides of the test wall are measured, complete data are available for calculating the over-all heat transmission coefficient for the test section. The apparatus is so designed that all air temperatures are automatically controlled and those in the test boxes may be maintained at any range up to 150° F., while those in the cold room may run as low as —35° F. All heat to the inner and outer test boxes is supplied by electric heating elements and that to the inner box is accurately metered. Since the only purpose of the outer box is to balance the inner box temperatures and prevent heat losses other than through the test section, it is not necessary to meter the current supplying the heat for this air. The distribution of the heating elements is shown in Figures 7, 8, and 13. There are eight each for the inner and the outer boxes and the greater number of them are placed near the bottom of the boxes to give better temperature distribution. Each element is wound with resistance wire so that four different heating rates may be obtained by externally operated switches.

In addition to distributing the greater part of the heating elements in the bottom portion of the test boxes, a uniform temperature of the air from top to bottom of the test section required a slight amount of agitation. For this purpose, two 8-inch fans were installed in each box, as shown. Those for the inner box were mounted on ball bearings and driven by an external motor at 240 revolutions per minute, which was



SECTION BB
Showing Construction and Position of Test Box and Test Wall.

FIGURE 7. SECTIONAL VIEW OF DOUBLE BOX AND WALL SECTION IN PLACE



SECTION AA
Showing Wall Section Removed

FIGURE 8. SECTIONAL VIEW OF COLD ROOM LOOKING INTO OPEN END OF TEST BOX

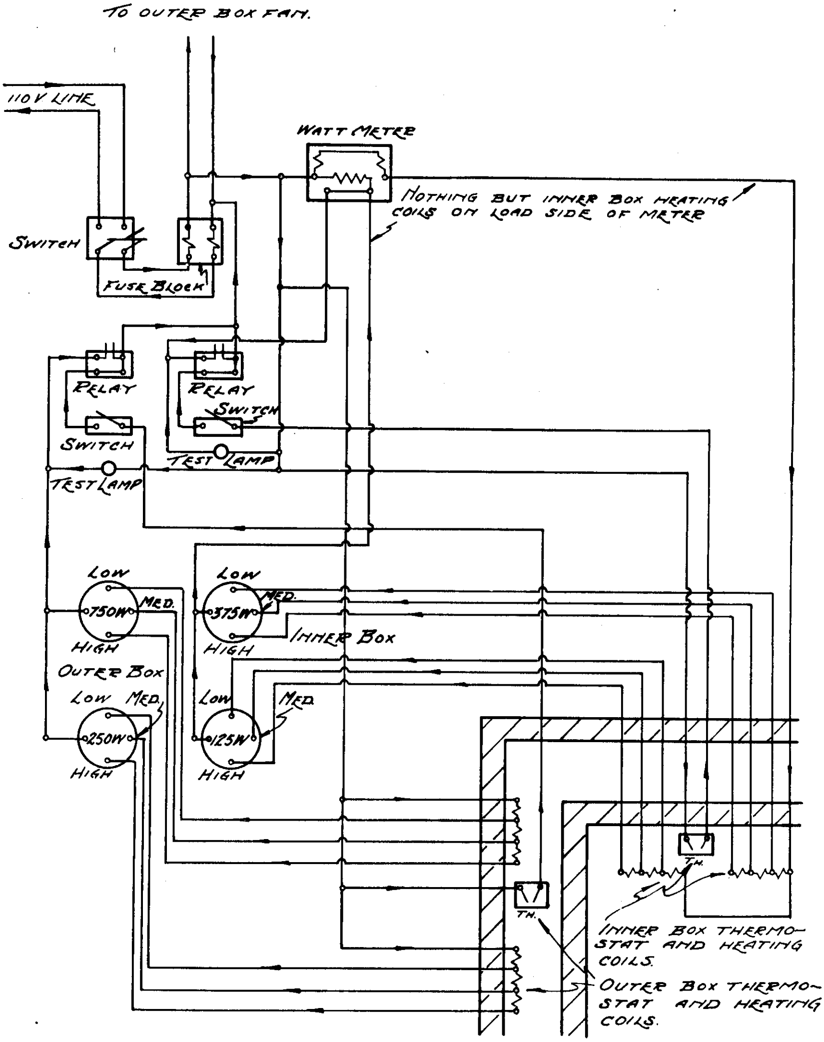


FIGURE 9. DIAGRAM OF ELECTRICAL WIRING FOR HEATING ELEMENT

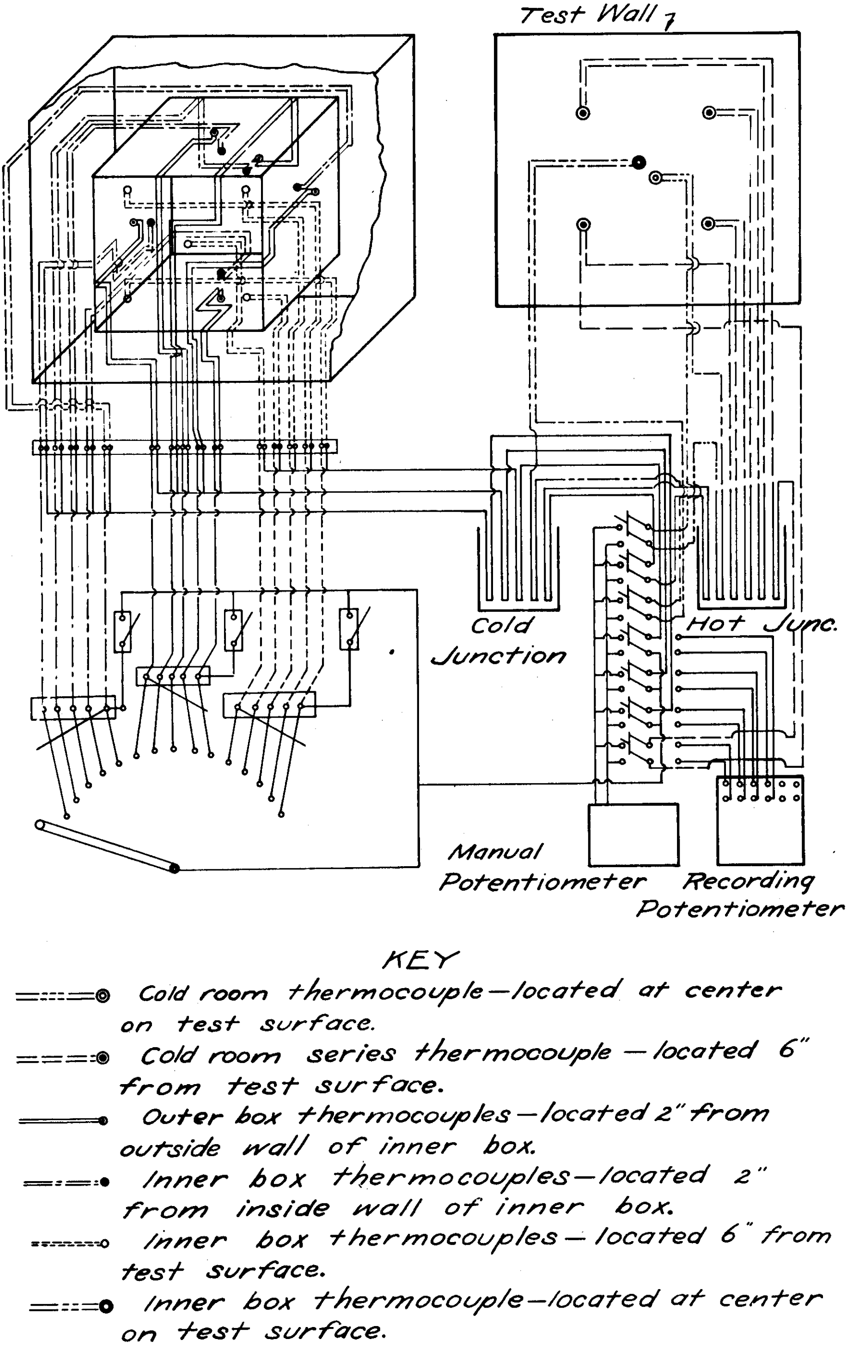


FIGURE 10. DIAGRAM SHOWING ARRANGEMENT OF THERMOCOUPLES IN HOT BOX

found sufficient to maintain uniform temperature over the test surface and yet have practically a still air condition. Calibrations were made to determine the heat generated by the friction of the bearings and belt of that part of the fan installation which was inside of the inner box. This amount of heat was added to that indicated by the electric meters for each test. The fans for the outer box were driven by direct connected motors placed in the outer box space. The air temperatures to both the inner and outer boxes were controlled by thermostats (Figs. 8 and 13).

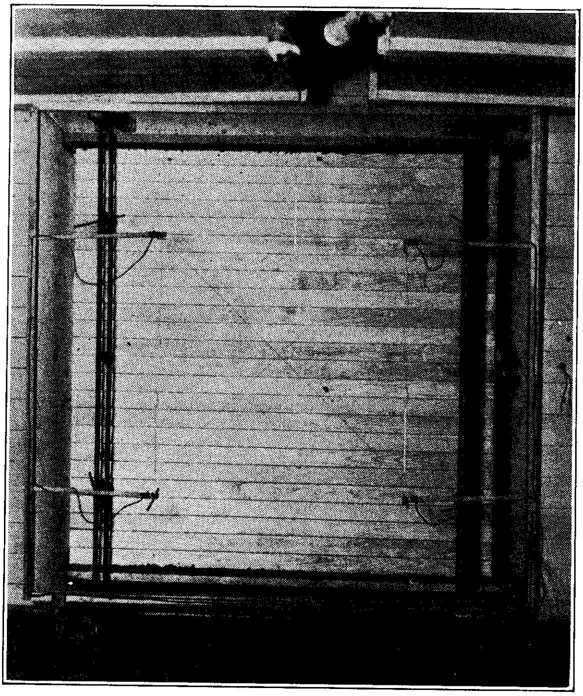


FIGURE 11. WALL SECTION IN PLACE FOR TEST

The air temperature on the cold side of the test specimen was maintained by a 7½-ton ammonia compression refrigerating machine and 1,500 feet of 1¼-inch direct expansion pipe placed in the ceiling and side wall of the cold room. To get more accurate temperature control than was possible by the expansion valve alone, a small, thermostatically controlled heat unit was installed. The refrigerating machine was set to give air temperatures slightly lower than required for the test, and the heating unit was relied upon for accurate control of the air temperature.

The wall under test is held in place by four locking screws which are carried by vertical bars placed at the outside edges of the test specimen. A rubber tube is used as a gasket to form a complete seal between the test wall and the inner box, and the space between the outer box and the wall section is carefully calked to make it airtight after a wall is in position for test. The locking screws are outside of the test section proper, and therefore do not interfere with air circulation over the test surface. Figure 11 shows a view in the cold room of a wall clamped in place and ready for test.

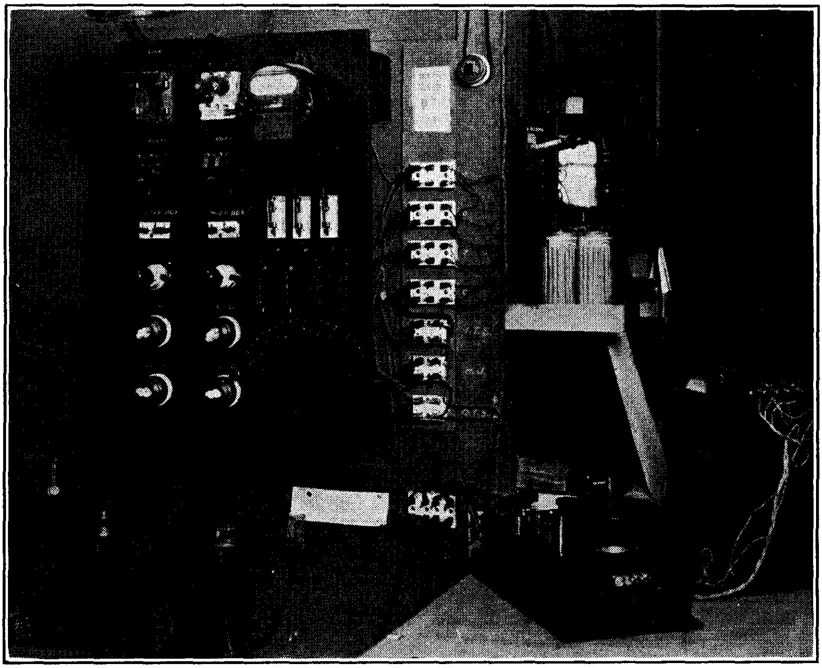


FIGURE 12. INSTRUMENT BOARD FOR HOT BOX TEST APPARATUS

A diagrammatic drawing of the electric wiring for the heating elements is shown in Figure 9. The heating current is brought to the control switch and fuse block, from which point it is taken through relays to the inner and outer box heating element. These relays are placed on a switchboard outside of the test apparatus and are controlled by thermostats placed in the inner and outer boxes. Only that portion of the current used to heat the inner box is passed through the electric meter.

All temperatures are measured by 28-gage copper constantan thermocouples. A recording instrument is used during the preliminary period, while the apparatus and test specimens are brought up to constant temperature conditions, and a Leeds-Northrup Type K potentiometer is used for the test data. A diagram of the principal thermocouples in the hot box proper is shown by Figure 10. These couples are arranged as follows:

1. A group of five thermocouples used to measure the air temperature of the inner box. These couples are arranged with one for each of the five sides of the inner box, and are centrally located 2 inches from the inner surface.

2. A group of five thermocouples used to measure the air temperature between the inner and outer box. This group is arranged with one couple for each of the five outer surfaces of the inner box, each couple is placed centrally with the side 2 inches from the outer surface.

3. A group of five thermocouples used to measure the air temperature for the inner side of the test section. These couples are uniformly distributed over the area and are placed 6 inches inside of the test surface.

4. A group of four thermocouples used to determine the air temperatures over the outer surface of the test section. These are placed in the cold room, distributed uniformly over the central or test section of the wall, and are 6 inches from the outer surface.

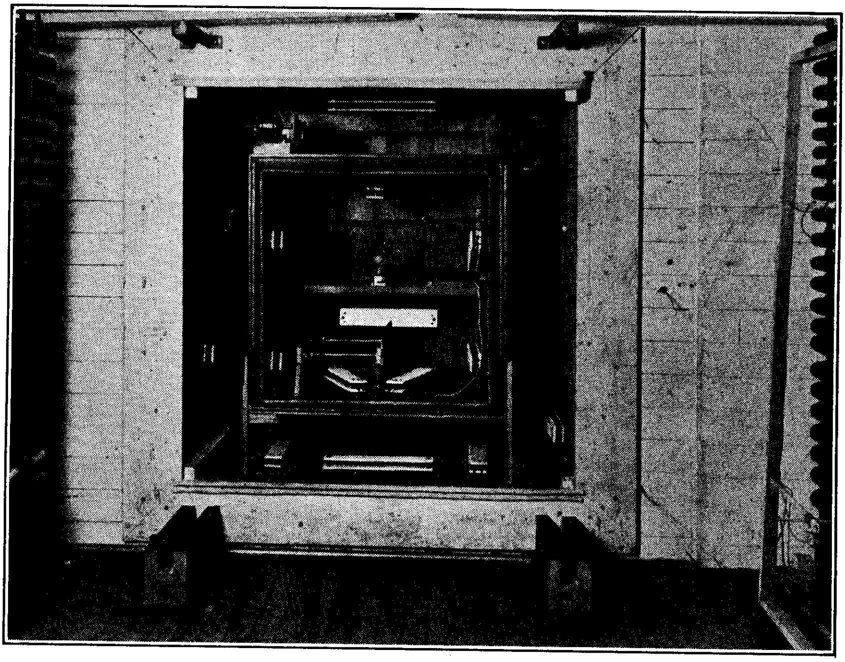


FIGURE 13. OPEN END VIEW OF HOT BOX FROM COLD ROOM

All of the above groups of couples are so arranged that temperatures may be taken for each couple individually, or the average of any group may be taken by one reading. In addition to the couples shown, there were individual couples to measure surface temperatures and the temperatures throughout various sections of the wall, depending upon the requirements of the test.

All thermocouple wires and electric connections are carried out of the box to an instrument board (Fig. 12). The relays and electric controls as well as the selective switches for the majority of the thermocouples are mounted on this board. The recording potentiometer is shown at the right of the switchboard, with the Type K potentiometer and galvanometer on the table beneath.

Special test apparatus was constructed for the purpose of determining surface coefficients as described later.

SURFACE CONDUCTANCE

The transfer of heat between air and the surface of a material is affected by several factors. Those which appear to be the most important are:

1. Air velocity.
2. Direction of air movement with reference to the surface of the material.
3. Mean temperature between the air and the surface of the material.
4. Character of the surface.

To determine the effects of these factors on the transfer of heat between air and surfaces, two series of experiments were conducted. In the first, the apparatus was arranged to give air velocities parallel to the test surface, ranging from 0 to 35 miles per hour, and with a mean temperature variation between the test surface and the air from 10° to 100° F. In this series, seven different surfaces were tested, ranging from plate glass to a rough stucco surface. In the second series of tests, the apparatus was arranged so that the angle between the wind velocity and the test surface could be varied from 0 to 90 degrees. In this series, only two surfaces were tested at a mean temperature of approximately 80° F.

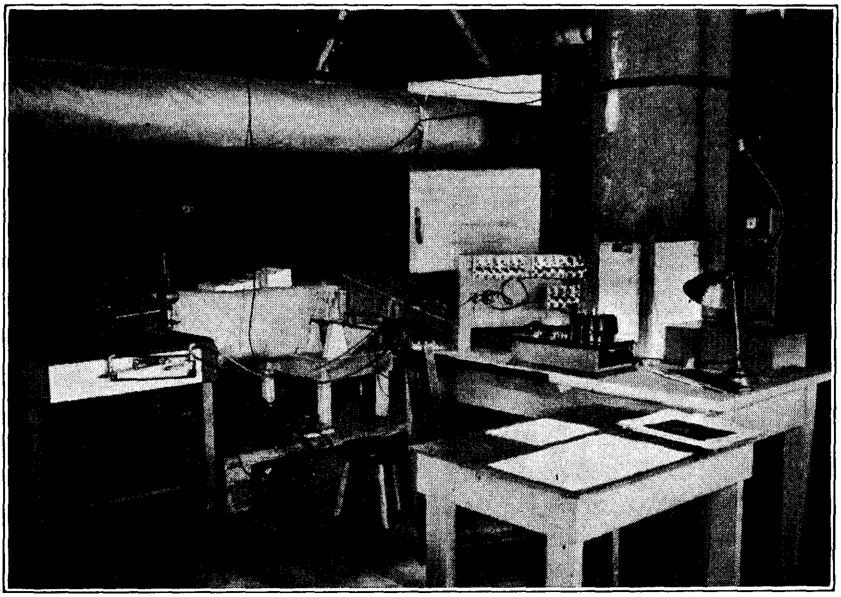


FIGURE 14. GENERAL VIEW OF SURFACE CONDUCTANCE TEST APPARATUS

In those tests made to determine the coefficients with air passing parallel to the surface, it was necessary to construct apparatus to provide the following conditions:

1. Air moving over a test surface parallel to the surface at various constant velocities.
2. Accurately controlled air temperatures.

3. Test surfaces which could be supplied with a measured amount of heat.
4. Instruments for measuring the air velocity, the temperature of the air over the test surface, and the amount of heat flowing through the test surface.

In order to obtain these conditions, the apparatus was set up as shown in the photograph of Figure 14 and the line drawings in Figures 15 and 16. Air of the required temperature taken from the cold room by a 12-inch multi-blade fan driven by a ½-horsepower variable speed direct current motor, was supplied from the cold room used in connection with the hot box apparatus. The air from the fan was delivered to a straight 6 × 12-inch rectangular duct 17 feet to the test surface. After passing the test surface, the air was brought by a return bend back to the cold room. The arrangement of the test surface, together with the method of measuring the air flow and air temperatures, can best be described by referring to Figure 16, which is an enlarged section from Figure 15. As shown in this drawing, the test material was placed with the test surface flush with the inside surface of the air duct. The test material was 12 inches square and varied in thickness from ¼ to ½ inch, depending upon the type of the surface. Heat for the test surface was applied by a hot plate, the quantity being measured by passing it through a heat meter. The hot plate was electrically heated with 110-volt direct current, controlled by a rheostat.

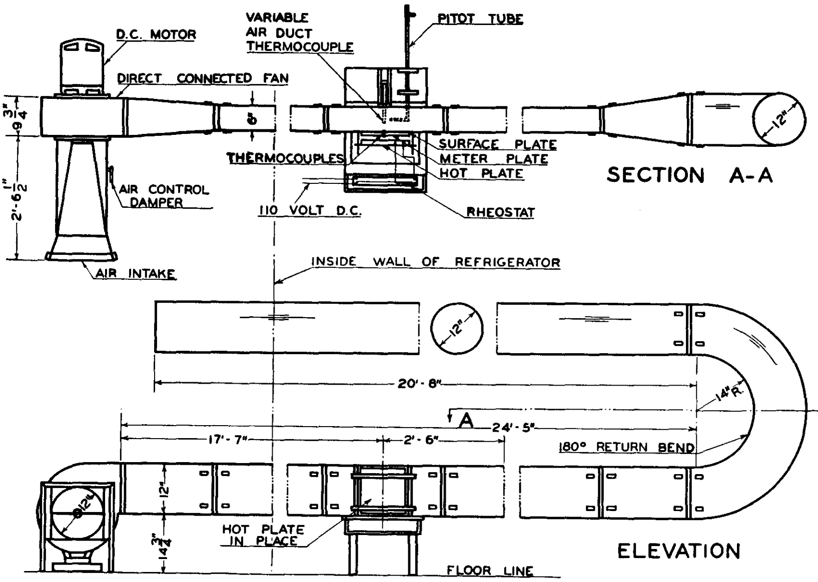


FIGURE 15. PLAN AND ELEVATION OF TEST APPARATUS FOR DETERMINING SURFACE CONDUCTANCES

The meter plate constructed of ⅛-inch bakelite was substantially the same as the Nicholls heat flow meter. Two parallel series of 28 pairs of 28-gage copper constantan thermocouples differentially wound on the plate were used. Of these, one series of 56 couples served to check the other series. Surface temperatures of the meter plate were also taken with three 28-gage copper constantan thermocouples on each side. The meter plate was calibrated by a standard hot plate apparatus, and readings for the transmission through the plate were taken directly from the calibration curve.

The air velocities at various distances from the test surface were measured by means of a Pitot tube and draft gage. For the lower velocities, the Wahlen gage was used, but for higher velocities, the inclined draft gage was found satisfactory.

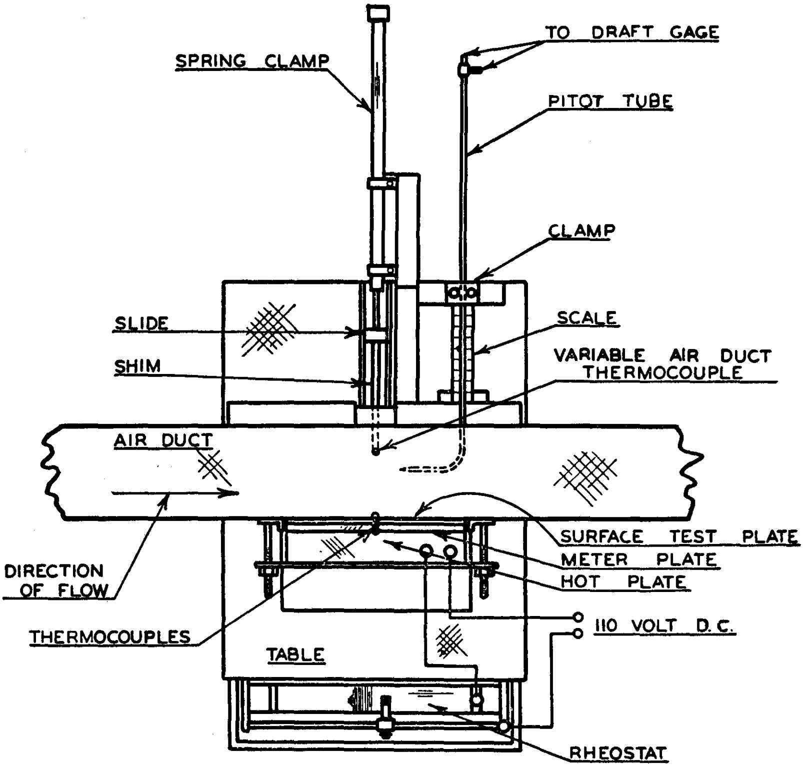


FIGURE 16. PLAN VIEW SHOWING ARRANGEMENT OF METER PLATE, TEST SPECIMEN, THERMOCOUPLE, AND PITOT TUBE IN RELATION TO AIR DUCT

The temperatures of the air passing over the test surface were measured with a 24-gage copper constantan thermocouple so arranged that it could be moved in and out from the test surface or held at any predetermined distance. Tests made both with and without a shield between the thermocouple and the test surface showed that, at the low temperatures used, radiation had no effect on the temperatures indicated by the couple; therefore, most of the tests were made without this shield. All thermocouple readings were read with a potentiometer, the cold junction in all cases being an ice bath.

In order to obtain average radiation conditions, the inside surface of the test duct was painted a dull gray, and all of the air pipes outside of the refrigerator room were covered with one inch of blanket insulating material. With this arrangement, the surfaces immediately around the test surface were at substantially the same temperature as the surrounding air, which is a practical condition for the average wall.

Two different methods were tried for determining surface temperature:

1. The couple was imbedded in the material to bring the junction flush with the test surface.
2. The couple was rigidly attached to the surface and covered with a thin vellum paper.

When the thermocouple was imbedded in the material, the difference between the air temperature and that of the indicated surface was greater than when it was placed on the surface, and, therefore, the calculated surface coefficients were somewhat lower. This difference, however, was very small and in all of the test results reported, the thermocouple was fastened to the surface and covered with vellum paper. The surface couples were made of 28-gage copper constantan wire flattened out at the junction, thus giving a very thin couple at the point of contact.

In the assembly of the test apparatus, the test surface, together with the heat meter and the hot plate, was placed in the side of the air duct and clamped in place with specially designed clamping screws. The conditions, such as air velocity, air temperature, and surface temperature, were then selected and the apparatus was operated under these conditions for a sufficient length of time to insure uniform results. The air velocity for the test was measured at the center of the duct, because this would be the maximum air velocity over the test surface. The air temperature was measured by placing the thermocouple one inch from the test surface. Preliminary tests had shown that when the thermocouple was placed in contact with the test surface and gradually moved away from it, the temperature steadily dropped until the couple was about one-half inch from the surface, after which this temperature remained uniform and equal to that of the air regardless of distance. One inch was therefore taken as a reasonable distance and was maintained throughout all tests. Data for tests were not recorded until preliminary observations taken at 15-minute intervals showed that the heat flow, room, surface, air temperatures, and air velocities were constant.

As all temperatures were taken at, or near, the center of the meter plate and test surface, and, as the meter plate and test surface were very thin, no allowance was made for end loss of heat from these plates. As an additional precaution, however, the edges of these plates were insulated with heavy layers of felt. Mean temperatures for a test were taken as the average between the air temperature and the surface temperature of the test specimen. Values of the surface conductance for a test were obtained by dividing the total heat leaving the test surface per square foot per hour by the temperature difference between the test surface and the air one inch away from the surface.

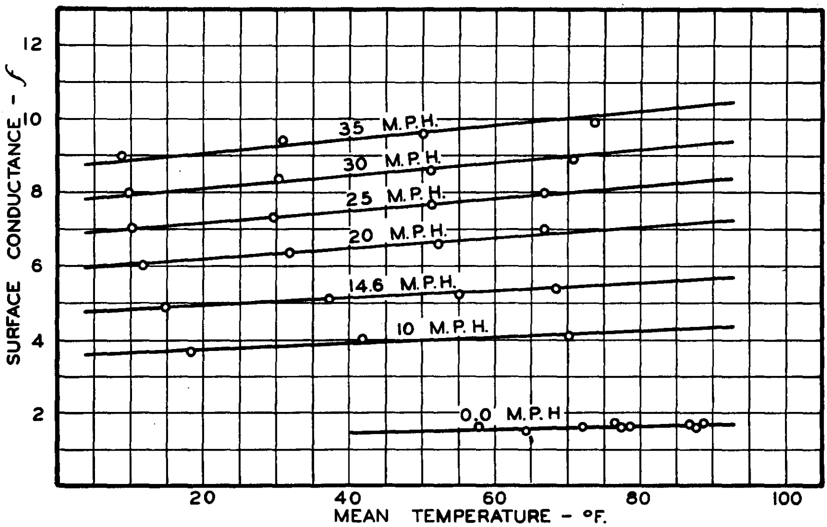


FIGURE 17. CONSTANT VELOCITY CURVES FOR GLASS SURFACE

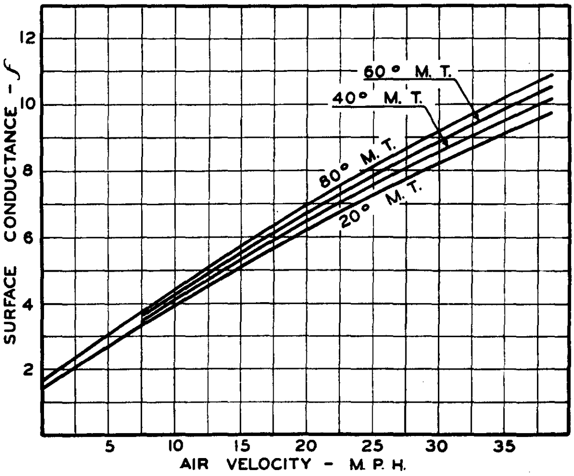


FIGURE 18. CONSTANT MEAN TEMPERATURE CURVES FOR GLASS SURFACE

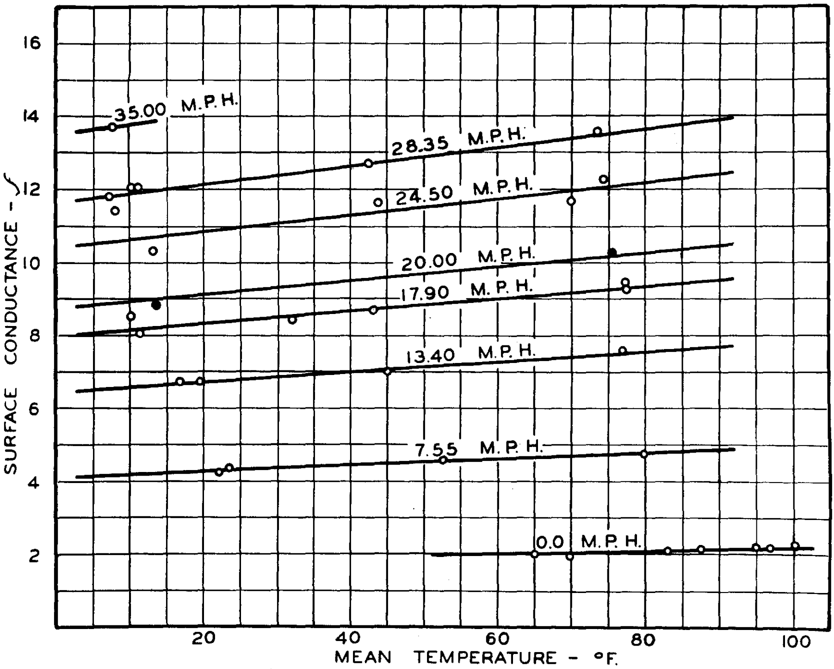


FIGURE 19. CONSTANT VELOCITY CURVES FOR BRICK SURFACE

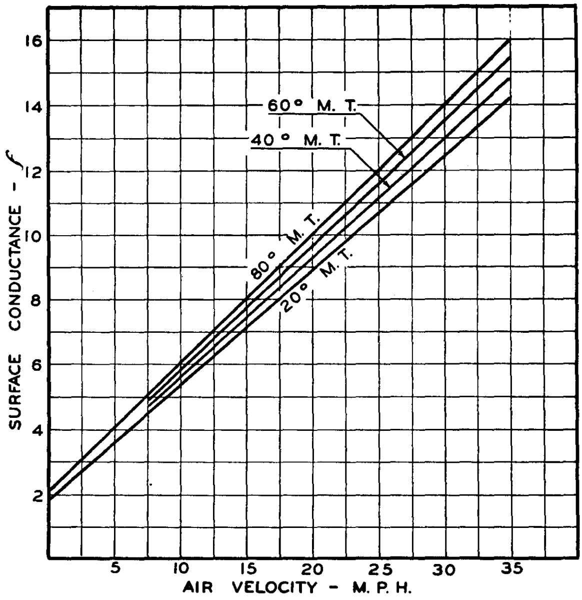


FIGURE 20. CONSTANT MEAN TEMPERATURE CURVES FOR BRICK SURFACE

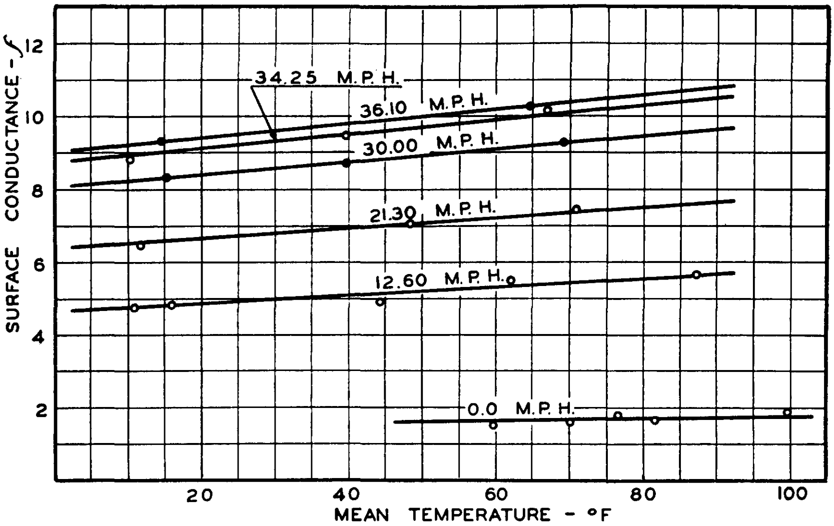


FIGURE 21. CONSTANT VELOCITY CURVES FOR WHITE PAINT SURFACE ON PINE

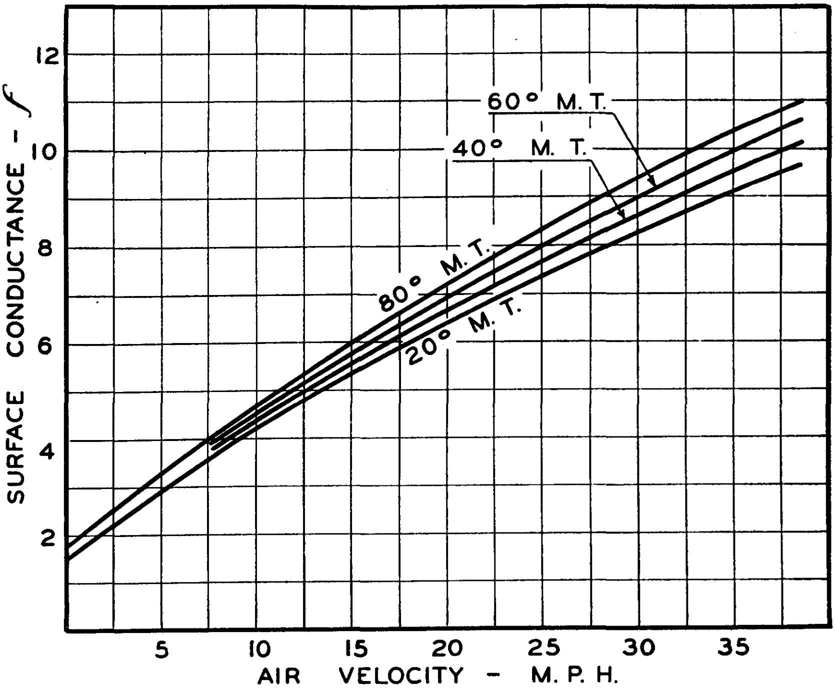


FIGURE 22. CONSTANT MEAN TEMPERATURE CURVES FOR WHITE PAINT SURFACE ON PINE

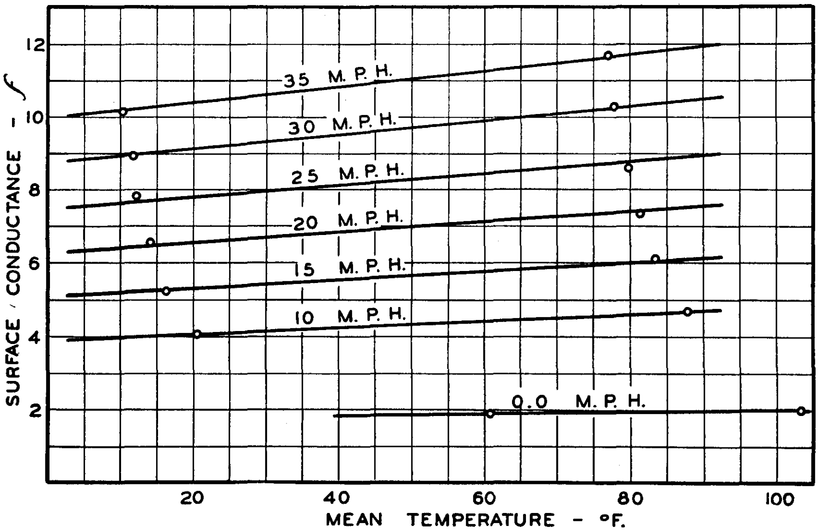


FIGURE 23. CONSTANT VELOCITY CURVES FOR SMOOTH PLASTER SURFACE

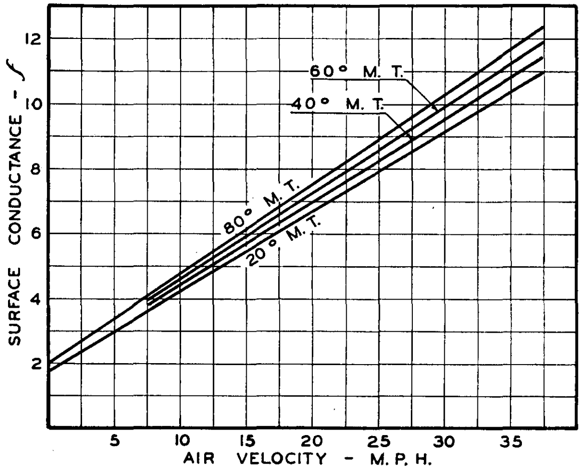


FIGURE 24. CONSTANT MEAN TEMPERATURE CURVES FOR SMOOTH PLASTER SURFACE

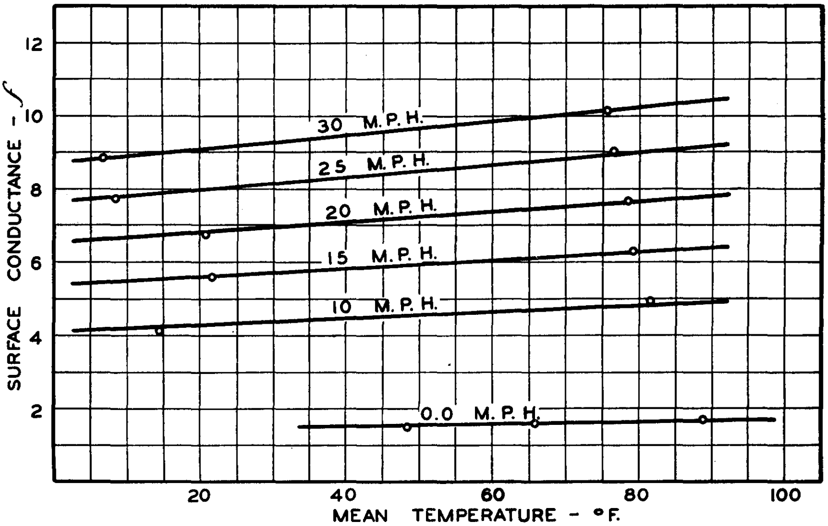


FIGURE 25. CONSTANT VELOCITY CURVES FOR CLEAR WHITE PINE SURFACE

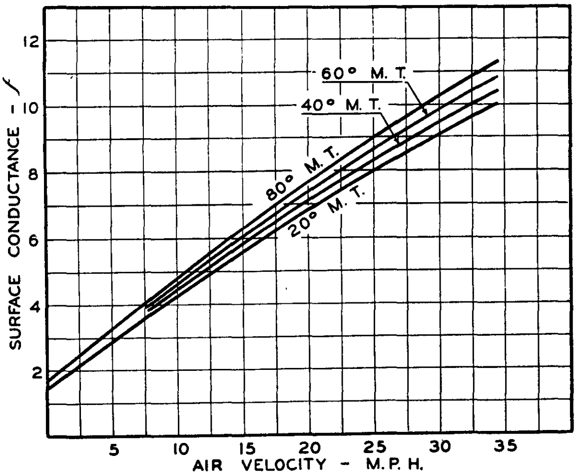


FIGURE 26. CONSTANT MEAN TEMPERATURE CURVES FOR CLEAR WHITE PINE SURFACE

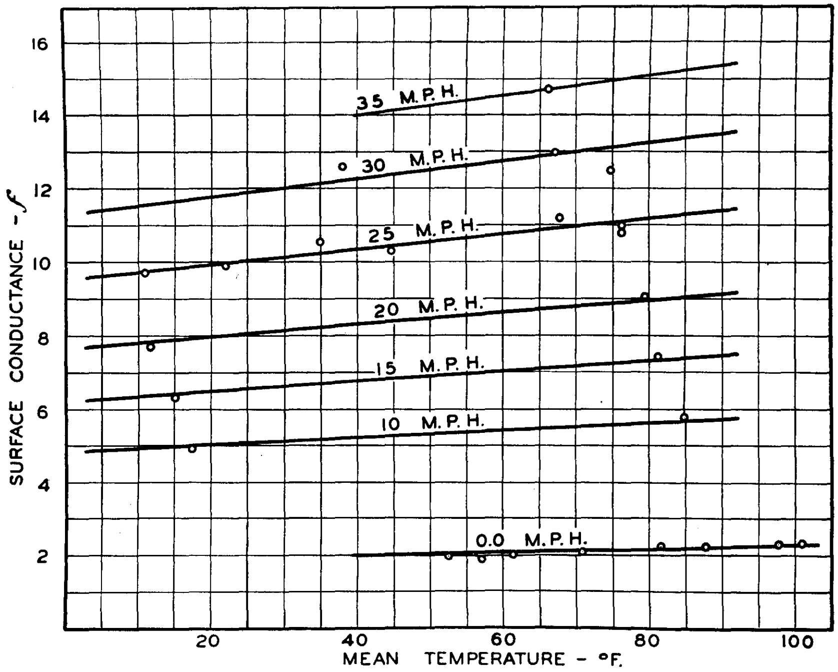


FIGURE 27. CONSTANT VELOCITY CURVES FOR CONCRETE SURFACE

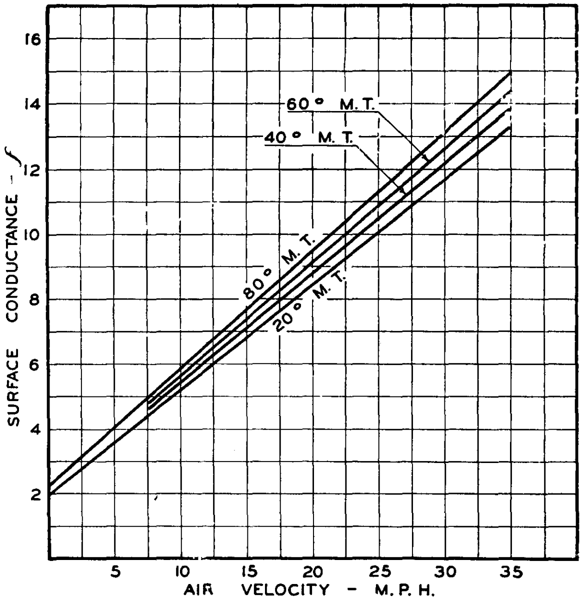


FIGURE 28. CONSTANT MEAN TEMPERATURE CURVES FOR CONCRETE SURFACE

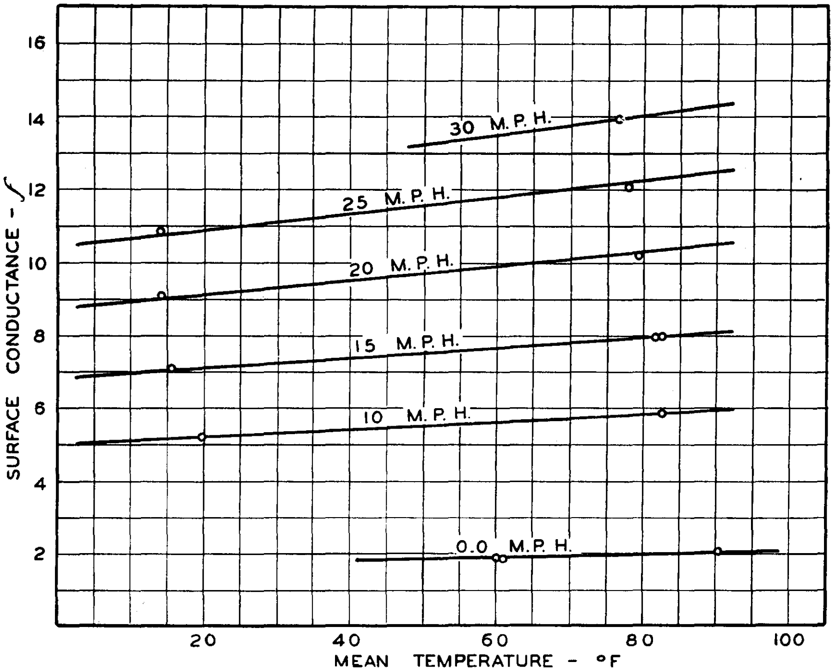


FIGURE 29. CONSTANT VELOCITY CURVES FOR ROUGH PLASTER SURFACE

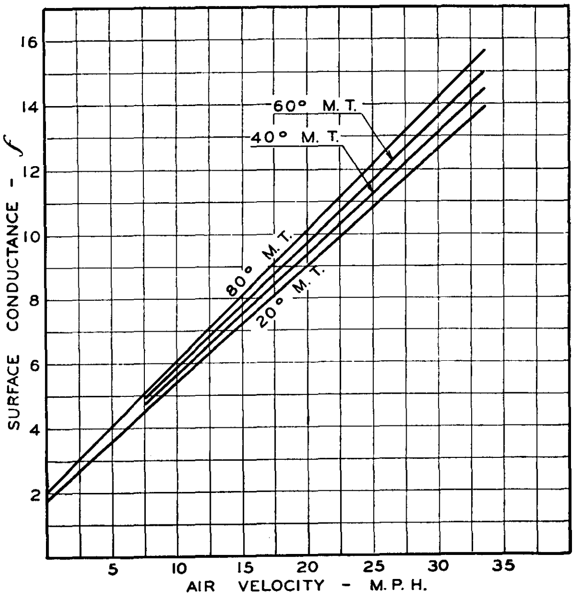


FIGURE 30. CONSTANT MEAN TEMPERATURE CURVES FOR ROUGH PLASTER SURFACE

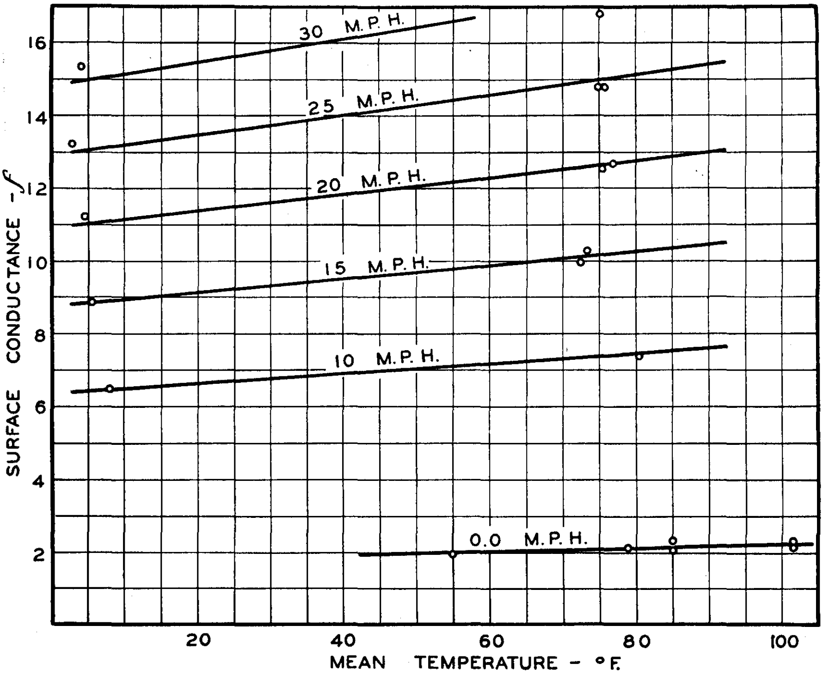


FIGURE 31. CONSTANT VELOCITY CURVES FOR STUCCO SURFACE

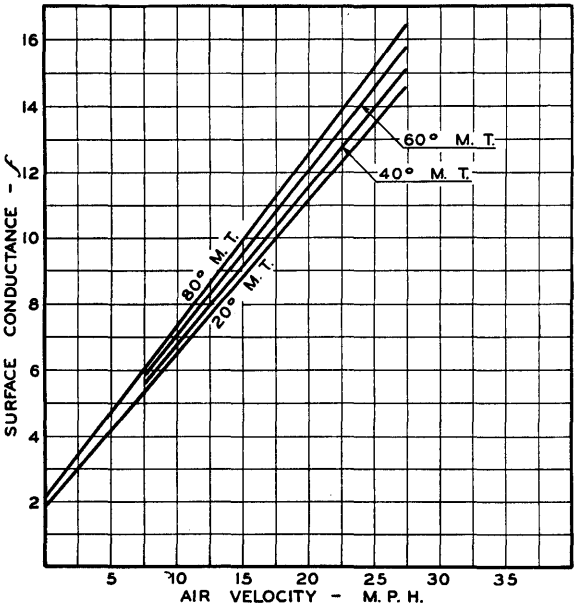


FIGURE 32. CONSTANT MEAN TEMPERATURE CURVES FOR STUCCO SURFACE

The value of the surface conductance for any particular surface varies with the mean temperature and the air velocity. Keeping one of these two variables constant, a series of tests was made to determine the effect of the other, and the results were plotted in the form of a curve. Several different air velocities were selected and runs were made at different mean temperatures for each air velocity.

The surfaces considered the most typical of building construction and used in the tests were glass, brick, white paint on pine, smooth plaster, clear white pine, concrete, rough plaster, and stucco. Very complete tests were made on the first three of these surfaces, four or more points being taken for each respective air velocity at different mean temperatures ranging from 0° to 100° F. It was found that these points lay practically in a straight line and when they were plotted on a large scale graph and the lines were extended, they crossed the line of zero surface conductance at absolute zero mean temperature, or, in other words, with total absence of heat, the surface conductance was zero. This was found true for all surfaces tested.

TABLE I

COEFFICIENTS OF SURFACE CONDUCTANCE, AIR FLOWING PARALLEL TO SURFACE

Surface Material	Mean Temp. °F.	Air Velocity in M.P.H.					
		5	10	15	20	25	30
Smooth plaster	20	2.96	4.20	5.45	6.65	7.90	9.15
	40	....	4.40	5.70	6.95	8.21	9.50
	60	....	4.60	5.94	7.22	8.58	9.90
	80	3.40	4.75	5.15	7.50	8.90	10.26
Rough plaster	20	3.55	5.40	7.20	8.96	10.80	12.60
	40	....	5.60	7.50	9.34	11.20	13.10
	60	....	5.82	7.80	9.70	11.82	13.60
	80	4.05	6.02	8.06	10.10	12.14	14.20
Concrete	20	3.55	5.20	6.80	8.41	10.04	11.65
	40	....	5.42	7.10	8.80	10.45	12.15
	60	....	5.61	7.40	9.10	10.85	12.60
	80	4.02	5.82	7.62	9.45	11.30	13.10
Stucco	20	4.18	6.50	8.80	11.16	13.42	....
	40	....	6.76	9.10	11.52	13.92	....
	60	....	7.05	9.50	12.01	14.60	....
	80	4.75	7.37	9.86	12.55	15.16	....
Glass	20	2.70	3.90	5.10	6.20	7.25	8.20
	40	....	4.15	5.30	6.45	7.57	8.55
	60	....	4.30	5.50	6.70	7.82	8.83
	80	3.10	4.45	5.70	6.95	8.10	9.20
Brick	20	2.70	5.35	7.10	8.85	10.65	12.40
	40	....	5.60	7.42	9.25	11.15	13.00
	60	....	5.80	7.70	9.60	11.60	13.50
	80	3.10	6.05	8.01	10.00	12.00	14.00
Clear white pine	20	2.83	4.21	5.55	6.80	8.00	9.05
	40	....	4.45	5.80	7.10	8.30	9.43
	60	....	4.60	6.03	7.39	8.62	9.81
	80	3.25	4.80	6.30	7.62	9.00	10.22
White paint on pine	20	2.90	4.20	5.35	6.40	7.35	8.22
	40	....	4.35	5.55	6.62	7.63	8.60
	60	....	4.50	5.75	6.90	7.98	8.96
	80	3.30	4.65	6.00	7.20	8.30	9.40

The results of the tests on the various surfaces are shown graphically in the curves of Figures 17 to 33, inclusive, and in Table I. Referring specifically to the curves of Figures 17 and 18, these results were obtained for a plate glass surface and are typical of all of the surfaces tested. In Figure 17, the points are plotted as determined from test data. The constant mean temperature lines of Figure 18 were taken directly from the group of curves on Figure 17. Other ranges of mean temperatures might have been plotted in the same manner.

The curves shown by Figures 19 to 32, inclusive, need no specific explanation, as they are similar to the curves of Figures 17 and 18 and were obtained from materials as indicated. The curves of Figure 33 were taken from the corresponding curve sheet for each of the materials at a mean temperature of 20° F. This group of curves shows the manner in which the surface characteristics of the material affect the heat transmission coefficients.

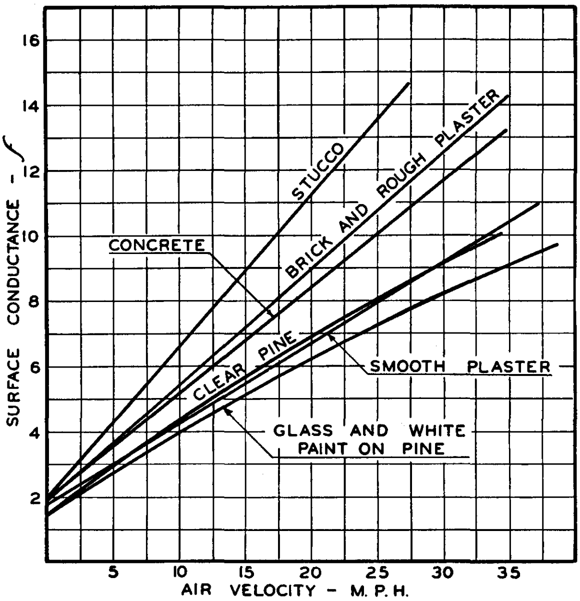


FIGURE 33. CURVES SHOWING RELATION BETWEEN SURFACE CONDUCTANCES FOR DIFFERENT SURFACES AT A MEAN TEMPERATURE OF 20° F.

SURFACE CONDUCTANCE AS AFFECTED BY DIRECTION OF WIND

In practice, the wind may blow at any angle to the exposed surface of the wall, and the question arises as to the relation of the surface coefficients for the different angles of incidence between the wind and the surface. To determine this relation, test apparatus as shown in Figures 34 and 35 was set up, and a series of tests were made with wind velocities varying from 0 to 30 miles per hour and at angles to the test surface varying from 0 to 90 degrees. The apparatus consisted essentially of a 30-inch air duct, 25 feet long, supplied with air by a variable speed fan. The air duct was provided with a Pitot tube and draft gage at a point 75 inches from the outlet end for measuring the air velocity.

The test surfaces were 15 inches square and were placed with the vertical center line 12 inches in front of the outlet end of the duct. Each surface was placed on a pedestal and arranged so that it could be rotated around the vertical axis to give any desired angle of incidence between the air and the test surface. A 12-inch wing or extension wall was placed on the leading edge of the test surface to direct the wind over the surface and prevent, as much as possible, disturbing eddy currents from interfering with the test plate proper.

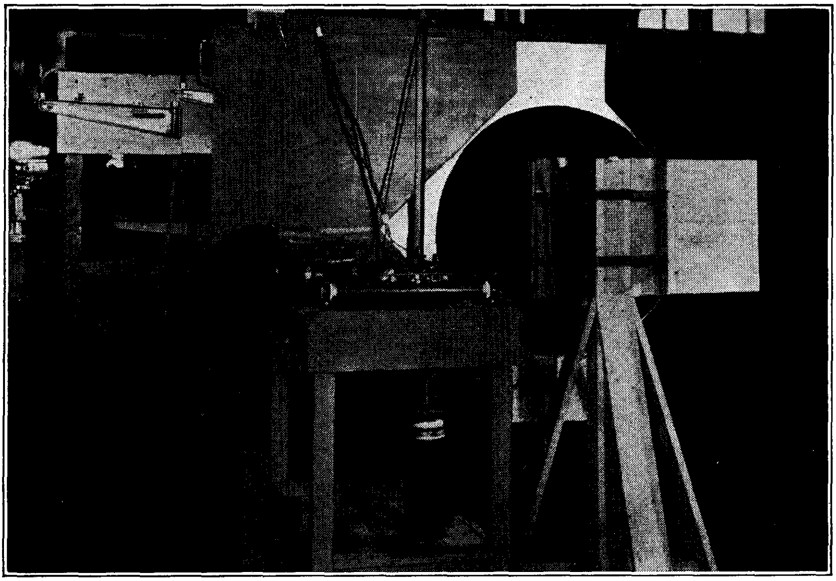


FIGURE 34. VIEW AT OUTLET END OF 30-INCH DUCT, SHOWING TEST SURFACE AND APPARATUS

The test surface was placed against a meter plate that was 12 inches square and was supplied by heat with an electrically heated plate with rheostat control. Figure 34 shows the open end of the 30-inch duct, together with the test specimen plate and the rheostat for controlling the temperatures of the test surface. Figure 35 shows a plan view of the outlet end of the air duct, together with a partial sectional view of the test surface and heat meter.

The differential temperatures of the heat meter, the surface temperatures of the test specimen, and the air temperatures were taken with copper constantan thermocouples and a Leeds-Northrup Type K potentiometer. The surface temperatures were taken by 28-gage copper constantan thermocouples flattened out and cemented to the surface of the test specimen and covered with thin vellum paper. The air temperatures were taken by the thermocouples placed 1½ inches in front of, and at the center of, the test surface. The air velocities in the duct were taken with a Pitot tube 75 inches from the outlet end and again by a Pitot tube placed close to the test surface in order to determine the velocities parallel to the test surface, and, also, the static pressures of the air at the surface.

In the set-up as made, it was impossible to vary the air temperatures through any wide range of temperature. Since the object of the test was to find the relation between the coefficients at different wind velocities and at different angles of the wind to the test surface, a mean temperature was selected which was within the range of the apparatus, and this temperature was approximated throughout all of the tests. A temperature of 83° F. was maintained throughout most of the tests, altho, in some cases, there was a variation in either direction of as much as 5 degrees in mean temperature. This variation, however, was not sufficient to make any particular difference in the final results. The mean temperature was taken as the average temperature between the test surface and the surrounding air, it being assumed that the surrounding objects were of the same temperature as the air.

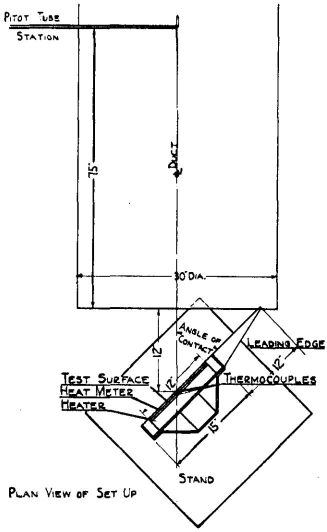


FIGURE 35. PLAN VIEW SHOWING RELATIVE POSITION OF TEST SECTION TO OUTLET END OF AIR DUCT

In making the tests, plate glass and smooth pine surfaces were used. The tests were made at angles of incidence varying from 0 to 90 degrees at 15-degree intervals. For each test, the velocity of the air in the duct was varied from 0 to nearly 30 miles per hour.

The results of the tests for a glass surface are shown graphically in Figure 36, and those for pine are shown in Figure 37. By comparing the curves for parallel air flow with those for the corresponding surfaces at 80° F. mean temperature as shown on the curves of Figures 18 and 36, it will be noted that for glass the two curves are practically identical up to 20 miles per hour. Above this, the curve on Figure 18 drops off, while that from Figure 36 continues as a straight line. For the pine surface, the coefficients of the second set of tests (Fig. 37) are slightly greater than those of the first set (Fig. 26). This may be owing to a slight difference in the smoothness of the two surfaces. The fact that the glass surfaces show coefficients which are practically the same for the two different series of tests would indicate that the coefficients by either method are substantially the same so long as the mean temperatures and air velocities agree.

Figures 36 and 37 show that, as the angle between the direction of the wind and the test surface is changed, the surface coefficients are slightly changed. The reduction for all angles is reasonably the same up to a wind velocity of 15 miles per hour. Above this velocity the reduction increases with the angle.

The reduction, however, at any point is not as great as might be expected. For a 15-mile wind, the average reduction in coefficients for both the glass and pine surface is 16 per cent. It seems reasonable, therefore, to assume a reduction of 15 per cent in surface coefficients as obtained by test methods with parallel air flow when applying these to practical walls.

To show the action of the air near the test surface, readings were taken to determine the velocity parallel to the surface and the static pressure of the air for the different angles of incidence between the air stream and the surface. The results of these readings are shown in Table II. From these data, it will be observed that, as the angle of incidence is increased, the static pressure is gradually increased at the surface until, at 60 degrees, the static pressure practically equals the velocity pressure in the main duct. At 75 and 90 degrees, the static pressure slightly exceeds the velocity pressure. Further, as the angle of incidence is increased, the velocity pressure on the surface, and, therefore, the surface velocities, are substantially the same as the velocity of the air in the duct until an angle of 45 degrees is reached, after which the surface velocity is gradually reduced until it reaches a minimum at an angle of 90 degrees. As the surface velocity is greatly reduced for the high angles of incidence, it might be assumed that the surface coefficients for these conditions should also be greatly reduced. The fact that they are not is probably owing to the corresponding increase in air pressure at the surface, which makes the contact between the air and surface more effective in removing the surface heat.

As a further study to determine the action of the air on the test surface for the various angles of incidence between the air and the surface, sheet metal plates 12 × 18 inches were placed perpendicular to the test wall and in the plane of the air flow. In this position, the plate did not disturb the air flow but merely separated the air as it approached the wall. A light coating of lampblack and kerosene was placed on the surface of the metal sheet and the air was blown onto the test surface for a sufficient length of time to impress or mark the direction lines of the air on the surface coating of the plate. Six of the typical plates as obtained from this test are shown in Figures 38 and 39. The lines on these plates showed very clearly the change in surface velocity conditions which took place after passing the 45-degree angle. It is very evident that, at the higher angles, the surface velocity is retarded and that the surface pressure is built up, as was indicated by the pressure gage.

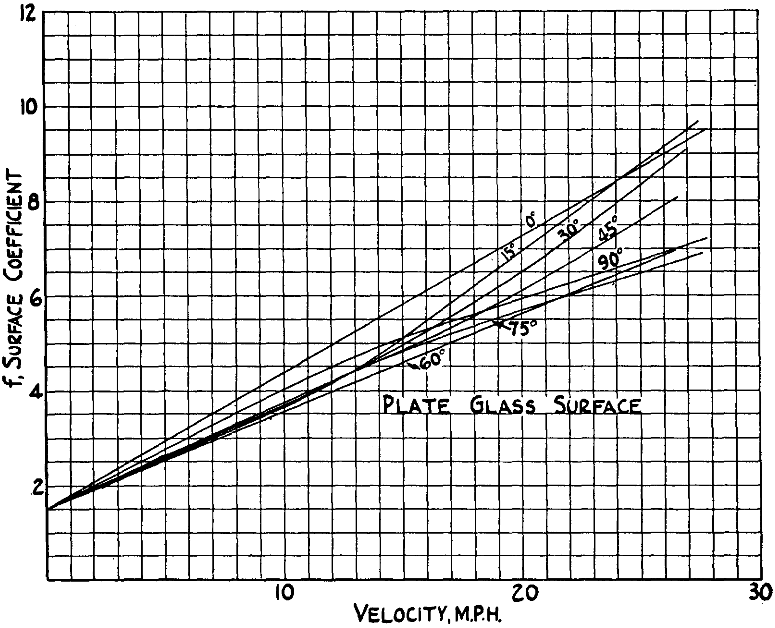


FIGURE 36. SURFACE COEFFICIENT FOR A PLATE GLASS SURFACE FOR WIND VELOCITIES VARYING FROM 0 TO 30 MILES PER HOUR AND WIND DIRECTION VARYING FROM 0 TO 90 DEGREES TO TEST SURFACE

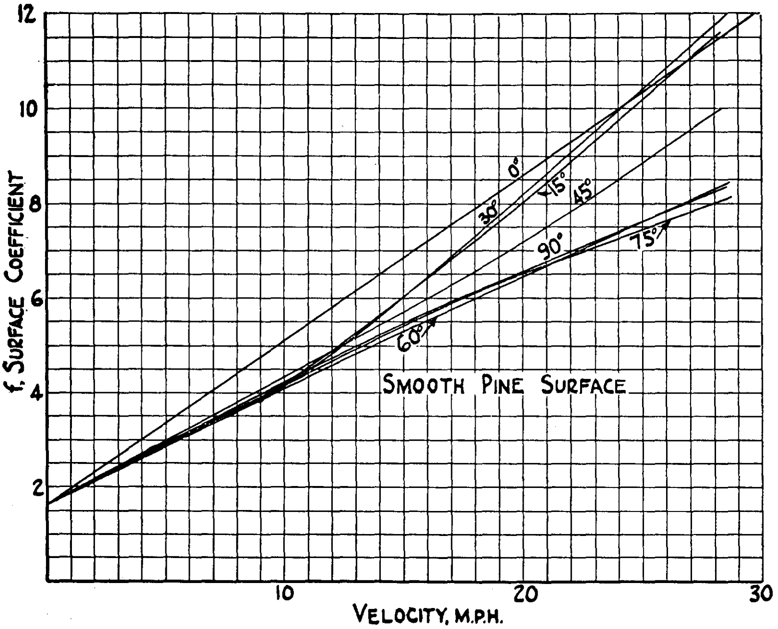


FIGURE 37. SURFACE COEFFICIENTS FOR A SMOOTH PINE SURFACE FOR A WIND VELOCITY VARYING FROM 0 TO 30 MILES PER HOUR AND WIND DIRECTION VARYING FROM 0 TO 90 DEGREES TO TEST SURFACE

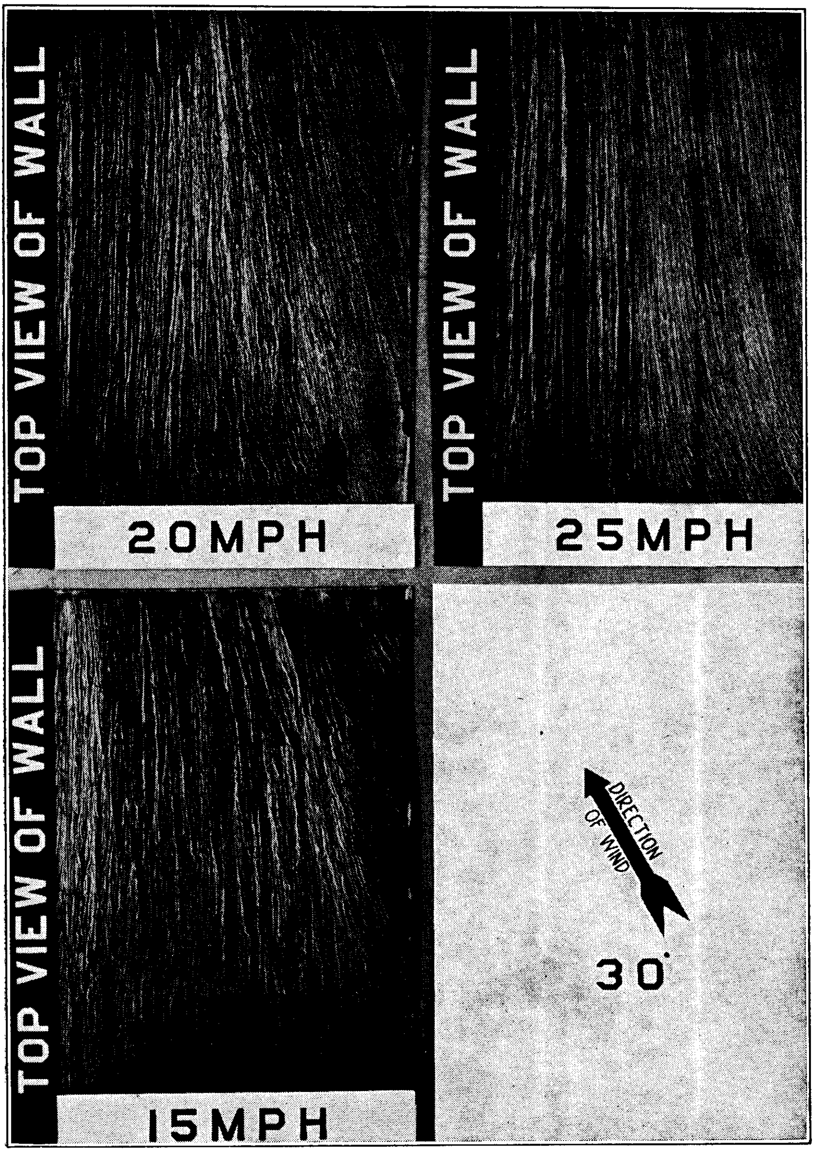


FIGURE 38. LINES SHOWING DIRECTION OF AIR CURRENT FOR A DISTANCE OF 12 INCHES FROM TEST SURFACE IN A PLANE PARALLEL TO WIND DIRECTION, ANGLE OF WIND TO TEST SURFACE, 30 DEGREES

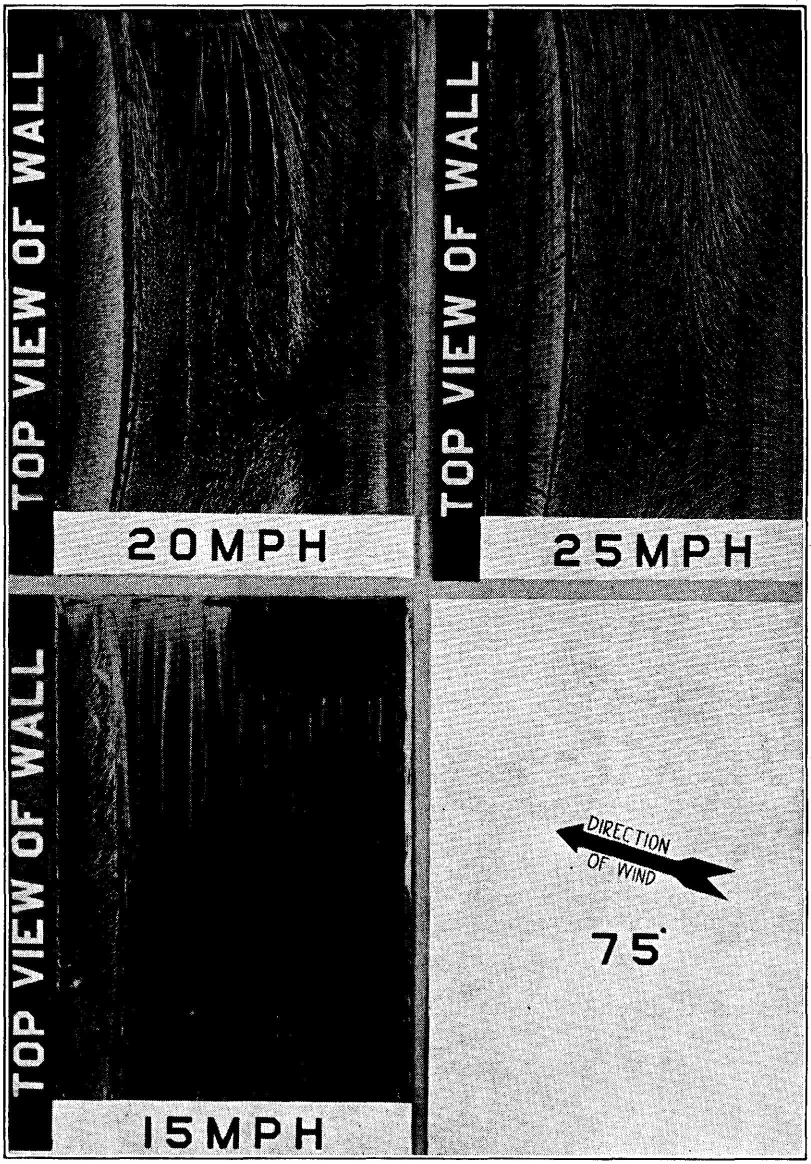


FIGURE 39. LINES SHOWING DIRECTION OF AIR CURRENT FOR A DISTANCE OF 12 INCHES FROM SURFACE IN A PLANE PARALLEL TO WIND DIRECTION, ANGLE OF WIND TO TEST SURFACE, 75 DEGREES

TABLE II

AIR VELOCITY AND STATIC PRESSURE AT SURFACE FOR VARIOUS ANGLES OF INCIDENCE OF WIND TO SURFACE

Wind Velocity, Miles per Hr.	Velocity Pressure in Duct Inches, Water	Velocity Pressure Parallel to Surface	Wind Velocity Parallel to Surface	Static Pressure at Surface Inches, Water
Angle of incidence = 0 degree				
10	.0465	.0420	9.50	0.000
15	.1045	.072	12.46	.004
20	.185	.170	19.12	.010
25	.290	.310	25.85	.019
Angle of incidence = 15 degrees				
10	.0465	.052	10.59	.004
15	.1045	.089	13.83	.007
20	.185	.192	20.35	.011
25	.290	.320	26.25	.016
Angle of incidence = 30 degrees				
10	.0465	.055	10.85	.016
15	.1045	.1045	15.0	.032
20	.185	.190	20.22	.054
25	.290	.308	25.75	.085
Angle of incidence = 45 degrees				
10	.0465	.0465	10.0	.030
15	.1045	.1045	15.0	.068
20	.185	.185	20.0	.120
25	.290	.306	25.67	.179
Angle of incidence = 60 degrees				
10	.0465	.032	8.3	.042
15	.1045	.064	11.74	.096
20	.185	.112	15.5	.182
25	.290	.192	20.3	.267
Angle of incidence = 75 degrees				
10	.0465	.013	5.29	.050
15	.1045	.024	7.19	.115
20	.185	.042	9.51	.195
25	.290	.076	12.8	.309
Angle of incidence = 90 degrees				
10	.0465	.002	2.07	.053
15	.1045	.004	2.94	.125
20	.185	.009	4.4	.230
25	.290	.020	6.57	.360

While tests were made on only two surfaces, it is probable that the same characteristics would prevail for other types of surfaces. For all practical purposes the surface coefficient as obtained for air flow parallel to the surface may be used when calculating heat flow through built-up wall sections or at most a reduction of 15 per cent may be made.

CONDUCTANCE OF AIR SPACES

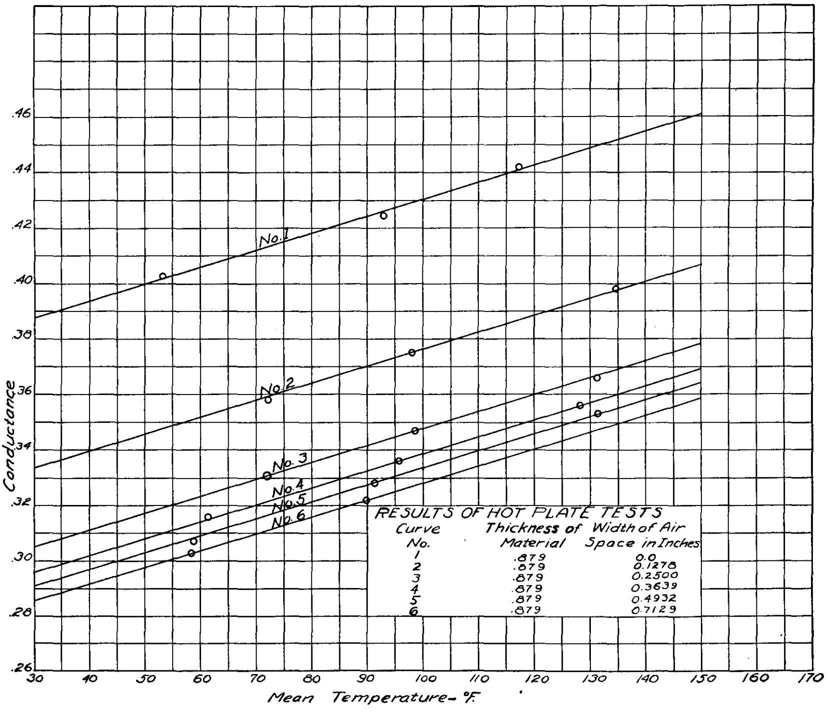
The thermal conductance of an air space will be affected by several factors; among these are width of air space, temperatures of surfaces, character of surfaces, the ratio of the area of the confined space to its thickness, and the position of the air space with respect to direction of heat flow. The effects due to width of space and mean temperature between surfaces should be the same for all surfaces. The surface effect will be different for different classes of material, altho, in many cases, it should be possible to group materials having similar characteristics. The effect of ratio of surface area to thickness of air space should be more pronounced for small ratios, and it is probable that for average building construction it may be neglected. In the following experiments, the air space coefficients were determined for different widths of air spaces and different mean temperatures. Such surfaces were used as Insulite, Masonite, Flaxlinum, Celotex, Compo-board, and Gypsum Board, the last two being paper covered. The limited area of the air spaces was 9 inches square for the tests made by the hot plate method, and 36 inches square for those made by the hot box method.

In performing the tests, sheets of homogeneous material of uniform thickness were selected. Their conductances were first obtained by the hot plate method, after which two sheets of the material were separated by skeleton separators to a given distance, and the conductance of the combined sheets with the enclosed air space determined. These tests were repeated, using various mean temperatures and different widths of air spaces. As the only difference in the construction of the several test specimens was the separation of the material forming different widths of air spaces, the air space resistance was readily calculated. By this method, air space coefficients were obtained for spaces varying from .05 up to .71 inch by the hot plate method, and from .50 inch to 1.50 inches by the hot box method. The separators were built of pine strips 1/8 inch wide for the hot plate tests, and 3/4 inch wide for the hot box tests. Thus the area occupied by the strips was very small as compared with the air space area. For those thicknesses of air space between 1/2 and 3/4 inch that were tested both by the hot plate and the hot box methods, the conductances were found to check, even tho the confined area for the hot plate test was only 9 inches square as compared with a 3-foot square area for the hot box test. It is therefore probable that, for all practical building construction, the area of the confined air space is not a factor so long as there is no direct leakage of air into or out of the air space.

Heat is transmitted through an air space by radiation, conduction, and convection. Radiation depends upon the nature of the surfaces and their temperatures. It is independent of the width of the air gap. For air without motion, the heat transmitted by conduction is inversely proportional to the thickness of the air space. The amount transmitted by convection is dependent upon the temperature difference between the two sides of the air space and the freedom of the air to circulate. Thus for two surfaces, at constant temperature difference, as the air space is increased from zero, the amount of heat transmitted by radiation will remain constant, the amount transmitted by conduction will be decreased, and the percentage transmitted by convection, increased.

As a very thin air space is increased in thickness, the gradual decrease in the heat transmitted by conduction is at first greater than the increase in the amount transmitted by convection. This ratio, however, changes until the greater part of the heat is transmitted by convection, and that transmitted by conduction becomes a negligible factor. This reasoning applies only to vertical air spaces.

The results of the tests are shown in the curves of Figures 40 to 43, inclusive, and in Table III which was taken directly from the curves of Figures 42 and 43. The points on the curves of Figure 40 were plotted directly from experimental data. The conductance curve of Figure 41 for the air spaces was calculated from the results shown in Figure 40. Thus Curve No. 1 of Figure 41 was calculated from data taken from Curves 1 and 2 of Figure 40, etc. The curves of Figure 42 were determined for the various mean temperatures from Figure 41. For instance, vertical lines on Figure 41 representing constant mean temperatures were drawn and the points where these lines crossed Curves 1 to 6, respectively, were plotted as the constant mean temperature curve for Figure 42. These vertical lines were taken from 20° to 150° F. mean temperature at 10-degree intervals. The curves of Figure 43 represent the resistance of the air spaces and are the reciprocals of the values taken from Figure 42. In this set of curves, it was assumed that the thermal resistance of a zero air space would be zero, and all of the lines were thus drawn through the zero point, as it was impossible to get these data from Figure 42. One point, however, was determined at approximately .05-inch air space for 60° F. mean temperature and found to fall on the line passing through the zero point.



RESULTS OF HOT PLATE TESTS

Curve No.	Thickness of Material	Width of Air Space in Inches
1	.879	0.0
2	.879	0.1278
3	.879	0.2500
4	.879	0.3639
5	.879	0.4932
6	.879	0.7129

FIGURE 40. CONDUCTANCE OF TWO SHEETS OF HOMOGENEOUS MATERIAL WITH AND WITHOUT AIR SPACES

From the results of these tests, it is evident that the thermal resistance of an air space gradually increases as the thickness of the air space is increased, until a thickness of approximately .8 inch is reached. After this, the resistance of the air space remains practically constant, regardless of its thickness. While these curves show thicknesses of only 1½ inches as a maximum, other tests were conducted with air spaces 3½ inches thick and found to bear out the conclusion of uniform resistance after a thickness of approximately .8 inch.

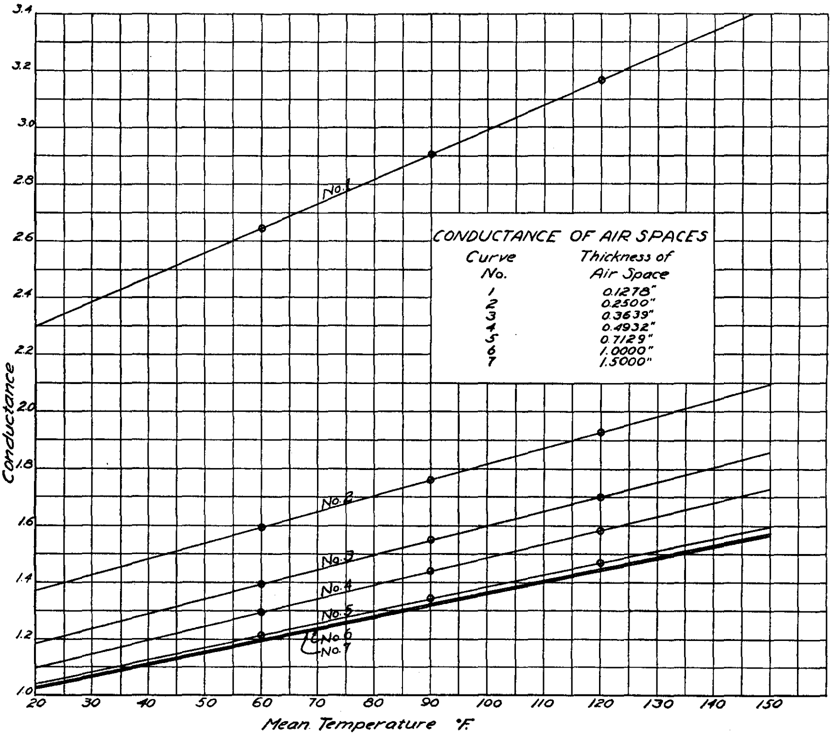


FIGURE 41. CONDUCTANCE OF AIR SPACES CALCULATED FROM DATA SHOWN IN CURVES OF FIGURE 40

TABLE III

CONDUCTANCES OF AIR SPACES FOR VARIOUS WIDTHS OF AIR SPACES IN INCHES

MEAN TEMP. DEG. FAHR.	.125	.250	.375	.500	.625	.750	1.000	1.250	1.500
20	2.300	1.370	1.172	1.095	1.058	1.040	1.030	1.026	1.022
30	2.381	1.425	1.223	1.141	1.100	1.080	1.070	1.067	1.065
40	2.469	1.480	1.275	1.186	1.142	1.120	1.112	1.108	1.105
50	2.564	1.535	1.330	1.235	1.188	1.162	1.152	1.150	1.149
60	2.667	1.590	1.380	1.288	1.228	1.201	1.195	1.191	1.188
70	2.747	1.648	1.427	1.332	1.275	1.248	1.240	1.234	1.228
80	2.833	1.702	1.482	1.375	1.315	1.288	1.280	1.275	1.270
90	2.915	1.757	1.532	1.427	1.365	1.339	1.320	1.315	1.310
100	3.003	1.813	1.585	1.478	1.408	1.378	1.362	1.356	1.350
110	3.086	1.870	1.638	1.528	1.454	1.420	1.402	1.397	1.392
120	3.175	1.928	1.688	1.572	1.501	1.460	1.445	1.440	1.435
130	3.268	1.980	1.740	1.622	1.545	1.500	1.485	1.480	1.475
140	3.356	2.035	1.796	1.675	1.590	1.540	1.530	1.525	1.519
150	3.448	2.090	1.840	1.718	1.633	1.586	1.569	1.564	1.559

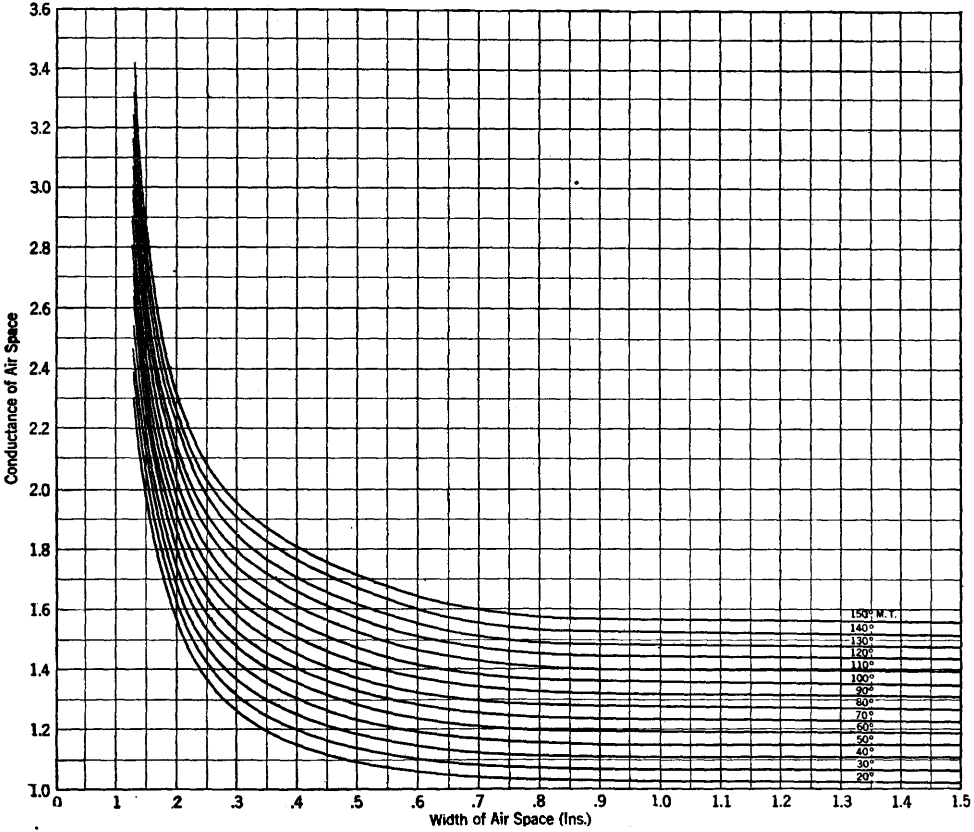


FIGURE 42. CONDUCTANCE OF AIR SPACES FOR DIFFERENT MEAN TEMPERATURES FAHRENHEIT

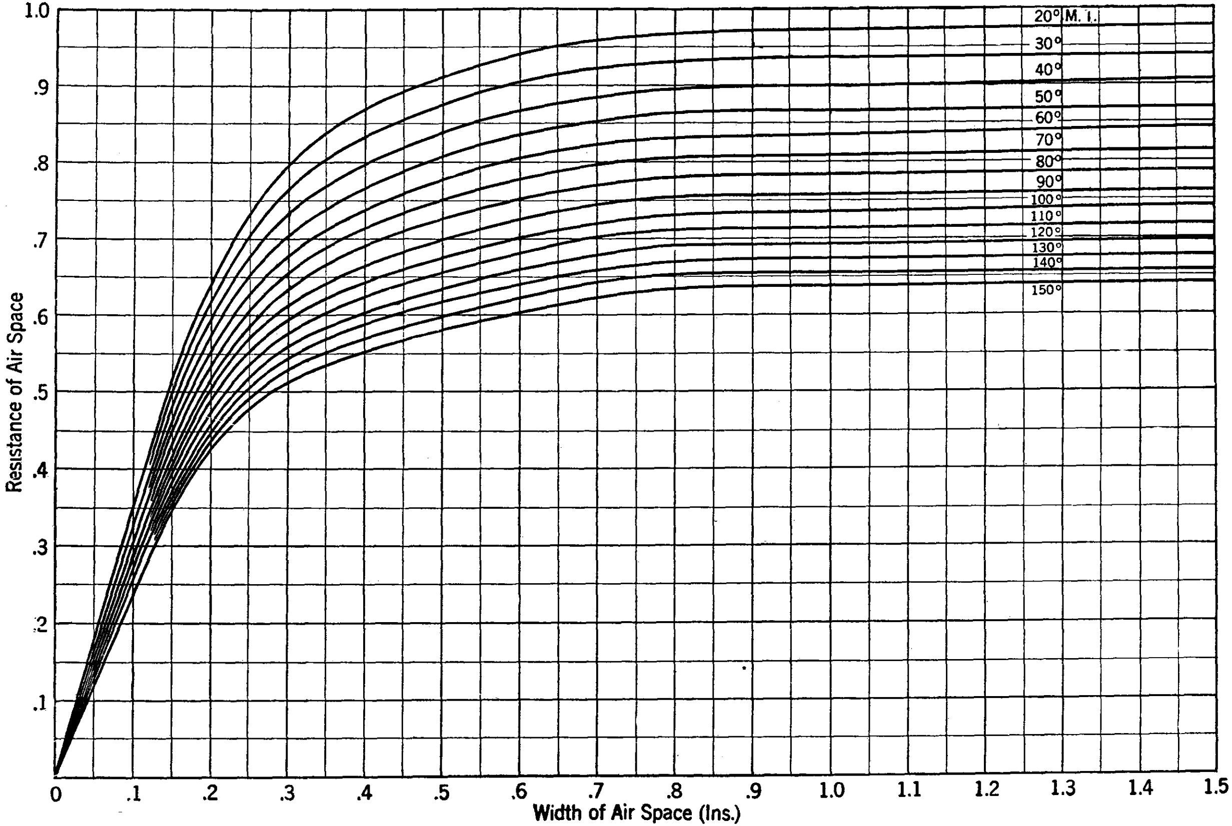


FIGURE 43. RESISTANCE OF AIR SPACES FOR DIFFERENT MEAN TEMPERATURES FAHRENHEIT

TRANSMISSION BY BRIGHT METALLIC SURFACES

Heat conduction across an air space or the transmission to or from an exposed surface takes place by radiation, conduction, and convection. The amount which is transmitted by radiation depends largely upon the character of the surface, and for those materials which have a high radiation or emissivity coefficient this may become an important factor in governing the total transmission. The well-known Stefan and Boltzmann Law gives the heat transmission by radiation as follows:

$$(3)\quad H = 0.172(A)\left[\left[\frac{T_1}{100}\right]^4 - \left[\frac{T_2}{100}\right]^4\right](F_a)\quad(F_e)$$

In this formula

H = the total amount of heat transmitted by radiation per hour
A = area of the surface in squart feet
T_1, T_2 = the absolute temperatures Fahrenheit of the boundary surfaces
F_a = an angle factor
F_e = an emissivity factor depending upon the materials

For practical purposes of air spaces bounded by parallel planes, F_a may be taken as 1 and the emissivity factor, $F_e = \dfrac{1}{\dfrac{1}{P_1} + \dfrac{1}{P_2} - 1}$ (4)

in which P_1 and P_2 are the emissivity coefficients for the materials on the corresponding sides of the air space. The emissivity coefficients have a wide variation for different materials, but it so happens that for such materials as wood, paper, brick, stone, concrete, plaster, etc., commonly used in buildings the emissivity factors are of substantially the same value and the heat transfer by radiation across an air space surrounded by these materials is substantially uniform. Thus the air space coefficients as shown in Figure 42 may be used for average building construction with reasonable accuracy. If, however, the surfaces of the air spaces are to be bounded by materials of low emissivity coefficients the amount of heat transmitted by radiation will be materially reduced and new coefficients must be selected.

In order to obtain practical coefficients which may be used for those materials having low emissivity coefficients, test samples were constructed with air spaces bounded by such materials and tests made by both the hot plate and hot box methods. The results for some of these tests are shown graphically in Figure 44. The values and methods of determination for the points, *A, B, C,* etc. of the curve are shown in the tabulated results of Table IV. All of the results for the other curves were obtained by the hot plate method.

Examination of the results shown in Figure 44 indicate that the heat transmitted across an air space may be materially reduced by the use of a surface lining with a low emissivity coefficient. Also, that for materials of the same character there is a variation in conductance which is undoubtedly due to a variation in the exact quality of the surface.

If the average emissivity coefficient, P_1, for nonreflecting materials such as wood, paper, etc. be taken as 0.90 and it is assumed that the amount of heat given off by convection is the same for both types of surfaces, the emissivity coefficient for aluminum foil may be calculated from the test results of Figures 44 and 42. This method of calculation gives an average emissivity coefficient of .08 for aluminum foil, which is somewhat larger than that often quoted. It does, however, show a reduction in radiant heat of over 90 per cent due to the substitution of aluminum foil for an ordinary nonreflective surface.

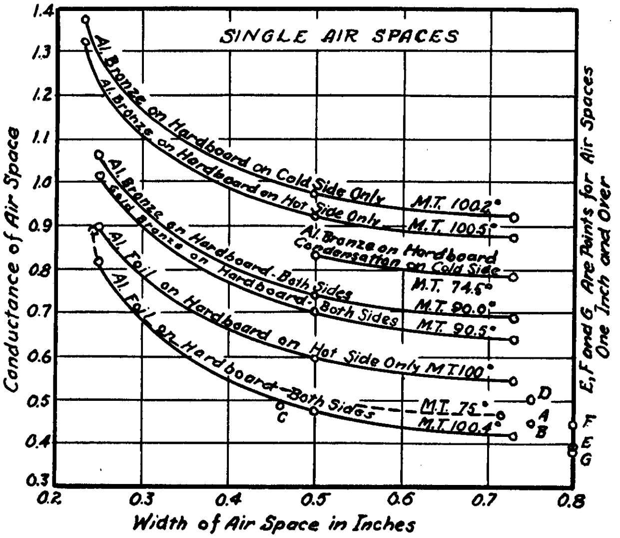


FIGURE 44. RESULTS OF INDIVIDUAL TESTS TO DETERMINE AIR SPACE CONDUCTANCE

If emissivity coefficients of 0.90 and 0.08 are used for wood and aluminum surfaces, respectively, and substituted in formula (3), the emissivity factor F_e may be calculated for an air space with various surface linings. In this calculation the values obtained for F_e are as follows:

No foil on either surface $F_e = 0.818$
Foil on one surface only $F_e = 0.079$
Foil on both surfaces $F_e = 0.042$

Thus, $\left[1 - \frac{.079}{.818}\right] \times 100 = 90.3$ per cent of radiant heat stopped by one surface lined and $\left[1 - \frac{.042}{.818}\right] \times 100 = 94.4$ per cent stopped by two surfaces lined.

The small difference gained by lining the second surface is due to the fact that the low emissivity coefficient cuts off substantially all of the radiant heat when the material is applied to a single surface, and there is but a small amount left to be reduced by the second surface lining. In the case of aluminum bronze in which the emissivity coefficient is higher than for aluminum foil, the reduction due to a single surface lining is not as great as when using bright aluminum foil, and there is a greater percentage to be saved by lining the second surface of an air space.

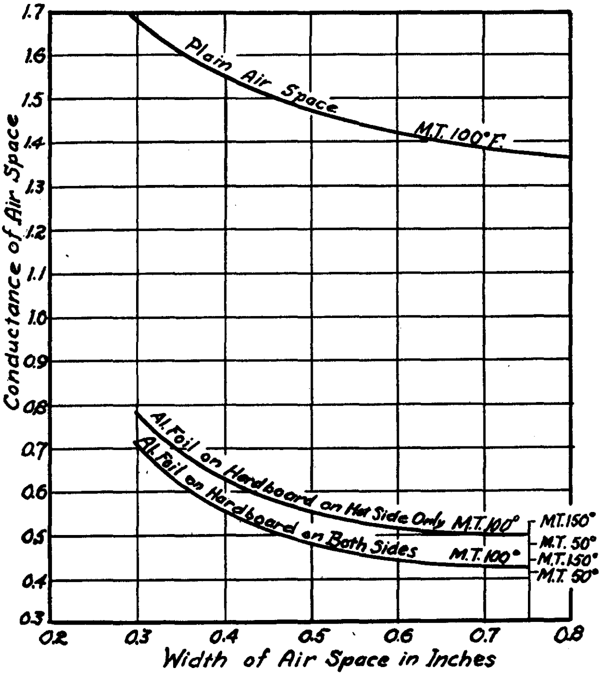


FIGURE 45. AVERAGE AIR SPACE CONDUCTANCE FOR 100° MEAN TEMPERATURE

In order to get average coefficients which may be used for bright aluminum foil-lined air spaces the results as shown in Figure 44 and Table IV were used to construct the two lower curves of Figure 45. As will be noted, these curves have been constructed on the basis of 100° F. mean temperature and points for air spaces .75 inches in thickness have been calculated for mean temperatures of 50° and 150° F. These calculations were made on the basis of emissivity coefficients of .90 and .08 for wood and aluminum foil, respectively. The upper curve of Figure 45 marked plain air space was taken directly from the values of Figure 42 in order to give a comparison between the unlined and lined air spaces. In using aluminum foil or any bright metallic surface one must recognize that the value lies in the low emissivity coefficient of the material, and to maintain this the exposed surface must be kept in its original bright polished condition. If moisture or dust is allowed to accumulate on the surface or if the surface is allowed to tarnish the emissivity coefficient will be changed and in extreme cases the value of the low coefficient will be entirely destroyed.

The outside surface coefficient of a wall is also affected by radiation, but in practice this coefficient is affected by air movement over the surface to a much greater extent than the average air space coefficient.

Surface radiation, therefore, becomes of less importance in its effect on the coefficient as a whole. The radiation coefficient remains the same for still air as for high wind velocities; therefore its percentage effect is much greater for still air conditions.

TABLE IV

TEST VALUES FOR THE CONDUCTANCES OF AIR SPACES AS USED IN FIGURE 44

Test Point Fig. 44	Date of Test	Test Method	Thickness Air Space, Inches	Surface Hot Side	Surface Cold Side	Conductance C	Deg. F. Mean Temp.
A	12/6/33	Hot plate	0.75	Aluminum foil	Aluminum foil	0.449	75
B	6/13/32	Hot plate	0.75	Aluminum foil	Wood fiber	0.447	90
C	6/16/32	Hot plate	0.46	Aluminum foil	Aluminum foil	0.485	77
D	5/6/33	Hot plate	0.75	Aluminum foil	Dull black	0.50	75
E	12/6/33	Hot box	3.50	Aluminum foil	Wood fiber board	0.393	40
F	8/4/32	Hot box	3	Aluminum foil	Aluminum foil	0.44	40
G	10/15/30	Hot box	1	Aluminum foil	Aluminum foil	0.383	40

TABLE V

RESULTS OF TESTS BY HOT BOX METHOD TO DETERMINE SURFACE COEFFICIENTS FOR A WALL WHEN COVERED WITH PAPER AND WITH ALUMINUM FOIL

Date of test	10/15/30	10/20/30
Wall number	78	78B
Lining for both surfaces	Paper	Aluminum foil
Mean temperature of test	40° F.	40° F.
Over-all coefficient, U	0.691	0.46
Conductance surface to surface, C	3.5	3.5
Average surface coefficient	1.72	1.06
Surface radiation	0.733	0.068
Surface convection	0.99−	0.99+

Table V shows the amount of heat given off by radiation and convection for two types of surfaces under normal still air conditions. These results were obtained at 40° F. mean temperature only. Calculated values for the reduction in surface coefficients caused by bright aluminum foil at other mean temperatures are shown in Table VI. From this table it is evident that the radiation becomes a much more important factor at high mean temperatures.

TABLE VI

REDUCTION IN AVERAGE SURFACE TRANSMISSION COEFFICIENTS CAUSED BY COVERING THE SURFACE WITH BRIGHT ALUMINUM FOIL

Mean Temperature ° F.	Reduction in Coefficient, B.t.u.
20	0.559
40	0.634
60	0.711
80	0.797
100	0.887
120	0.99
140	1.09

THERMAL PROPERTIES OF WOOD

Altho the thermal properties of wood are of importance in many lines of building construction there has been very little available information as to these properties. The records of those tests upon which practical conductivity values have been based have usually omitted much of the important data and have not been sufficiently extensive to make them applicable to different species of wood, or to various conditions of the same species.

In 1929 a co-operative research project was started by the University of Minnesota, the American Society of Heating and Ventilating Engineers, and the National Lumber Manufacturers Association. A preliminary study was made to determine the feasibility of a more extended research program and to identify the factors which should be investigated in regard to the thermal properties of wood. In this preliminary investigation over one hundred tests were made on fourteen pieces of material, the test panels being selected by the United States Forest Products Laboratory as representative in character. The results of this investigation lead to the following tentative conclusions:

1. That conductivity varies approximately in a straight line ratio with density in any given species.
2. That somewhat greater conductivity may be expected for heat flow tangential to the grain than for heat flow normal to the grain, in species with strongly marked annual rings.
3. That no consideration need be given to the position of annual rings in species of uniform grain.
4. That small crevices such as occur between boards in ordinary construction do not materially affect conductivity over the area tested, tho they may, in the absence of suitable precautions, affect air infiltration.
5. That conductivity varies substantially in a straight line ratio with moisture content if the latter is expressed in terms of weight per volume of wood.
6. That the inherent variability of wood makes a considerable number of tests of each species necessary in order to arrive at a fairly representative value for each species.

Pursuant to the above findings the following commercial species were selected as representative for further investigation.

California redwood
Douglas fir
Eastern hemlock
Hard maple
Longleaf yellow pine
Northern white pine
Norway pine
Ponderosa pine
Red cypress
Red oak
Shortleaf yellow pine
Sitka spruce
Soft elm
Soft maple
Sugar pine
West coast hemlock
Western larch
Western red cedar
White ash
White fir
White oak
Yellow birch

It was decided to select samples of each species covering the range of densities normally experienced in that species and to test the samples to determine the relation between thermal conductivity, density, and moisture content of the species. In order to reduce the amount of test work required for a complete determination of the moisture conductivity relation of all species the various materials were divided into six groups of similar characteristics, and one species from each group was selected for a complete series of tests to determine the conductivity moisture and density moisture relations. The results from the tests on each species selected were later used in applying correction factors to the other species in the group. The groups and representatives selected for tests were as follows:

Species in Group	Representative Species Tested
Northern white pine Norway pine Ponderosa pine Sugar pine	Ponderosa pine
California redwood Red cypress Western red cedar	Red cypress
Douglas fir Longleaf yellow pine Shortleaf yellow pine Western larch	Shortleaf yellow pine
Eastern hemlock Sitka spruce West coast hemlock White fir	West coast hemlock
Red oak White ash White oak	Red oak and white oak
Hard maple Soft elm Soft maple Yellow birch	Yellow birch

TEST METHODS

The samples for the extended series of tests were selected by the National Lumber Manufacturers Association and conditioned to approximately 8 per cent of moisture. These samples were then sent to the University of Minnesota where they were selected for uniform test panels of different densities. In this selection boards of substantially the same density were used to make up a pair of test panels and the panels were made up covering as wide a range of densities as possible from each species.

In preparing the test panels the boards for a complete set were run through a planer to give them a smooth surface on both sides and to make sure that all of the boards of each sample were of uniform thickness. The boards were then weighed and selected for density. A sample was selected from each board for moisture determination, the average results for all boards of a pair of test panels being taken as the average moisture content for the panel.

The pieces used for moisture determination were wrapped in oil paper as soon as cut from the test specimen. They were then taken to the laboratory, weighed, and dried to a constant weight at 175° F. The loss of weight divided by the dry weight was taken as the percentage of moisture in the sample.

In some of the earlier tests the moisture determinations were made at 212° F. These species were Douglas fir, white fir, and western cedar. All others were dried at 175° F. In the case of red oak the moisture content of the samples was dried at both 175° F. and 212° F., which resulted in an increase of about one per cent in loss for the higher temperatures.

For some of the samples there was a slight variation in the moisture content during the test, which was determined by weighing the panels both before and after testing. In these cases, the average moisture content was taken as the moisture content for the particular test, altho the variation was so slight in most cases that it was not necessary to take averages. An investigation was made to determine the effect of this moisture change during the test on thermal conductivity as obtained by the hot plate. It was shown that even tho all of the heat for evaporating the moisture might come from that supplied to the test section the error would be less than one per cent and in all cases negligible.

When the moisture content of a panel is given as the percentage by weight, the test results may be misleading, due to the fact that for the same percentage by weight there will be different amounts of moisture per unit volume. For this reason, the percentage of moisture by weight was converted to pounds of moisture per board foot. In making this conversion the volume of the sample was determined by measuring the length and width and by taking the thickness as determined in the test plate. The formula used for making the conversion was as follows:

$$\begin{array}{c}\text{Weight of moisture}\\ \text{per bd. ft.}\\ \text{(144 cu. in.)}\end{array} = \frac{\begin{array}{c}\text{(Average moisture per cent before and after test,}\\ \text{dry basis)} \times \text{(dry wt. sample)} \times 144\end{array}}{(2 \times \text{thickness of panel}) \times \text{length} \times \text{width}}$$

Since in some cases there might be a slight change in weight during the test, the density calculations were all made on the basis of weight and thickness taken at the beginning of the test, the change in density for a slight change in moisture being negligible. The warping of wood which sometimes occurs during a test might give a greater thickness reading of the test panel at the end of the test than at the beginning, even tho no additional moisture was added. In some cases, there was a slight warping of the test boards before the test, making it necessary to take the thickness readings of the individual boards and not to use the thickness as obtained during the test. When there was any appreciable warping, additional samples were selected and tested. In all cases of tests upon which the present data have been based, the density has been determined by the following formula:

$$\begin{array}{c}\text{Density, lb. per cu. ft.}\\ \text{before test}\end{array} = \frac{1728 \times \text{weight before test}}{\begin{array}{c}(2 \times \text{thickness of 1 panel}) \times \text{length} \times \text{width}\\ \text{(before test)}\end{array}}$$

All thermal conductivity tests were made with the standard hot plate apparatus at 75 degrees mean temperature. In each test the samples were prepared, placed in the test apparatus, and left at constant temperature conditions a sufficient length of time to insure uniform temperature gradients throughout the specimens. The temperatures of the test specimens were then taken and the rate of heat flow through the test section was calculated from the electric input to the heating element. In each case, readings at constant conditions were continued for average periods of five hours to insure uniform data. The thickness of the samples from which the thermal conductivities were calculated was taken as the distance between the test plates during the tests.

DENSITY-MOISTURE AND CONDUCTIVITY-MOISTURE RELATIONS

As previously stated all of the species of wood were divided into six groups and a representative species from each group was selected for a complete series of tests to determine the relation between density and moisture and conductivity and moisture.

For each representative species four or more pairs of test panels were selected and the conductivity and density of each pair was determined at several moisture contents covering the range from zero moisture to approximately the fiber saturation for the particular sample. The moisture content of the samples was changed by placing them in a saturated atmosphere for a sufficient length of time to take up the required moisture. They were then wrapped in oil paper and left for periods of two weeks or longer to give the moisture an opportunity to equalize throughout the sample.

In the dense woods, such as oak and birch, the higher moisture contents were accompanied by excessive warping of the boards. In the oak group the condition was so bad that it was necessary to run a large number of panels of both white oak and red oak in order to obtain satisfactory curves, two curves being taken from each group and averaged to give the final correction curve. No particular difficulty was experienced in conditioning the lighter species and with these, little trouble was experienced in warping during the test.

The test results for the moisture conductivity and density moisture relations for the six species selected to represent their respective groups are shown graphically in Figures 46 to 51, inclusive.

An examination of the density-moisture curves for each species shows that the test points lie substantially on a straight line, and in general the lines have the same slope for each species. There are, however, exceptions to this general rule. Consider the case of Ponderosa pine (Fig. 46). The lines for panels *L,L, X,X* have a steeper slope than the corresponding line for panels *H,H* and *K,K*. This indicates that for the first two panels the addition of moisture gave a higher rate of increase in density than for the second two panels. From this it would appear that the action of the moisture is different in the two cases, indicating that the rate of swelling or growth due to measured moisture content in the specimen is different. An examination of the moisture conductivity curve for Ponderosa pine (Fig. 46) shows that the rate of increase in conductivity is greater for panel *L,L* and *X,X* than it is for the other two panels. This general relation might be expected, yet it does not explain why there is a difference in the rate of density increase for different specimens with the same amount of moisture absorption. Considering the curve for yellow birch (Fig. 51) the relation between the conductivity-moisture curve does not definitely follow the relation between the density-moisture curve, altho in this case the points on the

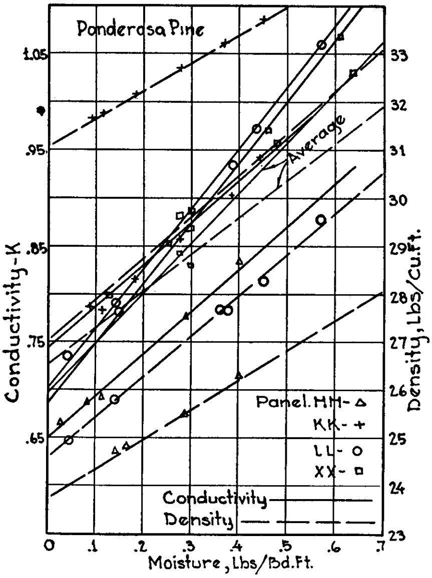


FIGURE 46. PONDEROSA PINE—THE EFFECT OF MOISTURE ON DENSITY AND CONDUCTIVITY

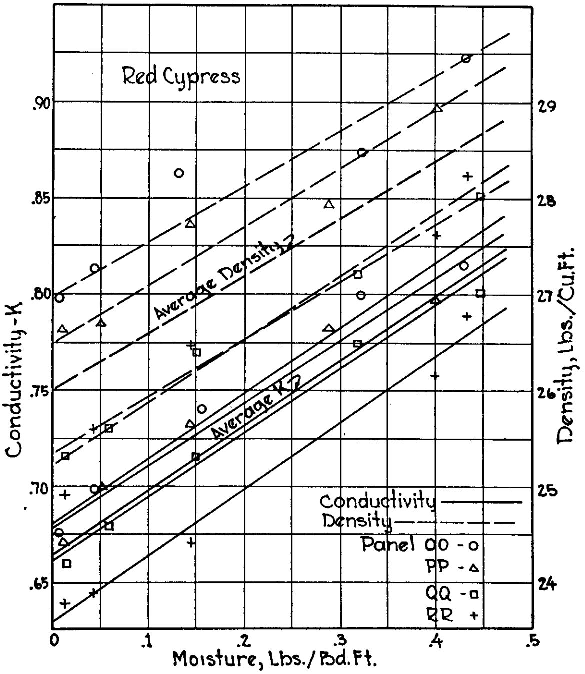


FIGURE 47. RED CYPRESS—THE EFFECT OF MOISTURE ON DENSITY AND CONDUCTIVITY

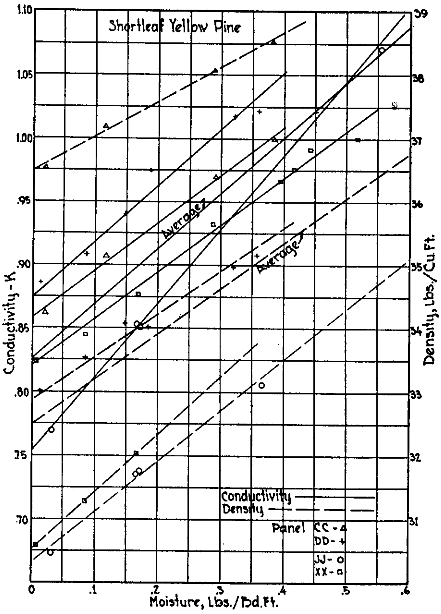


FIGURE 48. SHORTLEAF YELLOW PINE—THE EFFECT OF MOISTURE ON DENSITY AND CONDUCTIVITY

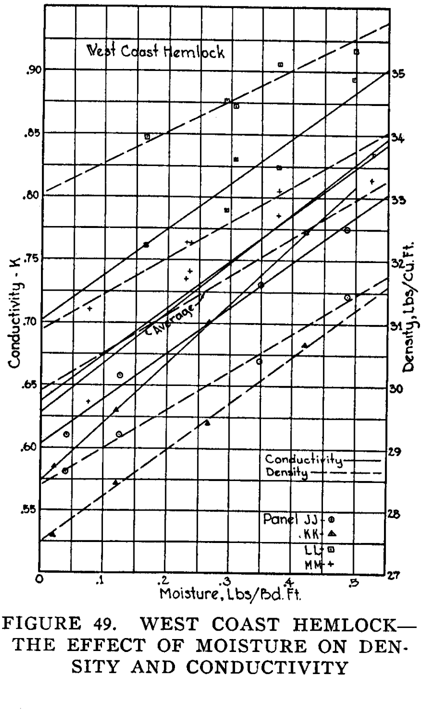


FIGURE 49. WEST COAST HEMLOCK—THE EFFECT OF MOISTURE ON DENSITY AND CONDUCTIVITY

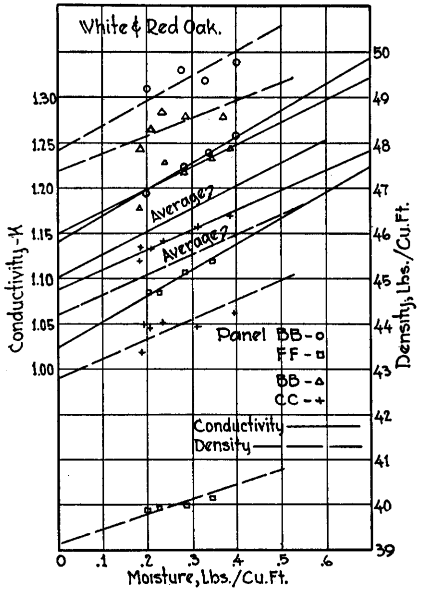


FIGURE 50. WHITE OAK AND RED OAK—THE EFFECT OF MOISTURE ON DENSITY AND CONDUCTIVITY

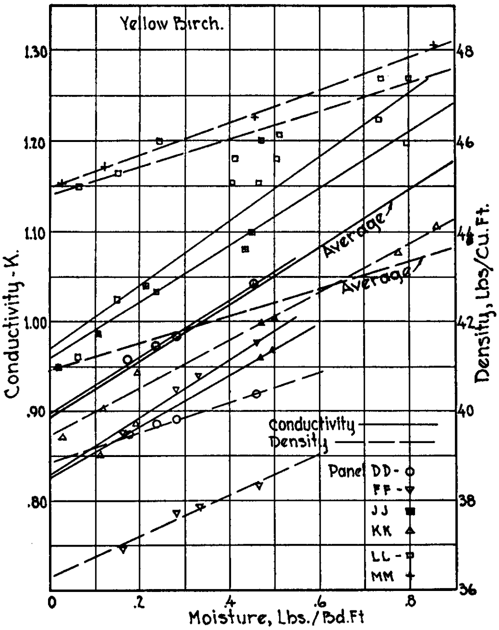


FIGURE 51. YELLOW BIRCH—THE EFFECT OF MOISTURE ON DENSITY AND CONDUCTIVITY

moisture conductivity curves are a little more scattered. For shortleaf yellow pine the moisture-density curves (Fig. 48) are fairly uniform in slope, but the moisture-conductivity curve for panel *J,J* has a very much greater slope than for the other panels. In the results obtained for west coast hemlock (Fig. 49) there is a close agreement between the slopes of the curves for both density-moisture and conductivity-moisture test results. In general it may be stated that the increase in density for the absorption of moisture is not at the same ratio for all specimens of the same species and the conductivity-moisture relation is similar to the density-moisture relation for different samples of the same species.

The average slope of the line showing conductivity and density variation at different moisture contents for each of the six species was selected from Figures 46 to 51, and from them the curves of Figures 52 and 53 were obtained. The curves of Figure 52 show the increase in density, pounds per cubic foot, caused by the increase in moisture, pounds per board foot. The curves of Figure 53 show the increase in thermal conductivity, *k*, with the increase in moisture, pounds per board foot, for each of the six samples tested. The curves for each species as shown in these two figures were used as typical for all of the species of the representative group and were used as correction curves for density and conductivity at various moisture contents for all of the samples.

CONDUCTIVITY-DENSITY RELATIONS FOR MOISTURE CONTENTS

The conductivity density relations as determined by tests for the various species are shown in the curve sheets of Figures 54 to 75, inclusive. For each species the conductivities were obtained for the different densities at moisture content as received, which varied from 4.5 to 11 per cent. The thermal conductivity and density values obtained in the test were corrected to zero per cent moisture and plotted on the curve sheets, Figures 54 to 75, inclusive. The conductivity-density curve for zero per cent moisture was then drawn and the values from this curve were used to determine the other conductivity values ranging up to 16 per cent moisture. In making the corrections in conductivity and density for zero per cent moisture the curves for moisture-density and moisture-conductivity (Figs. 52 and 53) were taken as determined for the species which was used as the representative of the particular material under test. From the density-moisture curve, the density at zero per cent moisture was determined, and from the conductivity-moisture curve the conductivity at zero per cent moisture was determined, thus giving the co-ordinates for conductivity-density corresponding to the particular sample tested. The points for all tests were corrected in this manner, and the zero per cent curve was drawn through these points by the method of least squares.

The points for the curves of higher percentages of moisture for a given species were calculated from the zero per cent curve in the following manner: For a given density in pounds per cubic foot and a given moisture content, the weight of moisture in pounds per board foot was calculated. From this value, the increase in density in pounds per cubic foot was obtained from the representative species (Fig. 52). In like manner, the increase in conductivity for the calculated moisture content in pounds per board foot was determined from Figure 53. These

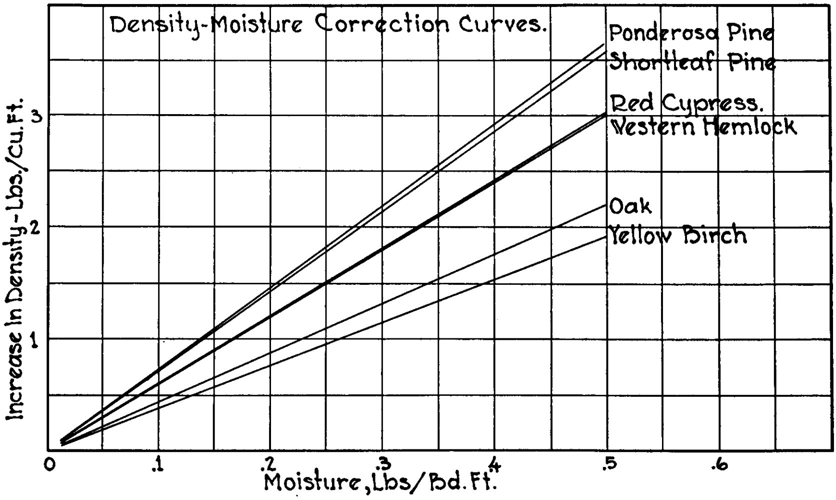


FIGURE 52. RELATION BETWEEN DENSITY AND MOISTURE CONTENT FOR THE REPRESENTATIVE SPECIES AS INDICATED

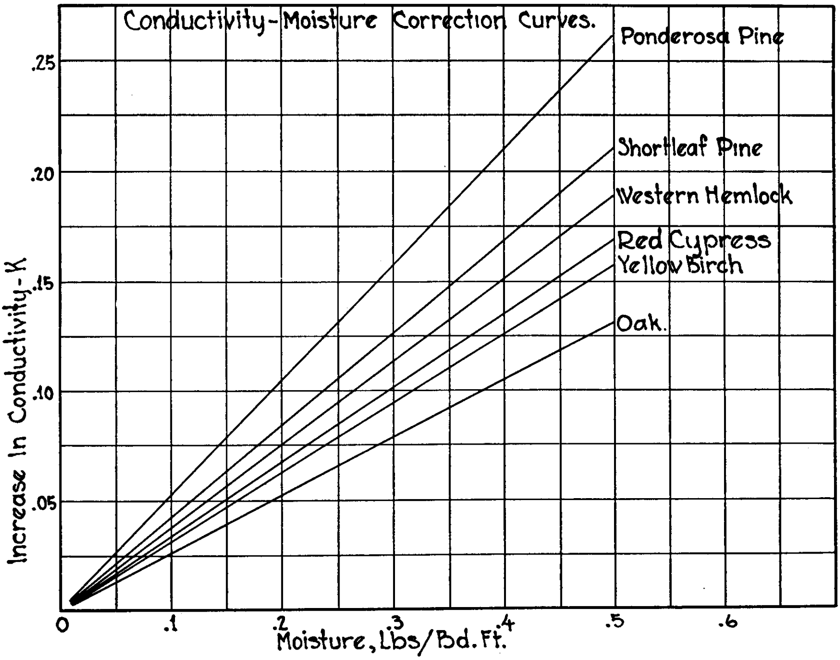


FIGURE 53. RELATION BETWEEN CONDUCTIVITY AND MOISTURE CONTENT FOR THE REPRESENTATIVE SPECIES AS INDICATED

increases in density and conductivity were added to the density and conductivity values for the original selected point, and the new values plotted on the curve sheet as a new point on the conductivity-density relation for the given percentage of moisture.

Since these lines were plotted as straight lines, it is evident that the calculation of two points for each moisture content was sufficient. As has been previously stated, there might be some question about the accuracy of correcting the values for a group of materials by a curve derived from one of the group as representative. It should be pointed out, however, that the tests were made at moisture contents ranging from 6 to 10 per cent. Thus, if there was an error in correcting back to the zero per cent moisture, this error would be eliminated in correcting the given point back to a percentage of moisture corresponding to test conditions.

In the curves (Figs. 54 to 75, inclusive) it should be noted that the moisture content in percentage is based on the total weight of the sample and not on dry material of the sample.

RELATION BETWEEN CONDUCTIVITY AND DENSITY FOR ALL MATERIALS AT 12 PER CENT MOISTURE

In order to get a comparison between the density and conductivity for the different species at the same moisture content, the curves of Figures 76 and 77 were plotted. The points for Figure 76 represent the conductivity at 12 per cent moisture for the average density of each species as tested. Those for Figure 77 represent the conductivities as taken from the 12 per cent moisture line, but the densities were the averages for the species as given in Technical Bulletin No. 158 of the United States Department of Agriculture. The densities used in plotting the points for Figure 77 were as follows:

Species	Density, Lb. per Cu. Ft.
California redwood	30
Douglas fir	31
Eastern hemlock	28
Hard maple	44
Longleaf yellow pine	41
Northern white pine	25
Norway pine	34
Ponderosa pine	28
Red cypress	32
Red oak	44
Shortleaf yellow pine	38
Sitka spruce	28
Sugar pine	25
West coast hemlock	29
Western red cedar	23
Western larch	36
White ash	42
White fir	26
White oak	48
Yellow birch	43

By comparing the densities of the materials tested with the average densities taken from Bulletin No. 158, it will be noted that, in a majority of cases, the selected values fall within the range of test values; in a few

(Continued on page 69)

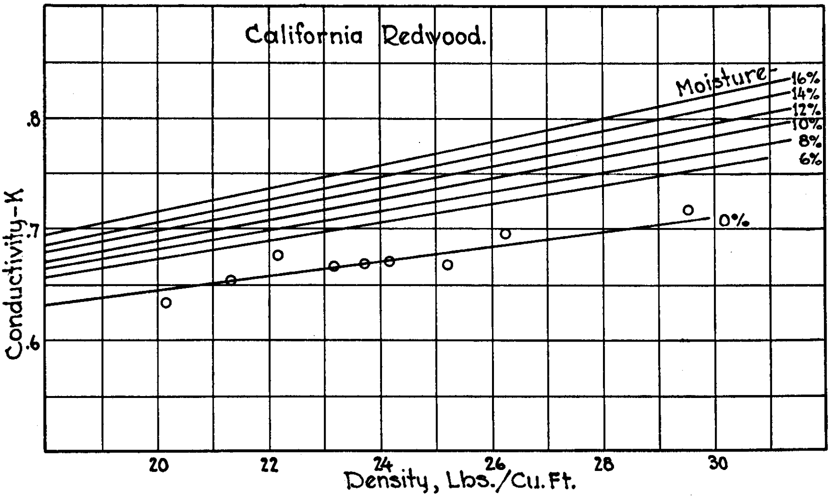


FIGURE 54. CALIFORNIA REDWOOD—DENSITY-CONDUCTIVITY RELATION FOR DIFFERENT PERCENTAGES OF MOISTURE

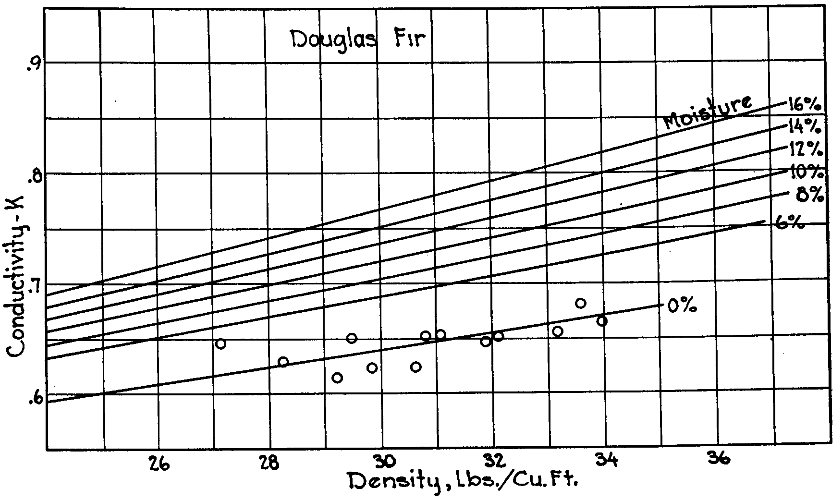


FIGURE 55. DOUGLAS FIR—DENSITY-CONDUCTIVITY RELATION FOR DIFFERENT PERCENTAGES OF MOISTURE

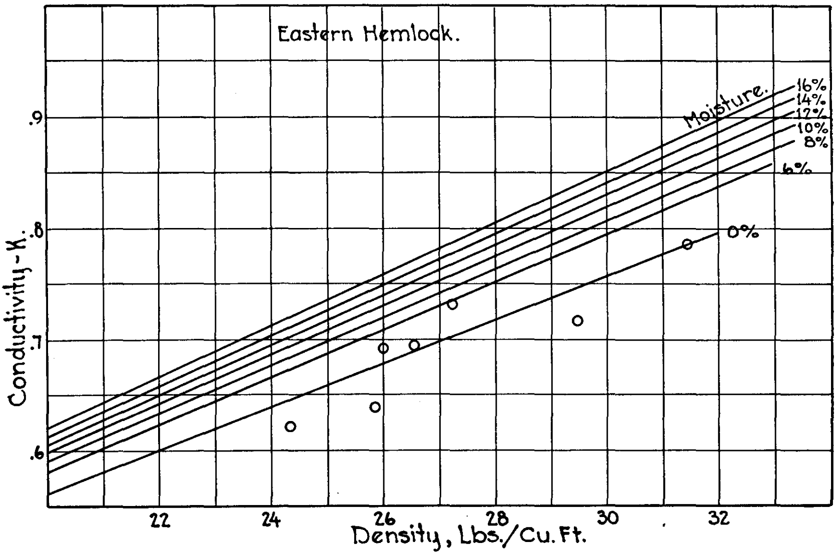


FIGURE 56. EASTERN HEMLOCK—DENSITY-CONDUCTIVITY RELATION FOR DIFFERENT PERCENTAGES OF MOISTURE

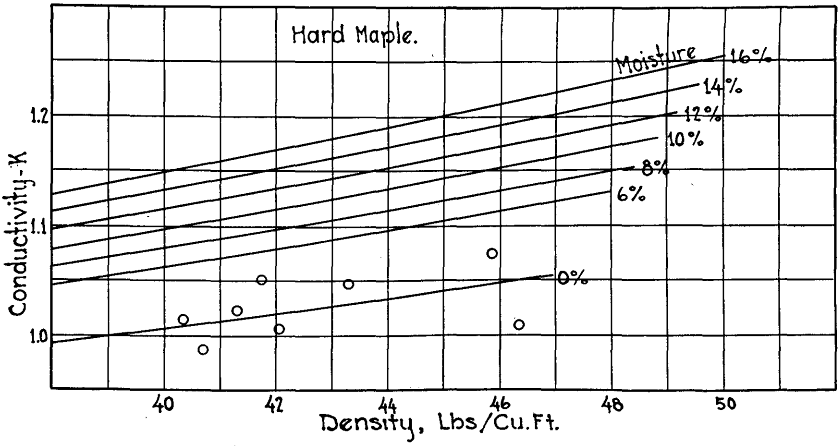


FIGURE 57. HARD MAPLE—DENSITY-CONDUCTIVITY RELATION FOR DIFFERENT PERCENTAGES OF MOISTURE

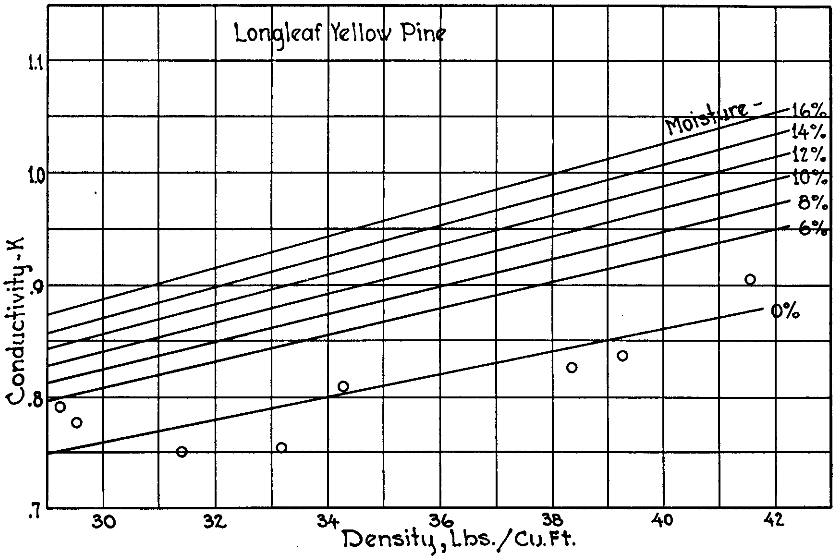


FIGURE 58. LONGLEAF YELLOW PINE—DENSITY–CONDUCTIVITY RELATION FOR DIFFERENT PERCENTAGES OF MOISTURE

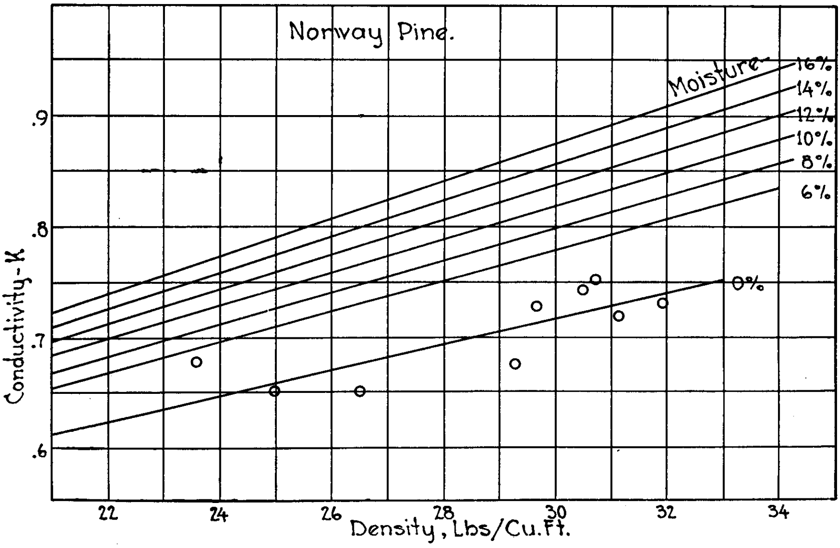


FIGURE 59. NORWAY PINE—DENSITY–CONDUCTIVITY RELATION FOR DIFFERENT PERCENTAGES OF MOISTURE

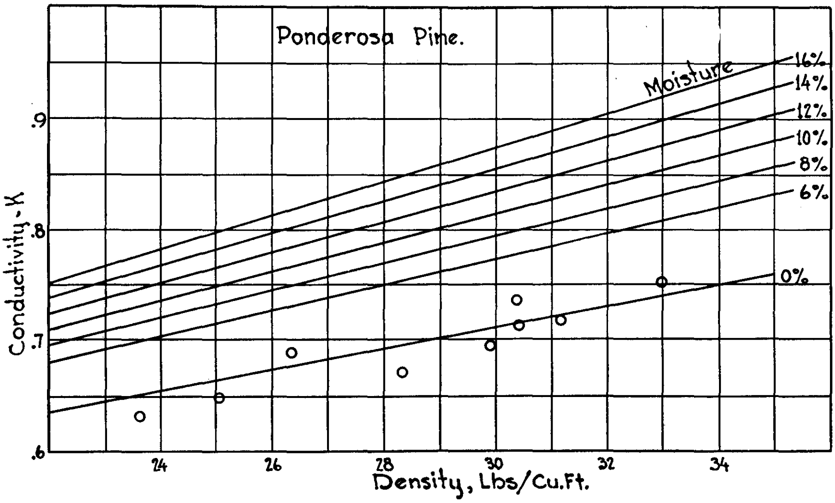


FIGURE 60. PONDEROSA PINE—DENSITY-CONDUCTIVITY RELATION FOR DIFFERENT PERCENTAGES OF MOISTURE

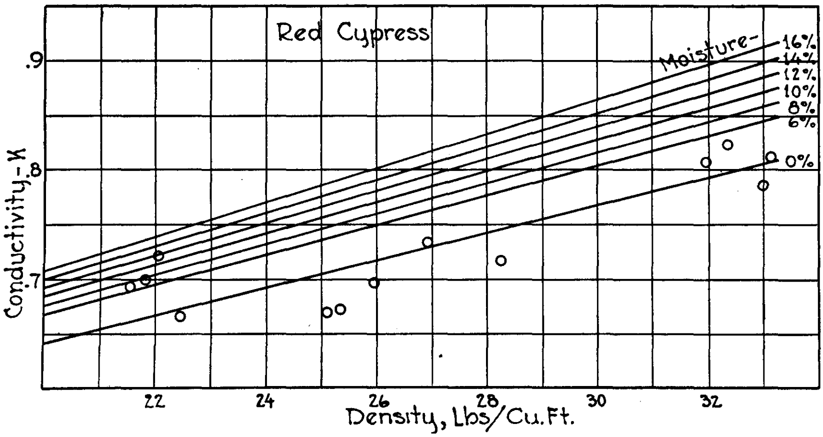


FIGURE 61. RED CYPRESS—DENSITY-CONDUCTIVITY RELATION FOR DIFFERENT PERCENTAGES OF MOISTURE

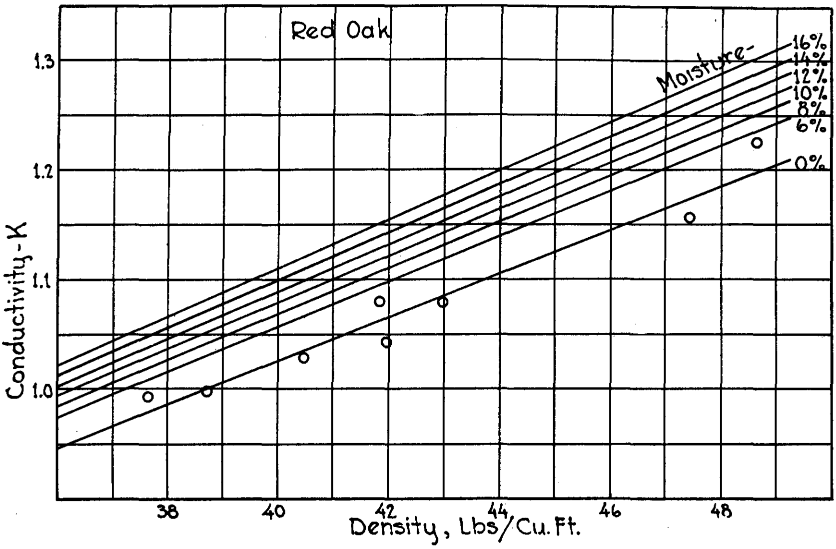


FIGURE 62. RED OAK—DENSITY-CONDUCTIVITY RELATION FOR DIFFERENT PERCENTAGES OF MOISTURE

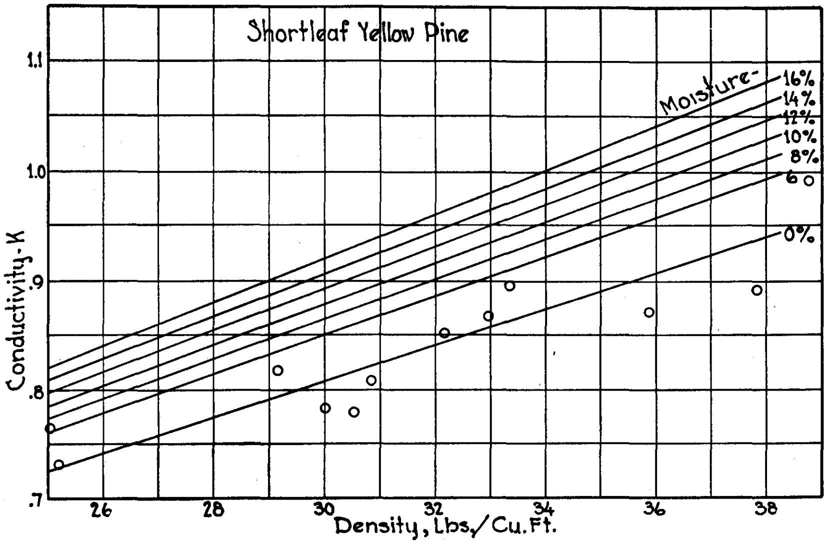


FIGURE 63. SHORTLEAF YELLOW PINE—DENSITY-CONDUCTIVITY RELATION FOR DIFFERENT PERCENTAGES OF MOISTURE

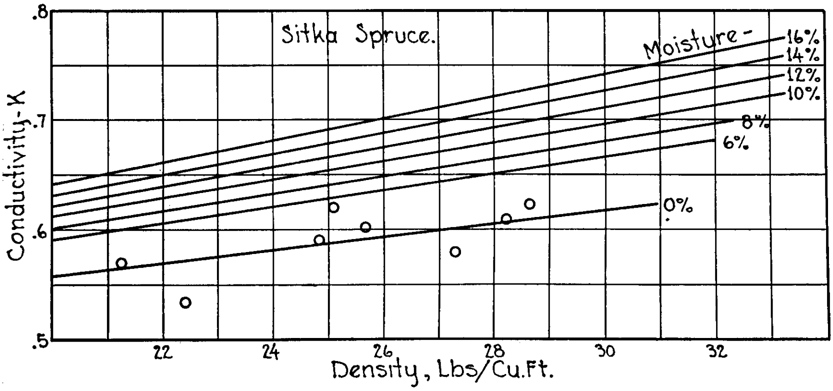


FIGURE 64. SITKA SPRUCE—DENSITY-CONDUCTIVITY RELATION FOR DIFFERENT PERCENTAGES OF MOISTURE

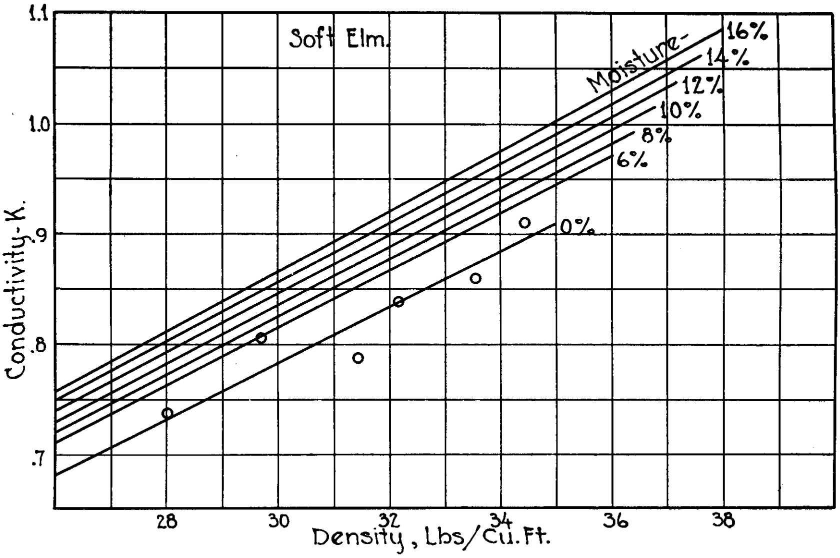


FIGURE 65. SOFT ELM—DENSITY-CONDUCTIVITY RELATION FOR DIFFERENT PERCENTAGES OF MOISTURE

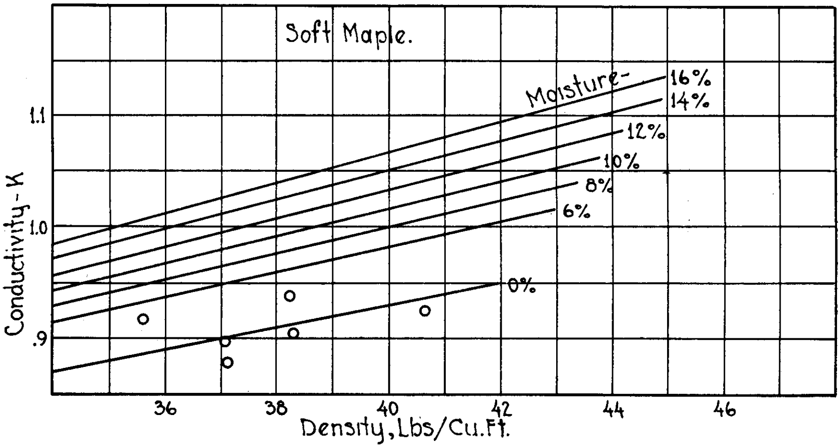


FIGURE 66. SOFT MAPLE—DENSITY-CONDUCTIVITY RELATION FOR DIFFERENT PERCENTAGES OF MOISTURE

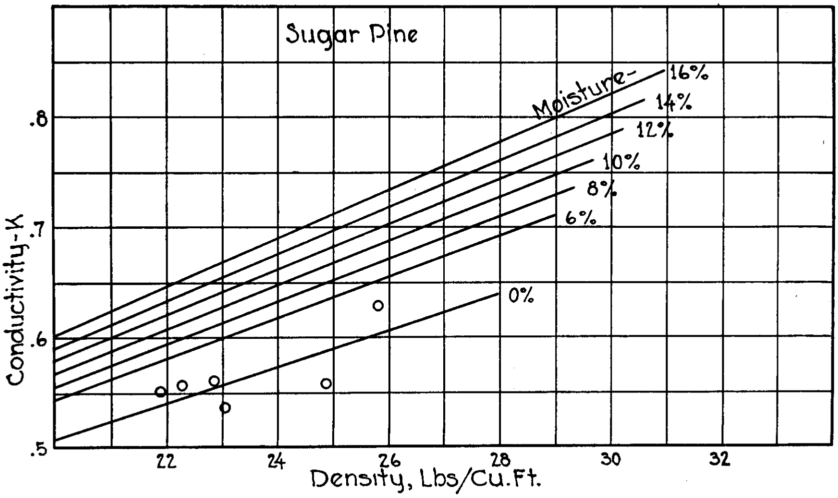


FIGURE 67. SUGAR PINE—DENSITY-CONDUCTIVITY RELATION FOR DIFFERENT PERCENTAGES OF MOISTURE

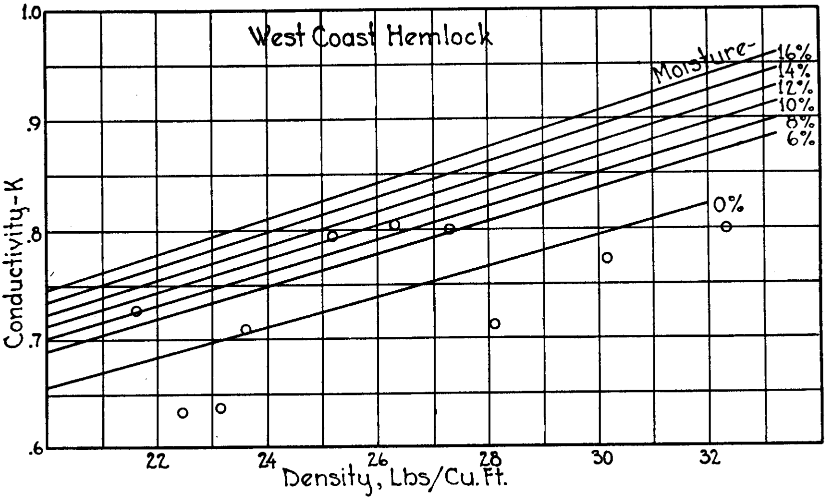


FIGURE 68. WEST COAST HEMLOCK—DENSITY-CONDUCTIVITY RELATION FOR DIFFERENT PERCENTAGES OF MOISTURE

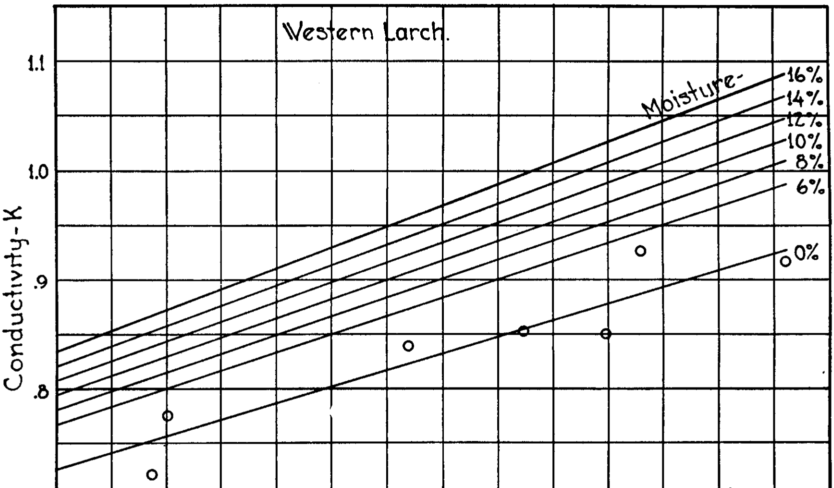


FIGURE 69. WESTERN LARCH—DENSITY-CONDUCTIVITY RELATION FOR DIFFERENT PERCENTAGES OF MOISTURE

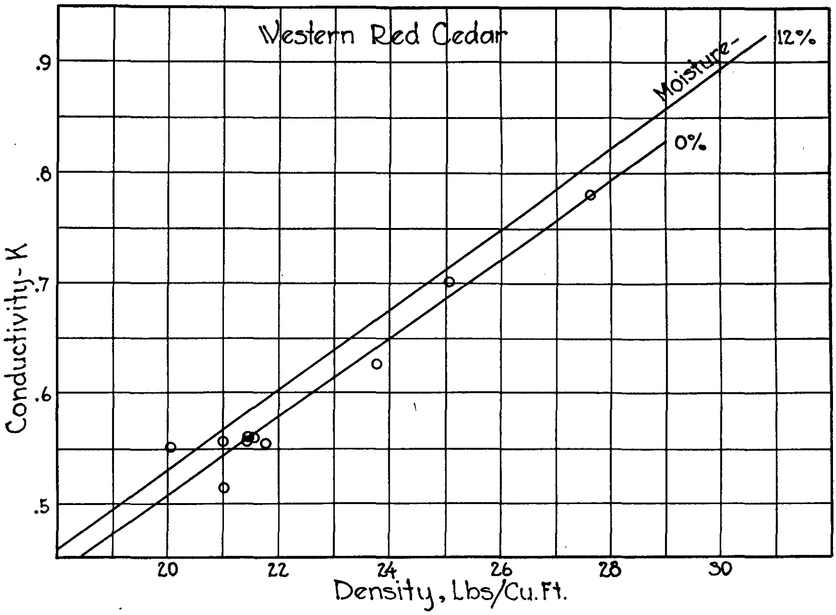


FIGURE 70. WESTERN RED CEDAR—DENSITY-CONDUCTIVITY RELATION FOR DIFFERENT PERCENTAGES OF MOISTURE

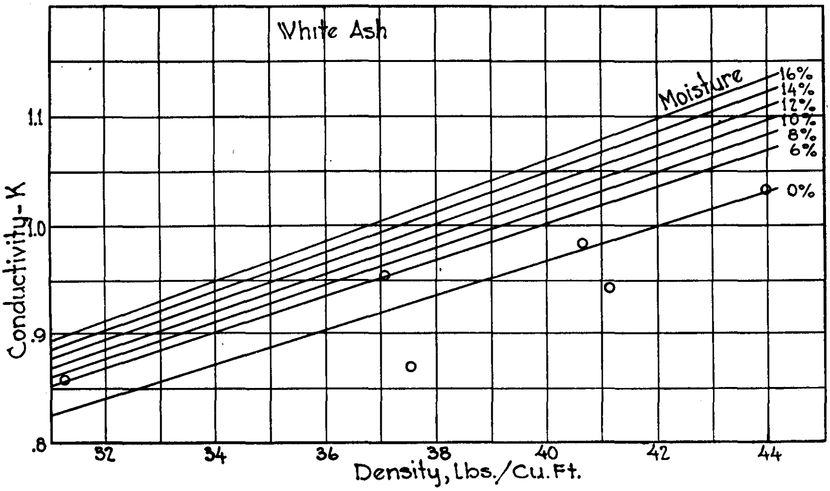


FIGURE 71. WHITE ASH—DENSITY-CONDUCTIVITY RELATION FOR DIFFERENT PERCENTAGES OF MOISTURE

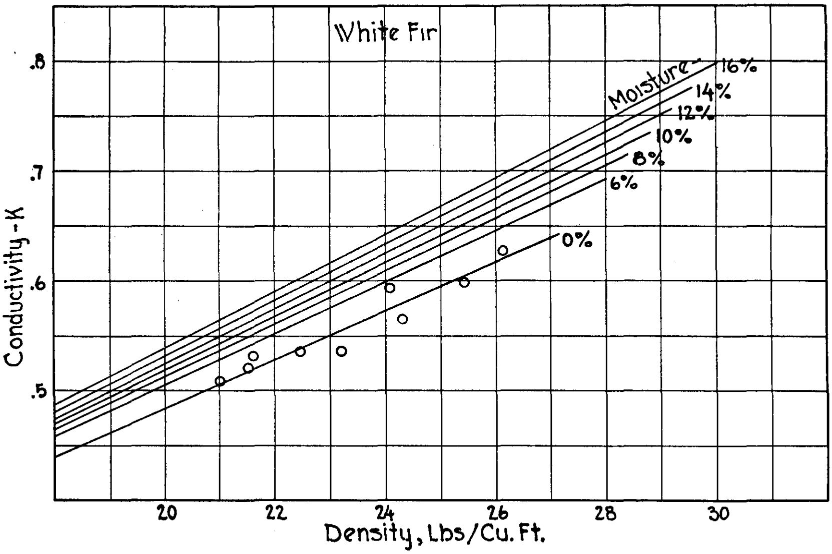


FIGURE 72. WHITE FIR—DENSITY-CONDUCTIVITY RELATION FOR DIFFERENT PERCENTAGES OF MOISTURE

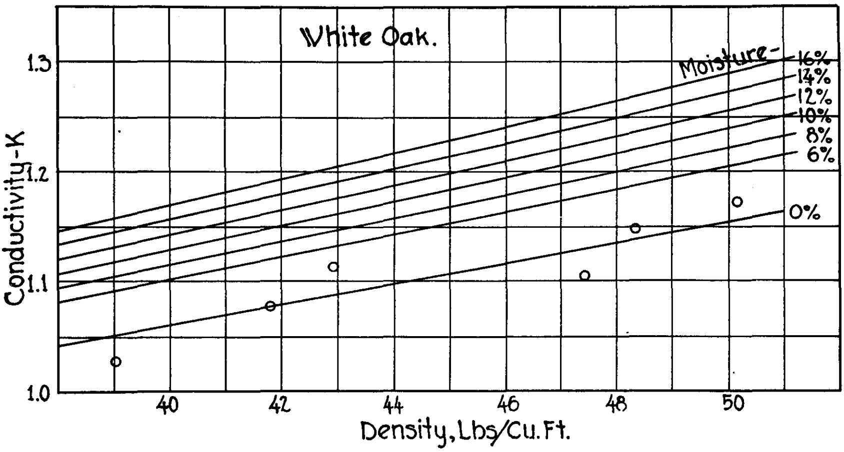


FIGURE 73. WHITE OAK—DENSITY-CONDUCTIVITY RELATION FOR DIFFERENT PERCENTAGES OF MOISTURE

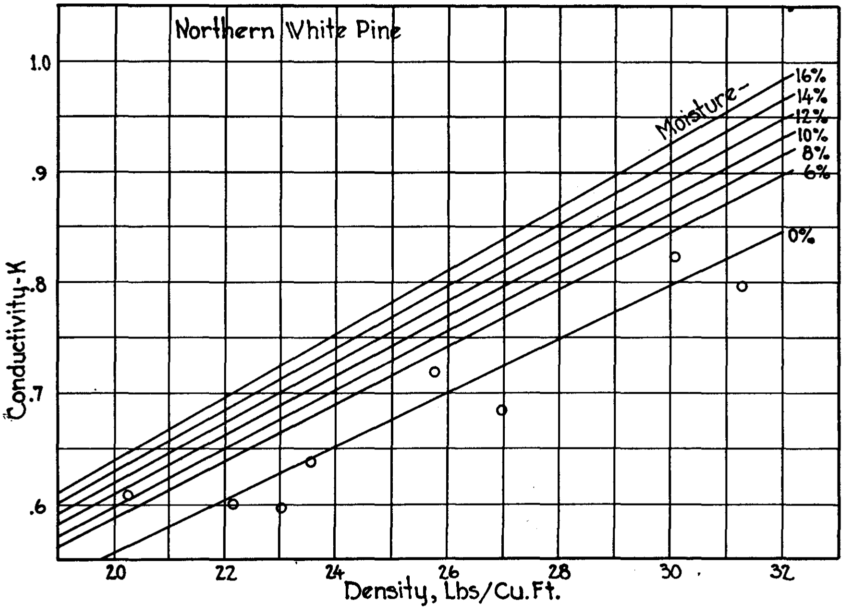


FIGURE 74. NORTHERN WHITE PINE—DENSITY-CONDUCTIVITY RELATION FOR DIFFERENT PERCENTAGES OF MOISTURE

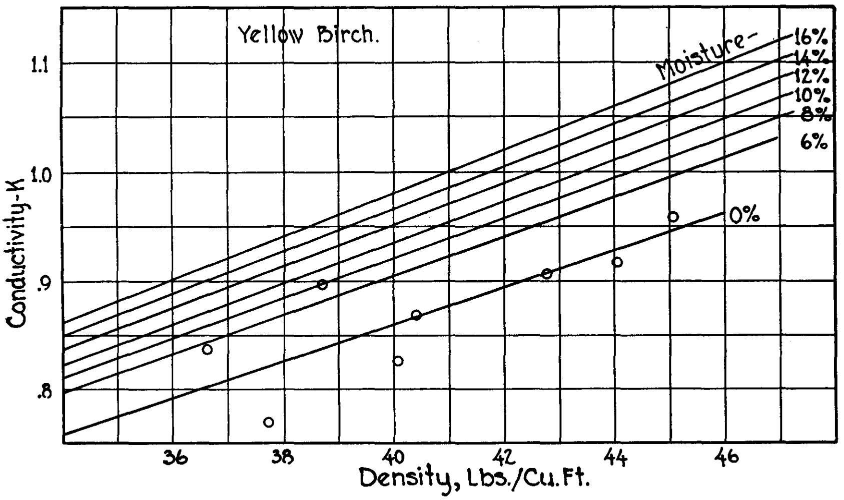


FIGURE 75. YELLOW BIRCH—DENSITY-CONDUCTIVITY RELATION FOR DIFFERENT PERCENTAGES OF MOISTURE

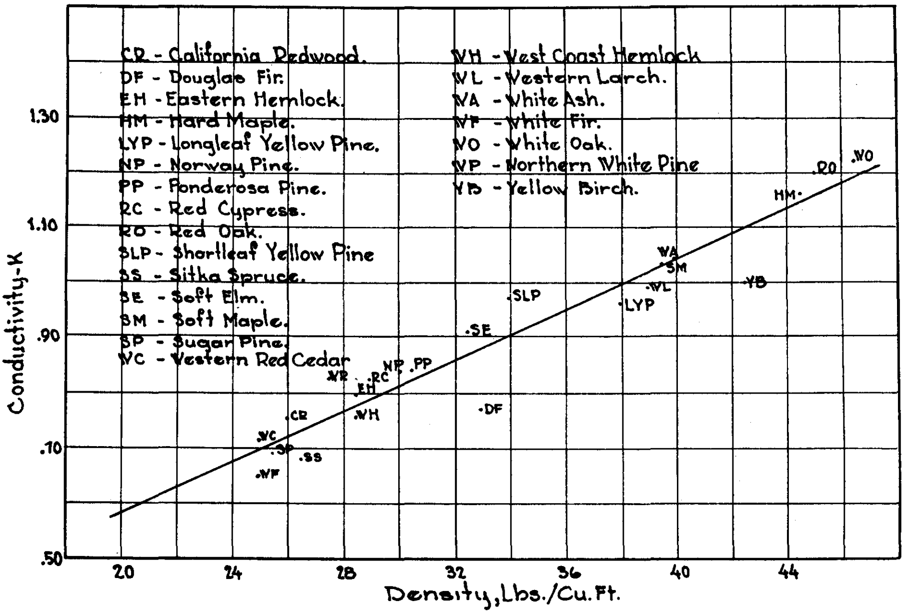


FIGURE 76. RELATION BETWEEN CONDUCTIVITY AND DENSITY AT 12 PER CENT MOISTURE FOR AVERAGE DENSITIES OF SPECIES AS TESTED

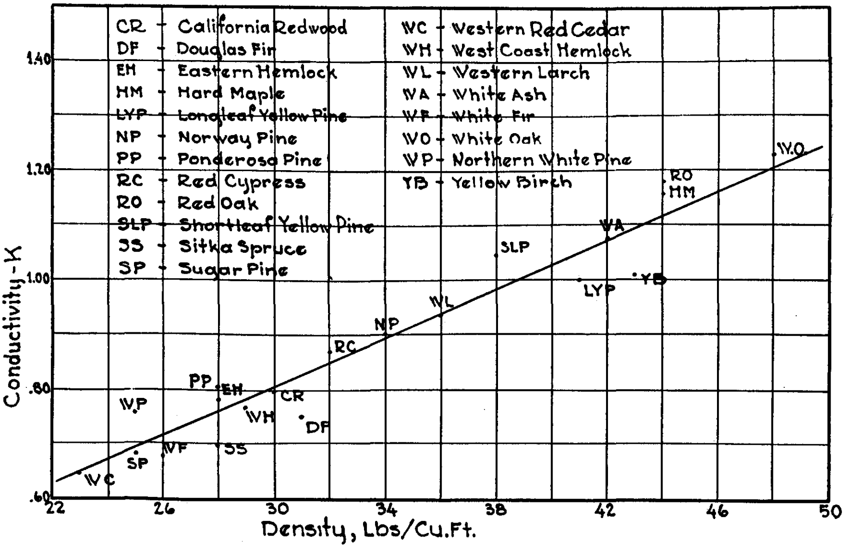


FIGURE 77. RELATION BETWEEN CONDUCTIVITY AND DENSITY AT 12 PER CENT MOISTURE FOR AVERAGE DENSITIES AS SELECTED FROM TECHNICAL BULLETIN NO. 158, UNITED STATES DEPARTMENT OF AGRICULTURE

cases such as California redwood, Norway pine, shortleaf pine, soft elm, white ash, and white fir, the densities of the materials tested were of a lower average than those given in the bulletin. The final curves of density-conductivity relation, however, for the several species as shown in Figures 76 and 77 are substantially the same.

The conductivity values for all species fall sufficiently close to the straight line to indicate that for practical purposes the straight line relation may be used when the moisture contents are the same.

For more complete data covering the actual samples selected and tested refer to paper, "Heat Conductivity of Wood at Climatic Temperature Differences," *Journal of the American Society of Heating and Ventilating Engineers,* Vol. 1, No. 1, pp. 313-23, June, 1933; *Transactions of the American Society of Heating and Ventilating Engineers,* Vol. 39, pp. 329-55. 1933.

RESULTS OF TESTS ON WALLS BY HOT BOX METHOD

Many different types of wall sections have been built up and tested by the hot box method to determine the over-all coefficient of thermal conductivity. About eighty of these tests were reported in Bulletin No. 8, *Heat Transmission through Building Materials,* and are included here in Figures 78 to 93, inclusive. This group includes frame, brick, tile, stone, concrete, and conder blocks with several special types of construction. A more extensive research was conducted on masonry and monolithic concrete construction as a co-operative research project by the Portland Cement Association, the American Society of Heating and Ventilating Engineers, and the University of Minnesota, the results of which are reported as a separate group of walls (see Figs. 94-106).

In all cases where a wall was built up with mortar joints or was given a plaster finish on the inside surface, sufficient time was allowed between the building and testing of the walls to thoroly dry the moisture from the mortar. In some cases walls were allowed to stand over and were tested at various intervals up to one year after construction to determine whether any change was taking place in the conductivity coefficient. As a general rule the walls were thoroly dried within a period of six weeks after construction. It is likely, however, that conditions surrounding many practical jobs are such that a longer period is necessary and in setting this time it is assumed that the concrete blocks used in the construction of the wall were thoroly dried out at the time of construction. Monolithic walls or heavy masonry walls would require a longer period before tests.

In making a test it was found necessary to place the wall in the test apparatus, adjust the air temperatures, and make an extended preliminary run in order to insure a uniform temperature gradient through the wall. The preliminary adjusting period depended on the conductivity and heat capacity of the wall under test. In heavy masonry construction it was necessary in some cases to run the apparatus under constant conditions for as much as 48 hours before test data were taken. After test conditions were established all readings were taken at 15-minute intervals and the test was continued until uniform results were insured. Various walls required from 8 to 16 hours for a complete test after constant conditions were established. Table VII gives test data as taken for Wall 53F and is typical for all test results.

TABLE VII

TYPICAL LOG OF TEST DATA

WALL 53F MARCH 27, 1929 RUN 556 - PAGE 2				HOT BOX READINGS					COLD ROOM READINGS			
				A	B	T	ITS		OTS		C	
READING No.	TIME	METER	WATTS	AIR TEMP. INNER BOX GROUP	AIR TEMP. OUTER BOX GROUP	AIR TEMP. INNER BOX GROUP-6" FROM WALL	TEMPERATURE INNER BOX-CENTER TEST SURFACE ITS-1	ITS-2	TEMPERATURE COLD ROOM CENTER TEST SURFACE OTS-1	OTS-2	AIR TEMPERATURE COLD ROOM SERIES 6" FROM WALL	
53	10:32:52	1039.20	7.75	1.032	1.031	1.026	.797	.800	-.400	-.413	-2.574	-.643
54	10:45			1.031	1.030	1.025	.796	.800	-.410	-.410	-2.601	-.650
55	11:00			1.033	1.032	1.023	.797	.801	-.405	-.415	-2.596	-.649
56	11:15			1.033	1.033	1.022	.796	.801	-.408	-.416	-2.631	-.658
57	11:41:07	1047.30	8.10	1.033	1.031	1.023	.799	.804	-.408	-.416	-2.570	-.648
58	11:45			1.033	1.031	1.023	.799	.804	-.412	-.426	-2.583	-.646
59	12:00			1.033	1.031	1.024	.797	.802	-.421	-.428	-2.593	-.648
60	12:15			1.032	1.030	1.024	.797	.803	-.422	-.427	-2.602	-.651
61	12:30			1.032	1.029	1.022	.797	.802	-.422	-.425	-2.590	-.647
62	12:44:47	1054.85	7.55	1.032	1.032	1.026	.797	.801	-.421	-.421	-2.574	-.643
63	1:00			1.031	1.030	1.026	.798	.803	-.418	-.415	-2.576	-.644
64	1:15			1.032	1.031	1.024	.797	.803	-.412	-.405	-2.568	-.642
65	1:30			1.031	1.033	1.024	.798	.802	-.401	-.410	-2.584	-.646
66	1:50:11	1062.70	7.85	1.031	1.033	1.025	.797	.803	-.405	-.425	-2.603	-.651
67	2:00			1.032	1.032	1.024	.798	.802	-.421	-.412	-2.596	-.649
68	2:15			1.032	1.032	1.025	.798	.803	-.404	-.418	-2.626	-.657
69	2:30			1.031	1.032	1.027	.799	.804	-.420	-.430	-2.651	-.663
70	2:48:25	1069.75	6.95	1.031	1.031	1.024	.798	.802	-.426	-.427	-2.638	-.659
71	3:00			1.031	1.031	1.022	.798	.802	-.421	-.428	-2.632	-.658
72	3:15			1.031	1.031	1.020	.797	.803	-.425	-.419	-2.625	-.656
73	3:30			1.032	1.033	1.025	.799	.804	-.429	-.418	-2.601	-.650
74	4:00			1.031	1.032	1.026	.798	.803	-.426	-.416	-2.535	-.634
75	4:15			1.031	1.032	1.024	.798	.804	-.415	-.413	-2.584	-.646
76	4:31:17	1082.10	12.45	1.032	1.032	1.026	.798	.803	-.415	-.430	-2.576	-.644
77	4:45			1.031	1.032	1.026	.797	.803	-.408	-.428	-2.568	-.642
78	5:00			1.032	1.032	1.023	.797	.803	-.410	-.415	-2.595	-.649
79	5:15			1.031	1.031	1.023	.797	.804	-.413	-.405	-2.552	-.638
80	5:35:38	1089.55	7.45	1.031	1.032	1.023	.798	.805	-.395	-.400	-2.572	-.643
81	5:45			1.034	1.034	1.023	.798	.804	-.390	-.406	-2.595	-.649
82	6:00			1.033	1.033	1.022	.799	.805	-.396	-.402	-2.583	-.646
83	6:15			1.032	1.032	1.023	.802	.807	-.395	-.398	-2.572	-.643
84	6:30			1.032	1.033	1.023	.801	.806	-.395	-.398	-2.535	-.634
85	6:49:10	1098.20	8.65	1.032	1.033	1.023	.802	.806	-.395	-.395	-2.556	-.639
	TOTAL 8.272	59.00		AVE. 1.032	AVE. 1.032	AVE. 1.024	AVE. .798	AVE. .803	AVE. .411	AVE. .415	AVERAGE	.647
				79.31°	79.30°	79.10°	69.05°		11.35°			+40°

TIME - START 6:49:10
END 10:32:52
TOTAL 8.272

METER - START 1039.20
END 1098.20
DIFF. 59.00

BOX CORR. = .298 x 45 x 8.272 x .01 = 1.109

$$U = \frac{[(59.00 \times 6.256) + (.34 \times 8.272)]\, 3.415 - 1.109}{78.91 \times 9 \times 8.272}$$

U = .2170 M.T. = 39.85°

$$C = \frac{1268.984}{57.70 \times 74.448} = .296$$

M.T. = 40.20°

$$f_i = \frac{1268.984}{10.26 \times 74.448} = 1.661$$

M.T. = 74.18°

$$f_o = \frac{1268.984}{10.95 \times 74.448} = 1.557$$

M.T. = 5.87°

For those walls reported in Bulletin No. 8 the details of construction are given in Tables VIII and IX and in Figures 78 to 93, inclusive. Each wall is designated by a number which is followed throughout the description and test results. The identifying numbers used for these walls are independent and must not be confused with the numbers used in the series of concrete walls which follow. The complete details of construction of each wall may be obtained by referring to Table VIII and the corresponding drawing of the wall. In cases where insulating materials were used in the wall construction they are designated by a letter. The thickness and location of the insulation material in the wall are shown in Table VIII while the description and insulating qualities of the material are given in Table IX. Due to the fact that many insulating materials of different trade names have similar characteristics and will give comparable results when placed in a wall in the same manner and also in order to avoid the use of trade names these materials were designated by letters, giving in so far as possible, the complete properties of the material. In all cases where building paper was used in the walls it was known as No. 2 building felt with an average weight of 44 to 45 pounds per roll of 324 square feet.

To get a complete description of any wall it is necessary to refer to the figure showing that wall, together with Table VIII. If insulating material has been used in its construction it is then necessary to refer to Table IX to get the thickness of the insulating material and its insulating value. In several cases a single figure represents more than one wall number. In case the walls are of identical construction the average value of *U* is given. If, however, the walls are of different construction such as having different thickness of insulating material, the heat transmission coefficients are given for each wall number.

A summary of test results for all walls is given in Table X. In this table, two values for the over-all coefficients *U* are given:

1. That obtained by test.
2. A coefficient corrected for a 15-mile wind velocity over the outside surface of the wall. In making this correction, an average outside surface coefficient of 1.65 was taken as that obtained by test. This was the average for all tests which were made under the same conditions of air velocity over cold surfaces. The average was used on account of the difficulty in obtaining accurate surface coefficients on such surfaces as stucco, lap siding, etc. The corrected coefficient for a 15-mile wind was taken from the curves of Figure 33. These values were reduced 15 per cent to get average conditions for all angles between direction of wind and test surface.

In many cases, several tests were run on the same wall, using different mean temperatures of the air on the two sides of the wall. In such tests the results at 40° F. mean temperature are reported as the value of *U,* which is given in Table X and with the figure showing the construction of the wall.

TABLE VIII

DESCRIPTION OF WALLS AS TESTED FOR FIGURES 78 TO 93

Wall No.	Figure Showing Construction	Type of Wall	Inside Construction	Outside Construction	Additional Insulation
7	78	Wood frame	⅜-inch gypsum with paper covered surfaces	Fir sheathing Building paper 4-inch pine lap siding	None
7-A	78	Wood frame	⅜-inch plaster ⅜-inch wood lath	Fir sheathing Building paper 4-inch pine lap siding	None
8	78	Wood frame	⅜-inch plaster ⅜-inch wood lath	Fir sheathing Building paper 4-inch pine lap siding	None
8-A	78	Wood frame	⅜-inch plaster ⅜-inch wood lath	Fir sheathing Building paper 4-inch pine lap siding	None
8-B	82	Wood frame	⅜-inch plaster ⅜-inch wood lath	Fir sheathing Building paper 4-inch pine lap siding	Two thicknesses of ⅛-inch corrugated paper spaced between studs to divide air space into 3 equal parts
9	80	Wood frame	⅜-inch plaster ⅜-inch wood lath	Fir sheathing Building paper 4-inch pine lap siding	Insulation D, flanged midway in air space between studding
10	78	Wood frame	⅜-inch plaster ⅜-inch wood lath	Insulation A Building paper 4-inch pine lap siding	None
11	78	Wood frame	⅜-inch plaster Insulation A	Insulation A Building paper 4-inch pine lap siding	None
12	79	Wood frame	⅜-inch plaster ⅜-inch wood lath	Fir sheathing Building paper 4-inch pine lap siding	Insulation F, ⅝ inch thick, flanged midway in air space between studding
15	79	Wood frame	⅜-inch plaster ⅜-inch wood lath	Fir sheathing Building paper 4-inch pine lap siding	Insulation G, ¼ inch thick, flanged midway in air space between studding
16	79	Wood frame	⅜-inch plaster ⅜-inch wood lath	Fir sheathing Building paper 4-inch pine lap siding	Insulation F, ⅝ inch thick, nailed on studding under sheathing

TABLE VIII—*Continued*

Wall No.	Figure Showing Construction	Type of Wall	Inside Construction	Outside Construction	Additional Insulation
17	83	Wood frame	⅜-inch plaster ⅜-inch wood lath	Fir sheathing Building paper 4-inch pine lap siding	Insulation K poured between studding, 3½ inches thick
18	83	Wood frame	⅜-inch plaster ⅜-inch wood lath	Fir sheathing Building paper Metal lath Stucco	Insulation I placed between studding, 3½ inches thick
19	80	Wood frame	⅜-inch plaster ⅜-inch wood lath	Fir sheathing Building paper 4-inch pine lap siding	Insulation D placed between studs against sheathing
21	87	8-inch 3-cell tile	½-inch plaster Insulation A 1-inch furring strips	¾-inch stucco on surface of tile	None
22	87	8-inch 3-cell tile	½-inch plaster on surface of tile	¾-inch stucco on surface of tile	None
23	85	Special	Insulation C	Insulation C	None
24	87	8-inch 3-cell tile	½-inch plaster ⅜-inch wood lath 1-inch furring strips	¾-inch stucco on surface of tile	None
25	85	Special	Insulation A	Insulation A	None
26	82	Wood frame	⅜-inch plaster Insulation C	Insulation C Building paper 4-inch pine lap siding	None
27	85	Wood frame	Insulation A	Insulation A Building paper 4-inch pine lap siding	None
28	82	Wood frame	⅜-inch plaster ⅜-inch wood lath	Fir sheathing Building paper 4-inch pine lap siding	Two thicknesses waterproofed roofing felt spaced between studs to divide air space into 3 equal parts
29	82	Wood frame	⅜-inch plaster ⅜-inch wood lath	Fir sheathing Building paper 4-inch pine lap siding	Two thicknesses waterproofed roofing felt nailed to each side of studs bowed in at center 1¼ inches

TABLE VIII—*Continued*

Wall No.	Figure Showing Construction	Type of Wall	Inside Construction	Outside Construction	Additional Insulation
30	78	Wood frame	⅜-inch plaster Insulation A	Insulation A Building paper 4-inch pine lap siding	None
31	85	Wood frame	⅜-inch plaster Insulation A, .7 inch thick	Insulation A, .7 inch thick 4-inch pine lap siding	None
32	80	Wood frame	⅜-inch plaster ⅜-inch wood lath	Fir sheathing Building paper 4-inch pine lap siding	Insulation D flanged midway in air space, between studding
33	83	Wood frame	⅜-inch plaster ⅜-inch wood lath	Fir sheathing Building paper 4-inch pine lap siding	Insulation J, 1.11 inches thick back against sheathing, blown in place
34	81	Wood frame	⅜-inch plaster ⅜-inch wood lath	Fir sheathing Building paper 4-inch pine lap siding	Insulation A with one surface papered, flanged midway in air space between studding
35	79	Wood frame	⅜-inch gypsum with paper covered surfaces	Fir sheathing Building paper 4-inch pine lap siding	Insulation F, ⅝ inch thick, flanged midway in air space between studding
36	80	Wood frame	⅜-inch gypsum with paper covered surfaces	Fir sheathing Building paper 4-inch pine lap siding	Insulation D papered surfaces, flanged midway in air space between studding
37	93	Wood frame	⅜-inch plaster ⅜-inch wood lath	Fir sheathing Building paper Face brick with three 1-inch holes in each brick	Insulation J, 1.11 inches thick back against sheathing, blown in place
40-B	79	Wood frame	⅜-inch plaster ⅜-inch wood lath	Fir sheathing Building paper 4-inch pine lap siding	Insulation F, 1 inch thick, flanged midway in air space between studding
41	81	Wood frame	⅜-inch plaster ⅜-inch wood lath	Fir sheathing Building paper 4-inch pine lap siding	Insulation H nailed on studding under sheathing.
42	93	Brick	⅜-inch plaster ⅜-inch wood lath	1⅝×1⅝-inch furring strip Common clay brick ¾-inch air space Face brick	Insulation J, .814 inch thick, against common clay brick, blown in place

TABLE VIII—*Continued*

WALL NO.	FIGURE SHOWING CONSTRUCTION	TYPE OF WALL	INSIDE CONSTRUCTION	OUTSIDE CONSTRUCTION	ADDITIONAL INSULATION
47	86	Special, two ⅜-inch panels with 1-inch air space	⅜-inch gypsum board, both surfaces covered with paper	⅜-inch gypsum board, both surfaces covered with paper	None
50	93	Brick	One tier of common yellow clay brick	One tier of common yellow clay brick	None
51	92	Brick	One tier of common yellow clay brick	One tier of common yellow clay brick	None
52	92	Brick	One tier of common yellow clay brick	One tier of red clay pressed brick	None
53-A	78	Wood frame	⅜-inch gypsum with paper covered surfaces	Fir sheathing Building paper 4-inch pine lap siding	None
53-B	81	Wood frame	⅜-inch gypsum with paper covered surfaces	Fir sheathing Building paper 4-inch pine lap siding	Insulation D flanged midway in air space between studding
53-C	81	Wood frame	⅜-inch gypsum with paper covered surfaces	Fir sheathing Building paper 4-inch pine lap siding	Insulation D flanged midway in air space between studding with 1 inch of insulation removed from top and bottom
53-D	81	Wood frame	⅜-inch gypsum with paper covered surfaces	Fir sheathing Building paper 4-inch pine lap siding	Insulation F flanged midway in air space between studding
53-E	81	Wood frame	⅜-inch gypsum with paper covered surfaces	Fir sheathing Building paper 4-inch pine lap siding	Insulation F flanged midway in air space between studding with 1-inch insulation removed from top and bottom
53-F	78	Wood frame	⅜-inch plaster ⅜-inch wood lath	Fir sheathing Building paper 4-inch pine lap siding	None
54	86	Special	Fir sheathing Building paper 4-inch pine lap siding	Fir sheathing Building paper 4-inch pine lap siding	None
55	93	Concrete, 5.95 inches thick	Concrete	Concrete	None

TABLE VIII—*Continued*

Wall No.	Figure Showing Construction	Type of Wall	Inside Construction	Outside Construction	Additional Insulation
56	86	Special	¾-inch stucco Metal lath Building paper Fir sheathing	¾-inch stucco Metal lath Building paper Fir sheathing	None
57	86	Special	⅜-inch plaster ⅜-inch wood lath	⅜-inch plaster ⅜-inch wood lath	None
57-B	86	Special	⅜-inch plaster ⅜-inch wood lath	⅜-inch plaster ⅜-inch wood lath	None
59	87	8-inch clay tile	Tile	Tile	None
60	88	8-inch clay tile	Tile	Tile	½-inch flexible insulating strips and pads in mortar joints
61	89	8-inch clay tile	⅜-inch plaster on surface of tile	Tile	½-inch flexible insulating strips and pads in mortar joints
61-A	88	8-inch clay tile	Tile	Tile	½-inch flexible insulating strips and pads in mortar joints
62	89	12-inch clay tile	Tile	Tile	None
63	88	8-inch clay tile	Tile	Tile	None
64	88	8-inch clay tile	Tile	Tile	None
65	89	8-inch clay tile	⅜-inch plaster on surface of tile	⅝-inch stucco on surface of tile	½-inch flexible insulating strips and pads in mortar joints
66	88	8-inch clay tile	Tile (solid mortar joint)	Tile (solid mortar joint)	None
67	89	8-inch clay tile	Tile (solid mortar joint)	Tile (solid mortar joint)	None
68	93	Concrete 6 inches thick	Concrete	Concrete	None
69	93	Concrete 6 inches thick	Concrete	Concrete	None
70	91	8-inch cinder block	Cinder block	Cinder block	None
71	92	8-inch concrete block	Concrete block	Concrete block	None

TABLE VIII—*Continued*

Wall No.	Figure Showing Construction	Type of Wall	Inside Construction	Outside Construction	Additional Insulation
72	92	8-inch concrete-block	Concrete block	Concrete block	None
73	92	12-inch concrete block	Concrete block	Concrete block	None
74	92	12-inch concrete block	Concrete block	Concrete block	None
75	91	Rubble stone, 8.03 inches thick	Rubble stone	Rubble stone	None
76	91	Rubble stone, 8.22 inches thick	Rubble stone	Rubble stone	None
77	83	Wood frame	⅜-inch plaster ⅜-inch wood lath	Fir sheathing Building paper 4-inch pine lap siding	Insulation I, 2.78 inches thick, placed back against sheathing, hand-packed in place
81	90	4-inch 3-cell gypsum partition tile	Plain gypsum surface	Plain gypsum surface	None
82	91	3-inch 4-cell gypsum partition tile	Plain gypsum surface	Plain gypsum surface	None
83	91	3-inch solid gypsum partition tile	Plain gypsum surface	Plain gypsum surface	None
86	84	Wood frame	⅜-inch plaster Insulation A	Fir sheathing Building paper 4-inch pine lap siding	None
87	84	Wood frame	⅜-inch plaster Insulation C	Fir sheathing Building paper 4-inch pine lap siding	None
88	84	Wood frame	⅜-inch plaster Insulation B	Fir sheathing Building paper 4-inch pine lap siding	None
89	84	Wood frame	½-inch plaster Insulation E	Fir sheathing Building paper 4-inch pine lap siding	None
90	90	8-inch clay tile	Tile	Tile	None
91	90	8-inch clay tile	Tile	Tile	None
92	90	8-inch clay tile	Tile	Tile	None

TABLE IX

DESCRIPTION OF INSULATING MATERIALS USED IN WALL CONSTRUCTION WITH CONDUCTIVITIES BY HOT PLATE METHOD FOR FIGURES 78 TO 93

Mark Designating Material	Description of Material	Tested	Average Thickness Inches	Average Density Lb./Cu. Ft.	M.T	Conductivity
A	Rigid wood fiber board	Dry	.500	16.12	75.06	.343
B	Rigid wood fiber board	Dry	.486	16.99	74.9	.373
C	Rigid cereal fiber board	Dry	.450	15.59	74.75	.348
D	Semi-rigid flax fiber board	Dry	.553	13.17	61.9	.312
		Dry	.500	12.76	75.6	.317
E	Semi-rigid flax fiber board with heavy waterproofed asphalt, paper, and metal lath on one side					
F	Felted wood fiber between 2 layers of heavy waterproofed paper	Dry	.496	4.39	77.3	.254
		As received	.497	3.65	76.8	.264
G	Hair felted and stitched between 2 layers of heavy waterproofed paper	As received	.269	9.72	66.9	.250
H	Ell grass felted and stitched between 2 layers of heavy waterproofed paper	As received	.413	8.38	75.7	.275
I	Limestone melted and blown into a fibrous form	As received	3.50 2.78	7.6	75.0	.260
J	Shredded paper with bonding solution sprayed on wall	As received	1.110 .814	5.78	61.6	.283
K	Cellular gypsum material poured into place	Dry	3.500	10.90	69.78	.447
		As received	3.500	11.05	72.50	.482

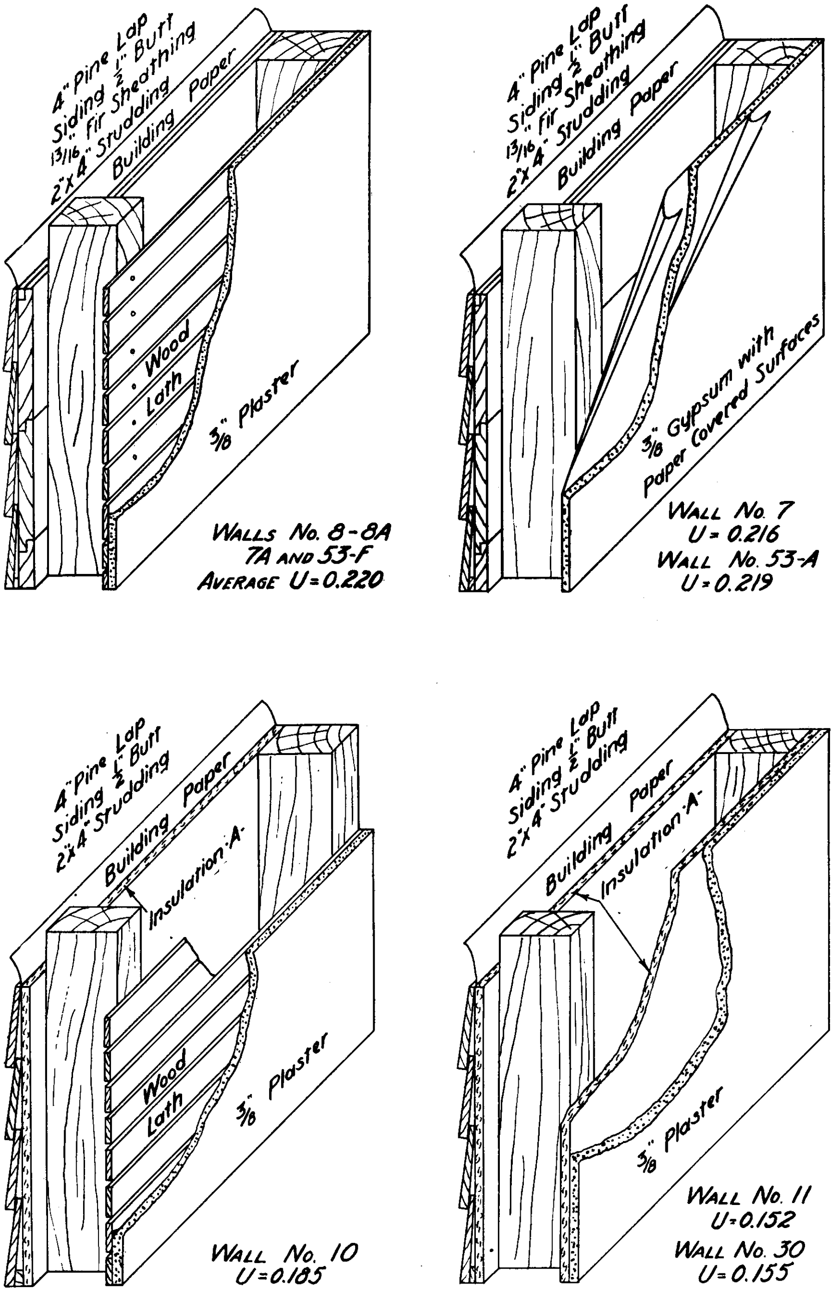


FIGURE 78. SECTIONAL VIEWS OF TEST WALLS

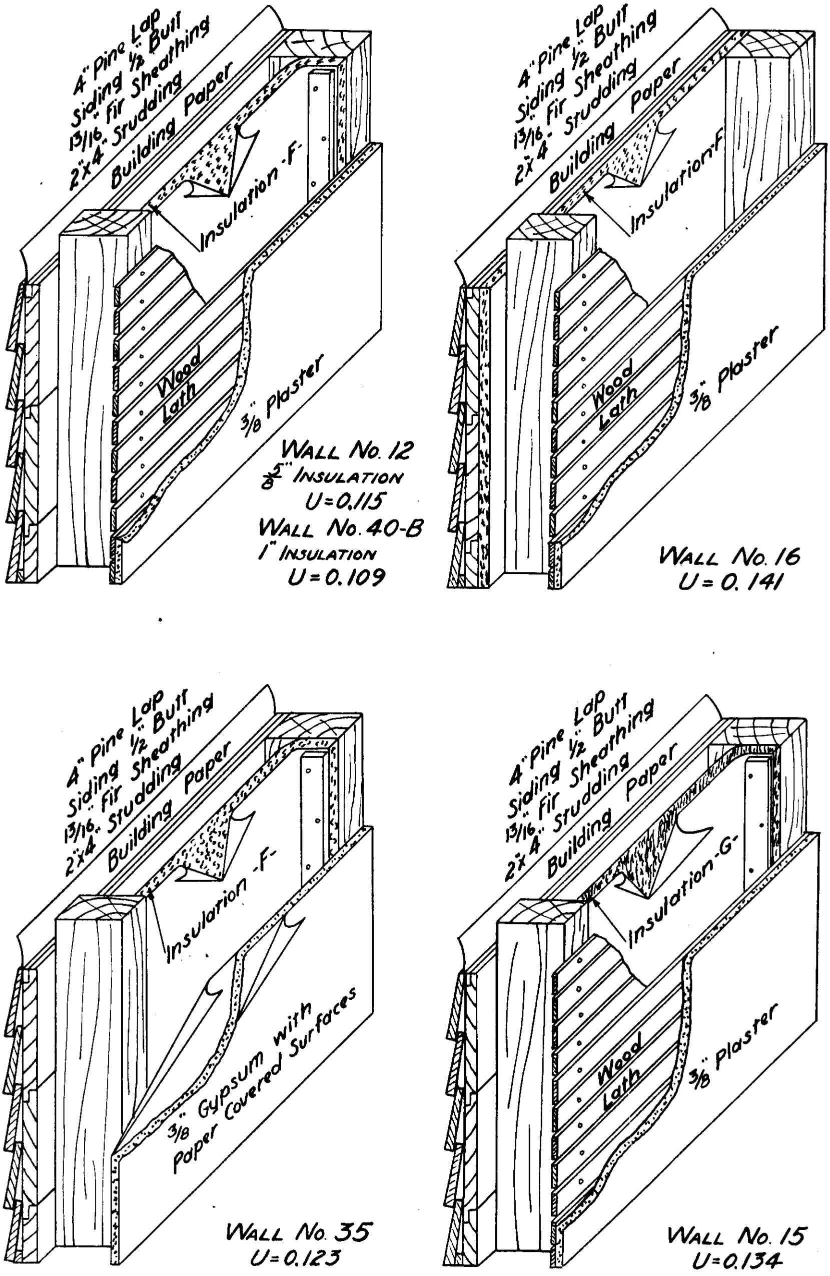


FIGURE 79. SECTIONAL VIEWS OF TEST WALLS

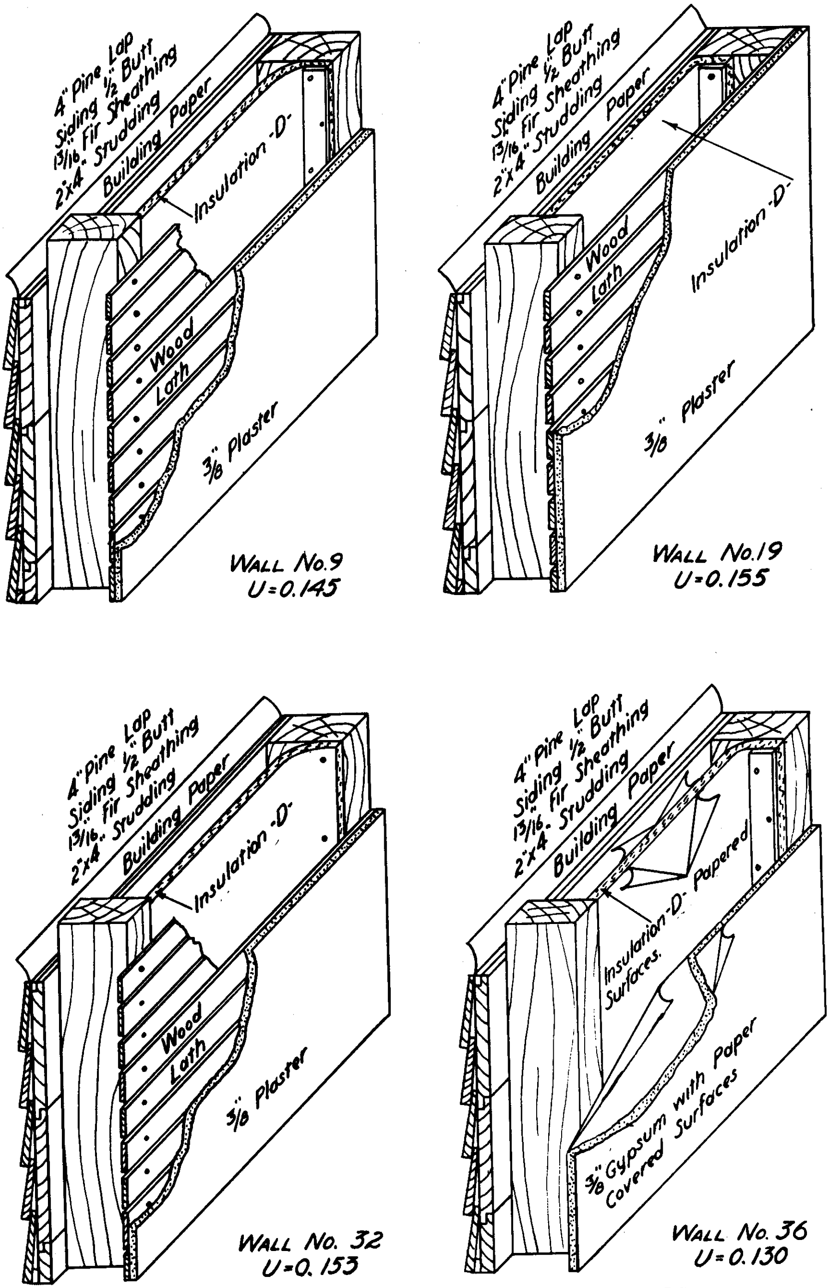


FIGURE 80. SECTIONAL VIEWS OF TEST WALLS

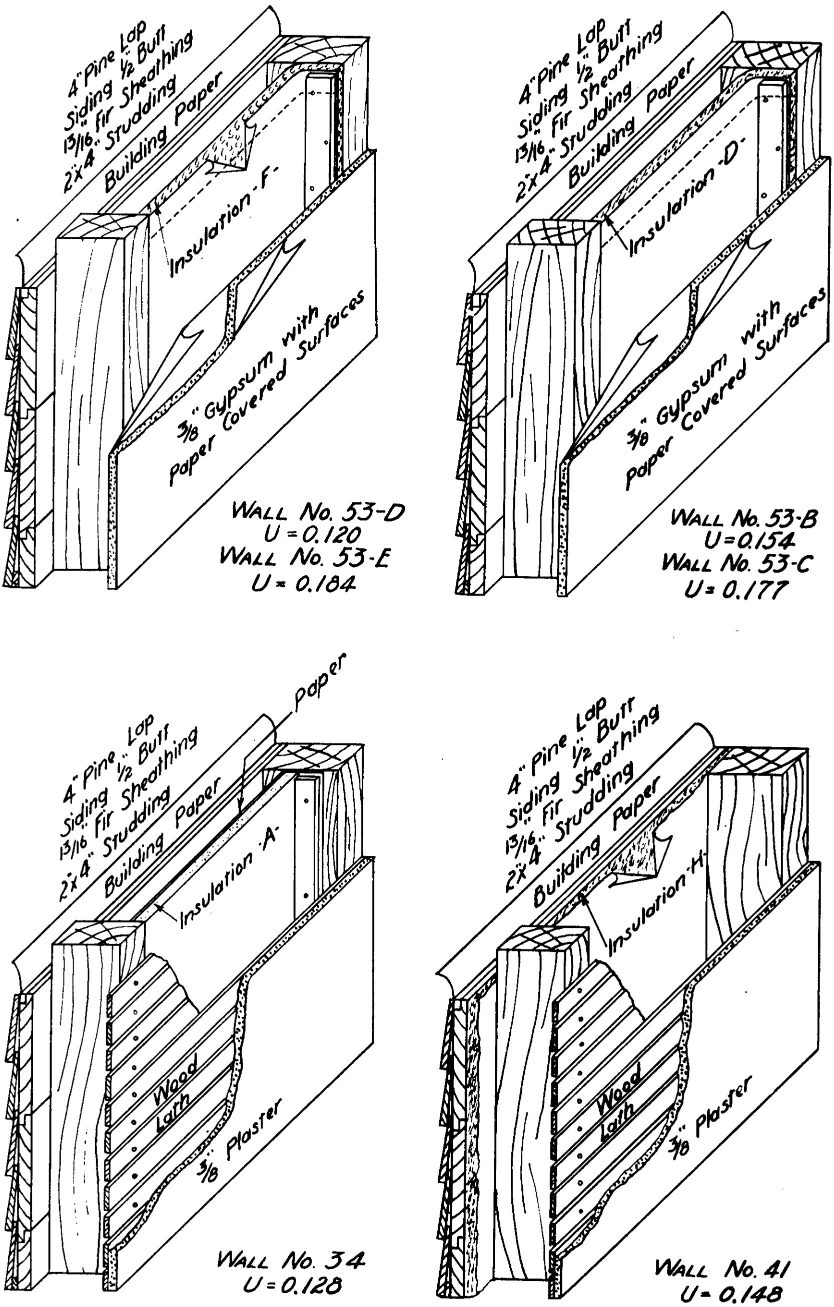
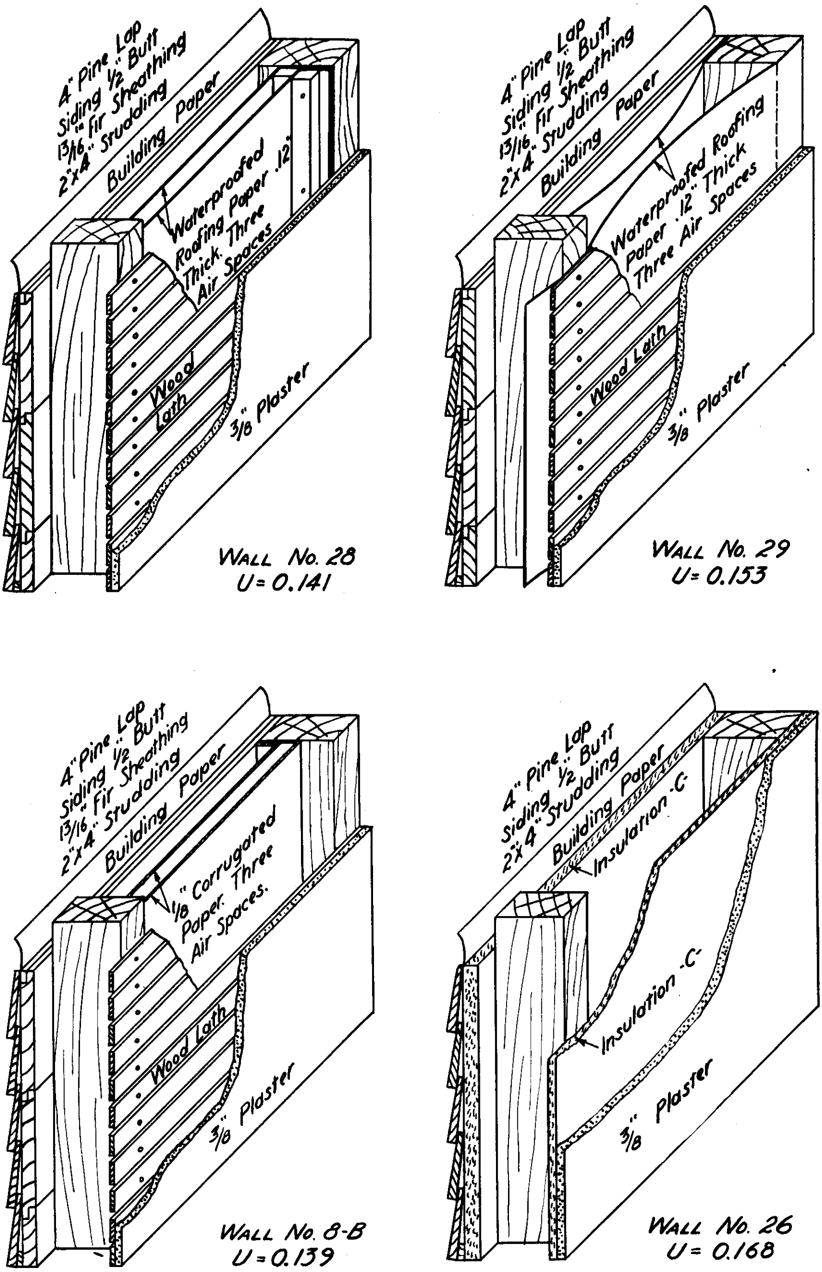


FIGURE 81. SECTIONAL VIEWS OF TEST WALLS



WALL No. 28
U= 0.141

WALL No. 29
U= 0.153

WALL No. 8-B
U= 0.139

WALL No. 26
U= 0.168

FIGURE 82. SECTIONAL VIEWS OF TEST WALLS

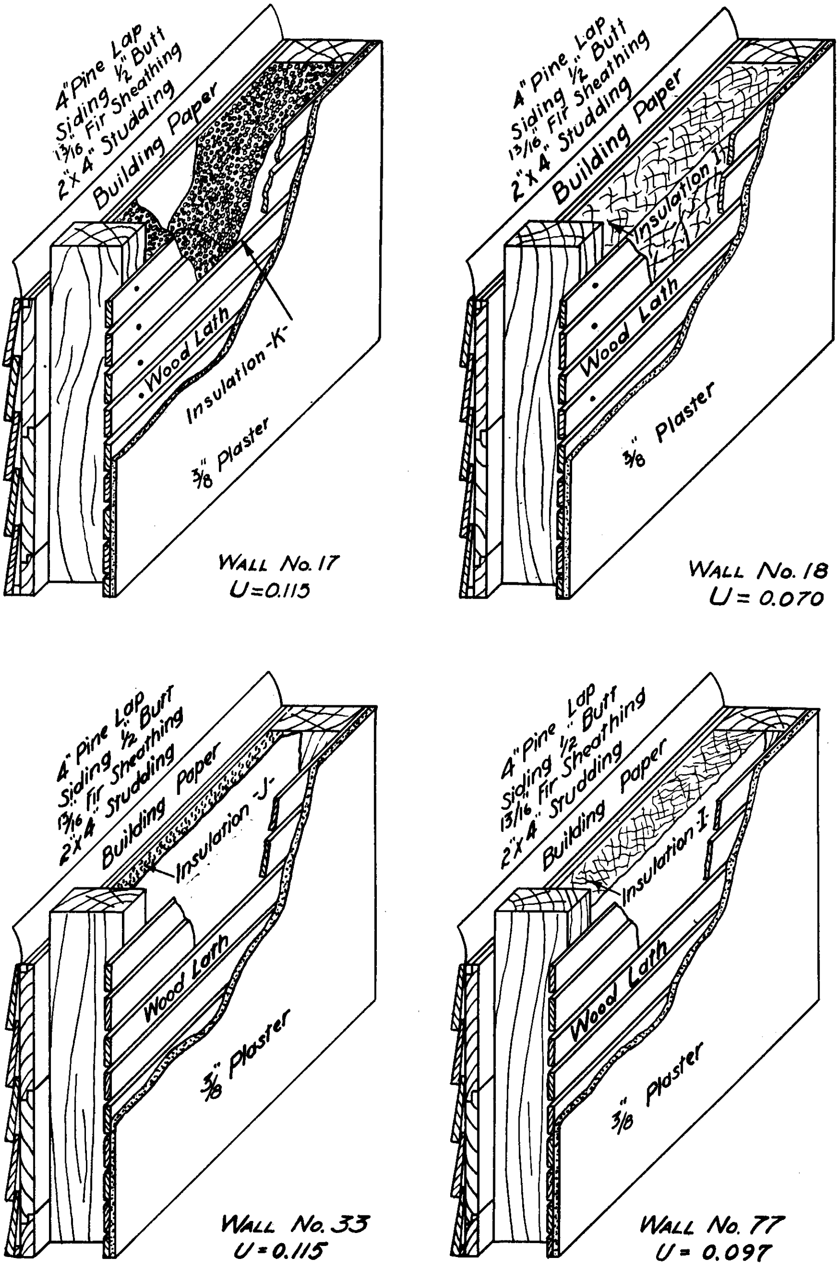


FIGURE 83. SECTIONAL VIEWS OF TEST WALLS

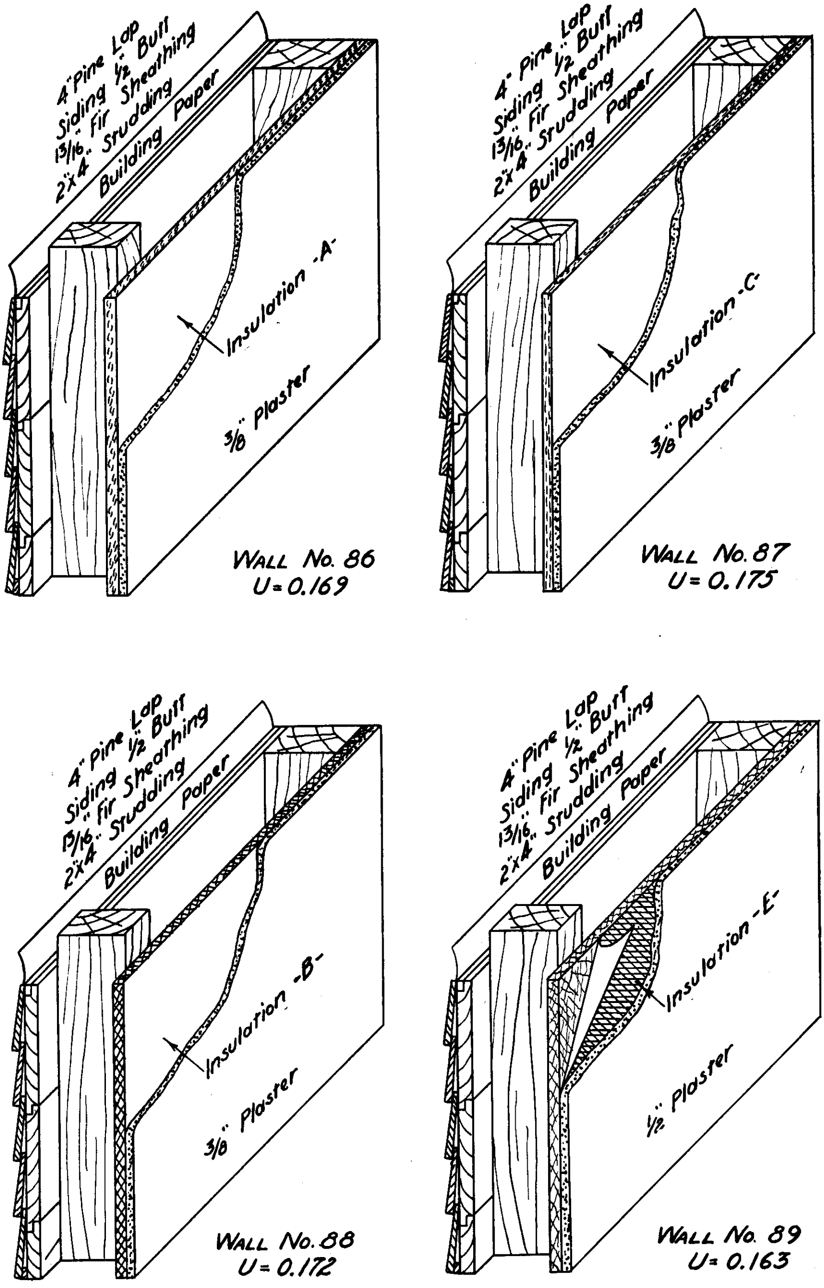


FIGURE 84. SECTIONAL VIEWS OF TEST WALLS

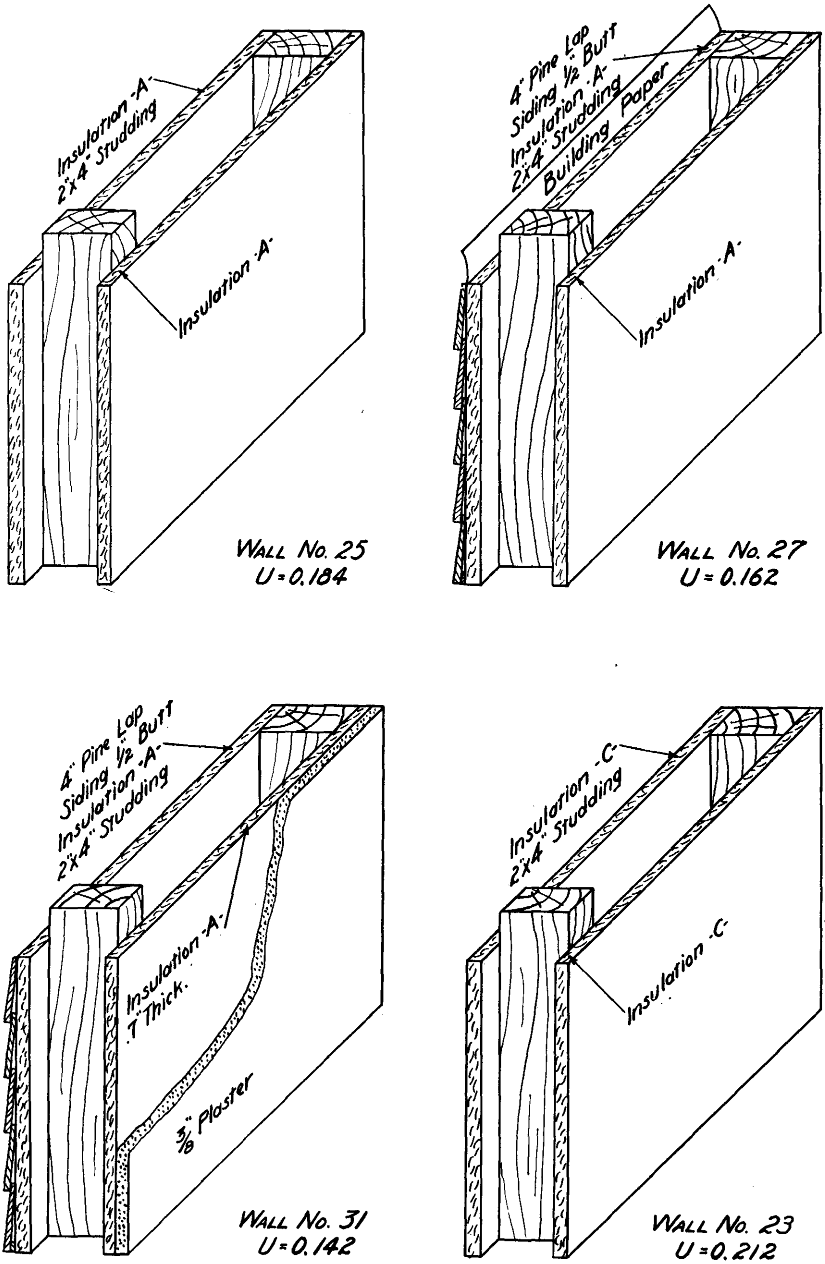


FIGURE 85. SECTIONAL VIEWS OF TEST WALLS

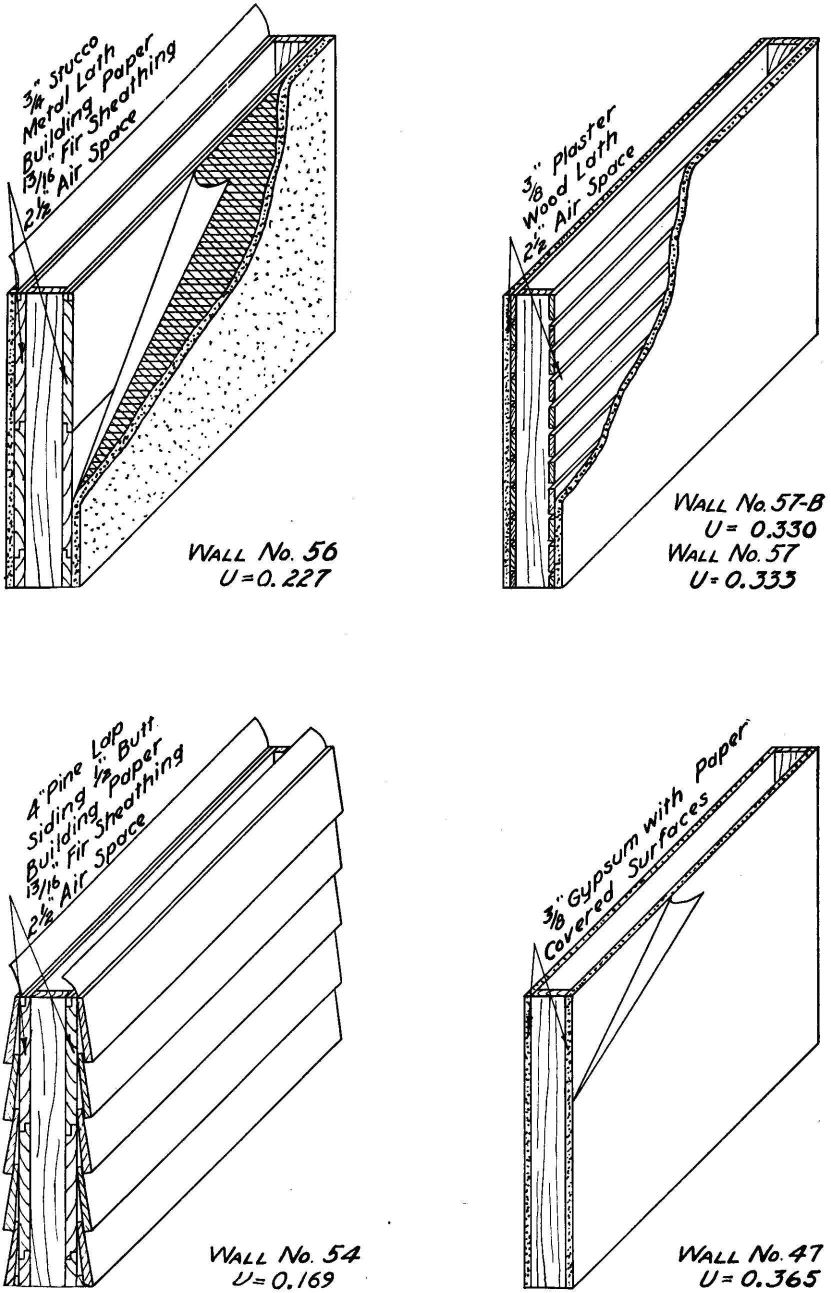


FIGURE 86. SECTIONAL VIEWS OF TEST WALLS

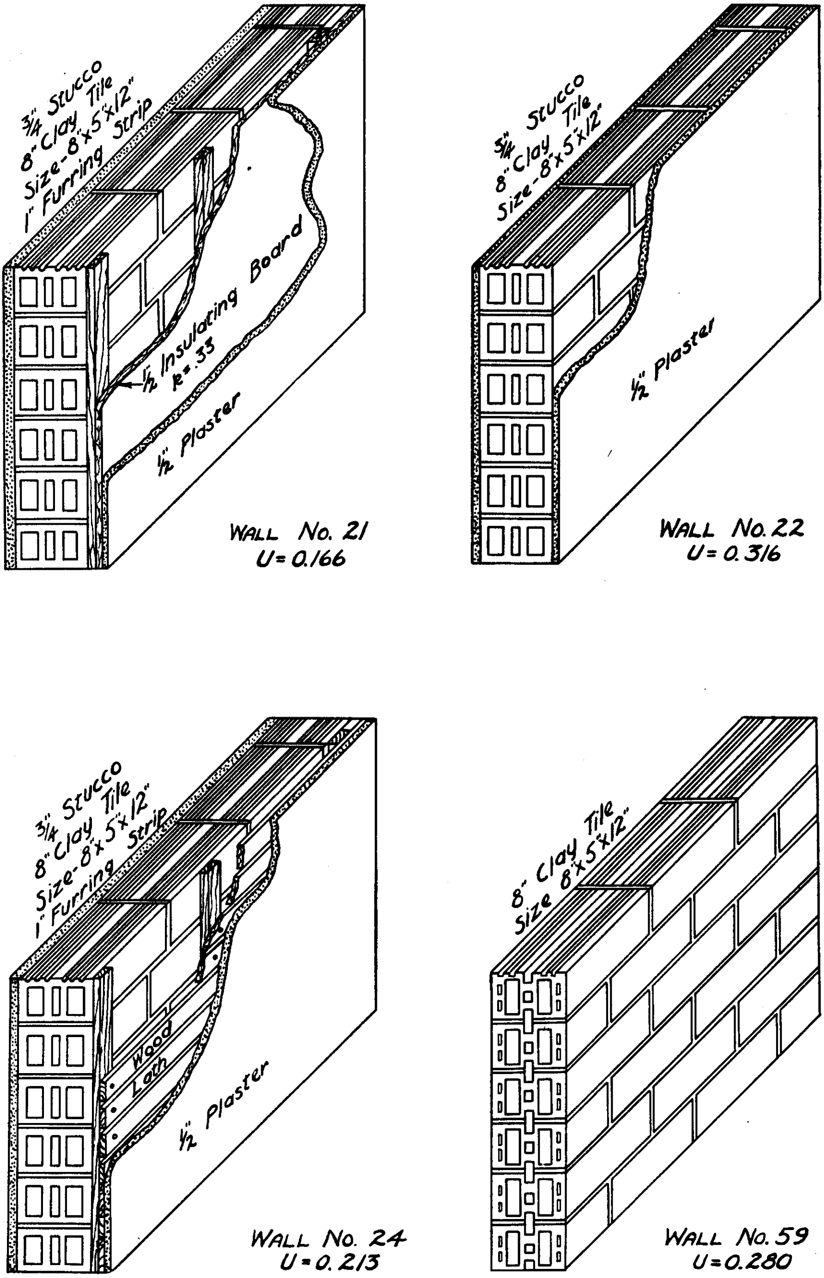


FIGURE 87. SECTIONAL VIEWS OF TEST WALLS

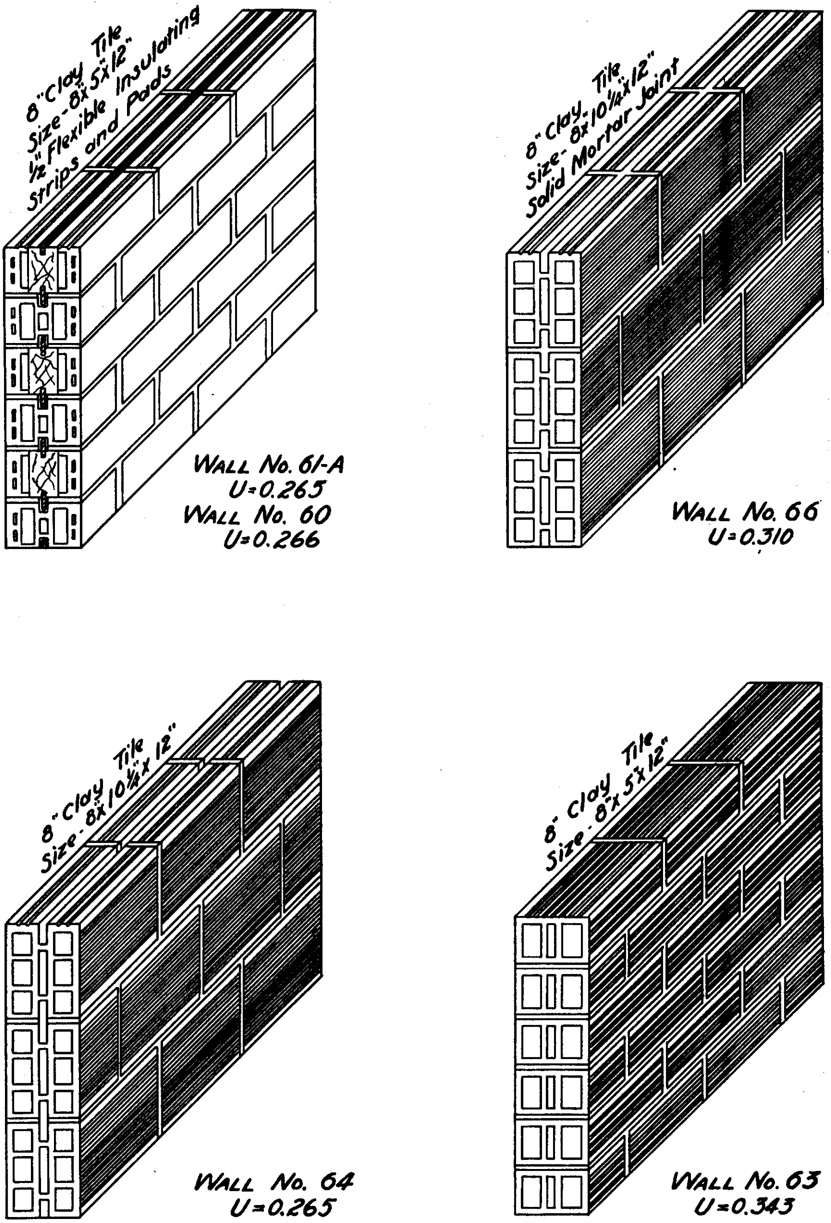


FIGURE 88. SECTIONAL VIEWS OF TEST WALLS

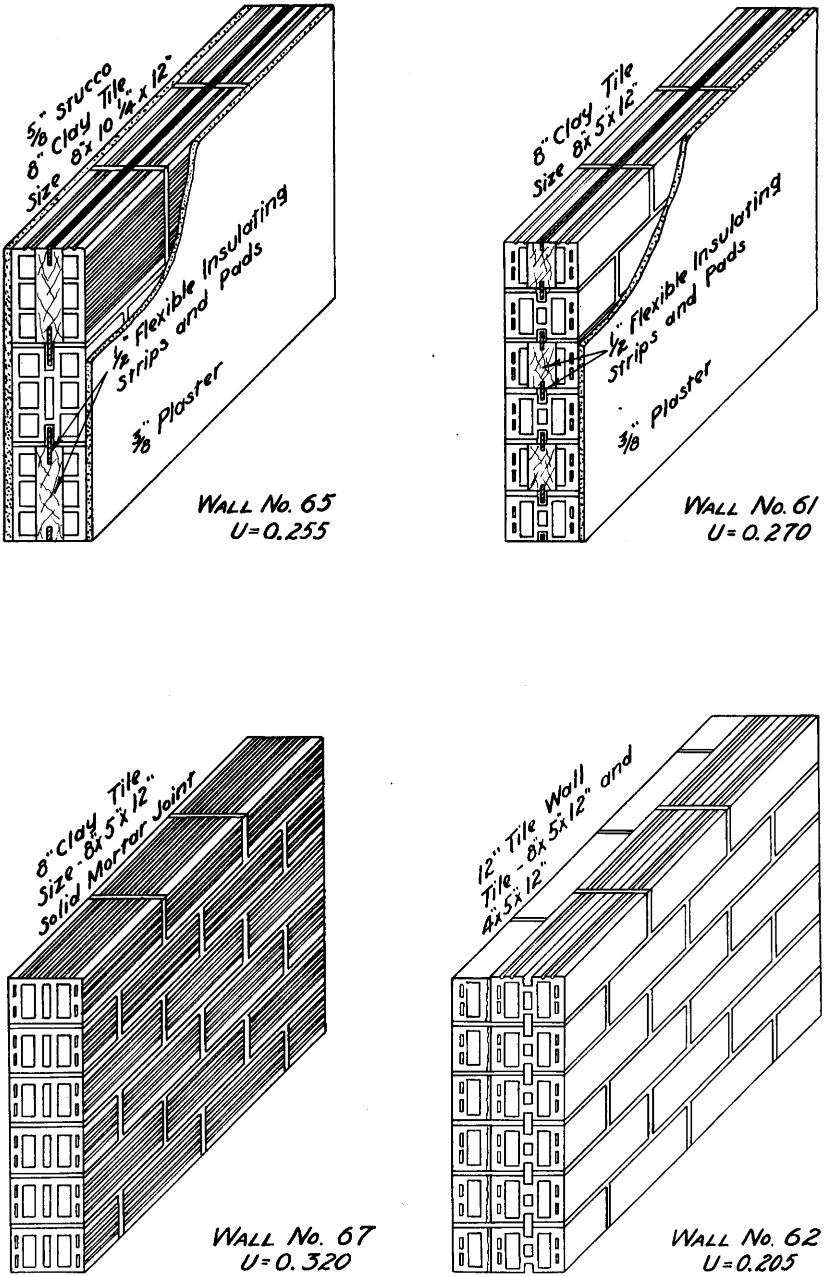


FIGURE 89. SECTIONAL VIEWS OF TEST WALLS

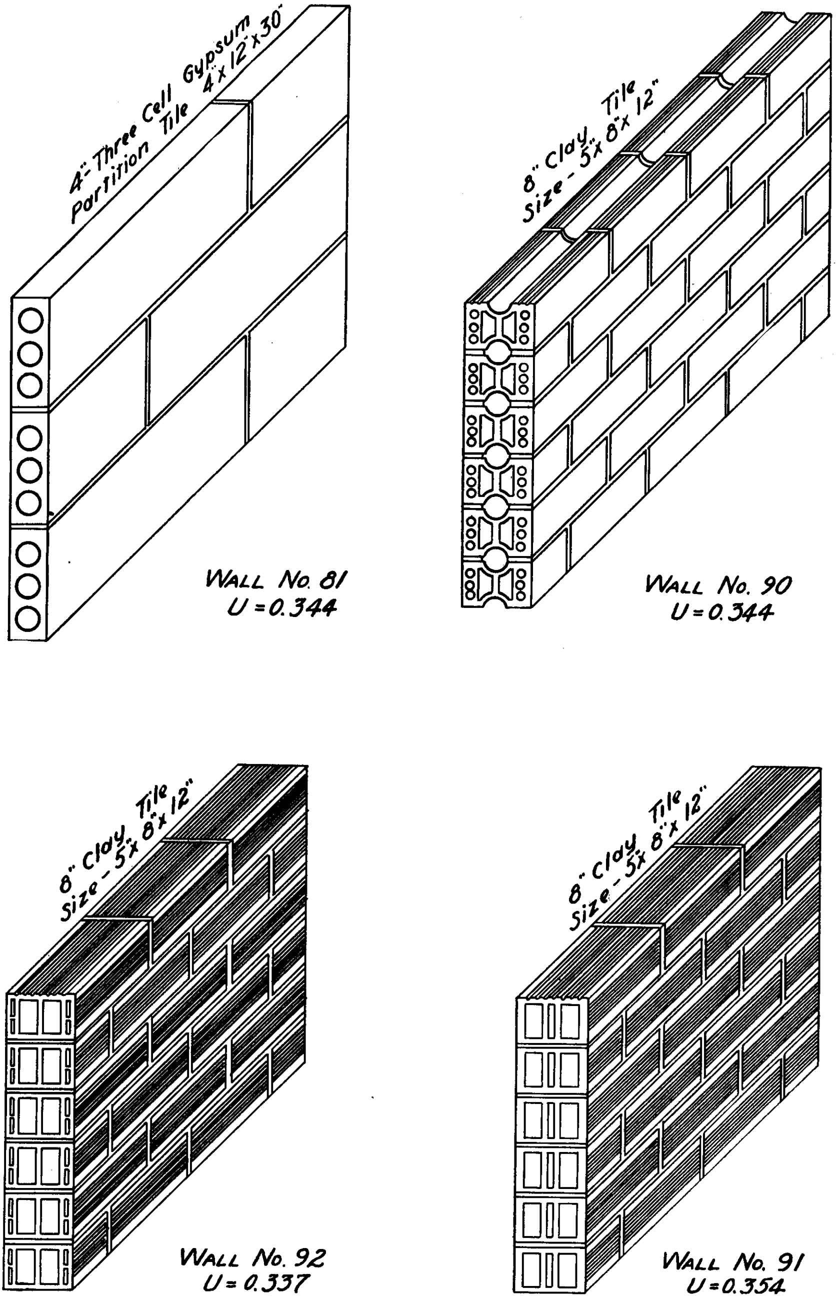


FIGURE 90. SECTIONAL VIEWS OF TEST WALLS

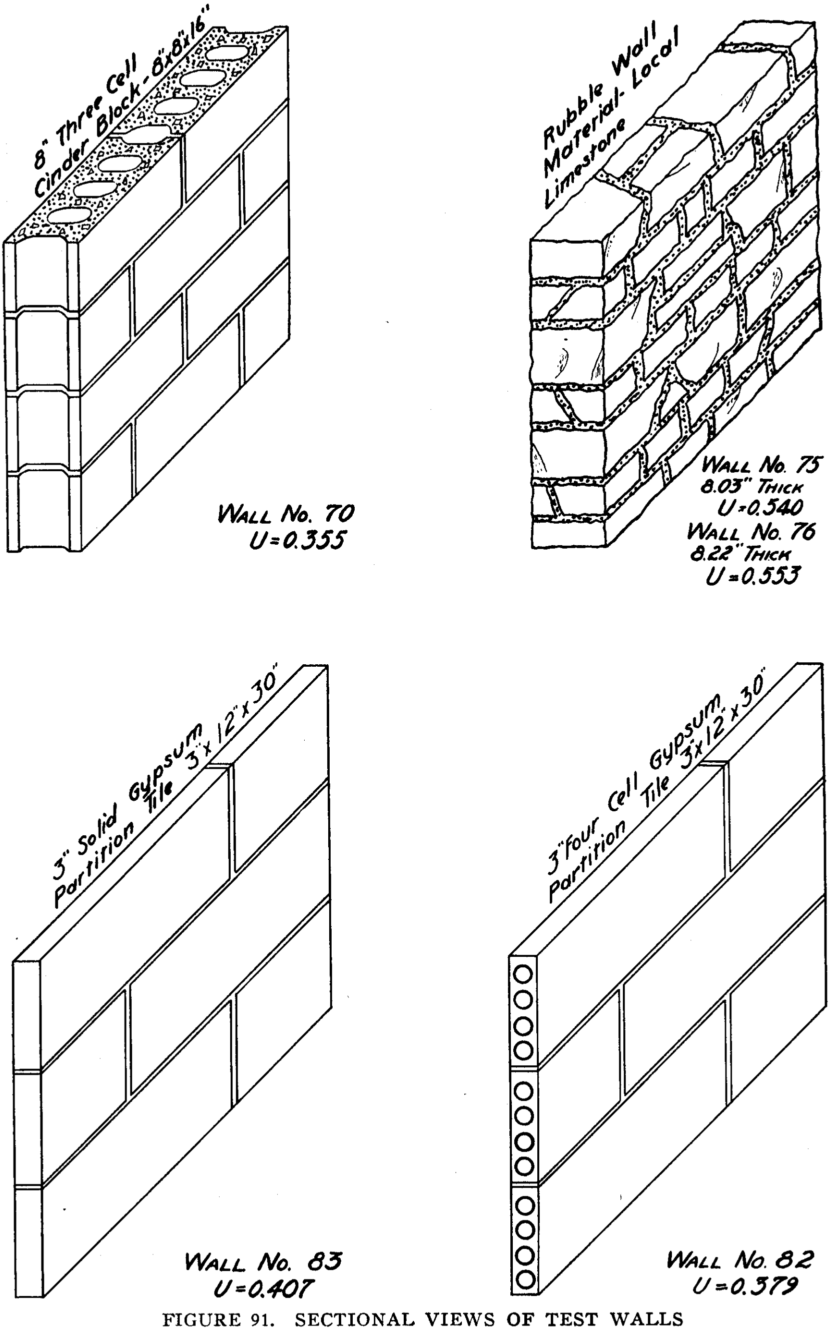


FIGURE 91. SECTIONAL VIEWS OF TEST WALLS

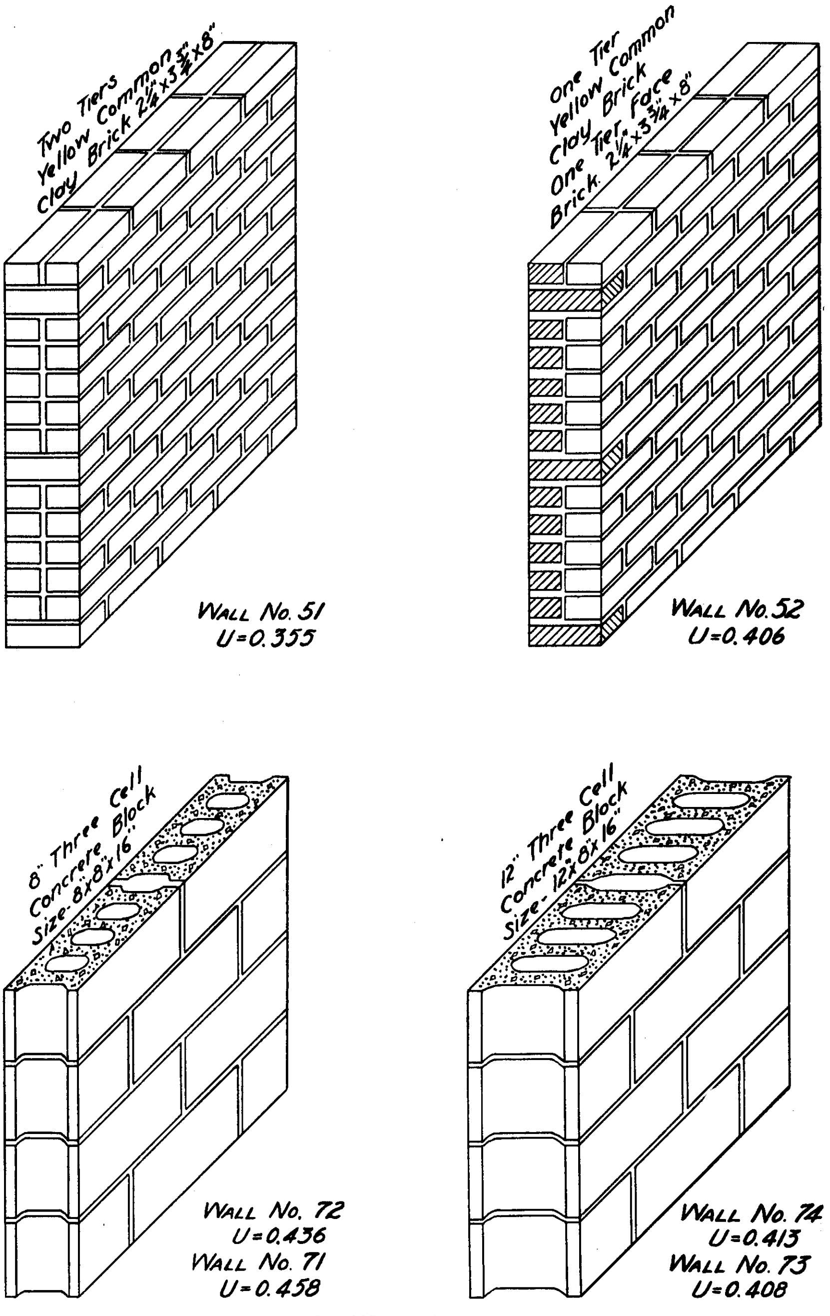


FIGURE 92. SECTIONAL VIEWS OF TEST WALLS

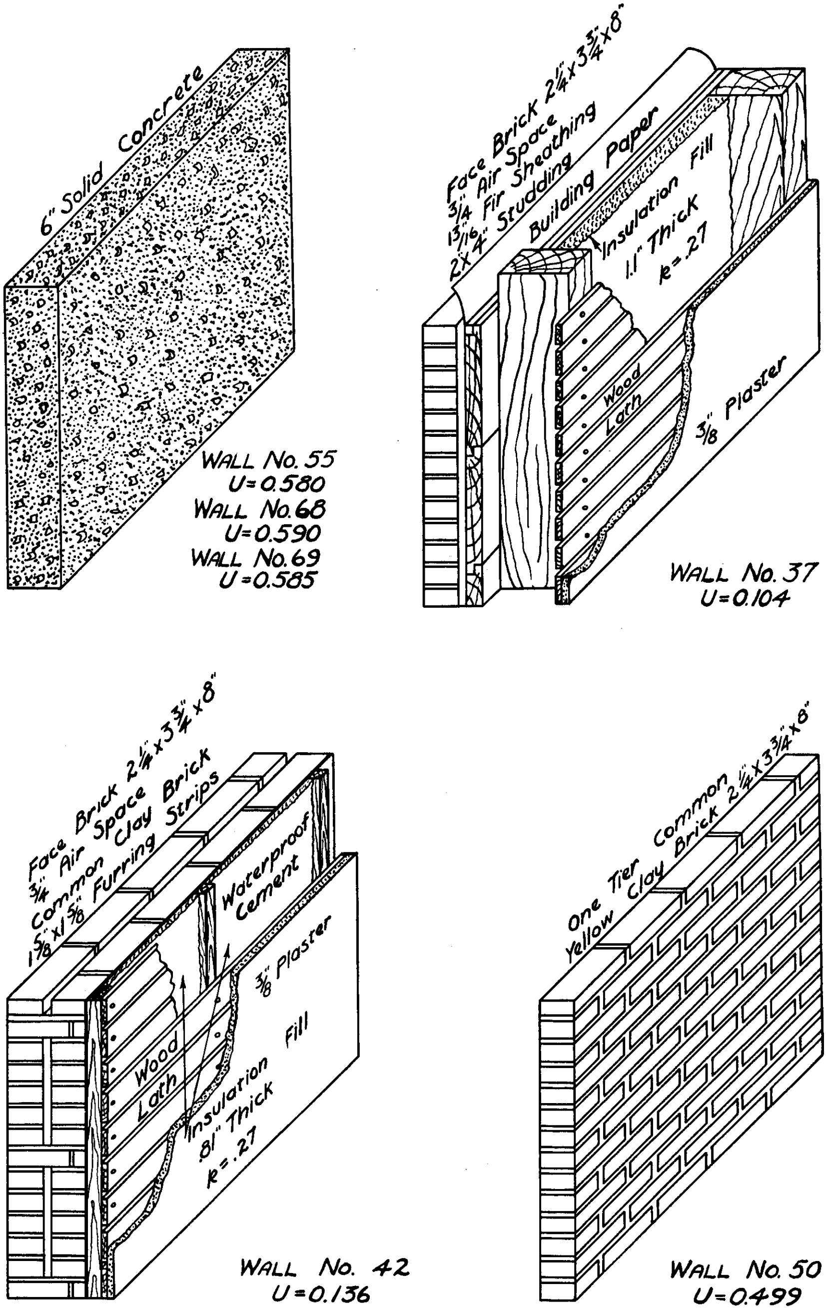


FIGURE 93. SECTIONAL VIEWS OF TEST WALLS

TABLE X

SUMMARY OF RESULTS OF TESTS ON WALL CONSTRUCTION BY THE HOT BOX METHOD FOR FIGURES 78 TO 93

Date of Test	Wall No.	Test No.	Air Temperature, Deg. F.			Surface Constants		Coefficient of Transmission U	
			High Side	Low Side	Mean Temp.	Inside, f_1	Outside, f_0	By Test	Corrected to 15-Mile Wind Velocity
12/22/27	7	401	80.7	−0.05	40.35	1.619	2.094	.216	.236
12/23/27	7	402	80.8	−0.10	40.35	1.619	2.081	.216	.236
1/24/28	7-A	418	80.45	0.1	40.27	1.748	1.803	.211	.231
1/25/28	7-A	419	80.5	0.4	40.45	1.769	1.732	.209	.228
12/19/27	8	400	81.2	−0.35	40.4	1.721	2.057	.226	.249
10/12/28	8-A	496	79.87	0.0	39.93	1.503	1.726	.229	.252
10/16/28	8-A	497	80.39	0.0	40.2	1.826	1.703	.222	.244
10/17/28	8-A	498	80.33	0.02	40.17	1.866	1.802	.228	.251
12/7/28	8-B	518	80.28	−0.41	39.93	1.584	1.455	.139	.147
4/10/28	9	452	80.1	0.0	40.05	1.647	1.856	.146	.154
4/11/28	9	453	80.1	0.0	40.05	1.629	1.780	.144	.152
12/28/27	10	403	80.4	−0.20	40.05	1.671	1.906	.184	.198
12/29/27	10	404	80.4	−0.30	40.0	1.665	1.918	.187	.202
1/6/28	11	409	80.4	−0.10	40.15	1.736	2.515	.153	.163
1/9/28	11	410	80.4	0.0	40.2	1.795	2.442	.152	.162
12/30/27	12	405	80.4	0.0	40.2	1.690	1.739	.113	.118
12/31/27	12	406	80.35	−0.1	40.2	1.650	1.811	.115	.120
1/26/28	12	420	80.5	−0.05	40.25	1.745	1.762	.117	.123
1/12/28	15	413	80.25	−0.15	40.0	1.750	2.595	.134	.141
1/13/28	15	414	80.2	−0.05	40.07	1.784	2.933	.133	.140
1/18/28	16	415	80.5	0.0	40.25	1.776	1.993	.141	.149
1/19/28	16	416	80.5	−0.05	40.25	1.747	1.943	.141	.149
1/20/28	16	417	80.5	−0.15	40.15	1.786	1.719	.142	.150
3/14/28	17	442	80.55	−0.20	40.15	1.754	1.490	.116	.121
3/16/28	17	443	80.65	0.1	40.3	1.827	1.399	.115	.120
1/29/35	18	746	80.70	−0.75	39.97	1.575	1.483	.070	.073
2/3/28	19	425	80.55	−0.2	40.15	1.625	1.825	.156	.166
2/8/28	19	426	80.8	0.9	40.9	1.639	1.835	.154	.165
2/17/28	21	431	80.5	0.0	40.2	1.844	1.403	.167	.181
2/21/28	21	432	80.6	0.0	40.3	1.830	1.629	.166	.180
3/21/28	22	445	80.05	0.05	40.1	2.007	2.188	.318	.375
3/22/28	22	446	80.2	0.0	40.1	1.981	2.168	.314	.369
2/28/28	23	434	80.5	0.3	40.35	1.753	1.684	.212	.232
2/29/28	23	435	80.45	0.05	40.3	1.737	1.637	.213	.233
3/28/28	24	448	80.2	−0.05	40.1	1.781	1.651	.212	.232
3/29/28	24	449	80.2	0.0	40.1	1.789	1.847	.214	.234
3/8/28	25	439	80.5	0.0	40.25	1.803	1.253	.184	.198
3/9/28	25	440	80.5	0.05	40.28	1.819	1.280	.185	.199
4/13/28	26	454	80.15	0.0	40.07	1.648	1.476	.168	.180

TABLE X—*Continued*

Date of Test	Wall No.	Test No.	Air Temperature, Deg. F.			Surface Constants		Coefficient of Transmission *U*	
			High Side	Low Side	Mean Temp.	Inside, f_1	Outside, f_0	By Test	Corrected to 15-Mile Wind Velocity
4/14/28	26	455	80.2	0.0	40.1	1.649	1.470	.169	.181
4/3/28	27	450	80.05	−0.05	40.0	1.921	1.387	.162	.173
4/4/28	27	451	80.05	−0.05	40.0	1.887	1.629	.163	.174
4/17/28	28	456	80.3	0.0	40.15	1.720	1.419	.141	.149
4/18/28	28	457	80.15	0.0	40.07	1.761	1.403	.142	.150
4/20/28	29	458	80.2	0.05	40.13	1.758	1.609	.154	.165
4/24/28	29	459	80.2	0.0	40.1	1.773	1.579	.153	.164
5/1/28	30	462	80.1	0.0	40.5	1.785	1.542	.154	.165
5/2/28	30	463	80.1	0.3	40.2	1.803	1.518	.156	.166
4/26/28	31	460	80.15	0.0	40.07	1.649	1.517	.142	.150
4/27/28	31	461	80.05	0.0	40.02	1.684	1.527	.143	.151
5/24/28	32	468	81.2	0.6	40.9	1.765	1.715	.153	.164
5/25/28	32	469	81.4	0.35	40.87	1.700	1.643	.151	.161
11/27/28	32	513	79.85	−0.08	39.89	1.798	1.614	.154	.165
6/6/28	33	470	80.25	0.0	40.12	1.867	1.387	.117	.123
6/7/28	33	471	80.25	0.0	40.12	1.794	1.307	.114	.119
6/8/28	33	472	80.2	0.0	40.1	1.778	1.422	.115	.120
6/21/28	34	473	80.25	0.3	40.27	1.664	2.110	.128	.135
6/22/28	34	474	80.3	−0.05	40.12	1.645	2.116	.129	.136
6/26/28	35	475	80.25	2.6	42.57	1.794	1.540	.123	.129
7/3/28	36	476	80.25	2.6	41.42	1.815	1.171	.130	.137
7/6/28	36	477	80.25	0.0	40.12	1.768	1.349	.131	.138
9/1/28	37	487	80.3	−0.15	40.07	1.675	.859	.101	.106
9/27/28	37	488	80.25	−0.35	39.95	1.819	.914	.107	.113
10/2/28	37	490	80.37	−0.23	40.07	1.834	.720	.099	.104
11/23/28	37	512	81.48	−1.0	40.24	1.855	1.291	.106	.111
10/19/28	40-B	499	80.13	−0.02	40.05	1.639	1.583	.109	.114
10/23/28	40-B	500	80.14	0.02	40.08	1.641	1.599	.109	.114
3/26/29	40-B	555	79.27	0.24	39.75	1.829	1.379	.109	.114
12/20/28	41	523	79.86	0.97	40.41	1.931	1.619	.148	.157
12/21/28	41	524	79.89	−0.37	39.76	1.956	1.785	.148	.157
10/30/28	42	502	80.37	0.00	40.18	1.658	1.235	.135	.144
10/30/28	42	502-A	80.39	0.00	40.19	1.678	1.465	.138	.147
12/4/28	47	516	80.26	−0.03	40.11	1.667	1.448	.365	.427
12/27/28	50	525	79.81	−0.57	39.62	1.680	1.567	.499	.640
2/5/29	50	541	80.46	−0.29	40.08	1.662	1.624	.499	.640
1/29/29	51	539	80.67	−0.38	40.14	1.690	1.548	.357	.425
4/23/29	51	566	80.59	−0.37	40.11	1.714	1.591	.354	.422
2/1/29	52	540	80.39	−0.32	40.03	1.808	1.571	.412	.504
4/18/29	52	565	80.66	−0.57	40.04	1.841	1.619	.401	.487
1/2/29	53-A	527	79.57	0.69	40.13	1.685	1.671	.223	.245
1/7/29	53-A	530	80.47	−0.63	39.92	1.561	1.588	.217	.238

TABLE X—*Continued*

DATE OF TEST	WALL NO.	TEST NO.	AIR TEMPERATURE, DEG. F.			SURFACE CONSTANTS		COEFFICIENT OF TRANSMISSION U	
			High Side	Low Side	Mean Temp.	Inside, f_1	Outside, f_0	By Test	Corrected to 15-Mile Wind Velocity
1/8/29	53-A	531	80.50	−0.82	39.84	1.553	1.644	.219	.240
1/12/29	53-B	533	80.31	−0.69	39.81	1.781	1.574	.155	.166
1/15/29	53-B	534	80.15	0.05	40.10	1.761	1.579	.153	.164
1/18/29	53-C	535	80.25	−0.04	40.10	1.586	1.528	.177	.190
1/21/29	53-D	536	80.10	−0.03	40.03	1.650	1.525	.120	.126
1/23/29	53-E	537	79.60	−0.17	39.72	1.646	1.580	.184	.198
3/27/29	53-F	556	79.31	0.40	39.85	1.669	1.564	.217	.235
1/10/29	54	532	80.33	−0.51	39.91	1.625	1.524	.171	.183
4/30/29	54	568	80.79	−0.98	39.90	1.716	1.526	.168	.180
1/25/29	55	538	80.81	−0.48	40.17	1.646	1.668	.588	.792
4/26/29	55	567	80.90	−1.07	39.91	1.646	1.625	.572	.762
11/5/29	55	583	80.27	−0.02	40.12	1.665	1.605	.579	.776
9/23/30	55	597	79.5	0.40	39.95	2.615	1.721	.582	.780
2/7/29	56	542	79.79	−0.04	39.88	1.768	1.486	.227	.254
2/8/29	56	543	79.81	0.0	39.90	1.777	1.493	.227	.254
2/14/29	57	544	79.73	−0.16	39.78	1.700	1.585	.331	.381
2/15/29	57	545	79.74	0.05	39.89	1.716	1.677	.335	.387
5/10/29	57-B	573	79.47	−0.33	39.57	1.649	1.511	.330	.380
6/18/29	59	575	80.94	−0.90	40.02	1.747	1.505	.280	.319
6/20/29	60	576	81.24	−1.08	40.08	1.831	1.474	.266	.301
6/22/29	61	577	79.93	0.02	39.98	1.602	1.561	.270	.306
7/9/29	61-A	582	79.98	0.13	40.05	1.777	1.480	.265	.300
6/27/29	62	579	79.92	0.01	39.96	1.815	1.884	.205	.226
7/2/29	63	580	79.93	0.22	40.07	1.726	1.800	.343	.403
6/25/29	64	578	79.94	0.14	40.04	1.708	1.318	.265	.299
7/6/29	65	581	79.99	0.13	40.06	1.733	1.528	.255	.290
5/24/30	66	589	80.30	−0.05	40.12	1.711	1.627	.310	.360
5/27/30	67	590	80.40	−0.15	40.12	1.732	1.654	.320	.372
10/2/30	68	599	79.81	0.05	39.93	1.803	2.247	.590	.795
9/26/30	69	598	79.89	0.09	39.99	1.924	1.655	.585	.785
6/10/30	70	594	80.09	0.10	40.09	1.544	1.981	.358	.425
10/9/30	70	601	79.80	0.20	40.00	1.618	1.618	.353	.418
6/13/30	71	595	80.10	0.15	40.12	1.594	1.605	.460	.576
10/7/30	71	600	79.85	0.10	39.97	1.622	1.559	.457	.571
6/6/30	72	593	80.07	0.0	40.04	1.571	1.575	.436	.540
6/3/30	73	592	79.85	0.35	40.10	1.632	1.648	.408	.497
6/18/30	74	596	80.08	0.33	40.20	1.604	1.895	.413	.504
1/20/31	75	627	79.98	0.13	40.05	1.623	1.477	.540	.707
1/14/31	76	626	79.90	0.04	39.97	1.622	1.529	.553	.729
5/29/30	77	591	79.90	0.10	40.00	1.428	1.789	.097	.101
10/15/30	78	602	79.82	0.52	40.17	1.954	1.616	.691	....
2/5/31	78-B	631	80.22	−0.43	39.89	1.246	0.923	.460	....
10/27/30	79	606	78.89	−0.04	39.42	1.761	1.588	.264	....

TABLE X—*Continued*

DATE OF TEST	WALL NO.	TEST NO.	AIR TEMPERATURE, DEG. F.			SURFACE CONSTANTS		COEFFICIENT OF TRANSMISSION U	
			High Side	Low Side	Mean Temp.	Inside, f_1	Outside, f_0	By Test	Corrected to 15-Mile Wind Velocity
10/30/30	79-A	608	80.16	−0.08	40.04	1.280	1.164	.169	....
11/10/30	79-B	610	80.12	0.06	40.09	1.230	1.467	.175	....
11/18/30	79-B	611	79.97	0.02	39.99	1.252	1.291	.171	....
10/28/30	80	607	79.87	−0.27	39.80	1.746	1.407	.257	....
5/26/31	80-A	661	81.00	2.08	41.54	0.814	1.757	.130	....
1/6/31	81	624	79.06	−0.20	39.43	1.671	1.542	.344	.405
1/8/31	82	625	80.02	0.0	40.01	1.701	1.429	.379	.454
11/25/30	83	613	79.60	0.07	39.83	1.726	1.623	.407	.495
3/18/31	85	641	75.14	−0.06	37.54	1.512	1.298	.235	....
4/1/31	86	646	80.73	−0.06	40.34	1.519	1.390	.169	.181
4/9/31	87	649	80.80	−0.10	40.35	1.519	1.130	.175	.188
4/7/31	88	648	80.86	−0.02	40.42	1.572	1.347	.172	.185
4/6/31	89	647	80.74	−0.16	40.29	1.519	1.367	.163	.174
4/13/31	90	650	80.38	−0.17	40.10	1.661	1.533	.344	.405
4/16/31	91	651	80.27	−0.01	40.13	1.719	1.532	.354	.418
4/20/31	92	652	80.31	0.19	40.25	1.760	1.575	.337	.396

NOTE.—Average Surface conductance (f_0) for walls as tested = 1.633.
Surface conductance (f_0) for pine surface for outside wind exposure of 15 miles per hour = 4.75.
Surface conductance (f_0) for stucco surface for outside wind exposure of 15 miles per hour = 7.50.
Surface conductance (f_0) for brick surface for outside wind exposure of 15 miles per hour = 6.10.
Surface conductance (f_0) for concrete, tile, cinder block, and rubble stone surfaces for outside wind exposure of 15 miles per hour = 5.78.
Surface conductance (f_0) for plaster surface for outside wind exposure of 15 miles per hour = 4.68.

DISCUSSION OF RESULTS OF WALL TESTS FOR FIGURES 78 TO 93

The walls tested are divided into two series or groups. The first group includes Figures 78 to 93, inclusive, and were reported in Bulletin No. 8 (Figs. 44 to 59). The second group, shown later in this bulletin, includes those walls shown by Figures 94 to 106, inclusive. In considering the over-all coefficients as given with the figures showing the type of wall, particular note should be taken of the fact that still air coefficients only are shown for the first group, while for the second group coefficients are shown for both still air as determined by tests and for a 15-mile surface wind velocity as determined by calculation. The 15-mile wind coefficients for the first group of walls are given in the corresponding tables of test data.

VARIATION IN WALL CONSTRUCTION

There is some variation in most building materials. In addition to this there is also likely to be a difference in the construction of two walls even tho they are built under careful laboratory supervision. Several of the tests reported represent the results on duplicate walls; some of which were constructed from materials of the same lot, and others of which were constructed at different times with materials selected from different lots. Some examples with the variations found are as follows:

1. Walls 7-A, 8, 8-A, and 53-F (Fig. 78) were all frame walls of the same construction but built at different times from different materials. The still air coefficients for these walls varied from .209 to .229—a difference of approximately 9 per cent. This difference might be accounted for by shrinkage of materials, differences in conductivity of the wood used in construction, or to a difference in actual construction.
2. Walls 7 and 53-A (Fig. 78) were of identical design built at different periods and with different materials. In this case the coefficients varied from .216 to .218.
3. Walls 11 and 30 (Fig. 78) were all built of a rather uniform quality of insulating board as sheathing and as plaster base. The over-all coefficient ranged from .152 to .155.
4. Walls 57 and 57-B (Fig. 86) were built at the same time and with materials taken from the same stock. The coefficients were .330 and .333, respectively.
5. Walls 75 and 76 (Fig. 91) were constructed of limestone taken from the same stock. The over-all coefficients were .540 and .553—a variation of 2.4 per cent.

In practice, walls constructed after the same specifications might show variations in conductivity coefficients even greater than those noted above. This might be due to poor construction or to using materials which have wide variations in thermal properties. In applying the conductivity coefficients to practice, one should take note of the fact that they represent the amount of heat transmitted by thermal conductivity only and do not include any air leakage that might be caused by wind pressure on the building. This must be considered as a separate factor in determining heat losses.

FRAME WALLS, TEST RESULTS

All frame walls were built of 2 × 4-inch studs spaced 16 inches on center. If 2 × 6-inch studding was substituted for the 2 × 4-inch studding the conductivity results should be substantially the same so long as the space between the studding was given the same treatment.

CLAY TILE WALLS, TEST RESULTS

Figures 87, 88, 89, and 90 show a group of fifteen clay tile walls. Fourteen of these are 8 inches thick, built with tile of different cell structure, and are treated differently as to joints and surface finish. The range in values of the conductivity coefficient *U* for the unfinished walls is from .354 for Wall 91 (Fig. 90) to .265 for Wall 64 (Fig. 88).

Walls 63 (Fig. 88) and 91 (Fig. 90) are built of a common type of three-cell tile, the construction being similar altho the tile was obtained from different manufacturers. The still air coefficients for these walls are .343 and .354, respectively, which may be taken as reasonable averages for this type of construction.

In Walls 92 (Fig. 90) and 67 (Fig. 89) the air cells have been broken up in such a manner as to give substantially four cells for Wall 92 and five cells for Wall 67. The coefficients of conductivity are .337 and .320, respectively, indicating that, as the air cells are broken up into greater numbers, the conductivity of the finished wall is decreased.

In each of the four walls, Nos. 63, 91, 92, and 67, there is a direct path for the flow of heat through the top and bottom surfaces of the individual tile. In other words, there is a direct line of low heat resisting material through which heat may flow from the hot to the cold surface of the wall. As a direct contrast to this, consider Wall 64 (Fig. 88) in which the air spaces are staggered, giving a longer path through the material for the flow of heat from surface to surface. For this wall the coefficient *U* is .265—a material reduction over the other type. Wall 66 (Fig. 88) was built of the same tile as Wall 64, but the joints were filled solid with mortar. The coefficient was increased to .31 as compared with .265 when the joints were not filled. Wall 65 (Fig. 89) was built of the same tile as Wall 64, but, for Wall 65, insulating strips were placed horizontally in the open air spaces at the joints, and insulating pads were placed at the end of each tile. These insulating pads and strips gave slightly better insulation than the air space and prevented any mortar from getting into the joints, and, as shown from the results, reduced the coefficient to .255 as compared with .265 without the strips. This reduction, however, may have been partly due to the surface finish on the wall.

Walls 59, 60, and 61-A (Figs. 87 and 88) were built of the same tile, the difference being that Walls 60 and 61-A have insulating strips placed in the joints, filling the central air space between the tile, and, also, insulating pads at the end of the tile. In these walls, the insulating strips reduced the coefficient from .28 to .265. Wall 61 (Fig. 89) was of the same construction as Walls 60 and 61-A, with the exception that ⅜-inch plaster was applied to the inner surface of Wall 61. In this case, the coefficient was .27 as compared with .265 without the plaster. This increase may have been due to some slight difference in surface coefficients or to a difference in construction which can always be expected in walls of this type.

Wall 62 (Fig. 89) was built of the same tile as Wall 59, the difference being that it was built 12 inches wide, using 1½ thicknesses of the tile. If, for these walls, the surface coefficients are deducted, it is found that the conductances are proportional to the thicknesses.

In general, the efficiency of a tile wall is increased by breaking up the air spaces and by eliminating any direct paths or tile connections between the two surfaces of the wall. The greatest improvement seems to be possible by breaking up the direct path for heat flow.

The effect of different surface finishes on the tile walls is shown by Walls 21, 22, and 24 of Figure 87. In these walls the same tile was used, the exterior finish in each case being ¾-inch stucco and the interior, ½-inch plaster applied directly to the tile for Wall No. 22; applied to wood lath furred out for Wall No. 24, and to ½-inch insulating board furred out for Wall No. 21. Wood lath on 1-inch furring strips reduces the coefficient from .316 to .213, while ½-inch insulating board A on 1-inch furring strips reduces it to .167.

BRICK WALLS, TEST RESULTS

In Figures 92 and 93, five brick walls are shown which are constructed either entirely of brick or of brick in combination with other materials. Walls 50 and 51 are both constructed of common yellow bricks, 2¼ × 3¾ × 8 inches in dimension. Wall 50 is a single row and Wall 51 a double row of brick. If for these walls the inside and outside coefficient of conductivity be taken as 1.65, the thermal conductivity is $k = 5.0$. Wall 52 is an 8-inch wall composed of one layer of 4-inch common yellow brick and one layer of pressed face brick. The coefficient U in this case is .406 as compared with .355 for the same thickness of wall built entirely of common brick, indicating that the surface brick has a much higher coefficient of conductivity than the common yellow clay brick. Wall 37 shows an insulated frame wall with a brick veneer finish and Wall 42 shows an 8-inch brick wall with insulating material, furring lath, and plaster on the inside.

GYPSUM PARTITION TILE WALLS, TEST RESULTS

Walls No. 81 (Fig. 90) and Nos. 82 and 83 (Fig. 91) were built of different thicknesses of gypsum partition tile as shown. By comparing the results for Walls 82 and 83, it is found that the cylindrical openings through the tile reduce the conductivity coefficient for the 3-inch wall from .407 to .379, or, in other words, these openings introduce a heat resistance into the wall equal to .18. If for Wall 83 the average inside and outside surface coefficients are taken to be 1.65, the thermal conductivity per inch of gypsum is found to be 2.5.

RUBBLE WALLS, TEST RESULTS

Walls 75 and 76 (Fig. 91) were built of limestone and were approximately 8 inches thick. The conductivities were .54 and .553, respectively, a variation well within experimental limits for walls of this type. If the average coefficient is used and the surface coefficients are taken as 1.65 for both inside and outside surfaces, the thermal conductivity k for the wall is found to be 12.5, or slightly higher than that found for concrete walls. It is probable, however, that the surface coefficients may be somewhat higher than the average of 1.65, due to the uneven character of the surfaces.

CONCRETE CONSTRUCTION

It is usually true that materials with high structural strength have low heat resistance, making it necessary to give special consideration to the methods of using such materials, and often to add special insulation where thermal resistance is an important factor. Concrete is such a material. It has excellent structural properties but when the ordinary aggregates are used without some consideration for insulating values a high thermal conductivity results. Since concrete is so extensively used in building construction and since thermal resistance is often an important factor, a special investigation has been made covering monolithic and masonry wall construction.

The thermal properties of concrete walls may be improved by such methods as changing the nature of the aggregate, constructing the wall with different types of air spaces, applying a special surface finish, or adding some insulating material to the wall. The investigation has covered monolithic and masonry walls, different aggregates, different surface finishes, various types of air space construction, and the application of insulating materials to monolithic and masonry walls. In the interests of economy the number of walls built and tested was limited to representative types.

AGGREGATES

In general, low density aggregates will result in lower thermal conductivity than will high density aggregates. This, however, is not always the case as low density may be accompanied by an excessive porosity which will allow the heat to be transferred through the wall by air circulation. Such a condition may be taken care of in part by the application of some impervious surface finish. This will exclude the surface air, but in extreme cases there may also be circulation of air within the wall itself. In this investigation sand and crushed limestone, sand and gravel, cinders, Haydite, and air-cooled slag were used as aggregates. These were graded as indicated by the description of the individual walls.

AIR SPACE CONSTRUCTION USED

There are two types of air spaces which may be built into a wall. First, the continuous air space as may be provided between two parallel walls; and second, irregular cored out sections as are usually provided in concrete block construction. In the first case all heat conducted from surface to surface must pass directly across the air space, and, if there are no connecting rods which serve as conductors, the efficiency of the air space could be very definitely determined from the known properties of such spaces. In the second case only a part of the heat must pass through the air spaces, the remainder passing through the solid material between the spaces. If the material proper has a high thermal conductivity and if the partitions between the cored out spaces are direct between the two surfaces and constitute a considerable percentage of the wall area, the effectiveness of the air space as an insulator may be very materially reduced. It is difficult to make calculations to determine the thermal conductivity of walls containing irregular air spaces, even tho the properties of the material are established. An efficient air space construction must either provide a continuous space over the full wall area or, if there are paths of solid material between the two surfaces, they should be designed as long and restricted in area as possible. In this investigation parallel or continuous air spaces were provided by constructing walls of parallel monolithic and masonry slabs and by furring out the surface for specific insulating finish. The cored air spaces were those commonly used in standard concrete block construction.

SURFACE FINISH

The effect of surface finish on a wall may be to reduce the normal air filtration into and out of the wall and thus improve the internal conductivity by eliminating convection currents, or to change the character of the surface and thereby change the surface coefficient of conductance. If the surface finish should be of material thickness and of an insulating value in itself, it would add to the thermal resistance of the wall. The surface finishes used in this investigation were in the nature of water cement paints and were primarily for the purpose of reducing any interchange of air through the boundary surfaces rather than for improving the surface conductance.

INSULATION

There are several methods by which thermal resistance may be built into a wall. As discussed previously, air space construction may be used for this purpose or specific insulating materials may be applied to the walls either in air spaces or on the surface. The effectiveness of any application will depend upon the amount of heat which must normally flow through the insulation. Thus, if insulating material is placed over the surface of the wall in a layer of uniform thickness, all heat must presumably pass through the material and it may be considered as an effective application. If the insulating material is placed in such manner as not to obstruct all paths for the flow of heat its effectiveness may be reduced. In this investigation insulating materials have been used in the cells or cores of the concrete blocks and also as a uniform sheet parallel to the surfaces of the walls.

METHOD OF PROCEDURE

In all cases the aggregate was selected and graded as per specifications. In each case a sieve analysis was made and the different aggregates were mixed in the required proportion to give the proper fineness modulus. Preliminary tests were made to determine the proper water to cement ratio to give the required slump and strength characteristics. The blocks for the masonry walls were constructed in a standard block machine at a plant in Minneapolis, Minnesota. These were steam cured for 24 hours, and then exposed to the air for the remainder of the curing period. After being thoroly cured and dried out they were built into test walls 5½ feet square with standard ⅜-inch mortar joints between the blocks. In constructing the walls the mortar was buttered on the edges but not on the cross partitions between the air cells, thus following recommended and standard construction practice for walls of this type. After a sufficient curing period to thoroly dry out the mortar between the joints the walls were tested by the standard hot box method.

For the monolithic walls the aggregates were selected and graded in the same manner as for the concrete blocks and the walls were constructed in the laboratory according to specifications. At the time of building the walls 6 × 12-inch cylinders were cast which were later tested to give the strength of the concrete. After the walls were thoroly cured and dried out they were tested by the standard hot box method to determine their thermal conductivity.

Test data and computed results for concrete walls and aggregates are given in Figures 94 to 106 with the accompanying tables and in Tables XI to XVIII, inclusive. In cases where several different types of surface finish or of insulation were used with a given wall, one figure has been used to represent all of the different combinations, the differences for each individual wall being shown in the accompanying table.

In order to get the complete construction and test data for any wall it is necessary to refer to both the figure and the accompanying table representing the wall, and the table giving construction data for the wall. Thus the construction data for all masonry walls is given in Table XI, and that for all monolithic walls is given in Table XII. For each figure a reference is made to the tables giving construction data, and for each wall in a table the wall number is followed by the figure number showing wall details. For all built-up walls the over-all coefficient U was determined for air temperatures of 80° F. on the high side, 0° F. on the low side, or a mean temperature of 40° F. for the wall. In all hot plate tests the thermal conductivity k was determined for a mean temperature of 75° F., the temperatures of high and low side of material being regulated to meet this mean temperature requirement.

In taking test data on certain walls it was difficult to get consistent surface temperatures from which to calculate surface conductance coefficients. This was due partly to the fact that the surfaces of some of the walls were rough, making it impossible to get precision measurements of surface temperatures, and partly to the fact that the masonry walls contained irregular cored out spaces which gave different heat resistances for different sections of the wall. For example, the surface temperatures of hollow concrete block walls would be different when taken at a point opposite an air space than when taken at a point opposite the partition between the air spaces. In such cases it would be impossible to get a consistent surface coefficient without taking the average of a large number of surface temperatures. Since the overall transmission coefficients U were calculated on the basis of air temperatures on the two sides of the wall, they were not affected by the irregularities of surface temperatures and were, therefore, taken as a basis for computing the results and making comparisons between the different types of walls. In order to take care of the irregularities in surface temperatures as mentioned and the resulting differences in surface coefficients, averages were taken of all the outside surface coefficients and of all the inside surface coefficients, and these averages taken as the true value for each test. The surface temperatures were corrected by using these coefficients. The average of all outside surface coefficients was 1.55 and of all inside surface coefficients 1.60. All of the tests by the hot box method were made at still air conditions and the coefficients for a 15-mile wind were calculated by correcting for the difference between the surface coefficients for a 0- and a 15-mile wind.

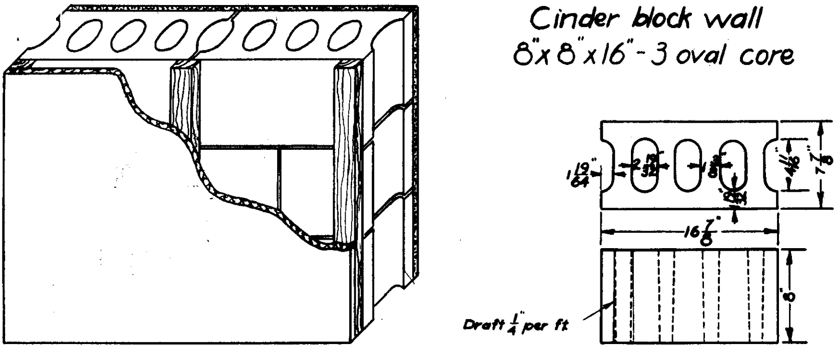


FIGURE 94. 8-INCH CINDER BLOCK WALL

CINDER BLOCK WALLS

For additional construction data see Table XI

Wall No.	Surface Finish		Insulation in Core Spaces			Coefficients of Heat Transmission		
	Inside	Outside	Kind	Density Lbs. Cu. Ft.	Lbs. Sq. Ft. of Wall Area	*C*	*U*	*U* Corrected to 15 M.P.H. Wind Vel.
1a	As laid	As laid	None	....	....	0.577	0.333	0.396
1b	As laid	Two coats waterproofed white Portland cement paint	None	....	....	0.522	0.314	0.370
1c	As laid	Two coats waterproofed white Portland cement paint	Granulated cork	5.12	1.34	0.238	0.189	0.201
1d	As laid	Two coats waterproofed white Portland cement paint	Dry cinders	69.7	18.29	0.364	0.249	0.283
1e	As laid	Two coats waterproofed white Portland cement paint	Rock wool	14.21	3.72	0.254	0.192	0.211
1f	½-inch plaster on metal lath furred 1 inch	Two coats waterproofed white Portland cement paint	Rock wool	14.21	3.72	0.198	0.158	0.171
1g	½-inch plaster applied direct	Two coats waterproofed white Portland cement paint	Rock wool	14.21	3.72	0.251	0.190	0.209
1h	½-inch insulation board furred 1-inch strips on center	½-inch plaster applied direct	Rock wool	14.21	3.72	0.164	0.136	0.147

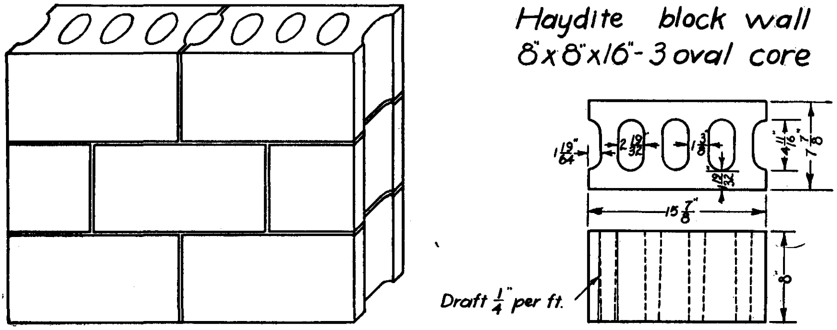


FIGURE 95. 8-INCH HAYDITE BLOCK WALL

HAYDITE BLOCK WALLS

For additional construction data see Table XI

	Surface Finish		Insulation in Core Spaces			Coefficients of Heat Transmission		
Wall No.	Inside	Outside	Kind	Density Lbs. Cu. Ft.	Lbs. Sq. Ft. of Wall Area	C	U	U Corrected to 15 M.P.H. Wind Vel.
2a	As laid	As laid	None	....	....	0.495	0.304	0.355
2b	As laid	Two coats waterproofed white Portland cement paint	None	....	....	0.454	0.289	0.334
2c	As laid	Two coats waterproofed white Portland cement paint	Granulated cork	5.06	1.33	0.199	0.159	0.172

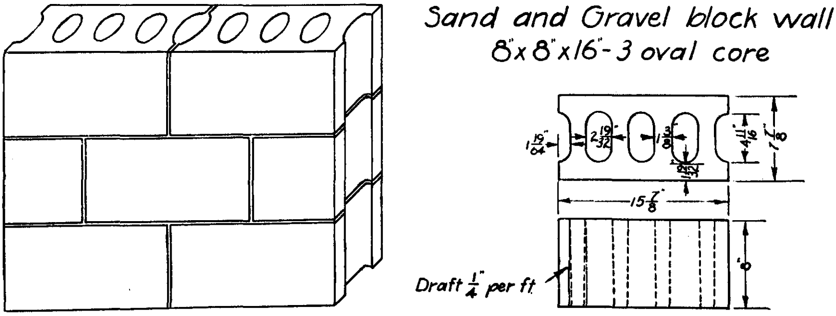


FIGURE 96. 8-INCH SAND AND GRAVEL BLOCK WALL

SAND AND GRAVEL BLOCK WALLS

For additional construction data see Table XI

	Surface Finish		Insulation in Core Spaces			Coefficients of Heat Transmission		
Wall No.	Inside	Outside	Kind	Density Lbs. Cu. Ft.	Lbs. Sq. Ft. of Wall Area	C	U	U Corrected to 15 M.P.H. Wind Vel.
3a	As laid	As laid	None	....	....	0.898	0.419	0.524
3b	As laid	Two coats waterproofed white Portland cement paint	None	....	....	0.851	0.409	0.509
3c	As laid	Two coats waterproofed white Portland cement paint	Granulated cork	5.14	1.35	0.542	0.321	0.379

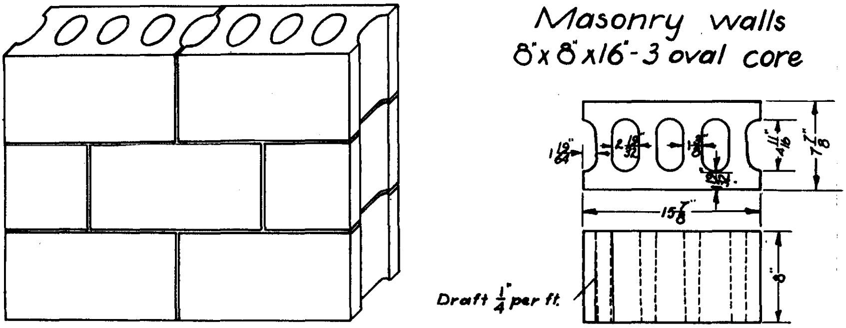


FIGURE 97. 8-INCH MASONRY WALL

MASONARY WALLS, FIVE DIFFERENT AGGREGATES

No Surface Finish or Additional Insulation

For additional construction data see Table XI

Wall No.	Description of Wall	Coefficients of Heat Transmission		
		C	*U*	*U* Corrected to 15 M.P.H. Wind Vel.
1a	Cinder block	0.577	0.333	0.396
2a	Haydite block	0.495	0.304	0.355
3a	Sand and gravel block	0.898	0.419	0.524
4a	Limestone block	0.856	0.410	0.510
11a	Air cooled slag block	0.677	0.364	0.441

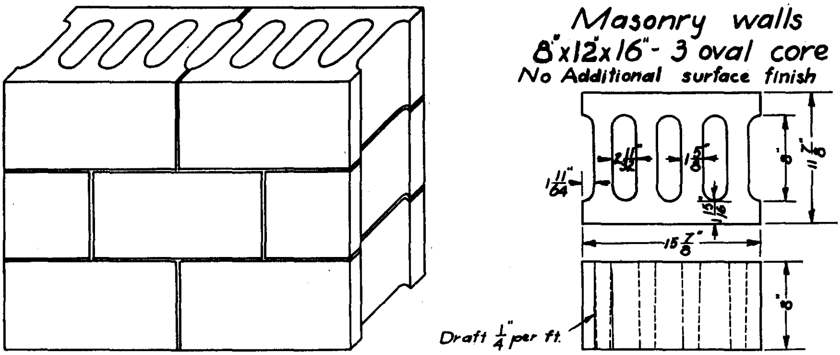


FIGURE 98. 12-INCH MASONRY WALL

MASONRY WALLS

For additional construction data see Table XI

Wall No.	Material Used in Blocks	Insulation in Cores			Coefficients of Heat Transmission		
		Kind	Density Lbs. Cu. Ft.	Lbs. Sq. Ft. Wall Area	*C*	*U*	*U* Corrected to 15 M.P.H. Wind Vel.
5a	Cinders	None	....	....	0.531	0.318	0.374
5b	Cinders	Granulated cork	5.24	2.10	0.237	0.182	0.199
6a	Sand and gravel	None	....	....	0.777	0.391	0.481
15a	Haydite	None	....	....	0.468	0.294	0.342
15b	Haydite	Granulated cork	5.60	2.38	0.168	0.139	0.148

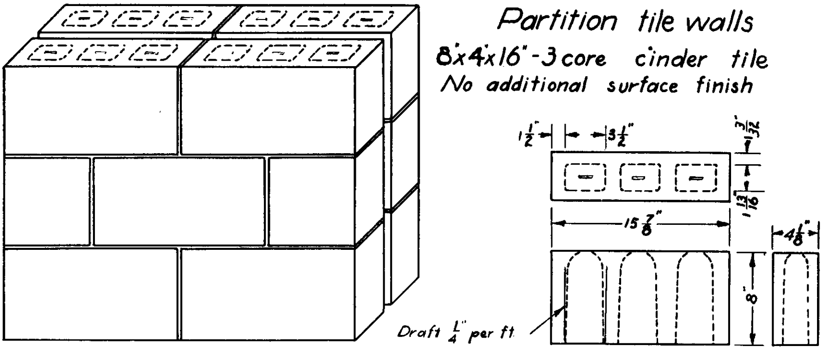


FIGURE 99. DOUBLE PARTITION TILE WALL

PARTITION TILE WALLS

The two walls were tied together with galvanized iron strips spaced 12 inches horizontally on top of each course of blocks and extending approximately 3 inches into each wall.

For additional construction data see Table XI

Wall No.	Description of Wall	Coefficients of Heat Transmission		
		C	U	U Corrected to 15 M.P.H. Wind Vel.
7a	Single, 4-inches thick	1.003	0.441	0.559
8a	Two 4-inch walls, 1-inch air space	0.358	0.247	0.279
8b	Two 4-inch walls, 1-inch rock wool between 9.97 lbs./cu. ft.	0.204	0.162	0.176

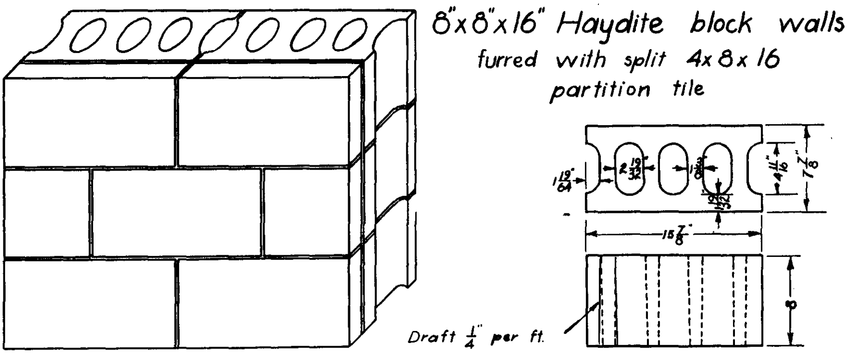


FIGURE 100. HAYDITE BLOCK WALL WITH FURRING UNIT

HAYDITE BLOCK WALLS FURRED WITH SPLIT 4×8×16-INCH PARTITION TILE

For additional construction data see Table XI

Wall No.	Inside Surface Finish	Outside Surface Finish	Coefficients of Heat Transmission C	U	U Corrected to 15 M.P.H. Wind Vel.
13a	As laid	Furred with cinder tile	0.343	0.239	0.270
14a	As laid	Furred with Haydite tile	0.362	0.248	0.281

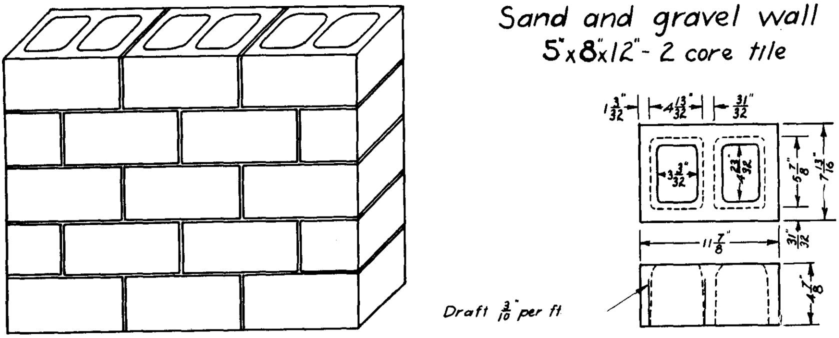


FIGURE 101. 8-INCH SAND AND GRAVEL TILE WALL

MASONRY WALLS

For additional construction data see Table XI

Wall No.	Inside Surface Finish	Outside Surface Finish	Coefficients of Heat Transmission C	U	U Corrected to 15 M.P.H. Wind Vel.
9a	As laid	As laid	0.947	0.430	0.541
9b	As laid	2 coats waterproofed white Portland cement paint	0.899	0.420	0.525

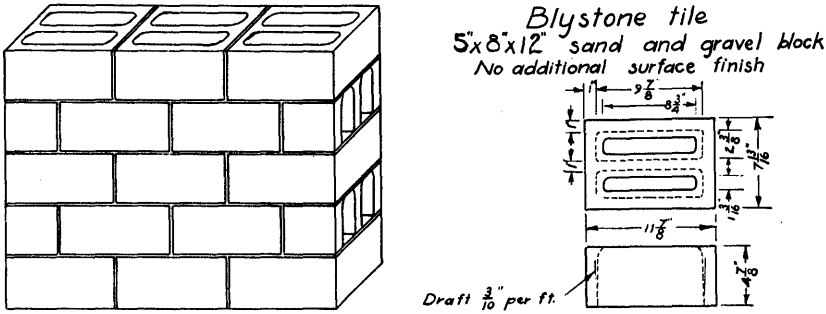


FIGURE 102. 8-INCH BLYESTONE TILE, SAND, AND GRAVEL

BLYSTONE TILE

For additional construction data see Table XI

Wall No.	Coefficient of Heat Transmission		
	C	U	U Corrected to 15 M.P.H. Wind Vel.
12a	0.735	0.380	0.465

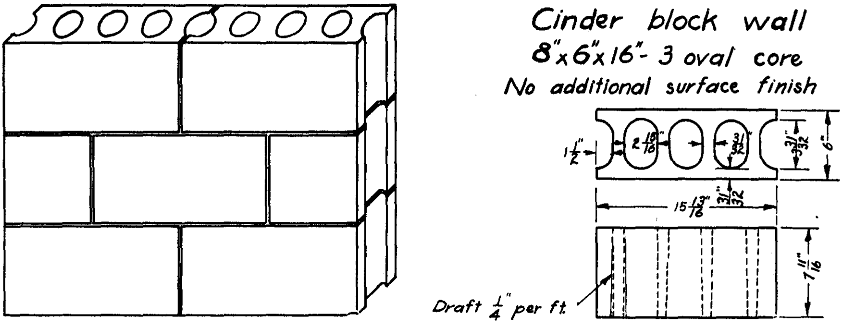


FIGURE 103. 6-INCH CINDER BLOCK WALL

CINDER BLOCK WALL

For additional construction data see Table XI

Wall No.	Coefficient of Heat Transmission		
	C	U	U Corrected to 15 M.P.H. Wind Vel.
10a	0.638	0.353	0.424

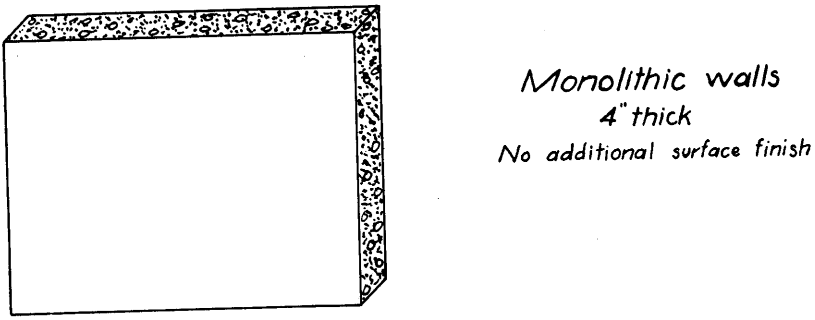


FIGURE 104. 4-INCH MONOLITHIC WALL

MONOLITHIC WALLS

For additional construction data see Table XII

Wall No.	Description of Wall	Coefficients of Heat Transmission		
		C	*U*	*U* Corrected to 15 M.P.H. Wind Vel.
30a	4-inch sand and limestone concrete, plastic mix	2.810	0.615	0.871
31a	4-inch sand and coarse gravel concrete, plastic mix	2.947	0.621	0.884
32a	4-inch sand and coarse gravel concrete, dry tamp mix	3.230	0.632	0.906
33a	4-inch cinder concrete, plastic mix	1.472	0.513	0.679
34a	4-inch Haydite concrete, plastic mix	0.943	0.429	0.540
36a	4-inch sand and coarse cinder concrete, dry tamp mix	2.160	0.577	0.797

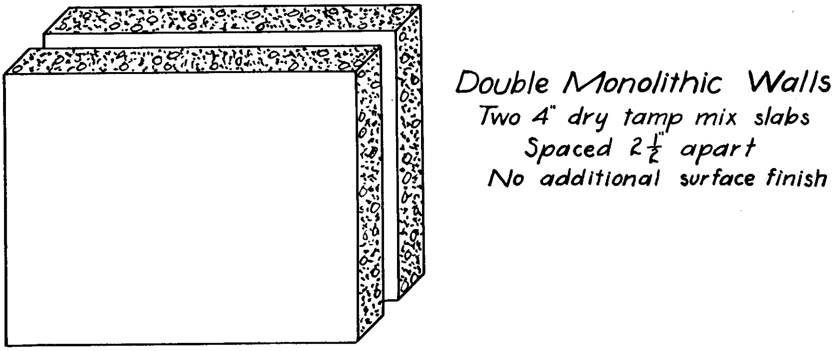


FIGURE 105. DOUBLE 4-INCH MONOLITHIC WALL

DOUBLE MONOLITHIC WALLS

Walls tied together with ¼-inch tie rods spaced 12 inches horizontally and 9 inches vertically and extending about 3 inches into each wall.

For additional construction data see Table XII

Wall No.	Space Between Slabs Filled With	Density of Insulating Material Lbs. Cu. Ft.	Weight of Insulation per Sq. Ft. of Wall Area	Coefficients of Heat Transmission		
				C	*U*	*U* Corrected to 15 M.P.H. Wind Vel.
35a	No fill	………	………	0.660	0.359	0.433
35b	Dry cinders 2.52 inches thick	75.4	15.87	0.509	0.320	0.378
35c	Rock wool 2.52 inches thick	14.3	2.99	0.170	0.140	0.150

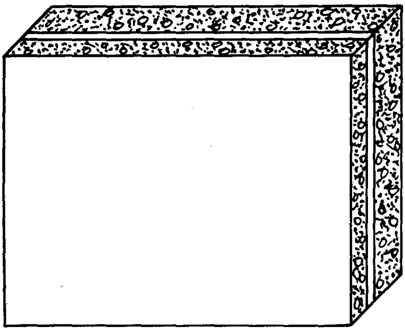


FIGURE 106. MONOLITHIC WALL WITH INSULATION BETWEEN SLABS

DOUBLE MONOLITHIC WALLS

Walls tied together with ¼-inch tie rods spaced to give the equivalent of one rod for each 4½ square feet of area.

Poured with Insulation between Slabs

Wall No.	Insulation between Slabs	Treatment Given Outside Surface	Water Absorbed, Per Cent of Dry Wall Weight	Coefficients of Heat Transmission		
				C	*U*	*U* Corrected to 15 M.P.H. Wind Vel.
38a	1-inch rigid insulation board	None	....	0.325	0.230	0.258
38b	1-inch rigid insulation board	Treated with fog spray 1 hour	.5	0.325	0.230	0.258
38c	1-inch rigid insulation board	Treated with fog spray 19 hours	1.16	0.321	0.228	0.256
39a	1-inch vapor-proof rigid insulation board	None	....	0.335	0.235	0.265
39b	1-inch vapor-proof rigid insulation board	Treated with fog spray 19 hours	1.24	0.331	0.233	0.262
40a	1-inch corkboard	None	....	0.360	0.247	0.280
41a	1-inch water-proof corrugated paper	None	....	0.360	0.247	0.280
42a	2-inch thermax insulation	None	....	0.377	0.255	0.290
42b	2-inch thermax insulation	Treated with fog spray 19 hours	....	0.366	0.250	0.284
43a	1-inch vermiculite and cement binder	None	1.00	1.083	0.456	0.583

Properties of Insulation Used

Wall No.	Insulation	Thickness Inches	Density Lbs. Cu. Ft.	Wt. Sq. Ft. Wall Area	Conductance *C*	Cond. per inch *k*
38a	Rigid insulation board	0.995	13.2	1.09	0.344	0.343
39a	Vapor-proof rigid insulation board	1.034	22.3	1.92	0.388	0.401
40a	Corkboard	0.993	8.7	.72	0.289	0.287
41a	Water-proof corrugated paper	1.046	10.0	.87	0.366	0.383
42a	Thermax insulation	2.001	29.8	4.96	0.385	0.770
43a	Vermiculite and cement binder	0.997	46.6	3.87	1.186	1.182

TABLE XI
MASONRY WALLS CONSTRUCTION DATA

Wall No.	Fig.	Density of Material in Blocks, Lbs. per Cu. Ft.	Percentage of Core Volume	Over-all Thickness of Wall in Inches	Aggregate Used in Wall Per Cent by Weight	Fineness Modulus of Aggregate			Dry Rodded Wt. of Aggregate Lbs. per Cu. Ft.		Mix Proportion Dry Rodded Volume	Water Cement Ratio W/C Gals. per Sack	28-Day Compressive Strength Air Dried					Per Cent Absorption at 28 Days	
													Area of Specimen Sq. In.		Total Breaking Load Lbs.	Breaking Load Lbs. per Sq. In.			
						Fine	Coarse	Combined	Fine	Coarse			Gross	Net		Gross	Net	By Wt.	By Vol.
1a-1h	94, 97	86.2	39.8	7.88	100% cinders ½ in. to 0	4.11	......	4.11	65	......	1:8	8.75	124.9	75.13	99,263	795	1,321	14.2	19.7
2a-2c	95, 97	67.7	39.6	7.91	64% Size A Haydite 36% Size B Haydite, by wt.	2.76	5.94	3.92	58	43	1:8½	10.82	125.5	75.75	97,780	779	1,289	24.4	25.5
3a-3c	96, 97	126.4	39.8	7.88	73% sand 27% pea gravel, by wt.	3.22	5.68	3.91	108	105	1:10	8.92	124.9	75.18	137,440	1,100	1,829	8.3	16.7
4a	97	134.3	40.2	7.83	78% limestone screenings 22% pea size limestone	3.33	5.89	4.00	111	94	1:9	9.92	123.6	73.88	198,050	1,602	2,683	7.9	17.0
5a-5b	98	86.2	40.2	11.88	100% cinders ½ in. to 0	4.05	......	4.05	63	......	1:8	12.30	188.5	112.8	154,557	820	1,369	14.4	19.9
6a	98	124.9	40.4	11.84	73% sand 27% pea gravel, by wt.	3.22	5.68	3.91	108	105	1:10	6.82	187.6	111.9	169,340	903	1,512	7.32	14.7
7a	99	99.9	33.9	4.17	100% cinders ½ in. to 0	4.11	......	4.11	65	......	1:8	7.72	66.3	43.8	55,600	838	1,268	11.95	19.1
8a-8b	99	99.9	33.9	9.33	100% cinders ½ in. to 0	4.11	......	4.11	65	......	1:8	7.72	66.3	43.8	55,600	838	1,268	11.95	19.1
9a-9b	101	133.9	49.3	7.78	72.3% sand, 27.7% gravel ⅜ in. to 0	3.15	5.74	3.88	113	105	1:7	7.50	91.2	46.3	11,800	1,295	2,550	5.7	12.2
10a	103	74.1	40.0	6.00	100% cinders ⅜ in. to 0	......	......	3.78	63	......	1:8	12.00	94.5	56.7	21,900	232	386	28.7	33.2
11a	97	126.3	42.4	7.85	100% slag, ½ in. to 0 56.5% fine, 43.5% coarse	2.29	5.92	3.92	105	79	1:8	7.30	124.1	71.5	113,400	914	1,588	8.8	17.9
12a	102	133.7	45.3	7.78	72.3% sand, 27.7% gravel ⅜ in. to 0	3.15	5.74	3.88	113	105	1:7	7.50	91.5	50.0	124,900	1,367	2,500	5.7	12.2
15a-15b	98	76.7	43.1	11.75	64% fine Haydite 36% coarse Haydite	2.76	5.94	3.92	58	43	1:8½	7.80	185.9	105.9	136,750	736	1,294	16.0	19.6
13a	100	67.7	39.6	9.69	64% fine Haydite 36% coarse Haydite	2.76	5.94	3.92	58	43	1:8½	10.82	125.5	75.75	97,780	779	1,289	24.4	25.5
14a	100	67.7	39.6	9.69	64% fine Haydite 36% coarse Haydite	2.76	5.94	3.92	58	43	1:8½	10.82	125.5	75.75	97,780	779	1,289	24.4	25.5

TABLE XII
MONOLITHIC WALLS CONSTRUCTION DATA

Wall No.	Fig.	Density of Concrete in Wall Lbs. per Cu. Ft.	Over-all Thickness of Wall in Inches	Aggregate Used in Wall Per Cent by Weight	Fineness Modulus of Aggregate			Dry Rodded Weight of Aggregate Lbs. per Cu. Ft.		Mix Proportion Dry Rodded Volume	Water Cement Ratio W/C Gal. per Sack	Average Slump Inches	28-Day Compressive Strength Wet			Per Cent Absorption at 28 Days	
					Fine	Coarse	Combined	Fine	Coarse				Area of Cylinder Sq. In.	Total Breaking Load Lbs.	Breaking Load Lbs. per Sq. In.	By Wt.	By Vol.
30a	104	140.3	4.32	39.3% sand 60.7% crushed limestone	3.00	6.80	5.33	109.9	97.53	1:2¼:4	8.0	5.50	28.84	111,253	3,853	6.02	13.51
31a	104	143.3	4.19	36.5% sand 63.5% gravel	3.00	6.71	5.36	109.9	107.6	1:2¼:4	8.0	5.90	28.59	107,867	3,772	5.24	12.03
32a	104	148.8	4.05	36.5% sand 63.5% gravel	3.00	6.71	5.36	109.9	107.6	1:2¼:4	6.0	0.50	28.25	152,173	5,385	4.17	9.95
33a	104	94.4	3.90	39.8% fine cinders 60.2% coarse cinders	3.24	6.77	5.37	65.5	55.64	1:2¼:4	11.2	3.94	28.06	28,312	1,009	16.55	24.98
34a	104	77.7	3.96	42.6% fine Haydite 57.4% coarse Haydite	2.76	6.67	5.00	58.6	44.41	1:2¼:4	10.5	4.87	28.80	64,992	2,252	23.07	28.80
35a-35c	105	148.25	10.66	36.5% sand 63.5% gravel	3.00	6.71	5.36	109.9	107.6	1:2¼:4	6.0	0.30	28.21	133,366	4,728	4.34	10.31
36a	104	118.7	3.96	52.6% sand 47.4% cinders	3.00	6.77	5.21	109.9	55.64	1:2¼:4	6.75	0.30	28.20	90,850	3,218	8.35	15.67
38a-38c	106	146.0	7.60	39% sand 61% gravel	2.96	6.15	4.91	98.2	98.9	1:2¼:3½	7.0	7.38	28.27	121,000	4,280	4.85	11.3
39a-39b	106	146.0	7.98	39% sand 61% gravel	2.96	6.15	4.91	98.2	98.9	1:2¼:3½	7.0	7.25	28.27	123,200	4,360	4.85	11.3
40a	106	146.0	7.59	39% sand 61% gravel	2.96	6.15	4.91	98.2	98.9	1:2¼:3½	7.0	7.25	28.14	119,100	4,230	4.85	11.3
41a	106	146.0	7.56	39% sand 61% gravel	2.96	6.15	4.91	98.2	98.9	1:2¼:3½	7.0	7.25	27.76	96,480	3,480	4.85	11.3
42a-42b	106	146.0	8.53	39% sand 61% gravel	2.96	6.15	4.91	98.2	98.9	1:2¼:3½	7.0	7.38	28.13	97,510	3,470	4.85	11.3
43a	106	146.0	7.22	39% sand 61% gravel	2.96	6.15	4.91	98.2	98.9	1:2¼:3½	7.0	7.25	28.55	98,480	3,440	4.85	11.3

TABLE XIII

THERMAL CONDUCTIVITY OF MONOLITHIC WALLS

WALL No.	DESCRIPTION	CONDUCTANCE C	THICKNESS INCHES	THERMAL CONDUCTIVITY, k
30a	4-inch sand and limestone concrete, plastic mix	2.810	4.318	12.14
31a	4-inch sand and coarse gravel concrete, plastic mix	2.976	4.168	12.40
32a	4-inch sand and coarse gravel concrete, dry tamp mix	3.230	4.050	13.10
33a	4-inch 100 per cent cinder concrete, plastic mix	1.472	3.902	5.75
34a	4-inch 100 per cent Haydite plastic mix	0.943	3.960	3.73
36a	4-inch sand and coarse cinder dry tamp mix	2.160	3.958	8.54

TABLE XIV. HOT PLATE TESTS OF 24×24×2-INCH CONCRETE SPECIMENS

(All tests made at 75° mean temperature)

Type of Aggregate	Mix Proportions by Volume			Slump Inches	Density of Concrete Lbs. per Cu. Ft.	Per Cent Absorption		Per Cent of Voids by Vol.	Density as of Test Lbs. per Cu. Ft.	Thickness Inches	Coefficients of Heat Transmission	
	Cement	Fine Aggregate 0 to No. 4	Coarse Ag. No. 4 to ½ inch			By Wt.	By Vol.				*C*	*k*
Sand and gravel	1	2.00	2.75	0	144.7	4.7	10.9	11.5	150.2	1.995	6.558	13.1
	1	2.75	4.50	0	145.7	4.5	10.4	10.9	150.1	1.990	6.507	12.9
	1	3.50	5.50	0	144.5	4.7	10.8	11.2	148.1	1.992	6.606	13.2
	1	2.00	2.75	5	142.5	5.9	13.4	13.9	148.2	1.988	6.099	12.1
	1	2.00	2.75	5	142.5	5.9	13.4	13.9	148.2	1.988	6.228	12.4
	1	2.75	4.50	5	141.1	6.3	14.2	14.6	146.4	1.985	6.256	12.4
	1	2.75	4.50	5	141.1	6.3	14.2	14.6	146.4	1.985	6.092	12.1
	1	3.50	5.50	5	139.2	6.5	14.4	14.7	144.7	1.982	6.485	12.85
	1	3.50	5.50	5	139.2	6.5	14.4	14.7	144.7	1.982	6.293	12.5
Limestone	1	2.00	2.75	0	135.3	7.4	16.0	16.6	141.0	1.985	5.670	11.2
	1	2.75	4.50	0	137.8	6.7	14.8	15.4	143.3	1.992	6.029	12.0
	1	3.50	5.50	0	136.4	7.2	15.7	16.3	141.7	1.996	5.775	11.5
	1	2.00	2.75	3	130.1	9.8	20.4	20.9	136.3	1.980	5.294	10.5
	1	2.75	4.50	3	126.0	11.4	23.0	23.4	132.6	1.983	5.070	10.0
	1	3.50	5.50	3	127.3	11.4	23.1	23.4	133.3	1.983	4.939	9.79
Cinders	1	2.00	2.75	0	103.6	10.5	17.4	18.2	110.0	2.038	2.272	4.63
	1	2.75	4.50	0	98.7	12.1	19.1	19.9	103.9	2.040	2.106	4.30
	1	3.50	5.50	0	92.0	13.8	20.2	21.4	97.0	2.041	1.829	3.73
	1	2.00	2.75	3	101.4	13.8	22.5	22.8	110.0	2.028	2.412	4.89
	1	2.75	4.50	3	94.0	17.0	25.6	26.0	101.9	2.032	2.156	4.38
	1	3.50	5.50	3	94.4	16.0	23.9	24.4	101.5	2.039	2.080	4.24
Haydite	1	2.00	2.75	0	80.7	13.5	17.5	18.0	87.7	2.023	2.050	4.15
	1	2.75	4.50	0	75.0	16.2	19.4	19.8	81.2	2.034	1.859	3.78
	1	3.50	5.50	0	71.7	18.6	21.3	21.8	78.4	2.030	1.810	3.67
	1	2.00	2.75	4	78.8	16.5	20.8	21.2	88.9	2.019	2.170	4.38
	1	2.75	4.50	4	72.4	18.8	21.8	22.2	80.7	2.017	1.931	3.89
	1	2.75	4.50	4	72.4	18.8	21.8	22.2	80.7	2.017	1.913	3.86
	1	3.50	5.50	4	71.0	20.3	23.0	23.9	80.3	2.018	1.980	4.00
			Fineness Modulus									
Expanded burned clay	1	8.00	3.75		57.9	18.2	16.8	18.4	59.9	2.014	1.134	2.28
Treated limestone slag	1	7.00	3.75		74.6	14.7	17.6	27.1	77.5	2.013	1.128	2.27
By-product of manufacture of phosphates	1	8.00	3.75		86.6	10.8	15.0	25.5	89.0	2.019	1.579	3.19
	1	8.00	3.75		91.1	10.5	15.3	21.1	93.4	2.034	1.683	3.42
Volco pumice mined in California	1	8.00	3.75		65.0	20.1	20.9	26.5	69.15	2.024	1.195	2.42
Haydite	1	8.50	3.75		67.1	17.7	18.9	21.8	70.45	2.024	1.427	2.89
	1	8.50	3.75		67.1	17.7	18.9	21.8	70.45	2.024	1.391	2.82

TABLE XV

EFFECT OF AGGREGATES ON CONDUCTANCE OF MASONRY WALLS

Wall No.	Description of Blocks Used	Conductance C
1a	8×8×16-inch 3-oval core cinder block	0.577
2a	8×8×16-inch 3-oval core Haydite block	0.495
3a	8×8×16-inch 3-oval core sand and gravel block	0.882
4a	8×8×16-inch 3-oval core limestone block	0.856
5a	8×12×16-inch 3-oval core cinder block	0.531
6a	8×12×16-inch 3-oval core sand and gravel block	0.777

TABLE XVI

INSULATION PLACED BETWEEN VERTICAL CONCRETE SURFACES

Wall No.	Description of Wall	Over-all Coeff. U 15-Mile Wind Vel.	Per Cent Improvement in Over-all Coeff. U Due to Insulation	Over-all Resistance $\frac{1}{U}$	Gain in Resistance Due to Insulation	Apparent Conductivity of Insulating Material after Correcting for Air Space
8a	Two masonry walls built of 4×8×16-inch 3-core cinder partition tile spaced 1 inch apart	0.279	....	3.58	....	....
8b	Same as 8a with air space filled with rock wool	0.176	36.9	5.68	2.10	0.33
35a	Two 4-inch monolithic sand and gravel, dry tamp mix, concrete walls spaced 2.52 inches apart	0.433	....	2.31	....	....
35b	Wall No. 35a. Air space filled with dry cinders	0.378	12.7	2.65	0.34	2.00
35c	Wall No. 35a. Air space filled with rock wool	0.150	65.3	....	4.02	0.478

TABLE XVII

OVER-ALL COEFFICIENTS BY TEST AND BY CALCULATION FOR MONOLITHIC WALLS CAST WITH INSULATING MATERIAL BETWEEN TWO SLABS

Inside Slab 4 Inches Thick, Outside Slab 2½ Inches Thick

Wall No.	Figure of Wall	Thickness, Inches		Thermal Conductivity, *k*			Coefficients of Heat Transmission							
				Concrete from Other Tests	Insulation				Calculated Values		Experimental Values		Per Cent Diff.	
		Wall	Insulation		Hot plate value	Corrected for tie rods	f_1	f_0	*C*	*U*	*C*	*U*	*C*	*U*
38a	106	7.60	0.995	12.0	0.343	0.368	1.60	1.55	0.307	0.221	0.325	0.230	5.5	3.9
39a	106	7.98	1.034	12.0	0.401	0.426	1.60	1.55	0.333	0.234	0.335	0.235	0.6	0.4
40a	106	7.59	0.993	12.0	0.287	0.312	1.60	1.55	0.268	0.200	0.360	0.247	25.5	19.0
41a	106	7.56	1.046	12.0	0.383	0.408	1.60	1.55	0.322	0.229	0.360	0.247	10.5	7.3
42a	106	8.53	2.001	12.0	0.770	0.795	1.60	1.55	0.327	0.231	0.377	0.255	13.3	9.4
43a	106	7.22	0.997	12.0	1.182	1.207	1.60	1.55	0.744	0.382	1.083	0.456	31.3	16.2

TABLE XVIII

INSULATING MATERIAL PLACED IN CORE SPACES OF MASONRY WALLS

Wall No.	Figure	Description of Blocks Used	Insulation Used	Density of Ins. Lbs. per Cu. Ft.	Lbs. of Insulating Material per Sq. Ft. Wall Area	Equivalent Thickness of Insulation over Wall Area, Inches	Over-all Coeff. of Conductivity *U* for 15-Mile Wind	Over-all Resistance 1/U	Per Cent Improvement in *U* Due to Insulation	Effective Conductivity *k* for Insulation
1b	94	8×8×16-inch 3-oval core cinder	None	....	....	....	0.370	2.70	....	....
1c	94	8×8×16-inch 3-oval core cinder	Granulated cork	5.12	1.34	3.15	0.201	4.97	45.7	1.38
1d	94	8×8×16-inch 3-oval core cinder	Dry cinders	69.7	18.29	3.15	0.283	3.53	23.5	3.80
1e	94	8×8×16-inch 3-oval core cinder	Rock wool	14.21	3.72	3.15	0.211	4.74	43.0	1.56
2b	95	8×8×16-inch 3-oval core Haydite	None	....	....	....	0.334	2.99	....	....
2c	95	8×8×16-inch 3-oval core Haydite	Granulated cork	5.06	1.33	3.15	0.172	5.81	48.5	1.12
3b	96	8×8×16-inch 3-oval core sand and gravel	None	....	....	....	0.509	1.96	....	....
3c	96	8×8×16-inch 3-oval core sand and gravel	Granulated cork	5.14	1.35	3.15	0.379	2.64	25.5	4.63
5a	98	12×8×16-inch 3-oval core cinder	None	....	....	....	0.374	2.67	....	....
5b	98	12×8×16-inch 3-oval core cinder	Granulated cork	5.24	2.10	4.81	0.199	5.03	46.8	2.04
15a	98	12×8×16-inch 3-oval core Haydite	None	....	....	....	0.342	2.92	....	....
15b	98	12×8×16-inch 3-oval core Haydite	Granulated cork	5.60	2.38	5.10	0.148	6.76	56.7	1.33

THERMAL CONDUCTIVITY OF MONOLITHIC CONCRETE

The thermal conductivity of monolithic concrete depends largely upon the density of the final concrete, which in turn depends upon the aggregates used and the amount of water used in the mix. In general, the more plastic the mix the lower the density and, therefore, the lower the conductivity for any given aggregate.

Thermal conductivity values for six monolithic walls as determined by the hot box method are shown in Table XIII and for various mixes of nine different aggregates when tested by the hot plate method in Table XIV. From Table XIV it will be noted that for the same aggregate and for the same slump test there are some differences in density caused by different grading of the aggregates. These variations in density are, however, not uniform throughout the range. For a given aggregate, the conductivities obtained are usually directly proportional to the density. For sand and gravel and limestone aggregates the dry mixes give the denser concrete with a higher conductivity. The dry tamp mix wall, 32a, of Table XIII gave a conductivity k of 13.1 while the plastic mix wall, 31a, gave a thermal conductivity k of 12.4. The densities were 148.8 and 143.3, respectively. From Table XIV the averages for three sand and gravel samples with zero slump were $k =$ 13.1, density 145 pounds, and for six samples of 5-inch slump they were $k = 12.4$, density 141.1 pounds. This shows a very close agreement between the conductivity as obtained by the hot plate and hot box method and sets the average values for sand and gravel concrete from 12.4 to 13.1.

Three limestone aggregates of zero slump, Table XIV, give an average conductivity of 11.56 at an average density of 136.5 pounds per cubic foot, and three samples of 3-inch slump give averages of 10.08 for the conductivity and 127.8 for the density. The sand and limestone wall shown in Table XIII gave a conductivity of 12.14 with a density of 140.3. The fact that the values for the wall are higher than for those samples tested by the hot plate method is due to the fact that sand was used in the aggregate giving a more dense concrete. If the conductivities for the three tests are plotted against densities, the results will be a straight line.

With the cinder and Haydite aggregates the relation between density and plasticity of mix is not as definite as with the other walls. For the cinder aggregates of Table XIV, the average density of three zero slump samples is 98.1 pounds per cubic foot with a conductivity k of 4.22, and the average of three 3-inch slump samples is 96.6 pounds per cubic foot with a conductivity of 4.45. The density relations are the same as for the other concrete samples, but the conductivities do not exactly follow the densities. This difference is small and might be accounted for by the fact that the surfaces of these samples are rough, and test results were more difficult to obtain. For Haydite aggregates the average for three samples with zero slump was density 75.8, conductivity 3.87, and for four samples with 4-inch slump the averages were density 73.6, conductivity 4.03. These results are substantially the same as for the cinder aggregates, indicating that for the lower density aggregates such as cinders and Haydite the plasticity of mix is not as important a factor in determining the density and the conductivity as it is for sand and gravel or for limestone aggregates.

EFFECT OF AGGREGATES ON CONDUCTANCE OF MASONRY WALLS

Since most masonry walls contain openings or cored out sections, the type of aggregate used cannot affect the conductance of the finished walls to the same extent as it affects a monolithic wall. From the results shown in Tables XIII and XV, a reduction in thermal conductivity for an 8-inch monolithic wall when using cinders as compared to the same wall using sand and gravel is:

$$\frac{13.1 - 5.75}{13.1} \times 100 = 56.1 \text{ per cent}$$

and for masonry walls it is:

$$\frac{0.882 - 0.577}{0.882} \times 100 = 34.6 \text{ per cent}$$

When using Haydite as an aggregate the reduction in thermal conductivity, as compared with sand and gravel is:

$$\frac{13.1 - 3.73}{13.1} \times 100 = 71.5 \text{ per cent for monolithic walls, and}$$

$$\frac{0.882 - 0.495}{0.882} \times 100 = 43.9 \text{ per cent for masonry walls}$$

The ratio of the reduction for monolithic, as compared with masonry walls is $\frac{56.1}{34.6}$, or 1.62, when using cinders, and $\frac{71.5}{43.9}$, or 1.63, when using Haydite.

The reason that the reduction is 62 per cent greater for the monolithic walls than for the block walls is due to the fact that a part of the heat passes directly through the air spaces in the masonry walls and is not affected by the kind of aggregate used.

INSULATION BETWEEN PARALLEL CONCRETE SURFACES

The test values given in Table XVI show the improvement in thermal conductivity of a wall obtained by placing insulation in the vertical space between two parallel walls. It also indicates some of the precautions which must be taken when insulating walls in this manner. The percentage of improvement shown in the fourth column was based on a comparison of the over-all conductivity coefficients for a 15-mile wind velocity. The apparent conductivity of the insulating material shown in the last column was calculated from the test results of the insulated and noninsulated walls by assuming the air space of the noninsulated wall to have a normal value for such air spaces. The conductivity value of .33 as calculated for the rock wool of Wall 8b is somewhat high for rock wool, but the calculated value of .478 for the same rock wool in Wall 35c is so far out of line as to require further investigation.

In Walls 35a and 35c there were two monolithic slabs 4 inches thick, spaced 2½ inches apart, and held together with tie rods which passed through the air space or insulating material as the case might be. These tie rods were imbedded in the concrete at both ends and provided paths of high heat conductivity.

If it is assumed that the contact between the ends of the rods and the concrete was of sufficient area to supply heat to the rods at one end and remove it from the other in the same proportion as it was supplied and taken away from the air space or the insulating material in the air space, then the insulating material and the rods would each transmit a part of the total heat, which would be proportional to their heat conducting capacity. In each case this capacity would be equal to the area of the material times its thermal conductivity. If the conductivity of rock wool is taken as 0.27 and that of iron at 324.0, one square foot of tie rod is equal to 324.0 ÷ 0.27, or 1200 square feet, of rock wool as a heat conductor.

In Wall 8b there were 15 tie strips of 28-gage metal ¾ inch wide, giving a total area of 0.146 square inch, or the equivalent of:

$$\frac{0.146}{144} \times 1200 = 1.22 \text{ square feet of rock wool}$$

Correcting the calculated value of 0.33 gives:

$$0.33 \times \frac{9(\text{square feet of test area})}{9 + 1.22(\text{equivalent area of insulation})} = 0.291$$

as the true thermal conductivity value for rock wool used in the masonry walls.

For Wall 35c there were twelve ¼-inch tie rods through the test area equal to 0.588 square inch in area, or the equivalent of:

$$\frac{0.588}{144} \times 1200 = 4.9 \text{ square feet of insulation}$$

Correcting the calculated value of 0.478 gives:

$$0.478 \times \frac{9}{9 + 4.9} = 0.31$$

as the true value of k for rock wool when using it in the monolithic wall.

While the assumptions as to the proportional amounts of heat conducted through the tie rods and the insulating materials are only approximately correct, the calculations based on them give reasonable values for the conductivity coefficient of the insulating material, and by this assumption calculated over-all coefficients agree reasonably well with test coefficients.

If metal tie rods, having their ends embedded in a high conductivity material, pass through an insulated area, they become important factors in the heat conductivity through that area and must be taken into consideration in making calculations. The effect of such rods becomes more important as the thermal conductivity of the space is reduced. For best results the area of the rods should be kept as low as consistent with structural requirements, and it is probable that a greater improvement in the over-all coefficient for the test walls might have been obtained by reducing the number and size of such tie rods to minimum requirements.

The effectiveness of insulating monolithic walls by inserting a slab of insulating material in the central plane of the wall before it is poured, and binding the two sections together with tie rods of limited area is shown by the test results for Walls 38a to 43a (Fig. 106 and Table XVII). Figure 106 shows the construction of the wall as built up of two monolithic slabs, the inner being 2½ inches thick and the outer 4 inches thick. These were tied together with tie rods.

The thickness and properties of the insulating material in the space between the slabs of concrete are shown in the tables accompanying Figure 106. The test and calculated coefficients for the walls as built and not treated with surface water are shown in Table XVII. The percentage variation between test and calculated values for the over-all coefficients as shown in the last column are reasonably small, with the exception of those for Walls 40a and 43a. Wall 40a was insulated with cork board and Wall 43a with vermiculite and a cement binder. These surfaces were somewhat rough, allowing the concrete to enter the surface of the insulating material as the wall was poured, thereby reducing its thermal value below that determined by the hot plate test. The material used in Wall 42a was also rough and porous on the surface, but in this case the material was 2 inches thick and also had a high thermal conductivity. The percentage reduction in conductivity caused by the mortar entering the surface was therefore less than for the thinner, lower conductivity materials used in Walls 40a and 43a. The material used to insulate Wall 39a was of a rather smooth waterproofed surface and there was a substantial agreement between test and calculated coefficients. In Wall 38a the surface of the material was reasonably smooth, but it was not waterproof. In this case there was 3.9 degrees variation for Wall 41a, the surface of the material was smooth, but was not firm, and there was a likelihood that it would be somewhat compressed or indented by the concrete.

In general the results from these tests indicate that if an insulating material is used between two monolithic slabs of concrete and the material is reasonably waterproof and of such nature as not to allow concrete to enter its surface, then if the conductivity of tie rods are taken into consideration, the over-all conductivity value of the wall may be calculated with reasonable certainty.

INSULATION PLACED IN CORE SPACE OF MASONRY WALLS

If core spaces are built into the blocks of a masonry wall, the heat flow through that wall will be divided, a part of it going through the air spaces and a part through the solid material dividing the air spaces. The amount of heat flowing through each path will depend upon its area and its thermal conductivity. Thus the cored out air space of a block is effective if the heat resistance of the air space as built is greater than the heat resistance of the material in place. The average conductance from surface to surface of an air space bounded by parallel surfaces perpendicular to the path of heat flow at 40° mean temperature is 1.1. This value applied to cored out air spaces which are over one inch thickness along the path of heat flow out will be shown later in this discussion. This method cannot be relied upon.

The insulating value of an air space may often be improved by filling it with some insulating material. The effectiveness of this treatment will depend not only upon the amount and kind of insulation used, but upon the shape of the air space and the amount of total heat which may pass through the uninsulated sections of the wall. For two walls of the same construction but having aggregates of different conductivities, air space insulation will be the most effective for that wall having low conductivity aggregates. If the wall is so constructed that the path for heat flow around the air spaces is restricted and a large percentage of the heat must flow through the air spaces, then insulation should be effective. If, on the other hand, it is so constructed that a large percentage of the heat may flow directly through the solid material around the air spaces, then the insulation of the air spaces may do but little good. In order to effectively insulate a wall, all paths of heat flow must be considered. For a masonry wall the solid bridges of concrete between the air spaces will carry the heat past the insulation the same as the tie rods will carry the heat through the insulation placed between parallel masonry or monolithic walls. Since it is necessary to have some bond or tie between the two surfaces of most walls this tie should be built with maximum heat resistance if the insulating qualities of the wall are important factors.

In order to show the value of insulating materials when placed in the core spaces of standard masonry walls using different aggregates, several masonry walls were constructed and tested with and without insulation. The combined results of these tests are shown in Table XVIII. In this series both 8-inch and 12-inch blocks were used, cinders, Haydite, and sand and gravel aggregates being used for the 8-inch blocks and cinders and Haydite aggregates for the 12-inch blocks. Four tests were made on the 8-inch cinder block wall, the first without insulation and the other three having the core spaces filled with granulated cork, dry cinders, and rock wool, respectively. For each of the other types of construction two tests were run, one without insulation and the other with granulated cork in the core spaces. The fourth from the last column in Table XVIII gives the conductivity coefficient corrected to a 15-mile wind velocity over the outside surface. Next to the last column gives the percentage improvement due to insulating the core spaces. This is the important factor in determining whether or not it is worth while to insulate. The last column gives the effective conductivity for the insulating material as used. It was obtained by assuming that the insulating material used was spread evenly over the full surface of the wall and by calculating the effective conductivity of this material from the test results with and without insulation. The high calculated effective value for these materials compared with their real thermal values is due to the fact that the heat passes around the air spaces regardless of how thoroly they may be insulated. Compare the results for Walls 1c, 2c, and 3c. These are all of the same type of block excepting that they are built of cinders, Haydite, and sand and gravel, respectively. The percentage improvement caused by filling the core spaces with granulated cork is 45.7, 48.5, and 25.5, respectively. Thus the sand and gravel wall which has a high conductivity aggregate as compared to either cinders or Haydite aggregates shows only about half the percentage improvement shown by cinders and Haydite. A comparison between Walls 1c and 2c shows a slightly better percentage reduction for Haydite than for cinders, a fact which would be expected since Haydite has the lower thermal conductivity.

A comparison between the 8-inch and 12-inch walls shows some interesting facts. The 8-inch cinder block wall, 1b, gave a coefficient of .370, whereas the 12-inch block wall, 5a, gave a coefficient of .374, which is slightly higher than that for the 8-inch block wall without insulation. The 8-inch Haydite block wall, 2b, without insulation, shows a coefficient of .334 and the 12-inch Haydite block wall, 15a, without insulation, shows a coefficient of .342, which is a slightly greater increase than shown for the cinder walls. An inspection of the drawings giving a cross-sectional view of the 8-inch and 12-inch blocks shows that the bridge wall between the cores of the 8-inch block is 1⅜ inches thick, whereas that between the cores of the 12-inch block is 1⅝ inches thick. There is, thus, a slightly larger cross section of solid material through the 12-inch block than through the 8-inch block, but in addition to this there is the difference in length of the path of heat flow. For the 8-inch block it is 4 11/16 inches long and for the 12-inch block it is 8 inches long. If no other factor affected the rate of heat flow it would be proportional to the area and inversely proportional to the length of path of solid material. On this basis the relative rates of flow through the solid material for the two blocks would be 1 for the 8-inch and about .7 for the 12-inch block. The increased area of the solid material for the 12-inch block can, therefore, be only partly responsible for the high conductivity recorded.

A reasonable explanation of the higher conductance of the 12-inch wall is that the heat which is transmitted to the solid partitions of the wall does not all continue to travel through the partitions to the opposite side of the wall. Of that heat which starts from the high temperature side of the wall a part of it continues through the solid portion and a part of it is transferred to the surface bounding the air space above where it is picked up by the air and transferred to the opposite side and is again reconducted into the solid material. Thus the side walls of the air space actually impair the effectiveness of the solid materials between them, causing more heat to be transferred across the air space by convection than would be the case if the side walls were not present. If this explanation holds, then the wide air space of the 12-inch wall actually carries more heat across the wall than the narrower air space of the 8-inch wall and, therefore, breaks down the effectiveness of the greater heat resistance of the solid part of the 12-inch wall. This increase of heat transfer across the wide air space as compared to that across the narrow air space would be greater for blocks built up of high resisting material, and if the resistance of the aggregate was sufficiently high the conductivity of the 12-inch wall might be greater than that of the 8-inch wall. An examination of the test results shows that this is exactly what has happened. The 12-inch cinder wall, 5a, the aggregate of which has a reasonably high heat resistance, gave about a 1 per cent higher coefficient than the 8-inch cinder wall, 1b, whereas the 12-inch Haydite wall, 15a, gave about a 2.3 per cent greater coefficient than the 8-inch Haydite wall, 2b. In previous tests (Fig. 92) 8-inch sand and gravel concrete block walls gave an average value of .447 as compared with .410 for the 12-inch sand and gravel block walls. These were still-air coefficients. In this case the conductivity of the solid material was higher; therefore the relative effect of the heat transferred across the air space by convection was less than for either the Haydite or the cinder block wall.

The reduction in heat transfer due to placing granulated cork in the 8-inch cinder block cores was 45.7 per cent, and that due to placing the granulated cork in the 12-inch cinder block was 46.8 per cent. For the Haydite wall, granulated cork gave a reduction of 48.5 per cent in the 8-inch wall and 56.7 per cent in the 12-inch wall. Thus, the percentage reduction in the over-all heat transfer coefficient caused by placing cork in the core spaces was greater for the 12-inch than for the 8-inch wall for both cinder and Haydite. The percentage gain was greater, however, for Haydite which had the highest thermal resistance in the aggregate and would, therefore, be subject to the effect of the high heat transfer across the uninsulated wide air space to a greater extent than would be the cinder wall.

CONDUCTIVITY OF INSULATED MONOLITHIC WALLS AS AFFECTED BY MOISTURE

In order to determine the effect of water on the outside surface of insulated monolithic walls, Walls 38c, 39a, and 42a, shown in Figure 106, were treated on the outside surface with a heavy fog spray for a period of 19 hours and then retested to determine whether or not the water would be transmitted to the concrete in sufficient quantities to affect the insulating materials. The results of these tests are shown in the table under Figure 106, Walls 38b, 38c, 39b, and 42b. These results show that there was practically no effect on the thermal conductivity caused by spraying the outside of the walls up to 19 hours. The maximum gain in weight was 1.24 per cent for Wall 39b.

INSULATING VALUE OF MATERIALS AS AFFECTED BY THEIR APPLICATION

The method of applying an insulating material often becomes the most important factor in determining its effectiveness. There are many methods of applying materials, and a selection must be governed by the kind of material, type of construction, and its effectiveness in stopping the heat flow through the wall. Most materials are best adapted to some specific application, and to get the best value applied to a wall one must consider all of the methods by which heat may be transferred through them. There is no use, for instance, in building high thermal resistance into a wall if at the same time the heat is traveling through the wall by air leakage at several times the rate it would travel through an uninsulated wall by transmission. Likewise there is no need for overinsulating one part of the wall and neglecting some other part of the building.

FACTORS AFFECTING CONDUCTIVITY OF WALLS

There are many factors which affect the over-all heat transfer coefficient of built-up wall sections and materials. To make a complete analysis the wall must be divided up into its component parts and the various factors affecting heat transfer through each component part must be considered. As previously stated, most walls can be divided

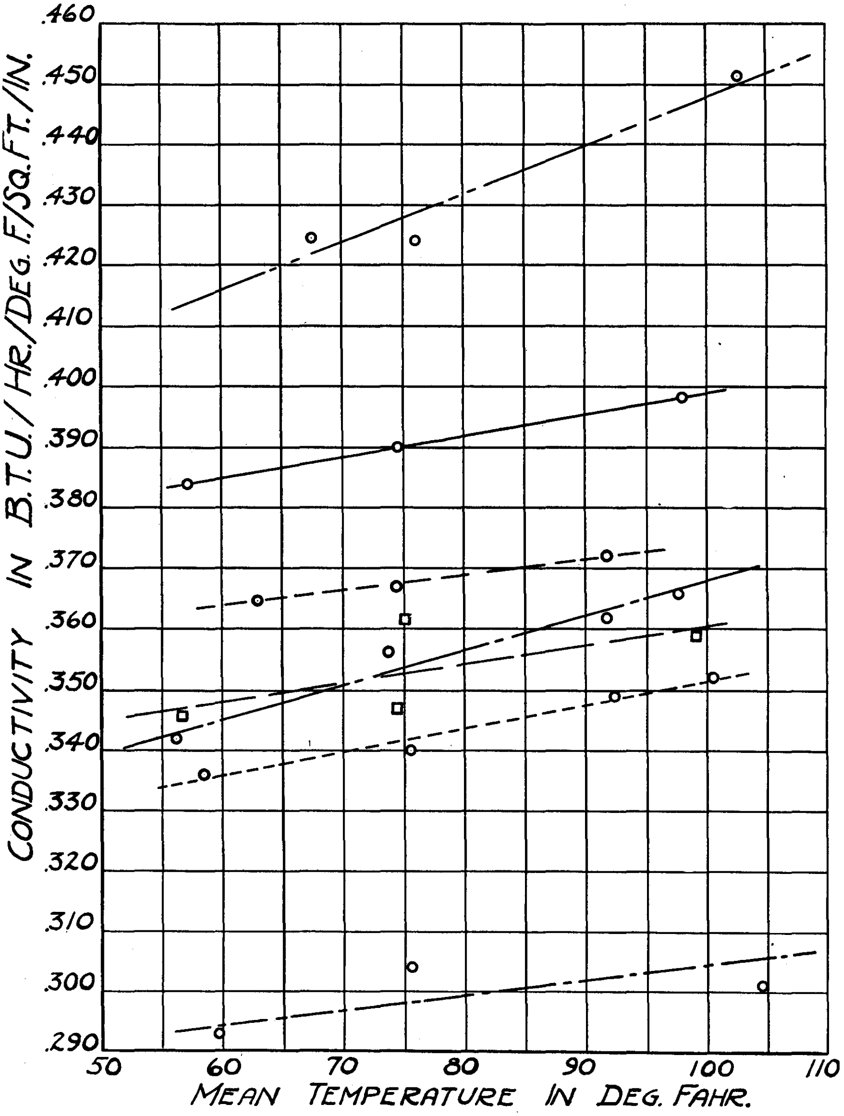


FIGURE 107. RELATION BETWEEN CONDUCTIVITY AND MEAN TEMPERATURE FOR VARIOUS INSULATING BOARDS

into outside surfaces, air spaces, and homogeneous materials. Those factors affecting the heat flow through surfaces and air spaces have been considered under the discussion of each, respectively, and briefly may be summarized as follows:

Heat transfer from or to a surface is by radiation, conduction, and convection, the radiation being controlled by the shape of the surface and its exposure to surrounding objects, the temperature of the surface, and the temperature of the surrounding objects, and the emissivity factor of both the surface and the surface of the surrounding objects. Conduction and convection are controlled by the nature of the surface and the air movement in contact with the surface. Heat is transferred across air spaces by radiation, conduction, and convection. The amount of radiation depends upon the shape of the boundary surfaces and the emissivity coefficient of the surface. The amount transmitted by convection and conduction depends upon the nature of the surface, the shape of the boundary surfaces, and the width of the air space.

The most common factors which affect the conductivity of homogeneous insulating materials are percentage of moisture in the material, mean temperature at which the conductivity coefficient is determined, and density of the material. There are also other factors such as size

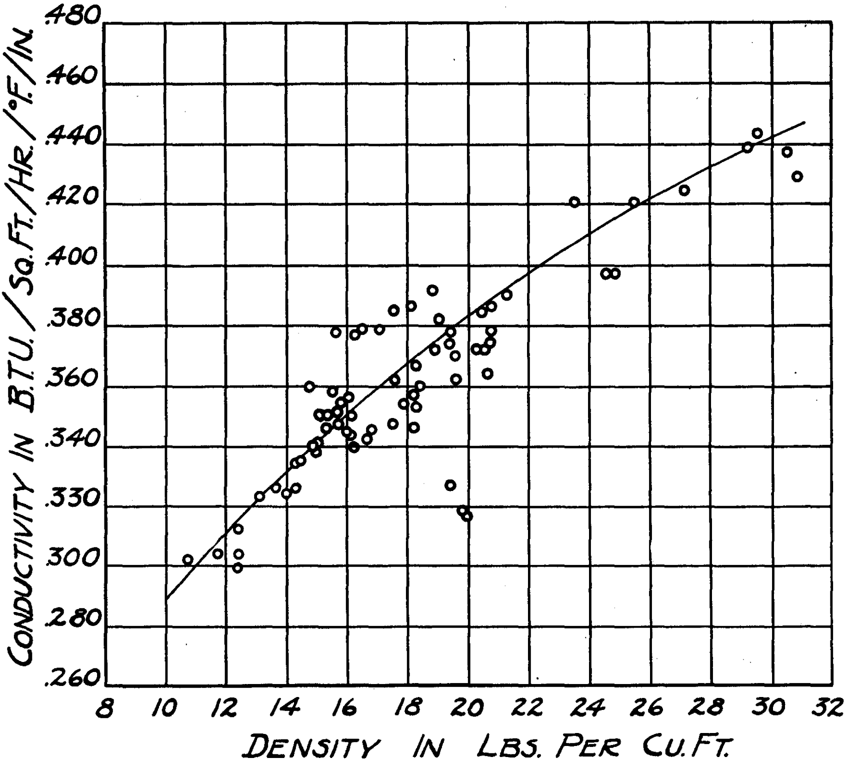


FIGURE 108. RELATION BETWEEN CONDUCTIVITY AND DENSITY FOR A GROUP OF DIFFERENT TYPES OF FIBER INSULATING BOARDS

and arrangement of fibers in fibrous materials which may also have a bearing on the conductivity. Most vegetable fiber insulating materials will absorb moisture from the atmosphere at an average gain from 6 to 10 per cent by weight, depending upon the nature of the material and the conditions of the atmosphere. The amount of moisture present in any material has a direct bearing upon its thermal conductivity and usually the coefficient increases directly in proportion to the per cent of moisture present. In order that test results may be comparable the material should be tested either on a bone-dry basis or else after being preconditioned in air of some specified temperature and humidity for a sufficient length of time to reach a moisture equilibrium. In this case the condition of the atmosphere and amount of moisture absorbed by the sample should be reported with the test.

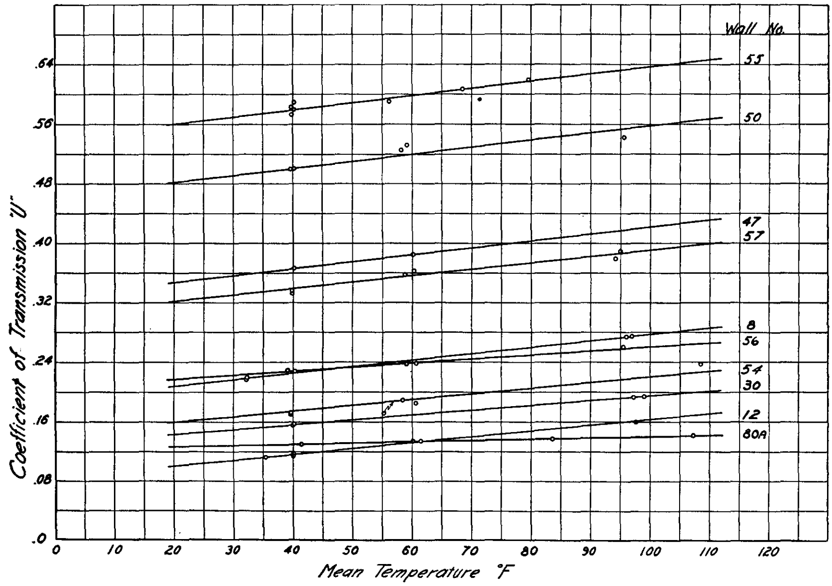


FIGURE 109. RELATION BETWEEN COEFFICIENT OF TRANSMISSION U AND MEAN TEMPERATURE FOR VARIOUS TYPES OF WALL CONSTRUCTION

The conductivity of most insulating materials increases directly with their densities. For the same insulating material with all other conditions equal this variation is usually a straight line. Other factors, however, such as moisture in the sample, arrangement and character of fibers in a fibrous insulation material may have a greater effect on the conductivity than density. For a fibrous insulating material the conductivity value is usually improved by so laminating and arranging the fibers that their general direction is in a line perpendicular to the heat flow. The points shown on the curve of Figure 108 represent test results for a group of insulating boards made of the same type of fibrous materials, but of different densities. In general, a line may be drawn through the entire group representing the relation between density and conductivity variation. Some points are, however, widely scattered from this line and indicate that other qualities in the material besides the density are affecting the conductivity.

The thermal conductivity of a homogeneous insulating material usually increases directly with the mean temperature. The increase in conductivity for several different fiber insulating materials is shown in the curves of Figure 107. While the rate of increase in conductivity is not the same for all of these materials, an average increase of .01 may be taken for each 30° F. increase in mean temperature, providing definite data are not available for the specific materials. In many materials, and particularly where the range in temperature is great the mean temperature variation is an important factor and should be considered in selecting a proper coefficient.

Several of the wall sections in the first series of hot box tests were tested at mean temperatures ranging from 32° F. to 108° F. The results from these tests are shown graphically in the curves of Figure 109. Inspection of these curves show the test points for each wall to fall substantially on a straight line and with the exception of Wall 80a the curves are substantially parallel. For Wall 80a, a wall not shown in this bulletin, the surfaces were lined with aluminum foil.

OVER-ALL HEAT TRANSMISSION COEFFICIENTS BY CALCULATION

If the thermal properties of all materials used in a wall are known and if they are so combined in a wall that their thermal resistances will be uniformly effective over the surface of the wall the over-all coefficients may be calculated and the results will check with those obtained by a test of the complete wall. To get an accurate check between the calculated and test results the conductance coefficient for the various materials and parts of the wall must be selected with regard to the mean temperature and moisture conditions under which they are used. In case the materials are so placed in the wall that there is parallel heat flow between materials of different resistances it will be necessary to select the combined conductivity values with caution and in many cases it will be preferable to select conductivity coefficients for combinations of different materials by test methods. This is true for hollow concrete block walls and in many cases where wall sections are tied together with high conductivity tie rods passing through insulated sections.

The thermal conductance of air spaces lined with ordinary material may be taken from Figures 42 and 43 of pages 41 and 42 of this bulletin. Average values for air spaces lined with bright metallic foil may be taken from Figure 45, page 45. The surface conductance for ordinary materials at different mean temperatures and air velocities may be taken from the curves of Figures 17 to 33, inclusive. The conductivity value of wood may be selected from the values of Figures 54 to 77, inclusive, and the conductivity value of insulating board may be selected according to the density of the board from Figure 108. Table XIX shows the conductance values for various combinations of materials as often used in wall construction.

For those walls which are of complicated construction, and for which calculated results are doubtful, it will usually be possible to select some of the several walls tested which are sufficiently close in construction to make reasonably certain of the calculated results.

TABLE XIX

CONDUCTANCE COEFFICIENTS USED FOR CALCULATING THE OVER-ALL TRANSMISSION COEFFICIENTS OF WALLS

MATERIALS	MEAN TEMPERATURE	CONDUCTANCE
⅜-inch lath and ⅜-inch plaster	70	$C = 2.50$
Fir sheathing, building paper, and pine lap siding	20	$C = 0.50$
Fir sheathing, building paper, and stucco	20	$C = 0.55$
Fir sheathing and building paper	30	$C = 0.71$
Building paper and 4-inch pine lap siding	15.5	$C = 0.85$
Yellow pine lap siding	....	$C = 1.28$
Gypsum plaster (⅜ inch thick)	73	$C = 8.80$
Surface conductance (still air)		f_1 or $f_0 = 1.65$
Surface conductance (15-mile wind velocity)		f_1 or $f_0 = 6.00$