Housing Research Paper No. 32
April 1954

HOUSING AND HOME FINANCE AGENCY • Albert M. Cole, Administrator

Office of the Administrator

DIVISION OF HOUSING RESEARCH • Joseph H. Orendorff, Director

Washington 25, D. C.

For sale by the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C.

Price 25 cents

● Modern trends in home design, using newly developed materials and novel methods of assembly, have created numerous problems in the field of thermal transmission and water-vapor migration through walls, floors, and ceilings. *U*-factors, vapor barriers, dewpoint temperatures, and similar terms, which had little significance within the home-building industry a few years ago, have now become common parlance and essential considerations among designers and builders. The popular and increasing acceptance, in residential properties, of equipment designed to provide summer cooling in addition to winter heating, has emphasized the economic and comfort aspects of thermal insulation.

It is seldom realized, however, that still air, whether trapped in the small cells of mass-type insulation, retained in a space contiguous to reflective-type insulation, or as a film on any surface, serves as one of the main retardants to thermal flow. Continuous airspaces created between structural elements are quite effective as heat barriers, and are always considered in calculating the thermal resistance of building components.

A recent review of the available information pertaining to the thermal resistance of airspaces, particularly when faced with reflective materials, revealed that the data were limited and incomplete. Additional data in regard to coefficients for total heat transfer of airspaces having different effective emissivities, and with various orientations and directions of heat flow, for the widths, temperature differences, and mean temperatures encountered in buildings, were needed to improve the reliability of essential engineering calculations.

In view of this need, the Division of Housing Research, HHFA, sponsored a research project (ME–12) at the National Bureau of Standards, United States Department of Commerce. The work was conducted and the report prepared by H. E. Robinson and F. J. Powlitch, under the direction of R. S. Dill, chief of the Heating and Air Conditioning Section, Building Technology Division.

THE THERMAL INSULATING VALUE OF AIRSPACES

Introduction

The total heat flow across a plane airspace is the result of heat flow by radiation and heat flow by convection and conduction combined between its facing surfaces. There are theoretical reasons for regarding these heat flows as taking place independently. Consequently, the coefficient for the total heat transfer across a plane airspace can be considered as the sum of two coefficients:

a. A radiation coefficient which depends only upon the emissivities and temperatures of the surfaces facing the air spaces, and

b. A coefficient for convection and conduction combined which does not depend upon the emissivities of the surfaces, but does vary with the thickness of the space, its orientation, and the direction of heat flow, and with the temperatures of the surfaces, assuming the surfaces are reasonably smooth.

Thus, a flexible means of calculating the total heat-transfer coefficients for a wide variety of airspaces would be provided if data as to the two component coefficients were available.

In 1945, at the request of the Federal Public Housing Authority, the National Bureau of Standards reviewed published data on the thermal conductance of reflective and nonreflective airspaces and submitted a summary of representative values. The review indicated that the then-available published data were limited and incomplete in regard to total heat-transfer coefficients for airspaces of various emissivities and with various orientations and directions of heat flow, and for the ranges of airspace thickness, temperature difference, and mean temperature encountered in building insulation service. Complete and consistent data as to the convection-conduction coefficient, over a wide range of pertinent conditions, particularly were not available at the time of the review mentioned.

The radiation coefficient can be calculated readily, by means of the Stefan-Boltzmann law, for given surface emissivities and temperatures.

However, no analytical method for calculating coefficients for combined convection and conduction across airspaces has yet been developed, and a series of experimental measurements was required for their determination.

This Paper presents the results of measurements of the heat-transfer for airspaces of various emissivities and thicknesses. The data were obtained for five different orientations and various directions of heat flow ranging from heat flow vertically upward to heat flow vertically downward, and encompass a range of values of temperature difference across the airspace.

The total coefficient for heat transfer across an airspace is shown to be the sum of a coefficient for heat transfer by radiation and a coefficient for heat transfer by combined convection and conduction. These two coefficients depend upon different variables characterizing the airspace. Curves are given for computation of the radiation coefficient for spaces of various emissivities and mean temperatures. Other curves give values of the convection-conduction coefficient for airspaces of different orientations and directions of heat flow, and for various airspace thicknesses and temperature differences. Equations are given for adjusting this coefficient for different mean temperatures.

The method of utilizing the data to calculate the insulating value of a particular airspace, or of airspaces in a building construction, is illustrated by several examples of general interest. A description is given of the guarded hot box heat-transfer apparatus and of the test airspaces used to obtain the data presented in this Paper.

Basic Considerations

Heat flows across a plane airspace, from the warmer to the cooler surface, by radiation, and by convection and conduction combined.

There are good theoretical reasons for considering that these two actions are independent of each other. For airspaces of different emissivities, or for the same airspace at different orientations, the amount of heat transmitted by each means varies.

The heat flow due to radiation depends only upon the absolute temperatures of the facing surfaces of the space, and upon their effective emissivity.

The heat flow due to convection and conduction combined, however, does not vary with the effective emissivity, but depends upon the orientation and thickness of the airspace, the temperature difference of the facing surfaces, the direction of heat flow, and, to a lesser extent, upon the mean temperature of the space.

The heat flow due to convection and conduction combined cannot be less than the heat flow for conduction alone through still air. It may increase materially above the latter value, if convection occurs in the space.

If the total heat flow is regarded as the sum of two independent components, then, the thermal conductance, C, or coefficient for total heat transfer across the space, may be regarded as the sum of two independent coefficients, as denoted by

$$C = Eh_r + h_c \tag{1}$$

where Eh_r is the radiation coefficient, and h_c is the convection-conduction coefficient.

The coefficient for heat transfer by radiation across an airspace, per unit of temperature difference of its surfaces, is given by Eh_r, where E is the effective emissivity of the space, and h_r is calculated by means of the Stefan-Boltzmann law, as follows:

$$h_r = \frac{0.172 \times 10^{-8}\ (T_1^4 - T_2^4)}{(T_1 - T_2)} = 0.00686 \left(\frac{T_m}{100}\right)^3 \text{ approximately, in B. t. u. per hour, per square foot, per } ^\circ\text{F.} \tag{2}$$

T_1 and T_2 = the absolute temperatures (° F.+460°) of the warmer and cooler surfaces, respectively.

$T_m = \frac{1}{2}(T_1 + T_2)$

Values of h_r for various airspace mean temperatures (expressed in ° F.) are given by the curve shown on figure 1.

Values of E, the effective emissivity of an airspace of uniform thickness, having its other dimensions large compared with its thickness, may be calculated by the equation:

$$\frac{1}{E} = \frac{1}{e_1} + \frac{1}{e_2} - 1 \tag{3}$$

e_1 and e_2 = respective total emissivities of the facing surfaces.

Values of E for various values of e_1 and e_2 are given by the curves shown on figure 2.

Values of the coefficient for combined convection and conduction, per unit of temperature difference of the surfaces, represented by h_c, cannot be calculated at present. Therefore it was necessary to determine them experimentally for the range of variables ordinarily encountered in airspaces in buildings.

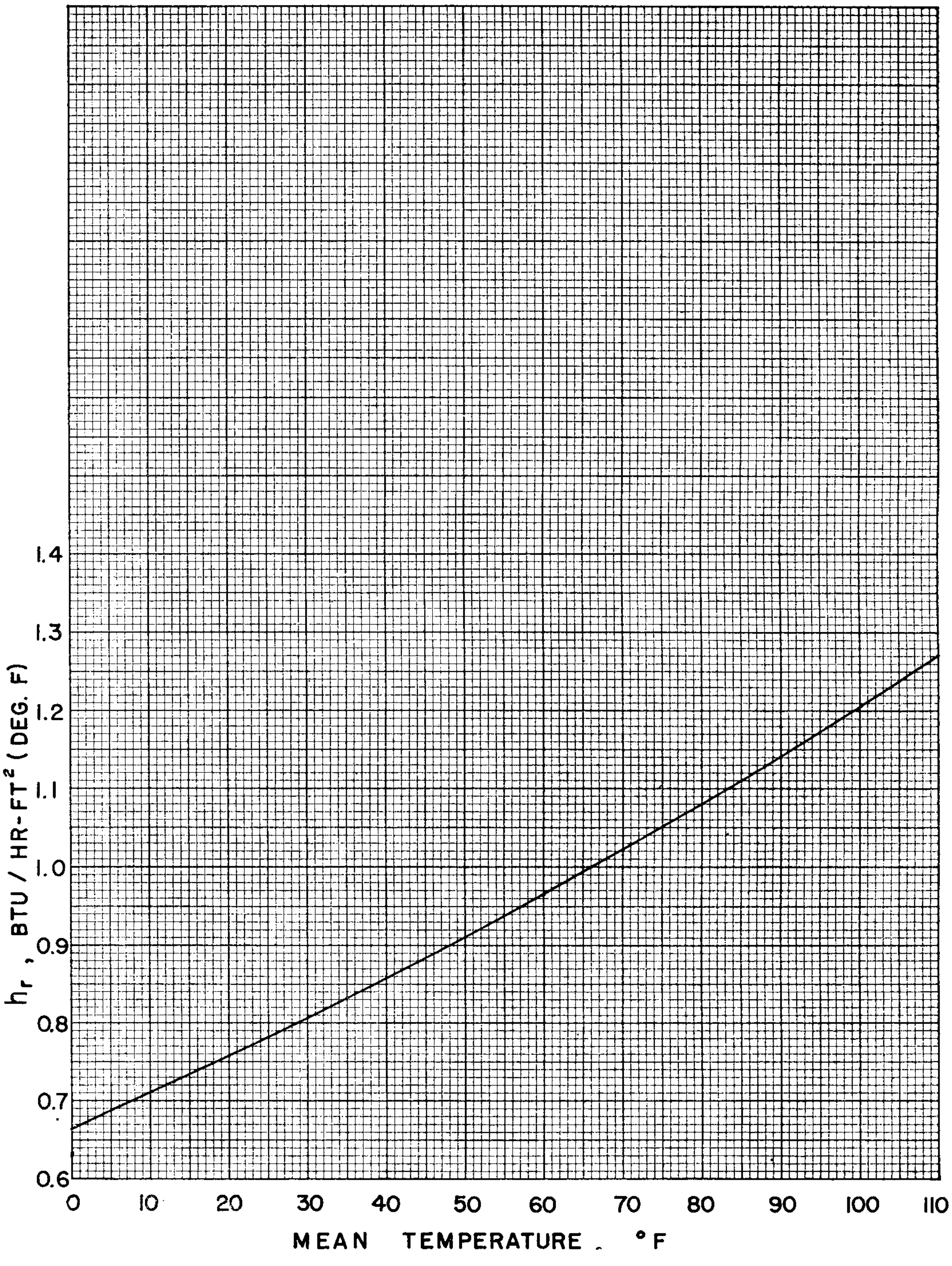
Determining Values for h_c

Using an apparatus of the guarded hot box type (described in appendix A), a total of 146 tests was made and measurements obtained on a number of airspaces, under various conditions of orientation and temperature, to determine for each condition the coefficient of total heat transfer (thermal conductance, C) of the space per unit of temperature difference between its facing surfaces. The value of C was adjusted to compensate for the effect of heat flow in the wood framing at the edges of the test airspace.

Separate measurements were made of the total emissivities of the surfaces of the various materials used to bound the test airspaces, in order to determine the values of e_1 and e_2 in each case.

With the values of e_1 and e_2 determined, the value of the coefficient for radiation (Eh_r) was computed for each test condition on which measurements for C were obtained above, using equations (2) and (3).

The value of h_c for each test condition was obtained by subtracting the calculated coefficient, Eh_r, from the observed total coefficient, C, in accordance with equation (1).



h_r , BTU / HR-FT^2 (DEG. F)
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
0
10
20
30
40
50
60
70
80
90
100
110
MEAN TEMPERATURE , °F

Figure 1.

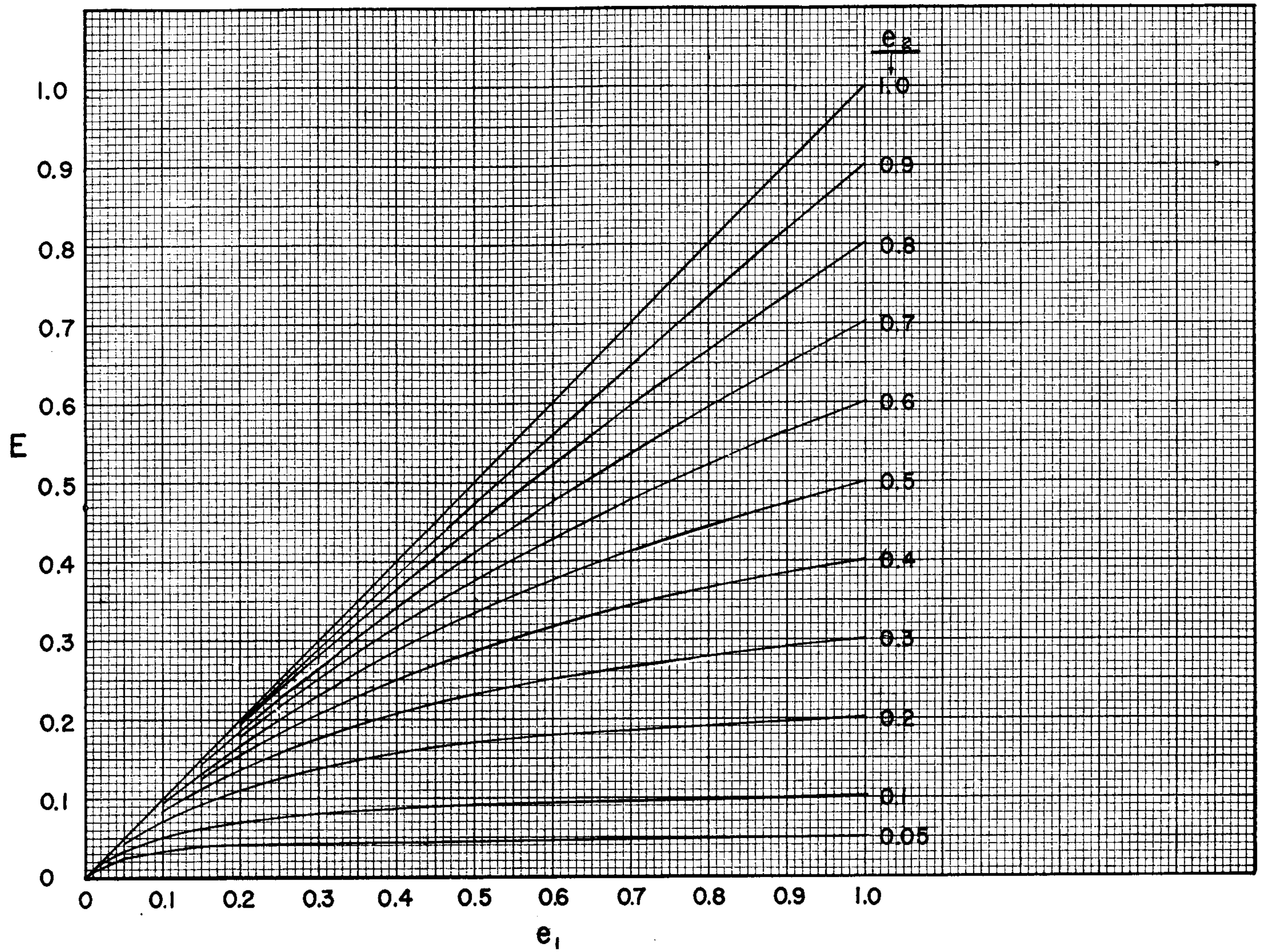


Figure 2.

The dependence of the value of h_c upon the various geometric and temperature conditions was then determined by dimensional analysis of the collected data.

This analysis led to a method of making adjustments of the results to correspond to one mean temperature (50° F. was selected), and to equations for adjusting values at 50° F. to other mean temperatures. See equations (4) and (5).

In most of the measurements for determining h_c, the airspaces used had low effective emissivities (E) so that the quantity Eh_r was a small fraction of the measured quantity C or the derived quantity h_c. However, tests were also made with spaces having large and intermediate values of E, to test the experimental validity of equation (1).

Values of h_c, the coefficient for heat transfer across airspaces by conduction and convection combined, are shown in a form convenient for general use, by the curves of figures 3 to 7.

Discussion of Data Presented on Figures 3 to 7

Each figure represents one orientation of the airspace and direction of heat flow, as indicated; e. g., a horizontal airspace with heat flow upward (fig. 3). The several solid curves on each figure give values of $(h_c)_{50}$, the convection-conduction coefficient at an airspace mean temperature of 50° F., versus the thickness of the space, l, in inches, for several selected values of the temperature difference across the space, θ, in degrees Fahrenheit. The dashed line gives the calculated heat-transfer coefficient for the space with heat transfer by conduction only, with no convection. In a sense, this curve represents the limiting value of $(h_c)_{50}$ as the temperature difference, θ, approaches zero.

Examination of these figures and curves shows that, except for a horizontal space with heat flow downward, the convection-conduction coefficient is considerably greater than that for conduction only, and that the effect of convection becomes greater as the temperature difference across a given space increases. However, when the thickness of the space is reduced to a small enough value, the coefficient approaches that for conduction only, regardless of the temperature difference, although the critical thickness is smaller for the larger temperature differences.

The effect of mean temperature on the value of the coefficient h_c depends upon whether convection is a factor in the heat transfer. For cases in which convection is a factor (that is, where $(h_c)_{50}$ departs from the near neighborhood

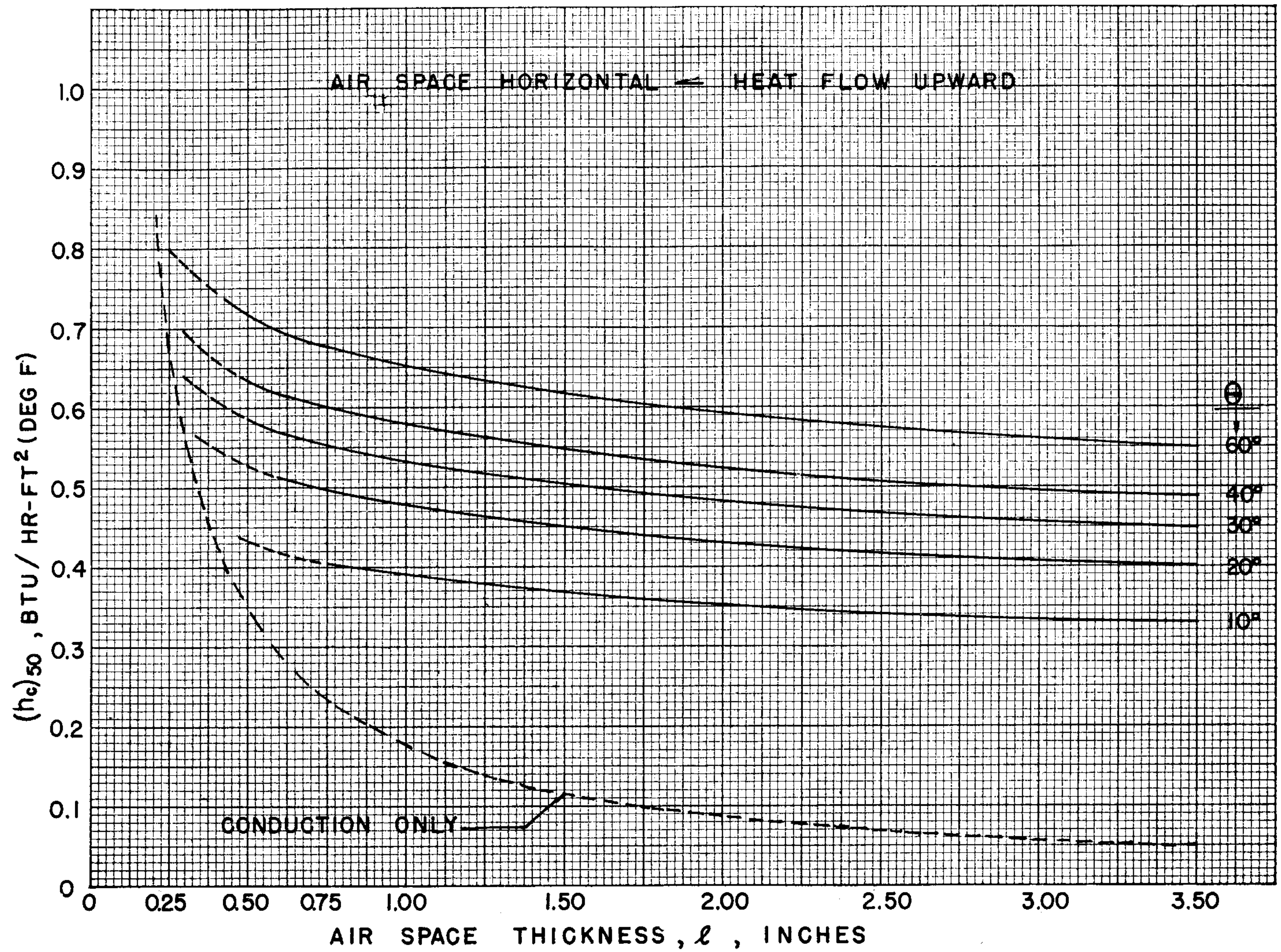

AIR SPACE HORIZONTAL — HEAT FLOW UPWARD
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
$(h_c)_{50}$, BTU / HR-FT^2 (DEG F)
0
0.25
0.50
0.75
1.00
1.50
2.00
2.50
3.00
3.50
AIR SPACE THICKNESS , ℓ , INCHES
Θ
60°
40°
30°
20°
10°
CONDUCTION ONLY

Figure 3.

of the "conduction only" curve), the value of h_c for an airspace mean temperature, t (° F.), is given approximately by

$$(h_c)_t = (h_c)_{50}\,[1 - 0.001\,(t - 50)] \qquad (4)$$

For cases in which convection is practically negligible (that is, where $(h_c)_{50}$ lies very close to the "conduction only" curve), the value of $(h_c)_t$ is given approximately by

$$(h_c)_t = (h_c)_{50}\,[1 + 0.0017\,(t - 50)] \qquad (5)$$

For intermediate cases, where $(h_c)_{50}$ is on the order of 50 percent greater than the corresponding value indicated by the "conduction only" curve, the temperature coefficient approaches zero, and mean temperature has little effect.

These adjustments for mean temperature are on the order of 1.0 to 1.7 percent of $(h_c)_{50}$ for a change of 10° F. in the airspace mean temperature. For many purposes in estimating the total conductances of building airspaces, especially of those which are not highly reflective, the change of h_c with mean temperature may be of little practical importance.

For vertical airspaces, and the spaces at 45° with heat flow upward or downward, the curves (figs. 5, 4, and 6, respectively) show that $(h_c)_{50}$ has a minimum value at a space thickness of an inch, more or less, depending upon the orientation and temperature difference, then increases slightly, and finally decreases slowly, as the space thickness increases. Thus, for a given orientation (vertical or oblique) and temperature difference, there is an optimum thickness at which the insulating value of the space is greater than for thicknesses somewhat larger or smaller than the optimum value. However, at considerably larger thicknesses, the insulating value of the space may be even greater than at the optimum thickness occurring at a value near one inch.

The results presented as curves in figures 3 to 7 were based upon the curves given in figure 8, which show in a more compact way the relationship between $(h_c)_{50}$ and the variables θ and l, for each orientation. The curves of figure 8, which were derived by dimensional analysis of the test data, are plotted on bilogarithmic coordinate paper, and show the variation of $(h_c l)_{50}$ for each orientation, versus the coordinate θl^3. The curves were drawn smoothly through the plotted points, which represent all of the values of h_c obtained in the 96 tests made on highly reflective airspaces (test panels 1.1 through 2.1, table 2, appendix B). Only 88 of the test points are plotted, since 8 practically coincided with 8 others.

In general, the plotted points representing the test data conform to within a few percent to the values indicated by the smooth curves, except for the case of a horizontal space with heat flow downward for values of θl^3 greater than 300. The accuracy of the results is best indicated by the congruence of the curves

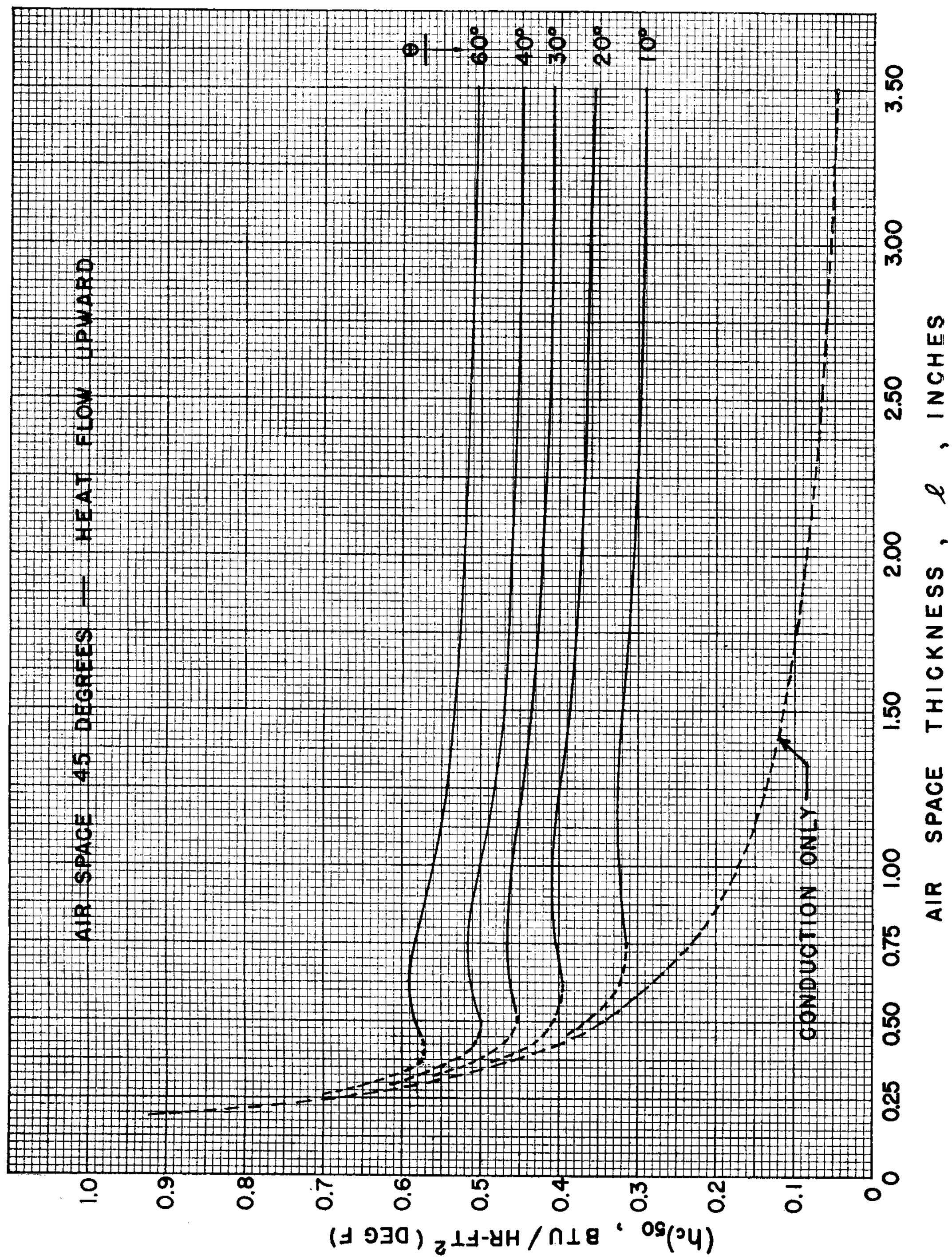

AIR SPACE 45 DEGREES — HEAT FLOW UPWARD
θ
60°
40°
30°
20°
10°
CONDUCTION ONLY
AIR SPACE THICKNESS, ℓ, INCHES
0
0.25
0.50
0.75
1.00
1.50
2.00
2.50
3.00
3.50
$(h_c)_{50}$, BTU / HR-FT^2 (DEG F)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

Figure 4.

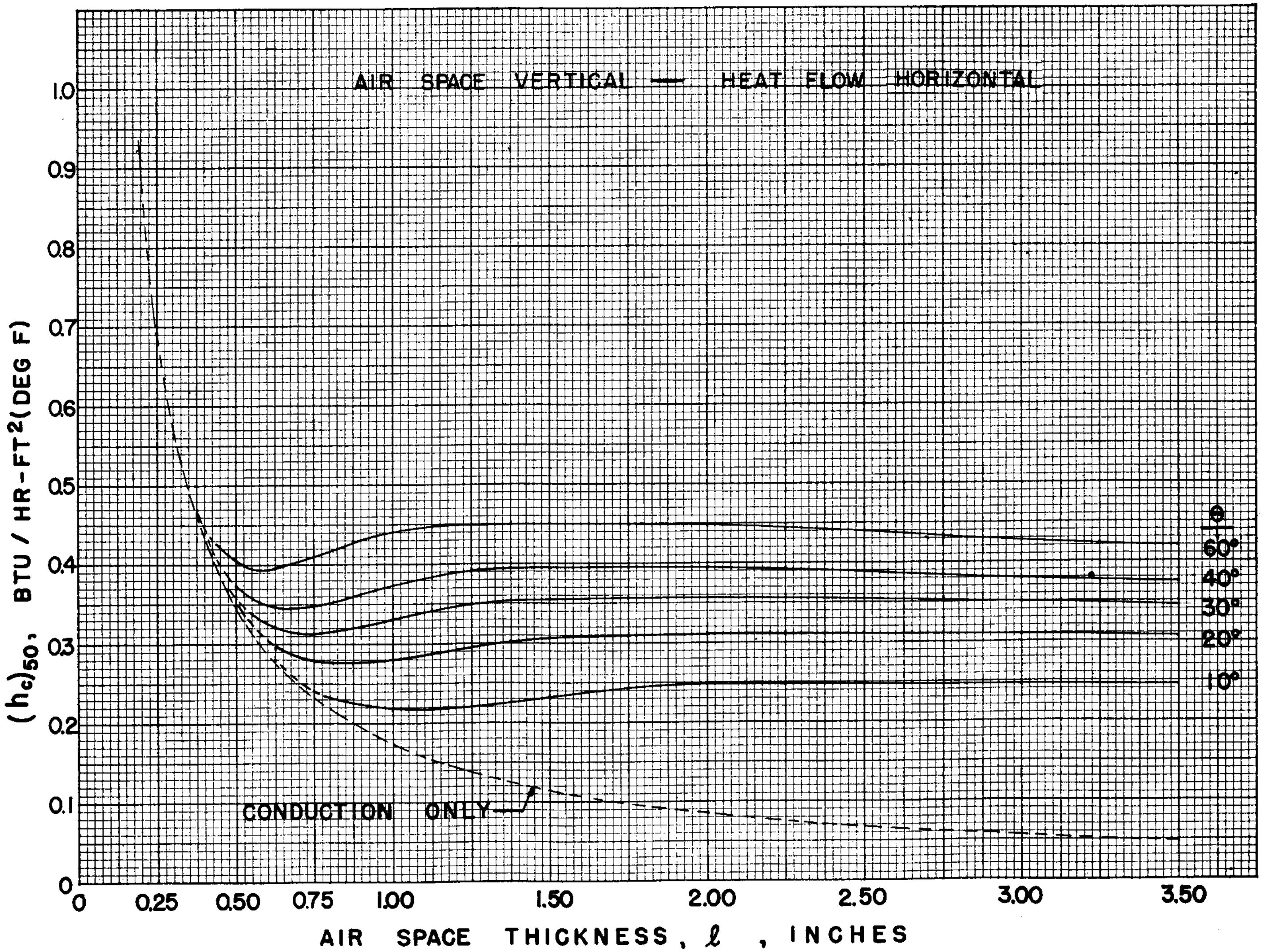

AIR SPACE VERTICAL — HEAT FLOW HORIZONTAL
θ
60°
40°
30°
20°
10°
CONDUCTION ONLY
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
$(h_c)_{50}$, BTU / HR-FT^2(DEG F)
0
0.25
0.50
0.75
1.00
1.50
2.00
2.50
3.00
3.50
AIR SPACE THICKNESS, ℓ, INCHES

Figure 5.

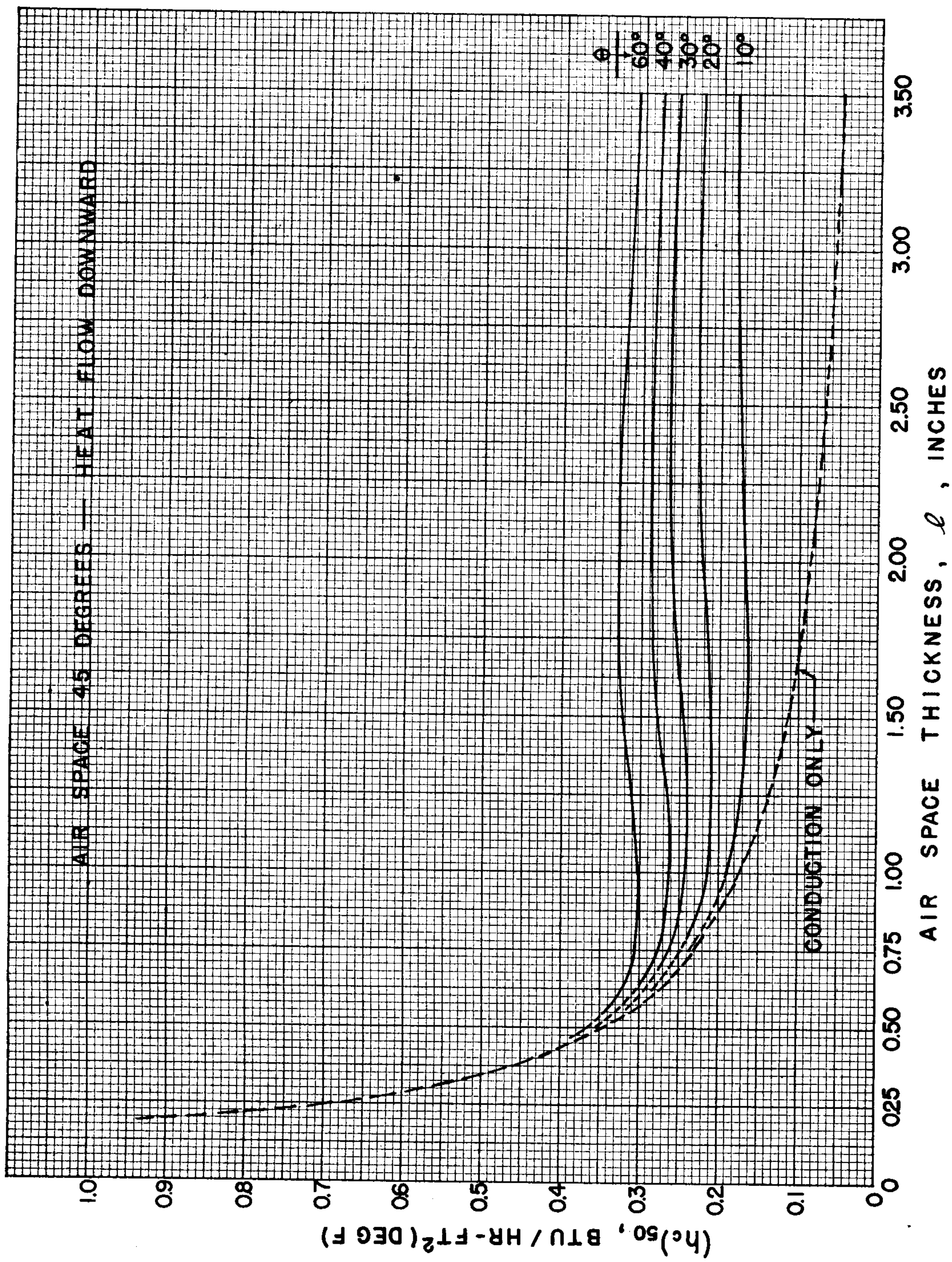

AIR SPACE 45 DEGREES — HEAT FLOW DOWNWARD
θ
60°
40°
30°
20°
10°
CONDUCTION ONLY
AIR SPACE THICKNESS, ℓ, INCHES
$(h_c)_{50}$, BTU / HR-FT^2(DEG F)
0
0.25
0.50
0.75
1.00
1.50
2.00
2.50
3.00
3.50
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

Figure 6.

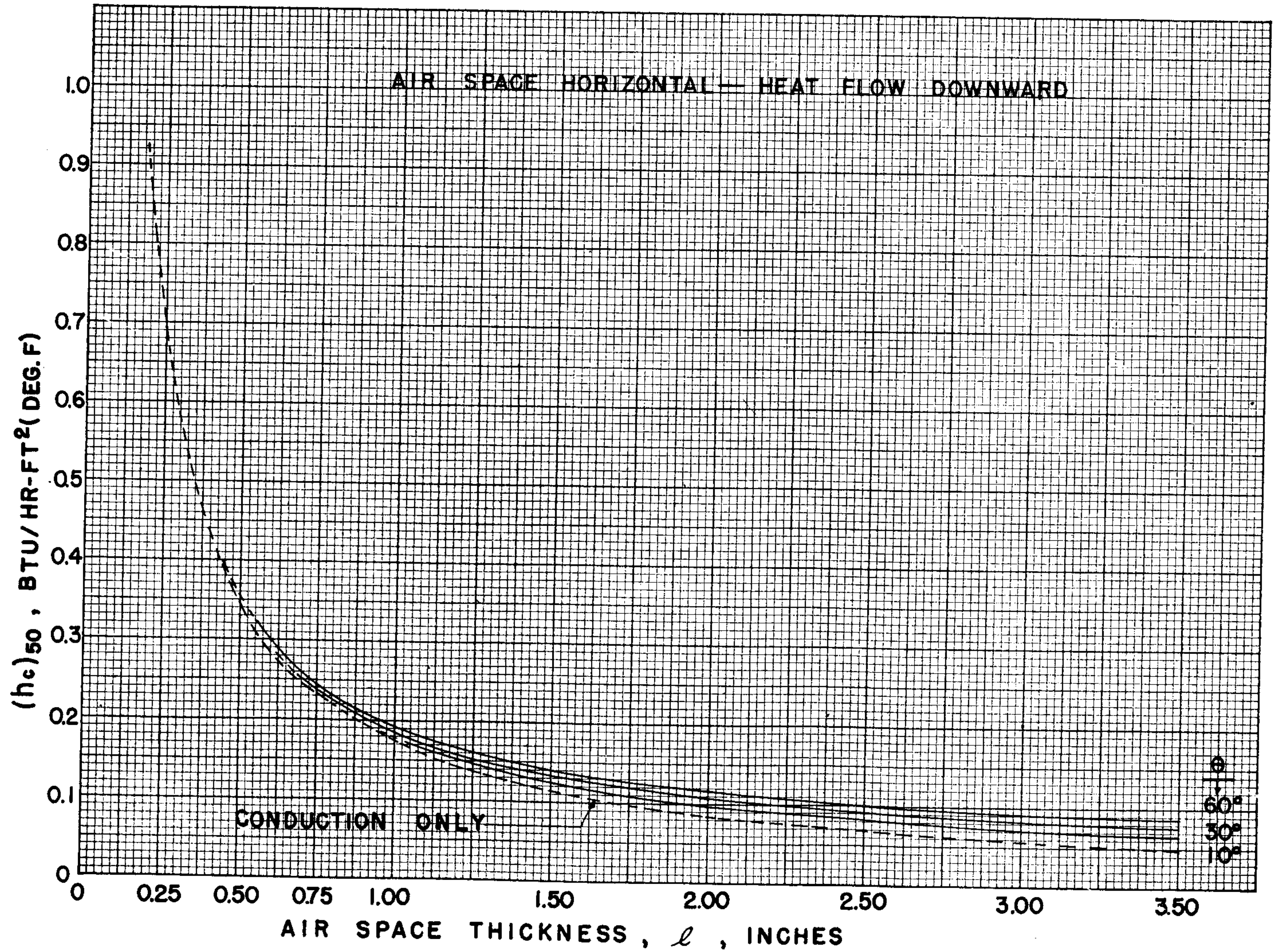

AIR SPACE HORIZONTAL — HEAT FLOW DOWNWARD
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
(hc)50 , BTU/HR-FT2(DEG. F)
0
0.25
0.50
0.75
1.00
1.50
2.00
2.50
3.00
3.50
AIR SPACE THICKNESS , ℓ , INCHES
CONDUCTION ONLY
θ
60°
30°
10°

Figure 7.

for a vertical space, and for spaces with heat flow downward, to the horizontal dashed line for conduction only, at low values of θl^3. The fact that these three curves become asymptotic to a horizontal line, at a value of $(h_c l)_{50}$ of about 0.175, is equivalent to a determination of the thermal conductivity of air at 50° F. as equal to 0.175 B. t. u./ hr./ft.^{2} (° F./in.), as compared with 0.173 as given for dry air at 50° F. in the *NBS–NACA Tables of the Thermal Properties of Gases* (table 2.42, 1950).

The data for the spaces with heat flow upward did not extend to values of θl^3 small enough for them to approach the "conduction only" line; these curves have been extended by dashed lines to indicate their probable trend. The curves of figures 3 to 7 are also represented by dashed lines where they are based upon this extrapolation.

The 50 tests conducted on airspaces of moderate and high emissivity (panels 3.1 through 6.2, table 2, appendix B) provided information as to the practical validity of equation (1). Values of $(h_c l)_{50}$ were obtained from the test results in the same manner as those calculated from the results obtained with highly reflective spaces. These values were divided by values of $(h_c l)_{50}$ taken from the curves of figure 8 at corresponding values of θl^3. The average value of the 50 quotients so obtained was 1.009. The limits of the average quotient, determined for a 95 percent confidence interval for a group of 50 values, were found to be 1.028 and 0.989. Since these limits bracket closely the ideal value 1.000, it is concluded that the practical validity of equation (1) is substantiated, and conversely, that the method and data given in this Paper, for calculating the total conductance, apply equally well for airspaces of low and of high emissivity.

Limitations on Applicability of the Data

The values of h_c in this Paper apply for airspaces of uniform thickness, with reasonably flat surfaces of moderate smoothness, and with no leakage of air into or out of the space, or between spaces where two spaces are used. In addition, the ratio of the height (or length) of the airspace to its thickness, ranged from about 18 to 96; and the average temperature gradient of its surfaces in the direction of the height (or length) was not greater than about 0.2 degree F. per foot for each B. t. u./hr./ft.^{2} of heat transfer across the airspace. A large proportion of the airspaces encountered in buildings conforms reasonably well to the characteristics described above, and the results herein are considered to be applicable and appropriate for such spaces.

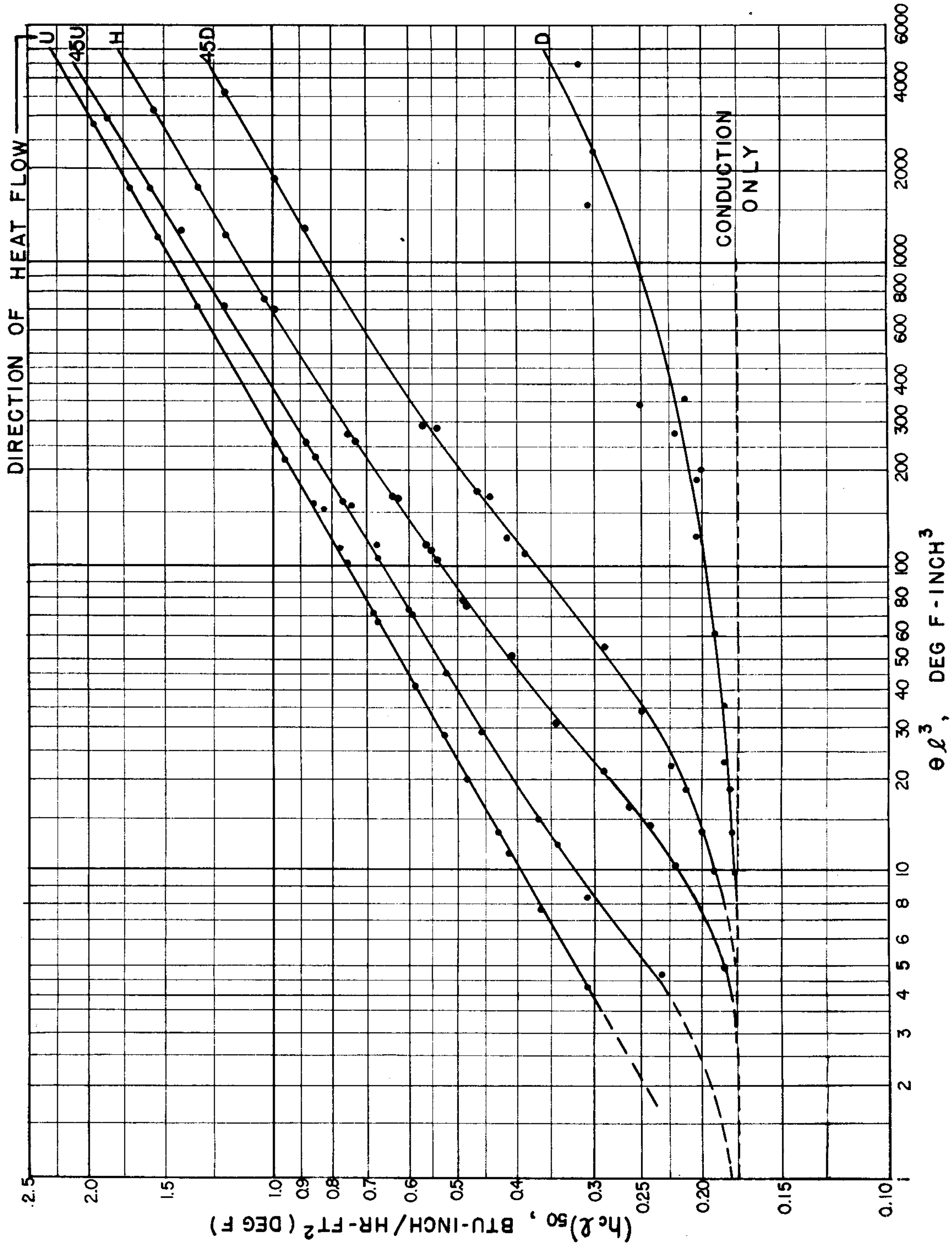

DIRECTION OF HEAT FLOW
U
45U
H
45D
D
CONDUCTION ONLY
$(h_c \ell)_{50}$, BTU-INCH/HR-FT^2 (DEG F)
$\theta \ell^3$, DEG F-INCH^3
2.5
2.0
1.5
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.25
0.20
0.15
0.10
1
2
3
4
5
6
8
10
20
30
40
50
60
80
100
200
300
400
600
800
1000
2000
4000
6000

Figure 8.

However, it must be recognized that some airspaces encountered or used in building constructions may depart significantly from the characteristics for which these data are pertinent. For example, two airspaces of nonuniform thickness may be formed by a membrane of foil or paper, laid over the faces of studs and bellied into the stud space. Again, the membrane dividing two airspaces may not be completely sealed at the edges or ends, or may be perforated or torn, allowing air to circulate between them. Further, a reflective dividing membrane may be inappropriately installed so that vapor may condense upon it under certain conditions, in which case its reflectivity might be impaired by an indeterminate amount. For cases such as these, there would be uncertainty in applying the results given in this Paper: in the first two cases, because appropriate values of h_c would not be known; and in the last case, because the appropriate value of E would not be known. In general, the heat transfer across such off-characteristic airspaces would be significantly greater than for the spaces considered in this investigation. Evaluation, even approximate, of the effect of such variables on the space conductance would be desirable but would entail further experimental study.

Utilization of the Data

Calculating Conductance of an Airspace

The total thermal conductance of a particular airspace can be readily computed if the following are known about the airspace:

a. Thickness of air space.
b. Orientation of air space.
c. Effective emissivity of air space.
d. Temperature difference of facing surfaces.
e. Mean temperature of air spaces.

Finding conductance (C) or resistance (r):

Example 1.

Thickness (depth) $=1\frac{1}{2}''$.
Orientation $=$Vertical.
Effective emissivity of space, $E=0.05$.
Temperature difference $=20°$ F.
Mean temperature $=50°$ F.
From figure 5 (or 8) for vertical spaces, $(h_c)_{50}=0.308$.
From figure 1, $(h_r)_{50}=0.91$.

To find conductance:

(Equation 1) $C = Eh_r + h_c$

$$C_{50} = 0.05\ (0.91) + 0.308$$

Conductance $= 0.354$ B. t. u./hr./ft.^{2} (° F.)

Thermal resistance $= 1/0.354$ or 2.8° F. per B. t. u./hr./ft.^{2}

Example 2. (Conditions of airspace same as in *Example 1*, except mean temperature = 30° F.)

(Equation 4) $(h_c)_t = (h_c)_{50}\ [1 - 0.001\ (t - 50)]$

$$(h_c)_{30} = (h_c)_{50}\ [1 - 0.001\ (30 - 50)]$$
$$= 0.308 \times 1.02$$
$$= 0.314$$

Figure 1, $(h_r)_{30} = 0.81$

To find conductance:

(Equation 1) $C = Eh_r + h_c$

$$C_{30} = 0.05\ (0.81) + 0.314$$
$$= 0.354 \text{ B. t. u./hr./ft.}^2\ (° \text{ F.})$$

In this instance, it happens that C_{30} equals C_{50}, but this would not necessarily be true in other cases although the difference may be negligible.

Values of the thermal resistance of 1½-inch airspaces at a mean temperature of 50° F. and for a temperature difference of 20° F. are given in table 1, for various orientations and effective emissivities (E). The tabulated resistance values indicate in an approximate way the relative insulating values of airspaces in different orientations and with different emissivities, and will be useful in making calculations for particular building constructions involving airspaces, as indicated later.

Table 1.—Thermal resistances [1] of 1½-inch airspaces

Temperature difference = 20° F. Mean temperature = 50° F.

Orientation of space	Direction of heat flow	Effective emissivity (E) of space			
		0.05	0.20	0.50	0.82
Horizontal	Down	5. 7	3. 2	1. 7	1. 1
45° angle	Down	3. 9	2. 6	1. 5	1. 0
Vertical	Horizontal	2. 8	2. 0	1. 3	. 9
45° angle	Up	2. 3	1. 8	1. 2	. 9
Horizontal	Up	2. 0	1. 6	1. 1	. 8

[1] Degree F./B.t.u./hr./ft.^{2}

Calculating Conductance of a Wall Space

Calculation of the conductance (or thermal resistance) of an airspace in a building component, such as a wall, is somewhat more complicated because the temperature difference across such a space depends upon the temperature difference across the construction, and upon the ratio of the thermal resistance of the space to the total thermal resistance of the construction, including that of the airspace (or spaces). In other words, it is necessary to know or assume the conductance or resistance of the space (or spaces) before a close computation can be made. The "trial and error" procedure required leads quickly to a correct result, as shown below.

Consider the wall construction shown in figure 9, with two airspaces formed by a central membrane dividing the 2-by-4 stud space. Using the quantities indicated in figure 9, the temperature drop, t_2-t_3, between the gyplath and sheathing is given by

$$t_2-t_3=(t_1-t_4)\times\frac{R_{2-3}}{R_{2-3}+(R_{1-2}+R_{3-4})} \tag{6}$$

The term $(R_{1-2}+R_{3-4})$ is seen to be the thermal resistance of the construction and the surface air films, exclusive of the resistance of the airspace or spaces, and is readily calculated for a given construction, using data given in references such as *Federal Housing Administration Technical Circular No. 7*, or the ASHVE *Guide.*

Similarly, the average mean temperature of the airspace or spaces is given by

$$t_m=t_4+(t_1-t_4)\times\frac{R_{3-4}+\frac{1}{2}(R_{2-3})}{R_{2-3}+(R_{1-2}+R_{3-4})} \tag{7}$$

These equations can be solved to obtain approximate values of t_2-t_3 and t_m, if appropriate values of R_{2-3} are assumed. In general, it will be found that the thermal resistances tabulated in table 1 will serve to provide good first approximations to R_{2-3}. To obtain a value of R_{2-3}, an approximate value of the resistance per space is taken from table 1, using an appropriate value of E, which can be taken as the average of the effective emissivities of the spaces, if there be more than one, as determined by the values of the surface emissivities e_2, e_2', e'_3, etc., and by means of figure 2. For values of E not given in the table, interpolation is permissible.

For example, assume $t_1=70°$ F., $t_4=0°$ F., e_2 and $e_3=0.9$ (ordinary building surfaces), and e_2' and $e'_3=0.05$ (reflective foil surfaces). Then each of the airspaces will have an effective emissivity (E) of 0.05 (fig. 2) and the average value is 0.05. Referring to table 1, the resistance of one space for this case

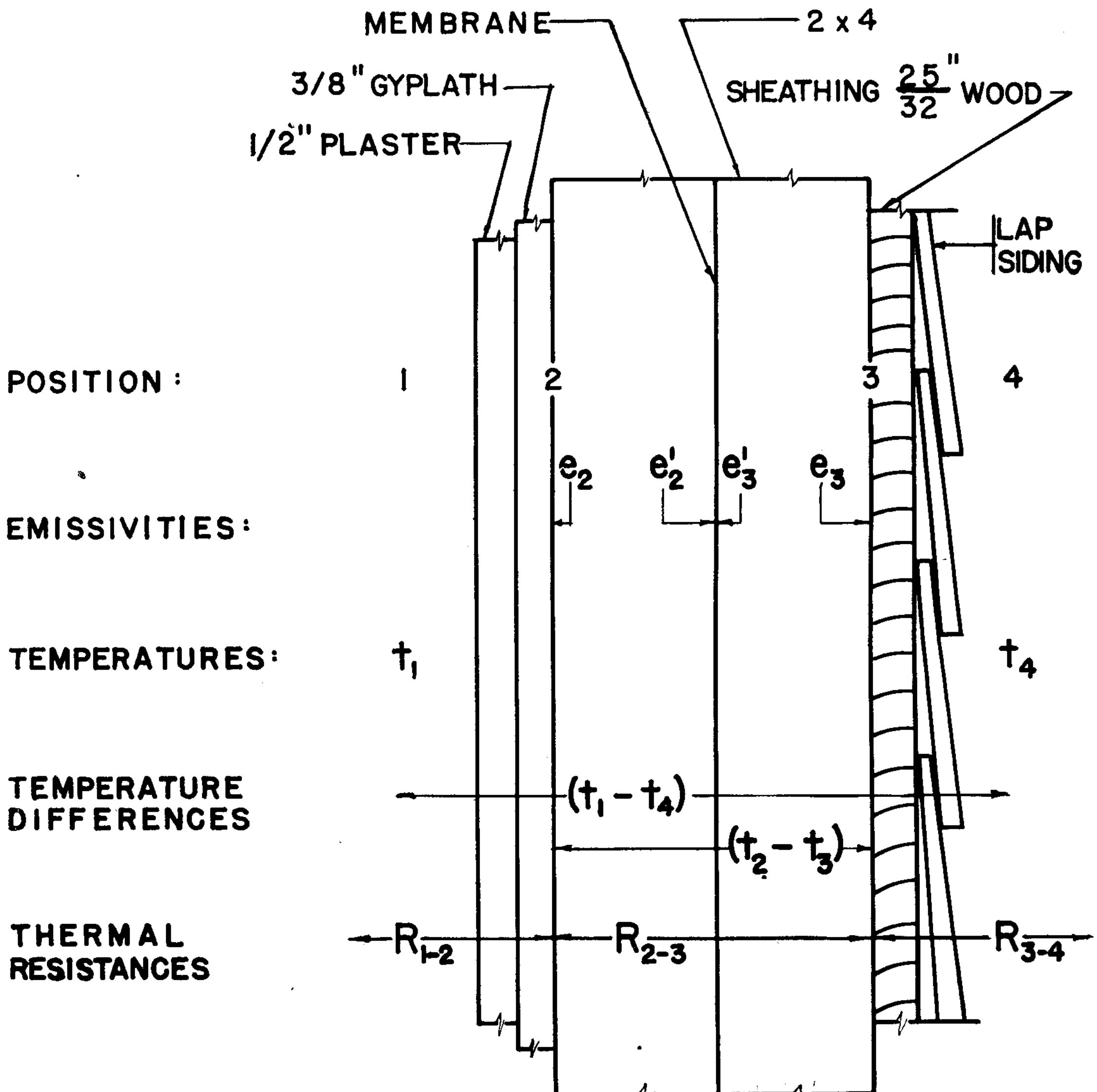


Figure 9.

is given as 2.8, and R_{2-3} for two spaces is, therefore, 5.6. For the construction indicated in figure 9, $R_{1-2}=1.03$ and $R_{3-4}=2.11$. Accordingly,

$$t_2-t_3=70\times\frac{5.6}{5.6+3.14}=70\times\frac{5.6}{8.74}=45^\circ \text{ F.}$$

$$t_m=0+70\times\frac{2.11+\frac{1}{2}(5.6)}{8.74}=70\times\frac{4.91}{8.74}=39^\circ\text{F.}$$

The temperature difference per space, since there are two spaces, is $\frac{1}{2}(t_2-t_3)$ or

22.5° F. Considered rigorously, the two spaces have different mean temperatures, given approximately by 39° F.±22.5/2, or 50° F. and 28° F.; but for the purposes of this calculation, the average value of 39° F. is satisfactory. Actually, as indicated in the earlier example, the effect of mean temperature for this case is negligible, and this example is, therefore, worked out using values for a 50° F. mean temperature.

Using figure 5, $(h_c)_{50}$ for a vertical space 1.8 inches wide, with a temperature difference of 22.5° F., is 0.32, and adding the radiation coefficient $(Eh_r)_{50}$, which equals 0.046, it is found that C_{50} is 0.366 and the airspace resistance is 2.73. This is so close to 2.8, the trial resistance, that recomputation is not necessary; and using the value 2.73, the U-value of the construction is given by

$$\frac{1}{U}=(R_{1-2}+R_{3-4})+2\ (2.73),\text{ whence, }U=\frac{1}{8.6}=0.116\text{ B. t. u./hr./ft.}^2\text{ (° F.).}$$

If a recomputation were made, using 2.73 as a trial resistance for each airspace the results would be $t_2-t_3=44.5$, $t_m=39.4$, and an average airspace resistance equal to 2.73, as before; thus indicating that the first results were satisfactorily correct.

It is pertinent to notice that the membrane temperature in this example is approximately the same as the mean temperature of the 2-by-4 stud space, or 39° F. If the membrane consisted of a metallic foil, impermeable to water vapor, the vapor pressure on its warm side would be substantially equal to that in the building, and condensation might occur on the foil when the dewpoint temperature indoors exceeded 39° F.

The temperature of the inner surface of single-glass windows, with 70° F. indoors and still air at 0° F. outdoors, would not ordinarily exceed 35° F.; and an indoor dewpoint of 39° F. could not be maintained without considerable condensation on the windows. Accordingly, condensation on a foil membrane would, in this case, be unlikely if single-glass windows in the house were free of excessive condensation. However, if storm sash or double glass were used in all the windows, the indoor dewpoint might rise to about 50° F. before window condensation occurred, and there would be considerable risk of condensation on the foil membrane. This risk could be eliminated by applying a vapor barrier, such as another sheet of foil, or a membrane of equal vapor resistance, at some position on the warm side of the stud space, such as position 2 in figure 9.

Calculated *U*-values for Typical House Components

The *U*-values of several typical wall, ceiling, and floor constructions used in houses, with various insulation applications, are given in the following pages. The U-values are expressed in B. t. u./hr./ft.^{2} per ° F. of air temperature difference on the two sides of the construction.

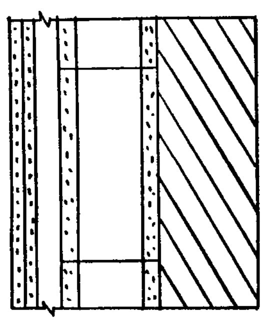
In the column headed "R_{sp}" is given the thermal resistance, in ° F./B. t. u./hr./ft.^{2}, of the airspace in the construction considered, under the assumed temperature conditions. Where there are two dissimilar airspaces in the construction, the resistance of the inner space is given first, and the resistance of the outer space is given next, in parentheses. Moderate changes in the other elements of the construction, that is, modifications which would cause a change of not more than about 20 percent in the U-value, would not significantly change the resistance of the described airspace. Hence, for reasonable modifications of the described constructions, the resistances of similar airspaces can be taken as equal to those indicated in the column headed "R_{sp}" with small error, and without the necessity of performing the "trial and error" procedure described earlier, using the approximate resistances given in table 2.

These values were calculated using the methods and data presented in this Paper, insofar as airspaces are concerned; and using for other components of the construction, coefficients taken from *Federal Housing Administration Technical Circular No. 7*, revised January 1947. In accordance with the U-value calculations given in *T. C. No. 7*, no allowance was made for the effect of wood studs or joists on the average U-value of the construction. In most cases, where the calculated U-value for the between-members area is of the magnitude of 0.08 to 0.14, the effect of the wood structural members is small. If it is desired to take into account the effects of heat flow through studs or joists, the procedure for parallel heat flow given in the section, "Computed Heat Transmission Coefficients," on pages 183–185 of the 1954 ASHVE *Guide*, may be used.

WALLS

1. 4-inch brick, 4-inch cinder block, 25/32-inch furring space, 1/2-inch plaster on 3/8-inch gyplath.

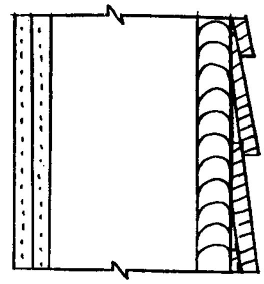
Assumed air temperatures: 70° and 0° F.



	U	R_{sp}
(a) Ordinary furring space, E of space=0.82	0.25	1.01
(b) Reflective-coated paper on gyplath, E of space=0.20	.20	2.08
(c) Aluminum-foil backing on gyplath, E of space=0.05	.18	2.68
(d) Space filled with fibrous insulation (if dry)	.17	----

2. Yellow pine lap siding, 25/32-inch wood sheathing, 2-by-4 stud space, 1/2-inch plaster on 3/8-inch gyplath.

Assumed air temperatures: 70° and 0° F.



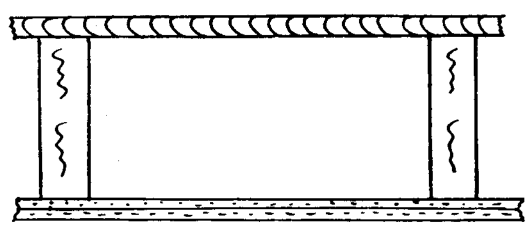
	U	R_{sp}
(a) Stud space uninsulated, one space, $E=0.82$	0.24	0.99
(b) Aluminum-foil backing on gyplath, one space, $E=0.05$	.18	2.54
(c) Stud space divided equally by ordinary kraft paper or cardboard, two spaces, $E=0.82$ for each	.19	1.01
(d) Stud space divided equally by vapor-permeable reflective-paper sheet, two spaces, $E=0.20$ for each	.138	2.05
(e) Stud space divided equally by aluminum-foil sheet, two spaces, $E=0.05$ for each	[1] .116	2.73
(f) Stud space divided equally by 1-inch fibrous blanket insulation with aluminum foil on warm side, two spaces, $E=0.05$ and 0.82	.091	2.98 (1.23)
(g) Two-inch fibrous blanket insulation against gyplath, with vapor-permeable reflective paper on cold side, one space, $E=0.20$	.078	2.25
(h) Same as (g), with ordinary paper on cold side of blanket, one space, $E=0.82$	.085	1.21
(i) Stud space divided into three equal spaces by two sheets of aluminum foil, E (avg.) $=0.04$	.077	[2] 3.30

[1] There may be danger of condensation of moisture on the foil surface, depending upon temperature conditions and the relative humidity inside the building.

[2] Average.

CEILINGS

3. 1/2-inch plaster on 3/8-inch gyplath, 2-by-8 joist space, 25/32-inch yellow pine flooring.



U_w is the U-value for winter conditions, with heat flow upward and assumed air temperatures of 80° (room) and 10° F. (attic).

U_s is the U-value for summer conditions, with heat flow downward and assumed air temperatures of 120° (attic) and 90° F. (room)

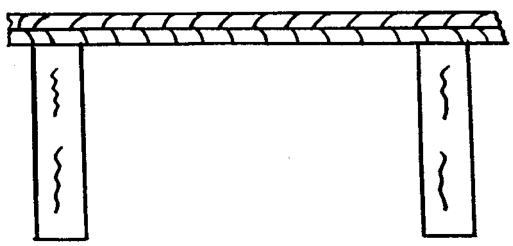
	U_w	$(R_{sp})_w$	U_s	$(R_{sp})_s$
(a) No insulation in joist space, one space, $E=0.82$	0.30	0.91	0.25	0.96
(b) Aluminum-foil backing on gyplath, one space, $E=0.05$	.22	2.21	.088	8.3
(c) Reflective-paper backing on gyplath, one space, $E=0.20$	.24	1.71	.156	3.36

	U_w	$(R_{sp})_w$	U_s	$(R_{sp})_s$
(d) Aluminum-foil sheet dividing joist space equally, two spaces, E=0.05 for each	[1] .146	2.20	.052	7.8
(e) Vapor-permeable reflective-paper sheet dividing joist space equally; two spaces, E=0.20 for each	.170	1.75	.105	3.25
(f) Two-inch blanket of fibrous insulation resting on gyplath, with vapor-permeable reflective paper on top side of blanket, one space, E=0.20	.084	2.04	.073	3.30
(g) One-inch blanket of fibrous insulation dividing joist space equally, with aluminum-foil membrane on underside of blanket, two spaces, E=0.05 and 0.82	.105	2.36 (1.05)	.065	7.7 (0.88)
(h) Four inches of fibrous insulation resting on gyplath, one space, E=0.82	.055	1.15	.053	.88
(i) Construction as shown, but with vapor-permeable reflective paper laid over joists in place of the wood flooring, one space, E=0.20, and top-surface film coefficient for reflective paper taken as 1.30 B. t. u./hr./ft.^{2} (° F.) for U_w and 0.56 for U_s	.30	1.68	.16	3.35

[1] There may be danger of condensation of moisture on the foil surface, depending upon temperature conditions and the relative humidity inside the building.

FLOORS

4. $1\frac{3}{16}$-inch hardwood flooring, building paper, $\frac{25}{32}$-inch yellow pine subflooring, 2-by-10 joists.



Assumed conditions: heat flow downward, from air at 65° (room) to 30° F. (under floor).

	U_s	R_p
(a) Uninsulated floor	0.28	----
(b) Sheet of aluminum foil fastened to bottom of joists, one space, E=0.05	.070	9.2
(c) Sheet of reflective paper fastened to bottom of joists, one space, E=0.20	.115	4.3
(d) Sheet of ½-inch rigid insulation board fastened to bottom of joists, one space, E=0.82	.158	1.30
(e) Same as (d) but with sheet of aluminum foil dividing joist space equally, two spaces, E=0.05 for each	.041	9.8
(f) Same as (d) but with sheet of reflective paper dividing joist space equally, two spaces, E=0.20 for each	.075	4.2
(g) Two-inch fibrous blanket insulation installed at midheight of joist space	.082	1.22

Discussion and Remarks

Study of the U-values for the various constructions indicates the following practical conclusions:

1. The insulating effect of a furring or stud space can be markedly increased at relatively low cost by use of a reflective surface on the back of the gyplath or other plaster base (compare Walls 1 (b) and 1 (c) with 1 (a) and 1 (d), and Wall 2 (b) with 2 (a)).

2. The thermal resistance of frame walls can be increased effectively by subdividing the stud space with one or more sheets of reflective paper or foil. Comparison of Walls 2 (a) and 2 (e) shows that the addition of one foil sheet (reflective, both sides) dividing the stud space into two airspaces, reduces the heat transmission by 50 percent. Comparison of Wall 2 (i) (wherein a second foil sheet is added, dividing the stud space into three airspaces) with Wall 2 (e) shows an additional reduction in thermal transmission, but by a percentage less than that attained with the first sheet of foil, demonstrating the law of diminishing returns. However, circulation of air between spaces must be prevented by adequate sealing of each dividing membrane; and in the case of vapor-impermeable membranes, consideration must be given to the possibility of moisture condensation on their surfaces.

3. The substantially increased value of reflective airspaces in reducing heat flow downward is indicated by comparisons of the U-values for summer and winter conditions for the ceiling constructions, and by the very considerable insulating effect of reflective spaces used under floors.

APPENDIX A

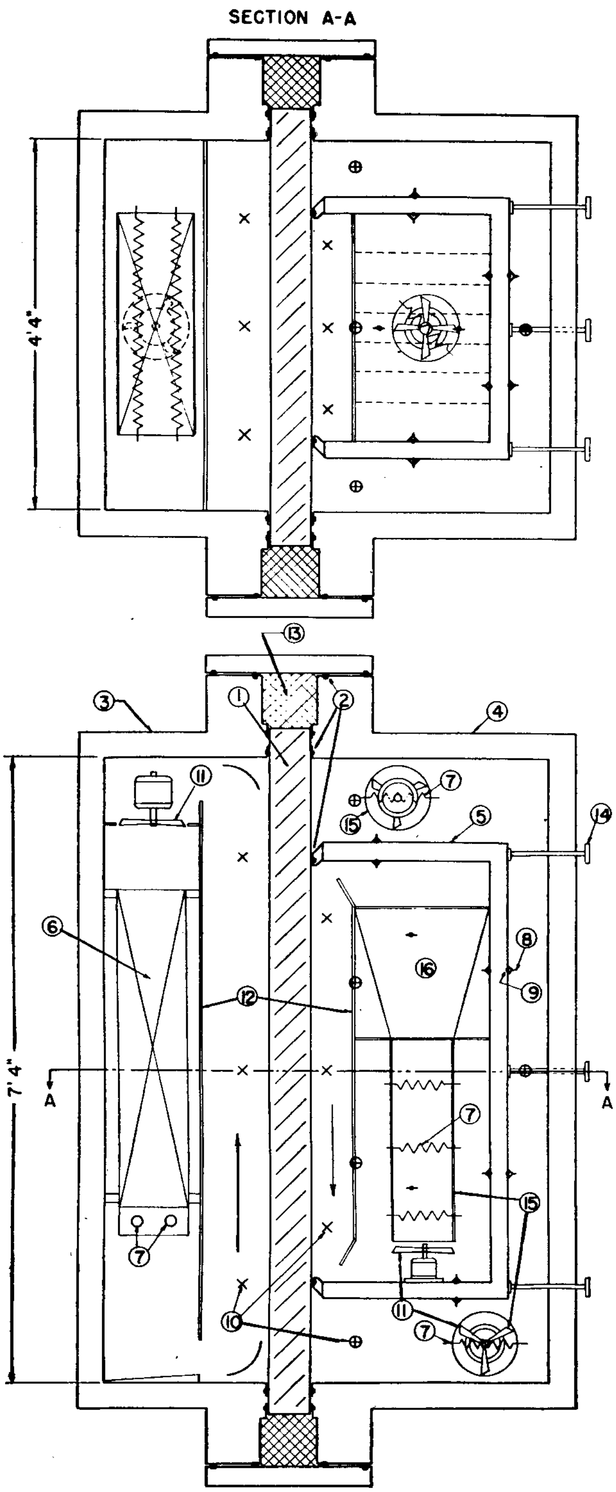
Test Apparatus and Test Method

The heat-transfer measurements were made on airspaces in test panels by means of a guarded hot box apparatus, shown schematically in the drawing of plate 1 and in the photograph of plate 2. The apparatus was designed for panels 5½ by 8 feet in size, up to 1-foot thick. As shown by the photograph, it was mounted on horizontal trunnions, which allowed the entire apparatus to be rotated to position the plane of the panel at any angle up to 90° from the vertical, in either direction.

The hot box apparatus conformed substantially to the requirements of *ASTM 236–53, Method of Test for Thermal Conductance and Transmittance of Built-Up Sections by Means of the Guarded Hot Box,* except for the additional feature of rotatability on trunnions.

As shown in plate 1, the apparatus consisted of a cold box (3) and a warm or guard box (4), between which the test panel (1) was interposed. The two boxes were held together by means of long bolts engaging lugs around the periphery of the joint, as shown in the photograph. The guard box contained a five-sided metering box (5), the open face of which was pressed against the face of the panel by four compression springs (14). The contact between the metering box and the panel was made substantially airtight by the rubber gasket (2), the centerline of which bounded the centrally located "metering area" of the panel, a rectangle 60 inches high and 32 inches wide, through which heat flow was measured during a test. The remainder of the panel area constituted a "guard," through which heat flow was not measured, but which protected the metering area against lateral heat flow. Peripheral insulation (13) was placed at the edges of the panel to minimize lateral heat flow.

During measurements, the guard and metering boxes were held at the same selected constant temperature by electric heaters (7) controlled by sensitive thermostats in each box. The cold box was held at the desired constant lower temperature by means of a refrigerating coil (6) and a small electric reheating coil (7) controlled by a thermostat. The air in each box was circulated continuously at a moderate rate by fans (11). In the metering and cold boxes, the circulated air was constrained by baffles (12) to pass downward and upward, respectively, along the surface of the panel. The direction of airflow on each side was the same as would result from natural convection at the panel faces. The average air velocity in the metering-box baffle space was about 39 ft./min. and in the cold box baffle space was about 92 ft./min.



① TEST PANEL
② RUBBER GASKETS
③ COLD BOX
④ GUARD BOX
⑤ METER BOX
⑥ REFRIGERATING COIL
⑦ ELECTRIC HEATERS
⑧ AIR COMPOUND THERMOCOUPLES
⑨ SURFACE COMPOUND THERMOCOUPLES
⑩ AIR TEMPERATURE THERMOCOUPLES
⑪ AIR CIRCULATING FANS
⑫ BAFFLES
⑬ EDGE INSULATION
⑭ COMPRESSION SPRING HANDWHEELS
⑮ HEATER DUCTS
⑯ METER HEAT DIFFUSER

Plate 1

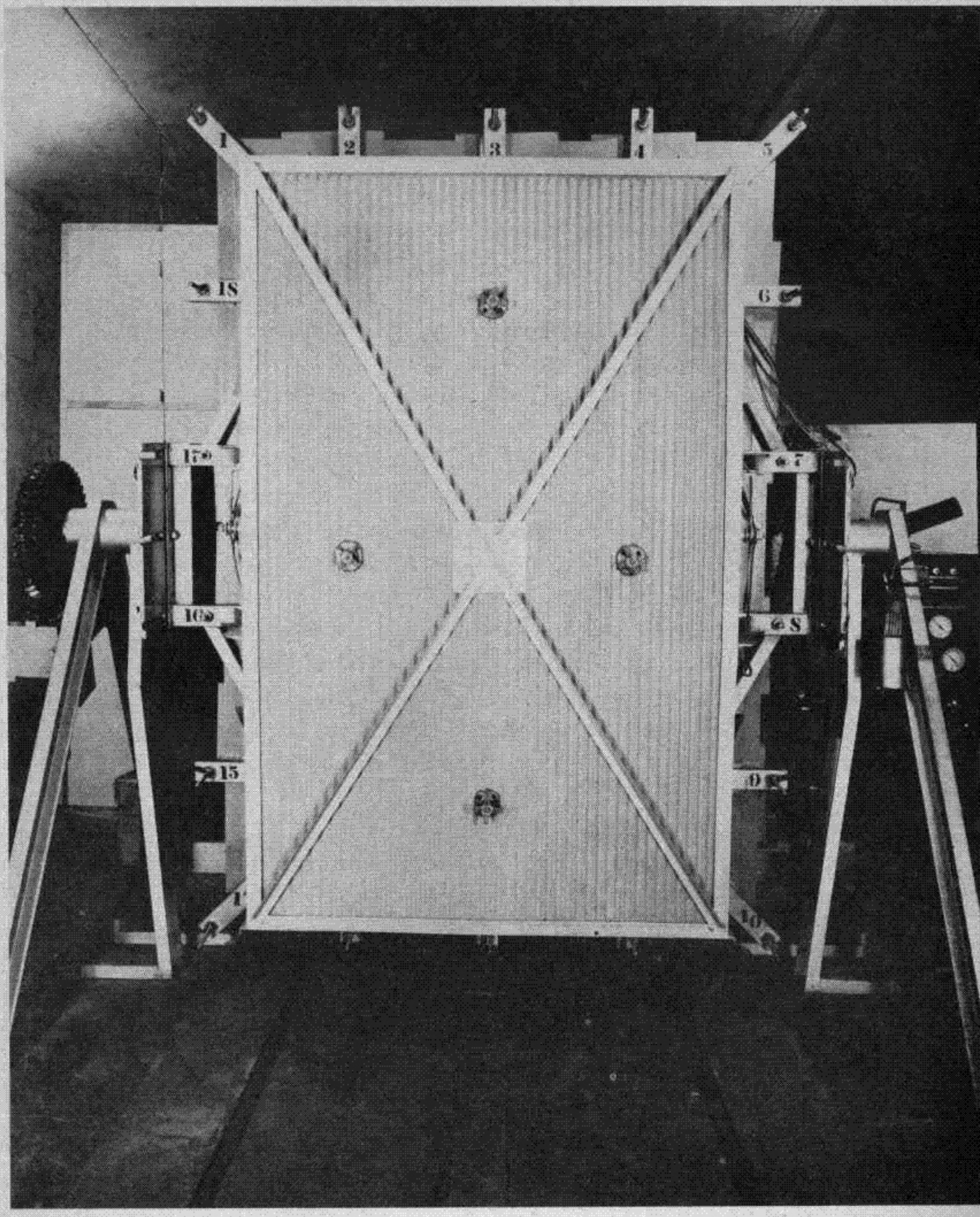


Plate 2

Air temperatures in the baffle spaces and at other locations in the boxes were measured by means of copper-constantan thermocouples (10), as indicated.

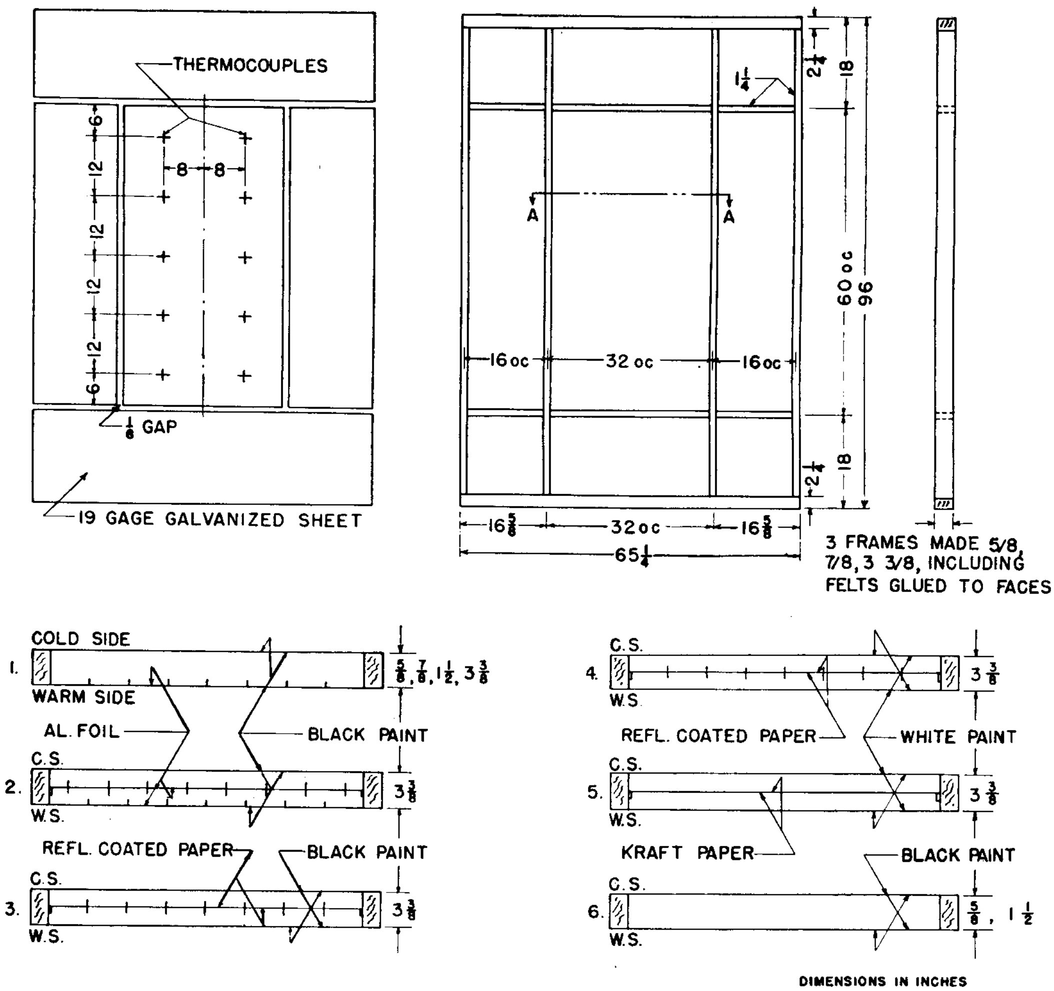
All electrical input to the heaters, fan, and other devices in the metering box was measured by means of a calibrated watt-hour meter readable to 1 watt-hour. Under steady temperature conditions, and with the guard box temperature adjusted to correspond to the metering box temperature, so that there was no average temperature difference or heat interchange through the metering box walls, all of the heat furnished to the metering box was transmitted to the cold box, through the known metering area (13.33 sq. ft.) of the panel. The average rate of heat flow per square foot of metering area could thus be determined.

To assure that there was little or no heat interchange between the metering box and the surrounding guard box, a compound thermocouple (9) was used, consisting of 10 series-connected differential thermocouples with the junctions of each pair cemented opposite each other in grooves in the surfaces of the metering box. The metering box, except for the hardwood nosepiece which carried the gasket (2), was made entirely of selected balsa wood, glued and doweled, forming walls 2.5 inches thick with a nearly uniform conductance of 0.16 B. t. u./hr./ft.^{2} (° F.). It was determined by calibration measurements that for a reading of 100 microvolts on the compound thermocouple (9), the heat flow between metering and guard boxes was approximately 3.5 B. t. u./hr., or 0.26 B. t. u./hr. per square foot of panel metering area. For most tests of this investigation, the average reading of this thermocouple during a test was less than 30 microvolts, indicating that heat interchange between guard and metering boxes was a very small percentage of the total heat input; nevertheless, for each test, the observed heat input was corrected for such interchange.

The guard box temperature was made to correspond automatically to that of the metering box, by means of a compound thermocouple (8) consisting of 10 differential thermocouples in series, arranged similarly to those of compound thermocouple (9) but with their junctions in the air about 1 inch from the surfaces of the metering box. The e. m. f. from the compound thermocouple (8) controlled a relay which supplied heat to the guard box as required. This system of control was very sensitive, and automatically kept the reading of compound thermocouple (9) steadily near zero throughout the tests.

The temperatures of the surfaces of the test panels bounding the air-spaces were determined by means of 10 thermocouples on each surface of the panel, as indicated in the description of the test panels (plate 3).

All test measurements were made under steady temperature conditions, following a prior period during which these conditions were attained. The duration of the steady-state test period, during which the periodic observations



TEST PANELS-SECTION A-A

Plate 3

were taken, from which the results were calculated, was in no case less than 16 hours; and in most tests, was more than 20 hours. All thermocouples were read manually by means of a potentiometer, with which temperature changes of less than 0.05° F. were readable. The steadiness of temperatures during almost all of the tests was such that average air or panel surface temperatures did not vary as much as 0.2° F. during the test period.

The average test conductance of the panel space was calculated from the average net heat flow into the panel, per square foot of metering area, and the average temperature difference between the panel surfaces. Since about 5 percent of the metering area included the wood members bounding the metering area airspace, a small correction was made to allow for the effect of heat conduction through the wood. The adjusted conductance thus obtained represented the average thermal conductance, C, of the panel airspace, or one-half the average conductance of each airspace if the panel space was divided into two approximately equal spaces in tandem.

APPENDIX B

Test Panels and Airspaces

The airspaces used were of various thicknesses and had various effective emissivities, due to the use of different materials for their bounding surfaces. In order to vary the airspace thicknesses, several test-panel frames of clear fir, substantially alike except for thickness, were used, as illustrated in plate 3.

The test area was the 32- by 60-inch rectangle at the center of the panel, and included half of the wood bounding the test airspace, which constituted 5 percent of the test area. The other airspaces of the panel constituted a guard area, and were made similar to the test space in all possible respects.

The faces of the panels were made of 19-gage galvanized sheet steel, painted on the outer surface, as indicated in plate 3. The sheet covering the metering area on both sides was separated by a ⅛-inch gap from the covers of the guard airspaces to minimize lateral heat flow into or out of the metering area. To seal the airspaces, the several sheets were screwed to the frames over 1/16-inch felt strips glued to the wood.

Thermocouples for measuring the temperature of the sheet-metal faces were permanently soldered to the outer surface of the sheet, at 10 positions on each face, as shown in plate 3. The thermocouple leads were cemented to the face of the sheet until they reached a takeoff point at the center of the sheet. The surface was painted after the thermocouples were attached.

For those tests in which the inside surface of the warm side of the airspace was highly reflective, very bright and clean aluminum foil was cemented to that surface. For some later tests, where it was desired that this surface be one of high emissivity, the aluminum foil was removed, and the surface was painted with black or white paint. In all of the tests, the inner surface of the cold side of the panel was painted with either black or white paint of high emissivity.

Single or double airspaces in the panel were obtained as indicated by the "sections A–A" of plate 3. Table 2 gives particulars as to the dimensions and nature of the spaces on which measurements were made; the decimal part of the "Panel Modification Number" differentiates panels in regard to thickness.

Table 2.—Description of Panels and Airspaces Tested

Test panel	Spaces	Space No. 1		Space No. 2		Orientations	Tests
		Thickness	E [1]	Thickness	E [1]		
	Number	*Inches*		*Inches*		*Number*	*Number*
1.1	1	5/8	0.028a			5	15
1.2	1	7/8	.028a			5	17
1.3	1	1 1/2	.028a			5	22
1.4	1	3 3/8	.028a			5	20
2.1	2	1 11/16	.014b	1 11/16	0.028a	5	22
Number of tests of highly reflective spaces, total							96
3.1	2	1 11/16	0.219c	1 11/16	0.219c	5	17
4.1	2	1 11/16	.195d	1 11/16	.195d	3	3
5.1	2	1 11/16	.764e	1 11/16	.764e	3	3
6.1	1	5/8	.712f			5	11
6.2	1	1 1/2	.712f			5	16
Number of tests of spaces of moderate and high emissivity, total							50

[1] *E* is the effective emissivity of the airspace, bounded by surfaces indicated by letters as listed below:

NATURE AND EMISSIVITIES OF SURFACES OF AIRSPACES

a—Aluminum foil, $e=0.028$; black paint, $e=0.832$
b—Aluminum foil, $e=0.028$; aluminum foil, $e=0.028$
c—Reflective-coated paper, $e=0.229$; black paint, $e=0.832$
d—Reflective-coated paper, $e=0.198$; white paint, $e=0.927$
e—Brown kraft paper, $e=0.813$; white paint, $e=0.927$
f—Black paint, $e=0.832$; black paint, $e=0.832$

The total emissivities of the surfaces of the materials used to bound the airspaces were determined by separate measurements made on samples of the materials, most of which were taken from the panels after the tests. The emissivities were determined by measuring the thermal radiation from the surface and the radiation from a black re-entrant cone at the same temperature, using a sensitive total-radiation pyrometer at a different temperature. The emissivity was calculated as the ratio of the two readings times the estimated virtual emissivity of the re-entrant cones used (0.98 and 0.99).

U. S. GOVERNMENT PRINTING OFFICE: 1954