H. M. Lemon, H. Wise, and M. Hamburger: Bacterial content of air in army barracks (*War Medicine* 6:92, 1944).

O. H. Robertson, M. Hamburger, C. G. Loosli, T. T. Puck, and H. M. Lemon: A study of the nature and control of air-borne infection in army camps (*Journal of the American Medical Association* 126:993, 1944).

O. H. Robertson et al: Lethal effects of triethylene glycol vapor on air-borne bacteria and influenza virus (*Science* 97: 142, 1943).

M. Hamburger, Jr., O. H. Robertson, and T. T. Puck: The present status of glycol vapors in air sterilization (*American Journal of the Medical Sciences* 209:162, 1945).

T. N. Harris and J. Stokes, Jr.: Summary of a 3-year study of the clinical applications of the disinfection of air by glycol vapors (*American Journal of the Medical Sciences* 209:152, 1945).

William Lester, Jr., Saul Kaye, O. H. Robertson, and Edward Dunklin: Factors of importance in the use of triethylene glycol vapor for aerial disinfection (*American Journal of Public Health* 40:813, July 1, 1950).

Edward Bigg, B. H. Jennings, and F. C. W. Olson: Triethylene glycol vapor distribution for air sterilization (ASHVE TRANSACTIONS, Vol. 53, 1947, p. 393).

Glycol vapors for disinfecting purposes (*Journal of the American Medical Association* 133:696, March 8, 1947).

W. J. McConnell: An experiment with triethylene glycol vapor for the control of colds among office employees (*Industrial Medicine* 18:5, page 192).

S. M. Wheeler, H. S. Ingraham, A. Hollaender, N. D. Lill, J. Gershon-Cohen, and E. W. Brown: Ultra-violet light control of airborne infections in a naval training center (*American Journal of Public Health*, Vol. 35, 1945, p. 457).

H. G. DuBuy, J. E. Dun, F. S. Brackett, W. C. Dressen, P. A. Nealand, and I. Possner: An evaluation of ultraviolet radiation of sleeping quarters as supplement of accepted methods of disease control (*American Journal of Hygiene*, September 1948, p. 207).

Recent studies on disinfection of air in military establishments (*American Journal of Public Health*, February 1947, p. 189).

Commercial exploitation of glycol vaporisers (*American Journal of Public Health*, February 1949, p. 222).

N. Pace, M. B. Fisher, J. E. Birren, G. C. Pitts, W. A. White, Jr., W. V. Consolazio, and L. J. Pecora: *A Comparative Study of the Effect on Men of Continuous Versus Intermittent Exposure to a Tropical Environment* (Research Project X-205, *Naval Medical Research Institute Report* No. 2, May 1945).

F. K. Hick and M. M. Montgomery: *Mechanism of Heat Retention* (unpublished).

A. R. Behnke: *Environmental and Physiologic Studies Aboard an Air-Cooled Hospital Ship En Route from Norfolk, Virginia, to Canal Zone* (*U.S.S. Tranquility*, AH-14, June 6–13 1945) (Research Project X-205, *Naval Medical Research Institute Report* No. 4, September 1945).

G. E. Burch: The influence of environmental temperature and relative humidity on the rate of water loss through the skin in congestive heart failure in a subtropical climate (*American Journal of Medical Science*, Vol. 211, 1946, p. 181). G. Berenson and G. E. Burch: The responses of patients with congestive heart failure to rapid elevation in atmospheric temperature and humidity (*American Journal of Medical Science*, Vol. 223, 1952, p. 45).

Gunner Edstrom, G. Lundin, and T. Wramer: Investigation into the effect of hot, dry microclimate on peripheral circulation in arthritic patients (*Annals of Rheumatic Diseases* 7:76, June 1948).

Fundamentals of Anesthesia (American Medical Association Press, Chicago, 1944, 2nd ed., p. 204).

B. A. Green: The hazard of fire and explosion in anesthesia (*Anesthesiology* 2:144, 1941).

R. M. Tovell and A. W. Friend: Control of physical hazards of anesthesia (*Canadian Medical Association Journal* 46: 560, 1942).

F. C. Houghten and W. L. Cook, Jr.: ASHAE RESEARCH REPORT No. 1111—Air conditioning requirements of an operating room and recovery ward (ASHVE TRANSACTIONS, Vol. 45, 1939, p. 161).

A. R. Behnke and O. Schneider: Unpublished naval studies (1940).

C. P. Yaglou and Ursula Wilson: *Disinfection of Air by Air Conditioning Processes* (American Association for the Advancement of Science, Publication No. 17, p. 129).

J. A. Reyniers: The control of cross-contamination by the use of mechanical barriers (American Association for the Advancement of Science, *Aerobiology* 17:254, 1942).

K. D. Blackfan, C. P. Yaglou, and K. McKenzie: The premature infant: a study of the effect of atmospheric conditions on growth and on development (*American Journal Diseases of Children* 46:1175, 1933).

I. Rosenstern: Observations on the control of respiratory contagion in the cradle (American Association for the Advancement of Science, *Aerobiology* 17:242, 1942).

F. H. Krusen: *Physical Medicine* (W. B. Saunders Co., Philadelphia, 1941).

F. C. Houghten, M. B. Federber, and Carl Gutberlet: ASHVE RESEARCH REPORT No. 1054—Fever therapy induced by conditioned air (ASHVE TRANSACTIONS, Vol. 46, 1940, p. 131). M. B. Federber, F. C. Houghten, and Carl Gutberlet: ASHVE RESEARCH REPORT No. 1161—Fever therapy locally induced by conditioned air (ASHVE TRANSACTIONS, Vol. 46, 1940, p. 307).

L. W. Crossman and S. K. Safford: Refrigeration for anesthesia and therapy (*The Modern Hospital* 64:86, 1945).

B. Z. Rappaport, T. Nelson, and W. H. Welker: The effect of low relative humidity and constant temperature on pollen asthma (*Journal of Allergy* 6:111, 1935).

C. P. Yaglou: Hospital air conditioning (*The Environment and Its Effect Upon Man*, Harvard School of Public Health, 1939, p. 244).

A. L. Barach: *Principles and Practices of Inhalational Therapy* (J. B. Lippincott Co., Philadelphia, 1944).

Cyril Tasker: What are the right conditions for comfort cooling? (*Heating, Piping and Air Conditioning*, August 1948, p. 84).

C. P. McCord and W. R. Witheridge: *Odors Physiology and Control* (McGraw-Hill Book Co., New York, 1949).

BIBLIOGRAPHY

R. P. Gaulin: Air conditioning the hospital (*Reference Section, Air Conditioning, Heating & Ventilating*, January 1957, p. 73).

W. W. Treichler, Jr.: Air conditioning the operating room (*Air Conditioning, Heating & Ventilating*, April 1957, p. 73).

CHAPTER 9

HEAT TRANSMISSION COEFFICIENTS OF BUILDING MATERIALS

Heat Transfer Symbols; Calculating Overall Coefficients; Conductivity of Homogeneous Materials; Soil Conductivity and Specific Heat; Surface and Air Space Conductance; Overall Coefficients and Their Practical Use; Computed Coefficients of Walls, Roofs, Ceilings, and Floors; Effect of Insulation; Combined Ceiling, Roof, and Floor Coefficients; Glass Coefficients; Calculating Surface Temperatures

THE design of air-conditioning or heating systems for buildings requires a knowledge of the thermal properties of the walls enclosing the space. (The term *walls* in this case, includes windows, doors, ceilings, floors, roofs, and skylights.) The rate of heat flow through the walls under steady-state conditions at design temperatures is usually the basis for calculating the heat required. For a given wall under standard conditions the rate is a specific value designated as U, the *overall coefficient of heat transmission* or thermal transmittance. It may be determined by test in a guarded hot box apparatus, or it may be computed from known values of the thermal conductance of the various components. Because it is impracticable to test all combinations of building materials, the procedure and necessary data for calculation of the value of U are given in this chapter, together with convenient tables of computed values for a large number of the more common constructions.

HEAT TRANSFER SYMBOLS

U = overall coefficient of heat transmission or thermal transmittance (air-to-air); the time rate of heat flow expressed in Btu per (hour) (square foot) (Fahrenheit degree temperature difference between air on the inside and air on the outside of a wall, floor, roof, or ceiling). The term is applied to the usual combinations of materials, and also to single materials, such as window glass, and includes the surface conductance on both sides. This term is frequently called the U value.

k = thermal conductivity; the time rate of heat flow through a homogeneous material under steady conditions per unit temperature gradient through unit area perpendicular to the temperature gradient. Its value is expressed in Btu per (hour) (square foot) (Fahrenheit degree per inch of thickness). Materials are considered homogeneous when the value of k is not affected by variation in thickness or size of sample within the range normally used in construction.

C = thermal conductance; the time rate of heat flow through a unit area of a material from one of its surfaces to the other per unit temperature difference *between the two surfaces*. Its value is expressed in Btu per (hour) (square foot) (Fahrenheit degree). The term is applied to specific materials as used, either homogeneous or heterogeneous, for the thickness or construction stated, not per inch of thickness.

f = film or surface conductance; the time rate of heat exchange by *radiation conduction and convection* of a unit area of a surface with *the surroundings* and the surrounding air or other fluid. Its value is expressed in Btu per (hour) (square foot of surface) (Fahrenheit degree temperature difference). Subscripts i and o are usually used to denote inside and outside surface conductances, respectively.

a = thermal conductance of an air space; the time rate of heat flow through a unit area of an air space per unit temperature difference *between the boundary surfaces*. Its value is expressed in Btu per (hour) (square foot of area) (Fahrenheit degree). The conductance of an air space is dependent on the temperature difference, the height, the depth, the position, character, and temperature of the boundary surfaces. Since the relationships are not linear, accurate values must be obtained by test and not by computation.

ϵ = emissivity; the ratio of the total radiant flux emitted by a surface to that emitted by an ideal black body at the same temperature.

E = effective emissivity; the combined effect of the surface emissivities ϵ of the boundary surfaces of an air space; the boundaries assumed to be parallel and of large dimensions as compared to the distance between them.

r = surface reflectivity; the ratio of the radiant flux reflected by an opaque surface to that falling upon it.

R = thermal resistance. Its value is obtained from the reciprocal of heat transfer as expressed by U, C, f, or a. It may be expressed in (Fahrenheit degrees per Btu)/(hour) (square foot). For example, a wall with a U value of 0.25 would have a resistance value of $R = 1/0.25 = 4.0$ *ru*. The word *ru* has been suggested as an abbreviation for resistance unit.

CALCULATING OVERALL COEFFICIENTS

From Chapter 5, Equation 7, the total resistance to heat flow through a wall is equal numerically to the sum of the resistances in series.

$$R_T = R_1 + R_2 + R_3 + R_4 + \cdots + R_n \qquad (1)$$

where R_1, R_2, etc., are the individual resistances of the wall components, and R_T is total resistance.

For a wall of a single homogeneous material of conductivity k and thickness x with surface coefficients f_i and f_o,

$$R_T = \frac{1}{f_i} + \frac{x}{k} + \frac{1}{f_o} \qquad (2)$$

Then by definition, $U = 1/R_T$

For a wall with air space construction and consisting of two homogeneous materials of conductivities k_1 and k_2, thicknesses x_1 and x_2, respectively, and separated by an air space of conductance a,

$$R_T = \frac{1}{f_i} + \frac{x_1}{k_1} + \frac{1}{a} + \frac{x_2}{k_2} + \frac{1}{f_o} \qquad (3)$$

and $U = 1/R_T$

For types of building materials having non-uniform or irregular sections such as hollow clay tile or concrete blocks, it is necessary to use the conductance C of the section unit as manufactured instead of a conductivity k. The resistance of the section $1/C$ is therefore substituted for x/k in Equations 2 and 3.

It will be noted that in order to compute the U value of a construction it is first necessary to know the conductivity