Thermal Design of Precast Concrete Buildings

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FORWARD

This report is an update and supersedes "Thermal Design of Precast Concrete Building Envelopes," developed by the Portland Cement Association, which appeared in the January-February 1978 PCI JOURNAL.

The document gives an overview of the principles and criteria involved in the thermal design of buildings for code compliance. The methods should not be used for complex structures which require sophisticated analysis and design by qualified mechanical engineers. However, this report can serve as a guide in making comparative assessments of materials used in wall and roof construction. It also presents the thermal advantages inherent in walls and roofs made of precast concrete.

CONTENTS

CHAPTER 1 — NOTATION

a = thermal conductance of an air space, Btu/(hr) (ft^2) (deg F) (see Glossary)
A = area (all areas are in square feet)
A_d = area of doors
A_f = area of glass (fenestration)
A_{f1} = area of glass (Wall 1)
A_{f2} = area of glass (Wall 2)
A_{fl} = area of floor, excluding openings
A_o = gross area
A_{ofl} = gross area of floor
A_{or} = gross area of roof
A_{ow} = gross area of walls
A_p = area of openings in floors
A_r = opaque area of roof
A_s = area of skylights
A_w = opaque area of walls
B = fuel cost, \$/Btu
C = thermal conductance for specified thickness, Btu/(hr) (ft^2) (deg F) (see Glossary)
C_f = resale value at end of study period, \$/ft^2
C_o = initial cost of insulation, \$/ft^2
D = heating degree day (65°F base) (see Glossary)
e = fuel escalation rate, percent
E = seasonal efficiency of heating equipment
f = film or surface conductance (see Glossary)
i = discount or interest rate, percent
IRR = internal rate of return, percent
k = thermal conductivity, Btu-in./(hr) (ft^2) (deg F) (see Glossary)
m = cost per unit R per unit area, \$/R value/ft^2
M = permeance, perms (see Glossary)
$MARR$ = minimum acceptable rate of return, percent
N = study period, years
NB = present value of net benefits, \$/ft^2
$OTTV$ = overall thermal transfer value
$OTTV_r$ = overall thermal transfer value for roof, Btu/(hr) (ft^2)
$OTTV_w$ = overall thermal transfer value for walls, Btu/(hr) (ft^2)
P = vapor pressure (all pressures are in inches of Hg)
P_a = actual vapor pressure drop
P_c = vapor pressure for continuity
P_s = saturation vapor pressure
Q = rate of heat flow, Btu/hr
R = thermal resistance [all thermal resistances are in units of (hr) (ft^2) (deg F)/Btu] (see Glossary)
R_a = thermal resistance of air space
R_{fi}, R_{fo} = thermal resistances of inside and outside surfaces
R_o = initial R value
R_{opt} = optimum R value determined by Eq. (11)
R_t = total thermal resistance
R_u = upgraded R value
$R_{1,2\ldots n}$ = thermal resistance of material layer 1, 2 . . . n
$R_{materials}$ = summation of thermal resistance of opaque material layers
RH = relative humidity, percent (see Glossary)
S = dollar value of energy savings, \$/ft^2/yr
SC = shading coefficient of fenestration
SC_s = shading coefficient of skylight
SF = solar factor, Btu/(hr) (ft^2)
SPV = single present value, $1/(1+i)^N$
SVP = vapor pressure at saturation, in. Hg
t = thickness of a material, in.

t_g = ground surface temperature, deg F

t_i = indoor temperature, deg F

t_o = outdoor temperature, deg F

t_s = dew point temperature of room air at design maximum relative humidity, deg F (see Glossary)

UPV = uniform present value modified

$= \left[\frac{1+e}{i-e}\right]\left[1-\left[\frac{1+e}{1+i}\right]^N\right]$; (equal to N when $i = e$) (see Chapter 11)

T = temperature, deg F

TC = specific heat × density × thickness, (Btu)/(ft^2) (deg F)

TD_{eq} = equivalent temperature difference, indoor-outdoor, deg F

TD_{eqr} = equivalent temperature difference, roof, deg F

TD_{eqw} = equivalent temperature difference, walls, deg F

TDR = temperature difference ratio, $(t_i - t_g)/\Delta t$

U = heat transmittance value [all heat and average transmittance values are in units of Btu/(hr) (ft^2) (deg F)] (see Glossary)

U_d = heat transmittance value of door

U_f = heat transmittance value of glass (fenestration)

U_{fl} = heat transmittance value of floor

U_o = average heat transmittance value

U_{ofl} = average heat transmittance value of floor

U_{or} = average heat transmittance value of roof

U_{ow} = average heat transmittance value of walls

$U_{ow1,2\ldots n}$ = average heat transmittance value of wall sections 1, 2 . . . n

U_p = heat transmittance value of openings in floor

U_r = heat transmittance value of opaque roof

U_s = heat transmittance value of skylight

U_w = heat transmittance value of opaque walls

VP = vapor pressure, in. Hg

Δt = temperature difference, indoor-outdoor, deg F

ΔT = temperature difference of below grade walls, deg F

ΔT_f = temperature difference of fenestration, indoor-outdoor, deg F, cooling design

ΔT_s = temperature difference of skylights

μ = permeability, permeance of a unit thickness of a given material, perm-in. (see Glossary)

ϕ = wall area/roof area, for use in Fig. 22

CHAPTER 2 — GLOSSARY

British thermal units (Btu) — Approximately the amount of heat to raise 1 lb of water from 59°F to 60°F.

Degree day (D) — A unit based on temperature difference and time, used in estimating fuel consumption and specifying nominal heating load of a building in winter. For any one day, when the mean temperature is less than 65°F, there are as many degree days as there are F degrees difference in temperature between the mean temperature for the day and 65°F.

Dew point temperature (t_s) — The temperature at which condensation of water vapor begins for a given humidity and pressure as the vapor temperature is reduced. The temperature corresponding to saturation (100 percent relative humidity) for a given absolute humidity at constant pressure.

Film or surface conductance (f) — The time rate of heat exchange by radiation, conduction, and convection of a unit area of a surface with its surroundings. Its value is usually expressed in Btu per (hr) (sq ft of surface area) (deg F temperature difference). Subscripts "*i*" and "*o*" are usually used to denote inside and outside surface conductances.

Heat transmittance (U value) — overall coefficient of heat transmission or thermal transmittance (air-to-air); the time rate of heat flow usually expressed in Btu per (hr) (sq ft of surface area) (deg F 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 single materials such as window glass, and includes the surface conductance on both sides. This term is frequently called the U value.

Perm — A unit of permeance. A perm is 1 grain per (sq ft of area) (hr) (in. of mercury vapor pressure difference).

Permeability, water vapor (μ) — The property of a substance which permits the passage of water vapor. It is equal to the permeance of 1 in. of a substance. Permeability is measured in perm inches. A material's permeability varies with barometric pressure, temperature, and relative humidity conditions.

Permeance (M) — The water vapor permeance of any sheet or assembly is the ratio of the water vapor flow per unit area per hour to the vapor pressure difference between the two surfaces. Permeance is measured in perms.

Two commonly used test methods are the wet cup and dry cup tests. Specimens are sealed over the tops of cups containing either water or desiccant, placed in a controlled atmosphere usually at 50 percent relative humidity, and weight changes measured.

Relative humidity (RH) — The ratio of water vapor present in air to the water vapor present in saturated air at the same temperature and pressure.

Thermal conductance (C) — The time rate of heat flow expressed in Btu per (hr) (sq ft of area) (deg F average temperature difference between two surfaces). The term is applied to specific materials as used, either homogeneous or heterogeneous, for the thickness or construction stated, not per in. of thickness.

Thermal conductance of an air space (a) — The time rate of heat flow through a unit area of an air space per unit temperature difference between boundary surfaces. Its value is usually expressed in Btu per (hr) (sq ft of area) (deg F).

Thermal conductivity (k) — The time rate of heat flow by conduction only through a unit thickness of a homogenous material under steady-state conditions, through unit area, per unit temperature gradient in the direction perpendicular to the isothermal surface. Its unit is Btu-in. per (hr) (sq ft of area) (deg F).

Thermal resistance (R value) — The reciprocal of a heat transmission coefficient, as expressed by U, C, f, or a. Its unit is (deg F) (hr) (sq ft of area) per Btu. For example, a wall with a U value of 0.25 would have a resistance value of $R = 1/U = 1/0.25 = 4.0$.

CHAPTER 3 — GENERAL

Thermal codes and standards prescribe in many different ways the heat transmission requirements for buildings. Therefore, it is important to have basic knowledge about the heat loss and heat gain of many materials.

This report presents the fundamentals and design aids that are needed to analyze and compare the heat losses and heat gains through building envelopes for code compliance.

Prescriptive standards specify U or R

values for each building component. Performance standards do not require adherence to the prescribed U or R values provided that an acceptable level of annual energy consumption is maintained. Using the performance approach, two building components are equivalent if they result in the same annual energy consumption, regardless of their U or R value. This allows the designer flexibility to choose the combination of conservation strategies that provide the required performance at the least first cost.

Precast and prestressed concrete construction have a unique advantage with their thermal inertia and thermal storage properties. Most codes are prescriptive in nature and procedures to account for the benefits of heavier materials are not usually given. Such procedures are presented in Chapter 8.

The trend is toward more insulation with little regard given to its total impact on the energy saved. Before assuming that thicker insulation is needed, mass effects, less glass area, reduced infiltration, and controlled ventilation should be considered.

Further considerations may include building orientation, exterior color, shading or reflections from adjacent structures, surrounding surfaces or vegetation, building aspect ratio, number of stories, and wind direction and speed.

Except where noted, the information and design criteria that follow are taken from or derived from the ASHRAE *Handbook of Fundamentals*,[1] hereafter referred to as the ASHRAE Handbook, and from the ASHRAE Standard 90A-1980, *Energy Conservation in New Building Design*,[2] hereafter referred to as the ASHRAE Standard.

It is important to note that all design criteria are not given in this report and the criteria used may change from time to time as the ASHRAE Standard and Handbook are revised.

Therefore, as the design procedures are applied, it is essential to consult the applicable codes and revised references for specified values and procedures that govern in a particular area.

CHAPTER 4 — THERMAL PROPERTIES OF MATERIALS, SURFACES AND AIR SPACES

The thermal properties of materials and air spaces are based on steady state tests. The tests establish the number of British thermal units (Btu) that pass from the warm side to the cool side of the item being tested.

The results of the tests determine the conductivity, k. For nonhomogeneous, compound sections and air spaces, the tests determine the conductance, C, for the total thickness.

The values k and C do not include surface conductances. The inside surface conductance, f_i, and the outside surface conductance, f_o, are considered separately.

The resistance method is used in the thermal design of wall, floor, and roof sections. Therefore, the resistance, R, i.e., the reciprocal of U, C, f_i, and f_o must be known. The R values of construction materials are not influenced by the direction of heat flow.

On the other hand, the R values of surfaces and air spaces differ depending on their orientation, that is whether they are vertical, sloping, or horizontal. Also, the R values of surfaces are affected by the velocity of air at the surfaces and by their reflective properties.

Tables 1 and 2 give the thermal resistances of surfaces and 3½ in. air spaces. Table 2 lists frequently used values for air space resistance. For other conditions, consult the ASHRAE Handbook, Chapter 23.

Table 3 gives the thermal properties of most commonly used building mate-

Table 1. Thermal Resistances, R_f, of Surfaces.

Position of surface	Direction of heat flow	Still air, R_{fi}			Moving air, R_{fo}	
		Nonreflective surface	Reflective surface		Nonreflective surface	
			A[*]	B[†]	15 mph[‡]	7½ mph[§]
Vertical	Horizontal	0.68	1.35	1.70	0.17	0.25
Horizontal	Up	0.61	1.10	1.32	0.17	0.25
	Down	0.92	2.70	4.55	0.17	0.25

[*] Aluminum coated paper, polished.

[†] Bright aluminum foil.

[‡] Winter design.

[§] Summer design.

Table 2. Thermal Resistances, R_a, of Air Spaces.[*]

Position of air space	Direction of heat flow	Air space		Nonreflective surface	Reflective surfaces		
		Mean temp. °F	Temp. diff. °F		One side[†]	One side[‡]	Both sides[‡]
Vertical		Winter					
	Horizontal (walls)	50	10	1.01	2.32	3.40	3.63
		50	30	0.91	1.89	2.55	2.67
		Summer					
	Horizontal (walls)	90	10	0.85	2.15	3.40	3.69
Horizontal		Winter					
	Up (roofs)	50	10	0.93	1.95	2.66	2.80
		50	30	0.84	1.58	2.01	2.09
	Down (floors)	50	30	1.22	3.86	8.17	9.60
		Summer					
	Down (roofs)	90	10	1.00	3.41	8.19	10.07

[*] For 3½ in. air space thickness. Values for vertical air space thicknesses between ¾ in. and 3½ in. are within 10 percent of those listed. Values for horizontal air spaces may vary by a wider margin. Refer to Table 2, Chapter 23 of the ASHRAE Handbook for values of other thicknesses, reflective surfaces, positions of air space, and directions of heat flow.

[†] Aluminum coated paper, polished.

[‡] Bright aluminum foil.

Table 3. Thermal Properties of Various Building Materials.*

Material	Unit weight, pcf	Resistance, R Per inch of thickness, 1/k	 For thickness shown, 1/C	Transmittance, U	Specific heat Btu/(lb)(°F)
Insulation, rigid					
Cellular glass	8.5	2.86			0.18
Glass fiber, organic bonded	4-9	4.00			0.23
Mineral fiber, resin binder	15	3.45			0.17
Mineral fiberboard, wet felted, roof insulation	16-17	2.94			—
Cement fiber slabs (shredded wood with magnesia oxysulfide binder)	22	1.75			0.31
Expanded polystyrene extruded cut cell surface	1.8	4.00			0.29
Expanded polystyrene extruded smooth skin surface	1.8-3.5	5.00			0.29
Expanded polystyrene molded bead	1.0	5.00			—
Cellular polyurethane	1.5	6.25			0.38
Miscellaneous					
Acoustical tile (mineral fiberboard wet felted)	18	2.86			0.19
Carpet, fibrous pad			2.08		0.34
Carpet, rubber pad			1.23		0.33
Floor tile, asphalt, rubber, vinyl			0.05		0.30
Gypsum board	50	0.88†			0.26
Particle board	50	1.06			0.31
Plaster					
cement, sand aggregate	116	0.20			0.20
gypsum, lightweight aggregate	45	0.63†			—
gypsum, sand aggregate	105	0.18			0.20
Roofing, ⅜ in. built-up	70		0.33		0.35
Wood, hard	45	0.91			0.30
Wood, soft	32	1.25			0.33
Plywood	34	1.25			0.29
Glass doors & windows‡					
Single, winter				1.10	
Single, summer				1.04	
Double, winter§				0.59	
Double, summer§				0.61	
Doors, metal**					
Insulated, winter				0.47	
Insulated, summer				0.46	

*See Table 4 for all concretes, including insulating concrete for roof fill.

†Average value.

‡Does not include correction for sash resistance. Refer to Chapter 23 of the ASHRAE Handbook for sash correction.

§¼ in. air space; coating on either glass surface facing air space.

**Solid polystyrene core with thermal break.

Table 4. Thermal Properties of Concrete.*

Description	Concrete weight, pcf	Thickness, in.	Resistance, R		Specific heat‡ Btu/(lb)(°F)
			Per inch of thickness, $1/k$	For thickness shown, $1/C$	
Concretes including normal weight, lightweight and lightweight insulating concretes	145		0.075		0.19
	140		0.083		
	130		0.11		
	120		0.14		
	110		0.19		
	100		0.24		
	90		0.30		
	80		0.37		
	70		0.45		
	60		0.52		
	50		0.67		
	40		0.83		
	30		1.00		
	20		1.43		
Normal weight tees† and solid slabs	145	2		0.15	0.19
		3		0.23	
		4		0.30	
		5		0.38	
		6		0.45	
		8		0.60	
Normal weight hollow-core slabs	145	6		1.07	0.19
		8		1.34	
		10		1.73	
		12		1.91	
Structural lightweight tees† and solid slabs	110	2		0.38	0.19
		3		0.57	
		4		0.76	
		5		0.95	
		6		1.14	
		8		1.52	
Structural lightweight hollow-core slabs	110	8		2.00	0.19
		12		2.59	

*Based on normally dry concrete (see Chapter 4 of Reference 3).

†Thickness for tees is thickness of slab portion including topping, if used. The effect of the stems generally is not significant, therefore, their thickness and surface area may be disregarded.

‡The specific heat shown is the mean value from test data compiled in Reference 4 and is sufficiently accurate for calculating *TC* of Fig. 6. For a more exact value, tests should be performed on the concrete mix being used.

rials. For glass, only U values are given since the glass alone has almost no thermal resistance. The resistances of the surfaces of the glass and air space between panes contribute most to the U value.

Table 4 gives the thermal properties of various weight concretes, including insulating concretes. It also gives the R values of some of the more commonly used prestressed concrete floor, roof, and wall units.

Thermal conductances and resistances are usually determined and reported for building materials in their oven dry condition. Conductances and resistances for concrete are often reported in its normally dry condition as well as in its oven dry condition.

Normally dry is the condition of concrete containing an equilibrium amount of free water after extended exposure to warm air at 35 to 50 percent relative humidity. Values given in the tables in this report are based on concrete that is considered normally dry.

It should be noted that normally dry concrete in combination with insulation generally provides about the same R value as equally insulated oven dry concrete. It should also be mentioned that normally dry concrete, because of its moisture content, has the ability to store a greater amount of heat than oven dry concretes, a beneficial property when considering the dynamic thermal response of concrete. However, higher moisture content in concrete causes higher thermal conductance, an undesirable property.

CHAPTER 5 — COMPUTATION OF THERMAL TRANSMITTANCE VALUES

The heat transmittance values (U values) of building wall, floor, or roof section are computed by adding together:

1. The R values of the layers of materials in the section;
2. The R_{fi} and R_{fo} values of the inside and outside surfaces; and
3. The R_a value of air spaces that may be within the section.

The reciprocal of the summation of all R values is the U value. For example, a typical wall with an air space is calculated as follows:

$$U = \frac{1}{R_{fi} + R_{materials} + R_a + R_{fo}} \qquad (1)$$

where $R_{materials}$ is a summation, that is, $R_1 + R_2 + R_3$, etc., of all opaque materials in the wall. Typical wall and roof calculations are made at the end of this chapter.

For the convenience of designers, a number of wall and roof U values have been computed. Tables 5, 6, and 7 contain winter and summer U values for concrete wall and roof sections of various thicknesses and designs with or without added insulation.

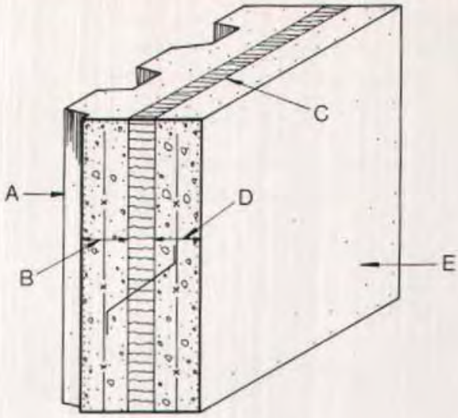
Wall tables can be applied to sandwich type panels as well as single wythe panels insulated on one side. Roof tables include added effect of acoustical tile ceilings either applied directly to the bottom of the prestressed units or suspended below.

The U values used in heating design may be modified to account for the effects of mass as given in Chapter 8. The U values used in cooling design are used without modification; mass effects are applied by using appropriate equivalent temperature differences, TD_{eq}, as explained in Chapter 7.

5.1 Design Examples

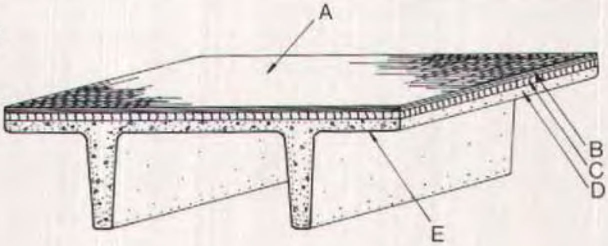
Two design examples (one for a wall and one for a roof) are given for calculating U values. Preliminary R values are taken from Tables 1 through 4.

Example 1 — Wall



	R Winter	*R* Summer	Table
A. Surface, outside	0.17	0.25	1
B. Concrete, 2 in. (110 pcf)	0.38	0.38	4
C. Polystyrene insulation, 1½ in.	6.00	6.00	3
D. Concrete, 2½ in. (110 pcf)	0.48	0.48	4
E. Surface, inside	0.68	0.68	1
Total *R* =	7.71	7.79	
U = 1/*R* =	0.13	0.13	

Example 2 — Roof



	R Winter	*R* Summer	Table
A. Surface, outside	0.17	0.25	1
B. Roofing, built-up	0.33	0.33	3
C. Polystyrene insulation, 2 in.	8.00	8.00	3
D. Concrete, 2 in. (145 pcf)	0.15	0.15	4
E. Surface, inside	0.61	0.92	1
Total *R* =	9.26	9.65	
U = 1/*R* =	0.11	0.10	

Table 5. Wall U Values: Prestressed Tees, Hollow-Core Slabs, Solid and Sandwich Panels; Winter and Summer Conditions.*

Concrete weight, pcf	Type of wall panel	Thickness, t, and resistance, R, of concrete		Winter $R_{fo}=0.17$, $R_{fi}=0.68$					Summer $R_{fo}=0.25$, $R_{fi}=0.68$				
				Insulation resistance, R									
		$t^{\dagger}$	R	None	4	6	8	10	None	4	6	8	10
145	Solid walls, tees, and sandwich panels	2	0.15	1.00	.20	.14	.11	.09	.93	.20	.14	.11	.09
		3	0.23	.93	.20	.14	.11	.09	.86	.19	.14	.11	.09
		4	0.30	.87	.19	.14	.11	.09	.81	.19	.14	.11	.09
		5	0.38	.81	.19	.14	.11	.09	.76	.19	.14	.11	.09
		6	0.45	.77	.19	.14	.11	.09	.72	.19	.14	.11	.09
		8	0.60	.69	.18	.13	.11	.09	.65	.18	.13	.10	.09
	Hollow-core slabs[‡]	6(o)	1.07	.52	.17	.13	.10	.08	.50	.17	.13	.10	.08
		(f)	1.86	.37	.15	.11	.09	.08	.36	.15	.11	.09	.08
		8(o)	1.34	.46	.16	.12	.10	.08	.44	.16	.12	.10	.08
		(f)	3.14	.25	.13	.10	.08	.07	.25	.12	.10	.08	.07
		10(o)	1.73	.39	.15	.12	.09	.08	.38	.15	.12	.09	.08
		(f)	4.05	.20	.11	.09	.08	.07	.20	.11	.09	.08	.07
		12(o)	1.91	.36	.15	.11	.09	.08	.35	.15	.11	.09	.08
		(f)	5.01	.17	.10	.08	.07	.06	.17	.10	.08	.07	.06
110	Solid walls, tees, and sandwich panels	2	0.38	.81	.19	.14	.11	.09	.76	.19	.14	.11	.09
		3	0.57	.70	.18	.13	.11	.09	.67	.18	.13	.11	.09
		4	0.76	.62	.18	.13	.10	.09	.59	.18	.13	.10	.09
		5	0.95	.56	.17	.13	.10	.09	.53	.17	.13	.10	.08
		6	1.14	.50	.17	.13	.10	.08	.48	.16	.12	.10	.08
		8	1.52	.42	.16	.12	.10	.08	.41	.16	.12	.10	.08
	Hollow-core, slabs[‡]	8(o)	2.00	.35	.15	.11	.09	.08	.34	.14	.11	.09	.08
		(f)	4.41	.19	.11	.09	.08	.07	.19	.11	.09	.07	.07
		12(o)	2.59	.29	.13	.11	.09	.07	.28	.13	.11	.09	.07
		(f)	6.85	.13	.09	.07	.06	.06	.13	.08	.07	.06	.06

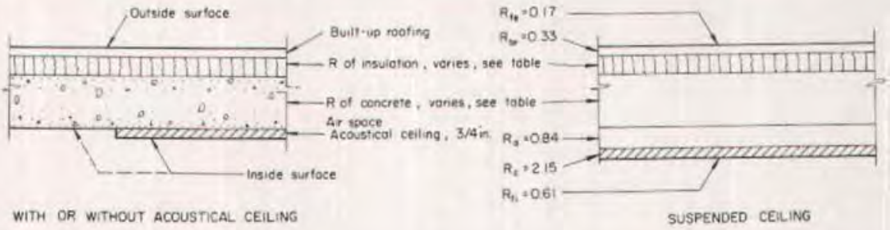
*U values listed are rounded to two decimal places. When insulations having other R values are used, U values can be interpolated with adequate accuracy, or U can be calculated as shown in Chapter 5. When a finish, air space or any other material layer is added, the new U value is:

$$\frac{1}{\dfrac{1}{U \text{ from table}} + R \text{ of added finish, air space, or material}}$$

[†] Thickness for tees is thickness of slab portion. For sandwich panels, t is the sum of the thickness of the wythes.

[‡] For hollow panels (o) and (f) after thickness designates cores open or cores filled with insulation.

Table 6. Roof *U* Values: Concrete Units with Built-Up Roofing, Winter Conditions, Heat Upward.*



Concrete weight, pcf	Prestressed concrete member	Thickness, *t*, and resistance, *R*, of concrete		Without ceiling				With ceiling							
								Applied direct				Suspended			
				Top insulation resistance, *R*											
		t†	*R*	None	4	10	16	None	4	10	16	None	4	10	16
145	Solid slabs and tees	2	0.15	.79	.19	.09	.06	.29	.13	.07	.05	.24	.12	.07	.05
		3	0.23	.75	.19	.09	.06	.29	.13	.07	.05	.23	.12	.07	.05
		4	0.30	.71	.18	.09	.06	.28	.13	.07	.05	.23	.12	.07	.05
		5	0.38	.67	.18	.09	.06	.27	.13	.07	.05	.22	.12	.07	.05
		6	0.45	.64	.18	.09	.06	.27	.13	.07	.05	.22	.12	.07	.05
		8	0.60	.58	.18	.09	.06	.26	.13	.07	.05	.21	.11	.07	.05
	Hollow-core slabs‡	6(o)	1.07	.46	.16	.08	.06	.23	.12	.07	.05	.19	.11	.07	.05
		(f)	1.86	.34	.14	.08	.05	.20	.11	.07	.05	.17	.10	.06	.05
		8(o)	1.34	.41	.16	.08	.05	.22	.12	.07	.05	.18	.11	.06	.05
		(f)	3.14	.24	.12	.07	.05	.16	.10	.06	.04	.14	.09	.06	.04
		10(o)	1.73	.35	.15	.08	.05	.20	.11	.07	.05	.17	.10	.06	.05
		(f)	4.05	.19	.11	.07	.05	.14	.09	.06	.04	.12	.08	.06	.04
		12(o)	1.91	.33	.14	.08	.05	.19	.11	.07	.05	.17	.10	.06	.05
		(f)	5.01	.16	.10	.06	.05	.12	.08	.05	.04	.11	.08	.05	.04
110	Solid slabs and tees	2	0.38	.67	.18	.09	.06	.27	.13	.07	.05	.22	.12	.07	.05
		3	0.57	.60	.18	.09	.06	.26	.13	.07	.05	.21	.12	.07	.05
		4	0.76	.53	.17	.08	.06	.25	.12	.07	.05	.21	.11	.07	.05
		5	0.95	.49	.17	.08	.06	.24	.12	.07	.05	.20	.11	.07	.05
		6	1.14	.44	.16	.08	.05	.23	.12	.07	.05	.19	.11	.07	.05
		8	1.52	.38	.15	.08	.05	.21	.11	.07	.05	.18	.10	.06	.05
	Hollow-core slabs‡	8(o)	2.00	.32	.14	.08	.05	.19	.11	.07	.05	.16	.10	.06	.05
		(f)	4.41	.18	.11	.06	.05	.13	.09	.06	.04	.12	.08	.05	.04
		12(o)	2.59	.27	.13	.07	.05	.17	.10	.06	.05	.15	.09	.06	.04
		(f)	6.85	.13	.08	.06	.04	.10	.07	.05	.04	.09	.07	.05	.04

---

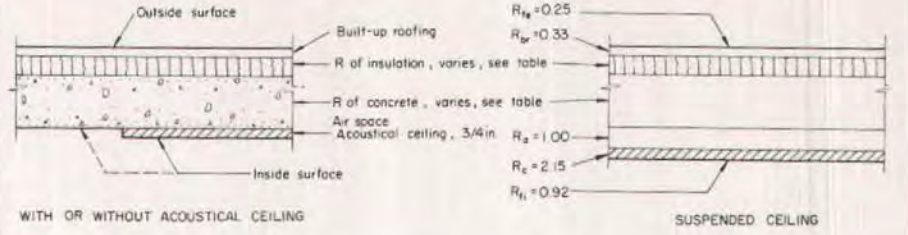
*U values listed are rounded to two decimal places. When insulations having other *R* values are used, *U* values can be interpolated with adequate accuracy, or *U* can be calculated as shown in Chapter 5. When a finish, air space, or any material layer is added, the new *U* value is:

$$\frac{1}{\dfrac{1}{U \text{ from table}} + R \text{ of added finish, air space, or material}}$$

† Thickness for tees is thickness of slab portion.

‡ For hollow panels (o) and (f) after thickness designates cores open or cores filled with insulation.

Table 7. Roof *U* Values: Concrete Units with Built-up Roofing, Summer Conditions, Heat Upward.*



Concrete weight, pcf	Prestressed concrete member	Thickness, *t*, and resistance, *R*, of concrete		Without ceiling				With ceiling							
								Applied direct				Suspended			
				Top insulation resistance, *R*											
		t[†]	R	None	4	10	16	None	4	10	16	None	4	10	16
145	Solid slabs and tees	2	0.15	.61	.18	.09	.06	.26	.13	.07	.05	.21	.11	.07	.05
		3	0.23	.58	.17	.09	.06	.26	.13	.07	.05	.20	.11	.07	.05
		4	0.30	.56	.17	.08	.06	.25	.13	.07	.05	.20	.11	.07	.05
		5	0.38	.53	.17	.08	.06	.25	.12	.07	.05	.20	.11	.07	.05
		6	0.45	.51	.17	.08	.06	.24	.12	.07	.05	.20	.11	.07	.05
		8	0.60	.48	.16	.08	.06	.24	.12	.07	.05	.19	.11	.07	.05
	Hollow-core slabs[‡]	6(o)	1.07	.39	.15	.08	.05	.21	.11	.07	.05	.17	.10	.06	.05
		(f)	1.86	.30	.14	.07	.05	.18	.11	.06	.05	.15	.10	.06	.04
		8(o)	1.34	.35	.15	.08	.05	.20	.11	.07	.05	.17	.10	.06	.05
		(f)	3.14	.22	.12	.07	.05	.15	.09	.06	.04	.13	.08	.06	.04
		10(o)	1.73	.31	.14	.08	.05	.19	.11	.07	.05	.16	.10	.06	.04
		(f)	4.05	.18	.10	.06	.05	.13	.09	.06	.04	.11	.08	.05	.04
		12(o)	1.91	.29	.13	.07	.05	.18	.10	.06	.05	.15	.09	.06	.04
		(f)	5.01	.15	.10	.06	.04	.12	.08	.05	.04	.10	.07	.05	.04
110	Solid slabs and tees	2	0.38	.53	.17	.08	.06	.25	.12	.07	.05	.20	.11	.07	.05
		3	0.57	.48	.16	.08	.06	.24	.12	.07	.05	.19	.11	.07	.05
		4	0.76	.44	.16	.08	.05	.23	.12	.07	.05	.18	.11	.06	.05
		5	0.95	.41	.16	.08	.05	.22	.12	.07	.05	.18	.10	.06	.05
		6	1.14	.38	.15	.08	.05	.21	.11	.07	.05	.17	.10	.06	.05
		8	1.52	.33	.14	.08	.05	.19	.11	.07	.05	.16	.10	.06	.05
	Hollow-core slabs[‡]	8(o)	2.00	.29	.13	.07	.05	.18	.10	.06	.05	.15	.09	.06	.04
		(f)	4.41	.17	.10	.06	.05	.12	.08	.06	.04	.11	.08	.05	.04
		12(o)	2.59	.24	.12	.07	.05	.16	.10	.06	.04	.14	.09	.06	.04
		(f)	6.85	.12	.08	.05	.04	.10	.07	.05	.04	.09	.06	.05	.04

[*] *U* values listed are rounded to two decimal places. When insulations having other *R* values are used, *R* values can be interpolated with adequate accuracy, or *U* can be calculated as shown in Chapter 5. When a finish, air space, or any material layer is added, the new *U* value is:

$$\frac{1}{\dfrac{1}{U \text{ from table}} + R \text{ of added finish, air space, or material}}$$

[†] Thickness for tees is thickness of slab portion.

[‡] For hollow panels (o) and (f) after thickness designates cores open or cores filled with insulation.

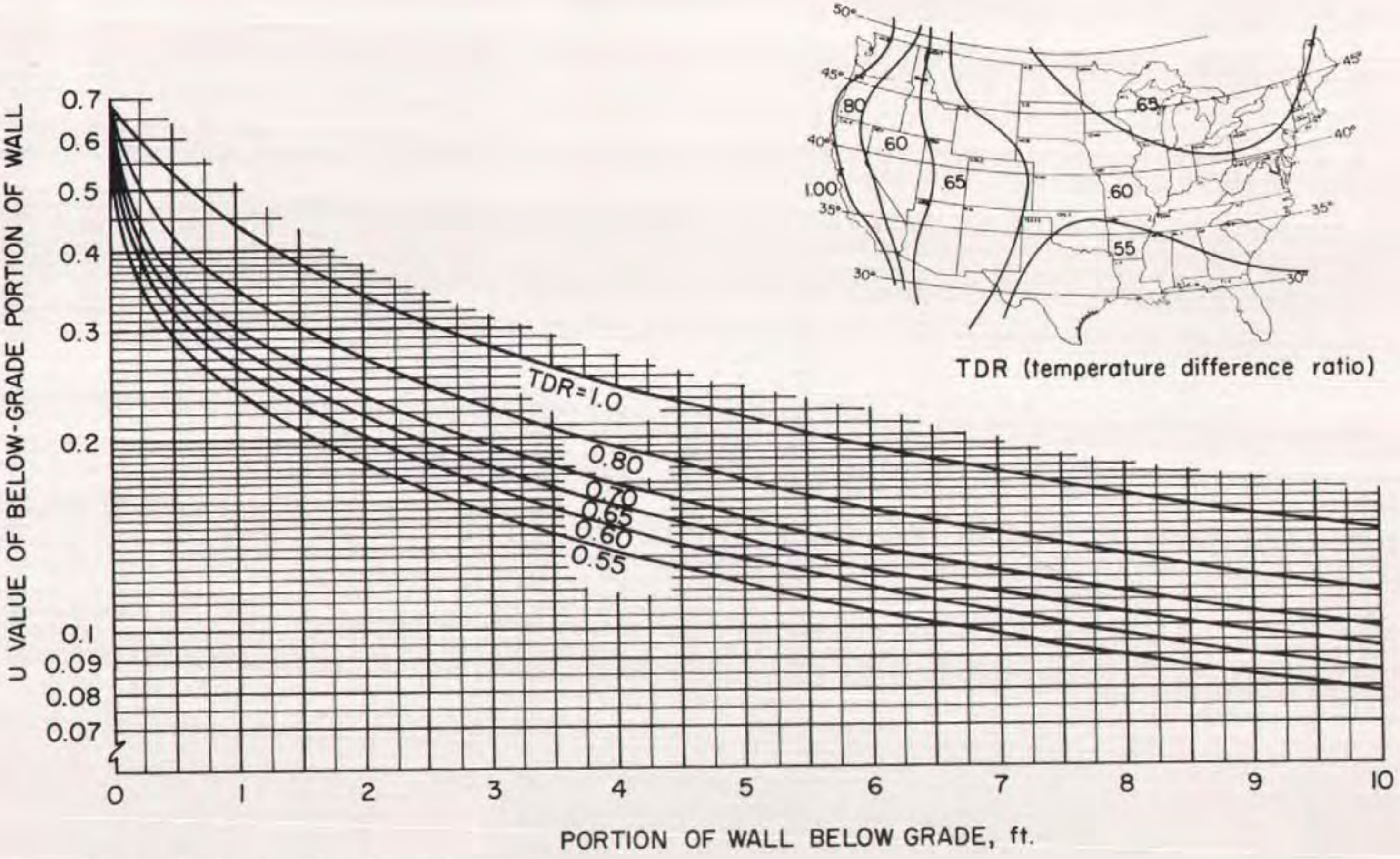


Fig. 1. Average *U* value for walls below grade.

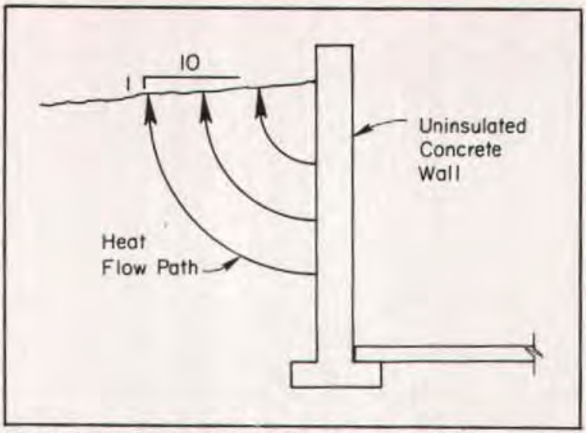


Fig. 2. Heat flow path for walls below grade.

CHAPTER 6 — HEATING DESIGN

6.1 Design Temperatures and Temperature Differences

To determine the critical hourly heat loss through opaque and glass areas, a temperature difference $(t_i - t_o = \Delta t)$ is multiplied by the applicable steady state U values. To account for the effects of mass in an opaque section, see Chapter 8.

For heated buildings, the maximum indoor temperature, t_i of habitable space is generally assumed as 72°F.

Outdoor design temperatures for major cities as recommended in the ASHRAE Handbook are listed in Table 8. The ASHRAE Standard permits the 97½ percent values to be used for buildings of all weights. The winter percentiles in Table 8 represent the percent of total hours (based on the month of January for Canadian locations and for December, January, and February for all other locations) that outdoor temperatures equalled or exceeded the listed values.

However, because of the high peak load problems that can develop in lightweight buildings, especially those with wall and roof sections weighing less than about 15 psf and those having large amounts of glass, the lower design temperatures should be considered for such buildings. See discussion on thermal storage effects in Chapter 8 for an explanation of peak loads.

The ΔT for below grade walls is not the difference between inside and outside temperature. Rather, it is the difference between inside and ground surface temperature. This is true because of the heat capacity of the soil.

The ASHRAE Handbook describes a method for determining the ΔT for below grade walls. Fig. 1 is used to analyze below grade walls based on this ΔT.

6.2 Thermal Transmittance Values

Many codes and standards specify average U values for walls, floors, and roofs designated as U_o. This is the procedure currently used by the ASHRAE Standard to designate heating requirements. The U_o value is the weighted average thermal transmittance of the gross area, A_o, of a building envelope component. The value includes more than one element; for example, opaque wall areas

Table 8. Outdoor Temperatures, Latitudes, and Degree Days.*

City†	Latitude		Winter temperatures* deg F		Winter degree days‡	Summer design dry bulb temperatures 2½ percent, deg F
	deg.	min.	99 percent	97½ percent		
UNITED STATES						
Albuquerque, NM (AP)	35	00	12	16	4,350	94
Atlanta, GA (AP)	33	40	17	22	2,960	92
Baltimore, MD (CO)	39	20	14	17	4,110	89
Baltimore, MD (AP)	39	10	10	13	4,650	91
Birmingham, AL (AP)	33	30	17	21	2,550	94
Bismarck, ND (AP)	46	50	−23	−19	8,850	91
Boise, ID (AP)	43	30	3	10	5,810	94
Boston, MA (AP)	42	20	6	9	5,630	88
Burlington, VT (AP)	44	30	−12	−7	8,270	85
Charleston, WV (AP)	38	20	7	11	4,480	90
Charlotte, NC (AP)	35	00	18	22	3,190	93
Casper, WY (AP)	42	50	−11	−5	7,410	90
Chicago, IL (CO)	41	50	−3	2	5,880	91
Chicago, IL (Midway AP)	41	50	−5	0	6,160	91
Chicago, IL (O'Hare AP)	42	00	−8	−4	6,640	89
Cincinnati, OH (CO)	39	10	1	6	4,410	90
Cleveland, OH (AP)	41	20	1	5	6,350	88
Columbia, SC (AP)	34	00	20	24	2,480	95
Concord, NH (AP)	43	10	−8	−3	7,380	87
Dallas, TX (AP)	32	50	18	22	2,360	100
Denver, CO (AP)	39	50	−5	−1	6,280	91
Des Moines, IA (AP)	41	30	−10	−5	6,590	91
Detroit, MI (AP)	42	20	3	6	6,230	88
Great Falls, MT (AP)	47	30	−21	−15	7,750	88
Hartford, CT (AP)	41	50	3	7	6,240	88
Houston, TX (CO)	29	50	28	33	1,280	95
Houston, TX (AP)	29	40	27	32	1,400	94
Indianapolis, IN (AP)	39	40	−2	2	5,700	90
Jackson, MS (AP)	32	20	21	25	2,240	95
Kansas City, MO (AP)	39	10	2	6	4,710	96
Las Vegas, NV (AP)	36	10	25	28	2,710	106
Lexington, KY (AP)	38	00	3	8	4,680	91
Little Rock, AR (AP)	34	40	15	20	3,220	96
Los Angeles, CA (AP)	34	00	41	43	2,060	80
Los Angeles, CA (CO)	34	00	37	40	1,350	89
Memphis, TN (AP)	35	00	13	18	3,230	95
Miami, FL (AP)	25	50	44	47	210	90
Milwaukee, WI (AP)	43	00	−8	−4	7,640	87
Minneapolis, MN (AP)	44	50	−16	−12	8,380	89
New Orleans, LA (AP)	30	00	29	33	1,380	92
New York, NY (La Guardia AP)	40	50	11	15	4,810	89
New York, NY (Kennedy AP)	40	40	12	15	5,220	87
Norfolk, VA (AP)	36	50	20	22	3,420	91

Table 8 (cont.). Outdoor Temperatures, Latitudes, and Degree Days.*

City[†]	Latitude		Winter temperatures* deg F		Winter degree days[‡]	Summer design dry bulb temperatures 2½ percent, deg F
	deg.	min.	99 percent	97½ percent		
UNITED STATES (cont.)						
Oklahoma City, OK (AP)	35	20	9	13	3,720	97
Omaha, NE (AP)	41	20	−8	−3	6,610	91
Philadelphia, PA (AP)	39	50	10	14	5,140	90
Phoenix, AZ (AP)	33	30	31	34	1,760	107
Pittsburgh, PA (CO)	40	30	3	7	5,050	88
Pittsburgh, PA (AP)	40	30	1	5	5,990	86
Portland, ME (AP)	43	40	−6	−1	7,510	84
Portland, OR (AP)	45	40	17	23	4,640	85
Portland, OR (CO)	45	30	18	24	4,110	86
Providence, RI (AP)	41	40	5	9	5,950	86
Rochester, NY (AP)	43	10	1	5	6,750	88
Salt Lake City, UT (AP)	40	50	3	8	6,050	95
San Francisco, CA (CO)	37	50	38	40	3,000	71
San Francisco, CA (AP)	37	40	35	38	3,020	77
Seattle, WA (CO)	47	40	22	27	4,420	82
Seattle, WA (Tacoma AP)	47	30	21	26	5,140	80
Sioux Falls, SD (AP)	43	40	−15	−11	7,840	91
St. Louis, MO (CO)	38	40	3	8	4,480	94
St. Louis, MO (AP)	38	50	2	6	4,900	94
Tampa, FL (AP)	28	00	36	40	680	91
Trenton, NJ (CO)	40	10	11	14	4,980	88
Washington, DC (National AP)	38	50	14	17	4,220	91
Washington, DC (Andrews AFB)	38	50	10	14	4,220	90
Wichita, KS (AP)	37	40	3	7	4,620	98
Wilmington, DE (AP)	39	40	10	14	4,930	89
ALASKA						
Anchorage (AP)	61	10	−23	−18	10,860	68
Fairbanks (AP)	64	50	−51	−47	14,280	78
CANADA						
Edmonton, AB (AP)	53	34	−29	−25	10,270	82
Halifax, NS (AP, CO)	44	39	1	5	7,360	76
Montreal, PQ (AP)	45	28	−16	−10	8,200	85
Saskatoon, SK (AP, CO)	52	10	−35	−31	10,870	86
St. John's, NF (AP)	47	37	3	7	8,990	75
Saint John, NB (AP, CO)	45	19	−12	−8	8,220	77
Toronto, ON (AP, CO)	43	41	−5	−1	6,830	87
Vancouver, BC (AP)	49	11	15	19	5,520	77
Winnipeg, MB (AP)	49	54	−30	−27	10,680	86

*ASHRAE Handbook, Chapter 24.

[†] (CO) stands for city and (AP) for airport. (AP, CO) airport data used for temperatures and city data for degree day value.

[‡] Rounded to nearest 10.

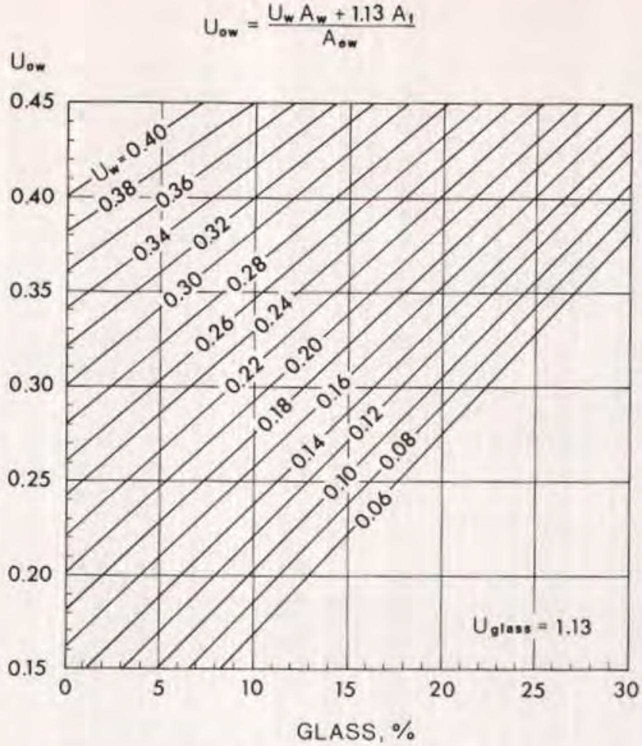


Fig. 3. Wall-glass heating design chart for single glass.

are combined with glazed areas to arrive at the U_o for the entire wall component.

The U_o limits vary depending on the geographical location of the building, its occupancy, and its height.

For any given geographical location usually there are only a few U_o values that apply. Consult local codes for applicable U_o values and regulations governing thermal design of various building components and building types.

For heating designs, the allowable or desired U_{ow}, U_{or}, or U_{ofl} of walls, roofs, and floors is calculated using the following equations:

$$U_{ow} = \frac{U_w A_w + U_f A_f + U_d A_d}{A_{ow}} \qquad (2)$$

$$U_{or} = \frac{U_r A_r + U_s A_s}{A_{or}} \qquad (3)$$

$$U_{ofl} = \frac{U_{fl} A_{fl} + U_p A_p}{A_{ofl}} \qquad (4)$$

It is important to note that any of the *UA* terms may be a combination of two or more areas.

Fig. 1 is a design aid for determining *U* values of below grade portions of walls. The graph is based on an assumed heat flow path and thermal and physical properties shown in Fig. 2 and is in accordance with the ASHRAE Handbook. The correction for the ΔT for below grade walls to account for the surface temperature of the soil (see Section 6.1) is the temperature difference ratio, *TDR*.

To show use of the graph, consider a building located in an area having a $TDR = 0.65$. The portion of wall below

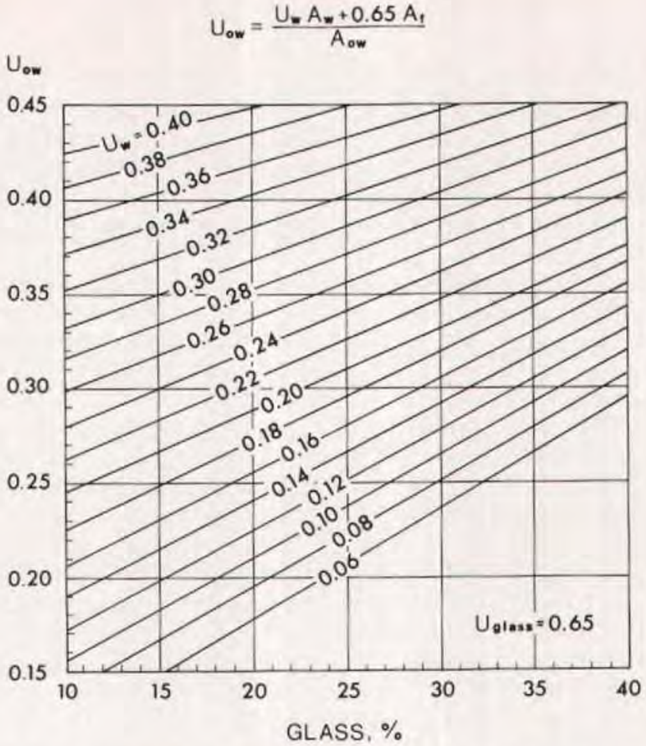


Fig. 4. Wall-glass heating design chart for double glass.

grade is 4 ft. To determine the *U* value, enter the graph at 4 ft, move vertically to *TDR* = 0.65, move horizontally and read the *U* value of the below grade portion of the wall = 0.155.

6.3 Trade-off Considerations, Opaque vs. Glass

Once the U_{ow}, U_{or}, and U_{oft} values are established for a given location, the designer is free to proportion opaque areas and glazed areas so that the heat transmission through the gross areas does not exceed the gross values allowed.

The combination of areas may consist of several walls having different U_w values combined with glass. In roofs, the U_r of opaque areas and the U_s of skylight areas may be proportioned and combined to conform to the allowable U_{or}.

To shorten design time when proportioning opaque and glass areas in walls, opaque wall vs. glass trade-off charts can be used. Fig. 3 is used to combine a percentage of single glass ($U_f = 1.13$) with opaque areas to meet a given U_{ow}. Fig. 4 is for use in selecting the percentage of double glass ($U_f = 0.65$) to combine with alternate choices of U_w values.

Assume that the applicable code or standard limits U_{ow} for walls to 0.30. If single glass is proposed ($U_f = 1.13$) and the U_w of the opaque area is 0.17, from Fig. 3, the area of glass is limited to 13½ percent of the gross area A_{ow}. From Fig. 4, the area of double glass ($U_f = 0.65$) is limited to 27½ percent of the gross wall area.

It can be seen that various combinations of glass and U_w values can be selected to comply with a designated U_{ow}.

CHAPTER 7 — COOLING DESIGN

7.1 Design Temperatures and Temperature Differences

For buildings that are cooled, an indoor temperature, t_i, of 78°F for habitable spaces is required for determining compliance with the ASHRAE Standard. Outdoor design temperatures are listed in Table 8. The Standard permits the use of 2½ percentile values. This percentile represents the percent of total hours (based on the month of July for Canadian locations and on the months of June through September for all other locations) that the outdoor temperature equalled or exceeded the listed value.

The hourly heat gain through both opaque and glass areas is calculated using the combined effects of solar radiation and outdoor air temperature, t_o. However, the procedure to calculate heat gains through opaque areas is different than through glass.

Heat gain through opaque areas is calculated in one step using an equivalent temperature difference, TD_{eq}. Realistic values for solar radiant temperature, air temperature, mass, insulation, and color were considered. TD_{eqw} is given in Fig. 5 for various wall weights. The equivalent temperature difference for roofs, TD_{eqr}, is given in Fig. 6 for various *U/TC* ratios.

Heat gain through glass is a function of both conduction caused by the temperature difference on each side of the glass, and solar gain. Calculation of solar gain is discussed in Section 7.2.

The air-to-air temperature difference, ΔT_f, for glass is the outdoor design temperature t_o (summer) from Table 8 minus the indoor temperature, t_i, of the conditioned space, taken as 78°F.

7.2 Overall Thermal Transfer Values

The ASHRAE Standard requires that the glass and opaque area be selected to limit the overall thermal transfer value ($OTTV_w$) for the above grade walls of the building. The value changes depending on latitude, and is specified by the governing code.

Below grade walls are not considered in the calculation of $OTTV_w$. The overall thermal transfer value for roofs ($OTTV_r$) is required by the ASHRAE Standard to be less than or equal to 8.5 Btu/(hr) (ft²).

The $OTTV_w$ (walls) and $OTTV_r$ (roofs) are calculated using the equations from the ASHRAE Standard [see Eqs. (5) and (6) below].

The first term in these equations reflects heat gain through opaque areas. The TD_{eqw} and TD_{eqr} values are given in Figs. 5 and 6. The second term in these equations reflects conduction heat gain through glass as a result of the air-to-air temperature difference, ΔT_f and ΔT_s, as explained in Section 7.1. The third term in the equations gives the average solar heat gain through glass.

Solar factors (*SF*) are given in Fig. 7. Shading coefficients (*SC*) are determined by the designer using guidelines in the ASHRAE Handbook or from manufacturers' literature and range from 1.00 for ⅛ in. clear glass to 0.53 for ½ in. heat absorbing glass.

$$OTTV_w = \frac{(U_w A_w TD_{eqw}) + (U_f A_f \Delta T_f) + (SF\ \ SC\ \ A_f)}{A_{ow}} \qquad (5)$$

$$OTTV_r = \frac{(U_r A_r TD_{eqr}) + (U_s A_s \Delta T_s) + (138\, SC_s A_s)}{A_{or}} \qquad (6)$$

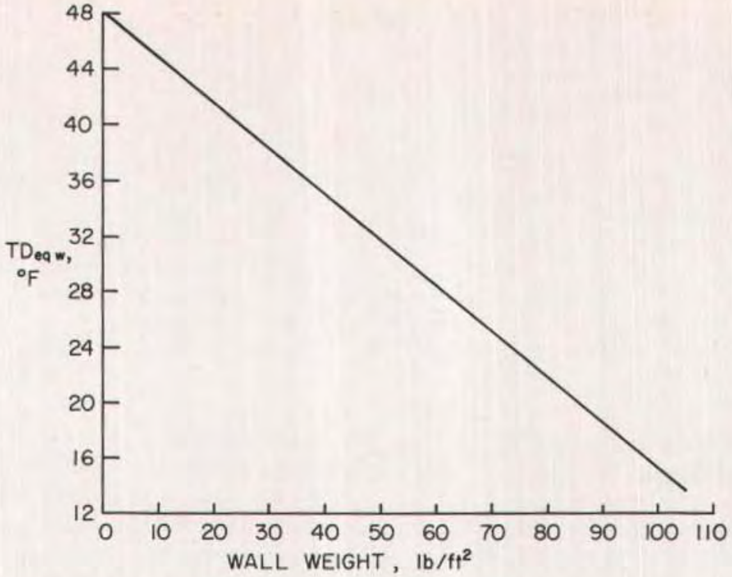


Fig. 5. Equivalent temperature difference for walls.

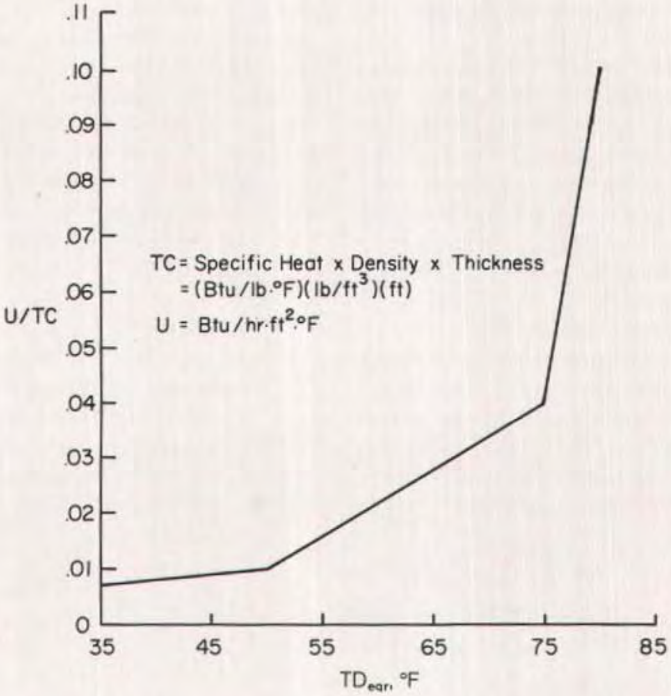


Fig. 6. Equivalent temperature difference for roofs.

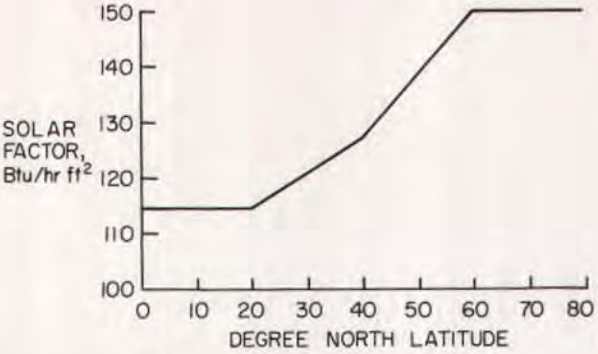


Fig. 7 Solar Factor (SF) values for various north latitudes.

7.3 Trade-off Considerations, Opaque vs. Glass

Once the limiting value for *OTTV* is determined, the designer is free to proportion opaque and glazed areas so that the heat gain through the gross area does not exceed the limit.

It is important to note that the ASHRAE Standard requires that the more stringent of heating or cooling criteria govern. In most cases the heating criteria govern.

When calculating $OTTV_w$, any combination of opaque areas and glass areas may be considered. When there are many alternatives, Eqs. (5) and (6) can be cumbersome to use. To simplify the problem of selecting the optimum combination of U_w, A_w, TD_{eqw}, U_f, A_f, and *SC*, design aid charts have been developed[5] using the equation for walls as given in the ASHRAE Standard.

Fig. 8 is an example of one of 60 charts developed. It is for a heavy wall ($TD_{eqw} = 23$) at 30 deg north latitude where criteria limit the $OTTV_w$ to 30.7 Btu/(hr) (ft^2). For 30 deg north latitude, *SF* is determined from Fig. 7 as 121 Btu/(hr) (ft^2). It is important to note that this particular chart is for double glass, $U_f = 0.61$.

As an example, if ΔT_f is 10°F, the glass U_f value is 0.61, and the wall U_w value is 0.18, then the double glass allowed (see Fig. 8) is approximately 27 percent for shading coefficient (*SC*) of 0.80. This value should be checked against the allowed heat loss as governed by the heating criteria, since most codes require that designs meet the more stringent conditions.

For roofs, charts have not been developed to select the percentage of skylights, therefore Eq. (6) is used. For example, assume ΔT_s is 15°F and $U_s = 0.61$, $SC = 1.0$, and $U_r = 0.10$. Also, assume the roof is 5 in. thick normal weight concrete with a specific heat of 0.19. The required $OTTV_r$ is 8.5 Btu/(hr) (ft^2). Substituting into the *TC* equation of Fig. 6:

$TC = (5/12)\,(145)\,(0.19) = 11.48$

and $U/TC = 0.10/11.48 = 0.0087$. Enter Fig. 6 with this value and read $TD_{eqr} = 43$°F. Determine the percentage of skylights allowed by solving Eq. (6) for percent A_s, which is $(A_s/A_{or})\,(100)$, and substitute appropriate values:

$$\text{Percent}\,A_s = \frac{(8.5 - TD_{eqr}U_r)\,(100)}{(138)\,SC_s + U_s\,\Delta T_s - TD_{eqr}U_r} \qquad (7)$$

$$= \frac{[8.5 - (43)\,(0.10)]\,(100)}{(138)\,(1.0) + (0.61)\,(15) - (43)\,(0.10)} = 2.9\ \text{percent}$$

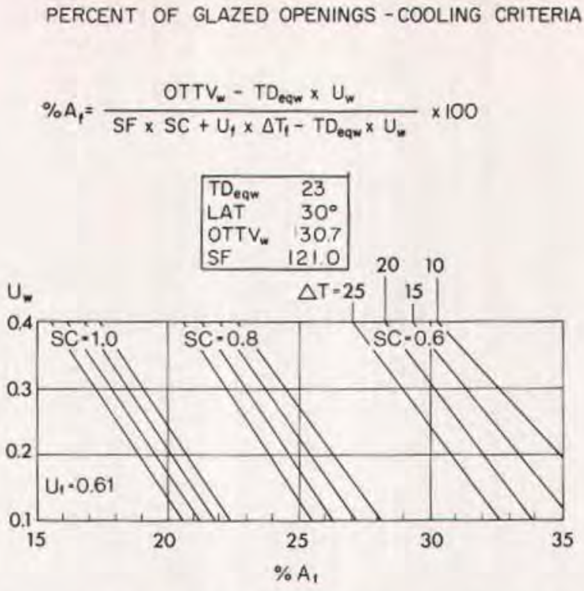


Fig. 8. Example of a wall-glass cooling design chart for double glass.

CHAPTER 8 — THERMAL STORAGE EFFECTS

For some time it has been known that walls and roofs of concrete and other massive materials react differently than lightweight materials to temperature variations. This is because heavy materials have greater heat storage capacity than lightweight building materials. Analytical and experimental investigations[6-22] have shown that the use of heavy materials in buildings has the effect of reducing heating and cooling loads.

The ASHRAE Standard considers thermal storage effects for cooling through the TD_{eq} calculation discussed in Chapter 7. However, a procedure to account for thermal storage effects for heating are not explicitly stated. The performance approach permitted by the ASHRAE Standard is a way to account for the benefits of mass when satisfying the heating criteria. This approach was used to develop design aids for concrete walls and roofs.

8.1 Reduction in Peak Heating and Cooling Loads

Computers now make it possible to account for mass effects with hour by hour calculations. As an example of the differences in behavior between light and heavy materials, consider the results of hour by hour computer analyses[18] for various building components shown in Figs. 9, 10, 11, and 12.

Fig. 9 compares the heating loads through three walls having identical steady state U values of 0.091, but differing in wall mass and constructions. The concrete wall construction consisted of a layer of insulation sandwiched between inner and outer wythes of 2 in. concrete and weighed 48.3 psf. The metal wall, weighing 3.3 psf, had insulation sandwiched between an exterior metal panel and ½ in. drywall on the inside. The wood frame wall, weighing 7.0 psf, had wood siding

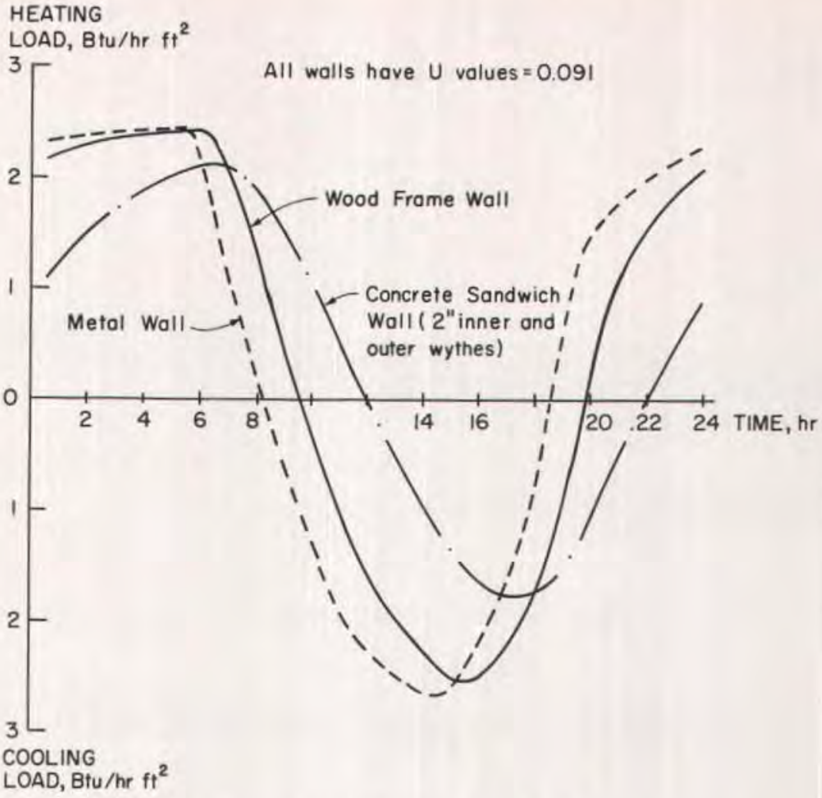


Fig. 9. Heating and cooling load comparison for walls.

on the outside, insulation between 2x4 studs, and ½ in. drywall on the inside. These walls were exposed to identical simulated outside temperatures that represented a typical spring day in a moderate climate. The massive concrete wall had lower peak loads by about 13 percent for heating and 30 percent for cooling than the less massive walls.

Concrete walls of various thicknesses having identical *U* values of 0.091 that were exposed to the same simulated outside temperatures as before, are compared in Fig. 10. The walls had a layer of insulation sandwiched between concrete on the outside and ½-in. drywall on the inside. The insulation thickness was varied to obtain equivalent wall *U* values. The comparison shows that the more massive the wall the lower the peak loads and the more the peaks were delayed.

Fig. 11 compares sandwich concrete walls having an outer wythe of 2 in. concrete, various thicknesses of insulation in the middle, and various thicknesses of concrete inner wythes. All walls had *U* values of 0.091 and were exposed to the same simulated outside temperatures as before. The comparison shows that by increasing the thickness of the inner concrete wythe, peak loads were reduced and occurrence of these loads was delayed. Comparing the wall having a 2 in. inner wythe to the one having a 8 in. inner wythe, peak loads were reduced by 58 percent for heating and 78 percent for cooling. These lower peak

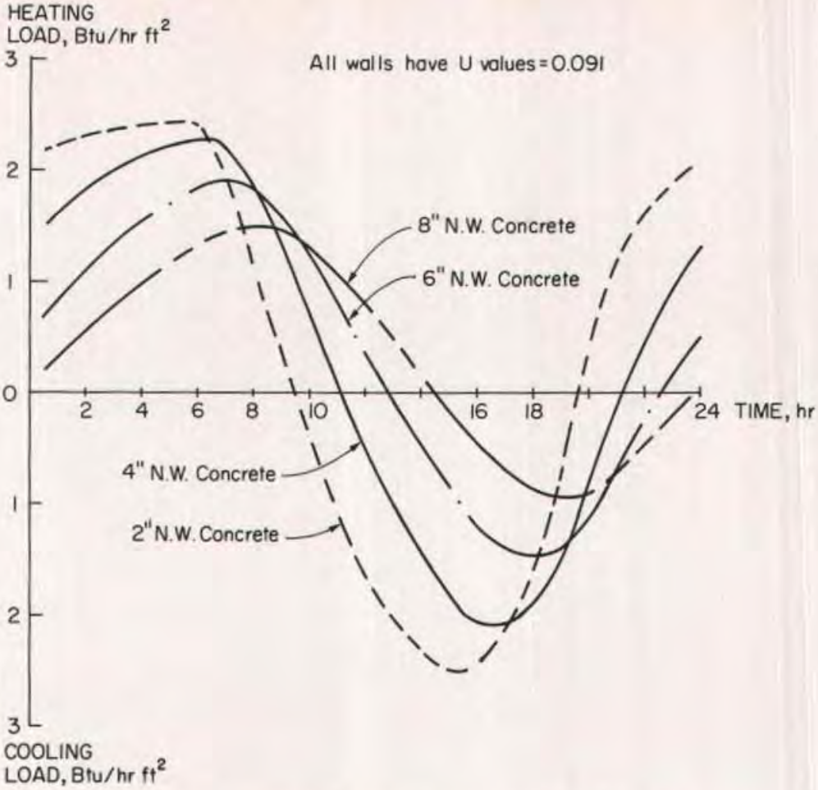


Fig. 10. Heating and cooling load comparison for concrete walls.

loads were delayed by 4.0 hours for heating and 3.5 hours for cooling.

A metal roof is compared to a concrete roof in Fig. 12. Both roof systems had a built-up roof on top of rigid board insulation on the outside with acoustical tile on the inside. The concrete roof weighed 48.3 psf and the metal roof, 1.5 psf. The roofs had identical *U* values of 0.10 and were exposed to the same simulated outside temperatures. The comparison shows that the more massive concrete roof had lower peak loads by 68 percent for heating and by 94 percent for cooling, and the peaks were delayed by about 1.8 hours for heating and about 4.0 hours for cooling.

Since the massive components delay the effect of outside temperatures on heating and cooling requirements, savings can accrue when lower off-peak pricing is in effect. Significant reduction in peak loads can also result in savings since many electric utilities have peak load charges.

8.2 Equivalent *R* Values for Concrete Walls and Roofs

Other studies of entire buildings[6-11,15,16,22] have shown that concrete buildings have lower annual heating and cooling loads than lightweight buildings for a given insulation level. This superior behavior of concrete buildings can be used to advantage to reduce the amount of insulation as compared to lightweight buildings. This is

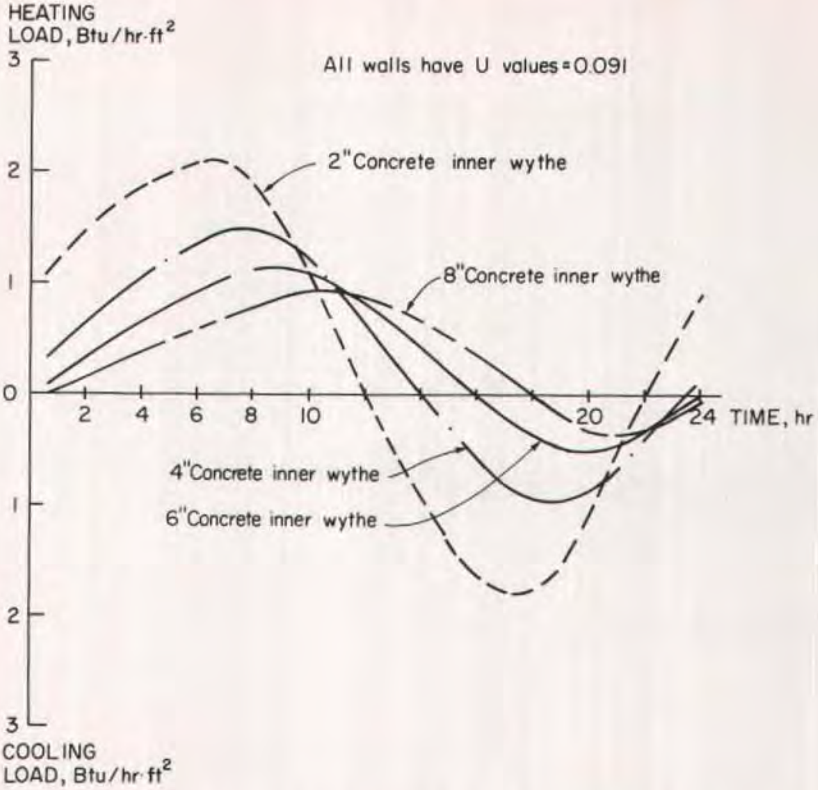


Fig. 11. Heating and cooling load comparison for concrete sandwich walls.

the performance approach to energy code compliance described earlier.

Based on this approach, the amount of insulation required in concrete walls and roofs of commercial buildings to yield energy consumption equivalent to low mass buildings was determined. These lower *R* values are the equivalent *R* values shown in Figs. 13 through 21.

Figs. 13 through 21 may be applied to buildings having similar amounts of internal heat gains from lights, equipment, people, and solar gains as those for which the analysis was conducted. The peak values for occupancy and lighting internal gains were 384 and 205 KBtu/hr, respectively. The hourly average for occupancy and lighting internal gains were 104 and 85 KBtu/hr. No other internal gains were considered. See References 6 and 7 for further details.

The building parameters chosen were generally conservative so the results can be applied to most commercial buildings with the possible exception of warehouses. The design aids can be used in conjunction with the heating analysis discussed in Chapter 6. The cooling analysis discussed in Chapter 7 must be carried out without using Figs. 13 through 21. Fig. 13 can be used for roofs weighing 52 psf or greater and having exposed ceilings.

To determine the equivalent *R* value of the massive roof assembly simply enter Fig. 13 at the heating degree day value for the building location. Move

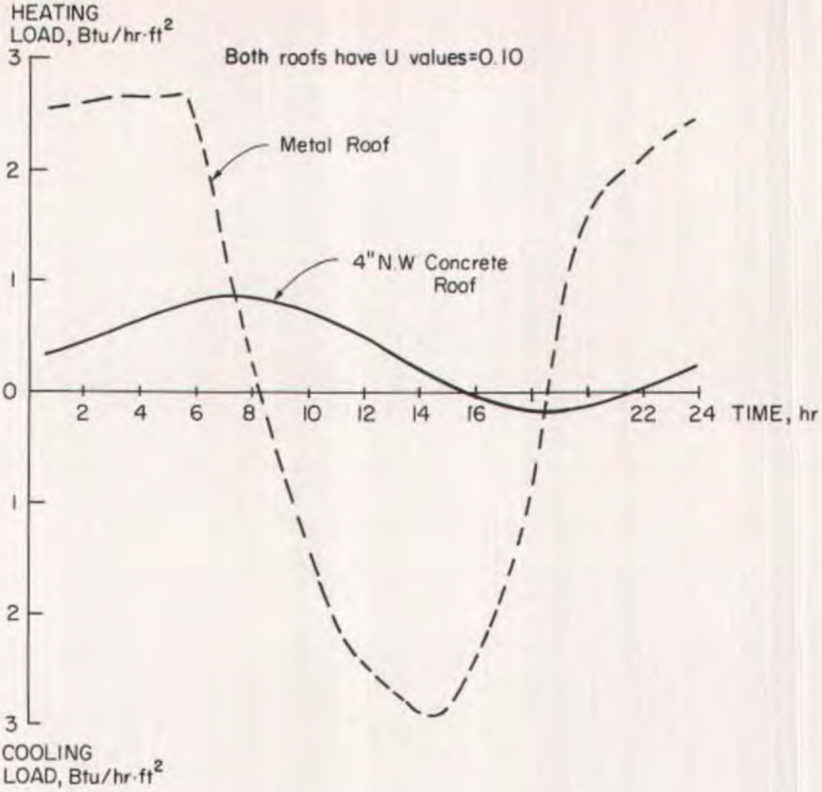


Fig. 12. Heating and cooling load comparison for roofs.

vertically to the equivalent R value line and then horizontally to read the equivalent R value for the massive roof. This R value is the insulation level that is equivalent to a lightweight roof system satisfying the ASHRAE Standard heating requirements.

Figs. 14 through 21 present the equivalent wall R values for various wall thicknesses. Two locations of insulation are considered: on the exterior of the concrete walls and on the interior of the concrete walls.

To use the design aid, choose the graph for the thickness of the wall being considered. For sandwich type construction use the design aid for exterior insulation and the thickness of the inner concrete wythe.

Enter the graph at the appropriate heating degree day total. Move vertically to the curve for the R value that satisfies the ASHRAE requirement for a lightweight wall. Interpolate between R value curves if necessary. Move horizontally and read the equivalent R value of the concrete wall. This is the R value for the concrete wall that satisfies the ASHRAE Standard heating requirements.

8.3 Design Example Using Equivalent *R* Values

As an example, consider a single-story mall building located in Chicago, Illinois, having a double-tee concrete roof with no skylights and sandwich walls

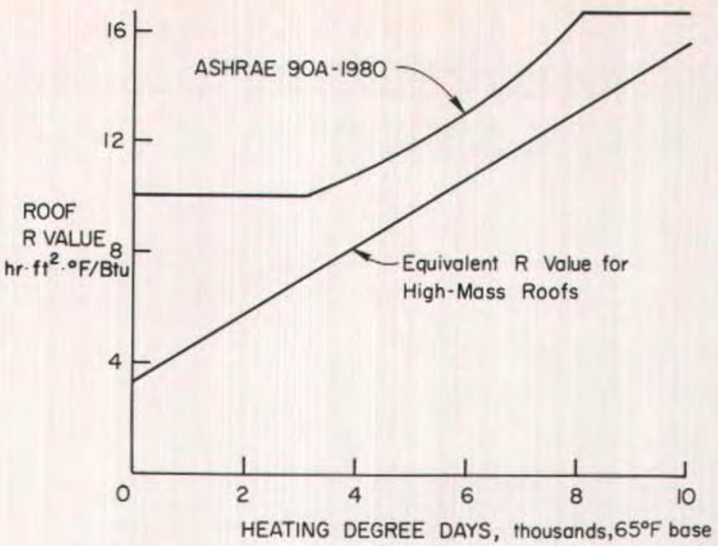


Fig. 13. Design aid for selecting equivalent *R* values for roofs.

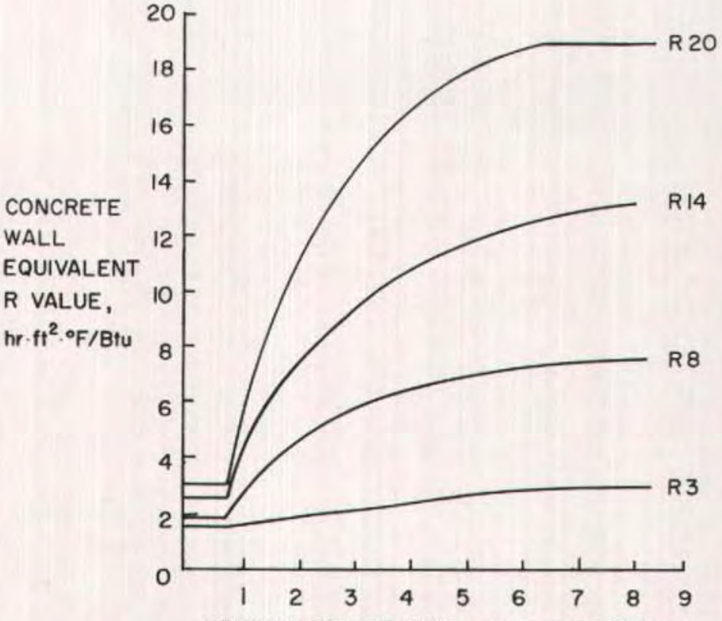


Fig. 14. Equivalent *R* values for 2 in. concrete walls with interior insulation.

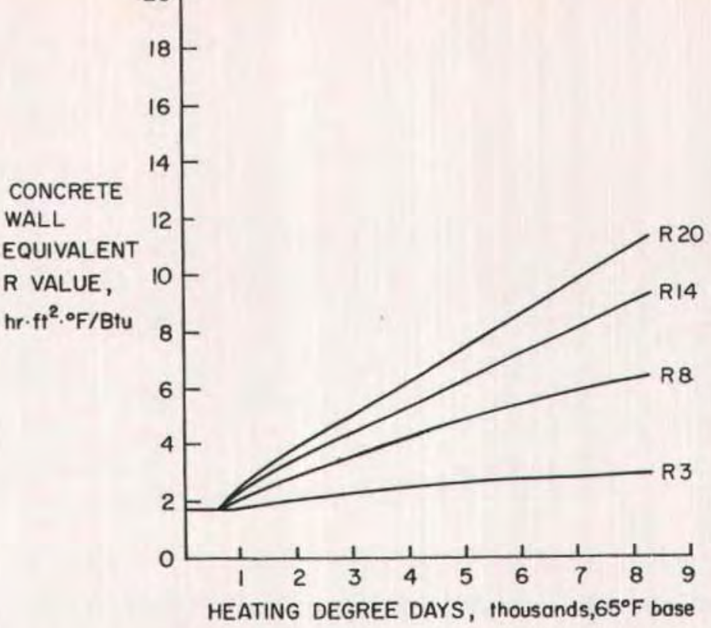


Fig. 15. Equivalent *R* values for 2 in. concrete walls with exterior insulation.

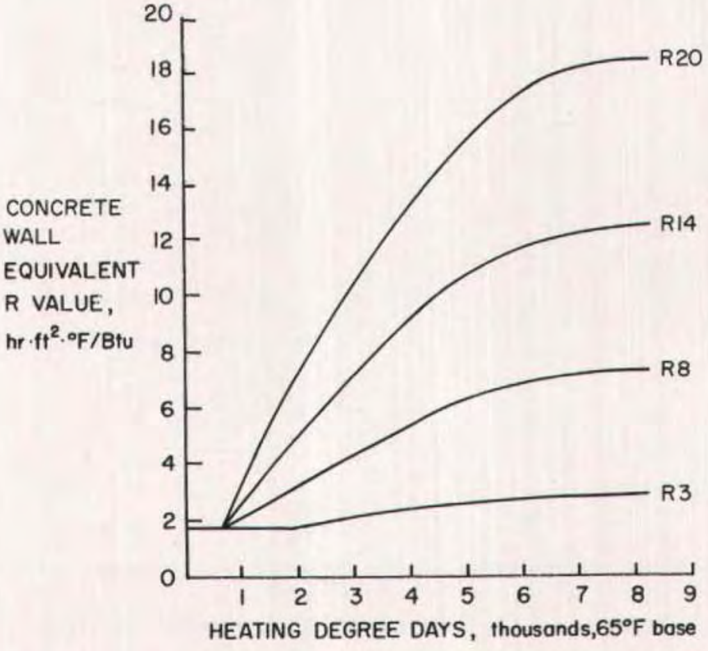


Fig. 16. Equivalent *R* values for 4 in. concrete walls with interior insulation.

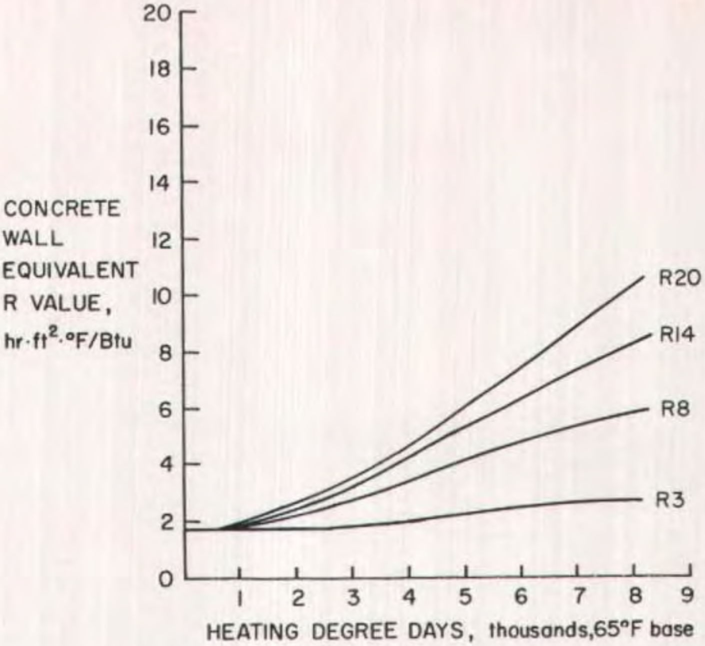


Fig. 17. Equivalent *R* values for 4 in. concrete walls with exterior insulation.

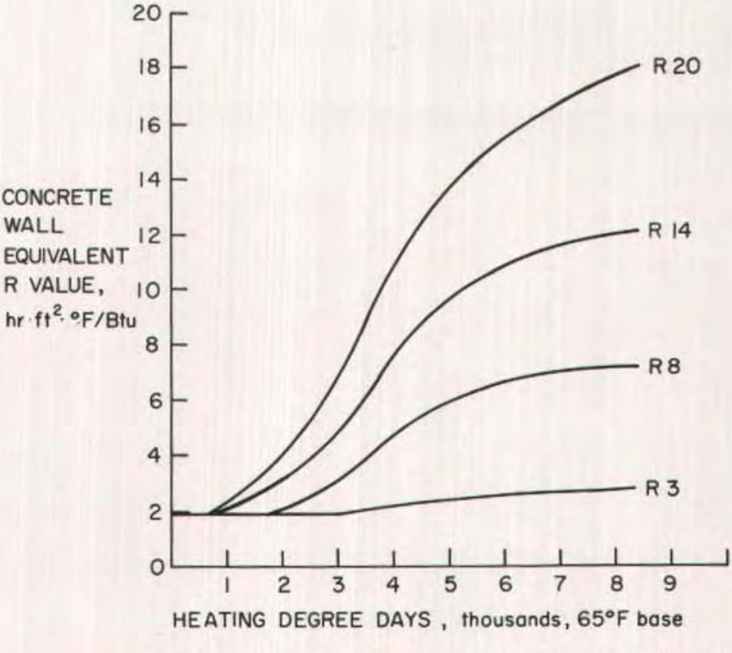


Fig. 18. Equivalent *R* values for 6 in. concrete walls with exterior insulation.

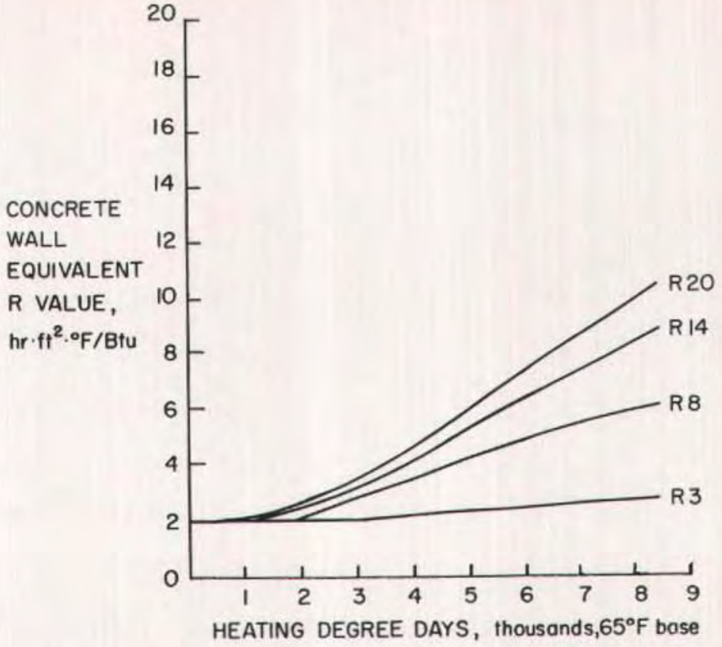


Fig. 19. Equivalent *R* values for 6 in. concrete walls with exterior insulation.

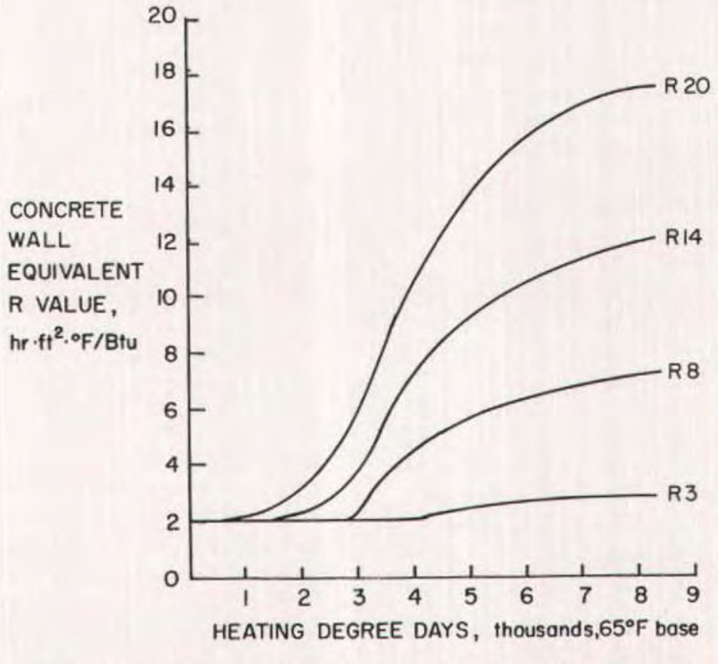


Fig. 20. Equivalent *R* values for 8 in. concrete walls with interior insulation.

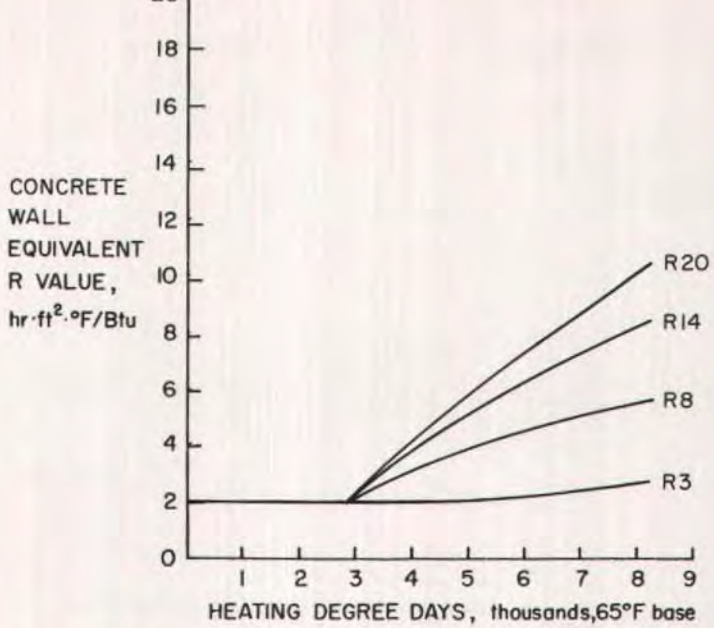


Fig. 21. Equivalent R values for 8 in. concrete walls with exterior insulation.

having an inner wythe of 4 in. concrete insulation, and 2 in. concrete outer wythe. Other parameters needed to check the heating criteria are as follows:

Heating degree days = 6160 (Table 8)
U_o maximum permitted for walls = 0.27
U_o maximum for roof = 0.075
$A_{ow} = 9000\ \text{ft}^2$
$A_w = 7546\ \text{ft}^2$
$U_w = 0.125$ (R8) for a lightweight wall
$A_f = 1334\ \text{ft}^2$, $U_f = 1.1$
$A_d = 120\ \text{ft}^2$, $U_d = 0.16$
$A_r = A_{or} = 20{,}000\ \text{ft}^2$
$U_r = 0.075$ (R13.3) for a lightweight roof

The U values for the lightweight walls and roof satisfy the ASHRAE requirement for heating. This can be shown by substituting appropriate values into Eqs. (2) and (3).

For walls:

$$U_{ow} = \frac{U_w A_w + U_f A_f + U_d A_d}{A_{ow}}$$

$$U_{ow} = \frac{0.125\,(7546) + 1.1\,(1334) + 0.16\,(120)}{9000}$$

$$= 0.27 \leq U_o \text{ maximum permitted for walls}$$

For the roof:

$$U_{or} = \frac{U_r A_r + U_s A_s}{A_{or}}$$

$$= \frac{0.075\,(20{,}000) + 0}{20{,}000}$$

$$= 0.075 \leq U_o \text{ maximum permitted for roof}$$

Determine equivalent R values for the concrete walls and roof. For the roof, enter Fig. 13 at a heating degree day value of 6160. Move vertically to the equivalent R value curve and read an equivalent R value of 10.8 ($U_r = 0.093$) on the vertical scale. This compares to an R value for the low mass roof of R13.3 ($U_r = 0.075$).

For the walls, enter Fig. 17 at a heating degree day value of 6160. Move vertically to the R8 curve and read the equivalent R value of 4.9 ($U_w = 0.204$) on the vertical scale.

Once the equivalent R value is determined for the concrete walls and roof, the components should be checked for compliance with the cooling criteria. For the walls, additional parameters are determined as follows:

For this sandwich wall weighing 72.5 psf, from Fig. 5, $TD_{eqw} = 24.3$; for the doors weighing 5 psf, from Fig. 5 $TD_{eqw} = 46.3$.

For the Chicago (Midway Airport) location, using Table 8, the summer outdoor design temperature is 91°F. According to the ASHRAE Standard the summer indoor temperature is 78°F. Thus, $\Delta T_f = 91° - 78° = 13°\text{F}$.

From glass manufacturer's data $SC = 0.94$.

From Table 8, the latitude = 41.83 deg. Using this value in Fig. 7, $SF = 129$.

Expanding the first term of Eq. (5) to include the doors and substituting appropriate values:

$$OTTV_w = \frac{(U_w A_w TD_{eqw}) + U_f A_f \Delta T_f) + (SF\ SC\ A_f)}{A_{ow}}$$

$$\begin{aligned} OTTV_w = {} & [0.204\,(7546)\,(24.3) \\ & + 0.16\,(120)\,(46.3) \\ & + 1.1\,(1334)\,(13) \\ & + 129\,(0.94)\,(1334)]/9000 \\ = {} & 24.4 < 34 \text{ maximum permitted by the ASHRAE Standard} \end{aligned}$$

To check for the roof compliance with the cooling criteria, consider only the 2 in. thick slab to be conservative. Additional parameters for the roof are determined as follows:

TC = specific heat × density × thickness

$= 0.19\,(145)\,(2)/12 = 4.59$

$U_r/TC = 0.093/4.59 = 0.020$

Using Fig. 6, $TD_{eqr} = 58.5°\text{F}$. Substituting into Eq. (6):

$$\begin{aligned} OTTV_r &= \frac{U_r A_r TD_{eqr} + U_s A_s \Delta T_s + 138\, SC_s A_s}{A_{or}} \\ &= \frac{0.093\,(20{,}000)\,(58.5) + 0 + 0}{20{,}000} \\ &= 5.44 < 8.5 \text{ maximum permitted by the ASHRAE Standard.} \end{aligned}$$

Since the cooling criteria do not govern, the equivalent R values can be used, and the reduced amounts of wall and roof insulation are satisfactory.

CHAPTER 9 — BUILDING ENVELOPE PERFORMANCE AND TRADE-OFF CONSIDERATIONS

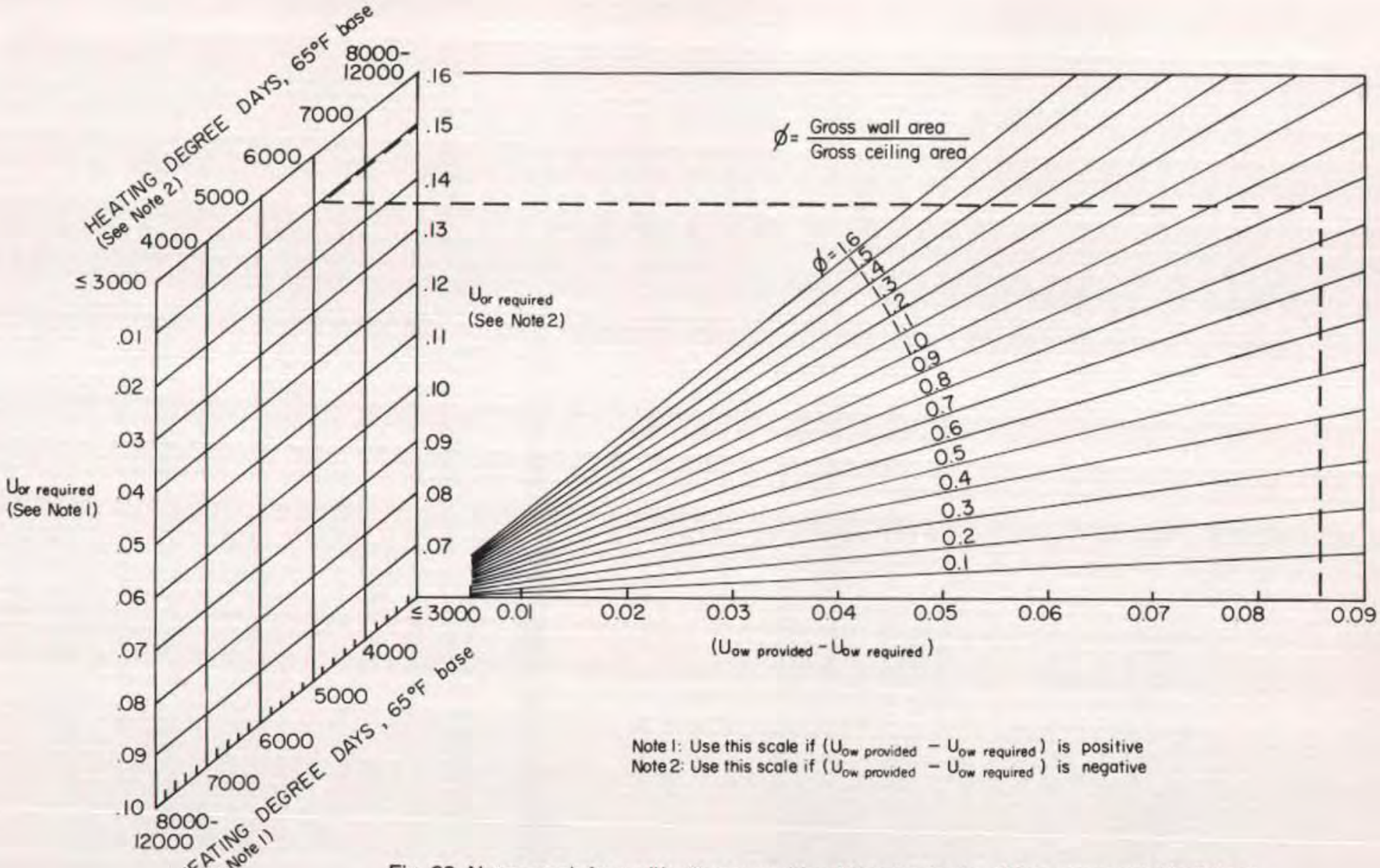
The ASHRAE Standard and some codes permit component trade-offs. That is, the stated U_o value of any one assembly, such as roof/ceiling, wall, or floor, may be increased and the U_o value for other components decreased, provided the overall heat transmission for the entire building envelope does not exceed the total allowed.

For buildings where the floors are not exposed to the outdoors, the allowed overall envelope hourly heat loss is:

$$Q = [(U_{ow} A_{ow}) + (U_{or} A_{or})]\Delta t \qquad (8)$$

Once Q has been determined based on U_o values specified, the U values in the equation can be altered from those given in the code or standard providing the value of Q is not exceeded.

Fig. 22 presents a nomograph to facilitate the use of the trade-off provisions of the ASHRAE Standard for commercial buildings. Given the ratio of the gross wall area to gross roof/ceiling area, the U_{ow} provided by design, the U_{ow} required by the ASHRAE Standard, and the heating degree days value, the U_{or} required by the trade-off provisions can



Note 1: Use this scale if ($U_{ow \text{ provided}} - U_{ow \text{ required}}$) is positive
Note 2: Use this scale if ($U_{ow \text{ provided}} - U_{ow \text{ required}}$) is negative

Fig. 22. Nomograph for wall/ceiling or wall/roof *U* value trade-off for commercial buildings.

be determined. Many wall insulation strategies can be quickly investigated to determine their effect on the required roof insulation level.

The trade-off concept is useful particularly for altering wall, floor, or roof criteria without exceeding the total loss allowed for the envelope. The concept also permits different U_w values on, for example, north and south exposures. Component trade-offs and trade-off of elements within components, such as opaque vs. glass presented in Chapter 7, permit considerable freedom in building envelope design. Also, with fewer prescriptive requirements, more efficient building designs are possible.

9.1 Design Example

Consider a building three stories high (25 ft) having plan dimensions of 80 x 200 ft located in Chicago, Illinois, near Midway Airport. From Table 8 this location has 6160 heating degree days. U_o values required by the ASHRAE Standard are 0.27 for walls, and 0.075 for roofs. The ground floor is on grade with edges insulated to meet requirements. Also, assume there are windows only on one 200 ft side of the building and that the U_{ow1} for that side has been calculated as 0.30. For the other three windowless sides, $U_{ow2} = 0.12$.

Calculate the average U_{ow} provided for the walls:

$$U_{ow} = \frac{U_{ow1}A_{ow1} + U_{ow2}A_{ow2}}{A_{ow}}$$

$$= \frac{0.30\,(200\text{x}25) + 0.12\,(360\text{x}25)}{(560\text{x}25)}$$

$$= 0.184\ \text{Btu/(hr)}\,(\text{ft}^2)^\circ\text{F}$$

To use the design aid presented in Fig. 22, first calculate:

$$\phi = \text{wall area/roof area}$$
$$= 560\text{x}25/80\text{x}200 = 0.875$$

Then compute:

$$U_{ow}\,(\text{provided}) - U_{ow}\,(\text{required})$$
$$= 0.184 - 0.27 = -0.086$$

Enter Fig. 22 at U_{ow} (provided) $- U_{ow}$ (required) $= 0.086$. Move vertically to the interpolated location of $\phi = 0.875$. Follow the dashed lines and read the $U_{or} = 0.150$.

This revised roof design which changes U_{or} from 0.075 to 0.15 means that the R value is reduced by $13.33 - 6.67 = 6.66$, representing 1½ to 1¾ in. less insulation. Thus, the trade-off concept is an important tool when considering and comparing total overall heat losses through envelopes.

CHAPTER 10 — CONDENSATION CONTROL

Moisture which condenses on the interior of a building is unsightly and can cause damage to the building or its contents. Even more undesirable is the condensation of moisture within a building wall or ceiling assembly where it is not readily noticed until damage has occurred.

Note that all air in buildings contains water vapor with warm air carrying more moisture than cold air.

In many buildings moisture is added to the air by industrial processes, cooking, laundering, or humidifiers. If the inside surface temperature of a wall, floor, or ceiling is too cold the air contacting this surface will be cooled below its dew point temperature and leave its excess water on that surface. Condensation occurs on the surface with the lowest temperature.

Once condensation occurs, the relative humidity of the interior space of a building cannot be increased since any additonal water vapor will simply condense on the cold surface. In effect, then, the inside temperature of an assembly limits the relative humidity which may be contained in an interior space.

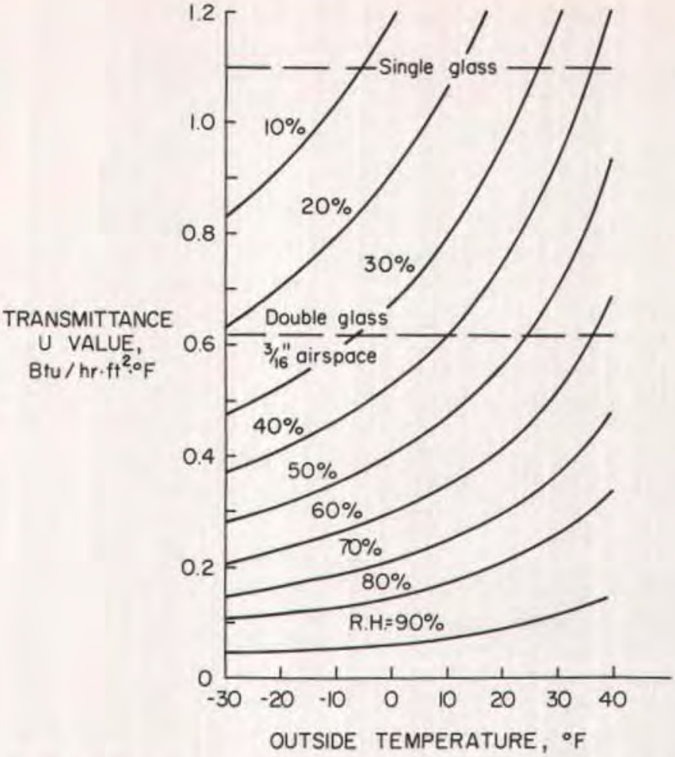


Fig. 23. Relative humidity at which visible condensation occurs on inside surfaces (inside temperature, 70°F).

10.1 Prevention of Condensation on Wall Surfaces

The *U* value of a wall must be such that the surface temperature will not fall below the dew point temperature of the air in the room, in order to prevent condensation on the interior surface.

Fig. 23 gives *U* values for any combination of outside temperatures and inside relative humidities above which condensation will occur on the interior surfaces. For example, if a building were located in an area with an outdoor design temperature of 0°F and it was desired to maintain a relative humidity within the building of 25 percent, the wall must be designed so that all components have a *U* value less than 0.78, otherwise there will be a problem with condensation. In many designs the desire to conserve energy will dictate the use of lower *U* values than those required to avoid the condensation problem.

The degree of wall thermal resistance that must be provided to avoid condensation may be determined from the following relationship:

$$R_t = R_{fi} \ \frac{(t_i - t_o)}{(t_i - t_s)} \qquad (9)$$

Dew point temperatures to the nearest deg F for various values of t_i and relative humidity are shown in Table 9.

As an example, determine R_t when the room temperature and relative humidity to be maintained are 70°F and 40 percent, and t_o during the heating season is −10°F. From Table 9, the dew point

Table 9. Dew Point Temperatures,* deg F.

Dry bulb or room temperature °F	Relative humidity, percent									
	10	20	30	40	50	60	70	80	90	100
40	−7	6	14	19	24	28	31	34	37	40
45	−3	9	18	23	28	32	36	39	42	45
50	−1	13	21	27	32	37	41	44	47	50
55	5	17	26	32	37	41	45	49	52	55
60	7	21	30	36	42	46	50	54	57	60
65	11	24	33	40	46	51	55	59	62	65
70	14	27	38	45	51	56	60	63	67	70
75	17	32	42	49	55	60	64	69	72	75
80	21	36	46	54	60	65	69	73	77	80
85	23	40	50	58	64	70	74	78	82	85
90	27	44	55	63	69	74	79	83	85	90

*Temperatures are based on barometric pressure of 29.92 in. Hg.

temperature, t_s, is 45°F and from Table 1, $R_{fi} = 0.68$.

$$R_t = \frac{0.68\,[70 - (-10)]}{[70 - 45]} = 2.18$$

10.2 Prevention of Condensation Within Wall Construction

Water vapor in air behaves as a gas and will diffuse through building materials at rates which depend upon vapor permeabilities of materials to water vapor and vapor pressure differentials. The colder the outside temperatures, the greater the pressure of the water vapor in the warm inside air to reach the cooler, drier outside air.

Also, leakage of moisture laden air into an assembly through small cracks may be a greater problem than vapor diffusion. The passage of water vapor through a material is in itself generally not harmful. It becomes of consequence when, at some point along the vapor flow path, a temperature level is encountered that is below the dew point temperature and condensation results.

Building materials have water vapor permeances from very low to very high (see Table 10). When properly used, low permeance materials keep moisture from entering a wall or roof assembly, and materials with higher permeance allow construction moisture and moisture which enters inadvertently or by design to escape.

When a material such as plaster or gypsum board has a permeance which is too high for the intended use, one or two coats of paint are frequently sufficient to lower the permeance to an acceptable level, or a vapor barrier can be used directly behind such products.

Polyethylene sheet, aluminum foil, and roofing materials are commonly used. Proprietary vapor barriers, usually combinations of foil and polyethylene or asphalt, are frequently used in freezer and cold storage construction.

Concrete is a relatively good vapor barrier. Permeance is a function of the water-cement ratio of the concrete. A low water-cement ratio, such as that used in most precast concrete members, results in concrete with low permeance.

Where climatic conditions demand insulation, a vapor barrier is generally necessary to prevent condensation. A closed cell insulation, if properly applied, will serve as its own vapor barrier. For other insulation materials a vapor barrier should be applied to the warm side of the insulation.

Table 10. Typical Permeance *(M)* and Permeability (μ) Values.*

Material	*M*, perms	μ, perm-in.
Concrete	—	3.2
Wood (sugar pine)	—	0.4-5.4
Expanded polystyrene—extruded	—	1.2
Paint—two coats		
Asphalt paint on plywood	0.4	
Enamels on smooth plaster	0.5-1.5	
Various primers plus one coat flat oil paint on plaster	1.6-3.0	
Expanded polystyrene-bead	—	2.0-5.8
Plaster on gypsum lath (with studs)	20.00	
Gypsum wallboard, 0.375 in.	50.00	
Polyethylene, 2 mil	0.16	
Polyethylene, 10 mil	0.03	
Aluminum foil, 0.35 mil	0.05	
Aluminum foil, 1 mil	0.00	
Built-up roofing (hot mopped)	0.00	
Duplex sheet, asphalt laminated aluminum foil one side	0.002†	

*ASHRAE Handbook, Chapter 21, Table 2.

†Dry cup.

Table 11. Water Vapor Pressures at Saturation for Various Temperatures.*

Temp., deg F	*SVP*, in. Hg	Temp., deg F	*SVP*, in. Hg	Temp., deg F	*SVP*, in. Hg	Temp., deg F	*SVP*, in. Hg
−30	0.007	+17	0.089	+38	0.229	+59	0.503
−20	0.0126	18	0.093	39	0.238	60	0.522
−10	0.022	19	0.098	40	0.248	61	0.540
−5	0.029	20	0.103	41	0.257	62	0.560
0	0.038	21	0.108	42	0.268	63	0.580
+1	0.040	22	0.113	43	0.278	64	0.601
2	0.042	23	0.119	44	0.289	65	0.622
3	0.044	24	0.124	45	0.300	66	0.644
4	0.046	25	0.130	46	0.312	67	0.667
5	0.049	26	0.137	47	0.324	68	0.690
6	0.051	27	0.143	48	0.336	69	0.714
7	0.054	28	0.150	49	0.349	70	0.739
8	0.057	29	0.157	50	0.362	71	0.765
9	0.060	30	0.165	51	0.376	72	0.791
10	0.063	31	0.172	52	0.390	73	0.818
11	0.066	32	0.180	53	0.405	74	0.846
12	0.069	33	0.188	54	0.420	75	0.875
13	0.073	34	0.195	55	0.436	76	0.905
14	0.077	34	0.203	56	0.452	77	0.935
15	0.081	36	0.212	57	0.468	78	0.967
16	0.085	37	0.220	58	0.486	79	0.999
						80	1.030

*Values listed are based on a barometric pressure of 29.92 in. Hg.
1 in. Hg (0.491) = 1 psi
Actual VP = *SVP* × *RH*

10.3 Design Example

The wall construction shown in Fig. 24 will be investigated for possible development of water vapor condensation. In roofs, the condensation problem is much the same as in walls.

Step 1 — The overall vapor pressure differential through the wall section may be determined from saturated vapor pressures (SVP) listed in Table 11 and the assumed temperatures and relative humidities shown below.

This vapor differential must be distributed among the components of the wall section according to their respective vapor transfer resistances.

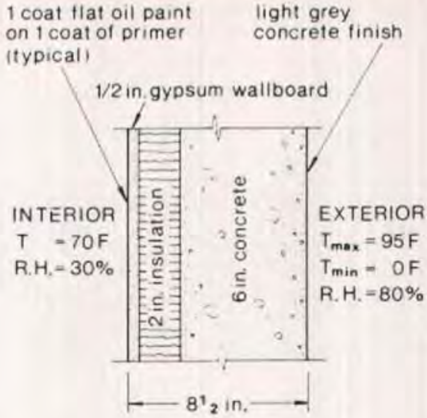


Fig. 24. Representative exterior wall panel.

	RH		SVP	
Room vapor pressure:	0.30	×	0.739	= 0.22 in. Hg
Outdoor vapor pressure:	0.80	×	0.038	= 0.03 in. Hg
Overall vapor pressure differential:				= 0.19 in. Hg

Step 2 — Using the table below, determine the heat flow properties of the wall section from data listed in Tables 1 through 4:

Individual heat flow resistances	Heat flow resistance R
Interior surface, R_{fi}	0.68
½ in. gypsum wallboard	0.45
2 in. expanded polystyrene insulation	8.00
6 in. normal weight concrete, 145 pcf	0.45
Outside surface, R_{fo}, 15 mph	0.17
Total resistance, R_t	9.75
U	0.10

Step 3 — The individual heat flow resistances involved in the wall section together with the sum of these resistances are necessary to establish the temperature gradient through the wall section and the location of possible vapor condensation points.

The total temperature drop through the wall in this case is 70°F and can be distributed among the individual components in proportion to their resistances. The interface temperatures can then be determined and the temperature gradient plotted as shown in Fig. 25 with the wall section drawn to physical scale.

Individual resistances, R	Temperature drop, deg F
Inside air to inside surface	(0.68/9.75)70 = 4.88
½ in. gypsum wallboard	(0.45/9.75)70 = 3.23
2 in. expanded polystyrene insulation	(8.00/9.75)70 = 57.44
6 in. normal weight concrete, 145 pcf	(0.45/9.75)70 = 3.23
Outside surface to outside air (15 mph wind)	(0.17/9.75)70 = 1.22
Total	= 70

As an alternate procedure to the arithmetic method for determining the temperature gradient under steady-state series heat flow, a graphical method may be used. In the graphical method, a cross section of the wall is drawn wherein the thickness shown for each component is proportional to its thermal resistance. Then, by plotting a temperature scale on the cross section and a straight line joining the inside and outside temperature (representing the temperature gradient), the temperature at any point in the construction can be read.

The assumed steady-state conditions are seldom reached owing to fluctuations in the temperatures to which the envelope is exposed and to the heat storage capacities of the concrete (see Chapter 8). Unless simplified procedures are followed, the solution of practical cases of heat flow through walls and roofs can become very complicated.

Some inaccuracies may be introduced by these simplifications, but the results obtained provide a valuable guide for design of walls and roofs. The determination of the interface temperatures to a precision greater than 1°F or 2°F is, however, unwarranted. Paths of high conductivity, called thermal bridges, do produce inaccuracies that often require special consideration (see Section 10.4).

The temperature existing at any point in a wall under any given exterior and interior temperature condition is of great significance in designing problem-free building enclosures. An ability to calculate the thermal gradient permits the designer to forecast the magnitude of the movements caused by external temperature changes; to predict the location of condensation and freezing planes in the wall; and to assess the suitability of any construction.

The temperature gradient will not, in itself, give the designer all the information he requires to select and assemble building components, but it is an essential first step.

The selection of appropriate outside air temperatures requires considerable judgment. The effects of heat storage in materials must be recognized, as must the fact that wall or roof surface temperatures can be higher than air temperatures because of solar radiation, and colder than air temperatures because of clear sky radiation. These temperature modifications vary with the color, texture, thickness, weight, and orientation of the surface materials and with the intensity of the radiation.

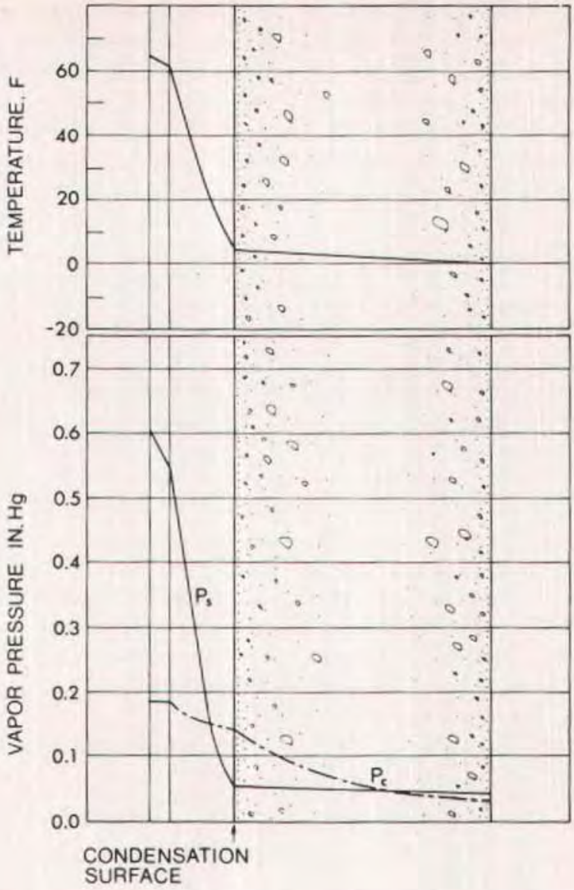


Fig. 25. Thermal and water vapor gradients across representative exterior wall for extreme winter conditions.

Step 4 — From Table 11 the saturated vapor pressures at various surfaces and interfaces within the wall section may be obtained from temperatures at these locations, using the previously calculated temperature drops:

Location (see Fig. 24)	Temp., deg F	SVP in. Hg
Room air	= 70	0.739
Inside surface	70 − 4.88 = 65.12	0.625
Interface wallboard and insulation	65.12 − 3.23 = 61.89	0.558
Interface insulation and concrete	61.89 − 57.44 = 4.45	0.047
Outside surface	4.45 − 3.23 = 1.22	0.040
Outside air	= 0	0.038

These saturated vapor pressures are plotted in Fig. 25 to form the SVP gradient, P_s, through the wall section.

Step 5 — To check the location where condensation is likely to take place, the vapor pressure gradient necessary for vapor transfer continuity, P_c, is plotted as shown in Fig. 25. The vapor pressure gradient, P_c, is obtained by a calculation procedure similar to that used to determine the temperature gradient, described in Step 3.

The value is based on the total vapor pressure drop (0.22 − 0.03 = 0.19 in. Hg) and the respective vapor transfer resistances of the different components of the section from Table 10, as shown below.

The actual vapor pressure drop, P_a, from the inside surface of the wall to any material interface may be taken as the difference between the vapor pressure at the inside wall surface and the saturated vapor pressure at the material interface.

Continuous vapor flow conditions are preserved provided this vapor pressure does not exceed the saturation vapor pressure. If P_c does cross P_s, condensation will occur, usually at the nearest outer interface or surface. For discontinuous vapor flow, the vapor flow to and away from the condensation surface must be recalculated. The difference will be equal to the condensation rate. The vapor flow to or from a point is equal to the actual vapor pressure difference divided by the vapor resistance to or from that point.

To ensure that condensation does not take place, the fundamental requirement is that, at all points through the thickness of the building enclosure, the vapor pressure set by the condition of continuous flow (P_c) must be less than the maximum permissible vapor pressure set by the saturation vapor pressure (P_s) corresponding to the temperature at that point.

Wall components	Vapor transfer resistance, $1/M$ or t/μ in. Hg	Vapor pressure drop for continuity	Vapor pressure for continuity
Inside surface film	0	0	0.220
One coat of primer and paint	0.50	(0.50/3.06)0.19 = 0.031	0.189
½ in. gypsum wallboard	0.02	(0.02/3.06)0.19 = 0.001	0.188
2 in. insulation	0.67	(0.67/3.06)0.19 = 0.042	0.146
6 in. concrete	1.87	(1.87/3.06)0.19 = 0.116	0.030
Outside surface film	0	0	0.030
Total R =	3.06	Total drop = 0.19	

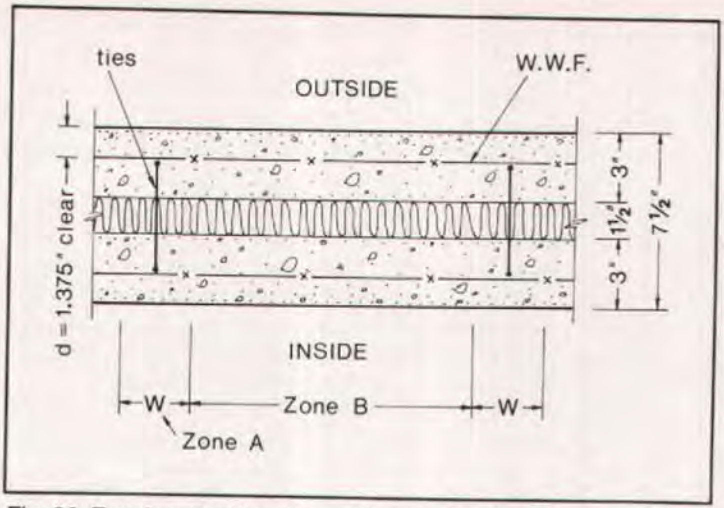


Fig. 26. Zonal separation of panel for use in calculating effect of thermal bridges.

This condition can be achieved either by changing the various vapor flow resistances to reduce the values of P_e (i.e., by adding a vapor barrier), or by changing the various thermal resistances to raise the temperature and thus the values of P_s, or by a combination of both methods.

10.4 Thermal Bridges

High conductivity metal paths through the wall or solid concrete paths through sandwich panels may lead to localized cold areas where surface condensation may occur. Because of the many variables and indeterminates, measured values and calculated values of heat flow differ. However, the zone method (explained in great detail in the ASHRAE Handbook, Chapter 23) can be used with a reasonable degree of accuracy.

With the zone method, the panel is divided into Zone A, which contains the thermal bridge, and Zone B, the remaining area where thermal bridges do not occur as shown in Fig. 26. The width of Zone A is calculated as $W = m + 2d$, where m is the width or diameter of the metal or other conductive bridge material and d is the distance from the panel surface to the metal.

After the width W and area of Zone A are calculated, the heat transmissions of the zonal sections are determined and converted to area resistances, which are then added to obtain the total resistance (R) of that portion of the panel. The resistance of Zone A is combined with that of Zone B to obtain the overall resistance and U_w value of the opaque walls.

For example, in Fig. 26, if the tie diameter is ¼ in., the width W of Zone A is $0.25 + 2 \times 1.375 = 3$ in. The U_w of the panel then varies with the width of Zone B. If Zone B is 13 in. wide (16 in. tie spacing), $U_w = 0.158$; if 21 in. wide (24 in. tie spacing), $U_w = 0.151$; or if 29 in. wide (32 in. tie spacing), $U_w = 0.147$.

The above values were obtained by repeating the zone method for the various widths and are not the result of simply multiplying the first U_w value by the ratio of the first and successive Zone B widths.

CHAPTER 11 — ECONOMICS OF INSULATION

Adding insulation to building assemblies normally reduces annual heating loads while having a minor impact on cooling loads. An important question is how much insulation is cost effective. This chapter presents methods for analyzing the cost effectiveness of added insulation.

Life cycle costing is a general method of economic evaluation which considers all pertinent costs associated with an investment during its study period.[23] Two life cycle costing techniques, the net benefit method and the internal rate of return method, are presented.

11.1 Law of Diminishing Returns

The law of diminishing returns affects the economics of insulation. An example of how this concept applies to insulation can be illustrated by the heat conduction equation, $Q = A(\Delta t)/R$. Rate of heat flow, Q, is inversely proportional to the thermal resistance, R.

Fig. 27 plots heat flow per unit surface area per unit temperature difference versus resistance. The graph shows that when the insulation level is doubled, say from an R value of 1 to 2, the heat flow is halved from 1 to 0.5. Increasing the insulation again from an R value of 2 to 3 cuts heat flow from 0.5 to 0.33. The first increment of insulation reduced the heat flow by 0.5 while the second increment reduced the heat flow by only 0.17.

When total annual heating and cooling loads of buildings are analyzed, similar diminishing returns are found. When insulation is added to wall or roof assemblies, the incremental savings in annual load diminishes quickly.

11.2 Simple Payback Method

The simple payback on an investment is the cost of the investment divided by the resulting annual savings. For insulation this would be the initial cost of added insulation divided by the energy savings in dollars per year. The result is the number of years to recoup the investment in insulation. This method is generally not recommended in the literature[24] but is often used as the first approximation of the benefits of an investment. It is reasonably accurate for very short study periods.

The method has many shortcomings and should not generally be used as a decision making tool. Among the items not considered are fuel escalation rates, the discount rate (time value of money), and the life of the investment. The simple payback method also ignores any savings beyond the payback period.

11.3 Net Benefits Analysis

Net benefits analysis considers all pertinent costs and benefits (savings) of an investment, usually discounted to the present. Any investment where the discounted benefits exceed the cost is acceptable.

Items that are usually considered when analyzing insulation strategies are: (1) initial cost of added insulation, (2) initial cost for fuel, (3) change in expected annual heating and cooling energy consumption, (4) expected fuel escalation rate, (5) the discount rate, (6) the study period, and (7) the resale value at the end of the study period.

Often, the results are not significantly affected by taxes, maintenance costs, or insurance costs and these parameters can be neglected. However, they should be considered when they are significant.

There are many assumptions involved in this type of analysis. Some parameters are not too difficult to determine. Initial costs of added insulation and fuel can be obtained from local suppliers. The dis-

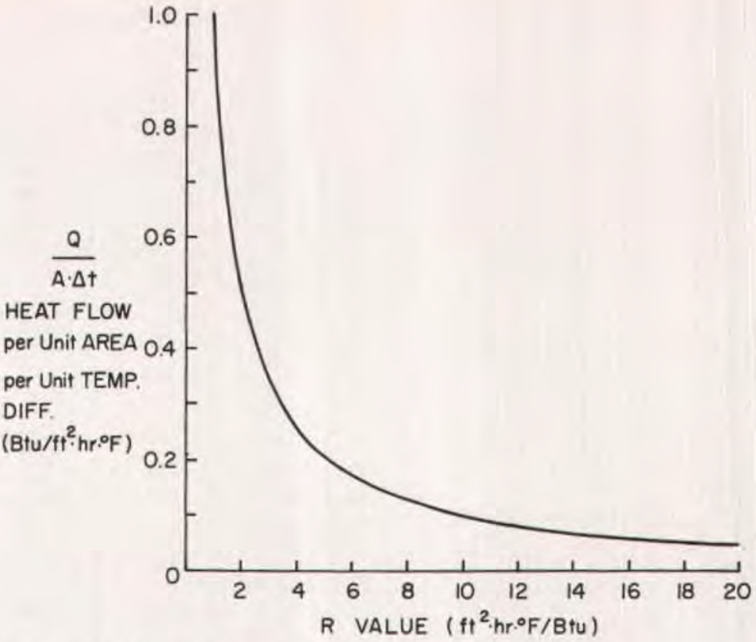


Fig. 27. Heat flow versus *R* value.

count rate is usually the rate of return that could be achieved from alternate investments. The study period may be taken as the length of time of property ownership, the depreciation period, or the length of time over which one expects to recoup his initial investment. The resale value can be equal to the initial cost, to some future value at the end of the study period or zero.

An accurate prediction for the change in heating and cooling energy usage with the associated change in insulation level is difficult to obtain without a sophisticated computer analysis. Heating energy can be approximated using simplified calculation procedures. Cooling energy is more difficult to calculate. However, insulation generally has little effect on cooling energy requirements and cooling energy can therefore be neglected.

Fuel escalation rates are more difficult to estimate so a range of values could be used and the calculation repeated to see what effect different rates have on the results. This sensitivity analysis could also be used for other uncertain values, but is time consuming.

The general equation for net benefit analysis can be found in the literature.[25] The net benefit equation as it applies to insulation can be written as follows:

$$NB = S\,(UPV) - C_o + C_f(SPV) \quad (10)$$

To use this formula, a base case must be established. An appropriate base case would be the case of no added insulation. The procedure is to calculate *NB* for each increment of insulation over the base case until *NB* reaches a maximum. The level of insulation where this occurs is the optimum insulation level.

The final choice of insulation level would have to meet or exceed the requirements of the governing energy code. For massive components the insulation level would have to be at least equal to the equivalent R value discussed in Chapter 8. A design example is presented in Section 11.6 using the net benefit method.

11.4 Internal Rate of Return Analysis

The internal rate of return, *IRR*, is the compound rate of interest that equates the dollar benefits to costs over the study period. It is found by setting NB in Eq. (10) equal to zero and solving by trial and error for the interest rate, i, which is the *IRR*. This method is useful when the analyst knows the minimum acceptable *IRR*.

The variables in this method are similar to the ones discussed for net benefit analysis with some additions. Incremental costs for insulation and fuel are needed for *IRR* analysis and can be obtained from local suppliers.

The *IRR* is calculated twice for each level of insulation. First, the *IRR* is calculated on total investment in insulation and total energy savings over the base case. Then, the *IRR* is calculated on the incremental investment and incremental energy savings over the last acceptable insulation level proceeding from lower to higher insulation levels.

The minimum acceptable rate of return, *MARR*, is used to judge the attractiveness of an investment. If the *IRR* of an investment is larger than or equal to the *MARR* then the investment is acceptable. If the *IRR* of an investment is less than the *MARR* it is rejected. The economic optimum level of insulation is the level with the highest R value having an *IRR* on both total and incremental investment that meets or exceeds the *MARR*. This level is the final choice if it meets or exceeds the governing energy code. A design example using the *IRR* method is given in Section 11.6.

11.5 Optimum R Value, R_{opt} Equation

The economic optimum R value for a building component can be determined by both the *IRR* method and the net benefits method previously discussed. Another method found in the literature[24] determines the optimum R value, R_{opt}, by Eq. (11) as follows:

$$R_{opt} = \sqrt{\frac{20DB\,(UPV)}{mE}} \qquad (11)$$

The term R_{opt} is the level of insulation where the net benefit is a maximum or the life cycle cost is a minimum. Assumptions made to arrive at Eq. (11) include: (1) the relationship between the R value and its cost is linear, (2) the only relevant costs are initial costs of insulation and dollar value of annual heating energy savings, and (3) the building has low "free" heat.

"Free" heat is heat not specifically purchased for space heating such as heat from lighting, occupants, and solar gains through windows. Examples of buildings with low "free" heat would be ordinary houses (not passive solar houses), motels, and heated warehouses. R_{opt} equations for other structures are not yet available.

11.6 Sample Problem Using Net Benefits, Internal Rate of Return and R_{opt} Equation

The dollar value of heating energy savings for buildings with low "free" heat as described in Section 11.5 can be approximated by:

$$S = \frac{20DB}{E}\left[\frac{1}{R_o} - \frac{1}{R_u}\right] \qquad (12)$$

The dollar value (S) of annual heating energy savings per sq ft of component area will be used in the following example for the net benefits and internal rate of return analyses.

Table 12. Optimum Insulation Level — Net Benefits Analysis.

Wall R value (hr•ft^2•°F/Btu)	S, Energy savings* (\$/yr/ft^2)	C_o, Insulation cost* (\$/ft^2)	NB, Net benefit (\$/ft^2)
2.7	0.164	0.29	1.47
3.7	0.240	0.58	1.99
4.7	0.283	0.87	2.16
5.7	0.312	1.16	2.18
6.7	0.331	1.45	2.10
7.7	0.346	1.74	1.97
8.7	0.357	2.03	1.79
9.7	0.366	2.32	1.60
10.7	0.373	2.61	1.39

*Compared to base case with no added insulation (R1.7).

Given:

- Heated warehouse
- Location has 6160 heating degree days
- Sandwich wall construction: 4 in. concrete inner wythe, insulation, 2 in. concrete outer wythe, ½ in. drywall interior
- Seasonal efficiency of heating equipment: 0.75
- Fuel cost: \$0.46/therm
- Fuel escalation rate: 10 percent
- Insulation cost: \$0.29/R value
- 15 year study period
- Resale value is negligible
- *MARR:* 15 percent
- Uninsulated wall has an R value of 1.7

Determine optimum wall insulation level by NB, IRR, and R_{opt} analyses.

First the values of S over the base case of no insulation are calculated. Table 12 lists the values of S for R values up to R10.7. Also listed are initial costs of insulation, C_o, over the base case.

Using Eq. (10) and setting $C_f = 0$, NB can be calculated for each S over the base case of no insulation. The UPV value for this problem is calculated as follows:

$$UPV = \left[\frac{1+e}{i-e}\right]\left[1-\left[\frac{1+e}{1+i}\right]^N\right]$$

$$UPV = \left[\frac{1+0.1}{0.15-0.10}\right]\left[1-\left[\frac{1+0.10}{1+0.15}\right]^{15}\right] = 10.71$$

Substituting appropriate values into Eq. (10) leads to:

$$NB = S(10.71) - C_o$$

The term NB is listed in Table 12 for each R value. The optimum wall R value is the one with the highest net benefit. For this example it is the R5.7 wall. This is a wall with about 1 in. of polystyrene board insulation.

The IRR method considers savings and investments over the base case and incrementally. Thus, Table 13 lists the values of S and C_o for insulation levels over the base case of no insulation and for each increment over the last acceptable increment of insulation. If the calculated IRR for a certain level of insulation is less than the $MARR$ then the insulation level is rejected and is not considered in subsequent calculations.

To calculate the IRR for the various wall R values, Eq. (10) is set equal to zero and appropriate values for the other variables are substituted as follows:

$$NB = S(UPV) - C_o + C_f(SPV)$$

Table 13. Optimum Insulation Level — Internal Rate of Return Analysis.

	Total investment*			Incremental investment†		
Wall *R* value (hr•ft²•°F/Btu)	*S*, Energy savings ($/yr/ft²)	C_o, Insulation cost ($/ft²)	*IRR* percent	*S*, Energy savings ($/yr/ft²)	C_o, Insulation cost ($/ft²)	*IRR* percent
2.7	0.164	0.29	72.1	0.164	0.29	72.1
3.7	0.240	0.58	55.3	0.076	0.29	37.9
4.7	0.283	0.87	45.2	0.043	0.29	23.4
5.7	0.312	1.16	38.7	0.029	0.29	16.1
6.7	0.331	1.45	33.8	0.019	0.29	9.8
7.7	0.346	1.74	30.1	0.034	0.58	8.3
8.7	0.357	2.03	27.1	0.045	0.87	6.7
9.7	0.366	2.32	24.7	0.054	1.16	5.4
10.1	0.373	2.61	22.7	0.061	1.45	4.2

*Compared to base case with no added insulation (R1.7).

†Compared to base case of last acceptable insulation level.

$$NB = S\left[\frac{1+0.1}{i-0.1}\right]\left[1-\left[\frac{1+0.1}{1+i}\right]^{15}\right]-C_o = 0$$

This equation is solved by trial and error for *i*, the interest rate. This is the *IRR* on the investment in insulation. The calculation is repeated for each increment of insulation.

The optimum insulation level is the one with the highest *R* value having an *IRR* on both total and incremental investment that meets or exceeds the *MARR* of 15 percent. The optimum *R* value by the *IRR* method is 5.7 as shown in Table 13. For this insulation level the total *IRR* is 38.7 percent and the incremental *IRR* in going from R4.7 to R5.7 is 16.1 percent.

Calculating the optimum insulation level by Eq. (11):

$$R_{opt} = \sqrt{\frac{20DB\,(UPV)}{mE}} = \sqrt{\frac{20(6160)\,(0.46/100{,}000)\,(10.71)}{0.29(0.75)}} = 5.3$$

The three methods are in close agreement for this example. Generally, the *NB* and *IRR* methods should yield the same optimum. If *S* is not calculated by Eq. (12), the R_{opt} equation might not yield an *R* value similar to the ones obtained by the *NB* or *IRR* methods. This is because Eq. (12) and the R_{opt} equation are based on the same approximation of heat flow. The final choice of insulation must always be checked for code compliance.

METRIC (SI) EQUIVALENT UNITS

1 ft = 0.305 m
1 in. = 25.4 mm
1 ft² = 0.0929 m²
1 Btu/(hr)(ft²)(deg F) = 5.678 W/m² deg C
C = (5/9)(F-32)
1 psf = 0.049 kPa
1 mph = 1.6 km/hr
1 pcf = 16.02 kg/m³

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DISCUSSION NOTE

The Editors welcome discussion of papers published in the PCI JOURNAL. The comments must be confined to the scope of the article being discussed. Please note that discussion of papers appearing in this issue must be received at PCI Headquarters by July 1, 1985.