CHAPTER 27

HEAT, AIR, AND MOISTURE CONTROL IN BUILDING ASSEMBLIES—EXAMPLES

THERMAL and moisture design as well as long-term performance must be considered during the planning phase of buildings. Installing appropriate insulation layers and taking appropriate air and moisture control measures can be much more economical during construction than later. Design and material selection should be based on

- Building use
- Interior and exterior climate
- Space availability
- Thermal and moisture properties of materials
- Other properties required by location of materials
- Durability of materials
- Compatibility with adjacent materials
- Performance expectations of the assembly

Designers and builders often rely on generic guidelines and past building practice as the basis for system and material selection. In many cases, this may still be a valuable approach, but for more difficult cases, selections and performance expectations should be set through engineering analysis. Recent developments have increased the capabilities of available tools and methods of thermal and moisture analysis.

This chapter draws on Chapter 25's fundamental information on heat, air and moisture transport in building assemblies, as well as Chapter 26's material property data. Examples here demonstrate calculation of heat, moisture, and air transport in typical assemblies. For design guidance for common building envelope assemblies and conditions, see Chapter 43 of the 2007 *ASHRAE Handbook—HVAC Applications*.

Insulation specifically for mechanical systems is discussed in Chapter 23. For specific industrial applications of insulated assemblies, see the appropriate chapter in other ASHRAE Handbook volumes. In the 2006 *ASHRAE Handbook—Refrigeration*, for refrigerators and freezers, see Chapters 46, 47, and 48; for insulation systems for refrigerant piping, see Chapter 33; for refrigerated facility design, see Chapters 14 and 39; for trucks, trailers, rail cars, and containers, see Chapter 30; for marine refrigeration, see Chapter 31. For environmental test facilities, see Chapter 37 in the 2002 *ASHRAE Handbook—Refrigeration*.

Engineering practice is predicated on the assumption that performance effects can be viewed in functional format, where discrete input values lead to discrete output values that may be assessed for acceptability. Heat transfer in solids lends itself to engineering analysis because material properties are relatively constant and easy to characterize, the transport equations are well established, analysis results tend toward linearity, and, for well-defined input values, output values are well defined. Airflow and moisture transport analysis, in contrast, is difficult: material properties are difficult to characterize, transport equations are not well-defined, analysis results tend toward nonlinearity, and both input and output values include great uncertainty. Air movement is even more difficult to characterize than moisture transport.

Engineering makes use of the continuum in understanding from physical principles, to simple applications, to complex applications, to design guidance. Complex design applications can be handled by computers; however, this chapter presents simpler examples as a learning tool. Because complex applications are built up from simpler ones, understanding the simpler applications ensures that a critical engineering oversight of complex (computer) applications is retained. Computers have facilitated the widespread use of two- and three-dimensional analysis as well as transient (time-dependent) calculations. As a consequence, steady-state calculations are less widely used. Design guidance, notably guidance regarding use of air and vapor barriers, faces changes in light of sophisticated transient calculations. ASHRAE *Standard* 160P creates a framework for using transient hygrothermal calculations in building envelope design.

HEAT TRANSFER

ONE-DIMENSIONAL U-FACTOR CALCULATION

Wall U-Factor

The U-factor for a building envelope assembly determines the rate of steady-state heat conduction through the assembly. One-dimensional heat flow through building envelope assemblies is the starting point for determining whole-building heat transmittance.

Example 1. Calculate the system R-value R_{system}, average total resistance $[R_{T(av)}]$, and U-factor of the structural insulated panel assembly shown in Figure 1, assuming winter conditions.

Solution: Determine indoor and outdoor air film resistances from Table 1 in Chapter 26, and thermal resistance of all components from Table 4 in that chapter. If any elements are described by conductivity

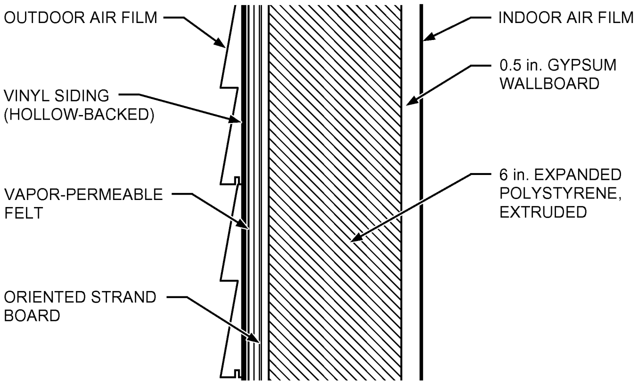


Fig. 1 Structural Insulated Panel Assembly (Example 1)

The preparation of this chapter is assigned to TC 4.4, Building Materials and Building Envelope Performance.

(independent of thickness) rather than thermal resistance (thickness-dependent), then calculate the resistance.

Element	R, h·ft^2·°F/Btu
1. Outdoor air film	0.17
2. Vinyl siding (hollow backed)	0.62
3. Vapor-permeable felt	0.06
4. Oriented strand board (OSB), 7/16 in.	0.62
5. 6 in. expanded polystyrene, extruded (smooth skin)	30.0
6. 0.5 in. gypsum wallboard	0.45
7. Indoor air film	0.68
Total	32.6

The conductivity k of expanded polystyrene is 0.20 Btu·in/h·ft^2·°F. For 6 in. thickness,

$$R_{foam} = x/k = 6/0.20 = 30.0 \text{ h·ft}^2\text{·°F/Btu}$$

To calculate the system's R-value in the example, sum the R-values of the system components only, disregarding indoor and outdoor air films.

$$R_{system} = 0.62 + 0.06 + 0.62 + 30.0 + 0.45 = 31.75 \text{ h·ft}^2\text{·°F/Btu}$$

The average total R-value ($R_{T(av)}$) consists of the system's R-value plus the thermal resistance of the interior and exterior air films.

$$R_{T(av)} = R_o + R_{system} + R_i = 32.6 \text{ h·ft}^2\text{·°F/Btu}$$

The U-factor for the wall is $1/R_{T(av)}$, or 0.031 Btu/h·ft^2·°F.

Roof U-Factor

Example 2. Find the U-factor of the roof assembly shown in Figure 2, assuming summer conditions.

Solution: The calculation procedure is similar to that shown in Example 1. Note the U-factor of nonvertical assemblies depends on the direction of heat flow [i.e., whether the calculation is for winter (heat flow up) or summer (heat flow down)], because the resistances of indoor air films and plane air spaces in ceilings differ, based on the heat flow direction (see Table 3 in Chapter 26). The effects of mechanical fasteners are not addressed in this example.

Element	R, h·ft^2·°F/Btu
1. Indoor air film	0.92
2. 4 in. concrete, 120 lb/ft^3 and k = 8	0.5
3. 3 in. cellular polyisocyanurate (CFC-11 exp.) (gas-impermeable facers)	28.2
4. 1 in. mineral fiberboard	2.94
5. 3/8 in. built-up roof membrane	0.33
6. Outdoor air film	0.25
Total	33.1

Using $U = 1/R_{T(av)}$, the U-factor is 0.030 Btu/h·ft^2·°F.

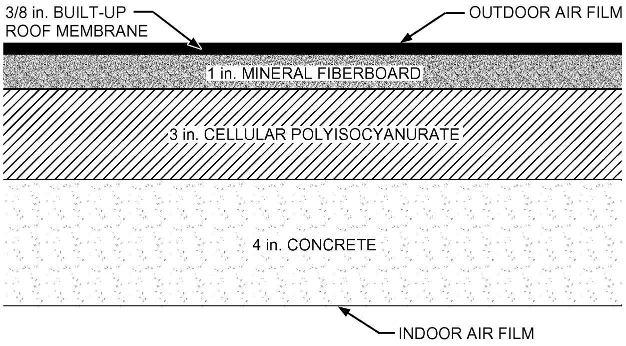


Fig. 2 Roof Assembly (Example 2)

Attics

During sunny periods, unconditioned attics may be hotter than outdoor air. Peak attic temperatures on a hot, sunny day may be 20 to 80°F above outdoor air temperature, depending on factors such as shingle color, roof framing type, air exchange rate through vents, and use of radiant barriers. Energy efficiency estimates can be obtained using models such as Wilkes (1991).

Basement Walls and Floors

Heat transfer through basement walls and floors to the ground depends on the following factors: (1) the difference between the air temperature in the room and that of the ground and outside air, (2) the material of the walls or floor, and (3) the thermal conductivity of surrounding earth. The latter varies with local conditions and is usually unknown. Because of the great thermal inertia of surrounding soil, ground temperature varies with depth, and there is a substantial time lag between changes in outdoor air temperatures and corresponding changes in ground temperatures. As a result, ground-coupled heat transfer is less amenable to steady-state representation than above-grade building elements. However, there are several simplified procedures for estimating ground-coupled heat transfer. These fall into two main categories: (1) those that reduce the ground heat transfer problem to a closed-form solution, and (2) those that use simple regression equations developed from statistically reduced multidimensional transient analyses.

Closed-form solutions, including Latta and Boileau's (1969) procedure discussed in Chapter 17, generally reduce the problem to one-dimensional, steady-state heat transfer. These procedures use simple, "effective" U-factors or ground temperatures or both. Methods differ in the various parameters averaged or manipulated to obtain these effective values. Closed-form solutions provide acceptable results in climates that have a single dominant season, because the dominant season persists long enough to allow a reasonable approximation of steady-state conditions at shallow depths. The large errors (percentage) that are likely during transition seasons should not seriously affect building design decisions, because these heat flows are relatively insignificant compared to those of the principal season.

The ASHRAE arc-length procedure (Latta and Boileau 1969) is a reliable method for wall heat losses in cold winter climates. Chapter 17 discusses a slab-on-grade floor model developed by one study. Although both procedures give results comparable to transient computer solutions for cold climates, their results for warmer U.S. climates differ substantially.

Research conducted by Dill et al. (1945) and Hougten et al. (1942) indicates a heat flow of approximately 2.0 Btu/h·ft^2 through an uninsulated concrete basement floor with a temperature difference of 20°F between the basement floor and the air 6 in. above it. A U-factor of 0.10 Btu/h·ft^2·°F is sometimes used for concrete basement floors on the ground. For basement walls below grade, the temperature difference for winter design conditions is greater than for the floor. Test results indicate that, at the mid-height of the below-grade portion of the basement wall, the unit area heat loss is approximately twice that of the floor.

For small concrete slab floors (equal in area to a 25 by 25 ft house) in contact with the ground at grade level, tests indicate that heat loss can be calculated as proportional to the length of exposed edge rather than total area. This amounts to 0.81 Btu/h per linear foot of exposed edge per degree temperature difference between indoor air and the average outdoor air temperature. This value can be reduced appreciably by installing insulation under the ground slab and along the edge between the floor and abutting walls. In most calculations, if the perimeter loss is calculated accurately, no other floor losses need to be considered. Chapter 17 contains data for load calculations and heat loss values for below-grade walls and floors at different depths.

The second category of simplified procedures uses transient two-dimensional computer models to generate ground heat transfer data, which are then reduced to compact form by regression analysis (Mitalas 1982, 1983; Shipp 1983). These are the most accurate procedures available, but the database is very expensive to generate. In addition, these methods are limited to the range of climates and constructions specifically examined. Extrapolating beyond the outer bounds of the regression surfaces can produce significant errors.

Guide details and recommendations related to application of concepts for basements are provided in Chapter 43 of the 2007 *ASHRAE Handbook—HVAC Applications*. Detailed analysis of heat transfer through foundation insulation may also be found in the *Building Foundation Design Handbook* (Labs et al. 1988).

TWO-DIMENSIONAL U-FACTOR CALCULATION

The following examples show three methods of two-dimensional, steady-state conductive heat transfer analysis through wall assemblies. They offer approximations to overall rates of heat transfer (U-factor) when assemblies contain a layer composed of dissimilar materials. The methods are described in Chapter 25. The **parallel-path method** is used when the thermal conductivity of the dissimilar materials in the layer are rather close in value (within the same order of magnitude), as with wood-frame walls. The **isothermal-planes method** is appropriate for materials with conductivities moderately different from those of adjacent materials (e.g., masonry). The **zone method** and the **modified zone method** are appropriate for materials with a very high difference in conductivity (two orders of magnitude or more), such as with assemblies containing metal.

Two-dimensional, steady-state heat transfer analysis is often conducted using computer-based finite difference methods. If the resolution of the analysis is sufficiently fine, computer methods provide better simulations than any of the methods described here, and the results typically show better agreement with measured values.

The methods described here do not take into account heat storage in the materials, nor do they account for varying material properties (e.g., when thermal conductivity is affected by moisture content or temperature). Transient analysis is often used in such cases.

Wood-Frame Walls

The average overall R-values and U-factors of wood-frame walls can be calculated by assuming either parallel heat flow paths through areas with different thermal resistances or by assuming isothermal planes. Equation (15) in Chapter 25 provides the basis for the two methods.

The **framing factor** expresses the fraction of the total building component (wall or roof) area that is framing. The value depends on the specific type of construction, and may vary based on local construction practices, even for the same type of construction. For stud walls 16 in. on center (OC), the fraction of insulated cavity may be as low as 0.75, where the fraction of studs, plates, and sills is 0.21 and the fraction of headers is 0.04. For studs 24 in. OC, the respective values are 0.78, 0.18, and 0.04. These fractions contain an allowance for multiple studs, plates, sills, extra framing around windows, headers, and band joists. These assumed framing fractions are used in Example 3, to illustrate the importance of including the effect of framing in determining a building's overall thermal conductance. The actual framing fraction should be calculated for each specific construction.

Example 3. Calculate the U-factor of the 2 by 4 stud wall shown in Figure 3. The studs are at 16 in. OC. There is 3.5 in. mineral fiber batt insulation (R-13) in the stud space. The inside finish is 0.5 in. gypsum wallboard, and the outside is finished with rigid foam insulating sheathing (R-4) and vinyl siding. The insulated cavity occupies approximately 75% of the transmission area; the studs, plates, and sills occupy 21%; and the headers occupy 4%.

Solution: Obtain the R-values of the various building elements from Tables 1 and 4 of Chapter 26. Assume R = 1.25 h·ft²·°F/Btu per inch for the wood framing (k = 0.8 Btu·in/h·ft²·°F). Also, assume the headers are solid wood, and group them with the studs, plates, and sills.

Two simple methods may be used to determine the U-factor of wood frame walls: parallel path and isothermal planes. For highly conductive framing members such as metal studs, the modified zone method must be used.

Parallel-Path Method:

Element	***R*** **(Insulated Cavity), h·ft²·°F/Btu**	***R*** **(Studs, Plates, and Headers), h·ft²·°F/Btu**
1. Outside air film, 15 mph wind	0.17	0.17
2. Vinyl siding (hollow-backed)	0.62	0.62
3. Rigid foam insulating sheathing	4.0	4.0
4. Mineral fiber batt insulation, 3.5 in.	11.7	—
5. Wood stud, nominal 2 × 4	—	4.38
6. Gypsum wallboard, 0.5 in.	0.45	0.45
7. Inside air film, still air	0.68	0.68
	R_1 = 17.79	R_2 = 10.3

Individual U-factors are reciprocals of the R-value, so U_1 = 0.052 and U_2 = 0.095 Btu/h·ft²·°F. If the wood framing is accounted for using the parallel-path flow method, the wall's U-factor is determined using Equation (15) from Chapter 25. The fractional area of insulated cavity is 0.75 and the fractional area of framing members is 0.25.

$$U_{av} = (0.75 \times 0.052) + (0.25 \times 0.095) = 0.063 \text{ Btu/h·ft}^2\text{·°F}$$

$$R_{T(av)} = 1/U_{av} = 15.87 \text{ h·ft}^2\text{·°F/Btu}$$

With the isothermal-planes method, the fractional areas are applied only to the building layer that contains the studs and cavity-fill insulation. The average R-value for this layer (R_{avs}) is added to the R-values of the other components for a total R for the assembly.

Isothermal-Planes Method:

Element	***R*** **(Stud Cavity Elements), h·ft²·°F/Btu**	***R*** **(Studs, Plates, and Headers), h·ft²·°F/Btu**
1. Outside air film, 15 mph wind		0.17
2. Vinyl siding (hollow-backed)		0.62
3. Rigid foam insulating sheathing		4.0
4. Mineral fiber batt insulation, 3.5 in.	11.7	8.71 (R_{avs})
5. Wood stud, nominal 2 × 4	4.38	
6. Gypsum wallboard, 0.5 in.		0.45
7. Inside air film, still air		0.68
		R_T = 14.63

The average R-value R_{avs} of the stud cavity is calculated using the fractional area of stud and insulation using Equation (15) from Chapter 25.

$$U_{avs} = 0.75(1/13.0) + 0.25(1/4.38) = 0.115$$

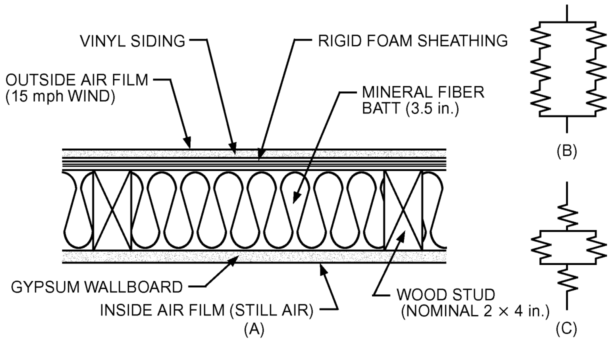


Fig. 3 (A) Wall Assembly for Example 3, with Equivalent Electrical Circuits: (B) Parallel Path and (C) Isothermal Planes

$$R_{avs} = 1/U_{avs} = 8.71\ \text{h·ft}^2\text{·°F/Btu}$$

If the wood framing is included using the isothermal-planes method, the U-factor of the wall is determined using Equations (10) and (11) from Chapter 25 as follows:

$$R_T = 14.8\ \text{h·ft}^2\text{·°F/Btu}$$

$$U_{av} = 1/R_T = 0.067\ \text{Btu/h·ft}^2\text{·°F}$$

For a frame wall with a 24 in. OC stud space, the average overall R-value is 15.18 h·ft²·°F/Btu. Similar calculation procedures may be used to evaluate other wall designs, except those with thermal bridges.

Masonry Walls

The average overall R-values of masonry walls can be estimated by assuming a combination of layers in series, one or more of which provides parallel paths. This method is used because heat flows laterally through block face shells so that transverse isothermal planes result. Average total resistance $R_{T(av)}$ is the sum of the resistances of the layers between such planes, each layer calculated as shown in Example 4.

Example 4. Calculate the overall thermal resistance and average U-factor of the 7 5/8 in. thick insulated concrete block wall shown in Figure 4. The two-core block has an average web thickness of 1 in. and a face shell thickness of 1 1/4 in. Overall block dimensions are 7 5/8 by 7 5/8 by 15 5/8 in. Measured thermal resistances of 112 lb/ft³ concrete and 7 lb/ft³ expanded perlite insulation are 0.10 and 2.90 h·ft²·°F/Btu per inch, respectively.

Solution: The equation used to determine the overall thermal resistance of the insulated concrete block wall is derived from Equations (7) and (15) from Chapter 25 and is given below:

$$R_{T(av)} = R_i + R_f + \left(\frac{a_w}{R_w} + \frac{a_c}{R_c}\right)^{-1} + R_o$$

where

$R_{T(av)}$ = overall thermal resistance based on assumption of isothermal planes
R_i = thermal resistance of inside air surface film (still air)
R_o = thermal resistance of outside air surface film (15 mph wind)
R_f = total thermal resistance of face shells
R_c = thermal resistance of cores between face shells
R_w = thermal resistance of webs between face shells
a_w = fraction of total area transverse to heat flow represented by webs of blocks
a_c = fraction of total area transverse to heat flow represented by cores of blocks

From the information given and the data in Tables 3 and 4, Chapter 26, determine the values needed to compute the overall thermal resistance.

$R_i = 0.68$
$R_o = 0.17$
$R_f = (2)(1.25)(0.10) = 0.25$
$R_c = (5.125)(2.90) = 14.86$
$R_w = (5.125)(0.10) = 0.51$
$a_w = 3/15.625 = 0.192$
$a_c = 12.625/15.625 = 0.808$

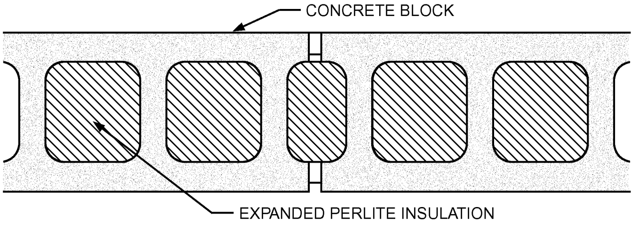


Fig. 4 Insulated Concrete Block Wall (Example 4)

Using the equation given, the overall thermal resistance and average U-factor are calculated as follows:

$$\begin{aligned} R_{T(av)} &= 0.68 + 0.25 + \frac{0.51 \times 14.86}{(0.808 \times 0.51) + (0.192 \times 14.86)} + 0.17 \\ &= 3.43\ \text{h·ft}^2\text{·°F/Btu} \\ U_{av} &= 1/3.43 = 0.29\ \text{Btu/h·ft}^2\text{·°F} \end{aligned}$$

Based on guarded hot-box tests of this wall without mortar joints, Tye and Spinney (1980) measured the average R-value for this insulated concrete block wall as 3.13 h·ft²·°F/Btu.

Assuming parallel heat flow only, the calculated resistance is higher than that calculated on the assumption of isothermal planes. The actual resistance generally is some value between the two calculated values. In the absence of test values, examination of the construction usually reveals whether a value closer to the higher or lower calculated R-value should be used. Generally, if the construction contains a layer in which lateral conduction is high compared with transmittance through the construction, the calculation with isothermal planes should be used. If the construction has no layer of high lateral conductance, the parallel heat flow calculation should be used.

Hot-box tests of insulated and uninsulated masonry walls constructed with block of conventional configuration show that thermal resistances calculated using the isothermal planes heat flow method agree well with measured values (Shu et al. 1979; Valore 1980; Van Geem 1985). Neglecting horizontal mortar joints in conventional block can result in thermal transmittance values up to 16% lower than actual, depending on the masonry's density and thermal properties, and 1 to 6% lower, depending on the core insulation material (McIntyre 1984; Van Geem 1985). For aerated concrete block walls, other solid masonry, and multicore block walls with full mortar joints, neglecting mortar joints can cause errors in R-values up to 40% (Valore 1988). Horizontal mortar joints, usually found in concrete block wall construction, are neglected in Example 4.

Constructions Containing Metal

Curtain and metal stud-wall constructions often include metallic and other thermal bridges, which can significantly reduce the thermal resistance. However, the capacity of the adjacent facing materials to transmit heat transversely to the metal is limited, and some contact resistance between all materials in contact limits the reduction. Contact resistances in building structures are only 0.06 to 0.6 h·ft²·°F/Btu, too small to be of concern in many cases. However, the contact resistances of steel framing members may be important. Also, in many cases (as illustrated in Example 5), the area of metal in contact with the facing greatly exceeds the thickness of metal, which mitigates contact resistance effects.

Thermal characteristics for panels of sandwich construction can be computed by combining the thermal resistances of the layers. R-values for assembled sections should be determined on a representative sample by using a hot-box method. If the sample is a wall section with air cavities on both sides of fibrous insulation, the sample must be of representative height because convective airflow can contribute significantly to heat flow through the test section. Computer modeling can also be useful, but all heat transfer mechanisms must be considered.

The metal studs in Examples 5 and 7 are 3.5 in. deep and placed at 16 in. on center. In Example 5, the metal member is only 0.020 in. thick, but it is in contact with adjacent facings over a 1.25 in. wide area. The steel member is 3.5 in. deep, has a thermal resistance of approximately 0.011 h·ft²·°F/Btu, and is virtually isothermal. The calculation involves careful selection of the thickness for the steel member. If the member is assumed to be 0.020 in. thick, the fact that the flange transmits heat to the adjacent facing is ignored, and heat flow through the steel is underestimated. If the member is assumed to be 1.25 in. thick, heat flow through the steel is overestimated. In

Example 5, the steel member behaves in much the same way as a rectangular member 1.25 in. thick and 3.5 in. deep with a thermal resistance of (1.25/0.020) × 0.011 = 0.69 h·ft^2·°F/Btu.

Example 5. Calculate the system R (i.e., the R-value of the assembly less the resistances of indoor and outdoor air films) of the insulated steel frame wall shown in Figure 5. The C-factor is the reciprocal of the system R. Assume that the steel member has an R-value of 0.69 h·ft^2·°F/Btu and that the framing behaves as though it occupies approximately 8% of the transmission area.

Solution: Obtain the R-values of the various building elements from Table 4 in Chapter 26.

Element	R (Insul.)	R (Framing)
1. 0.5 in. gypsum wallboard	0.45	0.45
2. 3.5 in. mineral fiber batt insulation	11	—
3. Steel framing member	—	0.69
4. 0.5 in. gypsum wallboard	0.45	0.45
	$R_1 = 11.90$	$R_2 = 1.59$

Because $C = 1/R$, $C_1 = 0.084$ and $C_2 = 0.629$ Btu/h·ft^2·°F.

If the steel framing (thermal bridging) is not considered, the C-factor of the wall is calculated using Equation (11) from Chapter 25 as follows:

$$C_{av} = C_1 = 1/R_1 = 0.084 \text{ Btu/h}\cdot\text{ft}^2\cdot°\text{F}$$

If the steel framing is accounted for using the parallel-flow method, the wall's C-factor is determined using Equation (15) from Chapter 25 as follows:

$$\begin{aligned} C_{av} &= (0.92 \times 0.084) + (0.08 \times 0.629) \\ &= 0.128 \text{ Btu/h}\cdot\text{ft}^2\cdot°\text{F} \\ R_{T(av)} &= 7.81 \text{ h}\cdot\text{ft}^2\cdot°\text{F/Btu} \end{aligned}$$

If the steel framing is included using the isothermal planes method, the C-factor of the wall is determined using Equations (10) and (11) from Chapter 25 as follows:

$$\begin{aligned} R_{T(av)} &= 0.45 + 1/[(0.92/11.00) + (0.08/0.69)] + 0.45 \\ &= 5.91 \text{ h}\cdot\text{ft}^2\cdot°\text{F/Btu} \\ C_{av} &= 0.169 \text{ Btu/h}\cdot\text{ft}^2\cdot°\text{F} \end{aligned}$$

For this insulated steel frame wall, Farouk and Larson (1983) measured an average R-value of 6.61 h·ft^2·°F/Btu. For the same assembly, the recommended modified zone method (see Example 7) gives an average R-value of 6.73 h·ft^2·°F/Btu. Two-dimensional analysis (THERM) yields $U_{av} = 0.1775$ or $R = 5.63$ h·ft^2·°F/Btu. ASHRAE/IESNA *Standard* 90.1 describes how to determine the thermal resistance of wall assemblies containing metal framing by using insulation/framing adjustment factors in Table A9.2B of the standard. For 2 by 4 steel framing, 16 in. OC, $F_c = 0.50$. Using the correction factor method, an R-value of 6.40 h·ft^2·°F/Btu [0.45 + 11(0.50) + 0.45] is obtained for the wall described here.

Zone Method of Calculation

For structures with widely spaced metal members of substantial cross-sectional area, the isothermal planes method can give thermal resistance values that are too low. For these constructions, the **zone method** can be used. This method involves two separate computations: one for a chosen limited portion, zone A, containing the highly conductive element; the other for the remaining portion of simpler construction, zone B. The two computations are then combined using the parallel-flow method, and the average transmittance per unit overall area is calculated. The basic laws of heat transfer are applied by adding the area conductances CA of elements in parallel, and adding area resistances R/A of elements in series.

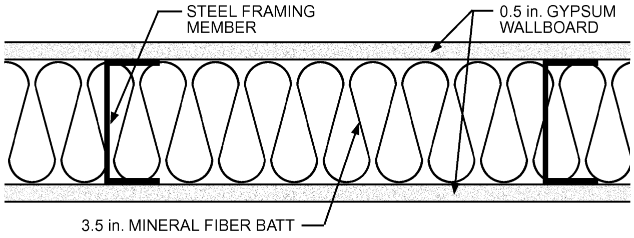


Fig. 5 Insulated Steel Frame Wall (Example 5)

The surface shape of zone A is determined by the metal element. For a metal beam (see Figure 6), the zone A surface is a strip of width W that is centered on the beam. For a rod perpendicular to panel surfaces, it is a circle of diameter W. The value of W is calculated from Equation (1), which is empirical. The value of d should not be less than 0.5 in. for still air.

$$W = m + 2d \tag{1}$$

where

m = width or diameter of metal heat path terminal, in.
d = depth from panel surface to metal, in.

Generally, W should be calculated using Equation (1) for each end of the metal heat path; the larger value, within the limits of the basic area, should be used as illustrated in Example 6.

Example 6. Calculate transmittance of the roof deck shown in Figure 6. Tee-bars at 24 in. OC support glass fiber form boards, gypsum concrete, and built-up roofing. Conductivities of components are: steel, 314.4 Btu·in/h·ft^2·°F; gypsum concrete, 1.66 Btu·in/h·ft^2·°F; and glass fiber form board, 0.25 Btu·in/h·ft^2·°F. Conductance of built-up roofing is 3.00 Btu/h·ft^2·°F.

Solution: The basic area is 2 ft^2 (24 by 12 in.) with a tee-bar (12 in. long) across the middle. This area is divided into zones A and B. Zone A is determined from Equation (1) as follows:

$$\text{Top side } W = m + 2d = 0.625 + (2 \times 1.5) = 3.625 \text{ in.}$$

$$\text{Bottom side } W = m + 2d = 2.0 + (2 \times 0.5) = 3.0 \text{ in.}$$

Using the larger value of W, the area of zone A is (12 × 3.625)/144 = 0.302 ft^2. The area of zone B is 2.0 – 0.302 = 1.698 ft^2.

To determine area transmittance for zone A, divide the structure within the zone into five sections parallel to the top and bottom surfaces (Figure 6). The area conductance CA of each section is calculated by adding the area conductances of its metal and nonmetal paths. Area

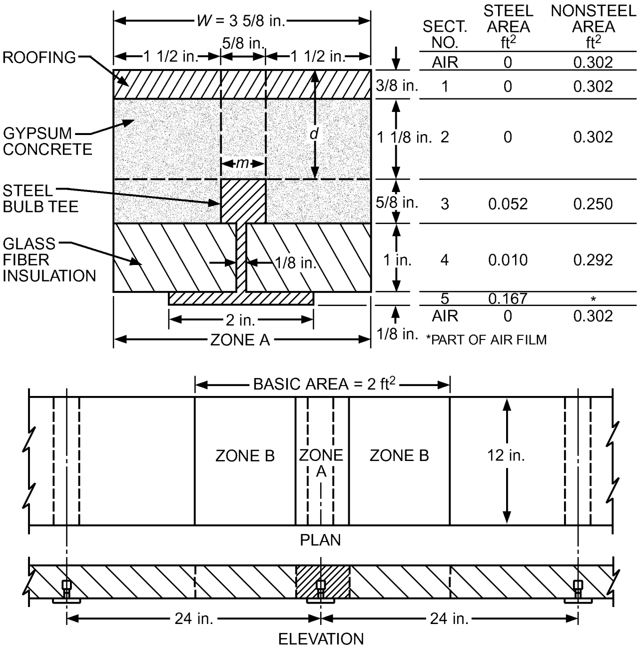


Fig. 6 Gypsum Roof Deck on Bulb Tees (Example 6)

conductances of the sections are converted to area resistances *R*/*A* and added to obtain the total resistance of zone A.

Section	Area	×	Conductance =	*CA*	$\frac{1}{CA} = \frac{R}{A}$
Air (outside, 15 mph)	0.302	×	6.00	= 1.81	0.55
1. Roofing	0.302	×	3.00	= 0.906	1.10
2. Gypsum concrete	0.302	×	1.66/1.125	= 0.446	2.24
3. Steel	0.052	×	314.4/0.625	= 26.2	0.04
Gypsum concrete	0.250	×	1.66/0.625	= 0.664	
4. Steel	0.010	×	314.4/1.00	= 3.14	0.31
Glass fiberboard	0.292	×	0.25/1.00	= 0.073	
5. Steel	0.167	×	314.4/0.125	= 420.0	0.002
Air (inside)	0.302	×	1.63	= 0.492	2.03
				Total *R*/*A* =	6.27

Area transmittance of zone A = 1/(*R*/*A*) = 1/6.27 = 0.159.

For zone B, the unit resistances are added and then converted to area transmittance.

Section	Resistance *R*
Air (outside, 15 mph)	1/6.00 = 0.17
Roofing	1/3.00 = 0.33
Gypsum concrete	1.75/1.66 = 1.05
Glass fiberboard	1.00/0.25 = 4.00
Air (inside)	1/1.63 = 0.61
Total resistance	= 6.16

Because unit transmittance = 1/*R* = 0.162, the total area transmittance *UA* is calculated as follows:

Zone B = 1.698 × 0.162 = 0.275
Zone A = 0.159
Total area transmittance of basic area = 0.434
Transmittance per ft^2 = 0.434/2.0 = 0.217
Resistance per ft^2 = 4.61

Overall R-values of 4.57 and 4.85 h·ft^2·°F/Btu were measured in two guarded hot-box tests of a similar construction.

When the steel member represents a relatively large proportion of the total heat flow path, as in Example 6, detailed calculations of resistance in sections 3, 4, and 5 of zone A are unnecessary; if only the steel member is considered, the final result of Example 6 is the same. However, if the heat flow path represented by the steel member is small, as for a tie rod, detailed calculations for sections 3, 4, and 5 are necessary. A panel with an internal metallic structure and bonded on one or both sides to a metal skin or covering presents special problems of lateral heat flow not covered by the zone method.

Modified Zone Method for Metal Stud Walls with Insulated Cavities

The modified zone method is similar to the parallel-path and zone methods; all three are based on parallel-path calculations. Figure 7 shows the width *w* of the zone of thermal anomalies around a metal stud. This zone can be assumed to equal the length of the stud flange *L* (parallel-path method), or can be calculated as a sum of the length of stud flange and a distance double that from wall surface to metal Σd_i (zone method). In the modified zone method, the width of the zone depends on three parameters:

- Ratio between thermal resistivity of sheathing material and cavity insulation
- Size (depth) of stud
- Thickness of sheathing material

Example 7. Calculate the U-factor of the wall section shown in Figure 7 using the modified zone method.

Solution: The wall cross section is divided into two zones: the zone of thermal anomalies around the metal stud (zone W), and the cavity zone (zone *cav*). Wall material layers are grouped into exterior and interior surface sections A (sheathing, siding) and B (wallboard), and interstitial sections I and II (cavity insulation, metal stud flange).

Assuming that the wall materials in section A are thicker than those in section B, as shown, they can be described as follows:

$$\sum_{i=1}^{n} d_i \geq \sum_{j=1}^{m} d_j$$

where

n = number of material layer (of thickness d_i) between metal stud flange and wall surface for section A
m = number of material layer (of thickness d_j) for section B

Then, the width *W* of zone W can be estimated by

$$W = L + z_f \sum_{i=1}^{n} d_i$$

where

L = stud flange size
d_i = thickness of material layer in section A
z_f = zone factor, shown in Figure 8 (z_f = 2 for zone method)

Kosny and Christian (1995) verified the accuracy of the modified zone method for over 200 simulated cases of metal frame walls with insulated cavities. For all configurations considered, the discrepancy between results were within ±2%. Hot-box-measured R-values for 15 metal stud walls tested by Barbour et al. (1994) were compared with results obtained by Kosny and Christian (1995) and McGowan and Desjarlais (1997). The modified zone method was found to be the most accurate simple method for estimating the clear-wall R-value of light-gage steel stud walls with insulated cavities. However, this analysis does not apply to construction with metal sheathing. Also, ASHRAE *Standard* 90.1 may require a different method of analysis.

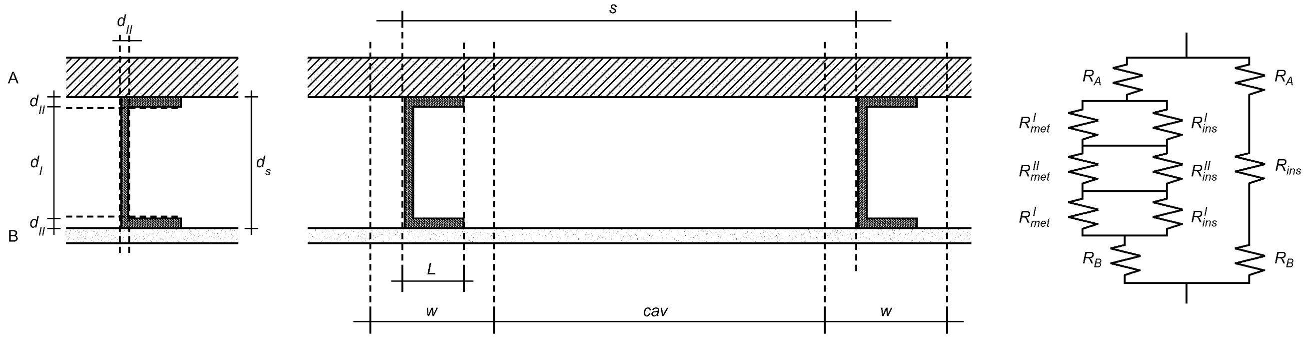
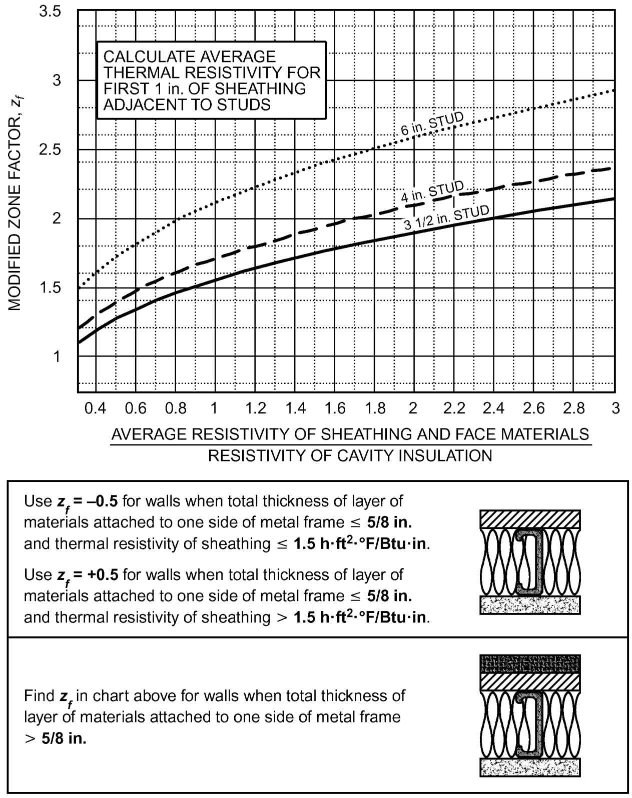


Fig. 7 Wall Section and Equivalent Electrical Circuit (Example 7)



Use **z_f = –0.5** for walls when total thickness of layer of materials attached to one side of metal frame ≤ **5/8 in.** and thermal resistivity of sheathing ≤ **1.5 h·ft^2·°F/Btu·in**.

Use **z_f = +0.5** for walls when total thickness of layer of materials attached to one side of metal frame ≤ **5/8 in.** and thermal resistivity of sheathing > **1.5 h·ft^2·°F/Btu·in**.

Find **z_f** in chart above for walls when total thickness of layer of materials attached to one side of metal frame > **5/8 in.**

Fig. 8 Modified Zone Factor for Calculating R-Value of Metal Stud Walls with Cavity Insulation

Step 1. Determine zone factor z_f, and the ratio of the exterior sheathing material's resistivity to the cavity material's resistivity. Resistivity r is the reciprocal of conductivity; Table 4 in Chapter 26, lists conductivities of various materials.

Element	Symbol	Value	Units
Stud spacing	s	16	in.
Resistivity of sheathing material	r_i	5.00	h·ft^2·°F/Btu·in
Resistivity of cavity insulation	r_{ins}	3.45	h·ft^2·°F/Btu·in
Ratio r_i/r_{ins}		1.449	(no units)
Zone factor from chart	z_f	1.71	(no units)

Step 2. Calculate width W of affected zone W:

$$W = L + z_f \sum d_i$$

Element	Symbol	Value	Units
Cavity thickness	d_s	3.5	in.
Thickness of metal	d_{II}	0.04	in.
Interior dimension between flanges	d_I	3.42	in.
Thickness of exterior insulating materials		2	in.
Flange length	L	1.5	in.
Affected zone thickness	W	4.920	in.

Step 3. Calculate the exterior and interior thermal resistances, using conductivity or thermal resistance values from step 1.

Element	Symbol	Value	Units
Exterior materials			
Thickness of first exterior material	d_e	1.5	in.
Resistivity of first exterior material	r_e	5.00	h·ft^2·°F/Btu·in
Resistance of first material		7.50	h·ft^2·°F/Btu
Resistances of other materials		0.825	
Sum of resistances of exterior materials	R_A	8.33	h·ft^2·°F/Btu
Interior materials			
Thickness of interior material	d_j	0.05	in.
Resistivity of interior material	r_j	0.90	h·ft^2·°F/Btu·in
Resistance of interior material	R_B	0.245	h·ft^2·°F/Btu

Step 4. Calculate the thermal resistance of the sections in zone around the metal element. The building elements in series from outside to inside are shown in Figure 7.

Element	Symbol	Value	Units
Resistivity of steel	r_{met}	0.0030	h·ft^2·°F/Btu·in
R^I_{ins}	d^I_{xri}	11.80	h·ft^2·°F/Btu
R^{II}_{ins}	d^{II}_{xri}	0.138	h·ft^2·°F/Btu
R^I_{met}	d^I_{xrmet}	0.0102	h·ft^2·°F/Btu
R^{II}_{met}	d^{II}_{xrmet}	0.00012	h·ft^2·°F/Btu

The particular thermal resistances of the zone elements are then calculated.

Zone W is the zone at the web of the metal member. For width W, the thermal conductance C is calculated as the sum of the contributory areas. Because the thickness of the web of the metal member is d_I and the length along the flange section is L,

$$C_I = \frac{W-d_I}{W}C_{ins} + \frac{d_I}{W}C_{met} \quad \text{and} \quad C_{II} = \frac{W-L}{W}C_{ins} + \frac{L}{W}C_{met}$$

Using resistance rather than conductance, the contributing R-values are calculated as

$$R_I = \frac{R^I_{met}R^I_{ins}W}{d_I(R^I_{ins}-R^I_{met}) + WR^I_{met}} \quad \text{and} \quad R_{II} = \frac{R^{II}_{met}R^{II}_{ins}W}{L(R^{II}_{ins}-R^{II}_{met}) + WR^{II}_{met}}$$

At the cavity, the sum of the series R-values is

$$\sum R_{cav} = R_A + R_B + R^I_{ins} + 2R^{II}_{ins}$$

In zone W, the sum of the R-values is

$$\sum R_W = R_A + R_B + R_I + 2R_{II}$$

The total conductivity across the length s is proportional to the contributing lengths of zone W and the cavity:

$$C_{tot} = \frac{W}{s}C_W + \frac{cav}{s}C_{cav}$$

or

$$R_{tot} = \frac{\sum R_W \sum R_{cav} s}{W\left(\sum R_{cav} - \sum R_W\right) + s\sum R_W}$$

Element	Symbol	Value	Units
Resistance at web	R_I	1.141	h·ft^2·°F/Btu
Resistance at flange	R_{II}	0.00039	h·ft^2·°F/Btu
Sum of resistances at cavity	ΣR_{cav}	20.65	h·ft^2·°F/Btu
Sum of resistances at zone W	ΣR_W	9.712	h·ft^2·°F/Btu
Total R	R_{tot}	15.34	h·ft^2·°F/Btu
Total U	U_{tot}	0.0652	Btu/h·ft^2·°F

In this example, the calculated total R-value for the wall is 15.34 h·ft^2·°F/Btu, and the wall's U-factor is 0.0652 Btu/h·ft^2·°F.

Complex Assemblies

Building enclosure geometry of two- and three-dimensional assemblies may be complex, including corners, terminations of materials, and junctures of different materials. Such assemblies cannot be analyzed effectively with explicit calculations; rather, they require iterative calculations using computers.

Figure 9 shows a corner composed of homogeneous material. Surface temperatures can be estimated from the intersections of isotherms and the surface. If, in this figure, the interior were warm with respect to outside, then the line at the corner would be colder than the

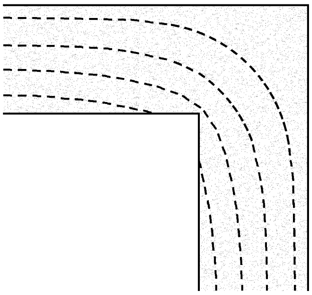


Fig. 9 Corner Composed of Homogeneous Material Showing Locations of Isotherms

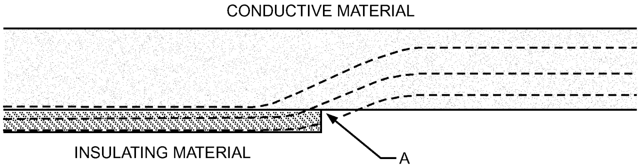


Fig. 10 Insulating Material Installed on Conductive Material, Showing Temperature Anomaly (Point A) at Insulation Edge

remainder of the interior surface. This effect may be exacerbated by the air film at the corner, which would have a greater effective thickness than on the plane of the wall, and would therefore offer greater thermal resistance, further lowering the corner temperature.

Figure 10 shows an insulating material applied to a conductive material. Insulation is placed at the inside, during a period of cold outdoor temperatures. A computer program may be used to trace the isotherms. The interior isotherm is cut where the insulating material is interrupted, indicating lowered temperature at that location (point A). In fact, the temperature at the edge of the interrupted insulation is even lower than the temperature at the surface of the uninsulated wall. Interruptions in insulation can lead to thermal bridges. For this reason, insulation of conductive assemblies such as masonry or concrete is often more successful when applied to the outside rather than to the inside of the building.

Windows and Doors

Table 4 of Chapter 15 lists U-factors for various fenestration products. For heat transmission coefficients for wood and steel doors, see Table 6 in Chapter 15. All U-factors are approximate, because a significant portion of the resistance of a window or door is contained in the air film resistances, and some parameters that may have important effects are not considered. For example, the listed U-factors assume the surface temperatures of surrounding bodies are equal to the ambient air temperature. However, the indoor surface of a window or door in an actual installation may be exposed to nearby radiating surfaces, such as radiant heating panels, or opposite walls with much higher or lower temperatures than the indoor air. Air movement across the surface of a window or door, such as that caused by nearby heating and cooling outlet grilles or by wind outdoors, increases the U-factor.

MOISTURE TRANSPORT

The following examples build on the previous sections by discussing methods that combine heat and moisture transport analysis. The methods include fundamental calculations that can be performed by hand as well as more advanced transient calculations that require computer modeling.

WALL OR ROOF WITH INSULATED SHEATHING

When insulating materials with low water vapor permeability are included in a building assembly, a simple moisture test can provide a satisfactory estimate of condensation resistance. This test assumes that interior surfaces may have little or no resistance to air or vapor flow. The section on Surface Condensation in Chapter 25 describes how to determine the risk of condensation on low-permeability surfaces.

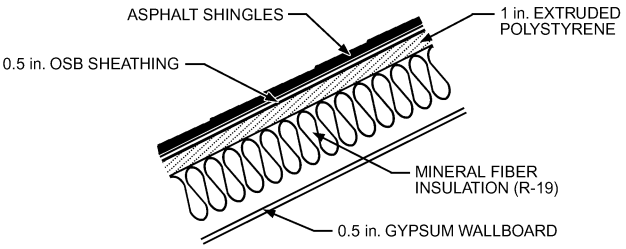


Fig. 11 Roof Assembly Using Foam Insulation

Example 8. For the assembly shown in Figure 11, determine the range of indoor relative humidity for which condensation does not occur on the underside of the insulating sheathing. Assume a design outdoor temperature of 30°F, and indoor temperature of 70°F. Assume that the cavity air is at the same vapor pressure as the indoor air, which can occur with openings through the ceiling. Ignore radiant effects on the roof surface. Assume the rigid insulation is vapor impermeable, and interior materials have little resistance to air or vapor flow.

Air Film or Material	Thermal Resistance, h·ft^2·°F/Btu
1. Indoor air film coefficient	0.68
2. Gypsum wallboard	0.32
3. Mineral fiber insulation	19
4. 1 in. extruded polystyrene	7
5. OSB sheathing, 1/2 in.	0.68
6. Asphalt shingles	0.44
7. Exterior air film coefficient	0.17
Total R-value	28.29

Solution: The temperature difference is 40°F. The sum of the R-values from the foam/mineral fiber interface inward is 20.0 h·ft^2·°F/Btu. The sum of the R-values from that interface outward is 8.29 h·ft^2·°F/Btu. The temperature difference ratio [Equation (14), Chapter 25] is 8.29/28.29, or 0.29. The interface temperature is 41.7°F. The saturation vapor pressure of indoor air is 0.74 in. Hg, and the saturation vapor pressure at the interface is 0.26 in. Hg (see Chapter 1). The upper bound for indoor relative humidity is therefore 0.26/0.74, or 35% rh.

Many factors influence the likelihood (or not) of damage in an assembly such as this with exterior rigid insulation. Solar effects generally ensure a period of high temperatures that allows drying. On the other hand, cold sky temperatures may increase heat loss from the assembly, which lowers the surface temperature below ambient. Even when indoor humidity is high enough that condensation at the interface is indicated, the rate of water formation may be slowed by airtightness at the ceiling and by vapor diffusion protection.

VAPOR PRESSURE PROFILE (GLASER OR DEW-POINT) ANALYSIS

The common steady-state one-dimension tool for evaluating moisture accumulation and drying within exterior envelopes (walls, roofs, and ceilings) is the dew-point or Glaser method. Users should recognize its limitations, which include the following:

- Strictly speaking, condensation is a phase change from vapor to liquid. Water that is attached to the surfaces of building materials is adsorbed or absorbed water, not liquid water. Increase in the moisture content of porous and hygroscopic building materials is properly called sorption, not condensation. Dew-point method results have often been interpreted to indicate condensation, when, in fact, increases in moisture content were through sorption, not condensation.

- Heat and moisture storage effects are not included in dew-point analysis. Experience shows storage effects to play a significant role in heat and moisture performance of assemblies.
- Diffusion is the only moisture transport mechanism considered. Airflow, capillary transport, rain wetting, initial conditions, latent effects, solar effects, and ventilation cannot be included in the method, and they may have a dominant effect on building assembly performance.
- The dew-point method allows calculation of a rate of moisture accumulation or rate of drying from a critical location within the assembly. However, the method has not shown how to estimate damage associated with any rate of accumulation or drying.

Chapter 25 discusses the Glaser method and its limitations in more detail.

ASHRAE does not recommend the dew-point method as the sole basis for hygrothermal design of building envelope assemblies. ASHRAE *Standard* 160P is being developed to assist in hygrothermal analysis for design purposes. The dew-point method is presented here for reasons of historical continuity, and because it serves as an illustration of the fundamental principles of conduction in heat transport and diffusion in moisture transport.

Winter Wall Wetting Examples

Example 9. For a wood-framed wall, assume monthly mean conditions of 70°F, 50% rh indoors and 20°F, 70% rh outdoors. Indoor and outdoor vapor pressures are 0.370 and 0.072 in. Hg, respectively.

Solution:

Step 1. List the components in the building assembly, with their R-values and permeances.

Air Film or Material	Thermal Resistance, h·°F·ft²/Btu	Proportional Temperature Drop	Vapor Permeance, perm	Vapor Diffusion Resistance, rep	Proportional Vapor Pressure Drop
1. Air film coefficient	0.68	0.049	160	0.006	0.003
2. Gypsum board, painted, cracked joints	0.45	0.032	5	0.200	0.088
3. Insulation, mineral fiber	11	0.790	30	0.033	0.015
4. OSB sheathing	0.62	0.045	0.5	2.0	0.881
5. Wood siding	1.0	0.072	35	0.029	0.013
6. Air film coefficient	0.17	0.012	1000	0.001	0.000
Totals	13.92	1.000		2.27	1.000

Step 2. List the indoor and outdoor temperature and relative humidity. Vapor pressure at indoor and outdoor locations is determined by multiplying the saturation vapor pressure at that temperature by the relative humidity.

Boundary or Interface Between Materials	Temperature, °F	Saturation Vapor Pressure, in. Hg	Relative Humidity, %	Initial Vapor Pressure, in. Hg	Corrected Vapor Pressure, in. Hg
Indoor air	70	0.740	50	0.370	0.370
1-2 interface	67.6	0.680		0.369	0.364
2-3 interface	65.9	0.643		0.343	0.171
3-4 interface	26.4	0.139		0.339	0.139
4-5 interface	24.2	0.126		0.076	0.073
5-6 interface	20.6	0.106		0.072	0.072
Outdoor air	20	0.103	70	0.072	0.072
Difference	50		Difference	0.298	

Step 3. Calculate the proportional temperature drop across each layer. The temperature drop is proportional to the R-value:

$$\frac{\Delta t_{layer}}{t_i - t_o} = \frac{R_{layer}}{R_T}$$

The table in step 1 lists the resulting proportional temperature drops. Calculate the proportional water vapor pressure drops across each layer. These are calculated the same way as the proportional temperature drops in step 1:

$$\frac{\Delta p_{layer}}{p_i - p_o} = \frac{Z_{layer}}{Z_T}$$

where

Z_T = total water vapor diffusion resistance of wall (sum of diffusion resistances of all layers), rep

p = partial water vapor pressure, in. Hg

Step 4. Determine the temperature at each interface, using the temperature difference from indoors to outdoors, and the proportional temperature drop. Find the saturation water vapor pressure corresponding to the interface temperatures from step 1. These values can be found in Table 2 in Chapter 1.

Step 5. From step 1, the total water vapor diffusion resistance of the wall without the vapor retarder is

$$Z_{wall} = 1/160 + 1/5 + 1/30 + 1/0.5 + 1/35 + 1/1000 = 2.27 \text{ rep}$$

The partial water vapor pressure drop across the whole wall is calculated from the indoor and outdoor saturation water vapor pressures and relative humidities (see the table in step 2).

$$p_{wall} = p_i - p_o = (50/100)0.740 - (70/100)0.103 = 0.298 \text{ in. Hg}$$

Step 6. Figure 12 shows the calculated saturation and partial water vapor pressures. Comparison reveals that the calculated partial water vapor pressure on the interior surface of the sheathing is well above saturation. This indicates incipient accumulation of water (condensation or sorption), probably on the surface of the sheathing, not within the insulation. If the accumulation rate is of interest, two additional steps are necessary.

Step 7. The calculated water vapor pressure exceeds the saturation water vapor pressure by the greatest amount at the back side of the sheathing (Figure 12). Therefore, this is the most likely location for accumulation. Under conditions of phase change (condensation or sorption), the water vapor pressure should equal the saturation water vapor pressure at that interface (see the corrected vapor pressure column in step 2 of Example 9).

Step 8. The change of water vapor pressure on the OSB sheathing alters all other partial water vapor pressures as well as water vapor flux through the wall. Calculating partial water vapor pressures is similar to

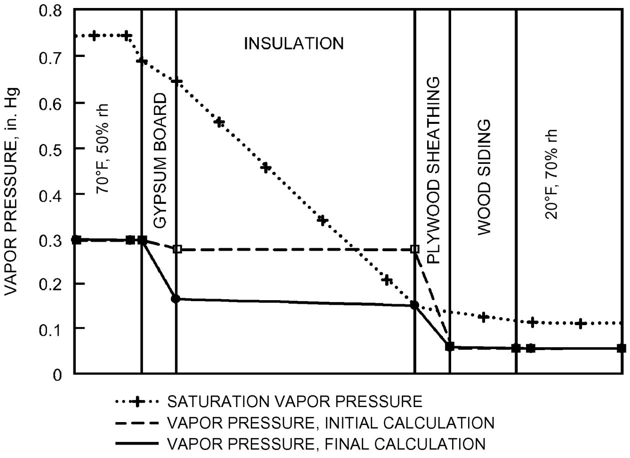


Fig. 12 Dew-Point Calculation in Wood-Framed Wall (Example 9)

the calculation in step 3, but the wall is now divided in two parts: one on the interior of the condensation interface (i.e., gypsum board and insulation) and the other on the exterior (OSB sheathing and wood siding). Water vapor pressure drop over the first (interior) part of the wall is

$$\Delta p_1 = 0.370 - 0.139 = 0.230 \text{ in. Hg}$$

and over the second (exterior) part is

$$\Delta p_2 = 0.139 - 0.072 = 0.067 \text{ in. Hg}$$

The diffusion resistances of both parts of the wall are

$$Z_1 = 1/160 + 1/5 + 1/30 = 0.239 \text{ rep}$$

$$Z_2 = 1/0.5 + 1/35 + 1/1000 = 2.03 \text{ rep}$$

The water vapor pressure drops across each material can be calculated from the part between the inside and sheathing

$$\frac{\Delta p_{layer}}{p_i - p'_{sheathing}} = \frac{Z_{layer}}{Z_i^{sheathing}}$$

and the part between the sheathing and outside

$$\frac{\Delta p_{layer}}{p'_{sheathing} - p_o} = \frac{Z_{layer}}{Z^o_{sheathing}}$$

	Z_{tot}, h·ft²·in. Hg/gr	Vapor Pressure Difference, in. Hg	Vapor Flow, gr/ft²·h
Indoor air to critical interface	0.239	0.230	0.9628
Critical interface to outdoor air	2.030	0.067	0.0332
Net accumulation, gr/ft²·h			0.9295

As shown in Figure 12, final calculations of water vapor pressure no longer exceed saturation, which means that the condensation plane was chosen correctly. However, vapor flux is no longer the same throughout the wall. The flux from inside increases; to the outside it decreases. The difference between both is the rate of moisture accumulation by interstitial condensation at the back side of the sheathing:

$$m_c = \frac{p_i - p'_{sheathing}}{Z_i^{sheathing}} - \frac{p'_{sheathing} - p_o}{Z^o_{sheathing}}$$

In this case $m_c = 0.9295$ gr/ft²·h. (One grain equals 1/7000 of a pound.) Assume the 0.5 in. OSB sheathing (density of 34 lb/ft³) begins with moisture content of 10%. The weight of dry OSB at that thickness is 1.42 lb/ft², so the weight of water is 0.14 lb. If these conditions persist for 30 days (720 h), then the amount of accumulated water is 0.04 lb. This raises the moisture content of the wood to 12.5%. It is evident that wetting by diffusion is very slow.

The Glaser method should not be used to show simply that calculated vapor pressure at one location exceeds saturation vapor pressure at that location. If that condition is detected, then the rate of accumulation must be calculated and the results compared to the affected material's estimated storage potential. Unfortunately, guidance on interpretation of accumulated water with the Glaser method is not available. Considerations of moisture storage potential in building materials can be addressed only with transient modeling, not with steady-state methods.

Example 10. A wood-framed construction has a wet layer inside. The wall layers include a 6 mil (0.006 in.) polyethylene membrane between insulation and gypsum board, and an exterior insulation and finish system (EIFS) with 1.5 in. of expanded polystyrene as substrate and a spun-glass reinforced stucco finish. If the OSB sheathing became soaked because of rain infiltration at the windows, how long before the OSB reaches hygroscopic equilibrium after leaks are sealed? Solve for two monthly mean conditions: winter, with 70°F, 40% rh indoors and 20°F, 50% rh outdoors; and summer, with 77°F, 70% rh indoors and 73°F, 70% rh outdoors.

Solution:

Step 1. List the components in the building assembly, with their R-values and permeances.

Air Film or Material	Thermal Resistance *R*, h·ft²·°F/Btu	Proportional Temperature Drop	Vapor Permeance, perm	Vapor Diffusion Resistance, h·ft²·in. Hg/gr	Proportional Vapor Pressure Drop
1. Air film coefficient	0.68	0.035	160	0.006	0.000
2. Gypsum board, painted	0.45	0.023	5	0.200	0.002
3. Polyethylene foil	0.0	0.000	0.01	125	0.974
4. Insulation, mineral fiber	11.0	0.573	30	0.033	0.000
5. OSB sheathing	0.62	0.032	0.5	2.000	0.016
6. EPS	5.7	0.297	1.3	0.769	0.006
7. EIFS stucco lamina and finish	0.57	0.030	3.2	0.313	0.002
8. Air film coefficient	0.17	0.009	1000	0.001	0.000
Total	19.19	1.000		128	1.000

Step 2. List the indoor and outdoor temperature and relative humidity. As in Example 9, indoor and outdoor vapor pressure is determined by multiplying the saturation vapor pressure at that temperature by the relative humidity.

Winter conditions:

	Temperature, °F	Saturated Vapor Pressure, in. Hg	Relative Humidity, %	Initial Vapor Pressure, in. Hg	Vapor Pressure, in. Hg
Indoors	70	0.740	40	0.296	0.296
1 and 2	68.22	0.696		0.296	0.296
2 and 3	67.05	0.668		0.295	0.296
3 and 4	67.05	0.668		0.057	0.233
4 and 5	38.39	0.233		0.057	**0.233**
5 and 6	36.78	0.218		0.053	**0.218**
6 and 7	21.93	0.113		0.052	0.215
7 and 8	20.44	0.105		0.051	0.177
Outdoors	20	0.103	50	0.051	0.051
Difference	50		Difference	0.244	

Summer conditions:

	Temperature, °F	Saturated Vapor Pressure, in. Hg	Relative Humidity, %	Initial Vapor Pressure, in. Hg	Vapor Pressure, in. Hg
Indoors	77	0.936	70	0.655	0.655
1 and 2	76.9	0.931		0.655	0.680
2 and 3	76.8	0.929		0.655	0.705
3 and 4	76.8	0.929		0.575	0.731
4 and 5	74.5	0.860		0.575	**0.860**
5 and 6	74.3	0.857		0.574	**0.857**
6 and 7	73.2	0.823		0.573	0.764
7 and 8	73.0	0.820		0.573	0.669
Outdoors	73	0.819	70	0.573	0.573
Difference	4		Difference	0.082	

Step 3. Indoor and outdoor vapor pressures are calculated from the given conditions of temperature and relative humidity. The vapor pressure at each side of the OSB sheathing is assigned the value of the saturation vapor pressure at that temperature (see bold values in the summer and winter condition tables).

Step 4. Calculate the total vapor resistance on either side of the critical OSB layer. Between inside and sheathing,

$$\frac{\Delta p_{layer}}{p_i - p'_{sheathing}} = \frac{Z_{layer}}{Z_i^{sheathing}}$$

Between sheathing and outside,

$$\frac{\Delta p_{layer}}{p'_{sheathing} - p_o} = \frac{Z_{layer}}{Z^o_{sheathing}}$$

From the summer and winter condition tables, the diffusion resistances of both parts of the wall are

$$Z_1 = 0.0062 + 0.20 + 125 + 3.31 \times 10^{-2} = 125.21 \text{ rep}$$

$$Z_2 = 0.79 + 0.31 + 1.00 \times 10^{-3} = 1.10 \text{ rep}$$

Step 5. Calculate the vapor pressure difference on either side of the critical OSB layer (the last column in the summer and winter condition tables). From the vapor resistance on each side and the vapor pressure difference on each side, vapor flow in each direction can be calculated.

Winter

$$m_{i,sheathing} = \frac{p_i - p'_{sheathing}}{Z^i_{sheathing}} = 0.0005 \text{ gr/ft}^2 \cdot \text{h}$$

$$m_{sheathing,o} = \frac{p'_{sheathing} - p_o}{Z^{sheathing}_i} = 0.154 \text{ gr/ft}^2 \cdot \text{h}$$

	Z_{tot}, h·ft²·in. Hg/gr	Vapor Pressure Difference, in. Hg	Vapor Flow, gr/ft²·h
Indoor air to critical interface	125.2	0.063	0.0005
Critical interface to outdoor air	1.10	0.167	0.1543
		Net drying	0.1538
	Net drying, gr/ft² per month		111

Summer

$$m_{i,sheathing,i} = \frac{p_i - p'_{sheathing}}{Z^i_{sheathing}} = -0.0016 \text{ gr/ft}^2 \cdot \text{h}$$

$$m_{sheathing,o} = \frac{p'_{sheathing} - p_o}{Z^{sheathing}_o} = 0.262 \text{ gr/ft}^2 \cdot \text{h}$$

	Z_{tot}, h·ft²·in. Hg/gr	Vapor Pressure Difference, in. Hg	Vapor Flow, gr/ft²·h
Indoor air to critical interface	125.2	–0.205	–0.0016
Critical interface to outdoor air	1.10	0.283	0.2618
		Net drying	0.2634
	Net drying, gr/ft² per month		187

Drying consequently amounts to 111 gr/ft² per month in winter and 187 gr/ft² per month in summer. OSB soaked with water can have excess moisture content of up to 0.98 lb/ft². Drying only by one-dimensional diffusion would appear to take several years at this rate. Radiation, air movement, and two- and three-dimensional effects can change the rate of drying.

Figures 13 and 14 show the calculated water vapor pressure in winter and summer. The OSB is at water vapor saturation pressure; saturation is not reached at any other interface.

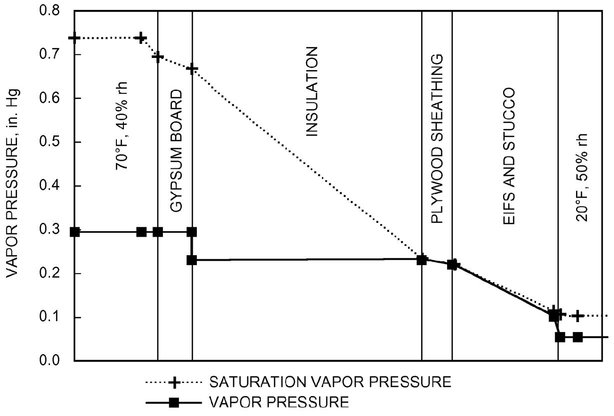


Fig. 13 Drying Wet Sheathing, Winter (Example 10)

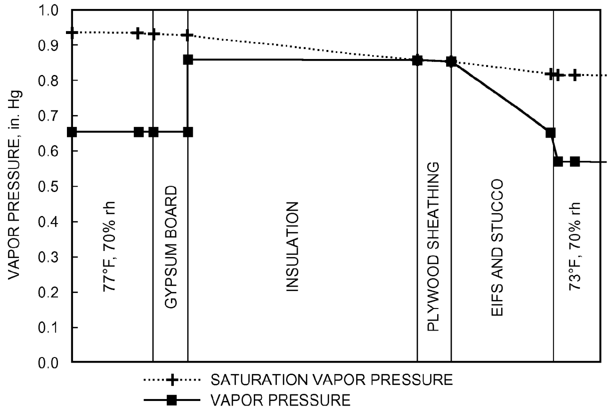


Fig. 14 Drying Wet Sheathing, Summer (Example 10)

TRANSIENT HYGROTHERMAL MODELING

Fundamentals of hygrothermal modeling tools, including modeling criteria and method of reporting, are discussed in Chapter 25. Although this chapter does not provide a complete example, it introduces input data commonly required by these programs and discusses considerations for analyzing output when using these tools.

For many applications and for design guide development, actual behavior of an assembly under transient climatic conditions may be simulated to account for short-term processes such as driving rain absorption, summer condensation, and phase changes. Computer simulations allow designers to model these conditions over time. It is important, however, to understand the model's application limits.

Applying one of these models requires at least the following information: exterior climate conditions, indoor temperature and humidity, and building assembly materials and sizes. Many programs include a material property database and exterior climate and indoor condition data, allowing simple modeling to be performed without customization. However, using generic material property and weather data may not accurately recreate actual target conditions.

Features of a complete moisture analysis model include

- Transient heat, air, and moisture transport formulation, incorporating the physics of
  - Airflow
  - Water vapor transport by advection (combination of water vapor diffusion and air-driven vapor flow)
  - Liquid transport by capillary action, gravity, and pressure differences
  - Heat flow by apparent conduction, convection, and radiation
  - Heat and moisture storage/capacity of materials
  - Condensation and evaporation processes with linked latent-to-sensible heat transformation
  - Freezing and thawing processes with linked latent-to-sensible heat transformation and based on laws of conservation of heat, mass, and momentum
- Material properties as functions of moisture content, relative humidity, and temperature, such as
  - Density
  - Air properties: permeability and permeance

  - Thermal properties: specific heat capacity, apparent thermal conductivity, Nusselt numbers, and long-wave emittance (for cavities and air spaces)
  - Moisture properties: porosity, sorption curve, water retention curve, vapor permeability, water permeability, or liquid diffusivity
- Boundary conditions (generally on an hourly basis)
  - Outside temperature and relative humidity
  - Incident short-wave solar and long-wave sky radiation (depending on inclination and orientation)
  - Wind speed, orientation, and pressures
  - Wind-driven rain at exterior surfaces (depending on location and aerodynamics)
  - Interior temperature, air pressure excess, relative humidity (or interior moisture sources and ventilation flows), and air stratification
  - Surface conditions
  - Heat transfer film coefficients (combined convection and radiation, separate for convection and radiation)
  - Mass transfer film coefficients
  - Short-wave absorptance of exterior surfaces
  - Long-wave emittance of exterior surfaces
  - Contact conditions between layers and materials. Interfaces may be bridgeable for vapor diffusion, airflow, and gravity or pressure liquid flow only. They may be ideally capillary, introduce additional capillary resistance, or behave as real contact.

Not all these features are required for every analysis, and some applications may need additional information (e.g., moisture flow through unintentional cracks and intentional openings, rain penetration through veneer walls and exterior cladding). To model these phenomena accurately, experiments may be needed to define systems and subsystems in field situation, because only then are all exterior loads and influences captured.

It is important to recognize that simulation results are based on input data. Therefore, the more accurate the input data used, the closer the results will match real-world conditions. Exterior weather conditions, material properties, and interior operating conditions all vary widely, so it is important to get the best data available on materials being modeled. For most users, this is a difficult task. Many product manufacturers do not provide the material property data needed for the simulations. Developing weather data for a particular site is also beyond the expertise of many.

Combined hear, air, and moisture models also have limitations. Users should be aware which transport phenomena and types of boundary conditions are included and which are not. For instance, some models cannot handle air transport or rain wetting of the exterior. Even an apparently simple problem, such as predicting rain leakage through a brick veneer, is beyond existing tools' capabilities. In such cases, simple qualitative schemes and field tests still are the way to proceed. In addition, results also tend to be very sensitive to the choice of indoor and outdoor conditions. Usually, exact conditions are not known.

Outputs from these programs typically include the moisture content of materials as well as relative humidity within the assembly. Interpretation of results is not easy: accurate data on moisture and temperature conditions that materials can tolerate are often not available. Although moisture accumulation may result in indoor air quality issues or material degradation, the effect of moisture accumulation in building assemblies depends on many factors, including choice of construction materials, and varies by building, making interpretation of results even more difficult.

AIR MOVEMENT

Research has demonstrated that air movement is more effective than water vapor diffusion for transporting water vapor within building envelopes. To minimize moisture penetration by air leakages, the building envelope should be as airtight as possible. The airflow retarder must also be sufficiently strong and well supported to resist wind loads.

In older residential buildings, air leakage provided sufficient ventilation and rarely led to interstitial condensation. However, in airtight buildings, mechanical ventilation is needed to ensure acceptable air quality and prevent moisture and health problems caused by excessive indoor humidity. Ventilation or drainage must go to the outside of the airtight layer of construction, or it will increase building air leakage. To avoid condensation on the airtight layer, either the layer temperature must be kept above the dew point by locating it on the warm side of the insulation, or the layer permeance must allow vapor transmission.

As described in detail in the section on Leakage Distribution in Chapter 16, air leakage through building envelopes is not confined to doors and windows. Although 6 to 22% of air leakage occurs there, 18 to 50% typically takes place through walls, and 3 to 30% through the ceiling. Leakage often occurs between sill plate and foundation, through interior walls, electrical outlets, plumbing penetrations, and cracks at top and bottom of exterior walls.

Not all cracks and openings can be sealed in existing buildings, nor can absolutely tight construction be achieved in new buildings. Provide as tight an enclosure as possible to reduce leakage, minimize potential condensation within the envelope, and reduce energy loss.

Moisture accumulation in building envelopes can also be minimized by controlling the dominant direction of airflow by operating the building at a small negative or positive air pressure, depending on climate. In cooling climates, pressure should be positive to keep out humid outside air. In heating climates, pressure should be neither strongly negative, which could risk drawing soil gas or combustion products indoors, nor strongly positive, which could risk driving moisture into building envelope cavities.

Equivalent Permeance

Dew-point analysis allows simple estimation of the effect of wall and roof cavity ventilation on heat and vapor transport by using parallel thermal and vapor diffusion resistances (TenWolde and Carll 1992; Trethowen 1979). These parallel resistances account for heat and vapor that bypass exterior material layers with ventilation air from outside. Equivalent thermal and water vapor diffusion resistances are approximated from the following equations:

$$R_{par} = \frac{S}{Q\rho c_p}$$

$$Z_{par} = \frac{S}{Q\rho c}$$

where

R_{par} = parallel equivalent thermal resistance, h·ft^2·°F/Btu
Z_{par} = parallel equivalent water vapor diffusion vapor flow resistance, rep
S = surface area of wall or ceiling, ft^2
Q = cavity ventilation airflow rate, ft^3/h
ρ = density of air, lb/ft^3
c = ratio of humidity ratio and vapor pressure, approximately 145 gr/lb·in. Hg
c_p = specific heat, Btu/lb·°F

REFERENCES

ASHRAE. 2006. Design criteria for moisture control in buildings. *Draft Standard* 160P.

ASHRAE. 2007. Energy standard for buildings except low-rise residential buildings. ANSI/ASHRAE/IESNA *Standard* 90.1-2007.

Barbour, E., J. Goodrow, J. Kosny, and J.E. Christian. 1994. *Thermal performance of steel-framed walls*. Prepared for American Iron and Steel Institute by NAHB Research Center.

Dill, R.S., W.C. Robinson, and H.E. Robinson. 1945. Measurements of heat losses from slab floors. National Bureau of Standards. *Building Materials and Structures Report* BMS 103.

Farouk, B. and D.C. Larson. 1983. Thermal performance of insulated wall systems with metal studs. *Proceedings of the 18th Intersociety Energy Conversion Engineering Conference*, Orlando, FL.

Hougten, F.C., S.I. Taimuty, C. Gutberlet, and C.J. Brown. 1942. Heat loss through basement walls and floors. *ASHVE Transactions* 48:369.

Kosny, J. and J.E. Christian. 1995. Reducing the uncertainties associated with using the ASHRAE zone method for R-value calculations of metal frame walls. *ASHRAE Transactions* 101(2):779-788.

Labs, K., J. Carmody, R. Sterling, L. Shen, Y.J. Huang, and D. Parker. 1988. Building foundation design handbook. *Report* ORNL/SUB/86-72143/1. Oak Ridge National Laboratory, Oak Ridge, TN.

Latta, J.K. and G.G. Boileau. 1969. Heat losses from house basements. *Canadian Building* 19(10).

McGowan, A. and A.O. Desjarlais. 1997. An investigation of common thermal bridges in walls. *ASHRAE Transactions* 103(1):509-517.

McIntyre, D.A. 1984. *The increase in U-value of a wall caused by mortar joints*. ECRC/M1843. The Electricity Council Research Centre, Copenhurst, U.K.

Mitalas, G.P. 1982. *Basement heat loss studies at DBR/NRC*. NRCC 20416. Division of Building Research, National Research Council of Canada, September.

Mitalas, G.P. 1983. Calculation of basement heat loss. *ASHRAE Transactions* 89(1B):420.

Shipp, P.H. 1983. Basement, crawlspace and slab-on-grade thermal performance. *Proceedings of the ASHRAE/DOE Conference, Thermal Performance of the Exterior Envelopes of Buildings II*, ASHRAE SP 38:160-179.

Shu, L.S., A.E. Fiorato, and J.W. Howanski. 1979. Heat transmission coefficients of concrete block walls with core insulation. *Proceedings of the ASHRAE/DOE-ORNL Conference, Thermal Performance of the Exterior Envelopes of Buildings*, ASHRAE SP 28:421-435.

TenWolde A. and C. Carll. 1992. Effect of cavity ventilation on moisture in walls and roofs. *Proceedings of ASHRAE Conference, Thermal Performance of the Exterior Envelopes of Buildings V*, pp. 555-562.

Trethowen, H.A. 1979. The Kieper method for building moisture design. BRANZ *Reprint* 12, Building Research Association of New Zealand.

Tye, R.P. and S.C. Spinney. 1980. A study of various factors affecting the thermal performance of perlite insulated masonry construction. Dynatech *Report* PII-2. Holometrix, Inc. (formerly Dynatech R/D Company), Cambridge, MA.

Valore, R.C. 1980. Calculation of U-values of hollow concrete masonry. American Concrete Institute, *Concrete International* 2(2):40-62.

Valore, R.C. 1988. *Thermophysical properties of masonry and its constituents*, parts I and II. International Masonry Institute, Washington, D.C.

Van Geem, M.G. 1985. Thermal transmittance of concrete block walls with core insulation. *ASHRAE Transactions* 91(2).

Wilkes, K.E. 1991. Thermal model of attic systems with radiant barriers. *Report* ORNL/CON-262. Oak Ridge National Laboratory, TN.

BIBLIOGRAPHY

Hens, H. 1978. Condensation in concrete flat roofs. *Building Research and Practice* Sept./Oct.:292-309.

TenWolde, A. 1994. Design tools. Chapter 11 in *Moisture control in buildings*. ASTM *Manual* MNL 18. American Society for Testing and Materials, West Conshohocken, PA.

Vos, B.H. and E.J.W. Coelman. 1967. Condensation in structures. *Report* B-67-33/23, TNO-IBBC, Rijswijk, the Netherlands.