Ch. 9 Heat Flow

9.1 The building envelope
9.2 Building envelope design intentions
9.3 Sensible heat flow through opaque walls and roofs
9.4 Latent heat flow through the opaque envelope
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9.6 Trends in envelope thermal performance
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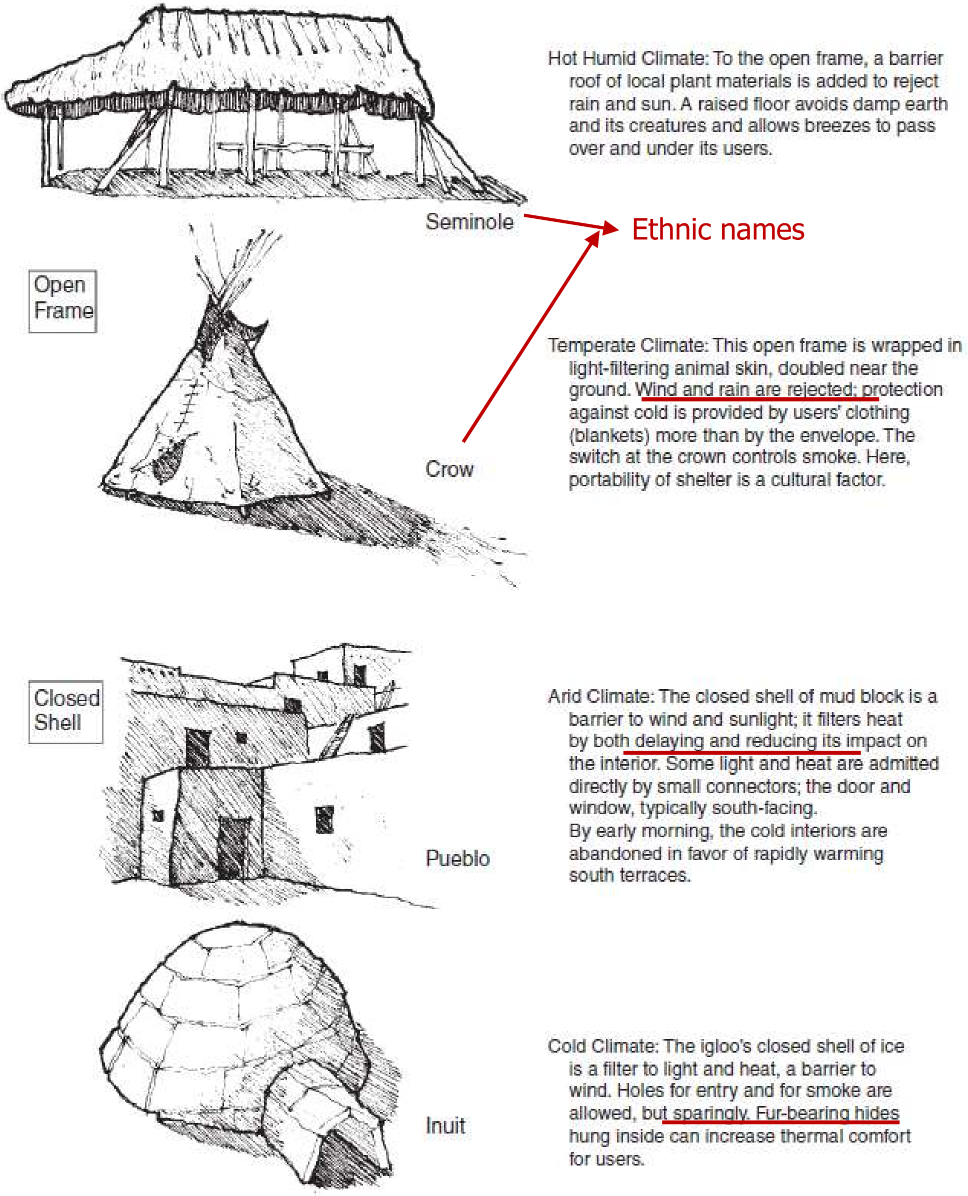
Building envelope

- Envelope = exterior enclosure consisting of materials and components
- The envelope is more than a surface. The envelope is not merely a 2D exterior surface, but a 3D transition space. (Fig.9.1)

Fig. 9.1 *The envelope is more than a surface. This south-facing office façade in Oregon forms a microclimate zone that buffers the transition between indoor and outdoor conditions. Groundcover plants at eye level for seated occupants and deciduous vines overhead give a seasonally changing view to the outdoors through a façade that also admits winter sun, year-round daylight, and summer breeze. (Photo by Amanda Clegg.)*

Building Envelope Design

- Basic components: windows, doors, floors, walls, roofs
  - Windows: skylights, clerestories, screens, shutters, drapes, blinds, glass, etc.
- Open frame or closed shell approach



Ethnic names

Hot Humid Climate: To the open frame, a barrier roof of local plant materials is added to reject rain and sun. A raised floor avoids damp earth and its creatures and allows breezes to pass over and under its users.

Temperate Climate: This open frame is wrapped in light-filtering animal skin, doubled near the ground. Wind and rain are rejected; protection against cold is provided by users' clothing (blankets) more than by the envelope. The switch at the crown controls smoke. Here, portability of shelter is a cultural factor.

Arid Climate: The closed shell of mud block is a barrier to wind and sunlight; it filters heat by both delaying and reducing its impact on the interior. Some light and heat are admitted directly by small connectors; the door and window, typically south-facing. By early morning, the cold interiors are abandoned in favor of rapidly warming south terraces.

Cold Climate: The igloo's closed shell of ice is a filter to light and heat, a barrier to wind. Holes for entry and for smoke are allowed, but sparingly. Fur-bearing hides hung inside can increase thermal comfort for users.

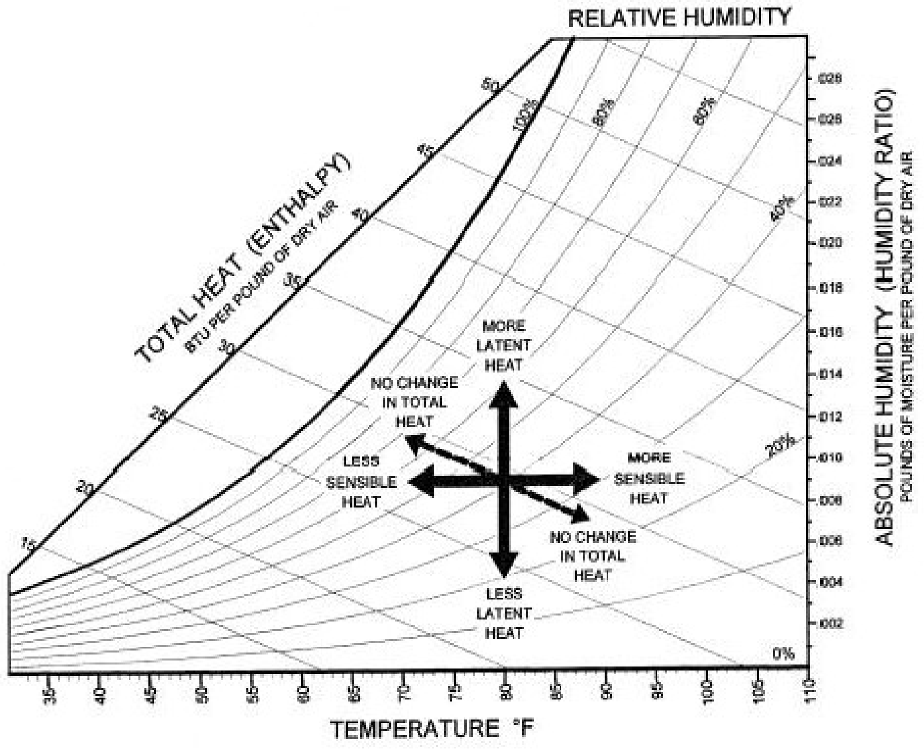
Fig. 9.2 *Open-frame (Seminole and Crow) and closed-shell (Pueblo and Inuit) envelope approaches are influenced by climate, materials, and culture. The influence of climate is dramatic, but material availability and cultural expectations also influence the envelope design solutions in these examples. (Drawing by Dain Carlson.)*

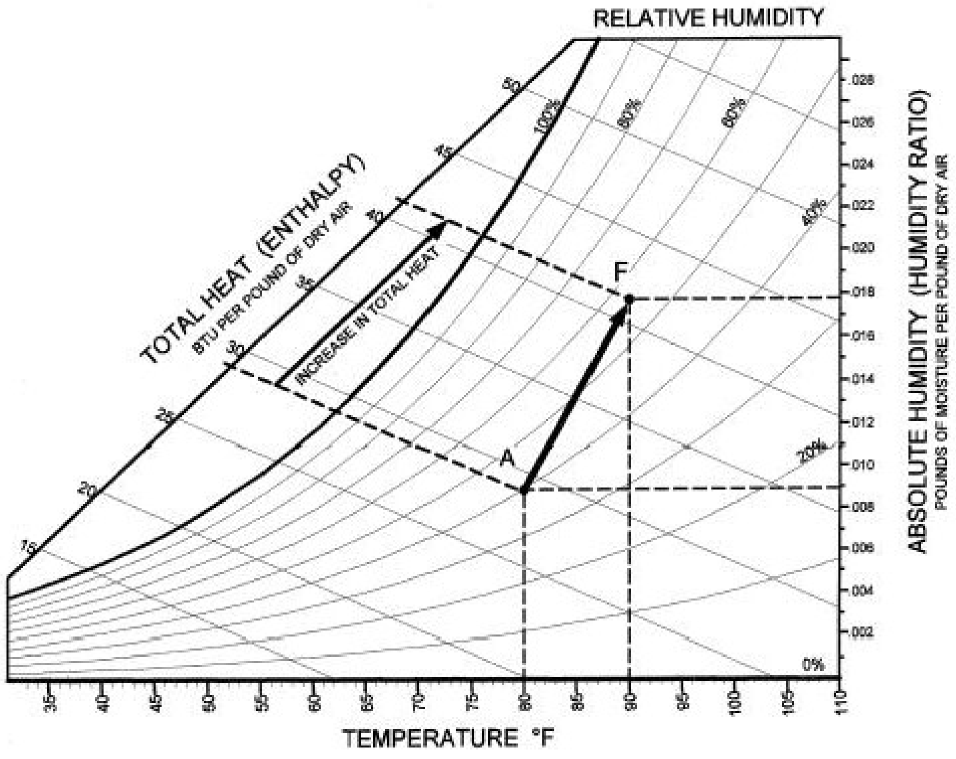
Basics for heat flow

- Sensible heat: a form of energy that flows whenever there is a temperature difference and that manifests itself as an internal energy of atomic vibration within all materials.
  - Temperature is an indication of the extent of such vibration, essentially the ‘density’ of heat within a material.
  - Sensible heat flow results in a change in temperature
- Latent heat: sensible heat used to change the state of water (evaporate or condense).
  - Latent heat flow results in a phase change, e.g., moisture content (often humidity of the air).
- Total heat flow = sensible + latent heat flow

Heat content of air

- Total heat (enthalpy) = sensible + latent





Static versus dynamic

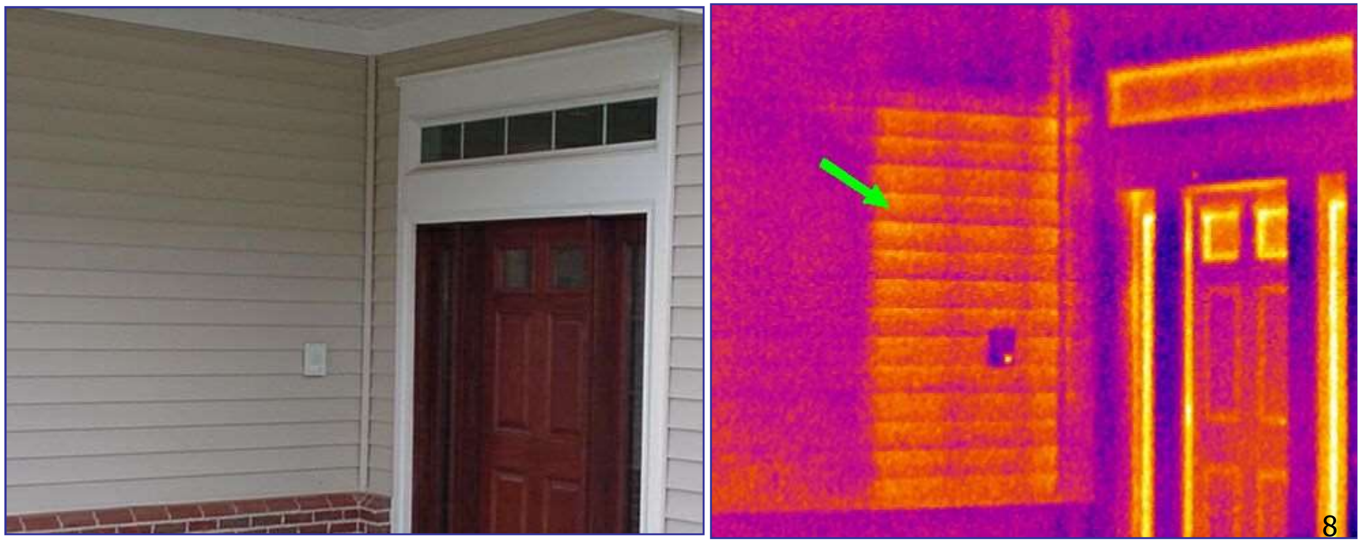
- Static = steady state
  - Key determinant: resistance
- Dynamic = unsteady, transient
  - Key determinant: capacitance

Heat flow process

- Heat flows from the hotter to the colder.
- Moisture flows from area of the greater concentration to area of the lesser concentration.

Three modes in heat transfer

- Conduction: heat transfer directly from molecule to molecule, within or between materials, with proximity of molecules (material density) playing a critical role in the extent of heat transfer
- $$q = kA\frac{T_1 - T_2}{L}$$



Low k material

Insulation slows conduction →

Convection

- Heat exchange between a fluid (typically air) and a solid, with motion of the fluid due to heating or cooling playing a critical role in the extent of heat transfer

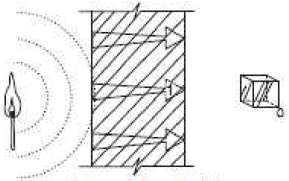
$$q_{conv} = h_c A(T_\infty - T_s)$$

Radiation

- Heat flows via electro-magnetic waves from hotter surfaces to detached colder ones - across empty space and potentially great distances. (with nothing solid or opaque in between)

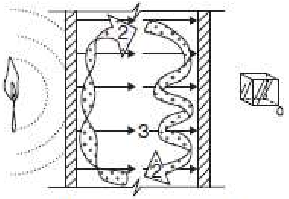
$$q_{rad} = \mathcal{E}\sigma A(T_s^4 - T_{sur}^4)$$

σ is the Stefan-Boltzmann constant [5.67×10^{-8} W/(m^2 ·K^4)].



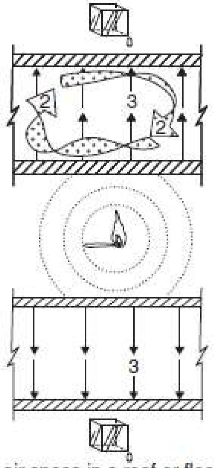
Any solid material
wall, floor, or roof

A single solid material illustrates the transfer of heat from the warmer to the cooler side by conduction (1).



An air space in a wall

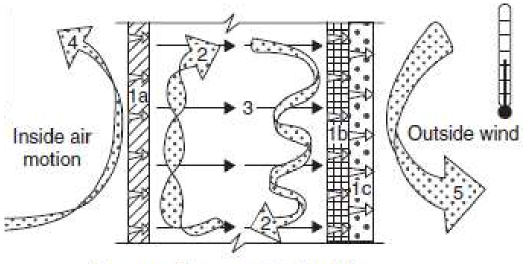
As air is warmed by the warmer side of the air space, it rises. As it falls down along the cooler side, it transfers heat to this surface (2). Radiant energy (3) is transferred from the warmer to the cooler surface. The rate depends upon the relative temperature of the surfaces and upon their emissive and absorptive qualities. Direction is always from the warmer to the cooler surface.



The convective action (2) in the air space of a roof is similar to that in a wall, although the height through which the air rises and falls is usually less. The radiant transfer is up in this case because its direction is always to the cooler surface.

When the higher temperature is at the top of a horizontal air space, the warm air is trapped at the top and, being less dense than the cooler air at the bottom, will not flow down to transfer its heat to the cooler surface. This results in little flow by convection. The radiant transfer in this case is down because that is the direction from the warmer surface to the cooler one.

An air space in a roof or floor



A composite assembly of building
materials in place at the site

This example of a wall in place illustrates the several methods by which heat is lost through a composite assembly of materials. Conduction at varying rates in different materials is accounted for in 1a, 1b, and 1c. Convection currents (2) and radiation (3) carry the heat across the air space.

. ·ₒ. ***9.6*** *Heat flow through materials, across air spaces, and through construction assemblies. Means of heat flow include conduction, convection, and radiation.*

Thermal properties of components

- Conductivity (k): the number of Watts that flow through 1 square meter(m^2) of material 1m thick when the temperature difference across that material is 1°K (equal to 1°C)
  - Unit: W/m°K
- Conductance (C): the number of Watts that flow through 1 square meter(m^2) of a given thickness of material when the temperature difference is 1°C
  - Unit: W/m^2°K
- Appendix Table E.1

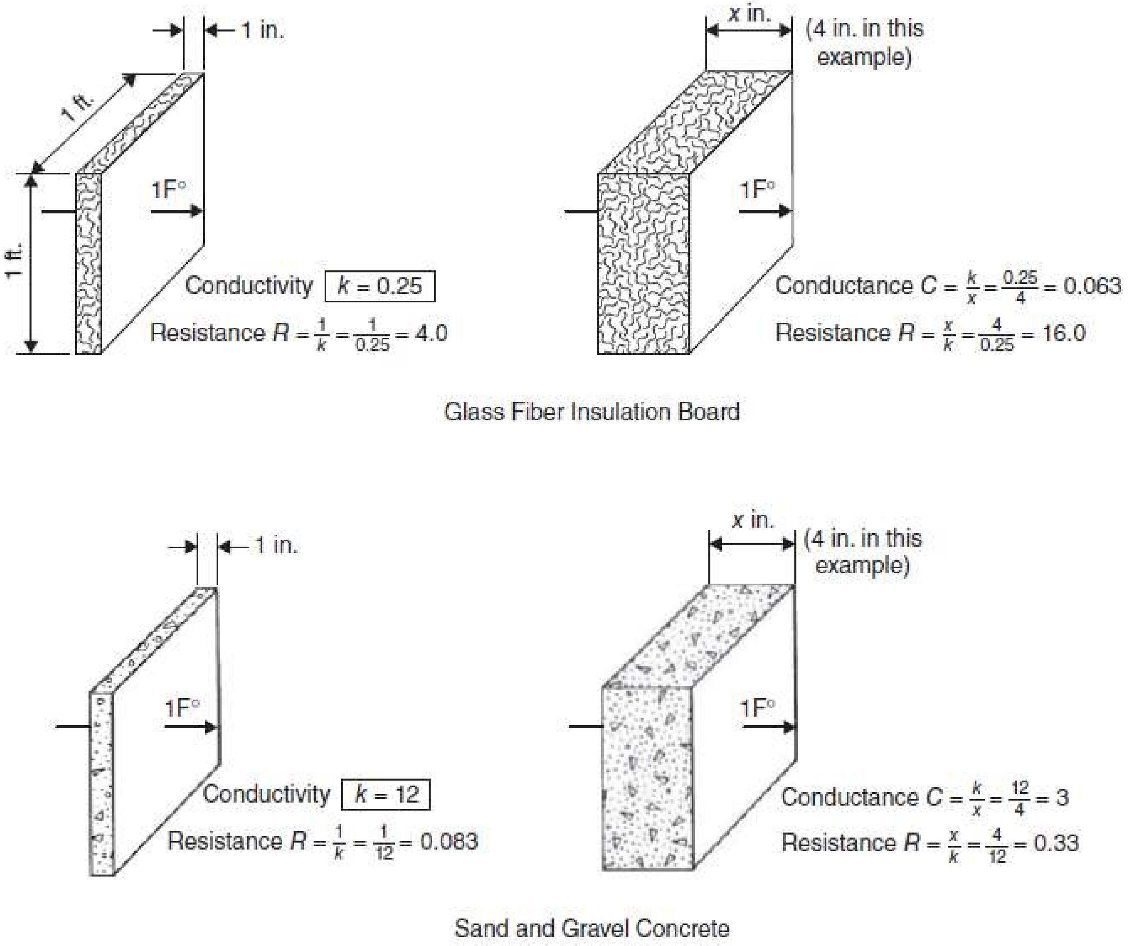


Fig. 9.7 *Relationship between conductivity, conductance, and resistance for two typical materials. Glass fiber is a material of low conductivity (high resistance); concrete is a material of high conductivity (low resistance). Note: Standard unit of area is 1 ft^2 (1 m^2); standard air temperature differential is 1F° (1C°).*

Table E.1 Thermal Properties of Conventional Building and Insulating Materials[a] (*Continued*)

Part B: SI Units

					SI Resistance[c] (R)		
Description		**Density kg/m^3**	**Conductivity[b] (k) W/m K**	**Conductance (C) W/m^2 K**	**Per Meter Thickness (1/k) K m/W**	**For Thickness Listed (1/C) K m^2/W**	**Specific Heat kJ/ kg K**
Building Board							
Asbestos–cement board		1900	0.58	—	1.73	—	1.00
Asbestos–cement board	3.2 mm	1900	—	187.4	—	0.005	—
Asbestos–cement board	6.4 mm	1900	—	93.7	—	0.011	—
Gypsum or plaster board	9.5 mm	800	—	17.6	—	0.056	1.09
Gypsum or plaster board	12.7 mm	800	—	12.6	—	0.079	—
Gypsum or plaster board	15.9 mm	800	—	10.1	—	0.099	—
Plywood (Douglas fir)[d]		540	0.12	—	8.66	—	1.21
Plywood (Douglas fir)	6.4 mm	540	—	18.2	—	0.055	—
Plywood (Douglas fir)	9.5 mm	540	—	12.1	—	0.083	—
Plywood (Douglas fir)	12.7 mm	540	—	9.1	—	0.11	—
Plywood (Douglas fir)	15.9 mm	540	—	7.3	—	0.14	—
Plywood or wood panels	19.0 mm	540	—	6.1	—	0.16	1.21
Vegetable fiber board							
Sheathing, regular density[e]	12.7 mm	290	—	4.3	—	0.23	1.3
	19.8 mm	290	—	2.8	—	0.36	—
Sheathing intermediate density[e]	12.7 mm	350	—	5.2	—	0.19	1.30
Nail-base sheathing[e]	12.7 mm	400	—	5.3	—	0.19	1.30
Shingle backer	9.5 mm	290	—	6.0	—	0.17	1.30
Shingle backer	7.9 mm	290	—	7.3	—	0.14	—
Sound-deadening board	12.7 mm	240	—	4.2	—	0.24	1.26
Tile and lay-in panels, plain or acoustic		290	0.058	—	17.0	—	0.59
	12.7 mm	290	—	4.5	—	0.22	—
	19.0 mm	290	—	3.0	—	0.33	—
Laminated paperboard		480	0.072	—	—	—	1.38
Homogeneous board from repulped paper		480	0.072	—		—	1.17
Hardboard[e]							
Medium density		800	0.105	—	9.50	—	1.30
High-density, service-tempered grade and service grade		880	0.118	—	8.46	—	1.34
High-density, standard-tempered grade		1010	0.144	—	6.93	—	1.34
Particle board[e]							

Absorptivity vs. Absorptance

- The ending “ivity” denotes a property of the bulk material independent of geometry or surface condition.
- The suffix “ance” denotes a property of a piece of material (an actual piece of material) as it exists.
- Thus, emittance, reflectance, absorptance, and transmittance refer to actual pieces of material.
- For example, the emittance is a function of the material, the condition of its surface, and the temperature of the surface.
- ASHRAE F.2001. 3.8

Resistance (*R*)

- The reciprocal of conductivity or conductance
- A measure of how effective any material is as an insulator (the greater R, the more effective the insulator)
- Table E.1: k, C, R

Blackbody radiation

- A blackbody absorbs all incident radiation, regardless of wavelength and direction.
- For a prescribed temperature and wavelength, no surface can emit more energy than a blackbody.
- As the perfect absorber and emitter, the blackbody serves as a standard against which the radiative properties of actual surfaces may be compared.

Emittance

- Defined as the ratio of the radiation emitted by a given material to that emitted by a blackbody at the same temperature
- A measure of how efficiently a surface emits energy relative to a blackbody
- The lower the emittance, the lower the radiative heat exchange
- Low-e glass

- Power: instantaneous flow of energy at a given time (HP, W[J/S], Btu/h)
- Energy: power usage over time (Btu, J, Wh)

Unit conversion: Appendix A or http://www.onlineconversion.com/

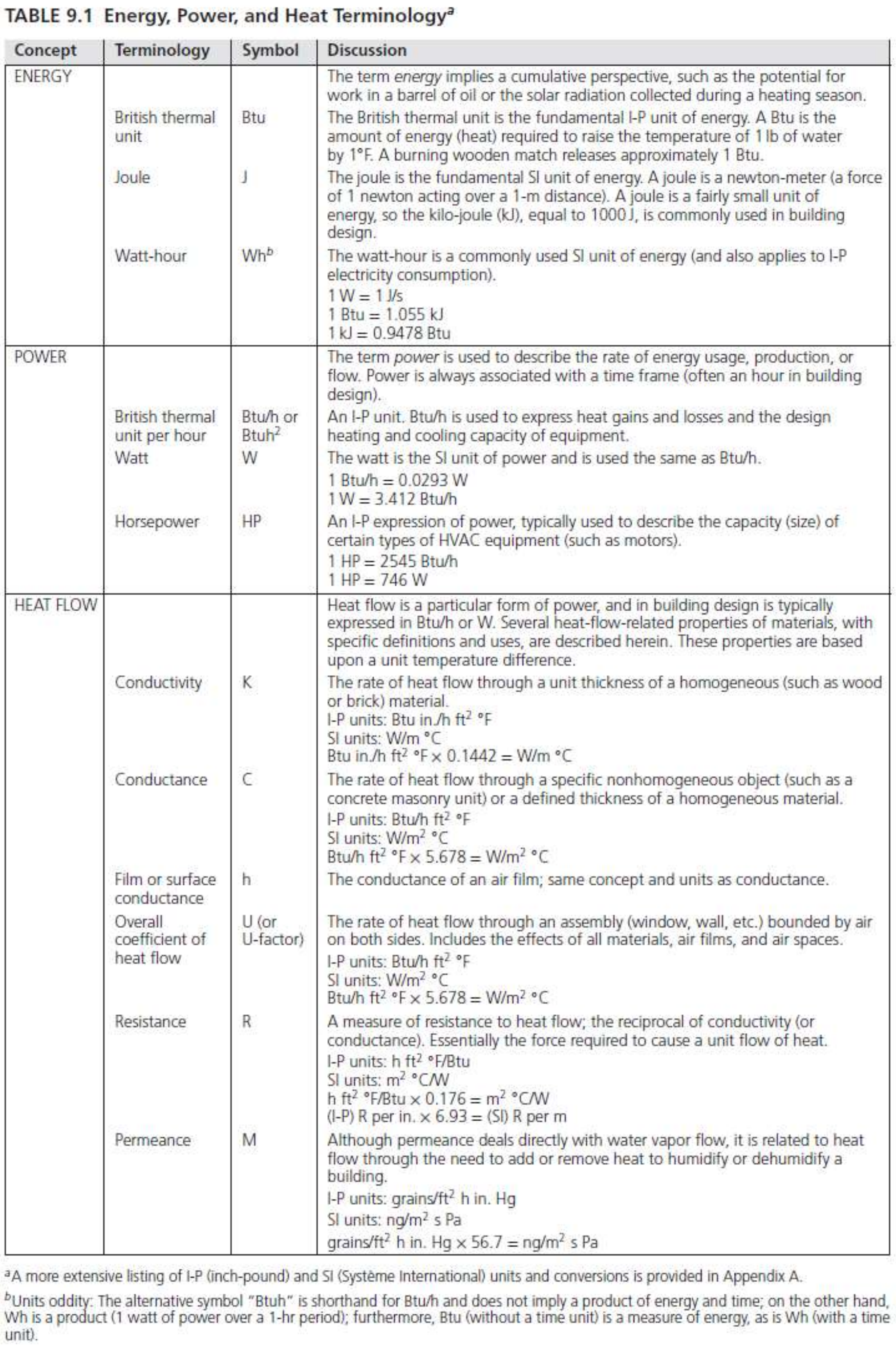


TABLE 9.1 Energy, Power, and Heat Terminology[a]

Concept	Terminology	Symbol	Discussion
ENERGY			The term *energy* implies a cumulative perspective, such as the potential for work in a barrel of oil or the solar radiation collected during a heating season.
	British thermal unit	Btu	The British thermal unit is the fundamental I-P unit of energy. A Btu is the amount of energy (heat) required to raise the temperature of 1 lb of water by 1°F. A burning wooden match releases approximately 1 Btu.
	Joule	J	The joule is the fundamental SI unit of energy. A joule is a newton-meter (a force of 1 newton acting over a 1-m distance). A joule is a fairly small unit of energy, so the kilo-joule (kJ), equal to 1000 J, is commonly used in building design.
	Watt-hour	Wh[b]	The watt-hour is a commonly used SI unit of energy (and also applies to I-P electricity consumption). 1 W = 1 J/s 1 Btu = 1.055 kJ 1 kJ = 0.9478 Btu
POWER			The term *power* is used to describe the rate of energy usage, production, or flow. Power is always associated with a time frame (often an hour in building design).
	British thermal unit per hour	Btu/h or Btuh^2	An I-P unit. Btu/h is used to express heat gains and losses and the design heating and cooling capacity of equipment.
	Watt	W	The watt is the SI unit of power and is used the same as Btu/h. 1 Btu/h = 0.0293 W 1 W = 3.412 Btu/h
	Horsepower	HP	An I-P expression of power, typically used to describe the capacity (size) of certain types of HVAC equipment (such as motors). 1 HP = 2545 Btu/h 1 HP = 746 W
HEAT FLOW			Heat flow is a particular form of power, and in building design is typically expressed in Btu/h or W. Several heat-flow-related properties of materials, with specific definitions and uses, are described herein. These properties are based upon a unit temperature difference.
	Conductivity	K	The rate of heat flow through a unit thickness of a homogeneous (such as wood or brick) material. I-P units: Btu in./h ft^2 °F SI units: W/m °C Btu in./h ft^2 °F × 0.1442 = W/m °C
	Conductance	C	The rate of heat flow through a specific nonhomogeneous object (such as a concrete masonry unit) or a defined thickness of a homogeneous material. I-P units: Btu/h ft^2 °F SI units: W/m^2 °C Btu/h ft^2 °F × 5.678 = W/m^2 °C
	Film or surface conductance	h	The conductance of an air film; same concept and units as conductance.
	Overall coefficient of heat flow	U (or U-factor)	The rate of heat flow through an assembly (window, wall, etc.) bounded by air on both sides. Includes the effects of all materials, air films, and air spaces. I-P units: Btu/h ft^2 °F SI units: W/m^2 °C Btu/h ft^2 °F × 5.678 = W/m^2 °C
	Resistance	R	A measure of resistance to heat flow; the reciprocal of conductivity (or conductance). Essentially the force required to cause a unit flow of heat. I-P units: h ft^2 °F/Btu SI units: m^2 °C/W h ft^2 °F/Btu × 0.176 = m^2 °C/W (I-P) R per in. × 6.93 = (SI) R per m
	Permeance	M	Although permeance deals directly with water vapor flow, it is related to heat flow through the need to add or remove heat to humidify or dehumidify a building. I-P units: grains/ft^2 h in. Hg SI units: ng/m^2 s Pa grains/ft^2 h in. Hg × 56.7 = ng/m^2 s Pa

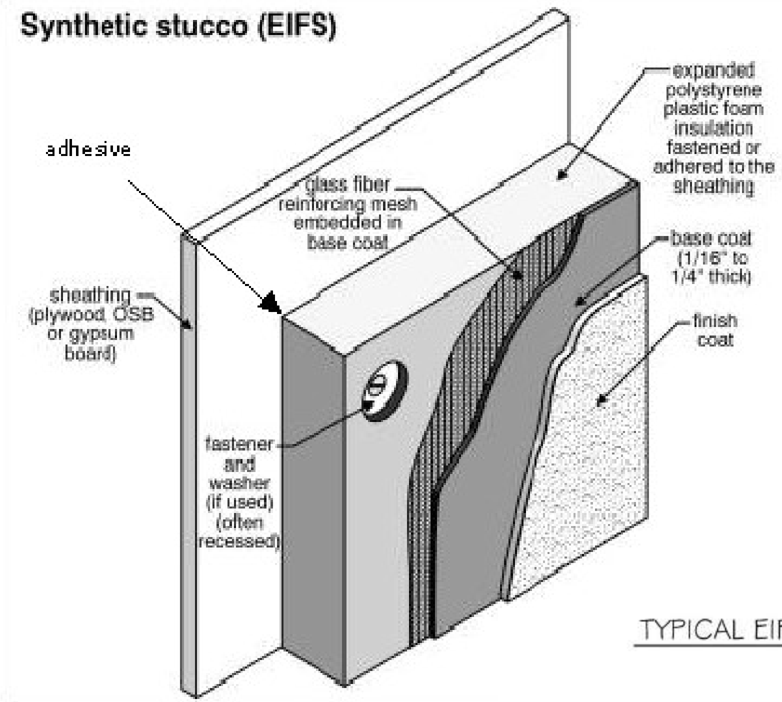
[a] A more extensive listing of I-P (inch-pound) and SI (Système International) units and conversions is provided in Appendix A.

[b] Units oddity: The alternative symbol "Btuh" is shorthand for Btu/h and does not imply a product of energy and time; on the other hand, Wh is a product (1 watt of power over a 1-hr period); furthermore, Btu (without a time unit) is a measure of energy, as is Wh (with a time unit).

Thermal classifications of materials

- Insulators, conductors, air films, air spaces
- Insulations:
  - materials: glass, rock wool, slag wool, perlite, vermiculite, cotton, synthetic fibers, cork, foamed rubber, polystyrene, etc.
  - forms:
    - Loose fill (as above a ceiling on the floor of an attic)
    - Insulating cement
    - Formed-in-place
    - Flexible and semi-rigid (batts and blankets): compressibility & adaptability
    - Rigid (little on-site adaptability)
    - EIFS (Exterior Insulation and Finish System)

EIFS: known as Dryvit (드라이비트 공법)



TYPICAL EIFS WALL SYSTEM