Built-Up Roofs

Built-up Roof Definition: An assembly of interacting components designed, as part of the building envelope, to protect the building interior, its contents, and its human occupants from the weather.

Design Factors: Roof must satisfy the local building code requirements and most probably an insurance company's requirement for wind and fire assistance. For each specific project, the best roof design results from the combination of many factors. Ultimately the roof specification should consider at least the following design factors:

1. First cost and life cycle (long term) cost
2. Value and vulnerability of building contents
3. Required roof life
4. Type of roof deck
5. Climate
6. Maintenance
7. Availability of materials and component applicators
8. Local practices.

Design of the built-up roof requires consultation with other members of the design team. The architect must confer with the mechanical engineer about the heating and cooling loads to design the insulation and to keep roof penetrations to a minimum. The architect must also consult with the structural engineer to ensure appropriate framing stiffness and slope to avoid ponding due to excessive deflections. The architect must also advise the owner to institute a periodic maintenance and inspection program. The single most important problem facing the designer is the roof slope. Through long, sad experience, roof designers have learned that ponded water is a major threat to the integrity of the roof system.

Roof Classification with Reference to Drainage:

a) Sloping: surfaced with overlapping shingles, tiles etc. Moderated to steep slope required for water-tightness. Shingles, tiles are overlapped for water control.

b) Flat or nearly flat: must be surfaced with a continuous waterproof membrane. - **Built-up roof systems.**

We will concentrate on the nearly flat category as most major buildings (Purdue University for example) use this type.

<u>Components of Built-up Roof System (Nearly Flat)</u>

A modern built-up roof system has the following basic components (see Fig. 1br):

a) structural deck,

b) vapor retarder, sometimes-used in roofs over humid interiors in northern climates (see Fig. 2br),

c) thermal insulation,

d) membrane: felts, bitumen, and mineral aggregate for surface protection,

e) flashing although not a basic component of the built-up roof system, is an important component. It seals joints wherever the membrane is either pierced or terminated - at gravel stops, walls, curbs, expansion joints, vents, and drains.

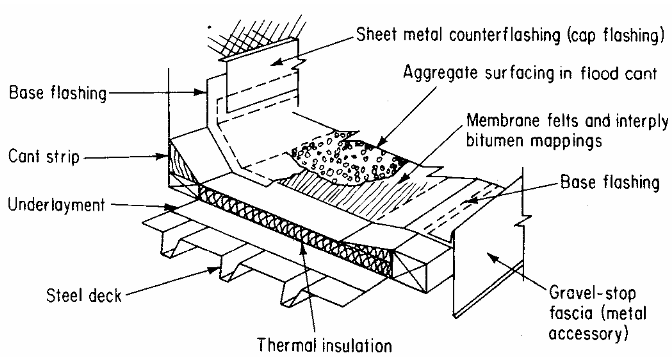


Figure 1br. Built-up system components

The built-up roof assembly including flashing, functions as a system in which each component depends on the satisfactory performance of the others. For example the integrity of the vapor retarder, insulation, and membrane depends on the satisfactory performance of the structural deck. Let’s discuss each component individually in the order they appear from the inside of the building:

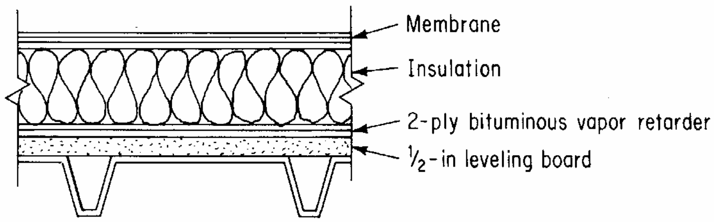


Figure 2br. Built-up roof system components including vapor retarder

<u>a) The Structural Deck</u>: it transmits gravity, earthquake and wind forces to the roof framing (structural system). Spans between roof beams or joists. Key design factors are:

1) Deflections
2) Anchorage of components
3) Strength and stability
4) Fire resistance

Types: - Reinforced concrete slabs, (CE 473)
- Timber or plywood (CE 479)
- Steel (ribbed metal deck, CE 479)

They can be classified as nailable or non-nailable for purposes of anchoring the vapor retarder, insulation, or membrane to the deck. For example, timber should only be nailed. Reinforced concrete is limited to non-nailed anchorages, except in rare instances when wood nailers are cast into its surface.

<u>b) Vapor barrier (Retarder - optional)</u>: can be made of many various materials. A common vapor retarder, often known as “vapor seal”, comprises three bituminous moppings with two plies of saturated felt or two bituminous moppings enclosing an asphalt-coated base sheet. It forms an essentially impermeable

surface on the warm, humid side of the roof sandwich, blocking the entry of water vapor. They are used only in roofing systems where the insulation is sandwiched between the structural deck and the built-up membrane. If properly designed can prevent condensation from forming within the built-up roofing system.

Water vapor flowing upward into the insulation impairs the insulation's thermal resistance, and may ultimately destroy the insulation itself. However, if the insulation contains moisture when installed, the vapor retarder does not allow it to escape because the retarder forms the bottom of a sandwich whose top is the membrane. Moreover, it is difficult to ensure its integrity under the rigors of construction. Thus a vapor retarder almost always admits some water vapor and the prudent designer will also design for its escape by providing some form of venting –edge venting or stack venting in large area roofs. During the winter in northern climates the water vapor flows upward through the roof, from a treated interior toward a colder drier exterior (i.e. from high to low pressure, along the pressure gradient.) A recommended vapor retarder assembly is the one shown in Fig. 2br.

To qualify as a vapor retarder, a materials vapor permeance rating should not exceed 0.1 perm. A material rated as 1 perm, admits 1 grain of water vapor per hour through 1 ft^2 of material under pressure differential of .491 psi (1 in. of Mercury, Hg). Vapor resistance is the reciprocal of permeance. <u>In severely cold northern climates, where the vapor-pressure differential may persist in the same upward direction for weeks, a virtually impermeable vapor barrier is needed to prevent a destructive moisture build-up within the built-up roof system. Normally, it should not be needed unless the interior relative humidity exceeds 40% and January temperature average less than 35^{o}F</u>.

<u>c) Thermal Insulation</u>: Reduces heating and cooling costs and prevents condensation on interior building surfaces. In cold weather, it raises interior surface temperatures, thus reducing radiative losses that chill

occupants. In the summer, it reduces interior surface. With its horizontal shearing resistance, it helps relieve stresses transferred to the membrane due to movement in the structural deck. It also provides an acceptable flat surface for the application of the membrane, particularly on steel decks. Although it is preferable to provide underneath the insulation a ½" board. It worst enemy is moisture or freeze-thaw damage.

Desired Characteristics:

- Good shearing strength, to distribute tensile stresses in the membrane and prevent splitting.
- Compressive strength to withstand traffic loads and, especially in the midwestern states, hailstone impact (30 psi minimum).
- Adhesive and cohesive strength to withstand wind uplift.
- Dimensional stability under thermal and moisture changes.

Because of these requirements, the design of thermal insulation and choice of materials is a complex task.

Drawbacks related to the use of insulation:

1. Increases the probability of condensation within the roof system in the winter months. The introduction of insulation between the deck and the membrane usually shifts the dew point from below the roof system to within the roof system. Thus migrating water vapor will condense probably at the underside of the membrane and will be trapped in the insulation material. Thus reducing its effectiveness.
2. It raises the surface, temperature in the summer (see Fig. 3br) by trapping heat at surface. This figure shows that extreme roof temperatures produced by insulation sandwiched between deck and roof membrane can make an insulated roof surface 40 °F hotter in sunlight and 10 °F colder at night than an uninsulated roof membrane. The extreme high temperatures accelerate the oxidizing chemical reactions that harden bitumen and make it more brittle and more subject to cracking and degradation in general. The extreme temperature cycling further accelerates the

membrane deterioration. The thermal contractions lead to splitting.

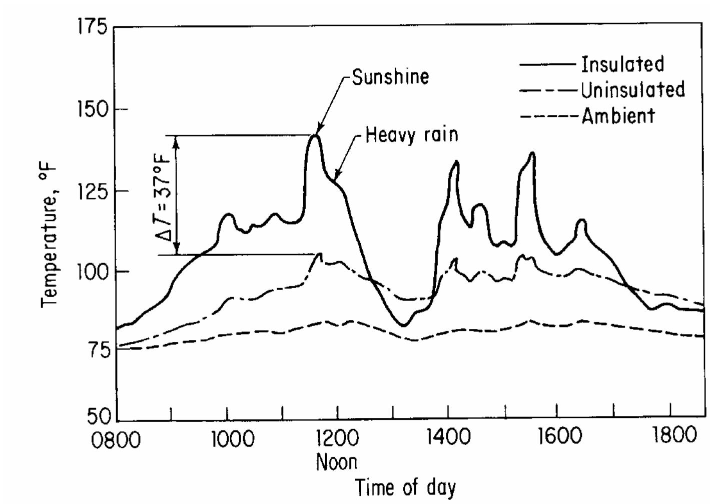


Figure 3br. Extreme roof temperatures produced by insulation

Types:

· *Rigid insulation:* prefabricated into boards applied directly to the deck surface.

· *Dual-purpose structural deck and insulating planks:* (Preformed, mineralized wood fiber, in 1½ to 3½ in. thick planks) - long wood fibers bonded with a cement binder (or resinous) and formed under a combination of heat and pressure. Some of these planks have an integrally bonded urethane foam surface, for a more efficient dual structural-insulating function (organic). Fiberboard insulations are the more vulnerable to moisture, which eventually roots and weakens any fibrous organic board.

· *Poured in place insulating concrete fills:*

Lightweight concrete using perlite or vermiculite aggregates, which, contains varied-sized cells that raise the concrete's thermal resistance to 14-20 times that of ordinary structural concrete.

- Perlite: silicaceous volcanic glass
- Vermiculite: expanded mica

They economically provide both insulation and a sloped roof surface for drainage. They also provide a smooth base on top of steel decks, precast concrete and other decks for applications of the membrane or additional insulation boards, if needed.

Another advantage over lighter materials, the more massive insulating materials such as lightweight concrete (which could weigh 50 times as much as say foamed plastic of an equivalent thermal resistance) stabilize the extreme fluctuations of an insulated roof's surface temperatures. A roof membrane directly on top of a light, highly efficient insulation reacts to the sudden heat of the sun like an empty pan on a burner. The metal in contact with a good insulator - in this case air - heats up faster than the metal of a pan filled with a poor insulator like water. A massive insulating material, like the water in the heated pan, has a greater heat capacity than a lighter more efficient insulator. Because they store and release heat slower than thinner, lighter insulation, these heavier materials tend to stabilize roof-surface temperatures. Thus, the temperature in the membrane reacts less quickly to the sudden heat of the sun emerging from behind the clouds, or to the chill of a sudden rain shower (sees Fig. 4br). The cooling-load temperature curves (for an interior temperature of 78 °F and for a summer day with maximum 95 °F air temperature) in Figure 4br show how increased roof-system mass reduces peak cooling load leading to a more uniform cooling-load curve from solar heat gain. Heavy roof construction retards solar heat gain by absorbing the heat and slowly releasing it. Lightweight roof construction in Fig. 4br is represented by steel deck + 1 to 2 in. of insulation + suspended ceiling, intermediate roof construction consists of wood decking = 1 to 2 in. of insulation + suspended ceiling, and heavy roof construction consists of 6 inches of concrete deck + 1 to 2 in. of insulation + suspended ceiling.

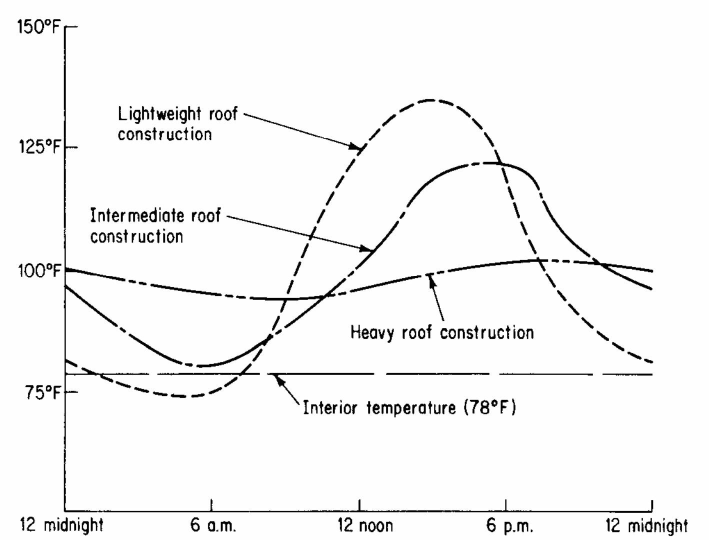


Figure 4br. Cooling-load curves from solar heat gain for three types of roofs

However, there are disadvantages with the use of this type of decking material. It poses an especially severe moisture-absorption problem because it may retain high-moisture content for years. Unless it is properly vented, lightweight concrete fill can maintain a considerable amount of entrapped water with the following consequences:

- shortened membrane life from increased probability of blistering (from vapor migrating upward into voids in the membrane) and splitting (from water weakening the membrane felts).
- Reduction in the roof system's thermal resistance. With dry-basis moisture (Eq. 1) of 50%, vermiculite aggregate concrete can suffer a reduction of up to 75% of its dry-state thermal

$$Dry\text{-}basis\ \%\ moisture = \frac{Total\ weight - oven\ dry\ wt.}{oven\text{-}dry\ wt.} \qquad (1)$$

insulating value.

The proper venting of this type of insulation material is critical. A poured-in-place structural concrete deck is a poor substrate for lightweight insulating concrete, and it is generally unacceptable to roofing manufacturers. **Lightweight insulating concrete should be restricted to decks with underside venting: slotted steel decks, permeable formboards (fiberglass), or precast sections with venting joints.** In general, although conventional wisdom of the roofing industry backs topside venting of insulation, it actually may do more harm than good. Underside venting is preferable. It is obligatory for lightweight concrete fills. As an alternative edge venting can be considered.

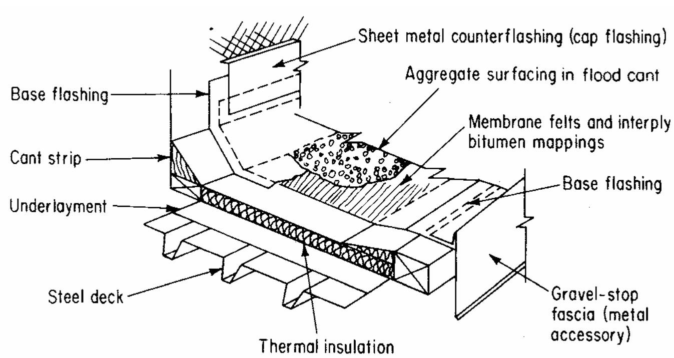
d) Built-up Membrane: (see Fig. 1br)

It is the weatherproofing component of the roof system:

Components:

- Felts: stabilize and strengthen bitumen
- Bitumen: water proofing agent

Fig. 1br



- Surfacing: mineral aggregate

Felts and bitumen are alternated, and the surfacing consists of mineral aggregate. The bitumen, asphalt, is the waterproofing agent. The felts stabilize and strengthen the bitumen (asphalt), control its flow when warm and tensile strength when cold and brittle. Mineral aggregate surfacing consists of gravel or crushed rock and it protects the bitumen from solar radiation, wind, and rain and foot traffic abrasion. The membrane forms a semi-flexible roof covering, with as few as two and as many as five plies of felt custom-built to fit the contours of the deck. No membrane can resist large movements in the deck or insulation. They have poor resistance against puncture. Where heavy traffic is expected, the designer should provide walkways.

e) Flashings: (see Fig 1br) they can be classified in two general types:

- Base Flashings: These form the upturned edges of the membrane where it is terminated. Normally made of bitumen and impregnated felts or fabrics.
- Counter flashing (cap-flashing): which shield the exposed joints of the base flashing. Often made of sheet metal: aluminum or galvanized steel. Must be paid close attention, as they are often source of roof leaks.

Principles of Thermal Insulation:

Heat is transferred through:

(1) Conduction

(2) Convection

(3) Radiation

Conduction: It depends on direct contact to transmit heat (kinetic energy).

Convection: It requires an air or liquid current, or some moving medium to transfer heat from one place to another.

Radiation: It transmits heat through electromagnetic waves emitted by all bodies (at an intensity varying with the fourth power of the absolute temperature).

Sun rays (radiation) account for the extremes in roof temperatures (surface), they can increase the surface temperature of an insulated roof 75^{o}F above air temperature, and on a clear night without cloud cover to reflect radiated heat back to earth, roof-surface temperature can be 10^{o}F or more below the air temperature. Thus, in a climate with design temperature varying from a summer maximum of 95^{o}F to a winter low of 0^{o}F, the annual variation in roof temperature may be 160^{o}F or more.

Because it conducts less heat to or from the roof surface, insulation within the roof sandwich "increases" the extremes in roof-surface temperature.

Heat primarily flows through building materials by means of conduction and convection. Through an air space all three modes of heat transfer are at work. Thermal insulation resists all three, but primarily conduction.

Factors Affecting Thermal Insulation:

1. % of air entrapment (air is a poor heat conductor) so the more air entrapped in all the cell, the lower the transfer of heat.

2. Capacity for impeding air flow.

3. Material's own thermal conductivity. A good thermal insulator is a poor thermal conductor.

4. Color: If it is sufficiently opaque, it resists the penetration of heat radiation.

5. Temperature: Rising temperature reduces insulation's thermal resistance (i.e. it increases thermal conductivity). Thermal conductivity increases with faster movement of gaseous molecules transmitting heat energy from one surface to another. Temperature is an index of this internal molecular movement.

6. Moisture: Water filling an insulating material void generally replaces air. Water's thermal conductivity is more than 20 times as much as air; at above-freezing temperatures, nearly 100 times as much at subfreezing temperatures. (Foamglass is the best: it has a water-resistant, closed-cell structure that protects it against water penetration)

Heat Flow Determination

Heat transfer calculations require the knowledge of four indicators of heat transmission:

1. **Thermal conductivity k -** heat [Btu] transferred per hour (Btu/hr) through a 1-in.-thick, 1-ft^2 area of homogeneous material per ^{o}F temperature difference from surface to surface. The unit for k is Btu(in)/[(hr)(ft^2)(^{o}F)]. To qualify as thermal insulation, a material must have a k $\leq$ 0.5.

2. **Conductance C** = k/thickness is the corresponding unit for a material of given thickness. (The unit for C is Btu/[(hr)(ft^2)(^{o}F)]. For a 2-in.-thick plank of material whose k = 0.20, C = 0.10.

3. **Thermal resistance R = 1/C** : indicates a material's resistance to conductive heat flow, the unit for R is $\frac{{}^oF \bullet hr \bullet ft^2}{Btu}$. A material with R = 5.0 (C = 0.2) means that for a 5^{o}F temperature difference surface-to-surface, 1 Btu/h flows through a 1-ft^2 specimen, or it would take 5 hours to transmit 1 Btu through 1 ft^2 per ^{o}F.

4. **Overall coefficient of transmission U**: measured in Btu/[(h) (ft^2 of construction) (^{o}F)] from air on one side to air on the other. It is a function of the several component materials in a wall or roof:

$$U \cong \frac{1}{\Sigma R}$$

where R = sum of the thermal resistances of the components, plus the resistances of the inside and outside air films.

To calculate the insulation's required thermal resistance, R_i, the designer usually starts with a target U factor set by the mechanical engineer. For the other components, the designer tabulates the resistances

R for all the other materials, including, outside and inside air films.

C, conductance of various material are available from the ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) Handbook and Product Directory (see Figure 5br).

NOTE: The customary units for resistance (*R*), either per inch (1/*k*) or for thickness stated (1/*C*), are given in Table 4.1. The SI units for resistance (last two columns) were calculated by taking the values from the two resistance columns under Customary Unit, multiplying by the factor 1/*k*(*r*/in.) and 1/*C*(*R*) for the appropriate conversion factor. Author's note: Actual (on-site) resistance values frequently are lower than the test-cell-determined "design" values listed in this table.

Description	Density (lb/ft³)	Conductivity, k $\left(\frac{\text{Btu-in.}}{\text{h-ft}^2\text{-°F}}\right)$	Conductance, C (h-ft²-°F)	Customary Unit Resistance, R[b] Per Inch Thickness 1/k	Customary Unit Resistance, R[b] For Thickness Listed, 1/C	Specific Heat, (Btu/lb-°F)	SI Unit Resistance, R[b] $\frac{(m\text{-}K)}{W}$	SI Unit Resistance, R[b] $\frac{(m^2\text{-}K)}{W}$
BUILDING BOARD								
Boards, Panels, Subflooring, Sheathing								
Woodboard Panel Products								
Asbestos-cement board	120	4.0	—	0.25	—	0.24	1.73	
Asbestos-cement board 0.125 in.	120	—	33.00	—	0.03			0.005
Asbestos-cement board 0.25 in.	120	—	16.50	—	0.06			0.01
Gypsum or plaster board 0.375 in.	50	—	3.10	—	0.32	0.26		0.06
Gypsum or plaster board 0.5 in.	50	—	2.22	—	0.45			0.08
Gypsum or plaster board 0.625 in.	50	—	1.78	—	0.56			0.10
Plywood (Douglas fir)	34	0.80	—	1.25	—	0.29	8.66	
Plywood (Douglas fir) 0.25 in.	34	—	3.20	—	0.31			0.05
Plywood (Douglas fir) 0.375 in.	34	—	2.13	—	0.47			0.08
Plywood (Douglas fir) 0.5 in.	34	—	1.60	—	0.62			0.11
Plywood (Douglas fir) 0.625 in.	34	—	1.29	—	0.77			0.19
Plywood or wood panels 0.75 in.	34	—	1.07	—	0.93	0.29		0.16
Vegetable fiberboard								
Sheathing, regular density[c] 0.5 in.	18	—	0.76	—	1.32	0.31		0.23
0.78125 in.	18	—	0.49	—	2.06			0.36
Sheathing intermediate density[c] 0.5 in.	22	—	0.82	—	1.22	0.31		0.21
Nail-base sheathing[c] 0.5 in.	25	—	0.88	—	1.14	0.31		0.20
Shingle backer 0.375 in.	18	—	1.06	—	0.94	0.31		0.17
Shingle backer 0.3125 in.	18	—	1.28	—	0.78			0.14
Sound deadening board 0.5 in.	15	—	0.74	—	1.35	0.30		0.24
Tile and lay-in panels, plain or acoustic	18	0.40	—	2.50	—	0.14	17.33	
0.5 in.	18	—	0.80	—	1.25			0.22
0.75 in.	18	—	0.53	—	1.89			0.33
Laminated paperboard	30	0.50	—	2.00	—	0.33	13.86	
Homogeneous board from repulped paper	30	0.50	—	2.00	—	0.28	13.86	
Hardboard[e]								
Medium density	50	0.73	—	1.37	—	0.31	9.49	
High density, service temp. service underlay	55	0.82	—	1.22	—	0.32	8.46	

Figure 5br. Thermal properties of construction materials
[From: Mechanical and Electrical Equipment for Buildings, Stein and Reynolds, 1992.

High density, std. tempered	63	1.00	—	1.00	—	0.32	6.93	
Particleboard[e]								
Low density	37	0.54	—	1.85	—	0.31	12.82	
Medium density	50	0.94	—	1.06	—	0.31	7.35	
High density	62.5	1.18	—	0.85	—	0.31	5.89	
Underlayment ... 0.625 in.	40	—	1.22	—	0.82	0.29		0.14
Wood subfloor ... 0.75 in.		—	1.06	—	0.94	0.33		0.17
BUILDING MEMBRANE								
Vapor—permeable felt	—	—	16.70	—	0.06			0.01
Vapor—seal, 2 layers of mopped 15-lb felt	—	—	8.35	—	0.12			0.02
Vapor—seal, plastic film	—	—	—	—	Negl.			
FINISH FLOORING MATERIALS								
Carpet and fibrous pad	—	—	0.48	—	2.08	0.34		0.37
Carpet and rubber pad	—	—	0.81	—	1.23	0.33		0.22
Cork tile ... 0.125 in.	—	—	3.60	—	0.28	0.48		0.05
Terrazzo ... 1 in.	—	—	12.50	—	0.08	0.19		0.01
Tile—asphalt, linoleum, vinyl, rubber	—	—	20.00	—	0.05	0.30		0.01
Vinyl asbestos						0.24		
Ceramic						0.19		
Wood, hardwood finish ... 0.75 in.			1.47		0.68			0.12
INSULATING MATERIALS								
BLANKET AND BATT[d,e]								
Mineral fiber, fibrous form processed from rock, slag, or glass								
Approx. 3–4 in.	0.3–2.0	—	0.091	—	11			1.94
Approx. 3.5 in.	0.3–2.0	—	0.077	—	13			2.29
Approx. 5.5–6.5 in.	0.3–2.0	—	0.053	—	19			3.35
Approx. 6–7.5 in.	0.3–2.0	—	0.045	—	22			3.87
Approx. 9–10 in.	0.3–2.0	—	0.033	—	30			5.28
Approx. 12–13 in.	0.3–2.0	—	0.026	—	38			6.69
BOARD AND SLABS								
Cellular glass	8.5	0.35	—	2.86	—	0.18	19.81	
Glass fiber, organic bonded	4–9	0.25	—	4.00	—	0.23	27.72	
Expanded perlite, organic bonded	1.0	0.36	—	2.78	—	0.30	19.26	
Expanded rubber (rigid)	4.5	0.22	—	4.55	—	0.40	31.53	
Expanded polystyrene extruded								
Smooth skin surface (CFC-12 exp.)	1.8–3.5	0.20	—	5.00	—	0.29	34.65	
Expanded polystyrene, molded beads	1.0	0.26	—	—	—	—	26.3	3.8
	1.25	0.25	—	—	—	—	27.8	4.0
	1.5	0.24	—	—	—	—	29.1	4.2
	1.75	0.24	—	—	—	—	29.1	4.2
	2.0	0.23	—	—	—	—	29.8	4.3

Figure 5br. Thermal properties of construction materials

[From: Mechanical and Electrical Equipment for Buildings, Stein and Reynolds, 1992

TABLE 4.2 Thermal Properties of Typical Building ...

Description	Density (lb/ft^3)	Conductivity, k $\left(\frac{Btu\text{-}in.}{h\text{-}ft^2\text{-}°F}\right)$	Conductance, C ($h\text{-}ft^2\text{-}°F$)	Customary Unit Resistance, R[b]: Per Inch Thickness 1/k	Customary Unit Resistance, R[b]: For Thickness Listed, 1/C	Specific Heat, (Btu/lb-°F)	SI Unit Resistance, R[b]: $\frac{(m\text{-}K)}{W}$	SI Unit Resistance, R[b]: $\frac{(m^2\text{-}K)}{W}$
Cellular polyurethane/polyisocyanurate[f] (CFC-11 exp.) (unfaced)	1.5	0.16–0.18	—	6.25–5.56	—	0.38	43.82–38.98	
Cellular polyisocyanurate[f] (CFC-11 exp.) (gas-permeable facers)	1.5–2.5	0.16–0.18	—	6.25–5.56	—	0.22	43.82–38.98	
Cellular polyisocyanurate[g] (CFC-11 exp.) (gas-impermeable facers)	2.0	0.14	—	7.20	—	0.22	51.75	
Cellular phenolic (closed cell) (CFC-11, CFC-113 exp.)	3.0	0.12	—	8.20	—	—	58.94	
Cellular phenolic (open cell)	1.8–2.2	0.23	—	4.40	—	—	31.62	
Mineral fiber with resin binder	15	0.29	—	3.45	—	0.17	23.91	
Mineral fiberboard, wet felted								
Core or roof insulation	16–17	0.34	—	2.94	—		20.38	
Acoustical tile	18	0.35	—	2.86	—	0.19	19.82	
Acoustical tile	21	0.37	—	2.70	—		18.71	
Mineral fiberboard, wet molded Acoustical tile[h]	23	0.42	—	2.38	—	0.14	16.49	
Wood or cane fiberboard								
Acoustical tile[h] 0.5 in.	—	—	0.80	—	1.25	0.31		0.22
Acoustical tile[h] 0.75 in.	—	—	0.53	—	1.89			0.33
Interior finish (plank, tile)	15	0.35	—	2.86	—	0.32	19.82	
Cement fiber slabs (shredded wood with portland cement binder	25–27	0.50–0.53	—	2.0–1.89	—	—	13.87	
Cement fiber slabs (shredded wood with magnesia oxysulfide binder)	22	0.57	—	1.75	—	0.31	12.16	
LOOSE FILL								
Cellulosic insulation (milled paper or wood pulp)	2.3–3.2	0.27–0.32	—	3.13–3.70	—	0.33	21.69–25.64	
Sawdust or shavings	8.0–15.0	0.45	—	2.22	—	0.33	15.39	
Wood fiber, softwoods	2.0–3.5	0.30	—	3.33	—	0.33	23.08	
Perlite, expanded			—	2.70	—	0.26	18.71	
	2.0–4.1	0.27–0.31	3.7–3.3					
	4.1–7.4	0.31–0.36	3.3–2.8					
	7.4–11.0	0.36–0.42	2.8–2.4					
Mineral fiber (rock, slag or glass)								
Approx. 3.5 in. (closed sidewall application)	2.0–3.5	—	—		12–14			
Approx.[e] 3.75–5 in.	0.6–2.0	—	—		11	0.17		1.94

Figure 5br. Thermal properties of construction materials
[From: Mechanical and Electrical Equipment for Buildings, Stein and Reynolds, 1992.

Approx.* 6.5–8.75 in.	0.6–2.0	—	—		19			3.35
Approx.* 7.5–10 in.	0.6–2.0	—	—		22			3.87
Approx.* 10.25–13.75 in.	0.6–2.0	—	—		30			5.28
Vermiculite, exfoliated	7.0–8.2	0.47	—	2.13	—	3.20	14.76	
	4.0–6.0	0.44	—	2.27	—		15.73	
MASONRY MATERIALS								
Concretes								
Cement mortar	105–135	5.0–10.5	—	0.20–0.10	—	—	1.39–0.69	
Gypsum-fiber concrete 87.5% gypsum, 12.5% wood chips	51	1.66	—	0.60	—	0.21	4.16	
Lightweight aggregates including expanded shale, clay or slate; expanded slags; cinders; pumice; vermiculite; also cellular concretes	120	5.5–11.0	—	0.18–0.09	—	—	1.25–0.62	
	100	3.7–5.9	—	0.27–0.17	—	0.20	1.87–1.18	
	80	2.5–3.5	—	0.40–0.29	—	0.20	2.77–2.01	
	60	1.6–1.8	—	0.63–0.56	—	—	4.36–3.88	
	40	0.93–1.11	—	1.08–0.90	—	—	7.49–6.24	
	30	0.75–0.91	—	1.33–1.10	—	0.20	9.22–7.63	
	20	0.63–0.83	—	1.59–1.20	—	—	11.02–8.32	
Perlite, expanded	50	1.4–1.8	—	0.71–0.56	—	—	4.92–3.88	
	40	0.93		1.08			7.48	
	30	0.71		1.41			9.77	
	20	0.50		2.00		0.32	13.86	
Sand and gravel or stone aggregate (oven dried)	140	8.0–16.0	—	0.13–0.06	—	0.18–0.22	0.90–0.42	
Sand and gravel or stone aggregate (not dried)	140	10.0–20.0	—	0.10–0.05	—	0.19–0.24	0.69–0.35	
Stucco	116	5.0	—	0.20			1.39	
MASONRY UNITS								
Brick, common	80	2.2–3.2	—	0.45–0.31	—	—	3.12–2.15	
	90	2.7–3.7	—	0.37–0.27	—	—	2.56–1.87	
	100	3.3–4.3	—	0.30–0.23	—	—	2.08–1.59	
	110	3.5–5.5	—	0.29–0.18	—	—	2.01–1.25	
	120	4.4–6.4	—	0.23–0.16	—	0.19	1.59–1.11	
	130	5.4–9.0	—	0.19–0.11	—	—	1.32–0.76	
Clay tile, hollow:								
1 cell deep 3 in.	—	—	1.25	—	0.80	0.21		0.14
1 cell deep 4 in.	—	—	0.90	—	1.11			0.20
2 cells deep 6 in.	—	—	0.66	—	1.52			0.27
2 cells deep 8 in.	—	—	0.54	—	1.85			0.33
2 cells deep 10 in.	—	—	0.45	—	2.22			0.39
3 cells deep 12 in.	—	—	0.40	—	2.50			0.44
Concrete blocks[f]								
Limestone aggregate								
8 in., 36 lb, 138 lb/ft³ concrete, 2 cores	—	—	—	—	—	—		
Same with perlite-filled cores	—	—	0.48	—	2.1	—		
12 in., 55 lb, 138 lb/ft³ concrete, 2 cores	—	—	—	—	—	—		
Same with perlite-filled cores	—	—	0.27	—	3.7	—		

Figure 5br. Thermal properties of construction materials
[From: Mechanical and Electrical Equipment for Buildings, Stein and Reynolds, 1992

Description	Density (lb/ft³)	Conductivity, k $\left(\frac{Btu\text{-}in.}{h\text{-}ft^2\text{-}°F}\right)$	Conductance, C $(h\text{-}ft^2\text{-}°F)$	Customary Unit Resistance, R[b] Per Inch Thickness 1/k	Customary Unit Resistance, R[b] For Thickness Listed, 1/C	Specific Heat, (Btu/lb-°F)	SI Unit Resistance, R[b] $\frac{(m\text{-}K)}{W}$	SI Unit Resistance, R[b] $\frac{(m^2\text{-}K)}{W}$
Normal weight aggregate (sand and gravel)								
8 in., 33–36 lb, 126–136 lb/ft³ concrete, 2 or 3 cores	—	—	0.90–1.03	—	1.11–0.97	0.22		
Same with perlite-filled cores	—	—	0.50	—	2.0	—		
Same with verm. filled cores	—	—	0.52–0.73	—	1.92–1.37	—		
12 in., 50 lb, 125 lb/ft³ concrete, 2 cores	—	—	0.81	—	1.23	0.22		
Medium weight aggregate (combinations of normal weight and lightweight aggregate)								
8 in., 26–29 lb, 97–112 lb/ft³ concrete, 2 or 3 cores	—	—	0.58–0.78	—	1.71–1.28	—		
Same with perlite-filled cores	—	—	0.27–0.44	—	3.7–2.3	—		
Same with verm. filled cores	—	—	0.30	—	3.3	—		
Same with molded EPS (beads) filled cores	—	—	0.32	—	3.2	—		
Same with molded EPS inserts in cores	—	—	0.37	—	2.7	—		
Lightweight aggregate (expanded shale, clay, slate or slag, pumice)								
6 in., 16–17 lb, 85–87 lb/ft³ concrete, 2 or 3 cores	—	—	0.52–0.61	—	1.93–1.65	—		
Same with perlite-filled cores	—	—	0.24	—	4.2	—		
Same with verm. filled cores	—	—	0.33	—	3.0	—		
8 in., 19–22 lb, 72–86 lb/ft³ concrete,	—	—	0.32–0.54	—	3.2–1.90	0.21		
Same with perlite-filled cores	—	—	0.15–0.23	—	6.8–4.4	—		
Same with verm. filled cores	—	—	0.19–0.26	—	5.3–3.9	—		
Same with molded EPS (beads) filled cores	—	—	0.21	—	4.8	—		
Same with UF foam-filled cores	—	—	0.22	—	4.5	—		
Same with molded EPS inserts in cores	—	—	0.29	—	3.5	—		
12 in., 32–36 lb, 80–90 lb/ft³ concrete, 2 or 3 cores	—	—	0.38–0.44	—	2.6–2.3	—		
Same with perlite-filled cores	—	—	0.11–0.16	—	9.2–6.3	—		
Same with verm. filled cores	—	—	0.17	—	5.8	—		
Stone, lime or sand	—	12.50	—	0.08	—	0.19	0.55	
Gypsum partition tile:								
3 × 12 × 30 in. solid	—	—	0.79	—	1.26	0.19		0.22
3 × 12 × 30 in. 4-cell	—	—	0.74	—	1.35			0.24
4 × 12 × 30 in. 3-cell	—	—	0.60	—	1.67			0.29
METALS **(See ASHRAE Handbook of Fundamentals)**								
PLASTERING MATERIALS								
Cement plaster, sand aggregate	116	5.0	—	0.20	—	0.20	1.39	

Figure 5br. Thermal properties of construction materials
[From: Mechanical and Electrical Equipment for Buildings, Stein and Reynolds, 1992

Sand aggregate .... 0.375 in.	—	—	13.3	—	0.08	0.20		0.01
Sand aggregate .... 0.75 in.	—	—	6.66	—	0.15	0.20		0.03
Gypsum plaster:								
Lightweight aggregate .... 0.5 in.	45	—	3.12	—	0.32			0.06
Lightweight aggregate .... 0.625 in.	45	—	2.67	—	0.39			0.07
Lightweight agg. on metal lath .... 0.75 in.	—	—	2.13	—	0.47			0.08
Perlite aggregate	45	1.5	—	0.67	—	0.32	4.64	
Sand aggregate	105	5.6	—	0.18	—	0.20	1.25	
Sand aggregate .... 0.5 in.	105	—	11.10	—	0.09			0.02
Sand aggregate .... 0.625 in.	105	—	9.10	—	0.11			0.02
Sand aggregate on metal lath .... 0.75 in.	—	—	7.70	—	0.13			0.02
Vermiculite aggregate	45	1.7	—	0.59	—		4.09	
ROOFING								
Asbestos-cement shingles	120	—	4.76	—	0.21	0.24		0.04
Asphalt roll roofing	70	—	6.50	—	0.15	0.36		0.03
Asphalt shingles	70	—	2.27	—	0.44	0.30		0.08
Built-up roofing .... 0.375 in.	70	—	3.00	—	0.33	0.35		0.06
Slate .... 0.5 in.	—	—	20.00	—	0.05	0.30		0.01
Wood shingles, plain and plastic film faced	—	—	1.06	—	0.94	0.31		0.17
Spray Applied								
Polyurethane foam	1.5–2.5	0.16–0.18	—	6.25–5.56	—	43.33–38.54		
Ureaformaldehyde foam	0.7–1.6	0.22–0.28	—	4.55–3.57	—	31.54–24.75		
Cellulosic fiber	3.5–6.0	0.29–0.34	—	3.45–2.94	—	23.92–20.38		
Glass fiber	3.5–4.5	0.26–0.27	—	3.85–3.70	—	26.69–25.65		
SIDING MATERIALS (ON FLAT SURFACE)								
Shingles								
Asbestos-cement	120	—	4.75	—	0.21			0.04
Wood, 16 in., 7.5 exposure	—	—	1.15	—	0.87	0.31		0.15
Wood, double, 16-in., 12-in. exposure	—	—	0.84	—	1.19	0.28		0.21
Wood, plus insul. backer board, 0.3125 in.	—	—	0.71	—	1.40	0.31		0.25
Siding								
Asbestos-cement, 0.25 in., lapped	—	—	4.76	—	0.21	0.24		0.04
Asphalt roll siding	—	—	6.50	—	0.15	0.35		0.03
Asphalt insulating siding (0.5 in. bed.)	—	—	0.69	—	1.46	0.35		0.26
Hardboard siding, 0.4375 in.	40	—	0.49	—	0.67	0.28	4.65	
Wood, drop, 1 × 8 in.	—	—	1.27	—	0.79	0.28		0.14
Wood, bevel, 0.5 × 8 in., lapped	—	—	1.23	—	0.81	0.28		0.14
Wood, bevel, 0.75 × 10 in., lapped	—	—	0.95	—	1.05	0.28		0.18
Wood, plywood, 0.375 in., lapped	—	—	1.59	—	0.59	0.29		0.10
Aluminum or steel,[i] over sheathing								
Hollow-backed	—	—	1.61	—	0.61	0.29		0.11

Figure 5br. Thermal properties of construction materials
[From: Mechanical and Electrical Equipment for Buildings, Stein and Reynolds, 1992

Description	Density (lb/ft³)	Conductivity, k (Btu-in./h-ft²-°F)	Conductance, C (h-ft²-°F)	Customary Unit Resistance, R[b] Per Inch Thickness 1/k	Customary Unit Resistance, R[b] For Thickness Listed, 1/C	Specific Heat, (Btu/lb-°F)	SI Unit Resistance, R[b] (m-K)/W	SI Unit Resistance, R[b] (m²-K)/W
Insulating-board backed nominal 0.375 in.	—	—	0.55	—	1.82	0.32		0.32
Insulating-board backed nominal 0.375 in., foil backed			0.34		2.96			0.52
Architectural glass	—	—	10.00	—	0.10	0.20		0.02
WOODS (12% Moisture Content)[c,k]								
Hardwoods						0.39		
Oak	41.2–46.8	1.12–1.25	—	0.89–0.80	—		6.17–5.55	
Birch	42.6–45.4	1.16–1.22	—	0.87–0.82	—		6.03–5.68	
Maple	39.8–44.0	1.09–1.19	—	0.92–0.84	—		5.68–5.82	
Ash	38.4–41.9	1.06–1.14	—	0.94–0.88	—		6.51–6.10	
Softwoods						0.39		
Southern pine	35.6–41.2	1.00–1.12	—	1.00–0.89	—		6.93–6.17	
Douglas fir–larch	33.5–36.3	0.95–1.01	—	1.06–0.99	—		7.39–6.86	
Southern cypress	31.4–32.1	0.90–0.92	—	1.11–1.09	—		7.69–7.56	
Hem–fir, spruce–pine–fir	24.5–31.4	0.74–0.90	—	1.35–1.11	—		9.36–7.69	
West Coast woods, cedars	21.7–31.4	0.68–0.90	—	1.48–1.11	—		10.26–7.69	
California redwood	24.5–28.0	0.74–0.82	—	1.35–1.22	—		9.36–8.46	

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[a] Representative values for dry materials at 75 F. They are intended as design (not specification) values for materials in normal use. Insulation materials in actual service may have thermal values which vary from design values depending on their in-situ properties such as density and moisture content. For properties of a particular product, use the value supplied by the manufacturer or by unbiased tests.

[b] Resistance values are the reciprocals of *C* before rounding off *C* to two decimal places.

[c] Forest Products Laboratory Wood Handbook, USDA Handbook 72, 1974, Tables 3 and 4.

[d] Does not include paper backing and facing, if any. Where insulation forms a boundary (reflective or otherwise) of an air space, see Tables 4.3 and 4.4 for the insulating value of air space for the appropriate effective emittance and temperature conditions of the space.

[e] Conductivity varies with fiber diameter. Insulation is produced in different densities; therefore, there is a wide variation in thickness for the same *R* value among manufacturers. No effort should be made to relate any specific *R* value to any specific thickness. Commercial thicknesses generally available range from 2 to 8.5.

[f] Values are for aged, unfaced, board stock. For change in conductivity with age of expanded urethane, see 1989 *Handbook of Fundamentals*, chapter 20.

[g] Time-aged values for board stock with gas-barrier quality (0.001 in. thickness or greater) aluminum foil facers on two major surfaces.

[h] Insulating values of acoustical tile vary, depending on density of the board and on type, size, and depth of perforations.

[i] Values for fully grouted block may be approximated using values for concrete with a similar unit weight.

[j] Values for metal siding applied over flat surfaces vary widely, depending on amount of ventilation of air space beneath the siding; whether airspace is reflective or nonreflective; and on thickness, type, and application of insulating backing board used. Values given are averages for use as design guides, and were obtained from several guarded hotbox tests (ASTM C236) or calibrated hotbox (ASTM 967) on hollow-backed types and types made using backing boards of wood fiber, foamed plastic, and glass fiber. Departures of ±50% or more from the values given may occur.

[k] L. Adams: Supporting cryogenic equipment with wood (*Chemical Engineering*, May 17, 1971). Conductivity values listed are for heat transfer across the grain.

Figure 5br. Thermal properties of construction materials
[From: Mechanical and Electrical Equipment for Buildings, Stein and Reynolds, 1992

Roof Drainage

Why Drainage in Flat Roofs (BUR)?

Damage from ponding on BUR

1) Freezing of ponded water which has penetrated can delaminate or split the membrane.

2) Standing water can promote the growth of vegetation, fungi etc.

3) Temperature variations on a randomly ponded roof can warp and wrinkle the membrane.

4) Evidence of ponded water nullifies some manufacturers' roofing bonds. (Manufacturer's bond - issued by manufacturer guarantees the owner that the manufacturer will finance membrane repairs required to stop leaks arising from ordinary wear).

Drainage systems are divided into two categories:

- interior
- peripheral

In an interior drainage system, water flows from elevated peripheral areas to interior roof drains. Leaders (usually located at columns) conduct water through the building interior (see Figure 6br).

In a peripheral system water flows in the opposite direction to leaders and scuppers located outside the building. The main advantage of the interior system is that it is weather protected.

To ensure good drainage, specify a minimum of two drains for a total roof area of less than 10,000 ft^2. Add at least one additional drain for each additional 10,000 ft^2 of roof area and limit the maximum spacing in any direction to 75 ft.

Provide sumps at drains to prevent local ponding. Required drain pipe size depends on:

· contributory area
· rainfall rate (in./hr)
· roof slope (in./ft)

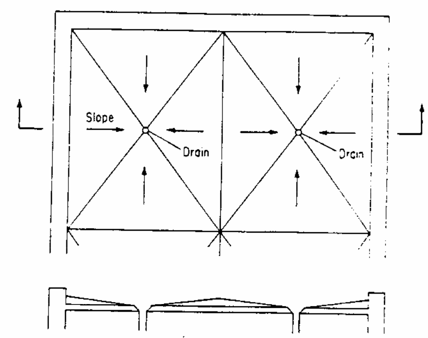
For example:

A 1in./hr rainfall rate builds up at a 0.0104 gpm/ft^2 rate. (1 gal = 231 in^3, gpm/ft^2 = 144/(231 x 60) = 0.0104 gpm (ft.in.hr) rainfall). For Indiana (see Figure 6br), say Indianapolis, rainfall is 2.8 in./hr. Hence gpm (2.8)(.0104) = 0.029. For a 10,000 ft^2 contributing drain area, you need a drain capacity of

From Figure 6br a single interior vertical drain pipe diameter of 5" would provide 360 gpm, giving adequate

$$0.029 \; x \; 10000 = 291.2 \; gpm$$

capacity. For the first 10,000 ft^2, since a minimum of two drains is required (with a capacity of at least 146 gpm each), a 4” pipe diameter would be adequate.



Inverted pyramidal pattern with interior drains is the most dependable roof drainage.

Maximum Rainfall Rates (in./h)*

State & city	Rainfall	State & city	Rainfall
Alabama:		Macon	3.7
Anniston	3.6	Savannah	4.0
Birmingham	3.6	Thomasville	4.0
Mobile	4.2	***Hawaii:***	
Montgomery	3.8	Hilo	3.0
Alaska:		Honolulu	3.2
Anchorage	1.0	***Idaho:***	
Fairbanks	1.2	Boise	1.1
Juneau	1.0	Lewiston	1.1
Arizona:		Pocatello	1.3
Phoenix	2.5	***Illinois:***	
Tucson	3.0	Cairo	3.4
Arkansas:		Chicago	3.0
Bentonville	3.8	Peoria	3.1
Fort Smith	3.9	Springfield	3.3
Little Rock	3.7	***Indiana:***	
California:		Evansville	3.0
Bakersfield	1.5	Fort Wayne	2.6
Eureka	1.6	Indianapolis	2.8
Fresno	1.5	South Bend	2.8
Los Angeles	2.0	Terre Haute	2.9
Sacramento	1.4	***Iowa:***	
San Diego	1.5	Burlington	3.3
San Francisco	1.6	Davenport	3.2

Pipe Sizing Data*

	Flow Capacity for storm drainage systems, gpm			
		Horiz. storm drainage piping		
		Slope, in./ft		
Pipe diameter, in.	***Roof drain and vertical leaders***	⅛	¼	½
2	30			
2½	54			
3	92	34	48	69
4	192	78	110	157
5	360	139	197	278
6	563	223	315	446
8	1208	479	679	958
10		863	1217	1725
12		1388	1958	2775
15		2479	3500	4958

*Tabulated data from Josam Manufacturing Co.

Figure 6br. Drain pipe design