CAE 463/524
Building Enclosure Design
Fall 2013

Additional lecture materials not covered in class
Application notes

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Dr. Brent Stephens, Ph.D.
Civil, Architectural and Environmental Engineering
Illinois Institute of Technology
brent@iit.edu

Introduction

- These slides are meant to provide additional information on a range of applications related to building enclosures

- These slides will take the place of the lecture(s) that were missed due to conference travel

- You will not be graded on this material

Outline

- Fenestration (also covered in 331/513 Building Science)

FENESTRATION

Lecture objectives

- Understand basic components of fenestration
- Understand various ways of representing heat transfer through fenestration
- Understand basic calculations for U values
- Understand basic calculations of SHGC

Fenestration

- Fenestration
  - Areas of the enclosure that let visible light through
  - Also the term used for windows, doors, and skylights
  - Fenestration concerns the units themselves, as well as placement and shading
    - Two buildings with the same windows that are located in different positions are considered to have different fenestration

- Placement is important both visually and for building physics
  - By changing the locations of windows and shading devices, the use of electric lighting and overall building energy use can be drastically altered

Fenestration and energy use

- Fenestration impacts building energy use by:
  - Thermal heat transfer
    - Conduction, convection, long-wave radiation
    - Use appropriate materials/assemblies to minimize heat transfer
  - Solar heat gain
    - Short-wave radiation
    - Utilize in cold climates; restrict in warm climates
  - Air leakage
    - Penetrations in walls and roofs for fenestration can be problematic
  - Daylighting
    - Utilize to reduce lighting requirements

Fenestration components

Fenestration consists of three main components:

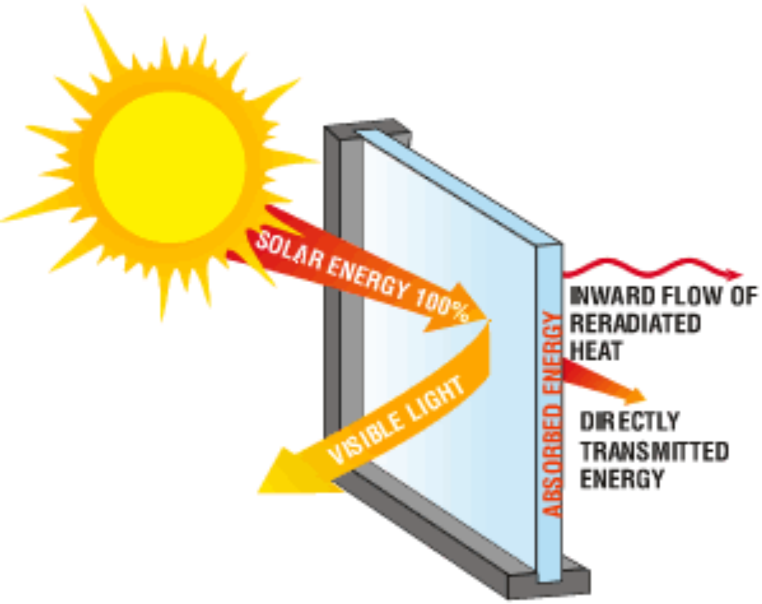
1. Glazing
   - The main part of fenestration that lets the light through
   - Usually glass
     - Occasionally plastic
   - A layer is called a glaze or a pane or a lite
2. Framing
   - The material that holds the glazing in place
     - Attaches it to the rest of the enclosure
   - Usually wood, metal, plastic or fiberglass
3. Shading devices and/or screens
   - A unit may or may not have shading
   - Either from other building components or shading devices that may or may not be an integral part of the overall assembly

Glazing units

- In some climates, single glazes of glass are used in windows or curtain wall assemblies
  - Single glazes have high U values (low R values)
    - Poor insulators
  - Single glazes must be quite thick for large sizes to handle wind loads
    - Thick glazes can have color and visibility distortions

- Throughout most of the U.S., a multiple glaze unit or insulated window assembly should be used
  - Also called an insulated glazing unit (IGU)
  - Much of IIT has single glaze windows because Mies van der Rohe used them
    - Before IGUs were available

Heat gain through fenestration



Energy flows through fenestration via:

- Conductive and convective heat transfer caused by I/O temperature difference (and wind speeds)
- Net long-wave radiation (> 2.5 μm wavelength) radiative exchange between fenestration and its surroundings
  - Also between glazing layers
- Short-wave (< 2.5 μm) solar radiation incident on the fenestration product
  - Part of the incident solar energy is **transmitted** and eventually absorbed by the room surfaces
    - That energy adds to heat gain
  - Part of the incident solar energy is **absorbed** by the fenestration and reradiated as thermal energy toward the inside

Total heat transfer

The heat gain through fenestration consists of two main components:

- $Q_{thermal}$ = heat transfer between indoor and outdoor air
  - This is positive or negative depending on temperature

- Q_{solar} = heat transfer from solar radiation
  - This is always a positive number

The total heat transfer through fenestration will then be:

$$Q_{total} = Q_{thermal} + Q_{solar}$$

Basic steady-state solution

- If we limit ourselves to steady state conditions, we can write the thermal and solar heat gains in terms of temperature differences and incident radiation as:

$$Q_{total} = U_{total} A_{proj}(T_{out} - T_{in}) + (SHGC) A_{proj} I_{total}$$

where

- U_{total} is the overall U factor for the assembly (W/m^{2}K)
- A_{proj} = total projected area of assembly (m^2)
- $SHGC$ = solar heat gain coefficient (dimensionless)
- I_{total} = total incident solar irradiance (W/m^2)

Another breakdown

- The previous equation is useful for bulk estimates of heat transfer through fenestration

- For more complete building heating and cooling models (heat balance, radiant time series, etc.), we need to break the solar term down further into:
  - Transmitted solar
  - Absorbed and reradiated thermal
  - Absorbed and conducted thermal

- So SHGC alone is not enough for detailed calculations
  - But good for overall estimate
  - More on SHGC later

FENESTRATION: THERMAL HEAT TRANSFER

Let us first begin with U Values

- Since fenestration has a frame and glazing, we must consider heat transfer through both
  - Need to know both areas A_{frame} and A_{glass}

- Because there is complex 2-D heat transfer around the frame/glazing interface, we break the glazing into:
  - (1) Frame area
  - (2) Center area
  - (3) Glazing area around the frame (i.e., "edge of glass")
    - This is the 2.5 inches (63 mm) of glazing adjacent to the frame
    - The center of glass area then is $A_{center} = A_{glass} - A_{edge\ of\ glass}$

- Each region has its own U value
- Total area:

$$A_{proj} = A_{frame} + A_{glass} = A_{frame} + A_{center} + A_{edge\ of\ glass}$$

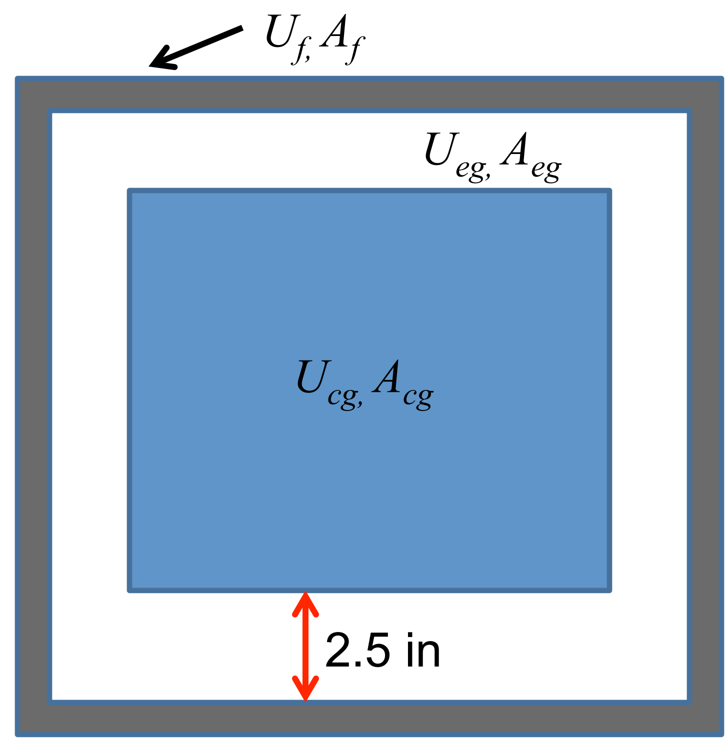
Computing the overall U Value

- The overall U value is therefore:

$$U_{tot} = \frac{U_{cg}A_{cg} + U_{eg}A_{eg} + U_{f}A_{f}}{A_{proj}}$$

where

- U_{cg} = center of glass U value
- U_{eg} = edge of glass U value
- U_{f} = U value of frame
- A_{cg} = center of glass area
- A_{eg} = edge of glass area
- A_{f} = frame area



A_{eg} is a 2.5 inch (6.4 cm) strip next to the frame

Computing U_{cg} for a single glaze

For a clear single glaze the computation can use simple conduction + convection

$$U_{cg} = \left(\frac{1}{h_{out}} + \frac{1}{h_{in}} + \frac{L}{k} \right)^{-1}$$

- h_{out}, h_{in} are the exterior and interior convection coefficients, L is the thickness, and k the glass conductivity

- Thermal conductivity of pure glass is ~1 W/mK

h_{out} and h_{in}

- h_{out} depends upon outside temperature and wind speed
  - For typical winter conditions:
    - h_{out} = 29 W/(m^{2}K) is typically used
- h_{in} from natural convection depends upon window size and temperature differences
  - h_{in} =8.3 W/(m^{2}K) is typically used
  - ASHRAE HOF 2005 gives values for better accuracy

Table 2 Indoor Surface Heat Transfer Coefficient h_i in W/(m^2·K), Vertical Orientation (Still Air Conditions)

			Winter Conditions			Summer Conditions		
Glazing ID	Glazing Type	Glazing Height m	Glass Temp. °C	Temp. Diff. °C	h_i W/(m^2·K)	Glass Temp. °C	Temp. Diff. °C	h_i W/(m^2·K)
1	Single glazing	0.6	–9	30	8.04	33	9	4.12
		1.2	–9	30	7.42	33	9	3.66
		1.8	–9	30	7.10	33	9	3.43
5	Double glazing with 12.7 mm airspace	0.6	7	14	7.72	35	11	4.28
		1.2	7	14	7.21	35	11	3.80
		1.8	7	14	6.95	35	11	3.55
23	Double glazing with e = 0.1 on surface 2 and 12.7 mm argon space	0.6	13	8	7.44	34	10	4.20
		1.2	13	8	7.00	34	10	3.73
		1.8	13	8	6.77	34	10	3.49
43	Triple Glazing with e = 0.1 on surfaces 2 and 5 and 12.7 mm argon spaces	0.6	17	4	7.09	40	16	4.61
		1.2	17	4	6.72	40	16	4.08
		1.8	17	4	6.53	40	16	3.81

Notes:
Glazing ID refers to fenestration assemblies in Table 4.
Winter conditions: room air temperature t_i = 21°C, outdoor air temperature t_o = –18°C, no solar radiation
Summer conditions: room air temperature t_i = 24°C, outdoor air temperature t_o = 32°C, direct solar irradiance E_D = 748 W/m^2
$h_i = h_{ic} + h_{iR} = 1.46(\Delta T/L)^{0.25} + e\Gamma(T_g^4 - T_i^4)/\Delta T$
where $\Delta T = T_g - T_i$, K; L = glazing height, m; T_g = glass temperature, K

Computing U_{cg} for a single glaze

$$U_{cg} = \left(\frac{1}{h_{out}} + \frac{1}{h_{in}} + \frac{L}{k} \right)^{-1}$$

$$U_{cg} = \left(\frac{1}{29 \frac{\mathrm{W}}{\mathrm{m^2K}}} + \frac{1}{8 \frac{\mathrm{W}}{\mathrm{m^2K}}} + \frac{0.003\ \mathrm{m}}{1\ \frac{\mathrm{W}}{\mathrm{mK}}} \right)^{-1} \approx 6 \frac{\mathrm{W}}{\mathrm{m^2K}}$$

Q: What contributes most to heat transfer resistance?

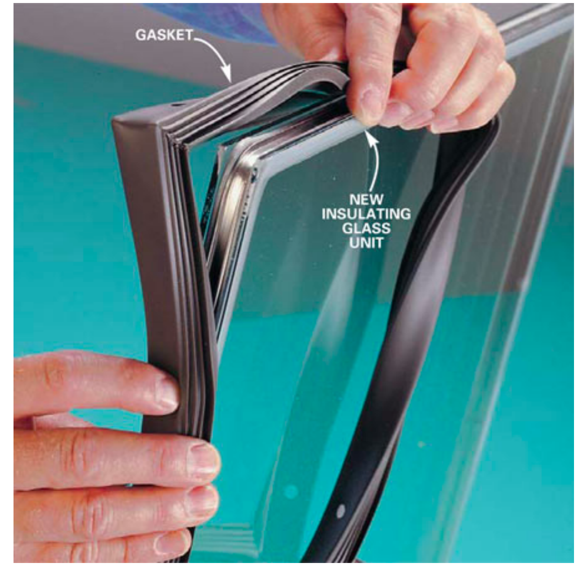
A: Not the glass! Actually the interior convection

What about double- and triple-glazed windows?

- Insulated glazing units (IGUs)
  - 2 or more glazes of glass
    - Separated with a spacer
  - Double Glazing: 2 sheets
  - Triple Glazing: 3 sheets
    - Much less common

- Primary purpose: thermal control
  - 2 glazes cuts heat loss nearly in half
  - 3 glazes cuts heat loss by about 2/3

- Higher initial costs but …
  - Reduces operating costs
  - Increases comfort
  - Provides additional architectural options



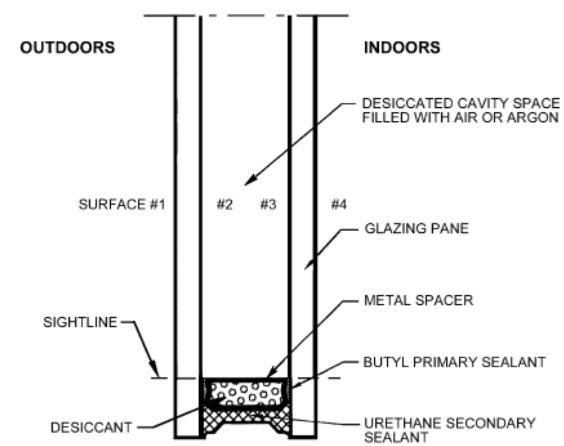
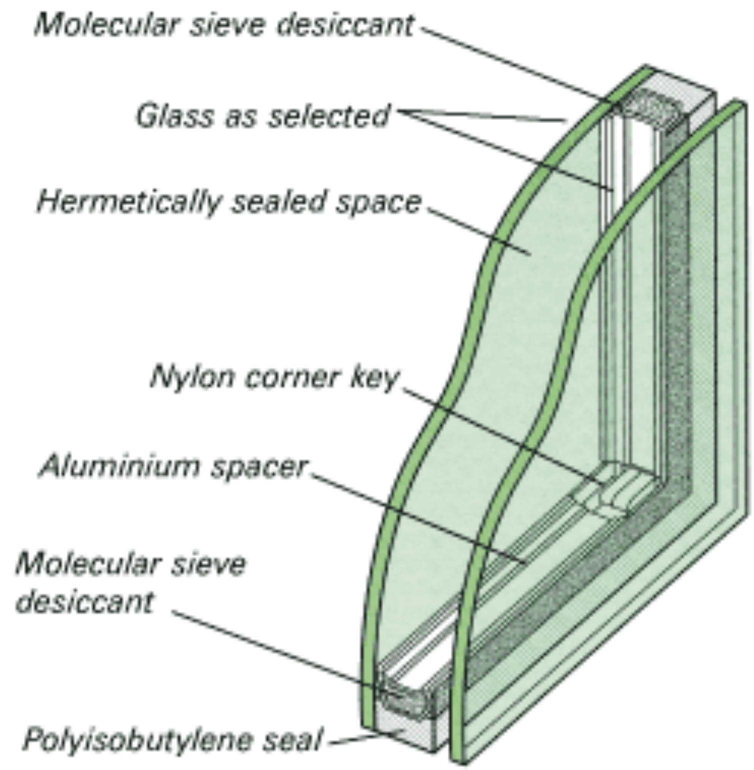


Fig. 1 Insulating Glazing Unit (IGU) Construction Detail

Components of insulated glazing units (IGU)

- Glass
  - Annealed, tempered, laminated
  - Clear, tinted, or reflective film
- Spacer
  - Separates the glazes
  - Metallic spacers act as thermal bridges but are commonly used
    - Insulating spacers must have similar thermal expansion coefficients to maintain seal
- Air space
  - Dry air or inert gas (Ar, Kr)
  - Desiccants added to absorb moisture and reduce fogging
- Sealant
  - Hermetically seals unit to prevent air escape & moisture penetration



Insulated Glazing Units

Computing U_{cg} for a double glaze with air cavity

- Start with single-glaze equation:

$$U_{cg} = \left(\frac{1}{h_{out}} + \frac{1}{h_{in}} + \frac{L}{k} \right)^{-1}$$

- Add terms for:
  - Conduction through second glass pane
  - Conduction through air space ($k_{still\ air}$ = 0.025 W/mK)
  - Convection (if any) in air space
  - Radiation within air space (long-wave)
- Ends up being a complex problem

U_{cg} for IGUs

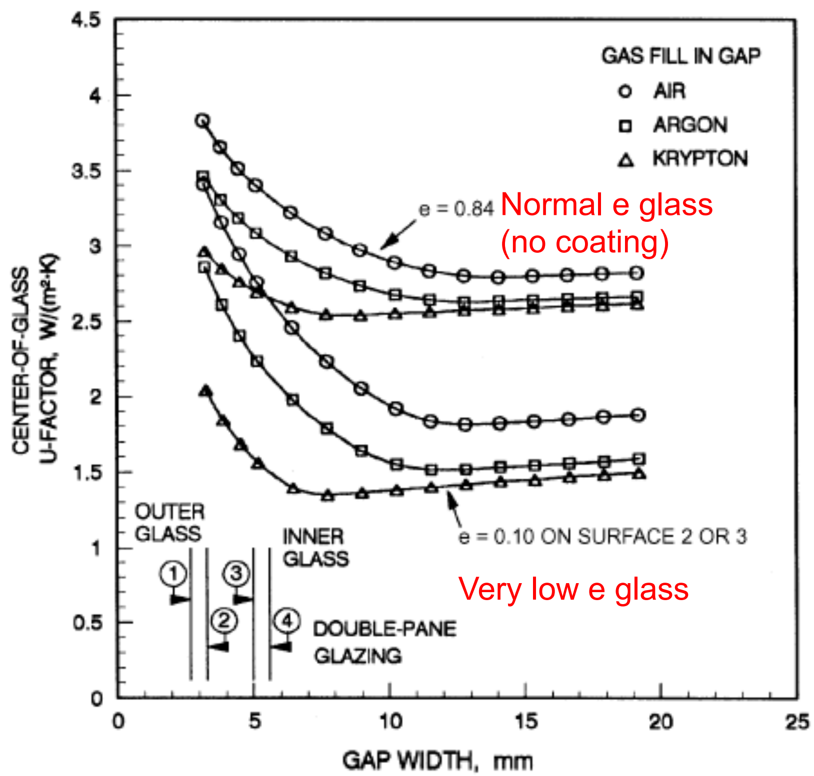
- For an insulated glass unit, there is an air space between the glazes
  - This cavity transmits heat by natural convection and radiation
- U_{cg} can be estimated with a program called WINDOW
  - Companion to THERM
  - This is the preferred method to get U_{cg}
- Decent estimates of U_{cg} can also be obtained using ASHRAE HOF for similar window constructions

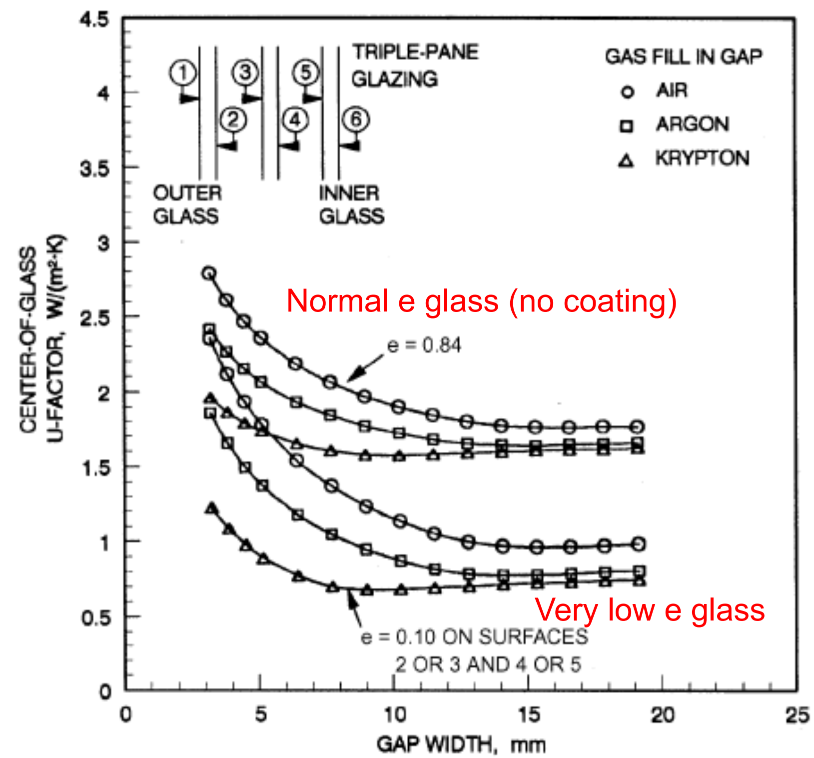
Product Type	Glass Only	
Frame Type ID Glazing Type	Center of Glass	Edge of Glass
Single Glazing		
1 3.2 mm glass	*5.91*	*5.91*
2 6.4 mm acrylic/polycarb	*5.00*	*5.00*
3 3.2 mm acrylic/polycarb	*5.45*	*5.45*
Double Glazing		
4 6.4 mm airspace	*3.12*	*3.63*
5 12.7 mm airspace	*2.73*	*3.36*
6 6.4 mm argon space	*2.90*	*3.48*
7 12.7 mm argon space	*2.56*	*3.24*
Double Glazing, e = 0.60 on surface 2 or 3		
8 6.4 mm airspace	*2.95*	*3.52*
9 12.7 mm airspace	*2.50*	*3.20*
10 6.4 mm argon space	*2.67*	*3.32*
11 12.7 mm argon space	*2.33*	*3.08*

Typical U_{cg} plots: Function of spacing

The ASHRAE HOF has these typical graphs of U_{cg} as a function of spacing between glazes

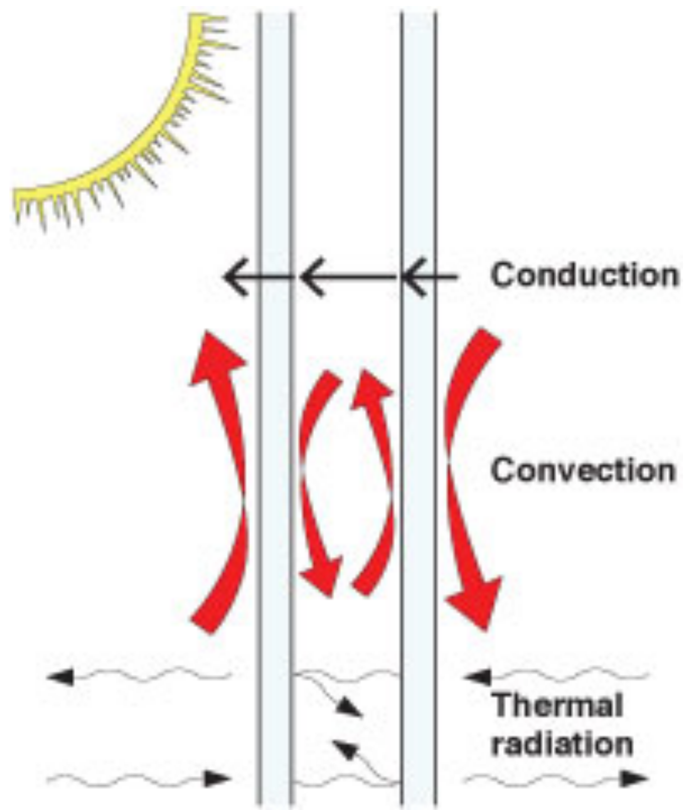
- Notice that the minimum U_{cg} is greater for air and Argon fill than for Krypton





Separation distance

- U_{cg} first decreases with separation distance and but then rises
  - Why would that happen?

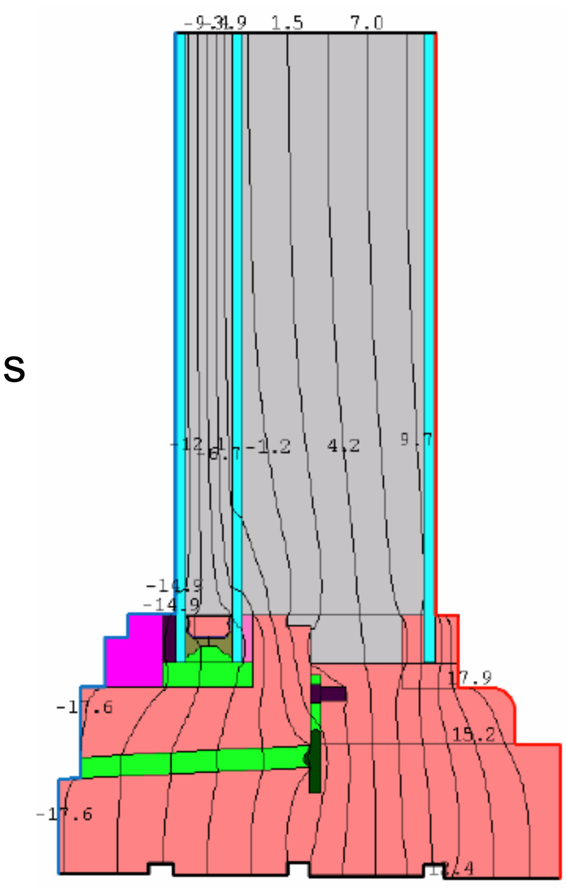


Separation distance

- U_{cg} first decreases with separation distance and but then rises
  - Why would that happen?
    - At first, the separation distance reduces conductive heat transfer through the gas
      - Spacing too low → conduction occurs easily
    - But with larger spacing, more convection can occur and the heat transfer actually improves
      - Spacing too high → convective currents
    - There is no real change in radiation transfer with spacing
    - Optimal spacing typically 15-20 mm
      - This is not an issue in vacuum insulated glass

Finding U_{eg} and U_f

- U_{eg} and U_f are usually determined experimentally or using computer software
  - THERM
  - WINDOW
    - Another free 2-D thermal finite element analysis program specially designed for computing window system heat transfer
- The frame shape and materials play a large role in determining both U_{eg} and U_f



Estimating U_f and U_{eg}

- If you need to get a U_f or a U_{eg} and do not have access to software (or don’t have hours to kill)
  - Can look up prototypical numbers in the ASHRAE HOF

Table 1 Representative Fenestration Frame U-Factors in W/($m^2 \cdot K$), Vertical Orientation

		Product Type/Number of Glazing Layers																
		Operable			Fixed			Garden Window		Plant-Assembled Skylight			Curtainwall[e]			Sloped/Overhead Glazing[e]		
Frame Material	Type of Spacer	Single[b]	Double[c]	Triple[d]	Single[b]	Double[c]	Triple[d]	Single[b]	Double[c]	Single[b]	Double[c]	Triple[d]	Single[f]	Double[g]	Triple[h]	Single[f]	Double[g]	Triple[h]
Aluminum without thermal break	All	13.51	12.89	12.49	10.90	10.22	9.88	10.67	10.39	44.57	39.86	39.01	17.09	16.81	16.07	17.32	17.03	16.30
Aluminum with thermal break[a]	Metal	6.81	5.22	4.71	7.49	6.42	6.30			39.46	28.67	26.01	10.22	9.94	9.37	10.33	9.99	9.43
	Insulated	n/a	5.00	4.37	n/a	5.91	5.79			n/a	26.97	23.39	n/a	9.26	8.57	n/a	9.31	8.63
Aluminum-clad wood/ reinforced vinyl	Metal	3.41	3.29	2.90	3.12	2.90	2.73			27.60	22.31	20.78						
	Insulated	n/a	3.12	2.73	n/a	2.73	2.50			n/a	21.29	19.48						
Wood /vinyl	Metal	3.12	2.90	2.73	3.12	2.73	2.38	5.11	4.83	14.20	11.81	10.11						
	Insulated	n/a	2.78	2.27	n/a	2.38	1.99	n/a	4.71	n/a	11.47	9.71						
Insulated fiberglass/ vinyl	Metal	2.10	1.87	1.82	2.10	1.87	1.82											
	Insulated	n/a	1.82	1.48	n/a	1.82	1.48											
Structural glazing	Metal												10.22	7.21	5.91	10.33	7.27	5.96
	Insulated												n/a	5.79	4.26	n/a	5.79	4.26

Note: This table should only be used as an estimating tool for early phases of design.
[a] Depends strongly on width of thermal break. Value given is for 9.5 mm.
[b] Single glazing corresponds to individual glazing unit thickness of 3 mm. (nominal).
[c] Double glazing corresponds to individual glazing unit thickness of 19 mm. (nominal).
[d] Triple glazing corresponds to individual glazing unit thickness of 34.9 mm. (nominal).
[e] Glass thickness in curtainwall and sloped/overhead glazing is 6.4 mm.
[f] Single glazing corresponds to individual glazing unit thickness of 6.4 mm. (nominal).
[g] Double glazing corresponds to individual glazing unit thickness of 25.4 mm. (nominal).
[h] Triple glazing corresponds to individual glazing unit thickness of 44.4 mm. (nominal).
n/a Not applicable

U_{cg}, U_{eg} and overall U factors

Table 4 U-Factors for Various Fenestration Products in W/(m²·K)

Product Type	Glass Only		Vertical Installation									
			Operable (including sliding and swinging glass doors)					Fixed				
Frame Type ID Glazing Type	Center of Glass	Edge of Glass	Aluminum without Thermal Break	Aluminum with Thermal Break	Reinforced Vinyl/ Aluminum Clad Wood	Wood/ Vinyl	Insulated Fiberglass/ Vinyl	Aluminum without Thermal Break	Aluminum with Thermal Break	Reinforced Vinyl/ Aluminum Clad Wood	Wood/ Vinyl	Insulated Fiberglass/ Vinyl
Single Glazing												
1 3.2 mm glass	*5.91*	*5.91*	7.24	6.12	5.14	5.05	4.61	6.42	6.07	5.55	5.55	5.35
2 6.4 mm acrylic/polycarb	*5.00*	*5.00*	6.49	5.43	4.51	4.42	4.01	5.60	5.25	4.75	4.75	4.58
3 3.2 mm acrylic/polycarb	*5.45*	*5.45*	6.87	5.77	4.82	4.73	4.31	6.01	5.66	5.15	5.15	4.97
Double Glazing												
4 6.4 mm airspace	*3.12*	*3.63*	4.93	3.70	3.25	3.13	2.77	3.94	3.56	3.19	3.17	3.04
5 12.7 mm airspace	*2.73*	*3.36*	4.62	3.42	3.00	2.87	2.53	3.61	3.22	2.86	2.84	2.72
6 6.4 mm argon space	*2.90*	*3.48*	4.75	3.54	3.11	2.98	2.63	3.75	3.37	3.00	2.98	2.85
7 12.7 mm argon space	*2.56*	*3.24*	4.49	3.30	2.89	2.76	2.42	3.47	3.08	2.73	2.70	2.58
Double Glazing, $e = 0.60$ on surface 2 or 3												
8 6.4 mm airspace	*2.95*	*3.52*	4.80	3.58	3.14	3.02	2.67	3.80	3.41	3.05	3.03	2.90
9 12.7 mm airspace	*2.50*	*3.20*	4.45	3.26	2.85	2.73	2.39	3.42	3.03	2.68	2.66	2.54
10 6.4 mm argon space	*2.67*	*3.32*	4.58	3.38	2.96	2.84	2.49	3.56	3.17	2.82	2.80	2.67
11 12.7 mm argon space	*2.33*	*3.08*	4.31	3.13	2.74	2.62	2.28	3.28	2.89	2.54	2.52	2.40
Double Glazing, $e = 0.40$ on surface 2 or 3												
12 6.4 mm airspace	*2.78*	*3.40*	4.66	3.46	3.03	2.91	2.56	3.66	3.27	2.91	2.89	2.76
13 12.7 mm airspace	*2.27*	*3.04*	4.27	3.09	2.70	2.58	2.25	3.23	2.84	2.49	2.47	2.35
14 6.4 mm argon space	*2.44*	*3.16*	4.40	3.21	2.81	2.69	2.35	3.37	2.98	2.63	2.61	2.49
15 12.7 mm argon space	*2.04*	*2.88*	4.09	2.93	2.55	2.43	2.10	3.04	2.65	2.31	2.29	2.17
Double Glazing, $e = 0.20$ on surface 2 or 3												
16 6.4 mm airspace	*2.56*	*3.24*	4.49	3.30	2.89	2.76	2.42	3.47	3.08	2.73	2.70	2.58
17 12.7 mm airspace	*1.99*	*2.83*	4.05	2.89	2.52	2.39	2.07	2.99	2.60	2.26	2.24	2.13
18 6.4 mm argon space	*2.16*	*2.96*	4.18	3.01	2.63	2.51	2.17	3.13	2.74	2.40	2.38	2.26
19 12.7 mm argon space	*1.70*	*2.62*	3.83	2.68	2.33	2.21	1.89	2.75	2.36	2.03	2.01	1.90

- U factors shown for winter conditions with 24 km/h (15 mph) winds

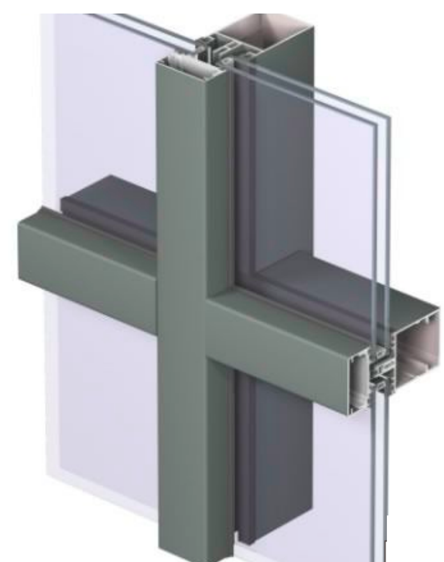
$U_{cg,}$ U_{eg} and overall U factors

Table 4 U-Factors for Various Fenestration Products in W/(m^2·K)

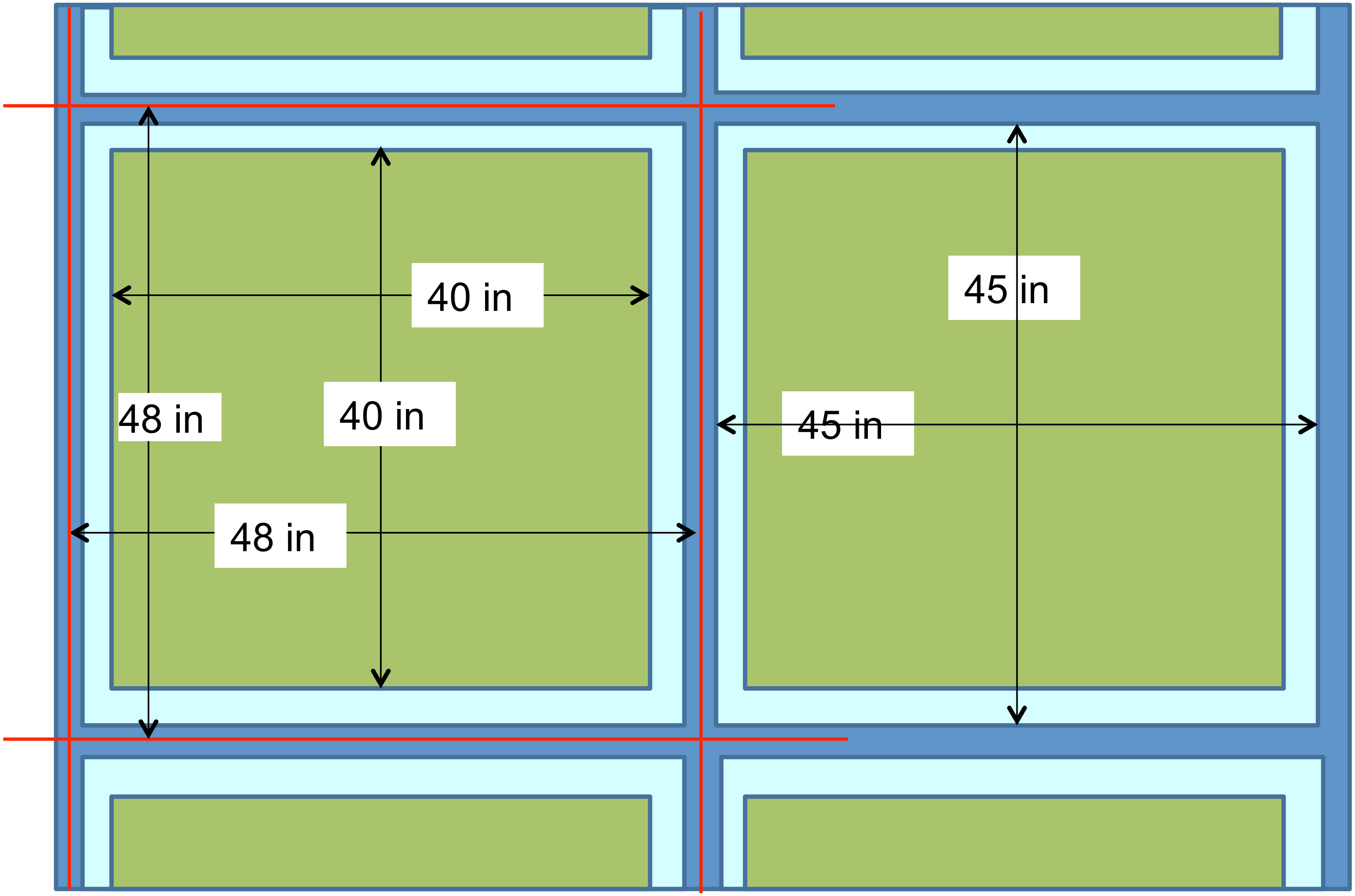
Product Type	Glass Only		Vertical Installation									
			Operable (including sliding and swinging glass doors)					Fixed				
Frame Type ID Glazing Type	Center of Glass	Edge of Glass	Aluminum without Thermal Break	Aluminum with Thermal Break	Reinforced Vinyl/ Aluminum Clad Wood	Wood/ Vinyl	Insulated Fiberglass/ Vinyl	Aluminum without Thermal Break	Aluminum with Thermal Break	Reinforced Vinyl/ Aluminum Clad Wood	Wood/ Vinyl	Insulated Fiberglass/ Vinyl
Double Glazing, *e* = 0.10 on surface 2 or 3												
20 6.4 mm airspace	*2.39*	*3.12*	4.36	3.17	2.78	2.65	2.32	3.32	2.93	2.59	2.56	2.45
21 12.7 mm airspace	*1.82*	*2.71*	3.92	2.77	2.41	2.28	1.96	2.84	2.45	2.12	2.10	1.99
22 6.4 mm argon space	*1.99*	*2.83*	4.05	2.89	2.52	2.39	2.07	2.99	2.60	2.26	2.24	2.13
23 12.7 mm argon space	*1.53*	*2.49*	3.70	2.56	2.22	2.10	1.79	2.60	2.21	1.89	1.86	1.76
Double Glazing, *e* = 0.05 on surface 2 or 3												
24 6.4 mm airspace	*2.33*	*3.08*	4.31	3.13	2.74	2.62	2.28	3.28	2.89	2.54	2.52	2.40
25 12.7 mm airspace	*1.70*	*2.62*	3.83	2.68	2.33	2.21	1.89	2.75	2.36	2.03	2.01	1.90
26 6.4 mm argon space	*1.87*	*2.75*	3.96	2.81	2.44	2.32	2.00	2.89	2.50	2.17	2.15	2.03
27 12.7 mm argon space	*1.42*	*2.41*	3.61	2.48	2.15	2.02	1.71	2.50	2.11	1.79	1.77	1.67
Triple Glazing												
28 6.4 mm airspace	*2.16*	*2.96*	4.11	2.89	2.51	2.45	2.16	3.10	2.73	2.38	2.33	2.25
29 12.7 mm airspace	*1.76*	*2.67*	3.80	2.60	2.25	2.19	1.91	2.76	2.39	2.05	2.01	1.93
30 6.4 mm argon space	*1.93*	*2.79*	3.94	2.73	2.36	2.30	2.01	2.90	2.54	2.19	2.15	2.07
31 12.7 mm argon space	*1.65*	*2.58*	3.71	2.52	2.17	2.12	1.84	2.66	2.30	1.96	1.91	1.84
Triple Glazing, *e* = 0.20 on surface 2,3,4, or 5												
32 6.4 mm airspace	*1.87*	*2.75*	3.89	2.69	2.32	2.27	1.98	2.86	2.49	2.15	2.10	2.03
33 12.7 mm airspace	*1.42*	*2.41*	3.54	2.36	2.02	1.97	1.70	2.47	2.10	1.77	1.73	1.66
34 6.4 mm argon space	*1.59*	*2.54*	3.67	2.48	2.13	2.08	1.80	2.61	2.25	1.91	1.87	1.80
35 12.7 mm argon space	*1.25*	*2.28*	3.40	2.23	1.91	1.86	1.59	2.32	1.96	1.63	1.59	1.52
Triple Glazing, *e* = 0.20 on surfaces 2 or 3 and 4 or 5												
36 6.4 mm airspace	*1.65*	*2.58*	3.71	2.52	2.17	2.12	1.84	2.66	2.30	1.96	1.91	1.84
37 12.7 mm airspace	*1.14*	*2.19*	3.31	2.15	1.84	1.78	1.52	2.23	1.86	1.54	1.49	1.43
38 6.4 mm argon space	*1.31*	*2.32*	3.45	2.27	1.95	1.90	1.62	2.37	2.01	1.68	1.63	1.56
39 12.7 mm argon space	*0.97*	*2.05*	3.18	2.03	1.72	1.67	1.41	2.08	1.71	1.39	1.35	1.29
Triple Glazing, *e* = 0.10 on surfaces 2 or 3 and 4 or 5												
40 6.4 mm airspace	*1.53*	*2.49*	3.63	2.44	2.10	2.05	1.77	2.57	2.20	1.86	1.82	1.75
41 12.7 mm airspace	*1.02*	*2.10*	3.22	2.07	1.76	1.71	1.45	2.13	1.76	1.44	1.40	1.33
42 6.4 mm argon space	*1.19*	*2.23*	3.36	2.19	1.87	1.82	1.55	2.27	1.91	1.58	1.54	1.47
43 12.7 mm argon space	*0.80*	*1.92*	3.05	1.90	1.61	1.56	1.30	1.93	1.57	1.25	1.21	1.15

Example 8.1

- Estimate U factor for the 4 ft x 4 ft vision glass section of a curtain wall
  – The vision IGU has low e glass (emissivity of 0.40)
  – ½" (12 mm) air space and metal spacer
- The aluminum mullions are 3 inches (76 mm) wide and have a thermal break
  – In a curtain wall, half the mullion is associated with one IGU and half with the other so we have 1.5 inch of mullion



Example 8.1



Example 8.1

- With a 3 inch mullion, there will be 1.5 inches of frame on each edge
  - The total glass dimension is 48 in – 1.5 in – 1.5 in = 45 in
- Edge-of-glass width is 2.5 inch
  - So center of glass dimension is is 45 - 5 = 40 inches

A_{cg} = (40)x(40)=1600 in^2

A_{eg} = (45x45) - A_{cg} = 425 in^2

A_f = (48x48)-(45x45) = 279 in^2

Example 8.1

- Find U_f

Table 1 Representative Fenestration Frame U-Factors in W/(m²·K), Vertical Orientation

		Product Type/Number of Glazing Layers																
		Operable			Fixed			Garden Window		Plant-Assembled Skylight			Curtainwall[e]			Sloped/Overhead Glazing[e]		
Frame Material	Type of Spacer	Single[b]	Double[c]	Triple[d]	Single[b]	Double[c]	Triple[d]	Single[b]	Double[c]	Single[b]	Double[c]	Triple[d]	Single[f]	Double[g]	Triple[h]	Single[f]	Double[g]	Triple[h]
Aluminum without thermal break	All	13.51	12.89	12.49	10.90	10.22	9.88	10.67	10.39	44.57	39.86	39.01	17.09	16.81	16.07	17.32	17.03	16.30
Aluminum with thermal break[a]	Metal	6.81	5.22	4.71	7.49	6.42	6.30			39.46	28.67	26.01	10.22	9.94	9.37	10.33	9.99	9.43
	Insulated	n/a	5.00	4.37	n/a	5.91	5.79			n/a	26.97	23.39	n/a	9.26	8.57	n/a	9.31	8.63
Aluminum-clad wood/ reinforced vinyl	Metal	3.41	3.29	2.90	3.12	2.90	2.73			27.60	22.31	20.78						
	Insulated	n/a	3.12	2.73	n/a	2.73	2.50			n/a	21.29	19.48						
Wood /vinyl	Metal	3.12	2.90	2.73	3.12	2.73	2.38	5.11	4.83	14.20	11.81	10.11						
	Insulated	n/a	2.78	2.27	n/a	2.38	1.99	n/a	4.71	n/a	11.47	9.71						
Insulated fiberglass/ vinyl	Metal	2.10	1.87	1.82	2.10	1.87	1.82											
	Insulated	n/a	1.82	1.48	n/a	1.82	1.48											
Structural glazing	Metal												10.22	7.21	5.91	10.33	7.27	5.96
	Insulated												n/a	5.79	4.26	n/a	5.79	4.26

Note: This table should only be used as an estimating tool for early phases of design.
[a]Depends strongly on width of thermal break. Value given is for 9.5 mm.
[b]Single glazing corresponds to individual glazing unit thickness of 3 mm. (nominal).
[c]Double glazing corresponds to individual glazing unit thickness of 19 mm. (nominal).
[d]Triple glazing corresponds to individual glazing unit thickness of 34.9 mm. (nominal).
[e]Glass thickness in curtainwall and sloped/overhead glazing is 6.4 mm.
[f]Single glazing corresponds to individual glazing unit thickness of 6.4 mm. (nominal).
[g]Double glazing corresponds to individual glazing unit thickness of 25.4 mm. (nominal).
[h]Triple glazing corresponds to individual glazing unit thickness of 44.4 mm. (nominal).
n/a Not applicable

U_f= 9.94 W/(m²K)

Example 8.1

- Find U_{cg} and U_{eg}

Table 4 U-Factors for Various Fenestration Products in W/(m²·K)

Product Type / Frame Type / ID Glazing Type	Glass Only: Center of Glass	Glass Only: Edge of Glass	Operable: Aluminum without Thermal Break	Operable: Aluminum with Thermal Break	Operable: Reinforced Vinyl/ Aluminum Clad Wood	Operable: Wood/ Vinyl	Operable: Insulated Fiberglass/ Vinyl	Fixed: Aluminum without Thermal Break	Fixed: Aluminum with Thermal Break	Fixed: Reinforced Vinyl/ Aluminum Clad Wood	Fixed: Wood/ Vinyl	Fixed: Insulated Fiberglass/ Vinyl
Single Glazing												
1 3.2 mm glass	*5.91*	*5.91*	7.24	6.12	5.14	5.05	4.61	6.42	6.07	5.55	5.55	5.35
2 6.4 mm acrylic/polycarb	*5.00*	*5.00*	6.49	5.43	4.51	4.42	4.01	5.60	5.25	4.75	4.75	4.58
3 3.2 mm acrylic/polycarb	*5.45*	*5.45*	6.87	5.77	4.82	4.73	4.31	6.01	5.66	5.15	5.15	4.97
Double Glazing												
4 6.4 mm airspace	*3.12*	*3.63*	4.93	3.70	3.25	3.13	2.77	3.94	3.56	3.19	3.17	3.04
5 12.7 mm airspace	*2.73*	*3.36*	4.62	3.42	3.00	2.87	2.53	3.61	3.22	2.86	2.84	2.72
6 6.4 mm argon space	*2.90*	*3.48*	4.75	3.54	3.11	2.98	2.63	3.75	3.37	3.00	2.98	2.85
7 12.7 mm argon space	*2.56*	*3.24*	4.49	3.30	2.89	2.76	2.42	3.47	3.08	2.73	2.70	2.58
Double Glazing, *e* = 0.60 on surface 2 or 3												
8 6.4 mm airspace	*2.95*	*3.52*	4.80	3.58	3.14	3.02	2.67	3.80	3.41	3.05	3.03	2.90
9 12.7 mm airspace	*2.50*	*3.20*	4.45	3.26	2.85	2.73	2.39	3.42	3.03	2.68	2.66	2.54
10 6.4 mm argon space	*2.67*	*3.32*	4.58	3.38	2.96	2.84	2.49	3.56	3.17	2.82	2.80	2.67
11 12.7 mm argon space	*2.33*	*3.08*	4.31	3.13	2.74	2.62	2.28	3.28	2.89	2.54	2.52	2.40
Double Glazing, *e* = 0.40 on surface 2 or 3												
12 6.4 mm airspace	*2.78*	*3.40*	4.66	3.46	3.03	2.91	2.56	3.66	3.27	2.91	2.89	2.76
13 12.7 mm airspace	*2.27*	*3.04*	4.27	3.09	2.70	2.58	2.25	3.23	2.84	2.49	2.47	2.35
14 6.4 mm argon space	*2.44*	*3.16*	4.40	3.21	2.81	2.69	2.35	3.37	2.98	2.63	2.61	2.49
15 12.7 mm argon space	*2.04*	*2.88*	4.09	2.93	2.55	2.43	2.10	3.04	2.65	2.31	2.29	2.17
Double Glazing, *e* = 0.20 on surface 2 or 3												
16 6.4 mm airspace	*2.56*	*3.24*	4.49	3.30	2.89	2.76	2.42	3.47	3.08	2.73	2.70	2.58
17 12.7 mm airspace	*1.99*	*2.83*	4.05	2.89	2.52	2.39	2.07	2.99	2.60	2.26	2.24	2.13
18 6.4 mm argon space	*2.16*	*2.96*	4.18	3.01	2.63	2.51	2.17	3.13	2.74	2.40	2.38	2.26
19 12.7 mm argon space	*1.70*	*2.62*	3.83	2.68	2.33	2.21	1.89	2.75	2.36	2.03	2.01	1.90

U_{cg} = 2.27 W/(m²K) and U_{eg} = 3.04 W/(m²K)

Example 8.1

- So, our info is:

A_{cg} = 1600 in^2, U_{cg}=2.27 W/(m^{2}K)

A_{eg} = 425 in^2, U_{eg}=3.04 W/(m^{2}K)

A_f = = 279 in^2, U_f= 9.94 W/(m^{2}K)

And thus the total U factor for the section is:

$$U = \frac{2.27 \times 1600 + 3.04 \times 425 + 9.94 \times 279}{48 \times 48} = 3.34 \text{ W/(m}^2\text{K)}$$

$$R = \frac{1}{3.34} = 0.30 \text{ (m}^2\text{K)/W (SI)} = \text{R-1.7 (IP)}$$

Doors

- Doors are often overlooked in terms of thermal integrity of the envelope in many buildings
  - Represent a small area fraction of the shell
    - But U value is usually quite large
    - Net impact is usually larger than the area fraction
- Doors are much bigger issues for some industrial buildings
  - Overhead loading bay doors
- Obvious issue for air leakage too

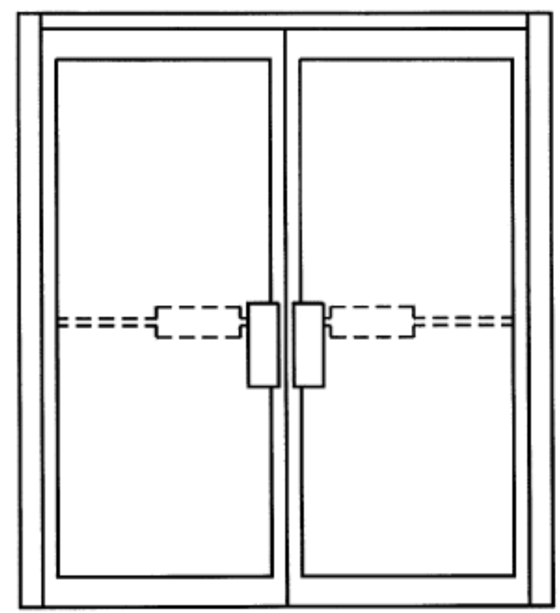


Fig. 5 Details of Stile-and-Rail Door

Doors

- U values for typical doors

Table 6 U-Factors of Doors in W/(m²·K)

Door Type	No Glazing	Single Glazing	Double Glazing with 12.7 mm Airspace	Double Glazing with $e = 0.10$, 12.7 mm Argon
SWINGING DOORS (Rough Opening, 970 × 2080 mm)				
Slab Doors				
Wood slab in wood frame[a]	2.61			
6% glazing (560 × 200 lite)	—	2.73	2.61	2.50
25% glazing (560 × 910 lite)	—	3.29	2.61	2.38
45% glazing (560 × 1620 lite)	—	3.92	2.61	2.21
More than 50% glazing		Use Table 4 (operable)		
Insulated steel slab with wood edge in wood frame[a]	0.91			
6% glazing (560 × 200 lite)	—	1.19	1.08	1.02
25% glazing (560 × 910 lite)	—	2.21	1.48	1.31
45% glazing (560 × 1630 lite)	—	3.29	1.99	1.48
More than 50% glazing		Use Table 4 (operable)		
Foam insulated steel slab with metal edge in steel frame[b]	2.10			
6% glazing (560 × 200 lite)	—	2.50	2.33	2.21
25% glazing (560 × 910 lite)	—	3.12	2.73	2.50
45% glazing (560 × 1630 lite)	—	4.03	3.18	2.73
More than 50% glazing		Use Table 4 (operable)		
Cardboard honeycomb slab with metal edge in steel frame	3.46			
Style and Rail Doors				
Sliding glass doors/ French doors		Use Table 4 (operable)		
Site-Assembled Style and Rail Doors				
Aluminum in Aluminum Frame	—	7.49	5.28	4.49
Aluminum in Aluminum Frame with Thermal Break	—	6.42	4.20	3.58
REVOLVING DOORS (Rough Opening, 2080 × 2130 mm)				
Aluminum in aluminum frame				
Open	—	7.49	—	—
Closed	—	3.69	—	—
SECTIONAL OVERHEAD DOORS (Nominal, 3050 × 3050 mm)				
Uninsulated steel (nominal $U = 6.53$)[c]	6.53	—	—	—
Insulated steel (nominal $U = 0.62$)[c]	1.36	—	—	—
Insulated steel with thermal break (nominal $U = 0.45$)[c]	0.74	—	—	—

Note: All dimensions are in millimetres.
[a] thermally broken sill (add 0.17 W/(m²·K) for non-thermally broken sill)
[b] non-thermally broken sill
[c] Nominal U-factors are through the center of the insulated panel before consideration of thermal bridges around the edges of the door sections and due to the frame.

Spandrel glass

- In some constructions, opaque glass is used for architectural purposes
  - "Spandrel glass"
- Spandrel glass should have insulation added to the inside improve the thermal performance
  - But the insulation will not reduce heat transfer through the **frame**

Ways to achieve low U values

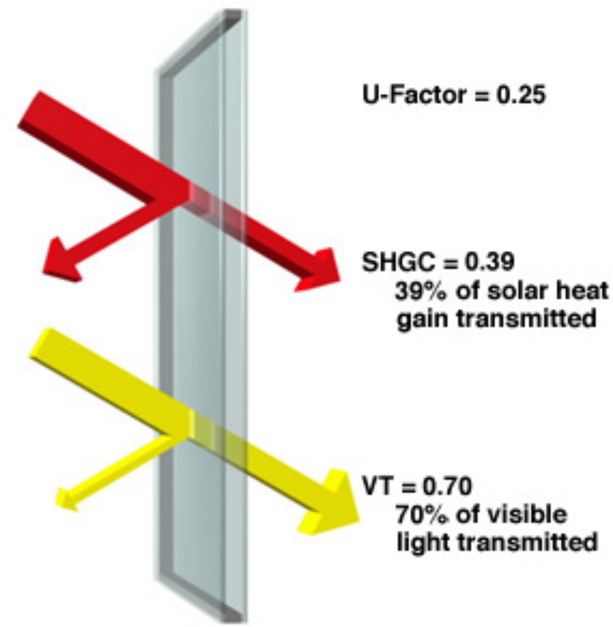
- Optimize air spaces
  - Air has a lower thermal conductivity than glass
  - Effectiveness is limited by convective heat transfer between glazes
    - So about 12 mm for Air or Argon fill
    - About 6 mm for Krypton fill
  - Triple panes can reduce convection at the expense of higher cost
    - Harder sealing and reduced optical transmission
- Heavy gas fill
  - Heavy gases like Argon or Krypton have lower conductivity than air
    - This is good for acoustics too
  - A vacuum between glazes is a great idea
    - But sealing is more difficult than for gas infill
- Low conductivity frames
  - Much heat is gained/lost through frames, especially in larger curtain walls
  - Good frames have thermal breaks of plastic or fiberglass
  - Thermal breaks need to have similar thermal expansion coefficients as other components to ensure seals can be maintained

WINDOW RATINGS: VT AND SHGC

Fenestration transmission terms

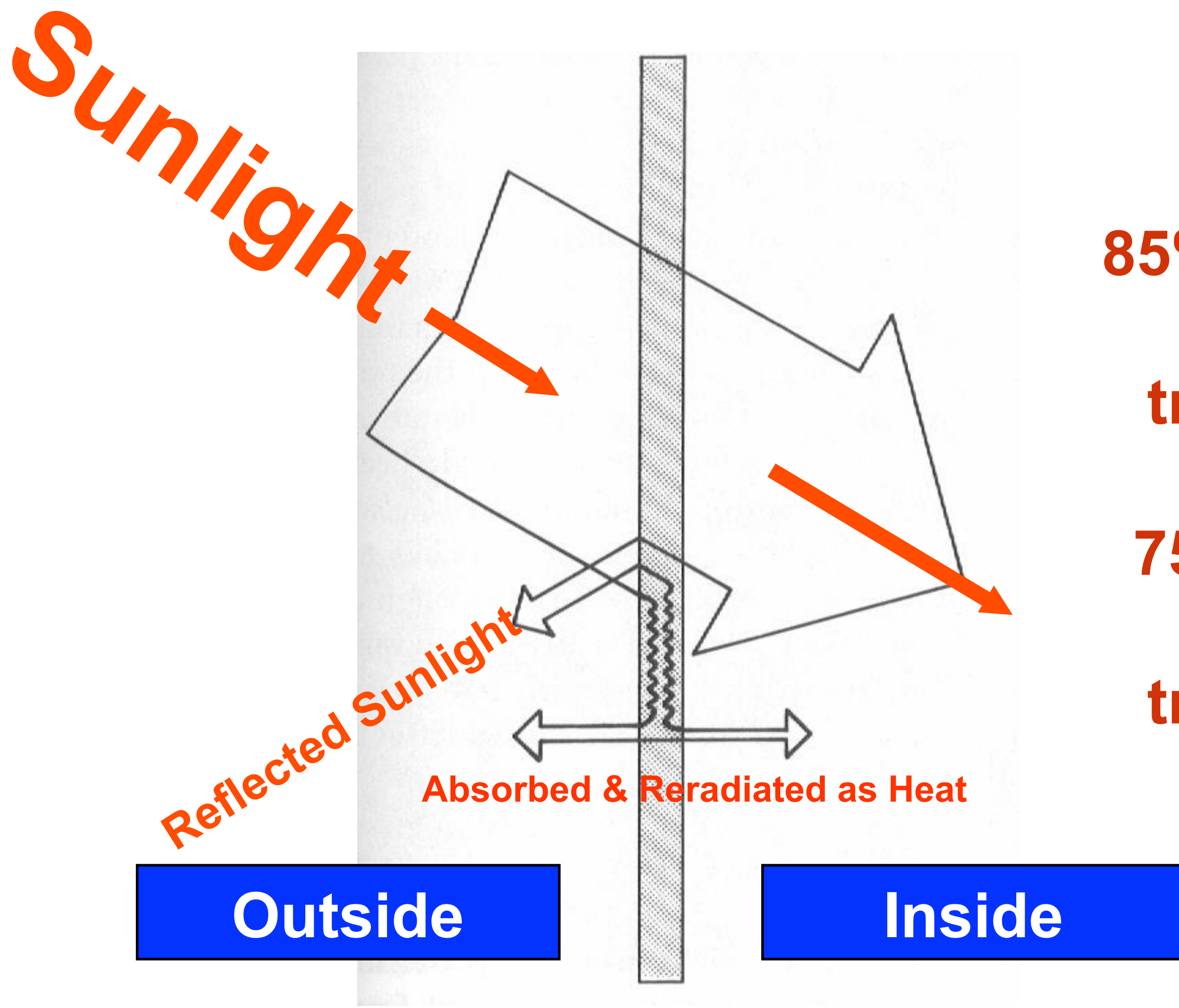
- So far we've only discussed thermal heat transfer
  - U value
    - Heat transfer coefficient for convective/conductive thermal transfer between indoor and outdoor air

- Fenestration also allows for solar heat transfer and transfer of visible light
  - **SHGC**: Solar Heat Gain Coefficient
    - Energy transfer coefficient for all wavelengths of solar thermal radiation
  - **VT**: Visible Transmission Coefficient
    - Transmission coefficient for visible wavelength solar radiation



U, SHGC, and VT for a window with a bronze reflective film

VT and SHGC concepts: clear glass example



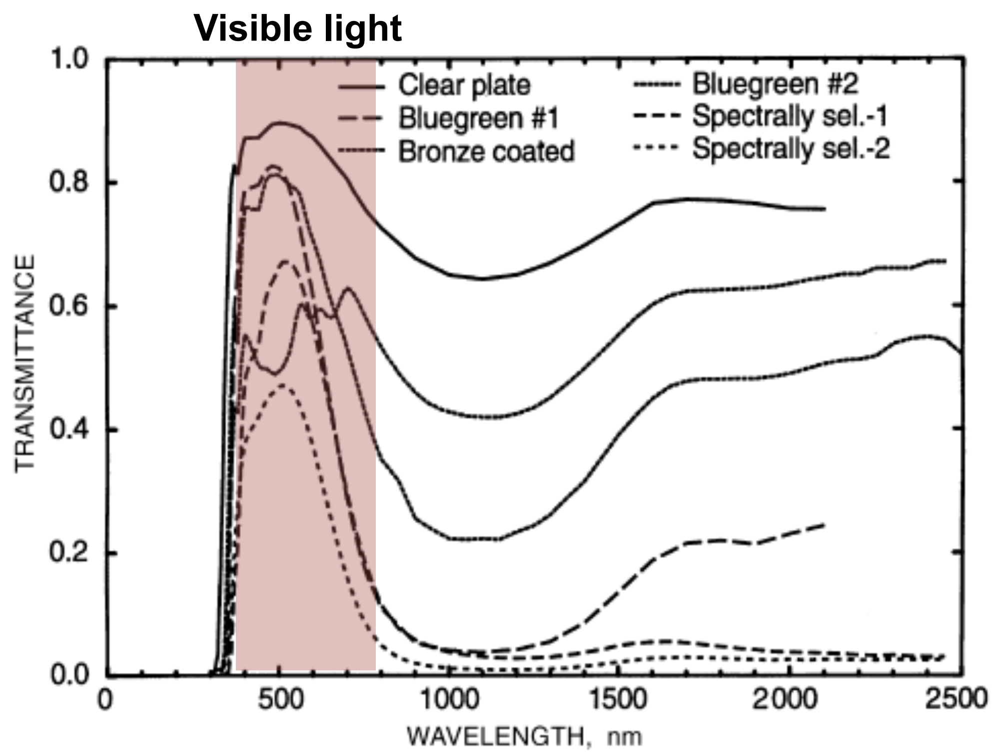
85% of visible energy transmitted

75% of total energy transmitted

Transmission of visible light: VT of glazing units

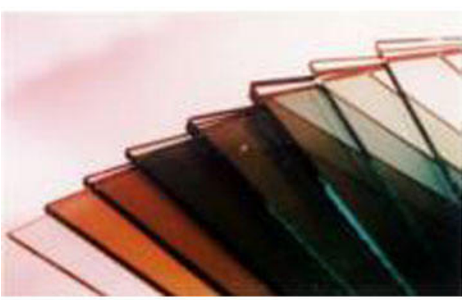
$$VT = \frac{\text{total visible light transmitted}}{\text{total visible light incident}}$$

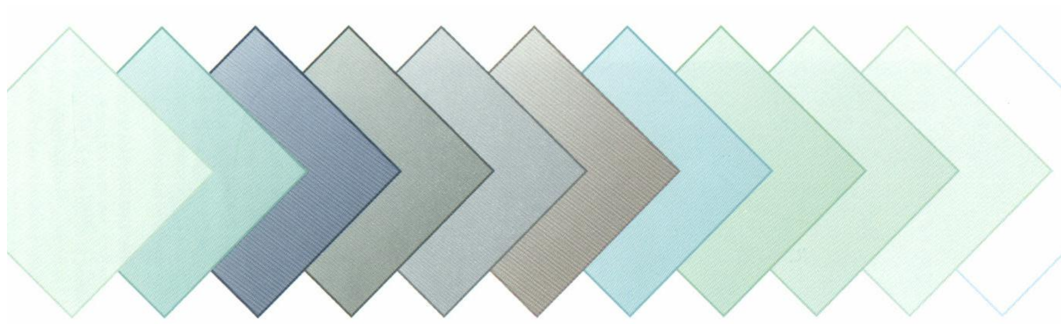
- Clear glass
  - Transmits 75% of incident solar radiation or more
    - Infrared (larger wavelength)
  - Transmits 85% of visible light
- Tinted glass
  - Available in many colors
  - Applied as coatings
  - Differ in solar radiation and visible light transmission
    - Typical range 40% to 80%
- Reflective glass
  - 5-40% VT



Tinted glass

- Glass with added chemical or metal particle additives
  - Iron oxides produce green tints
  - Selenium oxides produce bronze tints
  - Cobalt oxides produce blue tints

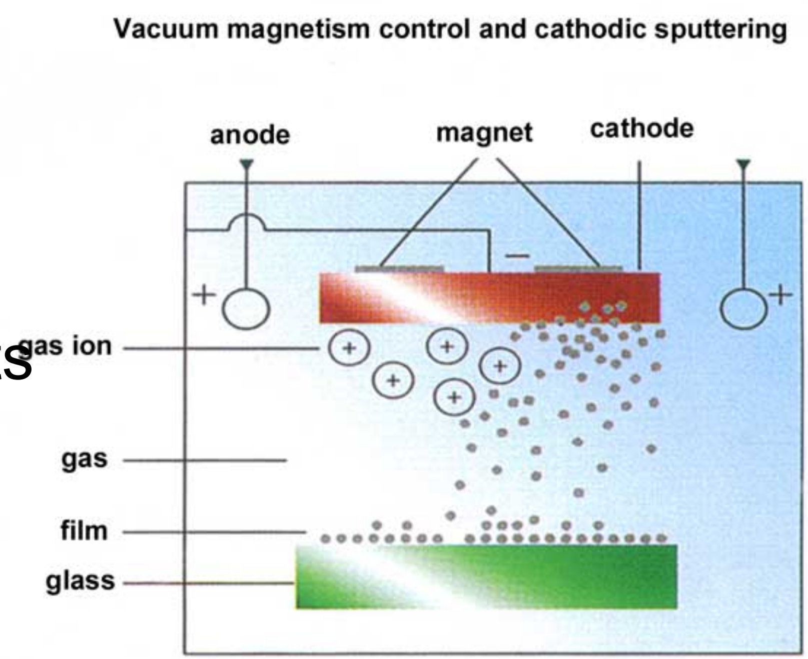




Tinted glass examples

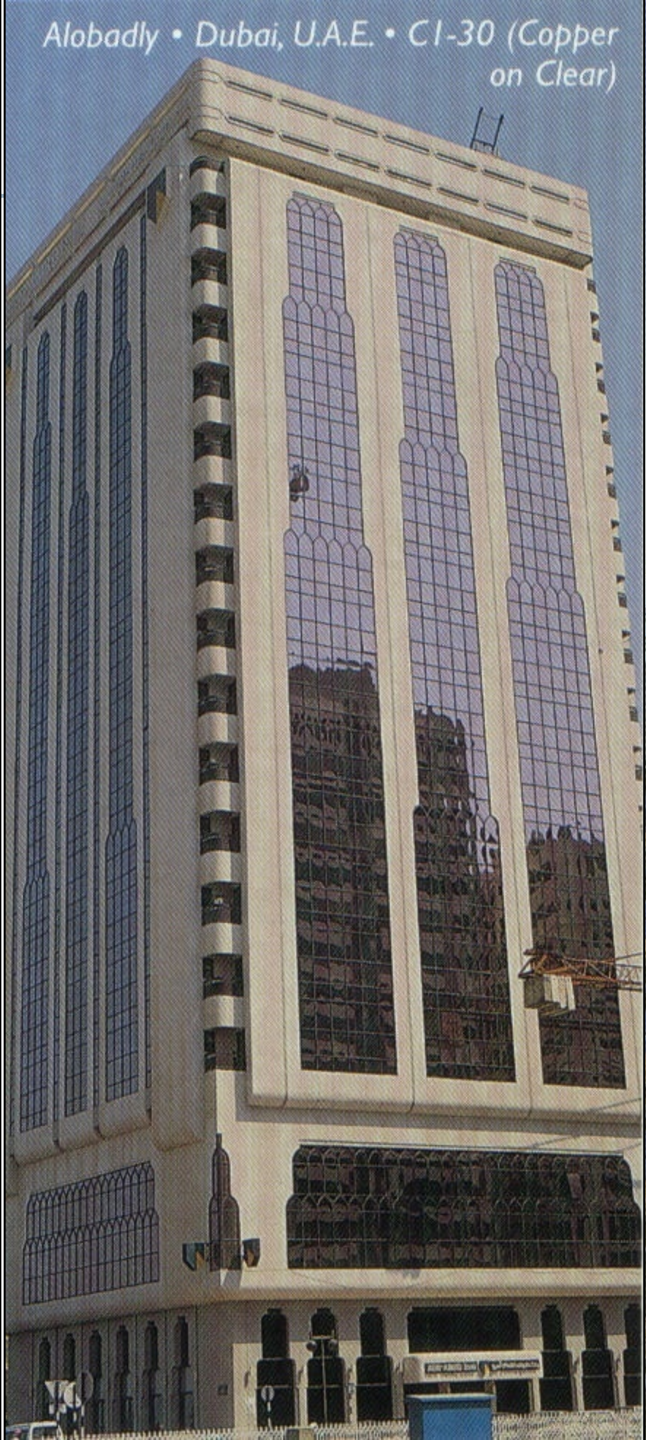
Reflective glass

- Glass with a film oxide coating applied to surface
  - Appears much like tinted glass
- Metal films allow for mirror effects as well as colors

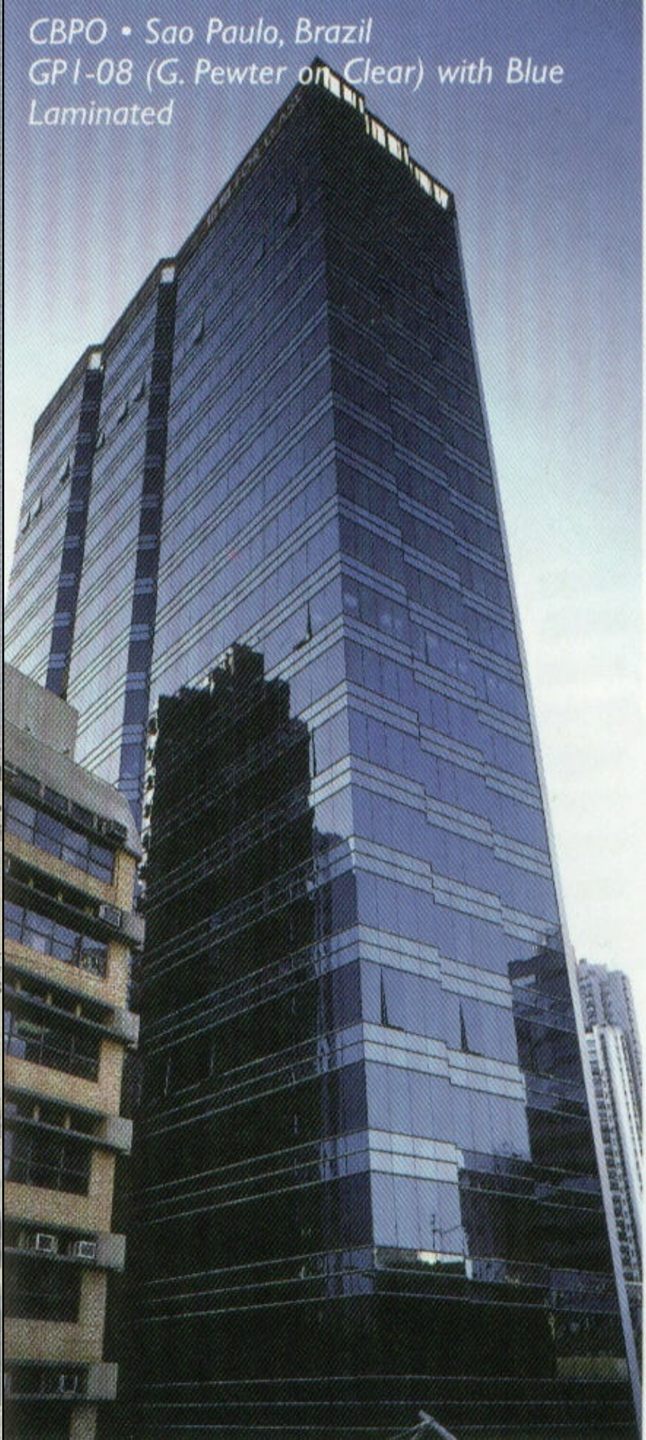


Reflective Glass

Guangdong
Hong Kong
S6-08 (Silver on Blue Green)



Alobadly • Dubai, U.A.E. • C1-30 (Copper on Clear)



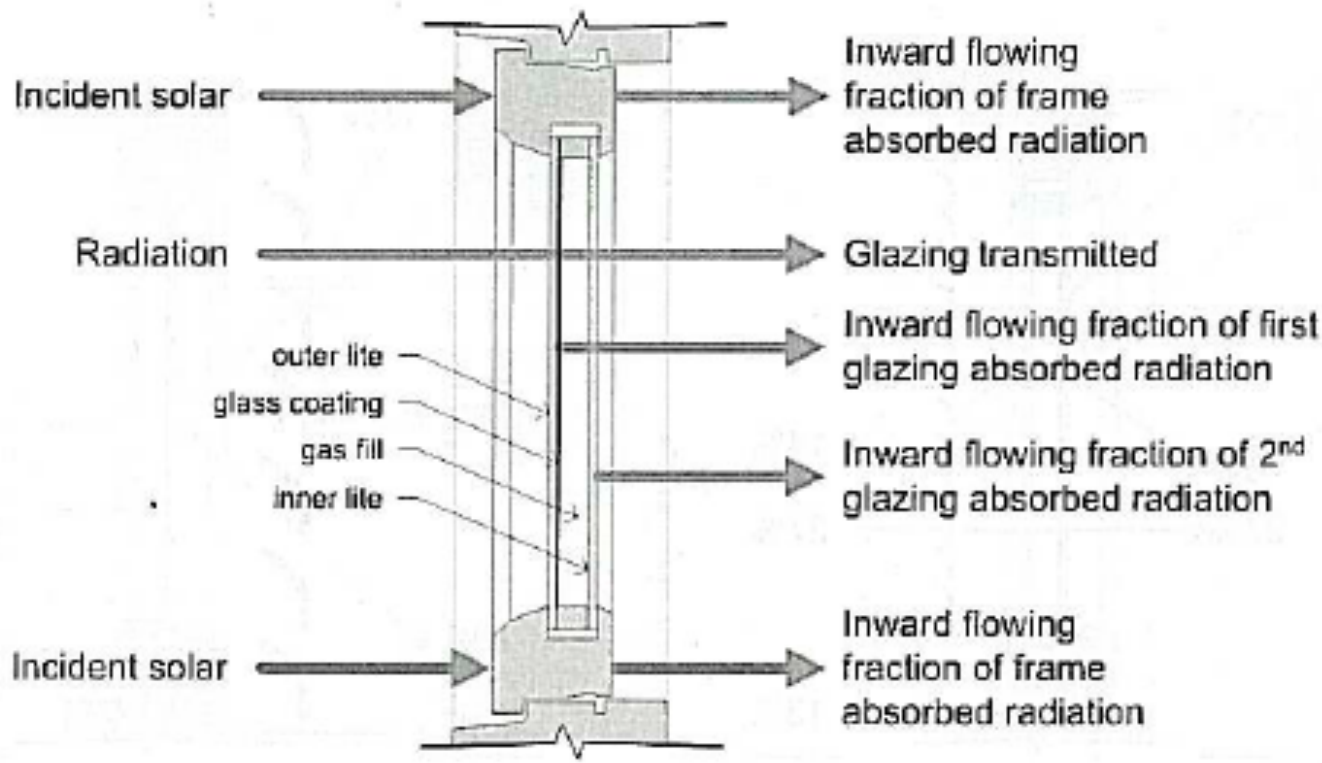
CBPO • Sao Paulo, Brazil
GP1-08 (G. Pewter on Clear) with Blue Laminated

Typical VT for different glazing types

Glazing	Visible T_v
Reflective blue-green	0.33
Film on clear glass	0.19
Green tinted, medium	0.75
Green low-e	0.71
Sun-control low-e + green	0.36
Super low-e + clear	0.71
Super low-e + green	0.60

Solar Heat Gain Coefficient (SHGC)

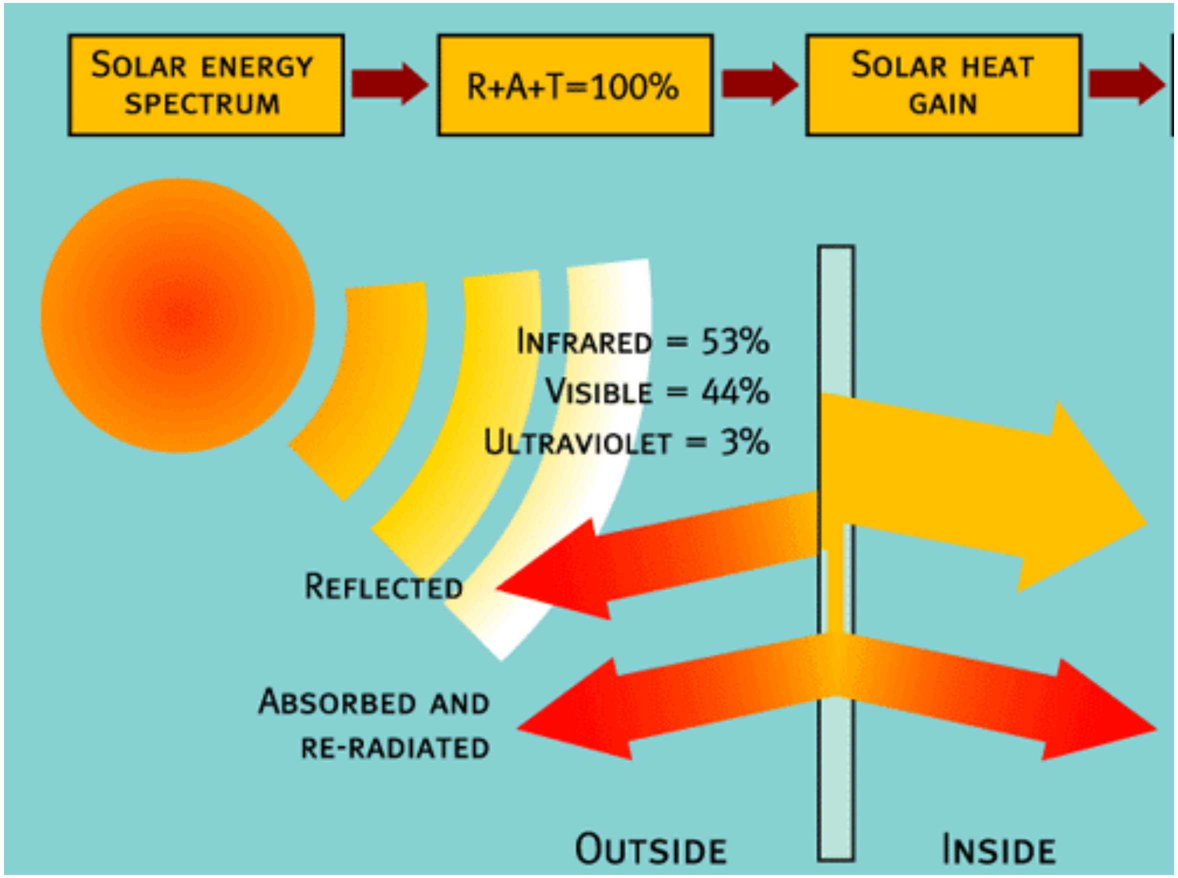
- The SHGC is the fraction of incident solar radiation that is transmitted through a window and becomes part of the heat gain for the interior



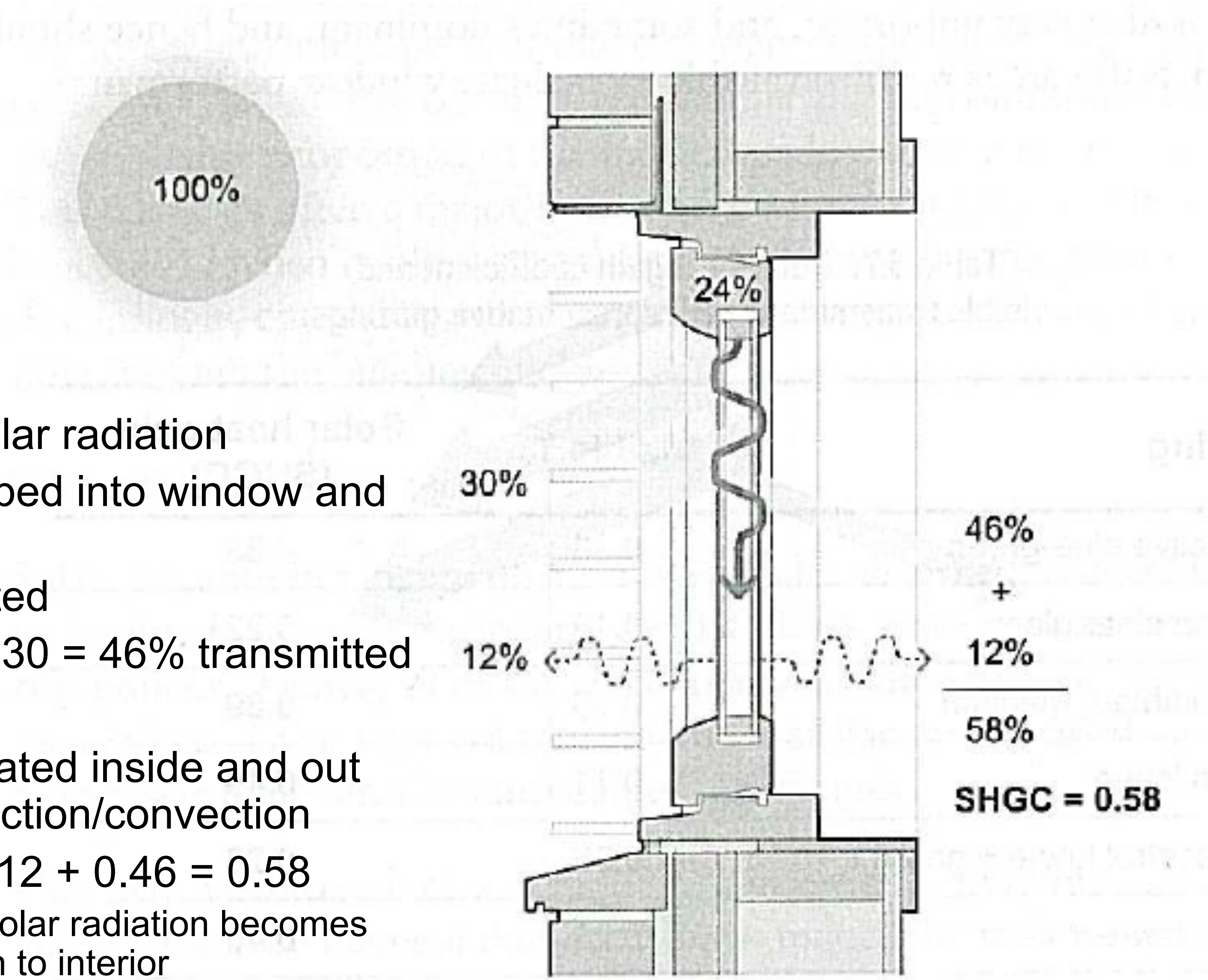
$$Q_{total} = U_{total} A_{proj} (T_{out} - T_{in}) + (SHGC) A_{proj} I_{total}$$

Solar Heat Gain Coefficient (SHGC)

- The SHGC is the fraction of incident solar radiation that is transmitted through a window and becomes part of the heat gain for the interior



Solar Heat Gain Coefficient (SHGC)



- In this case:
  - 100% of solar radiation
  - 24% absorbed into window and frame
  - 30% reflected
  - 100 – 24 – 30 = 46% transmitted
  - 12% reradiated inside and out after conduction/convection
  - SHGC = 0.12 + 0.46 = 0.58
    - 58% of solar radiation becomes heat gain to interior

Solar Heat Gain Coefficient (SHGC)

- The SHGC is the fraction of incident solar radiation that is transmitted through a window and becomes part of the heat gain for the interior

  Bounds:

  $0 < SHGC < 1$

- In general, SHGC is a function of both radiation wavelength and solar incident angle
- If only a single number is given, it will be normal incidence and averaged over all wavelengths
  - ASHRAE has some very complicated calculations for directional and spectral variations
    - We are not going to cover these

SHGC and energy use

- SHGC is directly related to building heating from the sun
- If we are dominated by the need for heating energy
  - We want to make use of solar energy to help heat our space
  - We want a higher SHGC
  - We would then use shading to reduce SHGC in summer
- If we are dominated by the need for cooling energy
  - We want a low SHGC to reduce solar heating
  - Can still use shading to help even more in the summer
- Note importance of dominant loads
  - Will explore in more detail in a future lecture

Typical VT and SHGC for different glazing types

Table 5.7: Solar heat gain coefficient and visible transmittance of representative glazings

Glazing	Visible T_v	Solar heat gain (SHGC)
Reflective blue-green	0.33	0.38
Film on clear glass	0.19	0.22
Green tinted, medium	0.75	0.69
Green low-e	0.71	0.49
Sun-control low-e + green	0.36	0.23
Super low-e + clear	0.71	0.40
Super low-e + green	0.60	0.30

Tinted glass heat gain

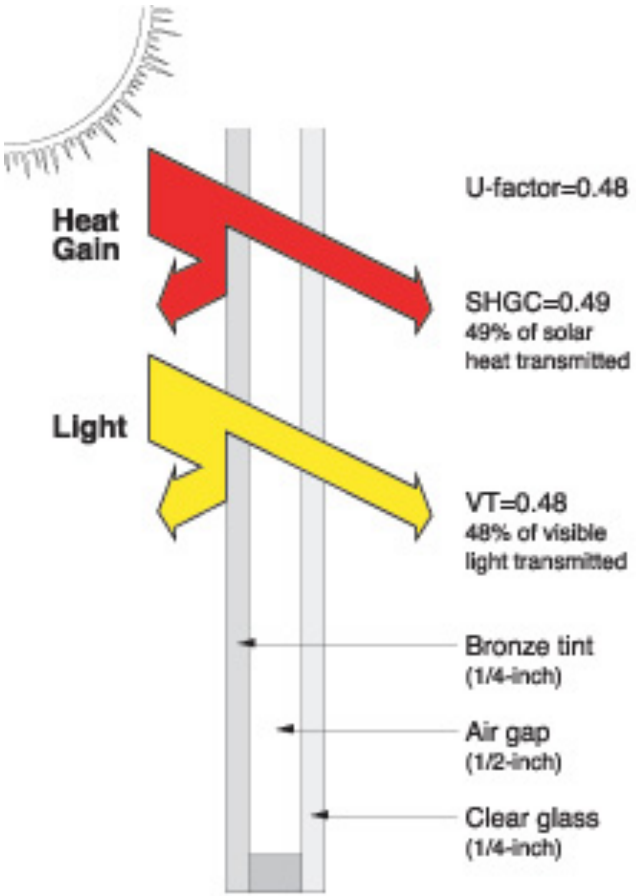


Figure 3-14. Double glazing with bronze-tinted glass on the outside layer

All values are for the glazing alone (center-of-glass).
Values for the total window will vary with frame type.
U-factor is in Btu/hr-sf-°F
SHGC=solar heat gain coefficient
VT=visible transmittance

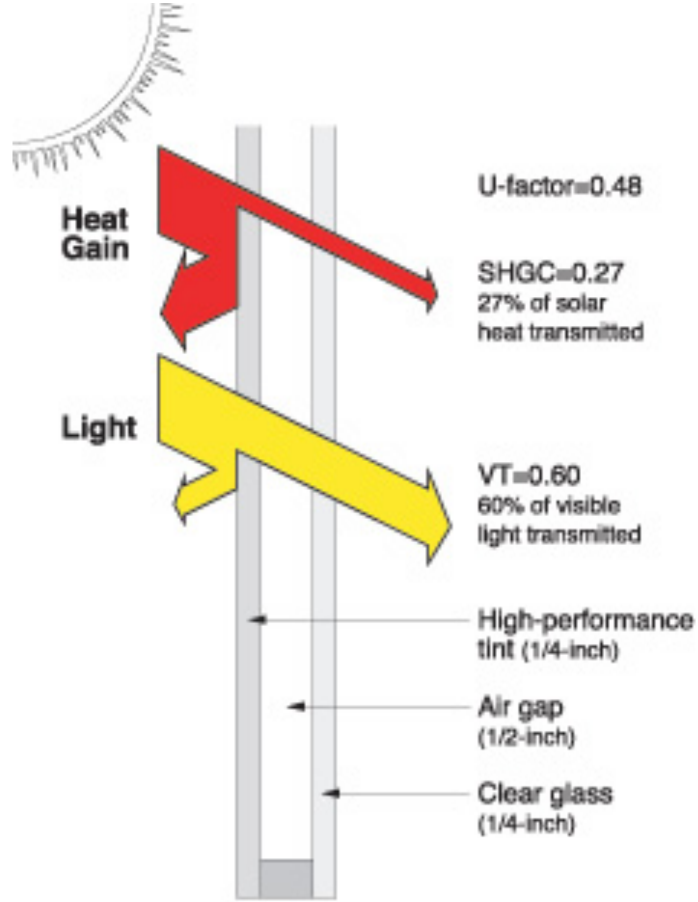


Figure 3-15. Double glazing with high-performance tint on the outside layer

All values are for the glazing alone (center-of-glass).
Values for the total window will vary with frame type.
U-factor is in Btu/hr-sf-°F
SHGC=solar heat gain coefficient
VT=visible transmittance

Low-emissivity (“low-e”) glass

- Improves thermal performance
  - Ultra-thin, transparent, metallic coating
  - Generally placed on glazing surfaces inside air space
    - Never on the exterior; condensation can increase emissivity
  - Reflects long wavelength IR radiation
    - Transmits most short-wave (sunlight)
      - Keeps thermal heat inside in winter
      - Keeps thermal heat outside in summer
  - Long wavelength emittance < 0.4 is typical
    - Standard glass is ~ 0.8
  - Result:
    - Reduced SHGC and U value for double glaze windows with under 10% reduction in visible light transmission

Finding SHGC, U, VT, and air leakage

- One place to start getting SHGC info is from the manufacturer label
- The SHGC given on the NFRC label is the <u>normal incident</u> and total assembly SHGC

NFRC

- The National Fenestration Rating Council (NFRC) is a non-profit devoted to developing standards for measuring and reporting important information about fenestration products
  - http://www.nfrc.org
- They compile a database of certified products with known values of U Factor, SHGC, Visible Transmittance, Air Leakage, and Condensation Resistance
- They also develop standards for measurement of the engineering data and labeling of products

Important standards

- These standards are freely available for download from NFRC.org
- NFRC 100 and 102: U Factors
  - This standard allows for you to estimate U factors using the Window and Therm programs product line if you have validated your simulation of specified "base windows"
- NFRC 200 and 201: SHGC and VT
- NFRC 300 and 301: Optical Properties and Emittance
- NFRC 400: Air Leakage
- NFRC 500: Condensation Resistance
- NFRC 600: Glossary and Terminology

Finding VT and SHGC data

- If the manufacturer does not provide more detailed data, you can get prototypical data from ASHRAE HOF

Table 13 Visible Transmittance (T_v), Solar Heat Gain Coefficient (SHGC), Solar Transmittance (T), Front Reflectance (R^f), Back Reflectance (R^b), and Layer Absorptance ($\mathcal{A}_n^f$) for Glazing and Window Systems

	Glazing System				Center-of-Glazing Properties							Total Window SHGC at Normal Incidence				Total Window T_V at Normal Incidence			
					Incidence Angles							Aluminum		Other Frames		Aluminum		Other Frames	
ID	Glass Thick., mm		Center Glazing T_V		Normal 0.00	40.00	50.00	60.00	70.00	80.00	Hemis., Diffuse	Operable	Fixed	Operable	Fixed	Operable	Fixed	Operable	Fixed
Uncoated Single Glazing																			
1a	3	CLR	0.90	SHGC	0.86	0.84	0.82	0.78	0.67	0.42	0.78	0.75	0.78	0.64	0.75	0.77	0.80	0.66	0.78
				T	0.83	0.82	0.80	0.75	0.64	0.39	0.75								
				R^f	0.08	0.08	0.10	0.14	0.25	0.51	0.14								
				R^b	0.08	0.08	0.10	0.14	0.25	0.51	0.14								
				$\mathcal{A}_1^f$	0.09	0.10	0.10	0.11	0.11	0.11	0.10								
1b	6	CLR	0.88	SHGC	0.81	0.80	0.78	0.73	0.62	0.39	0.73	0.71	0.74	0.60	0.71	0.75	0.79	0.64	0.77
				T	0.88	0.87	0.85	0.80	0.69	0.43	0.80								
				R^f	0.08	0.09	0.11	0.15	0.27	0.53	0.14								
				R^b	0.08	0.09	0.11	0.15	0.27	0.53	0.14								
				$\mathcal{A}_1^f$	0.16	0.17	0.18	0.19	0.19	0.17	0.17								

Finding VT and SHGC data

Table 13 Visible Transmittance (T_v), Solar Heat Gain Coefficient (SHGC), Solar Transmittance (T), Front Reflectance (R^f), Back Reflectance (R^b), and Layer Absorptance ($\mathcal{A}_n^f$) for Glazing and Window Systems

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ID	Glass Thick., mm		Center Glazing T_V		Normal 0.00	40.00	50.00	60.00	70.00	80.00	Hemis., Diffuse	Operable	Fixed	Operable	Fixed	Operable	Fixed	Operable	Fixed
Uncoated Double Glazing																			
5a	3	CLR CLR	0.81	SHGC	0.76	0.74	0.71	0.64	0.50	0.26	0.66	0.67	0.69	0.56	0.66	0.69	0.72	0.59	0.70
				T	0.70	0.68	0.65	0.58	0.44	0.21	0.60								
				R^f	0.13	0.14	0.16	0.23	0.36	0.61	0.21								
				R^b	0.13	0.14	0.16	0.23	0.36	0.61	0.21								
				$\mathcal{A}_1^f$	0.10	0.11	0.11	0.12	0.13	0.13	0.11								
				$\mathcal{A}_2^f$	0.07	0.08	0.08	0.08	0.07	0.05	0.07								
5b	6	CLR CLR	0.78	SHGC	0.70	0.67	0.64	0.58	0.45	0.23	0.60	0.61	0.63	0.52	0.61	0.66	0.69	0.57	0.68
				T	0.61	0.58	0.55	0.48	0.36	0.17	0.51								
				R^f	0.11	0.12	0.15	0.20	0.33	0.57	0.18								
				R^b	0.11	0.12	0.15	0.20	0.33	0.57	0.18								
				$\mathcal{A}_1^f$	0.17	0.18	0.19	0.20	0.21	0.20	0.19								
				$\mathcal{A}_2^f$	0.11	0.12	0.12	0.12	0.10	0.07	0.11								
5c	3	BRZ CLR	0.62	SHGC	0.62	0.60	0.57	0.51	0.39	0.20	0.53	0.55	0.57	0.46	0.54	0.53	0.55	0.45	0.54
				T	0.55	0.51	0.48	0.42	0.31	0.14	0.45								
				R^f	0.09	0.10	0.12	0.16	0.27	0.49	0.15								
				R^b	0.12	0.13	0.15	0.21	0.35	0.59	0.19								
				$\mathcal{A}_1^f$	0.30	0.33	0.34	0.36	0.37	0.34	0.33								
				$\mathcal{A}_2^f$	0.06	0.06	0.06	0.06	0.05	0.03	0.06								
5d	6	BRZ CLR	0.47	SHGC	0.49	0.46	0.44	0.39	0.31	0.17	0.41	0.44	0.46	0.37	0.43	0.40	0.42	0.35	0.41
				T	0.38	0.35	0.32	0.27	0.20	0.08	0.30								
				R^f	0.07	0.08	0.09	0.13	0.22	0.44	0.12								
				R^b	0.10	0.11	0.13	0.19	0.31	0.55	0.17								
				$\mathcal{A}_1^f$	0.48	0.51	0.52	0.53	0.53	0.45	0.50								
				$\mathcal{A}_2^f$	0.07	0.07	0.07	0.07	0.06	0.04	0.07								

Using $SHGC_N$

- If we are not worried about great accuracy, we can use the total window $SHGC_N$ with the overall incident solar radiation to find instantaneous solar heat gain q_{solar}

$$q_{solar} = SHGC_N I_{total}$$

where

$SHGC_N$ = total window SHGC at normal incidence

$I_{total} = I_{DN} \cos\theta + I_d + I_R =$ total solar irradiance

Example 8.2

- A fixed fenestration system has aluminum frames supporting a double glazed clear window (with VT of 78%)
  - If the direct incident solar radiation is 700 W/m^2 at an angle of 60° and the diffuse + reflected incident radiation is 70 W/m^2, what is the instantaneous solar heat gain?

Finding VT and SHGC data

Table 13 Visible Transmittance (T_v), Solar Heat Gain Coefficient (SHGC), Solar Transmittance (T), Front Reflectance (R^f), Back Reflectance (R^b), and Layer Absorptance ($\mathcal{A}_n^f$) for Glazing and Window Systems

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				T	0.70	0.68	0.65	0.58	0.44	0.21	0.60								
				R^f	0.13	0.14	0.16	0.23	0.36	0.61	0.21								
				R^b	0.13	0.14	0.16	0.23	0.36	0.61	0.21								
				$\mathcal{A}_1^f$	0.10	0.11	0.11	0.12	0.13	0.13	0.11								
				$\mathcal{A}_2^f$	0.07	0.08	0.08	0.08	0.07	0.05	0.07								
5b	6	CLR CLR	0.78	SHGC	0.70	0.67	0.64	0.58	0.45	0.23	0.60	0.61	0.63	0.52	0.61	0.66	0.69	0.57	0.68
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				R^f	0.11	0.12	0.15	0.20	0.33	0.57	0.18								
				R^b	0.11	0.12	0.15	0.20	0.33	0.57	0.18								
				$\mathcal{A}_1^f$	0.17	0.18	0.19	0.20	0.21	0.20	0.19								
				$\mathcal{A}_2^f$	0.11	0.12	0.12	0.12	0.10	0.07	0.11								
5c	3	BRZ CLR	0.62	SHGC	0.62	0.60	0.57	0.51	0.39	0.20	0.53	0.55	0.57	0.46	0.54	0.53	0.55	0.45	0.54
				T	0.55	0.51	0.48	0.42	0.31	0.14	0.45								
				R^f	0.09	0.10	0.12	0.16	0.27	0.49	0.15								
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				$\mathcal{A}_1^f$	0.30	0.33	0.34	0.36	0.37	0.34	0.33								
				$\mathcal{A}_2^f$	0.06	0.06	0.06	0.06	0.05	0.03	0.06								
5d	6	BRZ CLR	0.47	SHGC	0.49	0.46	0.44	0.39	0.31	0.17	0.41	0.44	0.46	0.37	0.43	0.40	0.42	0.35	0.41
				T	0.38	0.35	0.32	0.27	0.20	0.08	0.30								
				R^f	0.07	0.08	0.09	0.13	0.22	0.44	0.12								
				R^b	0.10	0.11	0.13	0.19	0.31	0.55	0.17								
				$\mathcal{A}_1^f$	0.48	0.51	0.52	0.53	0.53	0.45	0.50								
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Example 8.2

- A fixed fenestration system has aluminum frames supporting a double glazed clear window (with VT of 78%)
  - If the direct incident solar radiation is 700 W/m^2 at an angle of 60° and the diffuse + reflected incident radiation is 70 W/m^2, what is the instantaneous solar heat gain?
  - $SHGC_N = 0.69$

$$I_t = I_{DN}\cos\theta + I_d + I_R$$

$$I_t = 700\cos 60^\circ + 70 = 350 + 70 = 420\ \frac{\text{W}}{\text{m}^2}$$

$$q_s = SHGC_N \cdot I_t = 0.69 \cdot 420 = 290\ \frac{\text{W}}{\text{m}^2}$$

GLAZING: DESIGN CONSIDERATIONS

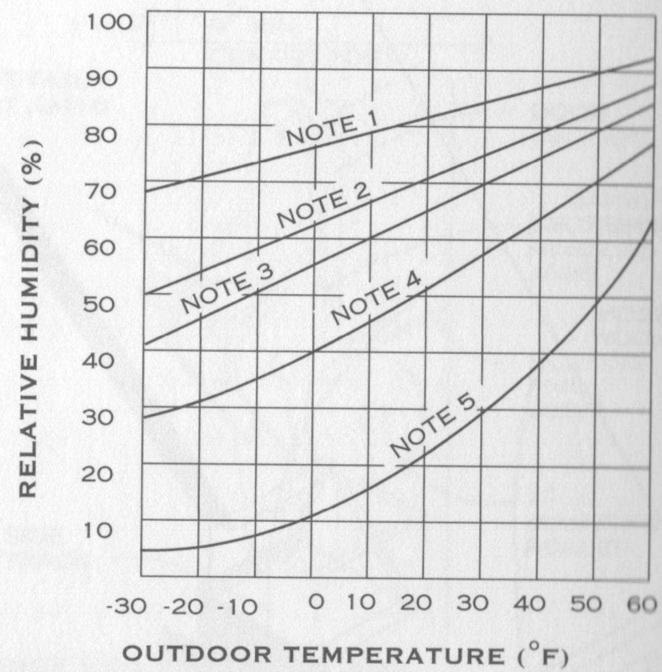
Why/why not design with glass?

- Benefits of using glass
  - Allows entry of high quality natural light
    - Proper use of daylight can reduce lighting energy costs
  - Entry of sunlight provides warmth
    - Passive solar heating can reduce heating costs
  - Provide views of exterior environment

- Disadvantages and design considerations
  - Limits occupant's privacy
  - Lower resistance to thermal transmission
  - Entry of sunlight adds to cooling load
  - High initial costs and ongoing maintenance costs
  - High embedded energy (from manufacturing)

Importance of heat transfer for condensation

- Heat transfer through fenestration is not only important for energy performance
  - Also for moisture performance
  - At low outdoor temperatures
    - Condensation will occur on the cold indoor surfaces of poorly insulated windows
    - Even at low indoor humidities



NOTES

1. Triple-glazed windows with two low-E coatings and argon gas fill.
2. Double-glazed windows with a low-E coating and argon gas fill.
3. Double-glazed windows with a low-E coating.
4. Double-glazed windows.
5. Single-glazed windows.

CONDITIONS THAT LEAD TO CONDENSATION ON WINDOWS

Importance of fenestration for practical concerns

- Selection of window frame materials
  - Design for energy, maintenance, and moisture concerns

WINDOW FRAME DETAILS

WINDOW FRAME TYPES

FRAME TYPE	CHARACTERISTICS	MAINTENANCE	FINISHES	HEAT TRANSFERENCE	SUSTAINABILITY	NOTES
Wood	Solid members; ease of milling into complex shapes; attractive and traditional appearance U-factor: 0.3–0.5	Rot prevention: refinish in 5 to 10-year cycle or permanent finish	Oil or latex paint, stains, oils, or varnishes; preservatives; polyurethane resin coatings; prefinished or site finished	Low	Renewable resource; requires high-quality solid stock	Traditional and typical material; variety of species available; easy repair
Wood with cladding	Metal- or plastic-clad wood U-factor for vinyl clad: 0.3–0.5; for metal clad: 0.4–0.6	Minimal	See metal and plastic frames	Low with vinyl cladding, slightly higher with metal	Use of less desirable wood materials; salvageable cladding	Wood for stability/ strength, cladding for maintenance
Hybrids	Wood interior, metal or plastic exterior U-factor for vinyl/wood: 0.3–0.5; for metal/wood: 0.4–0.6	See wood, metal, and plastic categories	See other categories	Low with vinyl/wood hybrid, slightly higher with metal/wood hybrid	Use of lower quantities of any one material	Good interior look with good exterior performance and low maintenance
Steel	Thin bar/ angle steel profiles; cast, extruded, forged U-factor: similar to that of aluminum	Rust prevention: refinish in 5 to 10-year cycle or permanent finish	Galvanizing, zinc-phosphate coatings; primed; painted; factory finishes: baked enamel, fluoropolymer, polyurethane coatings	High, unless thermal break is installed	Non-renewable, salvageable	High strength/smallest frame profiles of all types; stainless steel available but expensive
Aluminum	Box profiles; extrusions; lightweight U-factor: 1.0 (with thermal break), 1.9–2.2 (without thermal break)	Minimal	Natural; factory-applied: baked enamel, epoxy, anodized, electrostatic (powder), fluoropolymer coatings	High unless thermal break is installed	Non-renewable, salvageable	High strength, no maintenance
Vinyl (PVC)	High impact resistance; box profiles; multi-chambered extrusions U-factor for hollow: 0.3–0.5; for insulated: 0.2–0.4	Minimal	Integral when fabricated (limited colors)	Low	Non-renewable, petroleum-based	UV/sun protection from discoloration may be required; salt air and acid resistant
Fiberglass	Box profiles, polymer-based thermoplastic; dimensionally stable U-factor for hollow: 0.3–0.5; for insulated: 0.2–0.4	Minimal	Integral when fabricated	Low	Spun glass in resin binders	More expensive but more structurally stable than vinyl

John Carmody, University of Minnesota; Minneapolis, Minnesota
Stephen Selkowitz, Lawrence Berkeley National Laboratory; Berkeley, California

Can highly glazed building facades be ‘green’?

- What do you see?
  - Energy hog?
  - Energy efficiency?

Can highly glazed building facades be 'green'?

- In the past, windows did little to control heat loss and solar gain
  - Many older buildings had restricted window-to-wall areas
- Tremendous gains in glazing performance have been made in recent years
  - Are the gains good enough to warrant large amounts of glazing?
    - Floor-to-ceiling?
  - Biggest arguments *for* high-glazing
    - Increased daylighting
    - Occupant satisfaction
    - Aesthetics

Straube, 2008. *Building Science Insights* 006

Can highly glazed building facades be ‘green’?

- Let’s pick U values from our tables
  - Poor performing single-glazed window
    - U ~5 W/(m^{2}K) installed
    - R ~0.2 (m^{2}K)/W → R-1 (IP)
  - High performing triple glazed low-e argon window
    - U ~1 W/(m^{2}K) installed
    - R ~1 (m^{2}K)/W → R-5 (IP)

  - 1 inch (2.5 cm) of rigid insulation
    - R ~1 (m^{2}K)/W → R-5 (IP)

  - The best performing windows have worse thermal performance than the simplest lowest-cost wall with rigid insulation

Straube, 2008. *Building Science Insights* 006

Can highly glazed building facades be ‘green’?

- On a cold winter day, offices exposed to sun require cooling
  - Those in the shade still need heat
  - Many will be uncomfortable

- Poor thermal performance of highly glazed facades
  - The solar heat gain resulting from large amounts of glazing often drives the size of a building’s air-conditioning plant
  - Low-e coatings and other materials that let in visible light but block infrared heat radiation are miraculous
    - But we squander their potential by increasing window areas

Straube, 2008. *Building Science Insights* 006

Can highly glazed building facades be 'green'?

- One argument: daylighting
  - Glazing let's light in
- Daylighting can certainly offset the need for electric lighting
  - Also improve psychological attitude about a space
- But you don't need floor-to-ceiling windows to achieve adequate daylighting!
  - Very little benefit to vision glass installed at the floor
    - Unless you spend a lot of time lying on the floor
  - Typically no daylighting or energy benefits with window-to-wall ratios over 60%
    - 25-40% is usually optimum for achieving daylighting + energy conservation
    - Glazing should still be high performance

Straube, 2008. *Building Science Insights* 006

Can highly glazed building facades be 'green'?

- So which one of these do you choose?

Straube, 2008. *Building Science Insights* 006

Thermal design with glass

- There are many methods used to compensate for its poor thermal properties
  - Insulated windows with double & triple glazing
  - Low E coatings
  - Low conductivity gas fills
  - Tinting
  - Reflective coatings
  - Curtains and shutters
  - Window sizing & orientation on the building
  - Shading or overhangs

New technologies are pushing the boundaries on thermal performance

- Building Integrated Photovoltaic (BIPV)
  - Photovoltaic (PV) cells provide shading and generate electricity
  - Will have a project on BIPV
- Vacuum windows
  - Removing air eliminates conduction and convection
    - Effective but expensive to manufacturer
- Aerogel
  - Transparent silica gel with a very low density
  - Very high insulating properties
  - Very good sound absorption properties

Energy analysis for enclosures

- So far we have explored mostly single assemblies
  - Walls, roofs, windows, doors
  - Conduction, convection, radiation, air leakage
  - We now know how to put them all together in an envelope
  - **Combined thermal transmittance**: U_o
    - Area-weighted average U-value

$$U_o = (U_{wall} A_{wall} + U_{window} A_{window} + U_{door} A_{door}) / A_o$$

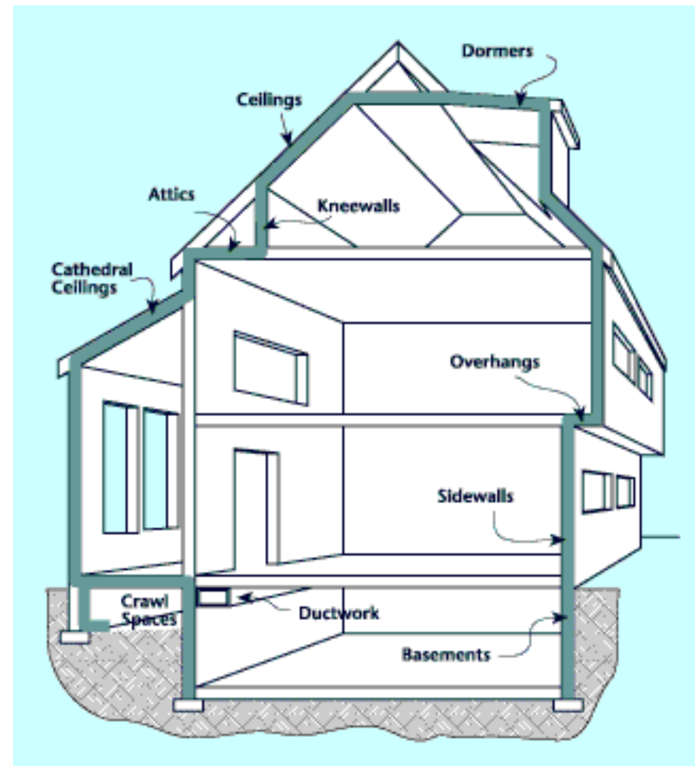
- How do we estimate the likely impact of all of these things working together in an entire building?
  - Building energy analysis/modeling

INSULATION MATERIALS

Applications

Building insulation

- Insulation is necessary to control heat flow through enclosure
- All opaque external surfaces should have insulation
  - Walls
  - Ceilings
  - Roof
  - Basements
- We've discussed insulation in terms of thermal conductivity, U-values, and R-values
  - ***A lot***



Important properties of insulation

- Thermal Resistance
  - Important for controlling heat flow
- Vapor Resistance
  - Important for controlling condensation
- Fire/Smoke Resistance
  - Important for fire and life safety considerations
- Sound Absorption
  - Important for noise control
- Structural Integrity
  - Important for use in certain applications (roofing)
- Chemical Composition
  - Important for knowledge of environmental considerations
- Cost
- Sustainability

Thermal resistance measures (IP units)

- R = R-Value [(h ft^2 °F)/Btu]
  - Thermal resistance per unit area
  - Larger R-Value is better
- U = U Value [Btu/(h ft^2 °F)]
  - $U = 1/R$ = Thermal conductance per unit area
  - Often used for doors and windows
- r = thermal resistivity [(h ft^2 °F)/Btu in]
  - $r = R/L$ = also **R per inch** of thickness
  - Larger r value is better
- k = thermal conductivity [Btu/(hr ft^2 °F in)]
  - $k = 1/r = L/R$
  - Smaller k value is better

- Thermal resistance is measured using ASTM C1114-00 and C1363-05

Notes for construction documents

- Conductivity of types of insulations can change from manufacturer to manufacturer
  - It is best to denote a required R value on the building drawings and in the specifications
  - Ensures that the required insulating value is installed

- When comparing insulations, it is better to compare r or k values because they are basic material properties
  - Not dependent on thickness

Vapor resistance measures (IP units)

- M_v = vapor permeance [IP perms] ≈ [57.2 ng/(s·m^2·Pa)]
  - $M_v < 0.1$ is a vapor barrier
  - $0.1 < M_v < 1$ is a vapor retarder
  - $1 < M_v < 10$ is vapor semi-permeable
- $Z = 1/M_v$ = vapor resistance [IP reps, inverse of M_v]
  - $Z > 10$ is a vapor barrier
  - $1 < Z < 10$ is a vapor retarder
  - $0.1 < Z < 1$ is a vapor semi-permeable
- Vapor resistance is tested using ASTM E96

Primary types of insulation

- Fiberglass
- Mineral Fibers
- Cellulose
- Natural Fibers
  - Cotton
  - Wool
- Spray on Foams
- Rigid Foams
- Structure-integrated insulations
  - EIFS, ICFS, SIPS

ASTM insulation standards

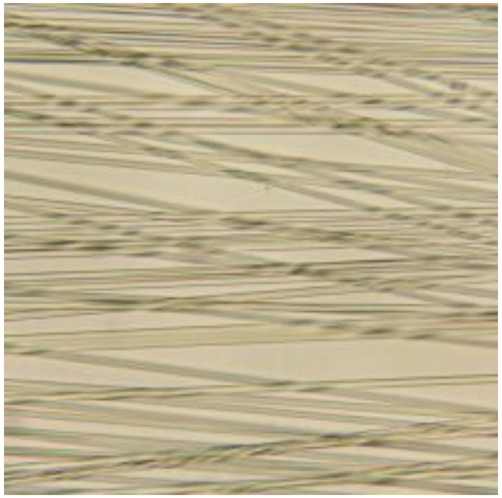
- C168-05 Standard Terminology for Thermal Insulation
- C165-05 Standard Test Method for Measuring Compressive Properties of Thermal Insulations
- C520-04 Standard Test Methods for Density of Granular Loose Fill Insulations
- C1058-03 Standard Practice for Selecting Temperatures for Evaluating and Reporting Thermal Properties of Thermal Insulation
- C1114-00 Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Thin-Heater Apparatus
- C1155-95(2001) Standard Practice for Determining Thermal Resistance of Building Envelope Components from the In-Situ Data
- C1158-01 Standard Practice for Installation and Use of Radiant Barrier Systems (RBS) in Building Construction
- C1363-05 Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus
- ASTM E96 / E96M - 05 Standard Test Methods for Water Vapor Transmission of Materials

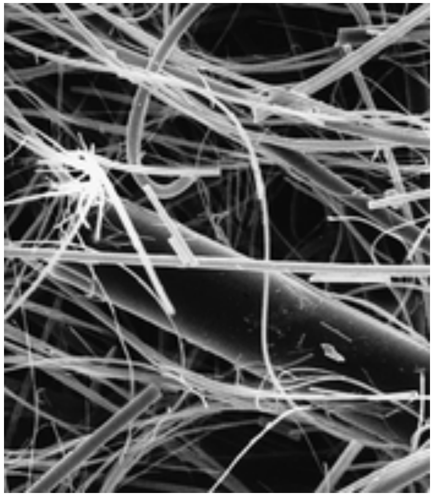
ASTM insulation specifications

- C578-05 Standard Specification for Rigid, Cellular Polystyrene Thermal Insulation
- C552-03 Standard Specification for Cellular Glass Thermal Insulation
- C553-02 Standard Specification for Mineral Fiber Blanket Thermal Insulation for Commercial and Industrial Applications
- C610-05 Standard Specification for Molded Expanded Perlite Block and Pipe Thermal Insulation
- C764-04 Standard Specification for Mineral Fiber Loose-Fill Thermal Insulation
- C1014-03 Standard Specification for Spray-Applied Mineral Fiber Thermal and Sound Absorbing Insulation
- C1126-04 Standard Specification for Faced or Unfaced Rigid Cellular Phenolic Thermal Insulation
- C1289-05 Standard Specification for Faced Rigid Cellular Polyisocyanurate Thermal Insulation Board

Fiberglass or glass wool insulation

- Fiberglass is made from thin filaments of glass
  - Also known as glass wool
- Fiberglass acts as an insulator by reducing internal convection and radiation
  - Glass fibers conduct heat better than still air, but the closely spaced fibers resist air motion and nearly eliminate convection
  - Radiation is absorbed and reradiated by fibers but each absorption and re-radiation reduces the energy transmission





Forms of fiberglass insulation

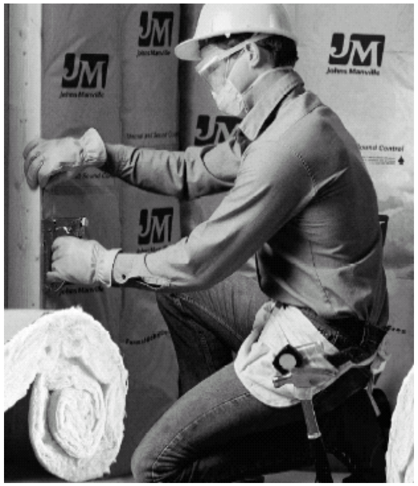
- Blankets
  - Faced or Unfaced Rolls and Batts
    - Kraft Paper Facing provides variable vapor resistance but reduces fire resistance
    - Foil Facing provides vapor resistance, fire resistance, and a radiative reflective barrier
    - MR Facing: Mold Resistant facing
  - Encapsulated batts
    - Poly-encapsulation acts as a vapor barrier and makes it easier to install without contacting fibers
- Loose-Fill
  - Blown in to place
  - Fits into nooks and crannies
- Rigid Boards
  - Used for acoustic panels and external insulation boards

Properties of fiberglass insulation

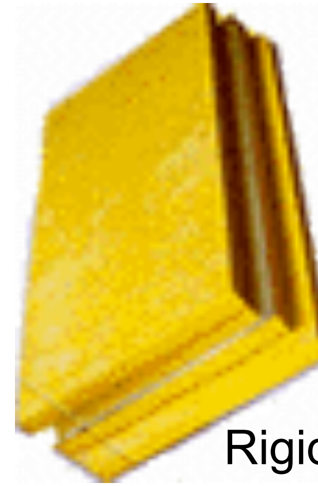
- $r \approx 3$ h ft^2 °F /Btu in with $2 < r < 3.7$
  - Starts a bit higher but usually drops as fiberglass settles
  - Must avoid compression to keep R-value high
    - A 6 inch fiberglass batt compressed to fit in a 2x6 stud has a lower R value than a 5 inch fiberglass batt undisturbed
- Usually sold according to its R-Value
  - R-11, R-13, R-19, etc. (or R per inch)
- Vapor Resistance (IP)
  - 0.001 rep (bare), ~0.1-5 rep (Kraft faced), 20 rep (foil faced)
- Density ≈ 1 pcf (pound per cubic foot)
- Compressive strength
  - 10-20 PSI for rigid fiberglass, 0 PSI for batting
- Costs: R-11 installed costs are as low as \$0.50/ft^2
  - More typically \$0.75-1/ft^2

Types of fiberglass insulation

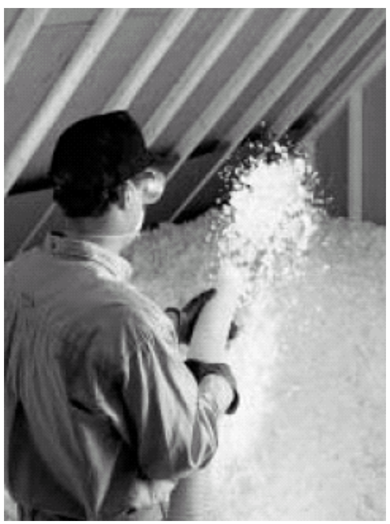
Kraft Faced



Poly Encapsulated



Rigid



Blown In

Foil Backed

Advantages and disadvantages of fiberglass

- Advantages
  - Low density
    - Easy storage and transport
  - Inexpensive (both material and installation costs)
  - Inorganic – fiberglass itself is fire and mold/bacteria growth resistant
- Disadvantages
  - Low density means surprisingly poor fire resistance
    - Material very difficult to ignite, but flame travels through air space fairly well
  - Fiberglass is a carcinogen
    - Very hazardous installation - must wear gloves, masks and goggles
    - Must keep fibers from getting airborne after installation
  - Can absorb moisture since there are no closed cells
    - R-value can drop when wet

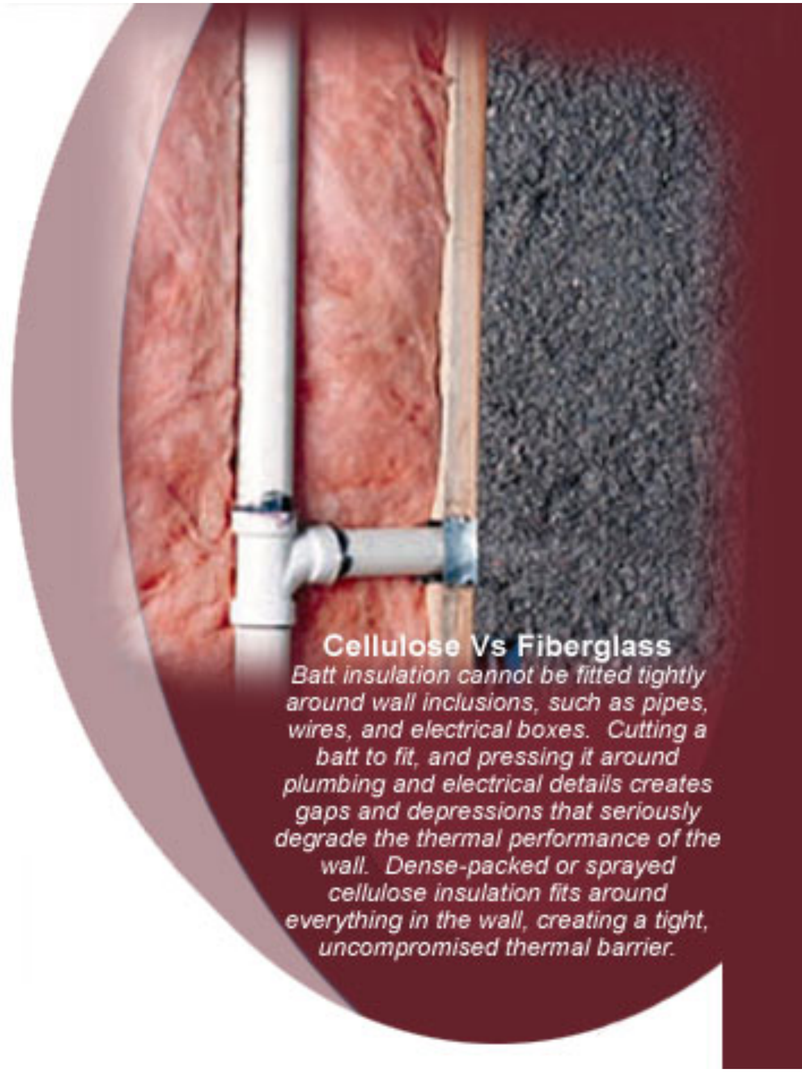
Rock and slag wool insulation (aka mineral wool)

- Rockwool
  - Made from basalt (a volcanic rock) and limestone
- Slagwool
  - Made from recycled blast furnace slag (byproduct of iron/steel)
- Density of 2.5 to 4.0 lb/ft^3
- r usually a bit higher than fiberglass
  - r is 3.7 h ft^2 °F/(Btu in) for 2.5 pcf rock wool
  - r is 3.9 h ft^2 °F/)Btu in) for 4 pcf rock wool
- Higher fire resistance than fiberglass
- Does not absorb moisture well
- Installed costs a bit higher than fiberglass

Mineral wool insulation

Cellulose insulation

- Made from shredded newspaper and wood pulp
  - Chemically treated to increase fire resistance
  - Noncarcinogenic
- r ≈ 3.6 h-ft$^{2°}$-F/(Btu in)
- Density ≈ 1.6 pcf
- Cellulose is applied wet and sticks to wall and fills gaps
- Installed costs a bit higher than blanket fiberglass
  - $1-1.5/ft^2



Advantages and disadvantages of cellulose

- Advantages
  - A very ‘green’ building product
    - 6x less energy than fiberglass to manufacture
    - 25 to 50x less embodied energy than other mineral fibers
  - Higher density than fiberglass reduces air flow
    - May reduce heat transfer even with a lower R value
    - Less air space means flame spread characteristics can be better than fiberglass
- Disadvantages
  - Absorbs and retains moisture, which reduces R-Value
  - More susceptible to mold/fungus growth than mineral fibers
  - Lower innate fire resistance than mineral fibers
    - Wet applied clings to walls which means quicker ignition
  - Wet Applied Cellulose must dry before walls are closed – slows down construction time

Cotton fiber insulation

- Made mostly from recycled cotton fibers
- r value ≈ 3-4 h ft^2 °F/(Btu in)
- Organic
  - Possible problems with mold/fire
  - Fire ratings are pretty good
- No problems with chemical emissions
  - Possible problems with allergies
- 'Green' manufacturing
  - 100% recyclable
  - Low energy to manufacture
- Installed cost is comparable to mineral fibers and cellulose

  ~$1.20-1.50/ft^2

Insulation made from recycled denim

Actual wool fiber insulation

- Made from Sheep's wool
- r-factor ≈ 3.5 to 3.8 h ft^2 $^\circ$F /(Btu in)
- Organic
  - Possible problems with mold/fire
  - Fire ratings are pretty good
- No problems with chemical emissions
  - Possible problems with allergies
- Somewhat 'green' manufacture
  - 100% recyclable
  - You can eat the production device
- Installed cost is much higher than mineral fibers

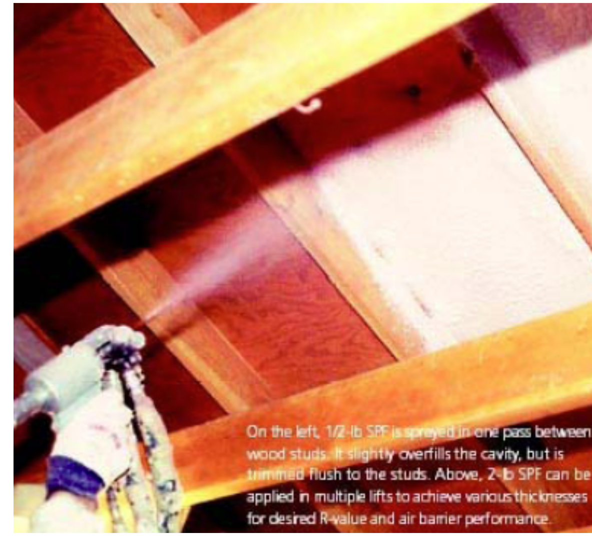
  ~\$2-2.50/ft^2

Foam insulations

- Foam building insulations offer an alternative to fibrous materials
- Liquid Foams are sprayed in and expand to fill cavities
  - Use in place of spray in fiberglass or cellulose
- Foam board is rigid and self supporting
  - Use in place of blanket, batt or rigid fiberglass insulation
  - Very useful for external and roof insulation

Spray-on expanding foam

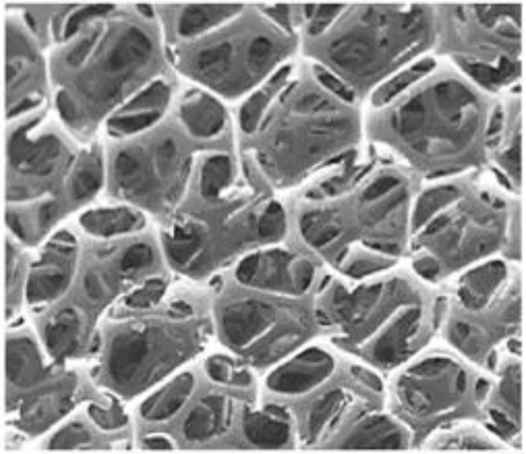
- Spray-on polyurethane material
- r ≈ 3-7 (h ft2 °F)/(Btu in)
- Density ≈ 2.0 pcf
- Spray in expanding foam fills cracks and gaps
- Closed cell completely eliminates the need for taping/sealing and air barrier material
  - This is great for trying to insulate existing construction where it is hard to cut around framing and piping
    - Spray in foam can be sprayed around it
- Installed costs are about $\$1.5\text{-}2/ft^2$
  - But you eliminate the cost to install an air barrier for closed cell foam

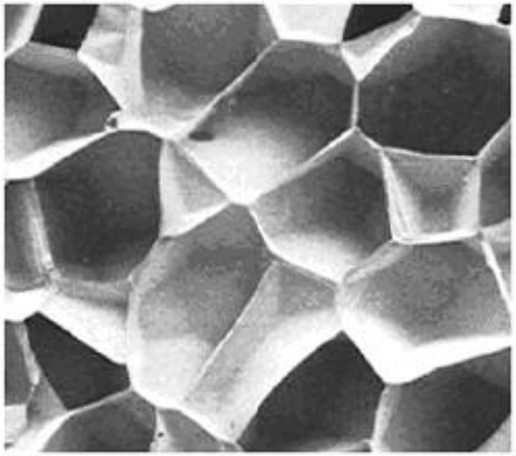


Open-cell:
r ~ 3.6 per inch

Closed-cell:
r ~ 6.5 per inch

Open-cell and closed-cell foams





Expanded polystyrene (EPS)

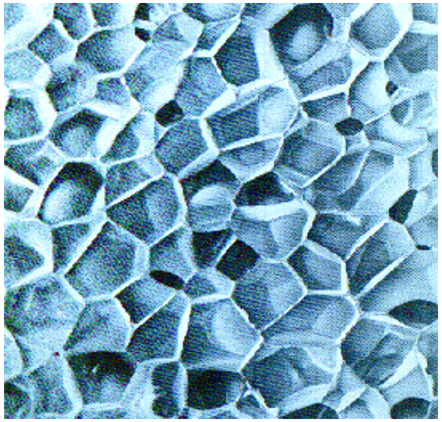
- Denoted EPS or MEPS (M = molded)
  - Commonly called styrofoam
- Polystyrene beads are heated in molds
  - Expands pentane within (C_5H_{12})
  - Resulting structure is touching spheres with gaps between
- More easily molded to different thicknesses than XPS

EPS properties

- $r \approx 4$ ft^2 °F /Btu in
- Density ≈ 1 - 5 pcf
- Vapor Resistance ≈ 0.3-3 rep/in
- Compressive Strength: 10 - 20 PSI
  - Much higher than non-rigid fiberglass
- Up to 4% or 5% water absorption
- Flame Spread: 20
- Smoke Developed: 150-300
- Material itself is usually 100% recyclable
  - But note that EPS cannot be made completely from recycled material, some virgin materials are necessary

Extruded expanded polystyrene

- XEPS or XPS
- Polystyrene is melted and injected with a blowing agent forming gas bubbles
- Resulting structure is more like a honeycomb with closed or open cells
- Often used as structural insulating panels (SIPs) or insulating concrete forms (ICF)
  - More on these later
- Because the cells are closed, it stores less moisture and is suitable for foundation insulation



XPS properties

- r-factor ≈ 5.5 h ft^2 °F /Btu in
  - A bit higher than EPS
- Density ≈ 1.5 - 5 pcf
- Vapor Resistance ≈ 0.4 – 2.2 rep/in
  - Compressive Strength: 20 – 100 PSI
- Flame Spread: 5
  - Closed cells reduce flame spread
- Smoke Developed: 175
- Material itself 100% recyclable
  - But XPS cannot be made completely from recycled material

Polyisocyanurate (“polyiso” or “PIR”)

- Low conductivity gas is injected to form bubbles
  - Decreases thermal conductivity
  - Increases thermal resistance
- Available in rigid board or as a spray on foam
- Foil backed boards repel water and reflect radiant energy

http://www.polyiso.org/

Polyiso insulation properties

- r-factor ≈ 8-10 h ft^2 °F /Btu in
  - Highest of all common building materials
  - Starts at 10 but stabilizes at 7-8 as gas escapes
- Vapor Resistance ≈ 0.5 reps/in
- Density ≈ 1.5 – 2 pcf
- Compressive Strength: 16 – 40 PSI
- Flame Spread: 5
- Smoke Development: 165

Advantages and disadvantages of foams

- Advantages
  - Highest r-factors = best insulating capabilities
  - Easy storage, transport, and installation
  - Easily shaped and tapered
    - Important for designing drainage in roofs
- Disadvantages
  - Least environmentally friendly to manufacture
    - Made from plastics (oil and natural gas inputs)
    - Blowing agents in XPS and polyiso are still usually HCFCs or HFCs
  - Foams generally have lower fire resistances and are toxic when ignited
  - Does have some water absorption properties (especially EPS)
  - Possible VOC off-gassing problems

Structural requirements of insulations

- On rooftops, the insulation must be able to support some load
  - Rain, snow, occasional people
- Fibrous materials need a supporting shell or need to be used interior only
- Rigid fiberglass is strong but expensive
- Foam insulations are self supporting and are used almost ubiquitously for external roofing insulation

Acoustic uses

- For acoustic uses, the insulation must allow sound into the porous structure and have minimal contact with walls
  - Fibrous materials like fiberglass, rockwool, cotton, and wool are good
  - Blown-in materials like cellulose are okay, but they have contact with both sides of walls
- Rigid foams are usually closed cell and do not provide any acoustic benefit
  - Rigid foams (either open or closed) in touch with two walls transmits vibration directly which will decrease sound isolation
    - Properly installed (i.e., only touching one wall) open cell foams can act similarly to a fiberglass batt

Applicability of insulations

- Fibrous, cellulose, and expanding foams are really only useful as cavity insulation

- Rigid foams are mostly used as exterior insulations
  - Even thin pieces of external insulation can reduce thermal bridging of structural elements

Comparing “greenness”

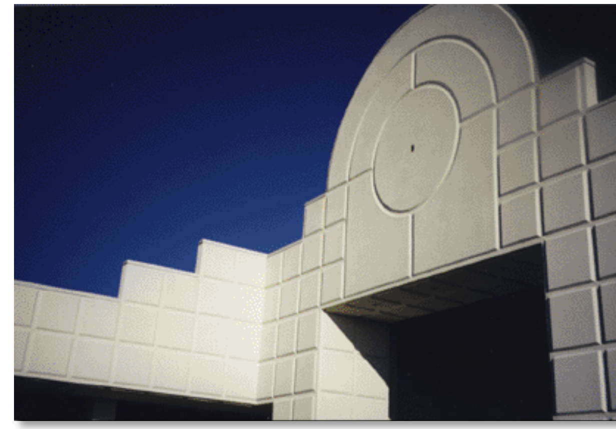
- Some man-made and natural fiber dealers claim theirs is the “greenest” insulation
  - Wool and cellulose in particular
- A proper comparison includes entire cost to manufacture, transport and install (embodied energy), as well as expected energy savings over the lifetime of the material
  - On an energy only basis, XPS and polyiso win out as the increased R value is so much higher than other insulations
- Sustainability should be included too
  - Wool and cellulose come from sustainable materials, but the growth and harvesting require the use of non-sustainable materials (namely fossil fuels)
  - Natural fibers are biodegradable, something that poly’s are not

Structure-integrated insulation systems

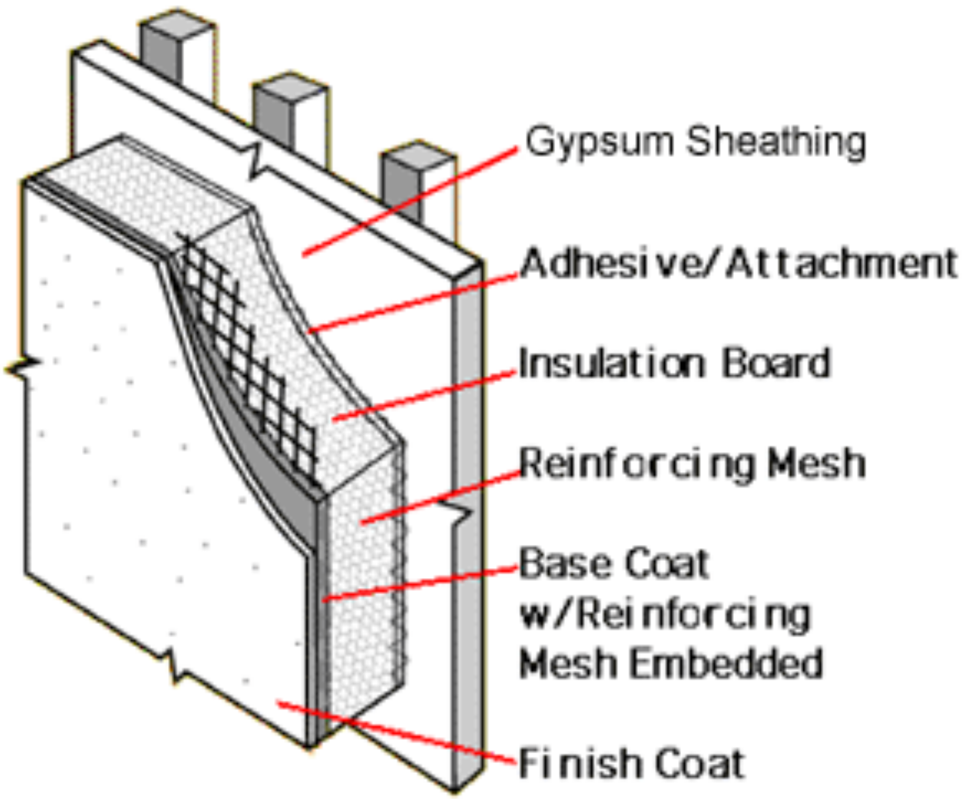
- EIFS
  - Externally Insulated Finish Systems
- ICFs
  - Insulated Concrete Forms
- SIPs
  - Structural Insulated Panels

EIFS

- Exterior Insulation and Finish Systems (EIFS) are insulated, multilayered exterior wall systems
  - Essentially this is synthetic stucco
  - Introduced into US in the 1970s to improve energy efficiency
  - First used on commercial buildings
    - Then used in homes as well
  - 30% of the commercial building exterior wall market



EIFS construction

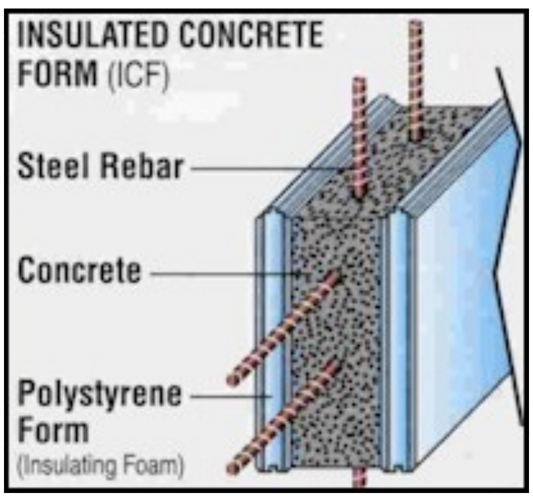


- OSB or plywood substrate
- Polystyrene or polyisocyanurate insulation
- Multi-coat acrylic polymer with fiberglass reinforcement
  - Basically, synthetic stucco

No more information because Stuart and Maria will tell us all about EIFS in their final project presentation!

ICFs: Insulated Concrete Forms

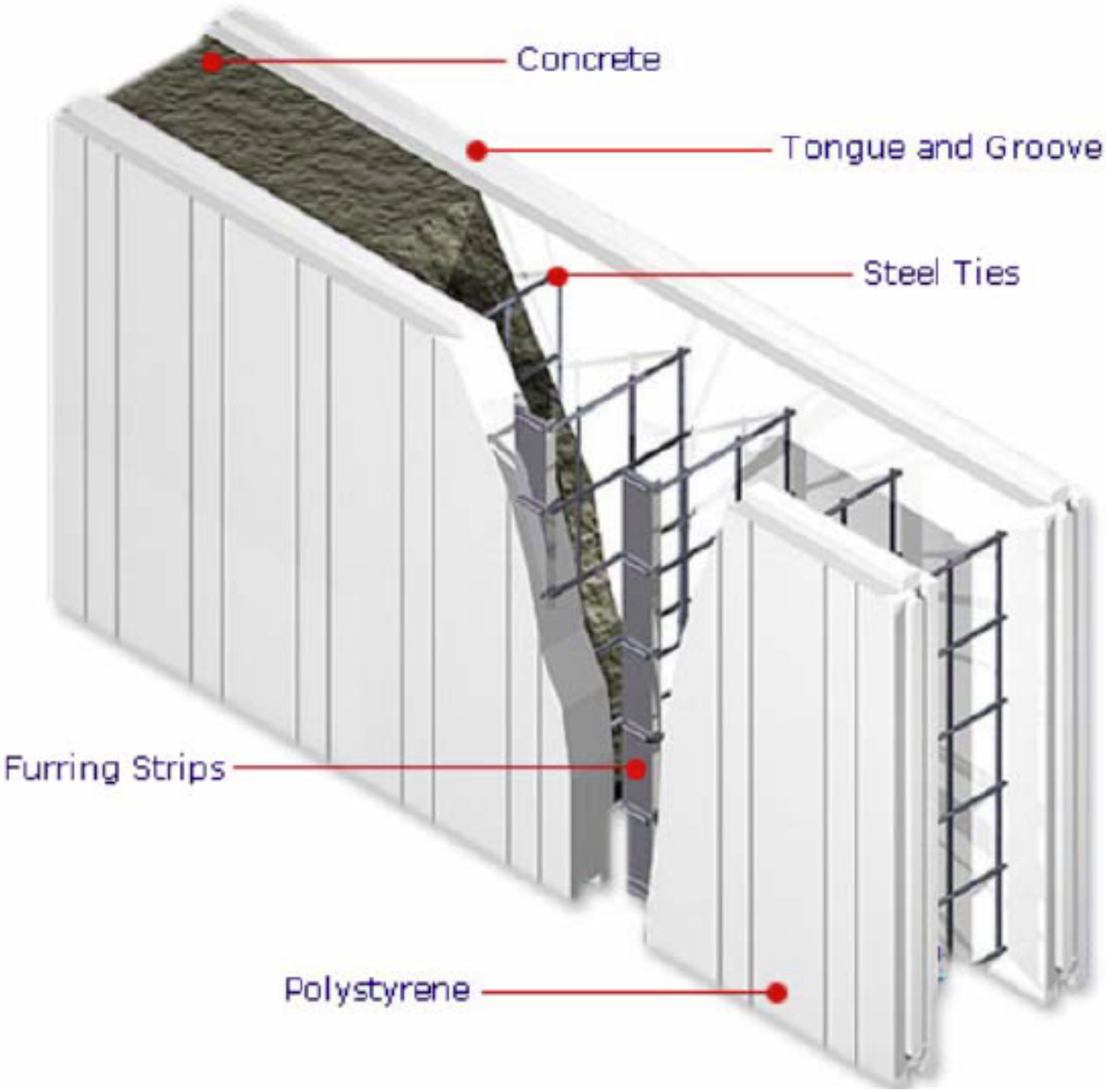
- Forms or molds that have made insulation for accepting reinforced concrete
- These forms are stacked and tied together, rebar is added, then filled with concrete
- Forms remain in place after concrete cures
  - It's like formwork you don't remove



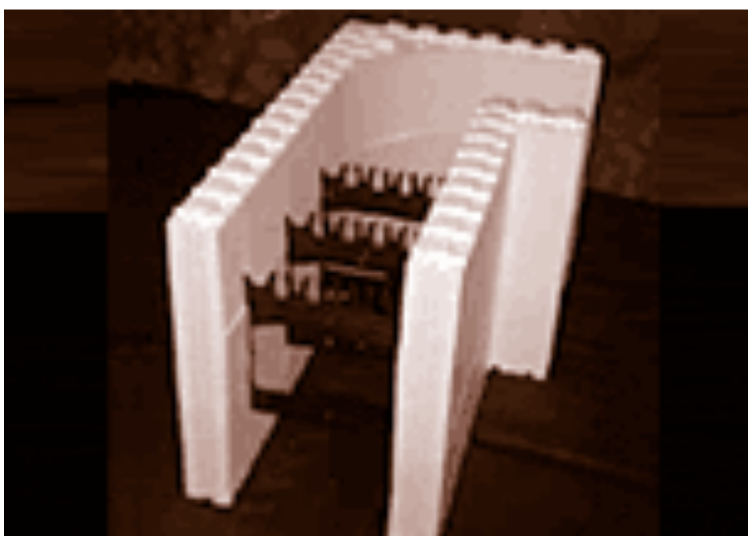
<u>Components</u>

- 2 Pieces of EPS or XPS 2-4 inches thick
- 4, 6, 8, or 12 inch thick concrete fill
- Steel rebar

ICFs


Concrete
Tongue and Groove
Steel Ties
Furring Strips
Polystyrene

ICFs

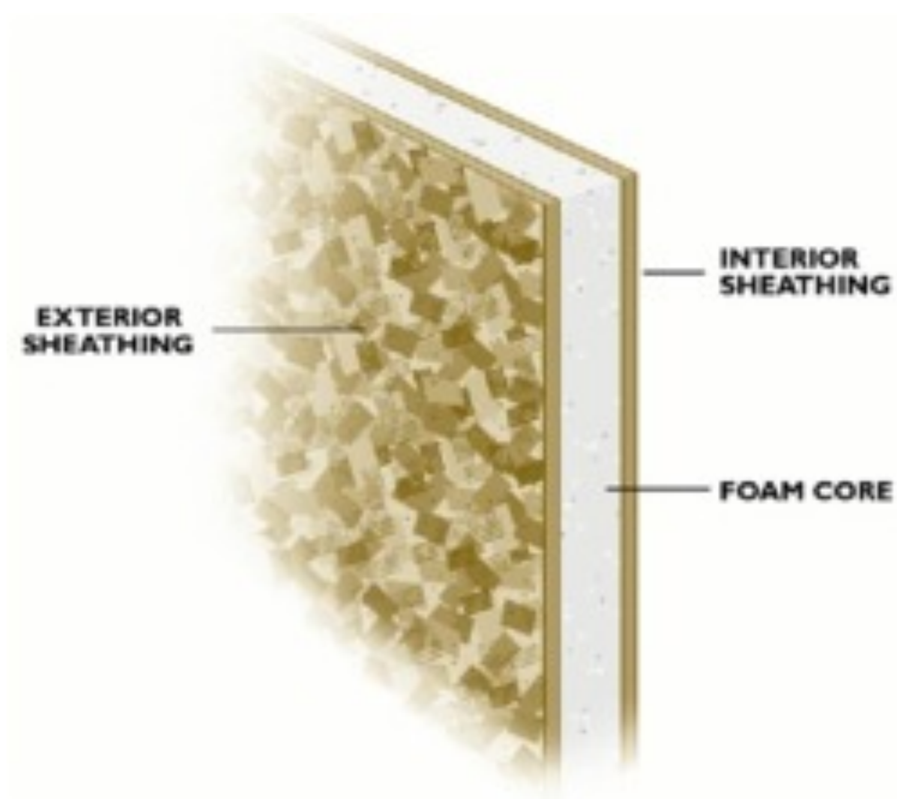


Advantages of ICFs

- Benefits of both thermal mass and high R value
  - R-20 to R-40 (IP) are commonly available
  - Peak energy reductions of 20-50% over frame buildings
- ICFs create a structural concrete wall that is up to 10 times stronger than wood framed structures
- High sound isolation
- Good protection against fire, water, insects
- Construction methods are easy to learn
- Flexibility in design
  - Can be externally cladded with EIFS to make virtually any shape

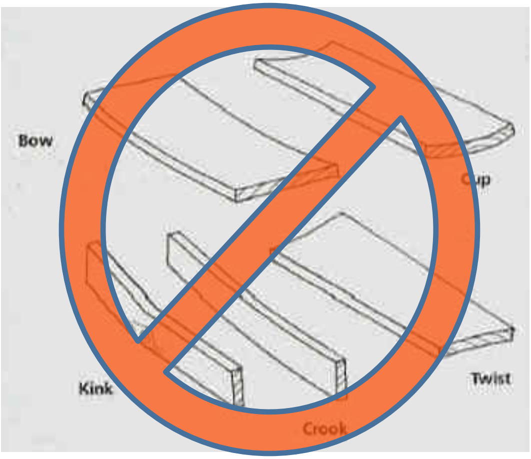
Structural Insulated Panels (SIPs)

- SIPs are a manufactured wall panel system usually constructed of two wood panels that sandwich a foam core
  - Usually OSB around EPS
  - Sometimes foam is XPS or polyiso



SIP construction benefits

- Panels can be pre-cut at the factory
- No framing = fewer workers
  - Retains very high structural strength
- Easier to hang drywall
  - No studs to mark and find
- Walls will be straighter
  - No cups, warps, etc., as found in most lumber
- Results
  - Faster construction
  - Up to 30%-40% reduction in labor costs



Disadvantages of SIPs

- Less flexibility for wires and pipes
  - Locations must be set before manufacture
  - Conduit not possible
- On the job design changes are difficult
- Cranes are needed for large panels

Structural strength of SIPs

- Structural sandwich provides very high strength
  - Handles higher axial and transverse loads than standard wood stud wall construction

- Can be used for almost any part of the enclosure
  - 4x8 foot sections typically used for walls
  - 8x24 foot sections typically used for roofs and floors

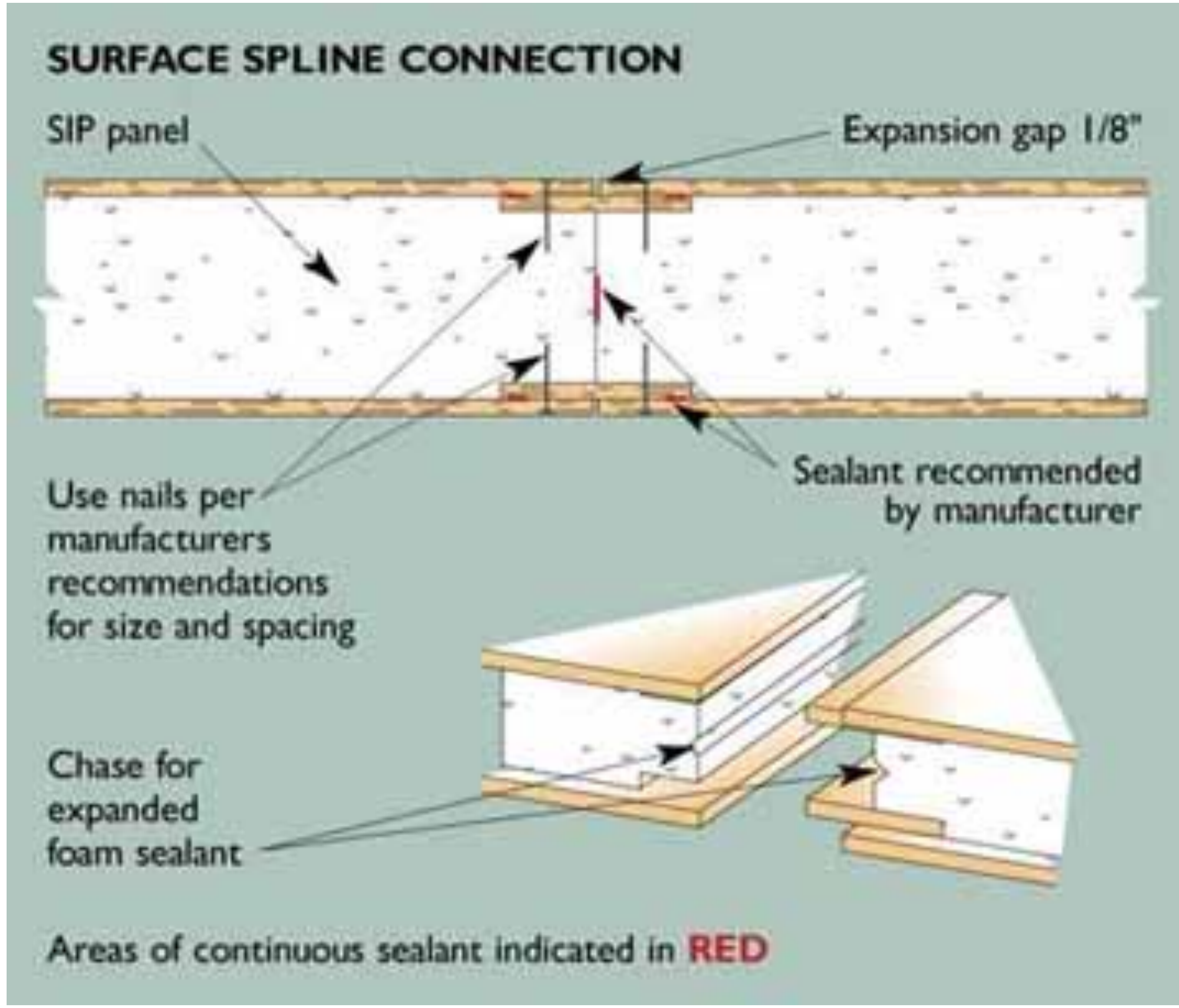
SIP thermal benefits

- Little framing means few thermal bridges
- Use of EPS/XPS/Polyiso foam insulation provides high inherent R-Value
  - A high R-Value maintained even when wet
- Lack of air gaps reduces air leakage considerably
  - Less chance for moisture to get to insulation
- Inherently high vapor resistance
  - Vapor barrier not needed in most climates

- Result: installed R-Value is near theoretical R-Value
  - A SIP wall is usually 25-50% more energy efficient than a wood frame wall of same thickness with fiberglass insulation

SIP connection details

- Surface spline connection eliminates thermal bridging
- Put together like puzzle pieces



SIPs

ROOFING

Applications

Roofing

- First line of weather defense
  - Precipitation (rain, snow)
  - Sun
  - Thermal Transmission

- Subjected to extreme heat and cold
  - Surface can have wide temperature swings

Notes on roofing

- The roof receives the most severe physical and chemical degradation of any building component
  - Extreme temperature swings
  - Extreme UV exposure
  - High wind and rain exposure
- Good roofing is hard to design
  - Roofing the subject of nearly 65% of the lawsuits against architects and builders[1]
  - Low-slope roofing has the shortest lifespan of any component – typically 12-15 years[1]

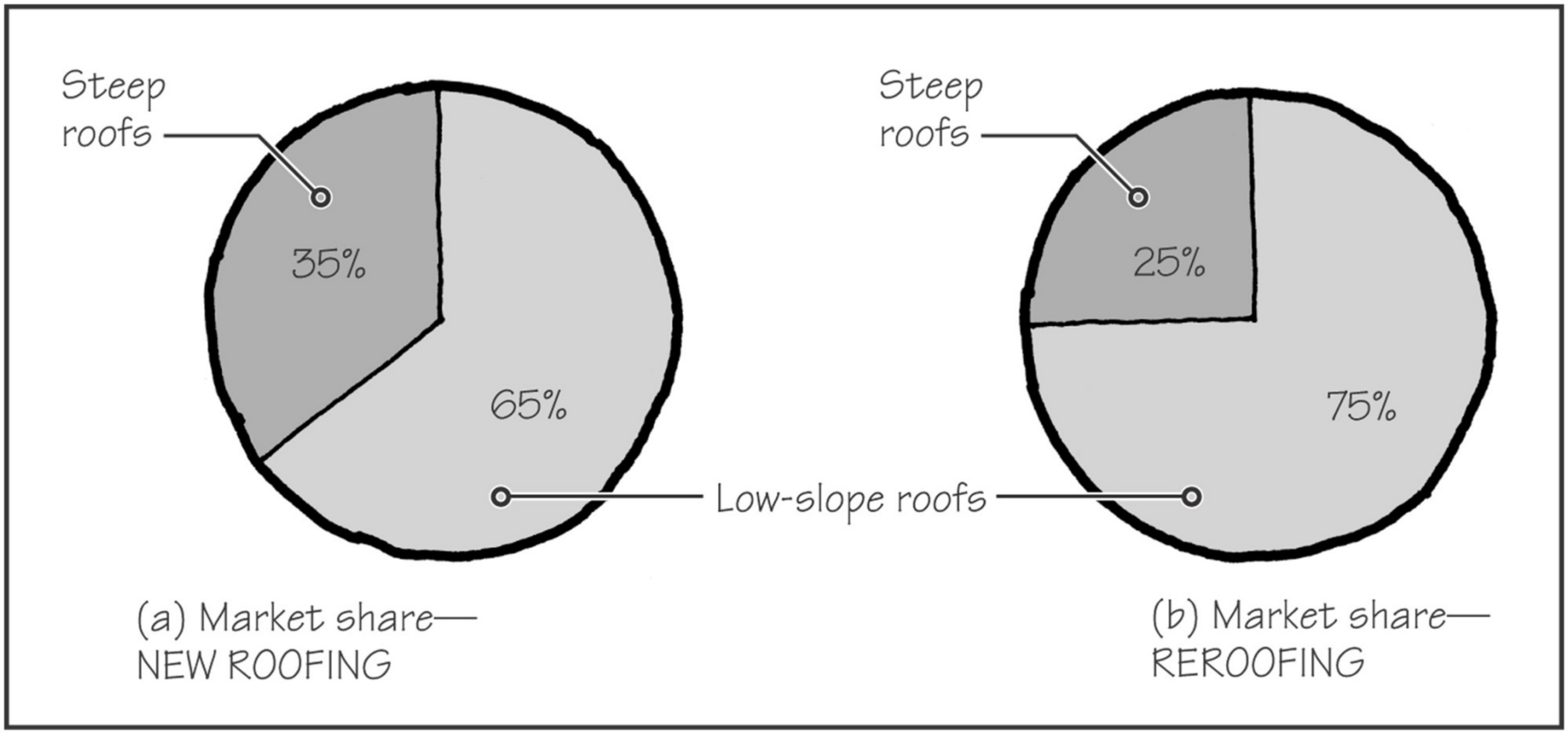
[1]Mehta, *Building Construction,* Pearson, 2008

Two principle types of roofs

- Steep Roofs
  - Used primarily on small buildings

- Low-Slope Roofs
  - Used on larger buildings

Market share: Low-slope and steep slope roofs



Design considerations

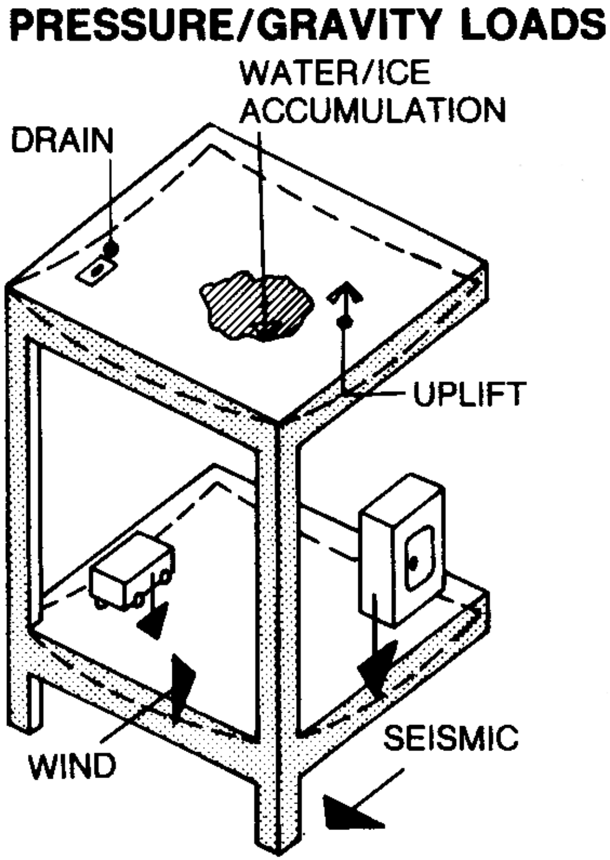
- Locally available technology and labor
- Suitability to local climate
  - Wind uplift and hail impact resistance
  - Drainage requirements
- Roof shape
- Chemical environment
- Roof warranty
- Long-term cost, including sustainability
- Life safety
- Fire safety

Principal elements of a roof system

- Substrate – support for roofing
  - Framing
  - Framing + Deck
  - Framing + Deck + Insulation or Concrete fill

- Roofing
  - Barrier formed to protect substrate from elements
  - Continuous membrane or overlapping units

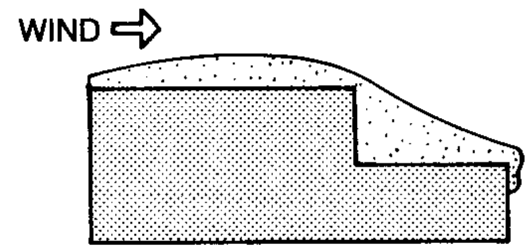
Structural loads



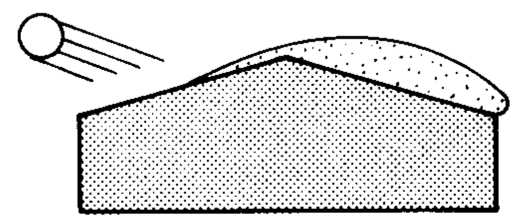
- Live loads
  - Water, snow, and ice accumulation
- Dead loads
  - Roof assembly
  - Rooftop equipment
- Shear loads
  - Wind
  - Seismic

Uneven live loads

- Wind loads are uneven
  - Negative for low slope
  - Positive for steep slope

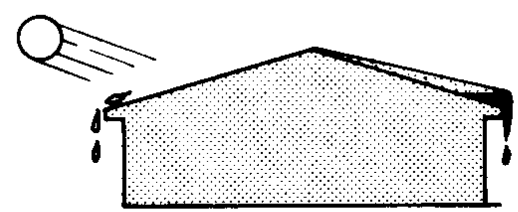


- Water/snow accumulation is uneven



SNOW ACCUMULATION

- Ice forms unevenly in cracks and low spots splitting roof membrane



ICE FORMATION

Low-slope Roofs

- Advantages
  - Can cover large horizontal surfaces
  - Simpler geometry, often less expensive
  - Roof can have other functions
    - patio, decks, parking, etc.

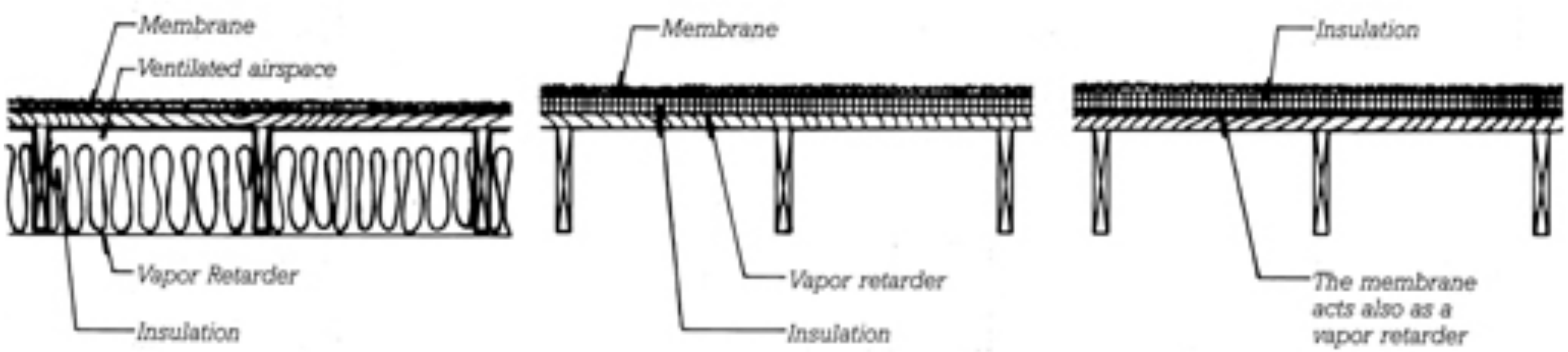
- Disadvantages
  - Water drains slowly
  - Slight structural movements can tear the membrane
  - Water vapor pressure can blister & rupture the membrane
  - Increased structural load from wind and accumulation

Low-slope roof components

- Structural Support: Deck on frame
- Thermal Insulation
- Roof Membrane
- Roof Ballast
- Drainage
- Flashing

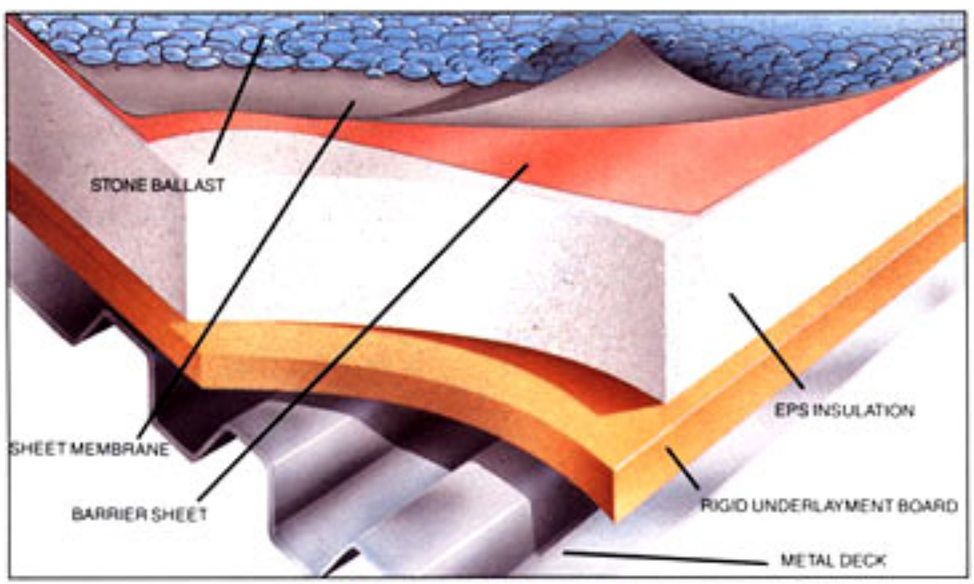
Roof thermal insulation

- Insulation is required to meet ASHRAE 90.1
- Location and placement
  - Below the deck: Thermal bridging is a problem
  - Between the deck and membrane: membrane exposed
  - Above the membrane: helps protect membrane
- Rigid insulation attachment
  - Adhered or mechanically attached



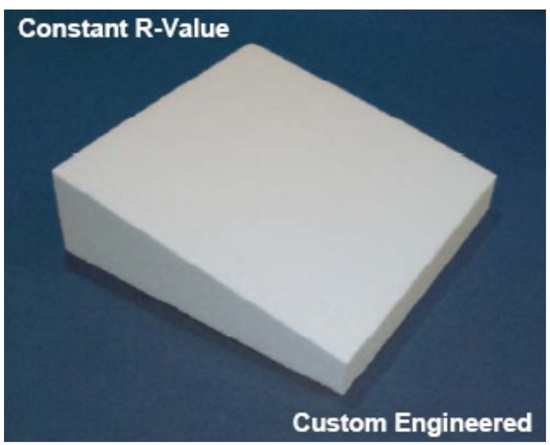
Typical roof insulation

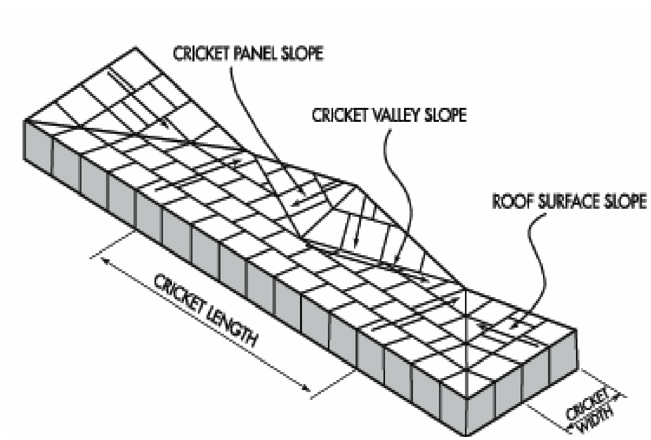
- Over-deck insulation is usually EPS, XEPS, polyiso, or rigid fiberglass
  - These are the only insulation materials that can handle the wind/snow/roofing loads and still provide high insulating capabilities
  - High inherent R values of EPS and polyiso gives good insulating capabilities with only a few inches of insulation

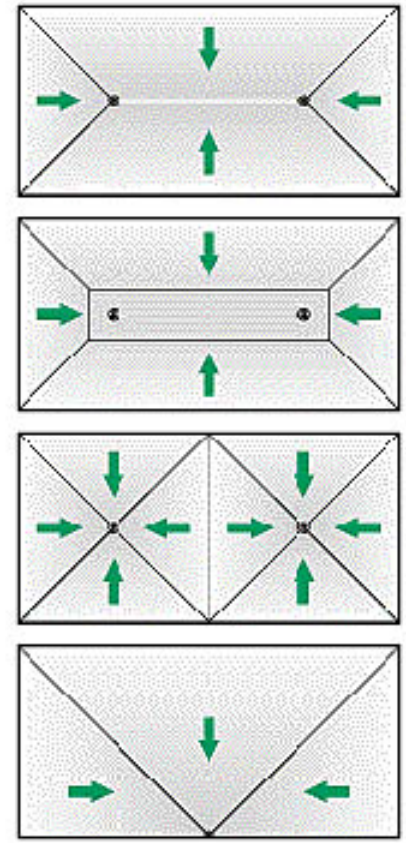


Tapered insulation

- To promote proper drainage roof should have a ¼” slope for every 12”
- This can be achieved through the use of tapered roof insulation







Typical Drainage Pattern

Insulating and foamed concrete

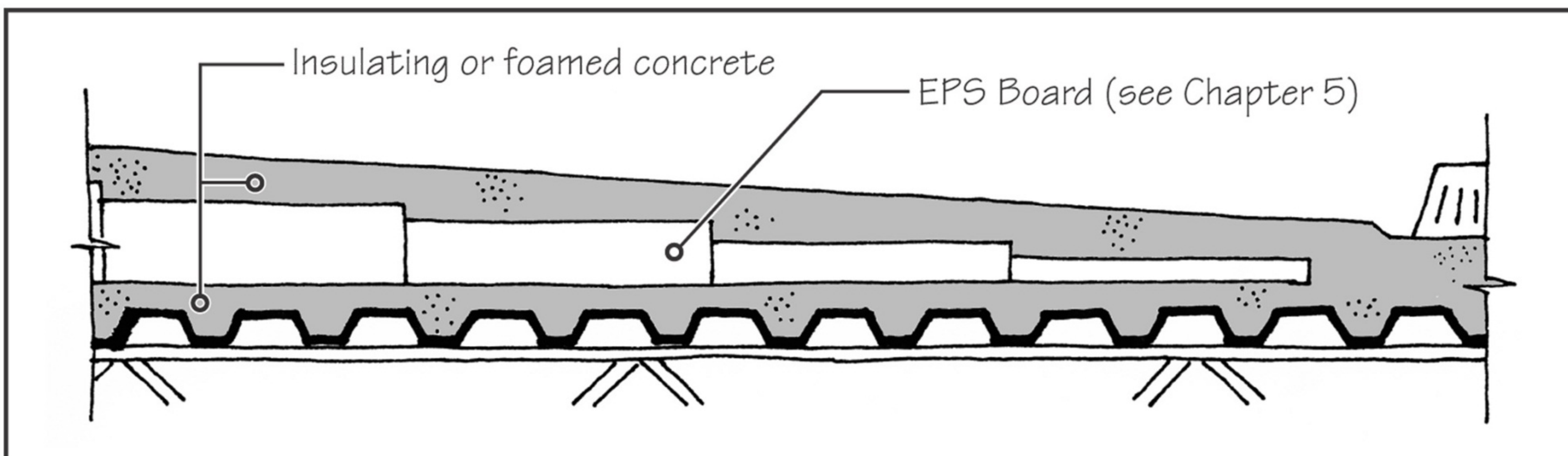
- *Insulating concrete* is a very lightweight concrete that with perlite or vermiculite as a high insulating granular additive
  - 0.8 < R per inch < 1.2 (normal concrete is about 0.2)

- *Foamed concrete* (also called cellular or aerated concrete) has a foaming concentrate that creates tiny air bubbles within the concrete
  - Increases thermal resistance
  - 0.5 < R per inch < 2

- Both of these are popular for use on roofs where the strength requirements are lower than for floors or walls

Embedded insulation

- EPS or Polyiso insulation can be embedded within the concrete itself
- This is commonly done with foamed or insulating concrete



Roof membranes

- Membrane roofing systems are used to prevent leaks and move water off of roofs
- Three main categories:
  - Built-up Roof (BUR) Membrane
  - Single-Ply Roof Membrane
  - Fluid Applied Roof Membrane

Built-up roofs (BUR)

- Standard Built-up Roof Membrane
  - A BUR is 3-5 layers of felts + bitumen (asphalt)
  - Bitumen provides waterproofing
    - Semi-solid crude oil product
  - Felt provides the structural support needed
    - Because bitumen will soften (and can even melt) at high temperatures
- Modified Bitumen Sheets
  - Bitumen has polymers added to improve the UV protection and make it more cold resistant
  - Felt or fiberglass sheets are embedded with modified bitumen
    - 2 to 3 layers of the sheets are installed with more modified bitumen between

BUR membrane

- Multiple plies of asphalt-impregnated felt bedded in bitumen (hot asphalt or coal tar)
- Forms a “laminated” membrane typically 2-4 plies thick
- Stinks during install!

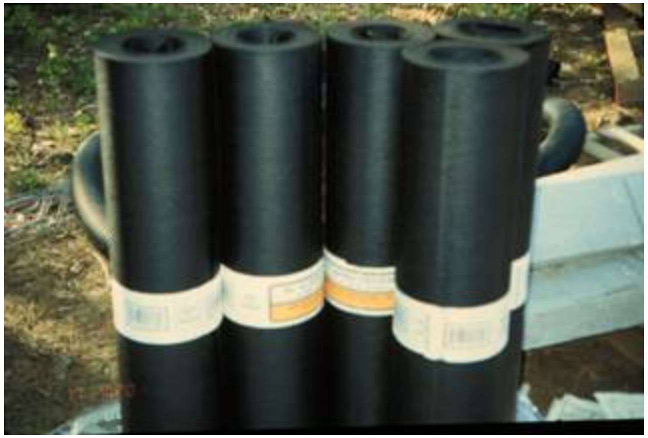
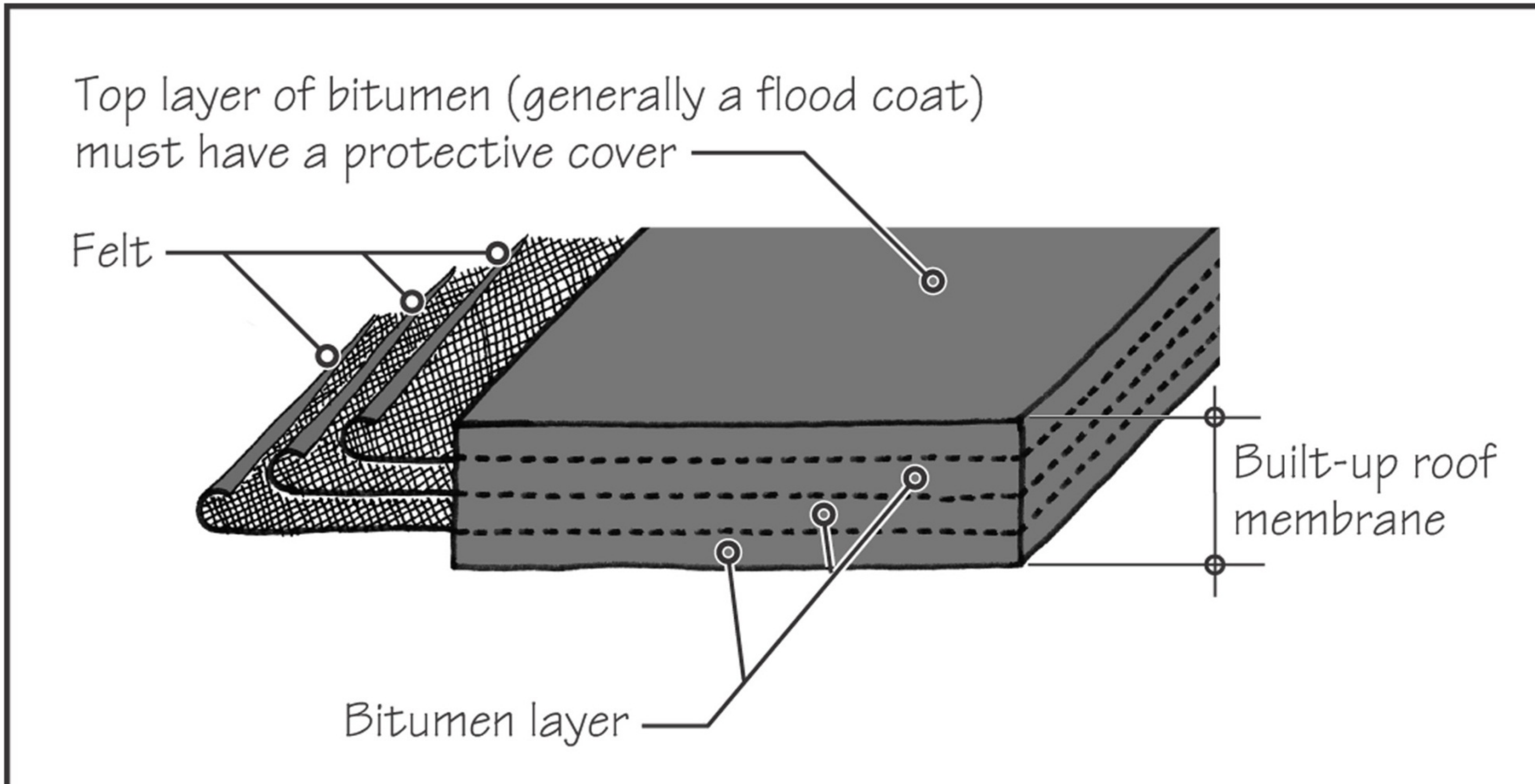
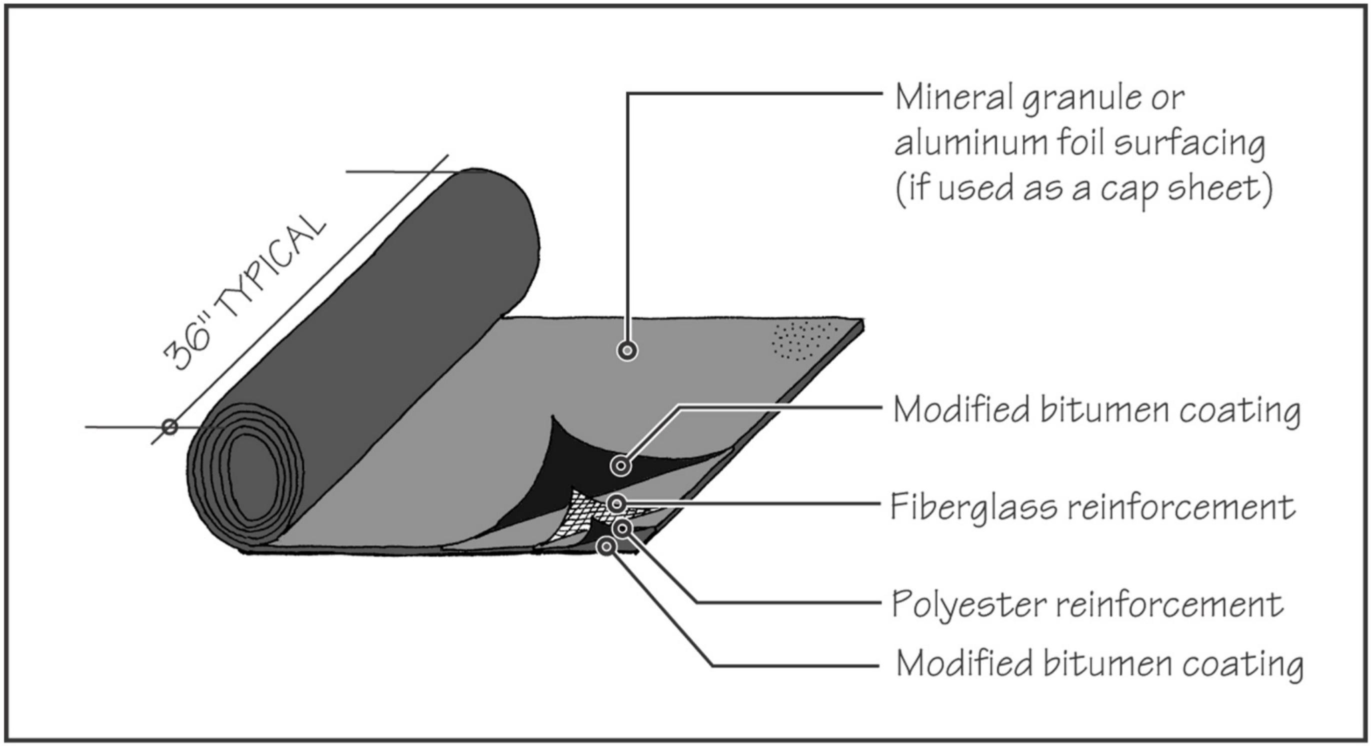


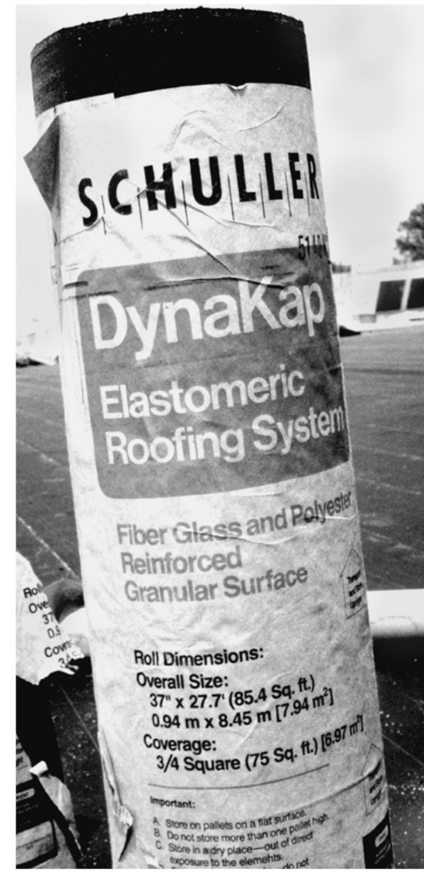
Diagram of BUR



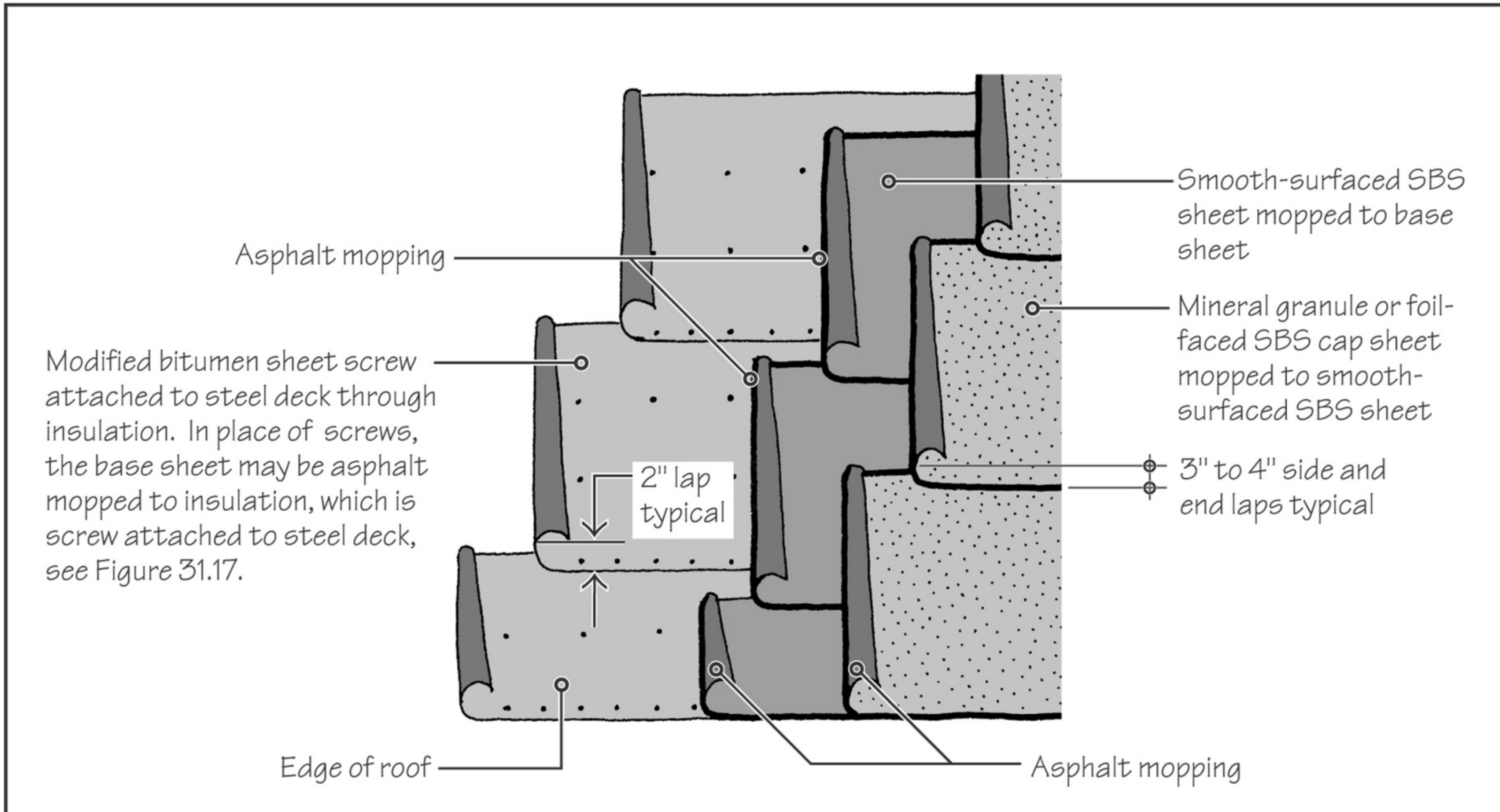
Kettle for heating the bitumen and pumping it to the roof

Modified bitumen membrane, cap sheet roll





3-ply SBS-modified bitumen roof membrane



Advantages and disadvantages of BUR

- Advantages
  - Can be easily repaired/patched in case of leaks
  - Can last longer than a single ply membrane roof
  - High tensile strength limits movement and reduces chances for fracturing
  - If structure does move, BUR can move with it

- Disadvantages
  - Not seamless, more locations for possible leaks
  - Higher cost (more materials, time and labor)
  - Less sustainable (uses much more raw materials and energy to install)
  - Fumes during installation

Single-ply roof membrane

- Sheet materials that are applied to the roof in a single layer

- Attached to the Roof:

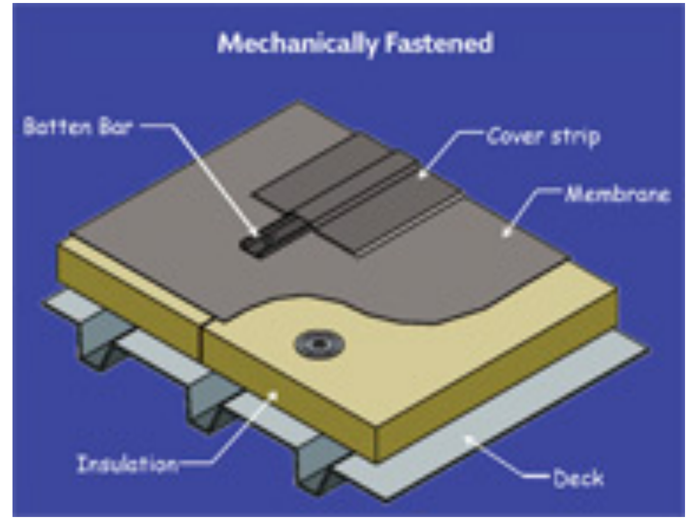
  Adhesives

  Ballast Weight

  Concealed fasteners

Single-ply materials

- Thermosetting
  - Compounded rubber polymer
  - Cannot be softened
  - Must be joined by adhesives or pressure sensitive tapes
  - EPDM
    - ethylene propylene diene monomer
    - Most widely used
    - Also Neoprene, CPE, etc.



- Thermoplastics
  - May be softened and joined by heat or solvent welding
  - Polyvinyl Chloride (PVC) – widely used, polymer-modified bitumens, PVC alloys, etc.

EPDM

- EPDM (ethylene propylene diene monomer) is a thermosetting polymer (a synthetic rubber) that does not soften once it has cured
  - This material can stretch, but cannot be heat welded
  - It must be adhered or taped
- EPDM can stretch 300-500% of its original length before tearing
- Typical thicknesses are 45 to 60 mm
- EPDM has poor inherent fire resistance
- EPDM is black and must be covered for high solar reflectivity

12 ft. wide EPDM membrane

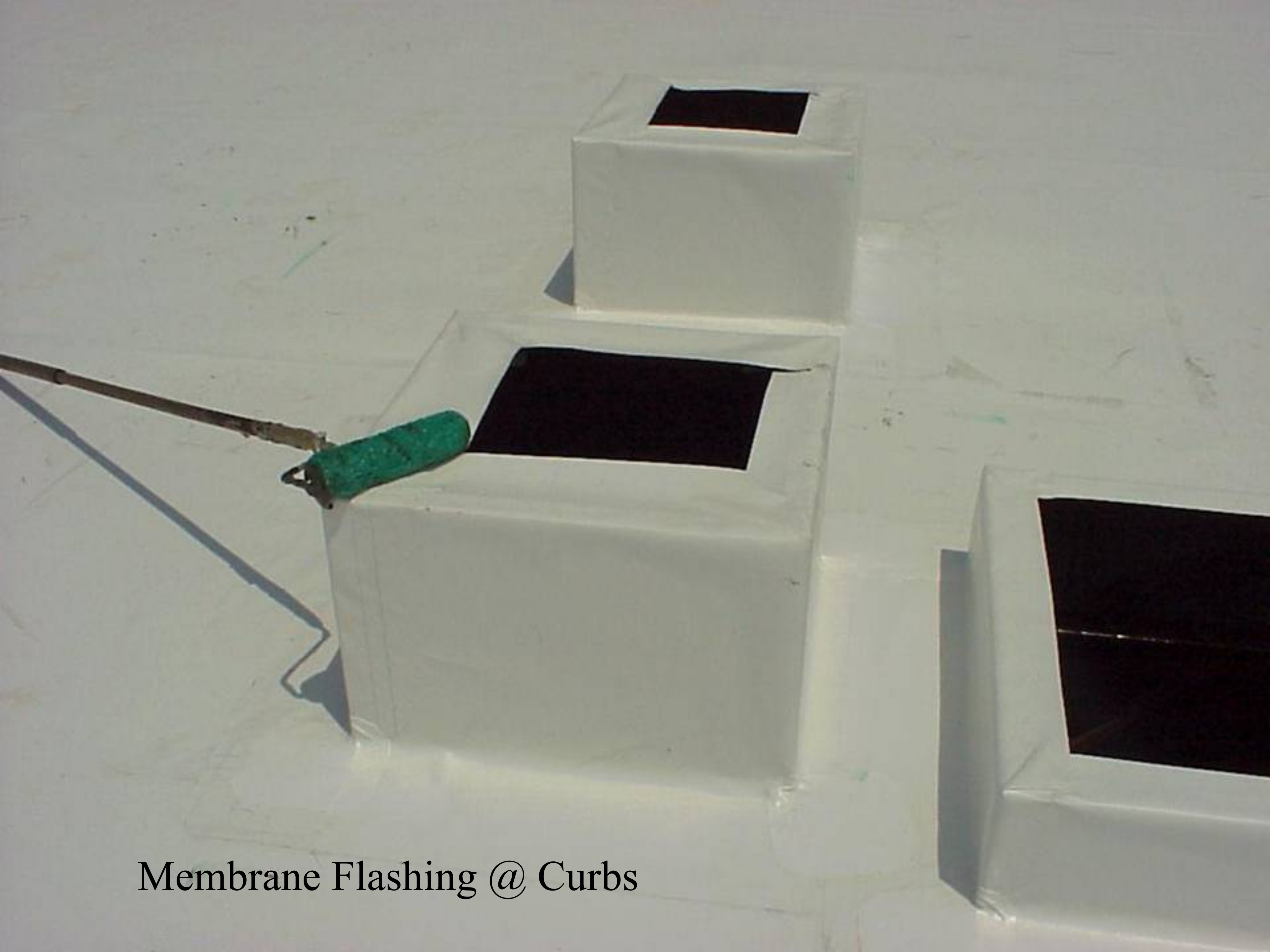
PVC and TPO

- PVC (polyvinyl chloride) is a soft and pliable form of the common plastic
  - PVC is very flexible, but is far less stretchable than EPDM
  - PVC membranes can be heat fused
- TPO (thermoplastic polyolefin) is also a thermoplastic
  - TPO is more flexible and stretchable than PVC but less than EPDM
  - TPO does not lose its flexibility over time like PVC
- These are easily used for cool roofing materials

Hand-held welding tool for PVC

Applying PVC or TPO

- Self-propelled hot air welding machine for PVC or TPO



Membrane Flashing @ Curbs

Fluid-applied membranes

- Fluids applied with a roller or spray gun and cure to form a rubbery membrane

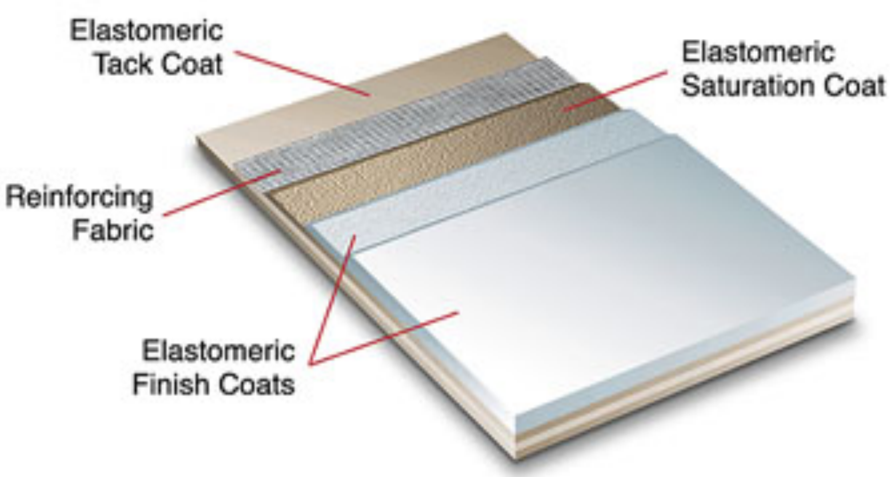
- Main Use: Complex shapes that are difficult to roof by conventional means such as domes and shells

– Fluid Applied Membranes can also be installed fairly quickly so when speed is more important than cost, consider these

Composite fluid membrane

- A typical composite fluid membrane is shown below
- The top 3 coats are fluid-applied membranes

- Fluid Applied Membranes can be used to replace standard membrane roofs too



Advantages and disadvantages of membranes

- Advantages
  - Lower cost
  - No seams (if properly installed)
  - Lighter weight
  - Can expand/contract much better than BUR
- Disadvantages
  - Any small puncture can cause leaks
  - Harder to repair small leaks
  - Must be completely (or near completely) replaced when repairs/ modifications are made
  - Shorter lifetime than BUR

Costs

- BUR
  - $8-10/ft^2 installed
    - Price includes EPS insulation and fiberboard overlay
  - Can be repaired or partially resurfaced without a complete tear-off and reinstall
  - 20-40 lifespan
    - Resurfacing every 10-15 years
- Modified Bitumen
  - $8-10/ft^2 installed
  - 10-15 year lifespan
  - Full tear-off required for replacement
- EPDM
  - $4-6/ft^2 installed
  - 10-15 year lifespan
  - Full tear-off required for replacement
- PVC
  - $6-8/ft^2 installed
  - 15-20 year lifespan
  - Full tear-off required for replacement
- TPO
  - $6-8/ft^2 installed
  - Lifetime unknown – it's too new
  - Full tear-off required for replacement

Ballast and traffic decks

- Ballast Material
  - Stone aggregate
  - Precast concrete blocks or Pavers
- Purpose
  - Hold down membrane
  - Protect membrane from ultraviolet light
  - Protect membrane from physical wear
- Traffic Decks – installed over membranes for walks, terraces, drives, etc.