Advanced Building Science

- Thermal Insulation
  - Key terms
  - Insulation basics
  - Temperature profiles
  - Optimizing insulation
    -
- Readings
  - HF: Chapter 25 => 25.1 to 25.7
  - HF: Chapter 26 => 26.1 to 26.13
  - HPE: 3.3 to 3.3.4 & Appendix A.

Thermal Insulation – Basics

- Steady-State Thermal Resistance
  - Calculated
    - properties under ideal conditions
  - Measured
    - guarded hot plate or hot box or in-situ

- Reality
  - installation issues (gaps/cracks/voids)
  - shrinkage/settling/compression
  - moisture content
  - airflow

Thermal Insulation – Key Terms

- Thermal transmission, heat transfer, rate of heat flow
  - Flow of heat induced by a temperature difference - may be a combination of conduction, convection, and radiation

- Thermal conductivity (k)
  - time rate of heat flow per unit area for a specified thickness (1”) per unit temperature gradient

Thermal Insulation – Key Terms

- Thermal conductance (C)
  - time rate of heat flow per unit area for a specified material per unit temperature difference

- Thermal transmittance (U-factor)
  - time rate of heat flow per unit area per unit temperature difference

Thermal Insulation – Key Terms

- Surface film coefficient (h)
  - heat transfer between a surface and a fluid per unit time and temperature difference
- Thermal resistivity (R_u)
  - reciprocal of thermal conductivity

Thermal Insulation – Key Terms

- Thermal resistance (R-value)
  - reciprocal of thermal conductance
- Surface film resistance
  - reciprocal of the surface film coefficient

Thermal Insulation – Functions

Retarding heat flow to …

- conserve energy
- control surface temperatures
- control the temperature of a process
- prevent vapor condensation on surfaces
- reduce temperature fluctuations and variations

Thermal Insulation - Functions

And may …

- add structural strength
- impede air flow and/or water vapor transmission
- provide support for a surface finish
- reduce noise and vibration

Thermal Insulation – Materials

- Inorganic
  - fibrous or cellular materials such as glass, rock, or slag
- Organic
  - fibrous materials such as cellulose, cotton, wool,
  - cellular materials such as cork, rubber, polymers
- Metallic/metallized reflective membranes
  - these surfaces must face an air, gas or evacuated space

Thermal Insulation – Forms

- Loose-fills
  - poured or blown in
- Flexible and semi-rigid
  - blankets, batts, felts
- Rigid
  - blocks, boards, sheets and panels
- Reflective
  - single and multi-layer
- Formed-in-place
  - poured, frothed or sprayed

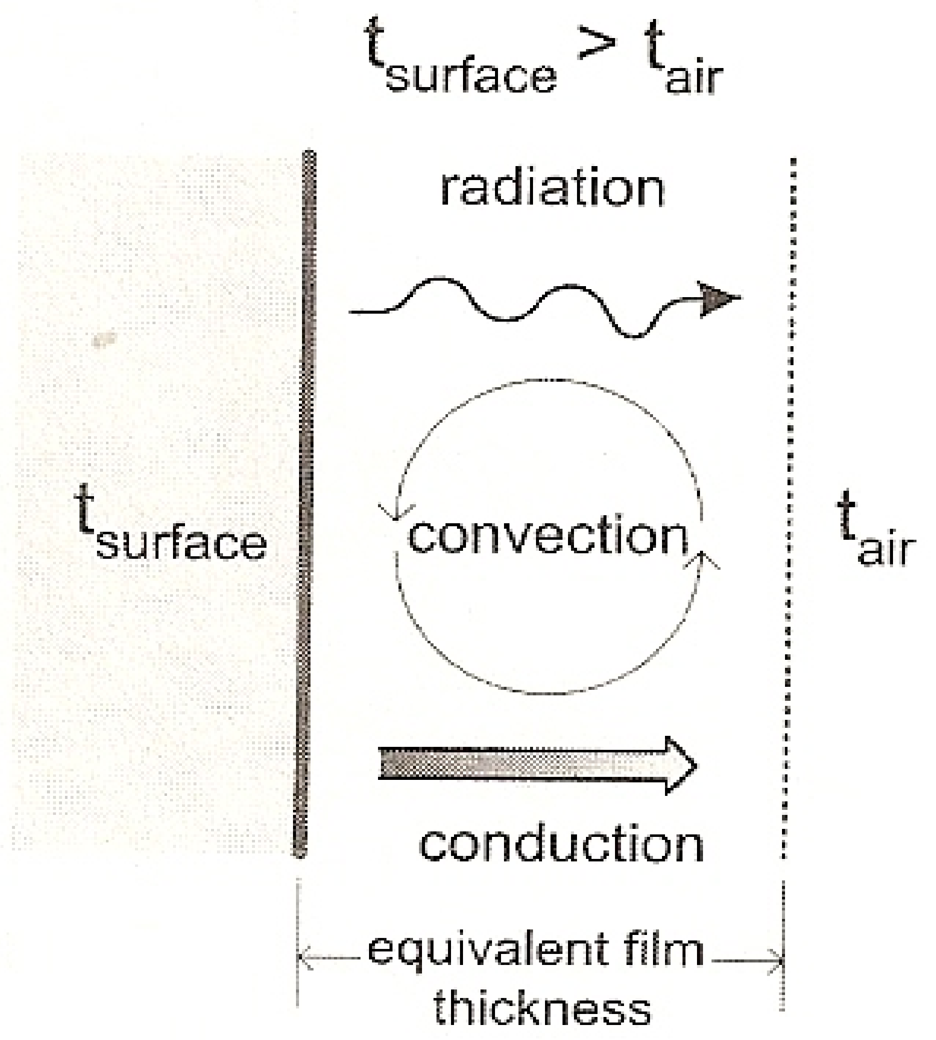


Figure 5.9: Surface film analogy of heat transfer at surfaces

Source: Straube & Burnett, Building Science for Enclosures, Chapter 5

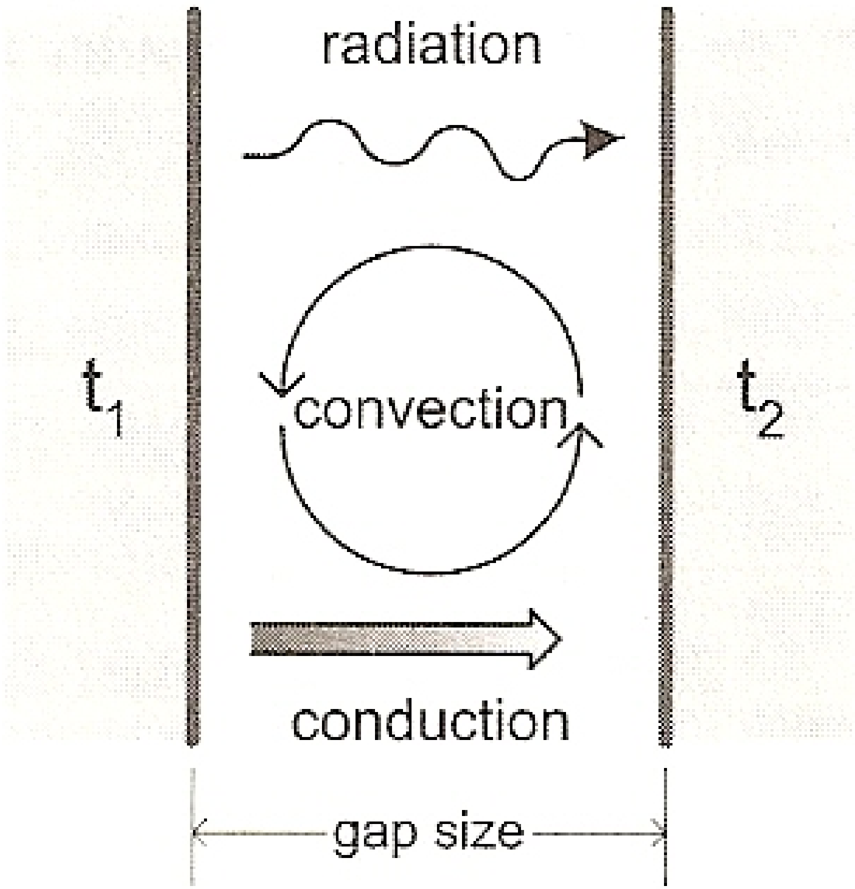
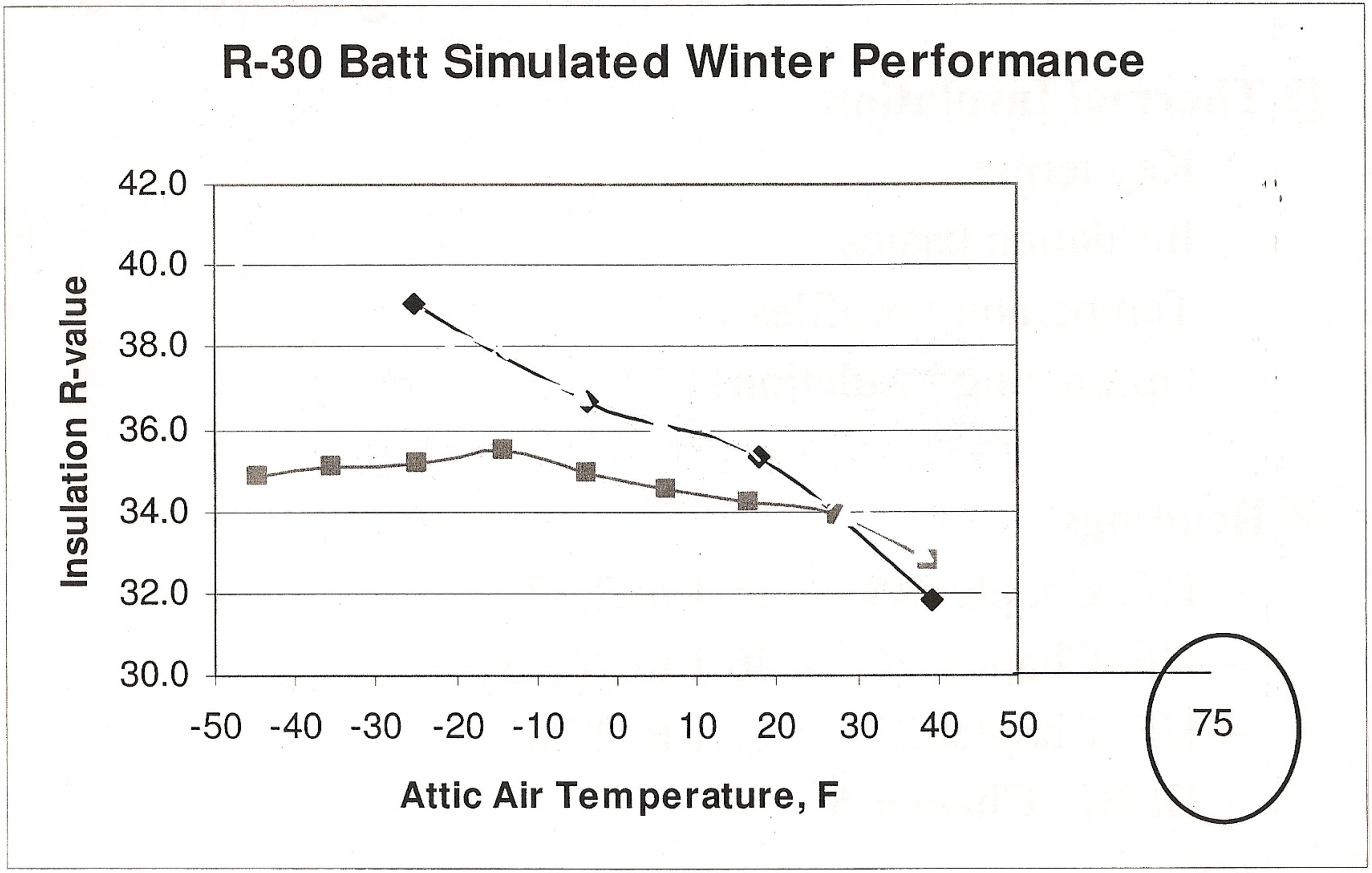


Figure 5.10: Heat transfer across plane airspaces

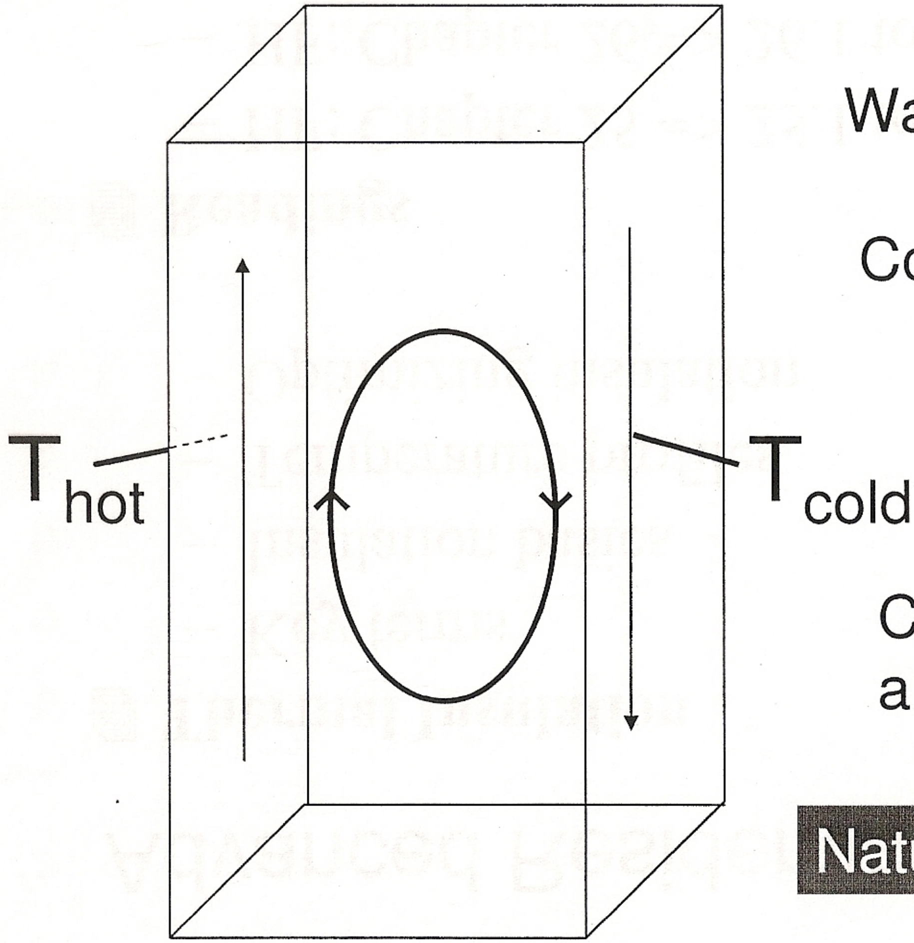
Source: Straube & Burnett, Building Science for Enclosures, Chapter 5

Measured R-value



Source: Marcus Bianchi, Johns Manville, Fibrous Insulation: How Does it Work?

An Uninsulated Cavity



Warmer air gets less dense

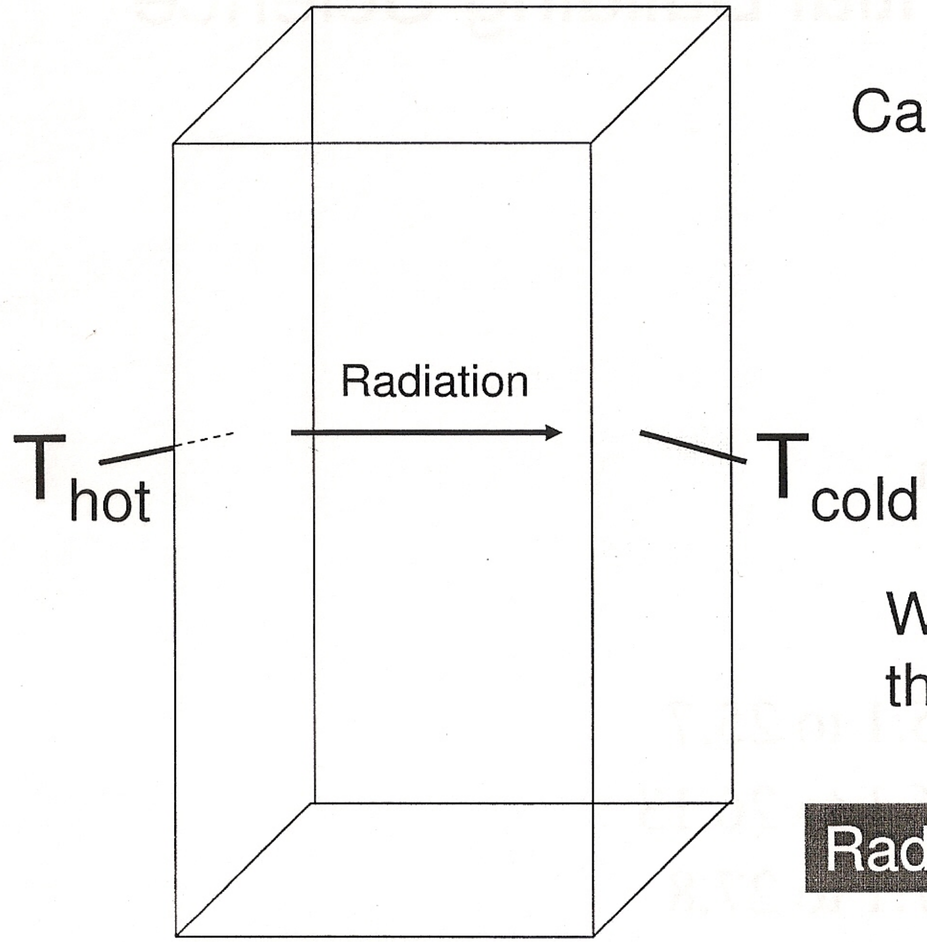
Colder air gets denser

Colder air sinks and warmer air floats - Recirculation

Natural convection takes place

Source: Marcus Bianchi, Johns Manville, Fibrous Insulation: How Does it Work?

An Uninsulated Cavity



Cavity walls have emissivity

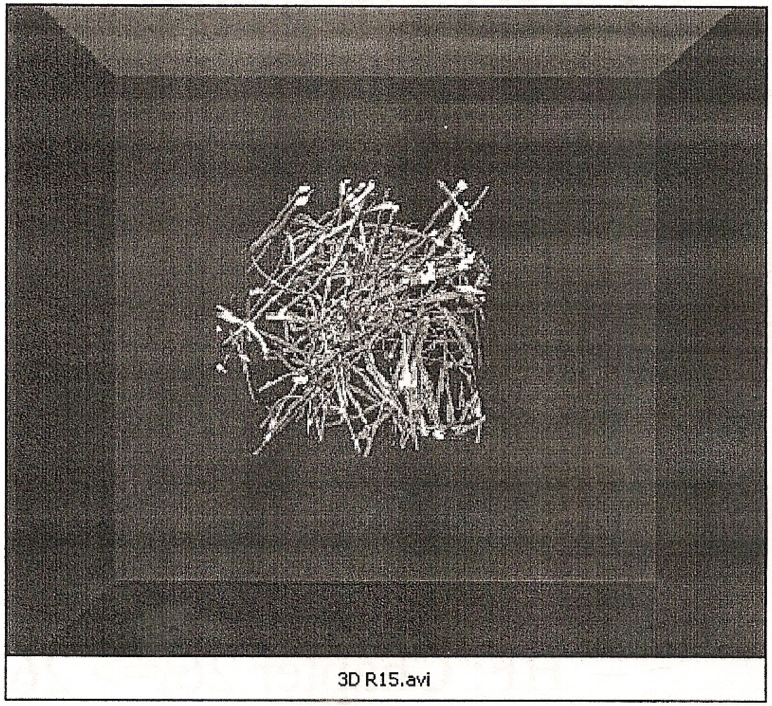
Warmer surface emits more than colder surface

Radiation takes place

Source: Marcus Bianchi, Johns Manville, Fibrous Insulation: How Does it Work?

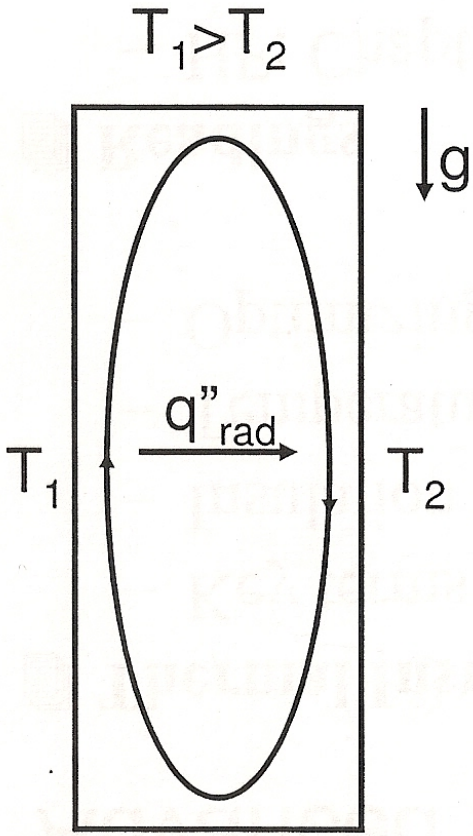
Add Fibrous Insulation

- Why add fibers?
  - Reduce the air permeability of the cavity; air finds obstacles to move.
  - Absorb and scatter thermal radiation; increase extinction coefficient.



Source: Marcus Bianchi, Johns Manville, Fibrous Insulation: How Does it Work?

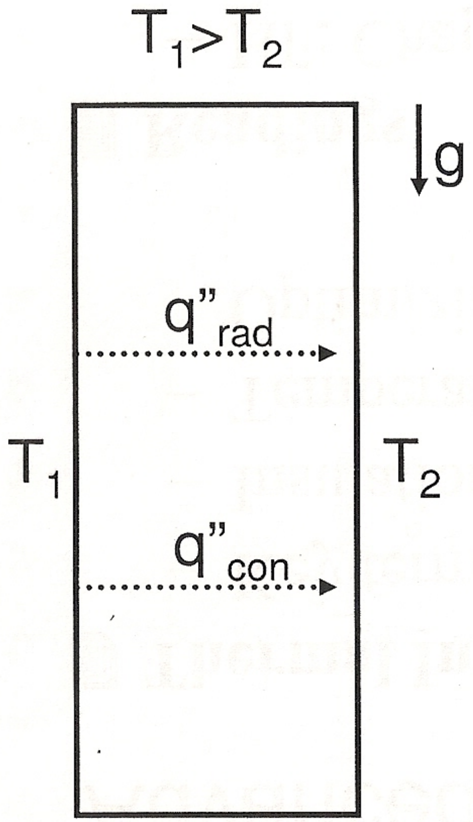
The Uninsulated Wall Cavity



- Radiation (~75%)
- Convection (~25%)
- Total ~ 190 W/m^2

Source: Marcus Bianchi, Johns Manville, Fibrous Insulation: How Does it Work?

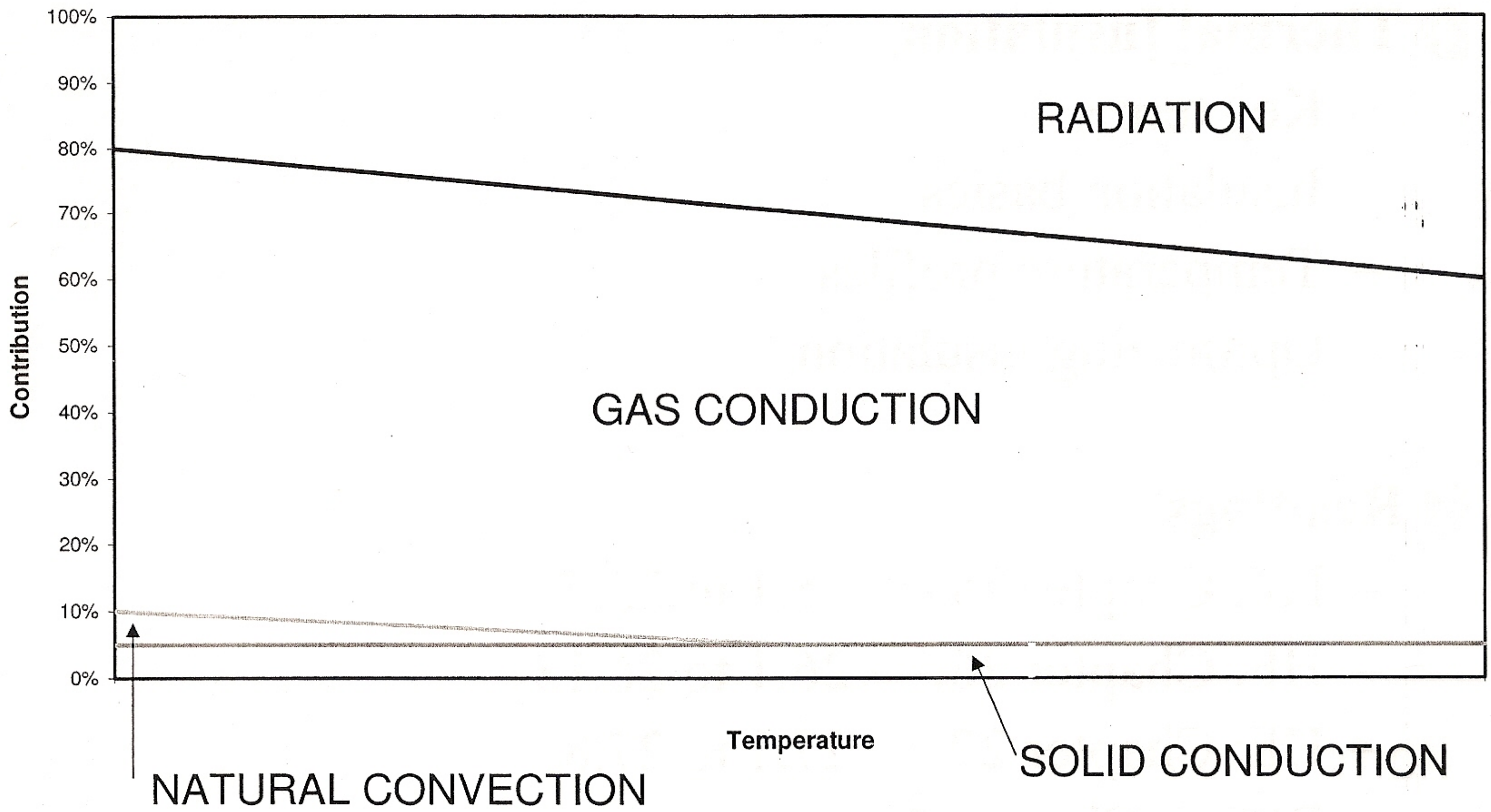
The Wall Cavity with Insulation



- Radiation (~25%)
- Conduction (~75%)
- Total ~ 7 W/m²

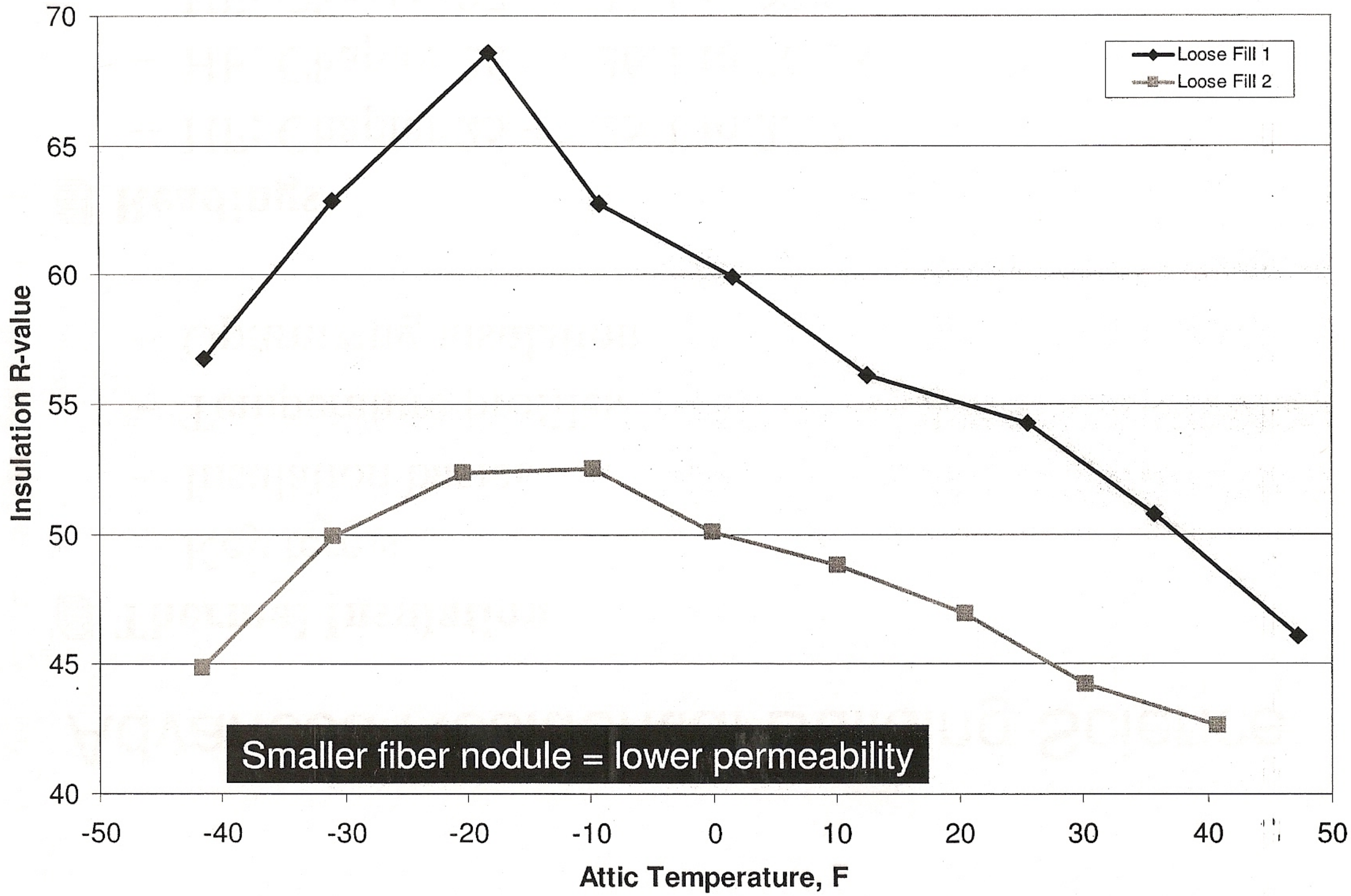
Source: Marcus Bianchi, Johns Manville, Fibrous Insulation: How Does it Work?

Various Modes



Source: Marcus Bianchi, Johns Manville, Fibrous Insulation: How Does it Work?

Loose Fill Attic Insulation



Source: Marcus Bianchi, Johns Manville, Fibrous Insulation: How Does it Work?

Thermal Insulation – Performance

Factors Affecting Heat Flow

- Mean temperature, moisture content, air infiltration, orientation, and direction of heat flow.

- Thermal conductivity varies with density

Table 1 Surface Conductances and Resistances for Air

Position of Surface	Direction of Heat Flow	Nonreflective ε = 0.90 h_i	Nonreflective ε = 0.90 R	Reflective ε = 0.20 h_i	Reflective ε = 0.20 R	Reflective ε = 0.05 h_i	Reflective ε = 0.05 R
Still Air							
Horizontal	Upward	1.63	0.61	0.91	1.10	0.76	1.32
Sloping at 45°	Upward	1.60	0.62	0.88	1.14	0.73	1.37
Vertical	Horizontal	1.46	0.68	0.74	1.35	0.59	1.70
Sloping at 45°	Downward	1.32	0.76	0.60	1.67	0.45	2.22
Horizontal	Downward	1.08	0.92	0.37	2.70	0.22	4.55
Moving Air (any position)		h_o	R				
15 mph wind (for winter)	Any	6.00	0.17	—	—	—	—
7.5 mph wind (for summer)	Any	4.00	0.25	—	—	—	—

Source: ASHRAE Fundamentals Handbook 2009, Chapter 26)

Table 3 Thermal Resistances of Plane Air Spaces,[a,b,c] h·ft²·°F/Btu

Position of Air Space	Direction of Heat Flow	Air Space		Effective Emittance ε_{eff}[d,e]									
				0.5 in. Air Space[c]					0.75 in. Air Space[c]				
		Mean Temp.,[d] °F	Temp. Diff.,[d] °F	0.03	0.05	0.2	0.5	0.82	0.03	0.05	0.2	0.5	0.82
		90	10	2.13	2.03	1.51	0.99	0.73	2.34	2.22	1.61	1.04	0.75
		50	30	1.62	1.57	1.29	0.96	0.75	1.71	1.66	1.35	0.99	0.77
		50	10	2.13	2.05	1.60	1.11	0.84	2.30	2.21	1.70	1.16	0.87
Horiz.	Up ↑	0	20	1.73	1.70	1.45	1.12	0.91	1.83	1.79	1.52	1.16	0.93
		0	10	2.10	2.04	1.70	1.27	1.00	2.23	2.16	1.78	1.31	1.02
		−50	20	1.69	1.66	1.49	1.23	1.04	1.77	1.74	1.55	1.27	1.07
		−50	10	2.04	2.00	1.75	1.40	1.16	2.16	2.11	1.84	1.46	1.20
		90	10	2.44	2.31	1.65	1.06	0.76	2.96	2.78	1.88	1.15	0.81
		50	30	2.06	1.98	1.56	1.10	0.83	1.99	1.92	1.52	1.08	0.82
		50	10	2.55	2.44	1.83	1.22	0.90	2.90	2.75	2.00	1.29	0.94
45° Slope	Up ↗	0	20	2.20	2.14	1.76	1.30	1.02	2.13	2.07	1.72	1.28	1.00
		0	10	2.63	2.54	2.03	1.44	1.10	2.72	2.62	2.08	1.47	1.12
		−50	20	2.08	2.04	1.78	1.42	1.17	2.05	2.01	1.76	1.41	1.16
		−50	10	2.62	2.56	2.17	1.66	1.33	2.53	2.47	2.10	1.62	1.30
		90	10	2.47	2.34	1.67	1.06	0.77	3.50	3.24	2.08	1.22	0.84
		50	30	2.57	2.46	1.84	1.23	0.90	2.91	2.77	2.01	1.30	0.94
		50	10	2.66	2.54	1.88	1.24	0.91	3.70	3.46	2.35	1.43	1.01
Vertical	Horiz. →	0	20	2.82	2.72	2.14	1.50	1.13	3.14	3.02	2.32	1.58	1.18
		0	10	2.93	2.82	2.20	1.53	1.15	3.77	3.59	2.64	1.73	1.26
		−50	20	2.90	2.82	2.35	1.76	1.39	2.90	2.83	2.36	1.77	1.39
		−50	10	3.20	3.10	2.54	1.87	1.46	3.72	3.60	2.87	2.04	1.56
		90	10	2.48	2.34	1.67	1.06	0.77	3.53	3.27	2.10	1.22	0.84
		50	30	2.64	2.52	1.87	1.24	0.91	3.43	3.23	2.24	1.39	0.99
		50	10	2.67	2.55	1.89	1.25	0.92	3.81	3.57	2.40	1.45	1.02
45° Slope	Down ↘	0	20	2.91	2.80	2.19	1.52	1.15	3.75	3.57	2.63	1.72	1.26
		0	10	2.94	2.83	2.21	1.53	1.15	4.12	3.91	2.81	1.80	1.30
		−50	20	3.16	3.07	2.52	1.86	1.45	3.78	3.65	2.90	2.05	1.57
		−50	10	3.26	3.16	2.58	1.89	1.47	4.35	4.18	3.22	2.21	1.66
		90	10	2.48	2.34	1.67	1.06	0.77	3.55	3.29	2.10	1.22	0.85
		50	30	2.66	2.54	1.88	1.24	0.91	3.77	3.52	2.38	1.44	1.02
		50	10	2.67	2.55	1.89	1.25	0.92	3.84	3.59	2.41	1.45	1.02
Horiz.	Down ↓	0	20	2.94	2.83	2.20	1.53	1.15	4.18	3.96	2.83	1.81	1.30
		0	10	2.96	2.85	2.22	1.53	1.16	4.25	4.02	2.87	1.82	1.31
		−50	20	3.25	3.15	2.58	1.89	1.47	4.60	4.41	3.36	2.28	1.69
		−50	10	3.28	3.18	2.60	1.90	1.47	4.71	4.51	3.42	2.30	1.71

Source: ASHRAE Handbook Fundamentals 2009, Chapter 26

		Air Space		1.5 in. Air Space[c]					3.5 in. Air Space[c]				
Horiz.	Up	90	10	2.55	2.41	1.71	1.08	0.77	2.84	2.66	1.83	1.13	0.80
		50	30	1.87	1.81	1.45	1.04	0.80	2.09	2.01	1.58	1.10	0.84
		50	10	2.50	2.40	1.81	1.21	0.89	2.80	2.66	1.95	1.28	0.93
		0	20	2.01	1.95	1.63	1.23	0.97	2.25	2.18	1.79	1.32	1.03
		0	10	2.43	2.35	1.90	1.38	1.06	2.71	2.62	2.07	1.47	1.12
		–50	20	1.94	1.91	1.68	1.36	1.13	2.19	2.14	1.86	1.47	1.20
		–50	10	2.37	2.31	1.99	1.55	1.26	2.65	2.58	2.18	1.67	1.33
45° Slope	Up	90	10	2.92	2.73	1.86	1.14	0.80	3.18	2.96	1.97	1.18	0.82
		50	30	2.14	2.06	1.61	1.12	0.84	2.26	2.17	1.67	1.15	0.86
		50	10	2.88	2.74	1.99	1.29	0.94	3.12	2.95	2.10	1.34	0.96
		0	20	2.30	2.23	1.82	1.34	1.04	2.42	2.35	1.90	1.38	1.06
		0	10	2.79	2.69	2.12	1.49	1.13	2.98	2.87	2.23	1.54	1.16
		–50	20	2.22	2.17	1.88	1.49	1.21	2.34	2.29	1.97	1.54	1.25
		–50	10	2.71	2.64	2.23	1.69	1.35	2.87	2.79	2.33	1.75	1.39
Vertical	Horiz.	90	10	3.99	3.66	2.25	1.27	0.87	3.69	3.40	2.15	1.24	0.85
		50	30	2.58	2.46	1.84	1.23	0.90	2.67	2.55	1.89	1.25	0.91
		50	10	3.79	3.55	2.39	1.45	1.02	3.63	3.40	2.32	1.42	1.01
		0	20	2.76	2.66	2.10	1.48	1.12	2.88	2.78	2.17	1.51	1.14
		0	10	3.51	3.35	2.51	1.67	1.23	3.49	3.33	2.50	1.67	1.23
		–50	20	2.64	2.58	2.18	1.66	1.33	2.82	2.75	2.30	1.73	1.37
		–50	10	3.31	3.21	2.62	1.91	1.48	3.40	3.30	2.67	1.94	1.50
45° Slope	Down	90	10	5.07	4.55	2.56	1.36	0.91	4.81	4.33	2.49	1.34	0.90
		50	30	3.58	3.36	2.31	1.42	1.00	3.51	3.30	2.28	1.40	1.00
		50	10	5.10	4.66	2.85	1.60	1.09	4.74	4.36	2.73	1.57	1.08
		0	20	3.85	3.66	2.68	1.74	1.27	3.81	3.63	2.66	1.74	1.27
		0	10	4.92	4.62	3.16	1.94	1.37	4.59	4.32	3.02	1.88	1.34
		–50	20	3.62	3.50	2.80	2.01	1.54	3.77	3.64	2.90	2.05	1.57
		–50	10	4.67	4.47	3.40	2.29	1.70	4.50	4.32	3.31	2.25	1.68
Horiz.	Down	90	10	6.09	5.35	2.79	1.43	0.94	10.07	8.19	3.41	1.57	1.00
		50	30	6.27	5.63	3.18	1.70	1.14	9.60	8.17	3.86	1.88	1.22
		50	10	6.61	5.90	3.27	1.73	1.15	11.15	9.27	4.09	1.93	1.24
		0	20	7.03	6.43	3.91	2.19	1.49	10.90	9.52	4.87	2.47	1.62
		0	10	7.31	6.66	4.00	2.22	1.51	11.97	10.32	5.08	2.52	1.64
		–50	20	7.73	7.20	4.77	2.85	1.99	11.64	10.49	6.02	3.25	2.18
		–50	10	8.09	7.52	4.91	2.89	2.01	12.98	11.56	6.36	3.34	2.22

Source: ASHRAE Handbook Fundamentals 2009, Chapter 26

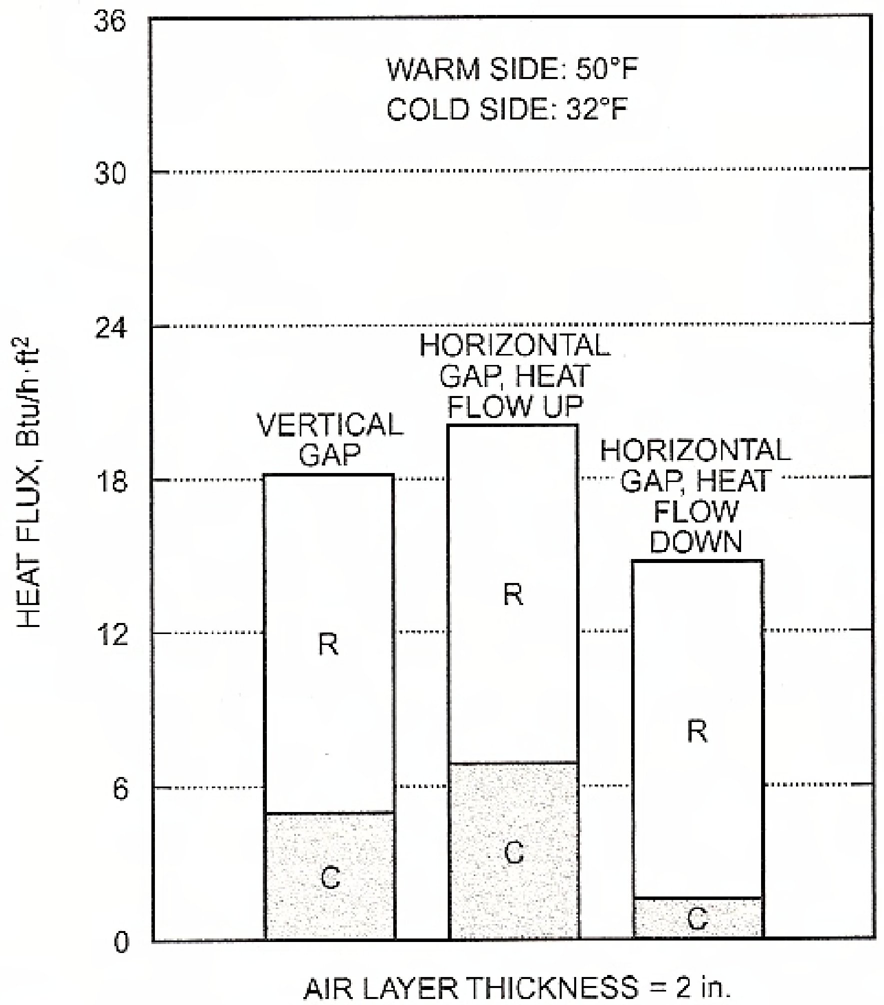


Fig. 5 Heat Flux by Thermal Radiation and Combined Convection and Conduction Across Vertical or Horizontal Air Layer

Source: ASHRAE Handbook Fundamentals 2013, Chapter 25.7

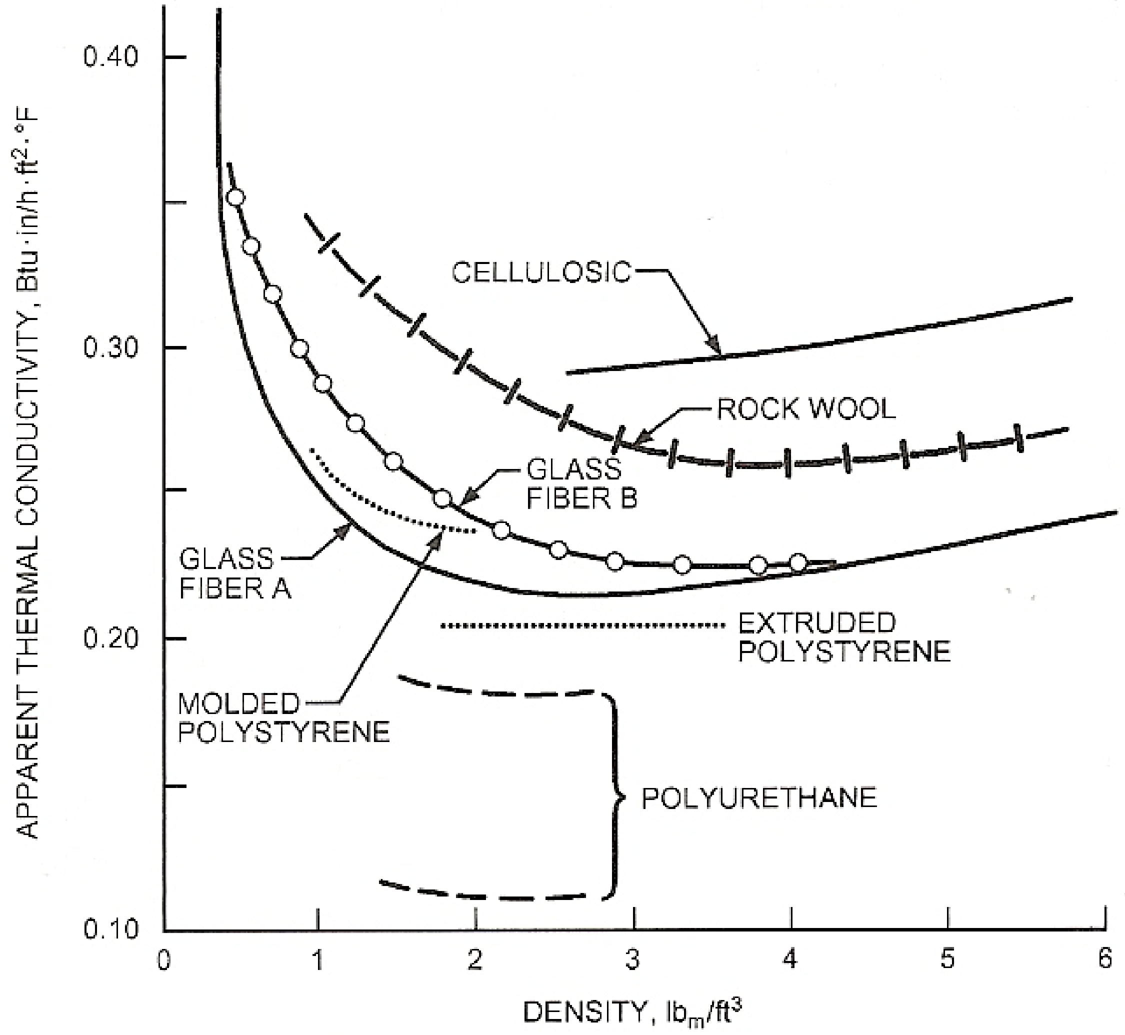


Fig. 2 Apparent Thermal Conductivity Versus Density of Several Thermal Insulations Used as Building Insulations

Source: ASHRAE Handbook Fundamentals 2009, Chapter 26

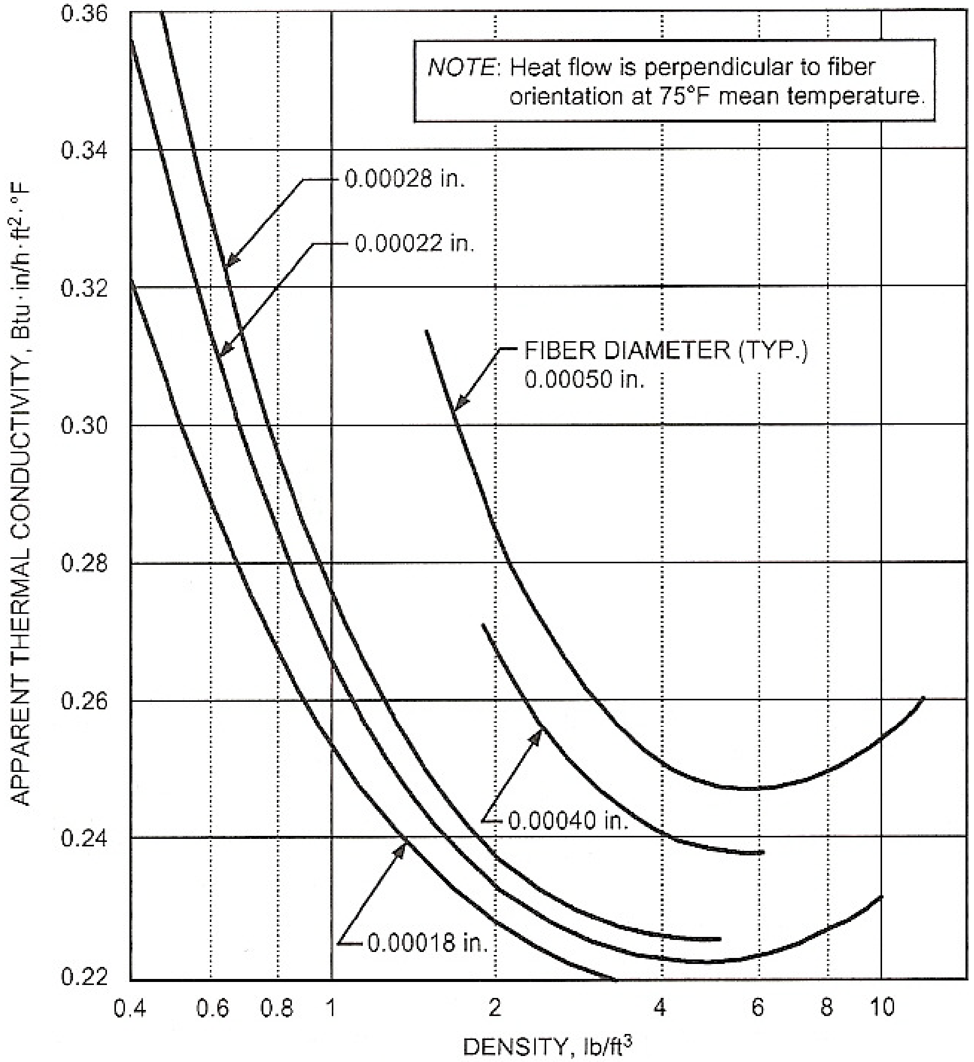


Fig. 3 Variation of Apparent Thermal Conductivity with Fiber Diameter and Density

Source: ASHRAE Handbook Fundamentals 2009, Chapter 26

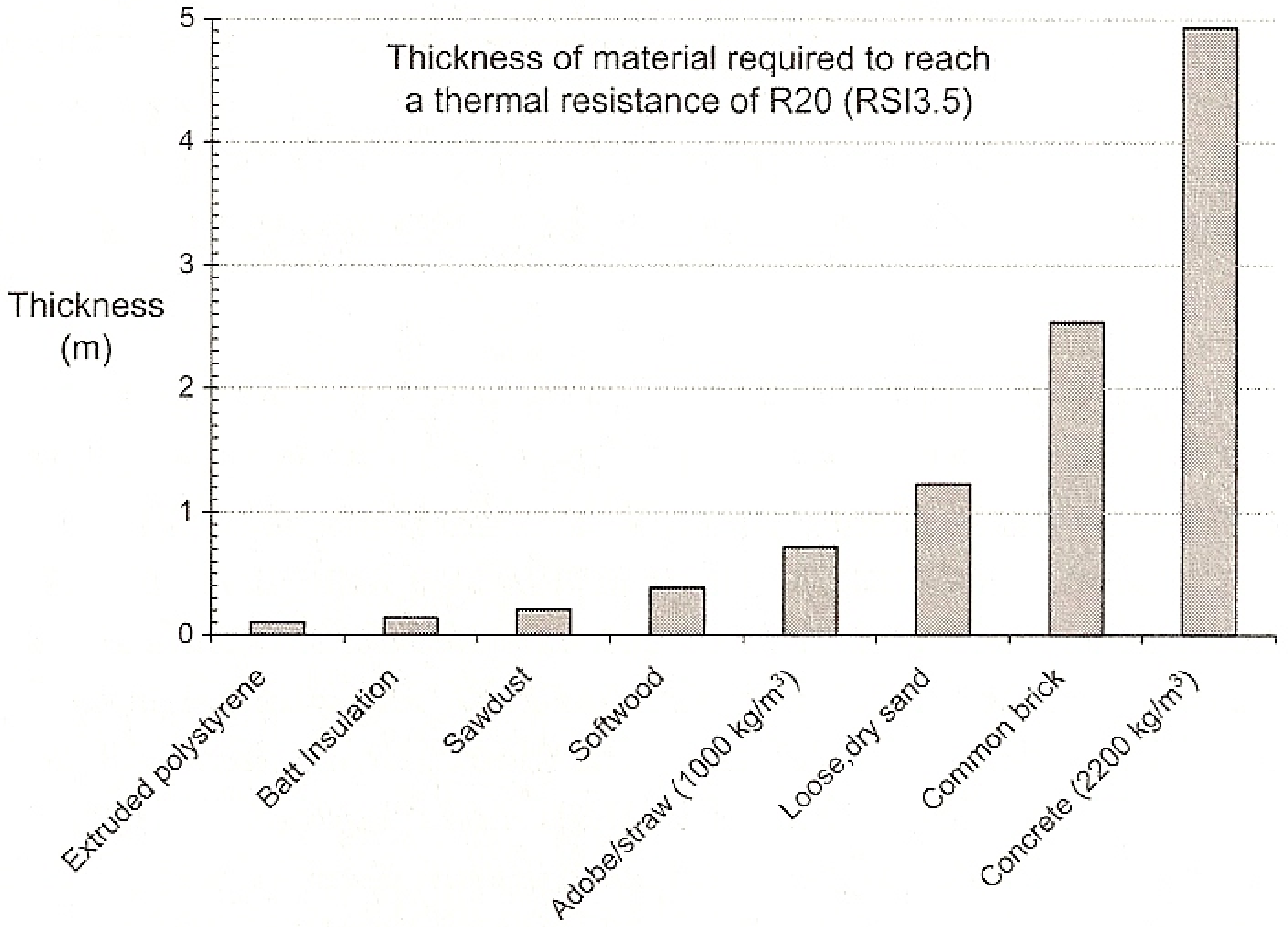


Figure 5.7: Comparison of the thickness of various materials required to achieve RSI3.5

Source: Straube and Burnett, Building Science for Building Enclosures, Chapter 5

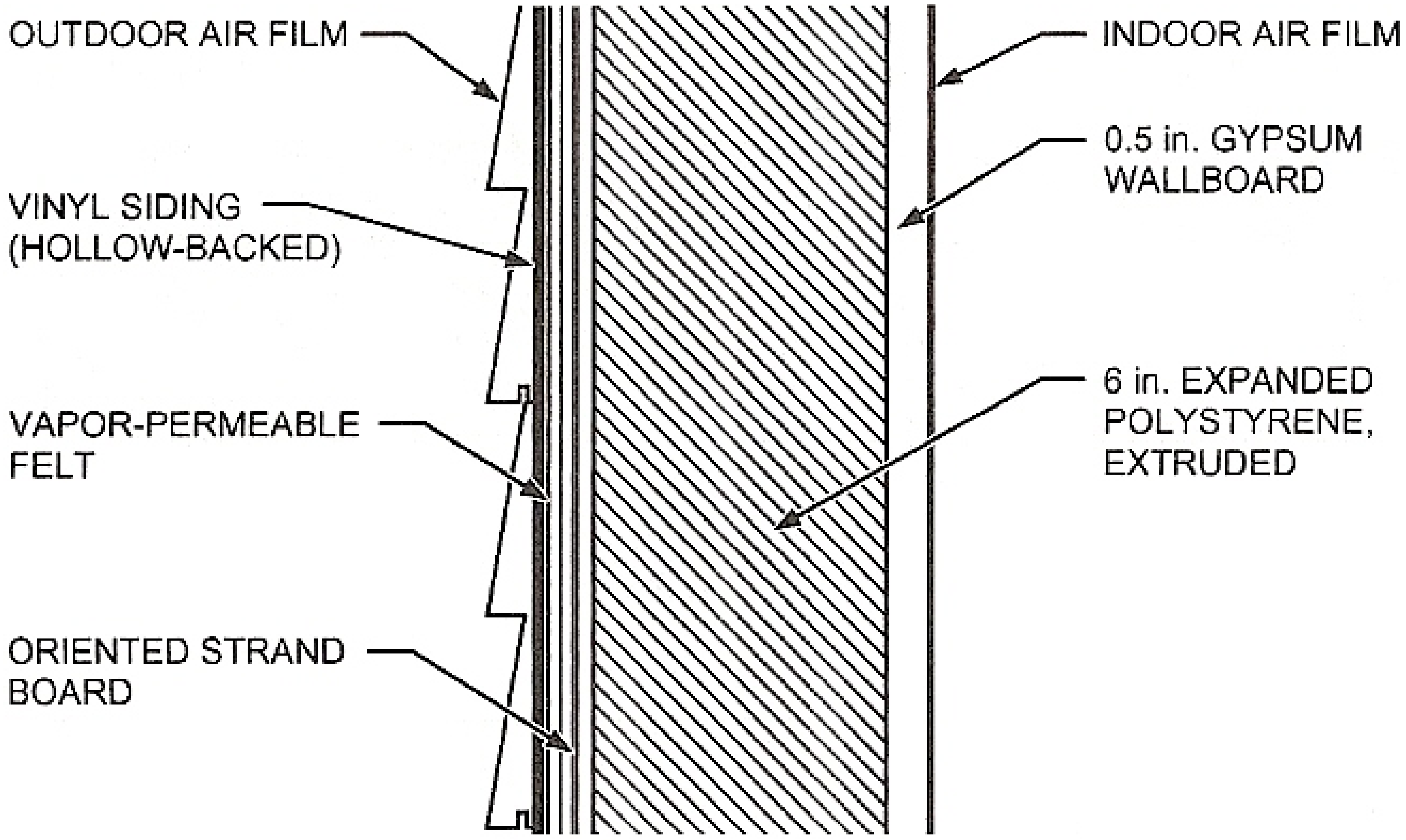


Fig. 1 Structural Insulated Panel Assembly (Example 1)

Source: ASHRAE Fundamentals Handbook 2013 Chapter 27.2

Element	R, h·ft²·°F/Btu
1. Outdoor air film	0.17
2. Vinyl siding (hollow backed)	0.62
3. Vapor-permeable felt	0.06
4. Oriented strand board (OSB), 7/16 in.	0.62
5. 6 in. expanded polystyrene, extruded (smooth skin)	30.0
6. 0.5 in. gypsum wallboard	0.45
7. Indoor air film	0.68
Total	32.6

Source: ASHRAE Fundamentals Handbook 2013 Chapter 27.2

Element	R, h·ft²·°F/Btu
1. Indoor air film	0.92
2. 4 in. concrete, 120 lb/ft³ and $k = 8$	0.5
3. 3 in. cellular polyisocyanurate (CFC-11 exp.) (gas-impermeable facers)	28.2
4. 1 in. mineral fiberboard	2.94
5. 3/8 in. built-up roof membrane	0.33
6. Outdoor air film	0.25
Total	33.1

Using $U = 1/R_{T(av)}$, the U-factor is 0.030 Btu/h·ft²·°F.

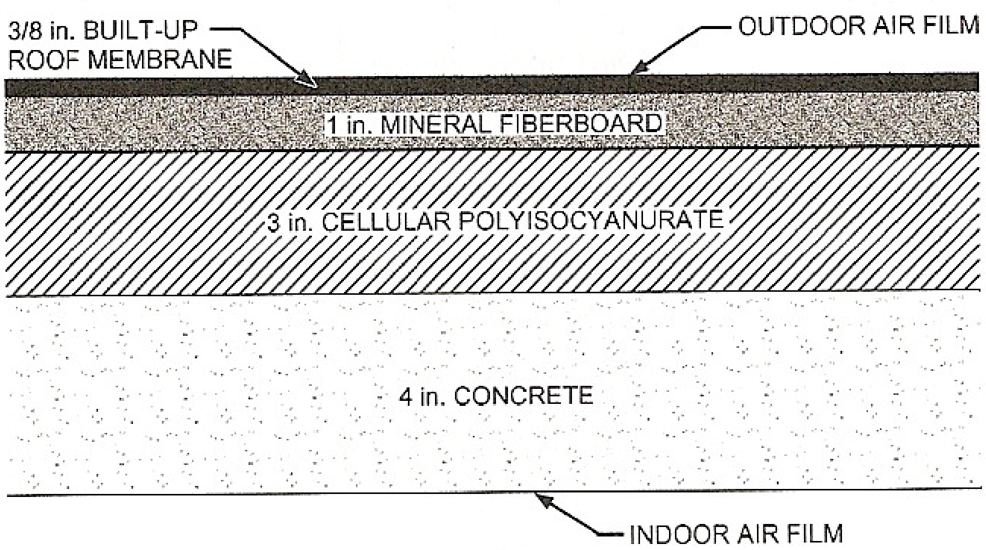


Fig. 2 Roof Assembly (Example 2)

Source: ASHRAE Fundamentals Handbook 2013 Chapter 27.2

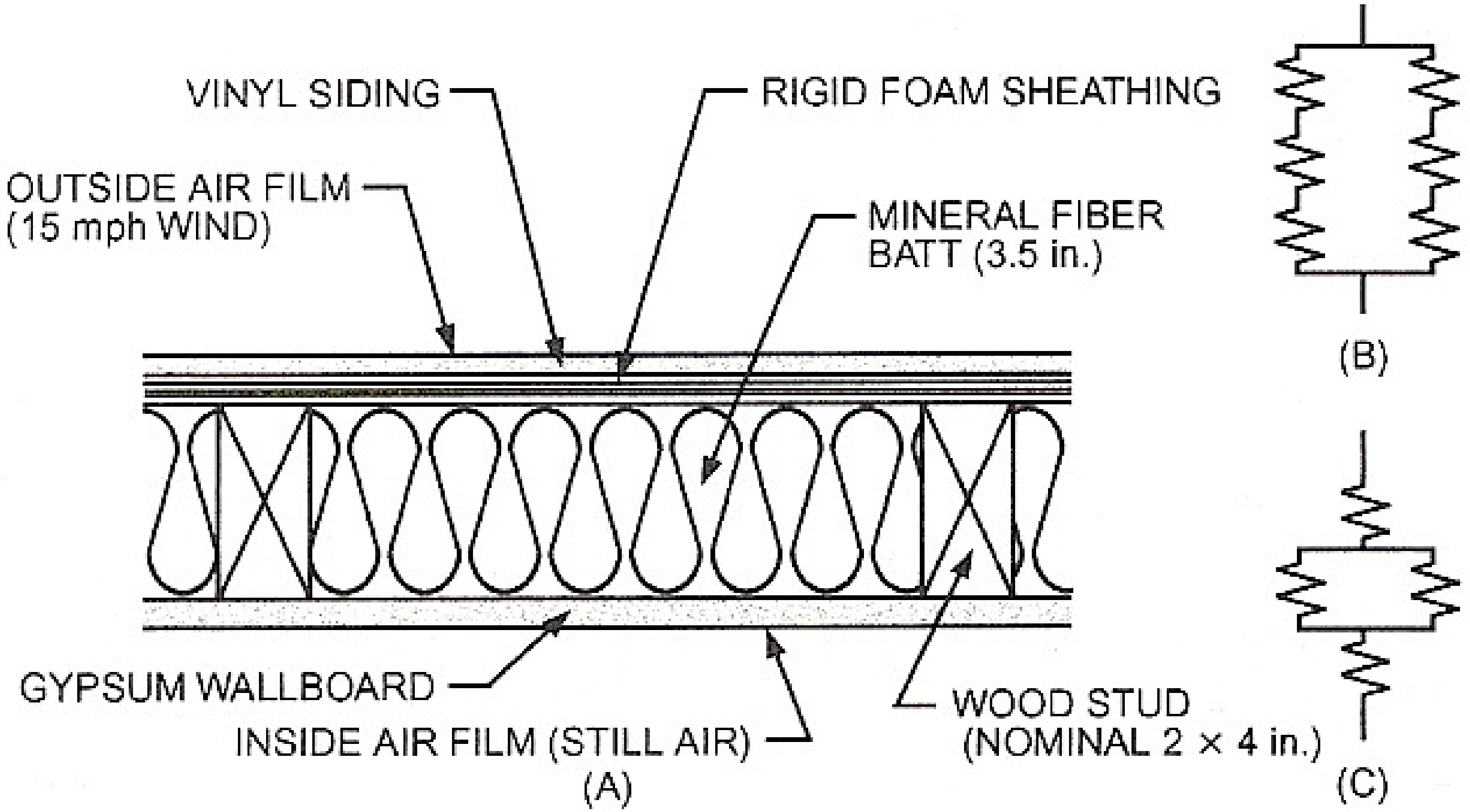


Fig. 3 (A) Wall Assembly for Example 3, with Equivalent Electrical Circuits: (B) Parallel Path and (C) Isothermal Planes

Source: ASHRAE Fundamentals Handbook 2013, Chapter 27.3

Parallel-Path Method:

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

Source: ASHRAE Fundamentals Handbook 2013, Chapter 27.3

Isothermal-Planes Method:

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

Source: ASHRAE Fundamentals Handbook 2013 Chapter 27.4

When Thermal Bridges Matter

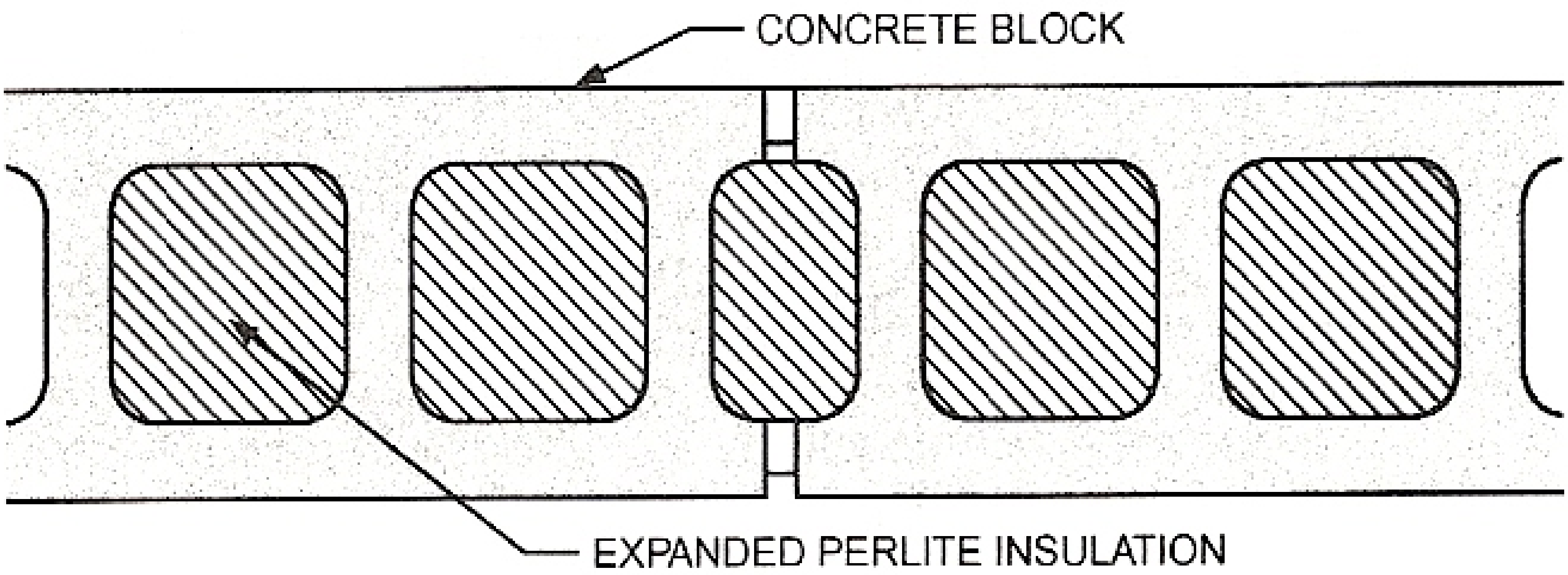


Fig. 4 Insulated Concrete Block Wall (Example 4)

Source: ASHRAE Fundamentals Handbook 2013, Chapter 27.4

When Thermal Bridges Matter

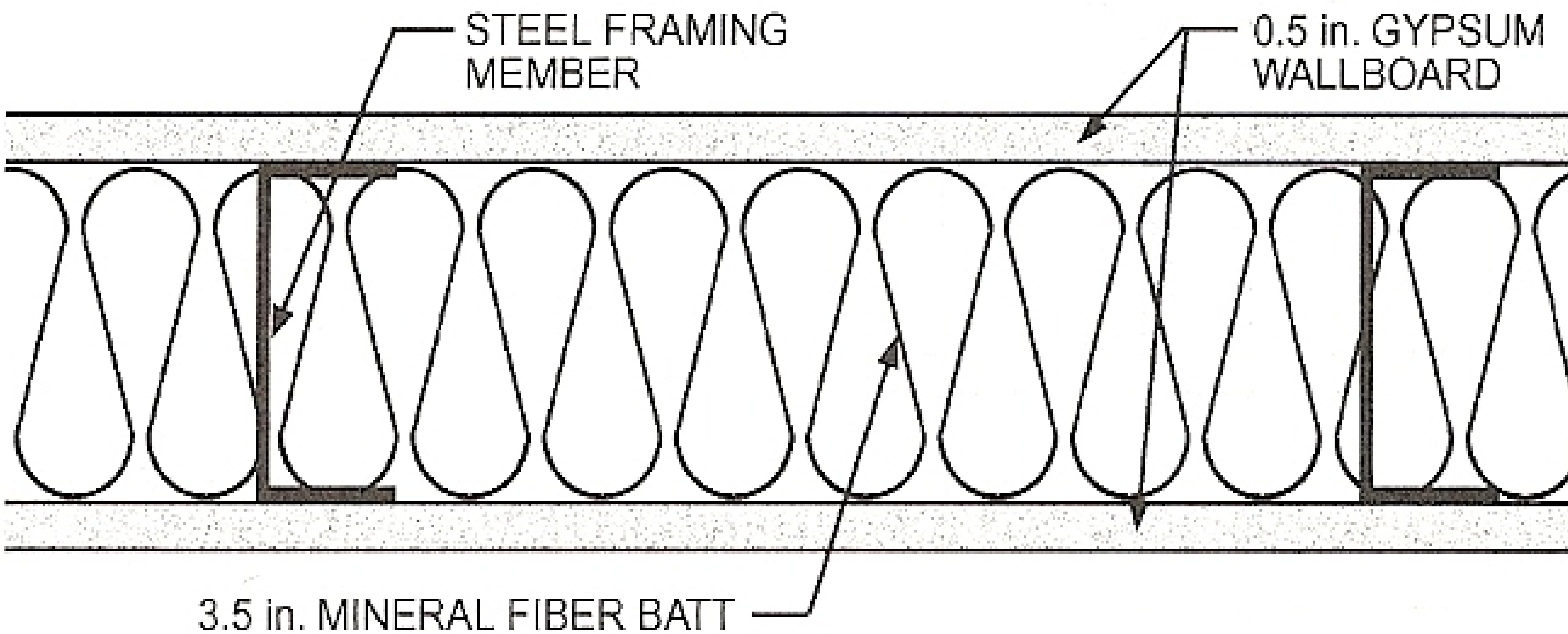


Fig. 5 Insulated Steel Frame Wall (Example 5)

Source: ASHRAE Fundamentals Handbook 2009, Chapter 27.5

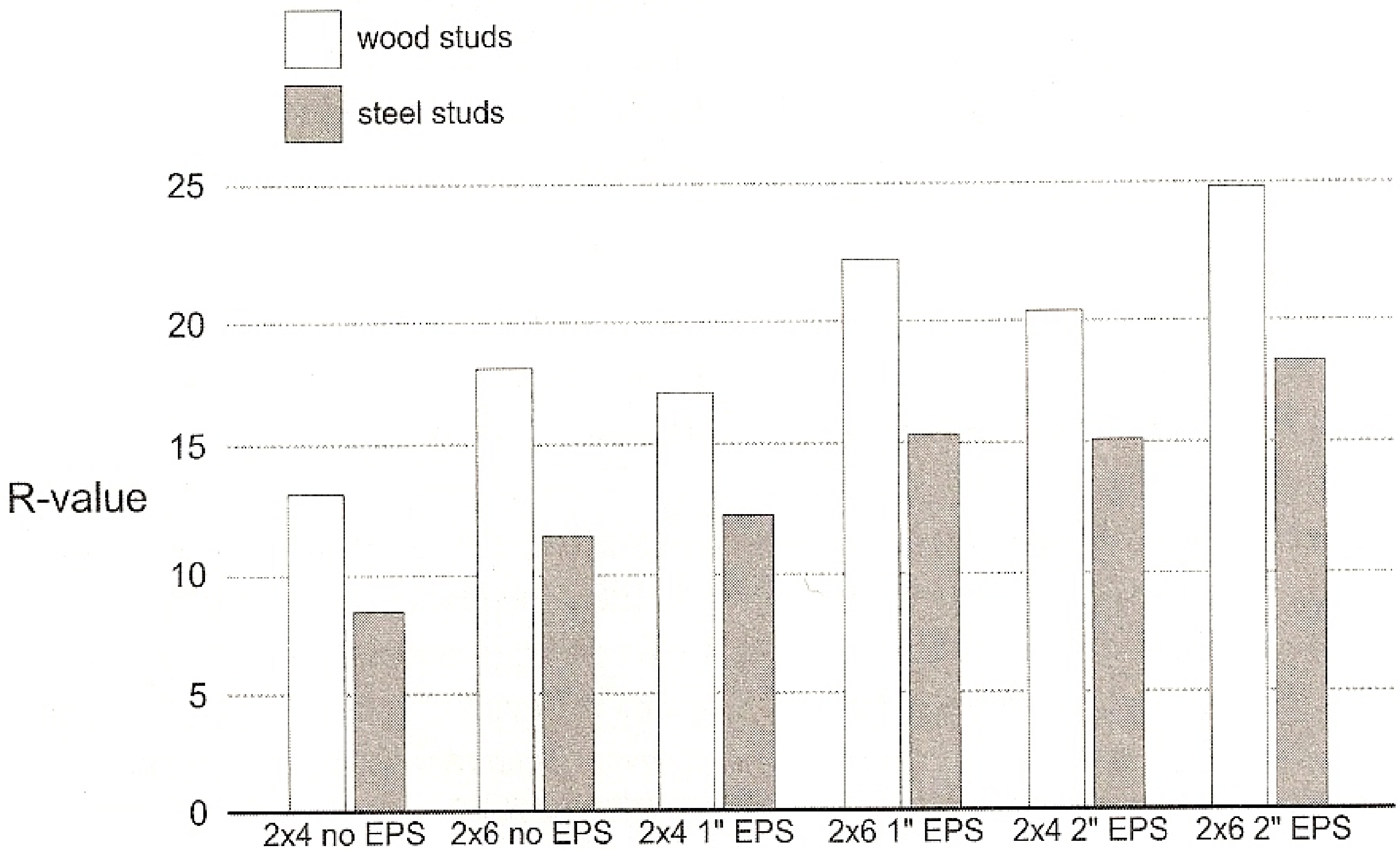


Figure 5.12: Two-dimensional heat flow calculations for wood and steel framing

Source: Straube and Burnett, Building Science for Building Enclosures, Chapter 5

Temperature Profiles

Calculating interface temperatures

- Temperature drop across any element is proportional to the R-value of the element compared to the total R-value

$$T_{surface} = T_{in} - \frac{R_{(interior)}}{R_{(total)}} \times (T_{in} - T_{out})$$

How Much Insulation?

Optimizing Insulation Levels

- Insulation costs versus lost energy costs
  - cost of insulation isn't smooth due to changes in structural requirements and mechanical systems
- Must use same time frame
  - bring back to net present value or annualized capital costs
- Other factors
  - comfort issues
  - energy supply

Thermal Insulation – Final Thoughts

- Type of Building
  - Skin dominated versus internal load dominated
- New versus adding
- Concept of insulation packages or ratios
  - Why do we put more insulation in a ceiling than a wall?

In Summary

Questions and Discussion

Next Class

- Pyschrometrics
  - Key aspects of the psychrometric chart
  - Using the chart to plot basic processes
  - Using the chart to solve specific problems

- Readings
  - HF: Chapter 1 (1-16)
  - HPE: 3.4