Advanced Building Science

- Moisture Control in Insulated Assemblies
  - General moisture concerns
  - Moisture in building materials
  - Moisture migration
  - Vapor diffusion vs. convective mass transport

- Readings
  - HF: Chapter 25 => 25.10 to 25.17
  - HF: Chapter 26 => 26.13 to 26.20
  - HF: Chapter 27 => 27.7 to 27.12
  - HPE: Chapter 3.5 & 3.6
  - BG: Pages 105 to 130 (Appendix II & III for editions prior to 2004)

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Moisture Control in Insulated Buildings

General Moisture Concerns

- Invisible
  - degradation of thermal resistance
  - decrease in strength/stiffness of building materials (esp. wood)
- Visible
  - mold and mildew
  - decay of wood-based materials
  - spalling of brick, masonry, and concrete
  - hydration of plastic materials
  - corrosion of metals
  - damage due to expansion
  - decline in visual appearance

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Moisture Control in Insulated Buildings

Moisture in Building Materials

- Typical sorption isotherms for hygroscopic materials
  - adsorption => as relative humidity rises, materials gain moisture
  - desorption => as relative humidity drops, materials lose moisture
  - hysteresis => differential isotherms for wetting and drying

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Sorption Isotherms for Materials

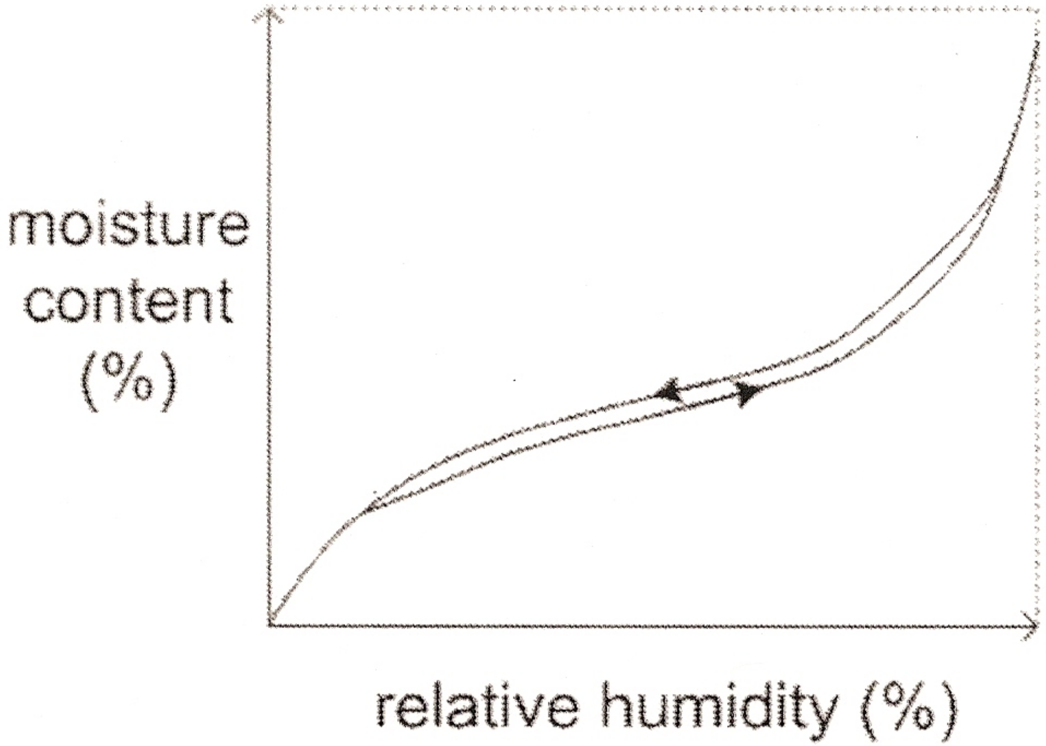

Figure 8.18: Typical sorption isotherm of a hygroscopic material

Source: Straube & Burnett, Building Science for Building Enclosures, Chapter 8

Sorption Isotherms for Materials

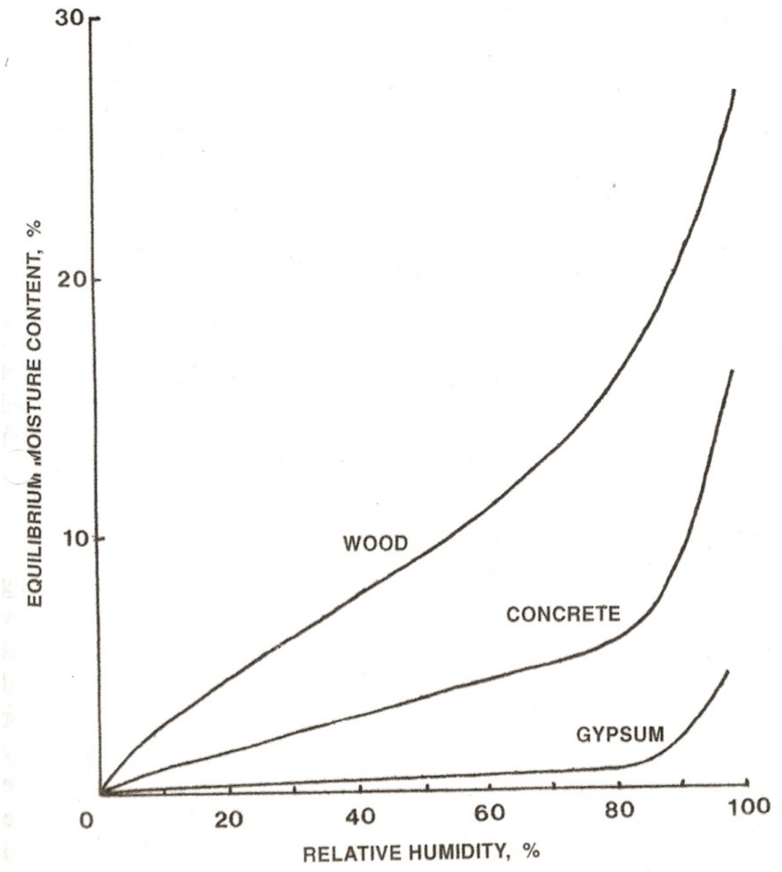

Fig. 9 Typical Sorption Isotherms for Wood, Concrete, and Gypsum (Hysteresis Is Ignored)

Source: ASHRAE Fundamentals Handbook 2005, Chapter 23.6

Sorption Isotherms for Materials

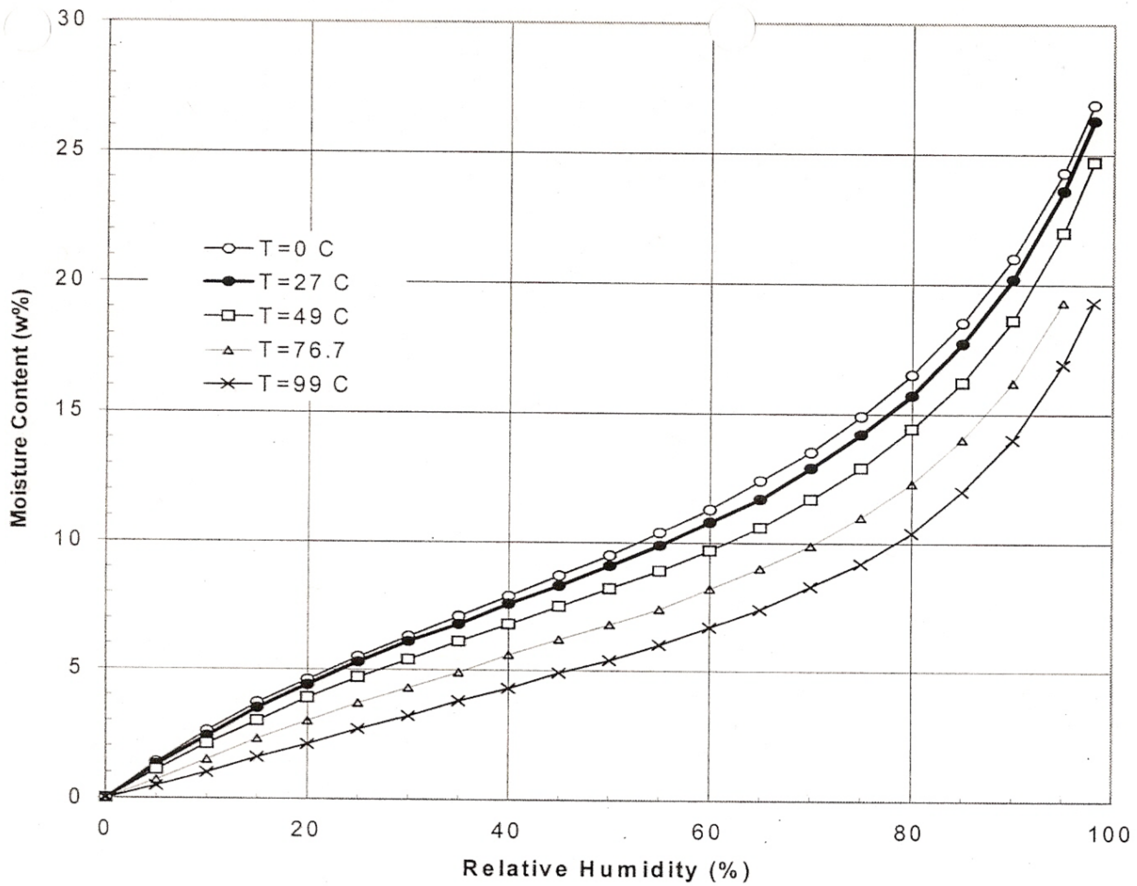

Figure 8.20: Average sorption isotherm for wood as a function of temperature

Source: Straube & Burnett, Building Science for Building Enclosures, Chapter 8

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Sorption Isotherms for Materials

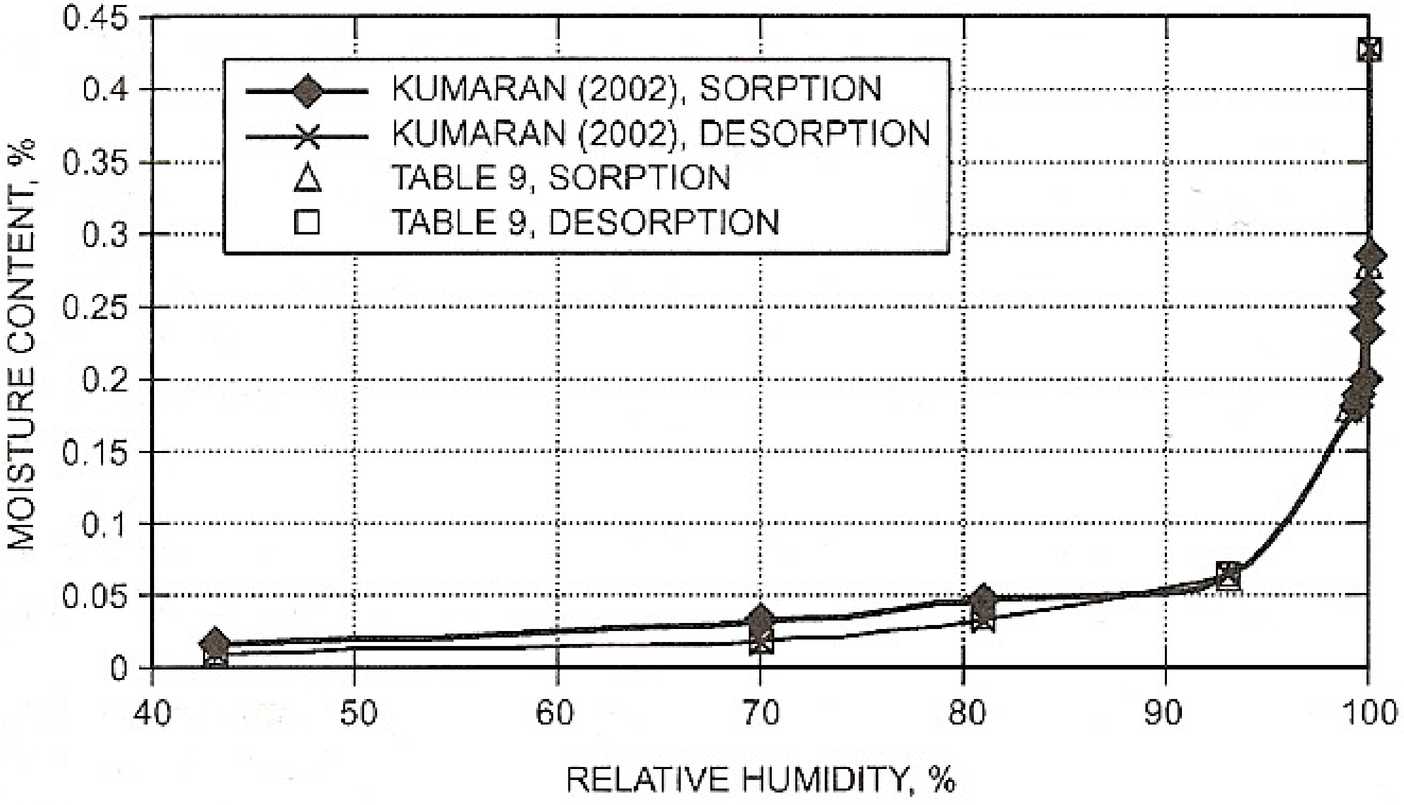

Fig. 8 Sorption/Desorption Isotherms, Cement Board

SOURCE: ASHRAE Handbook Fundamentals 2009, Chapter 26

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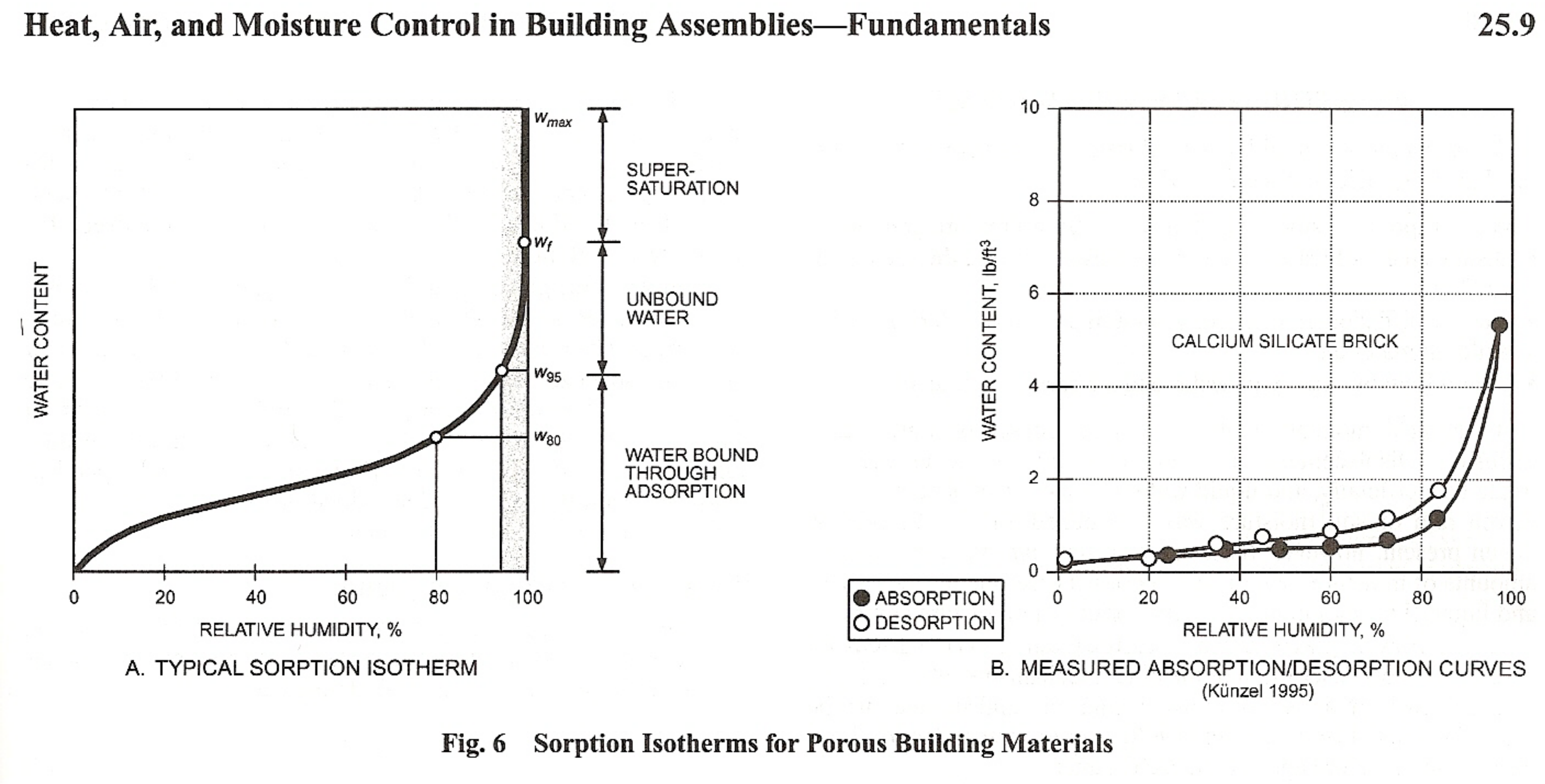
Sorption Isotherms for Materials


Heat, Air, and Moisture Control in Building Assemblies—Fundamentals 25.9

A. TYPICAL SORPTION ISOTHERM

B. MEASURED ABSORPTION/DESORPTION CURVES (Künzel 1995)

Fig. 6 Sorption Isotherms for Porous Building Materials

SOURCE: ASHRAE Handbook Fundamentals 2009, Chapter 25

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Moisture in Porous Materials

8. Moisture Storage and Transport Processes in Porous Media

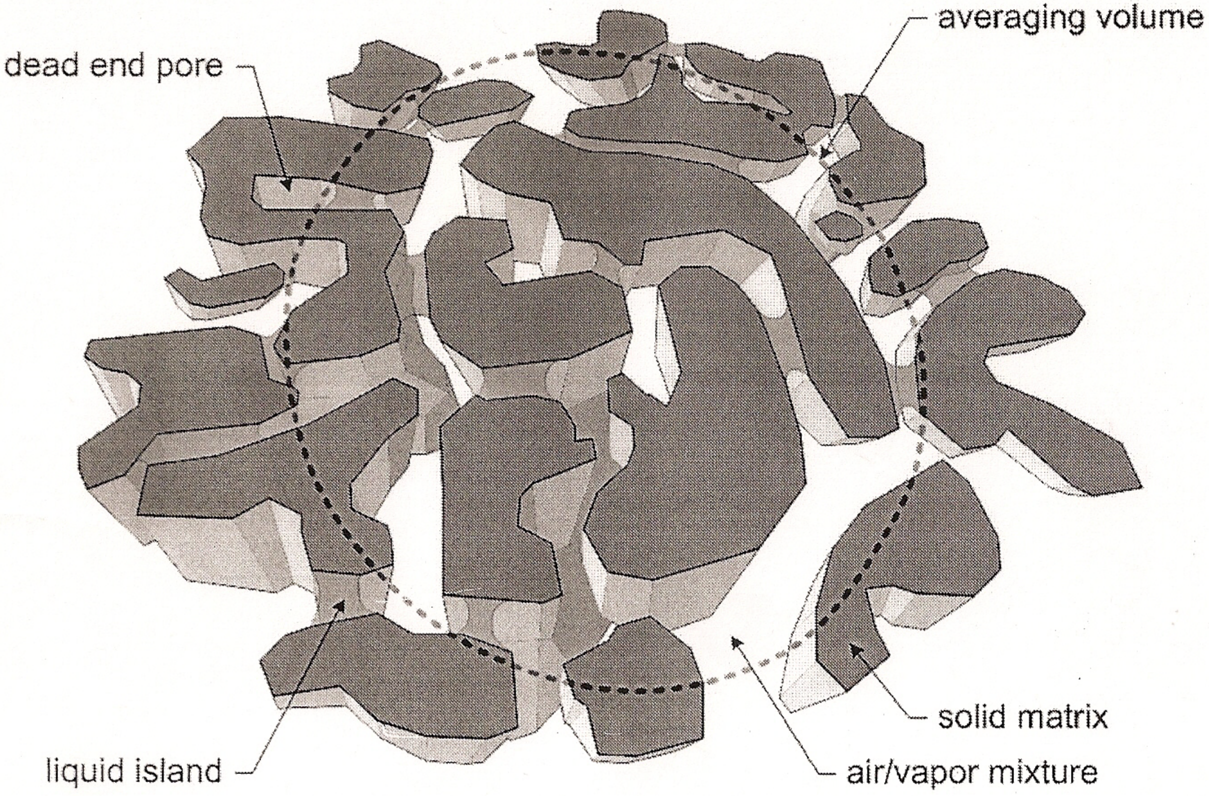

Figure 8.3: Porous Media Definitions

Source: Straube & Burnett, Building Science for Building Enclosures, Chapter 8

Moisture in Porous Materials

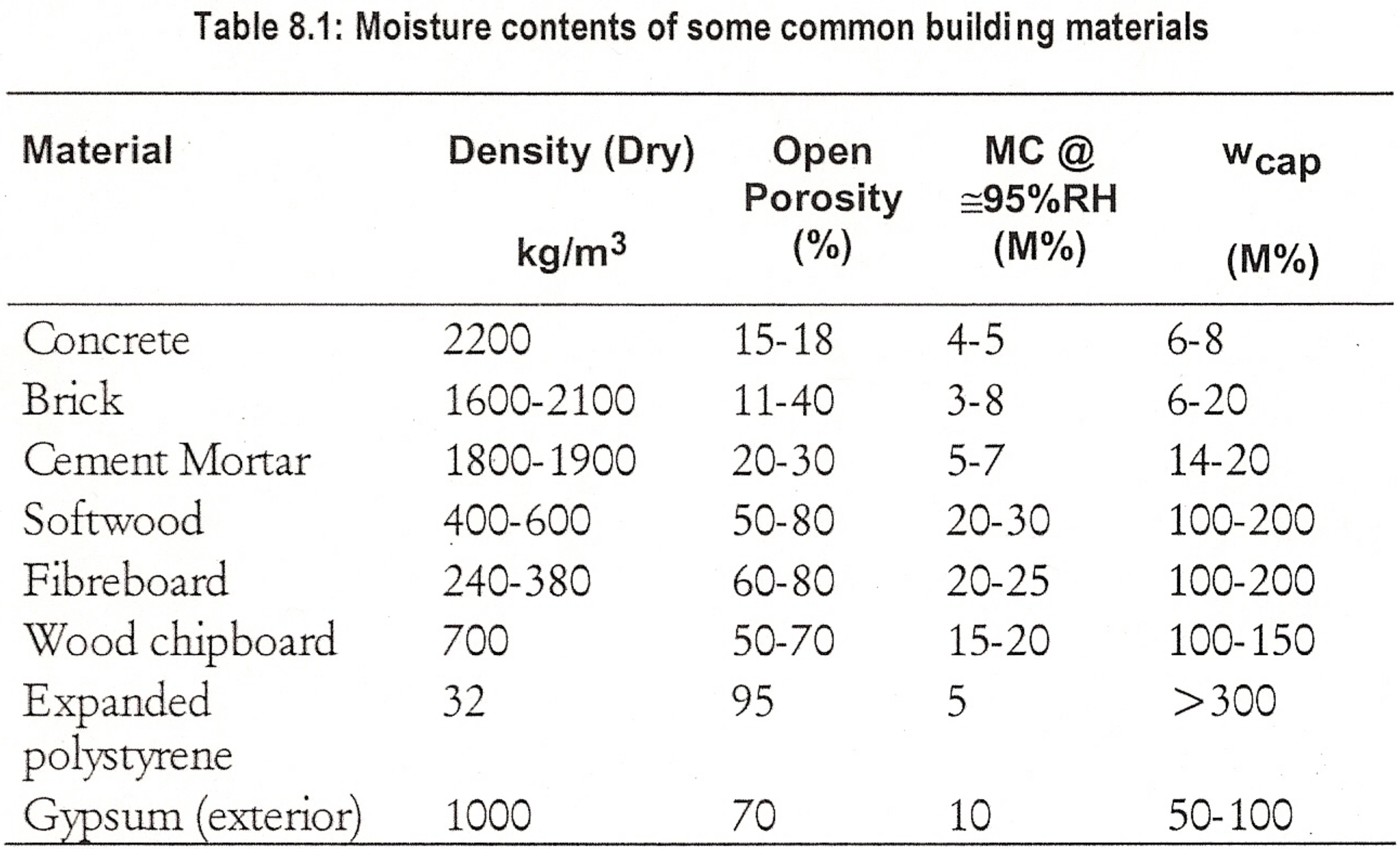

Table 8.1: Moisture contents of some common building materials

Material	Density (Dry) kg/m^3	Open Porosity (%)	MC @ ≅95%RH (M%)	w_{cap} (M%)
Concrete	2200	15-18	4-5	6-8
Brick	1600-2100	11-40	3-8	6-20
Cement Mortar	1800-1900	20-30	5-7	14-20
Softwood	400-600	50-80	20-30	100-200
Fibreboard	240-380	60-80	20-25	100-200
Wood chipboard	700	50-70	15-20	100-150
Expanded polystyrene	32	95	5	>300
Gypsum (exterior)	1000	70	10	50-100

Source: Straube & Burnett, Building Science for Building Enclosures, Chapter 8

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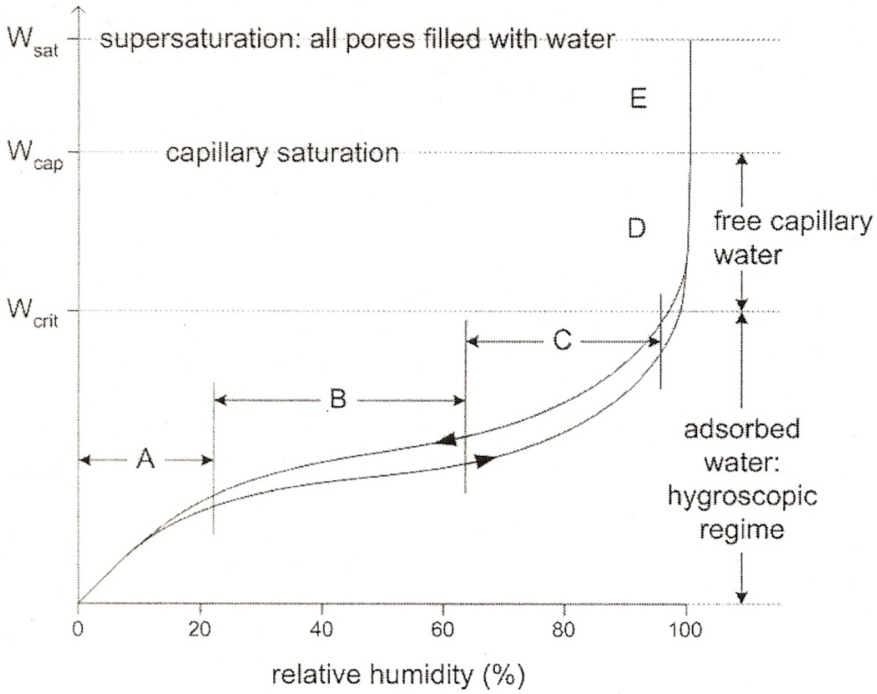
Moisture in Porous Materials



A: Single-layer of adsorbed molecules
B: Multiple layers of adsorbed molecules
C: Interconnected layers (internal capillary condensation
D: Free water in Pores, capillary suction
E: Supersaturated Regime

Figure 8.21: Regimes of moisture storage in a hygroscopic porous material

Source: Straube & Burnett, Building Science for Building Enclosures, Chapter 8

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Moisture in Porous Materials

25.12

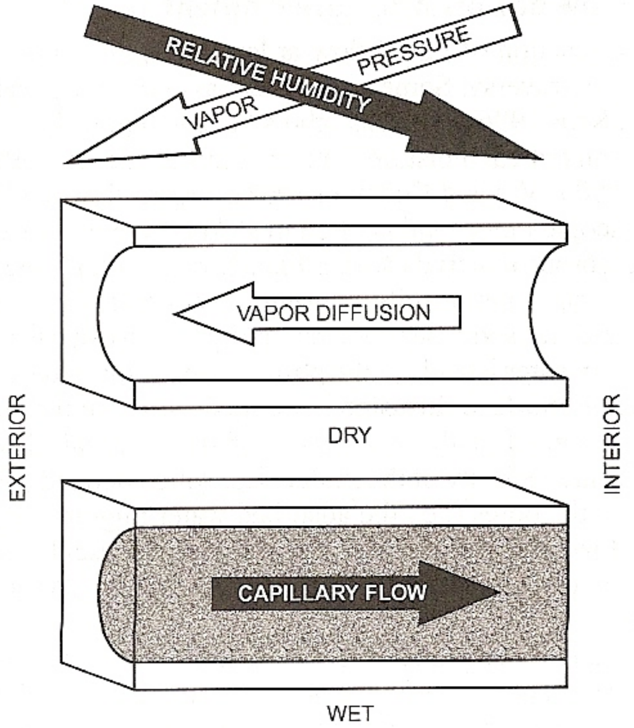

Fig. 10 Moisture Fluxes by Vapor Diffusion and Liquid Flow in Single Capillary of Exterior Wall under Winter Conditions

SOURCE: ASHRAE Handbook Fundamentals 2009, Chapter 25

Moisture Control in Insulated Buildings

Moisture Migration

- Liquid
  - bulk flow by gravity or air pressure
  - capillary suction in porous materials

- Vapor
  - convective mass transport due to air pressure difference
  - diffusion due to vapor pressure difference

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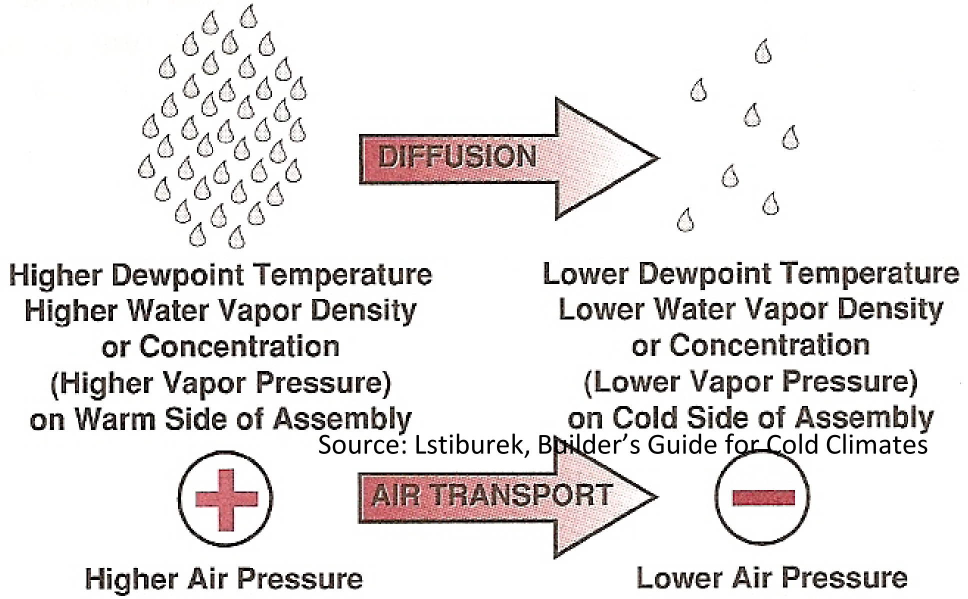
Water Vapor Transport



Source: Lstiburek, Builder's Guide for Cold Climates

Figure III.1
Water Vapor Movement

- Vapor diffusion is the movement of moisture in the vapor state as a result of a vapor pressure difference (concentration gradient) or a temperature difference (thermal gradient)
- Air transport is the movement of moisture in the vapor state as a result of an air pressure difference

Source: Lstiburek, Builder's Guide for Cold Climates 2001

Water Vapor Transport

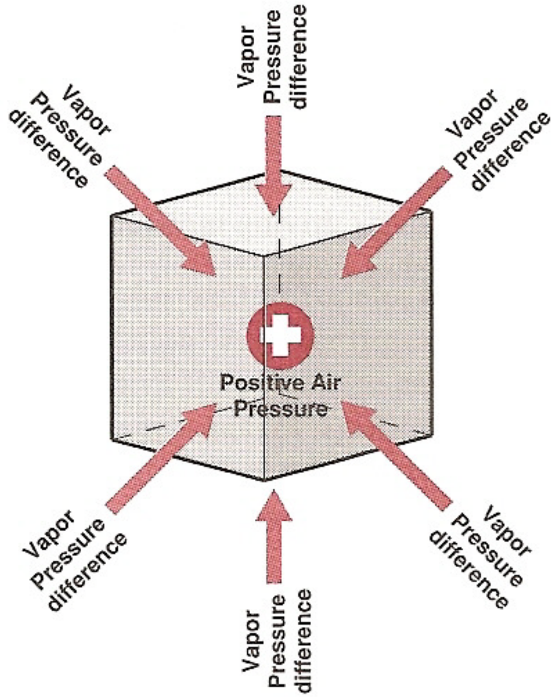


Figure III.2

Opposing Air and Vapor Pressure Differences

- The atmosphere within the cube is under higher air pressure but lower vapor pressure relative to surroundings
- Vapor pressure acts inward in this example
- Air pressure acts outward in this example

Source: Lstiburek, Builder's Guide for Cold Climates 2001

Water Vapor Transport

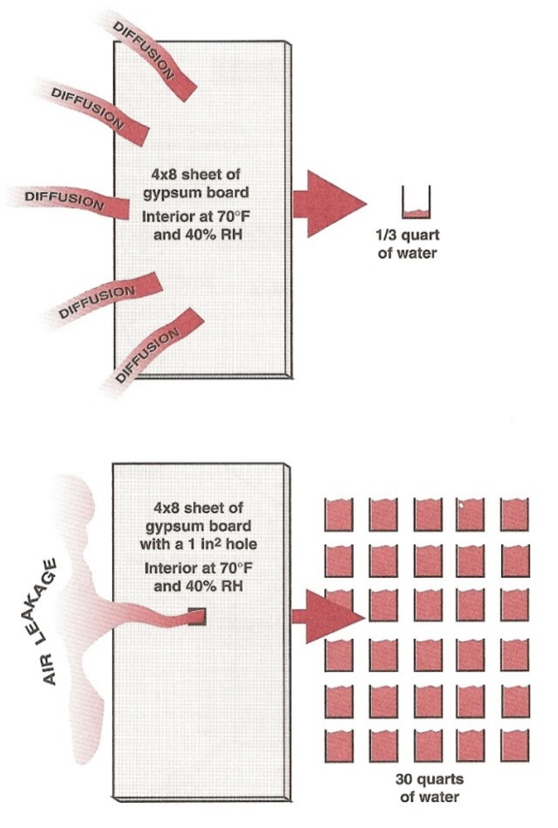


Figure III.4

Diffusion vs. Air Leakage

- In most cold climates over an entire heating season, $^1/_3$ of a quart of water can be collected by diffusion through gypsum board without a vapor diffusion retarder; 30 quarts of water can be collected through air leakage

Source: Lstiburek, Builder’s Guide for Cold Climates 2001

Moisture Control in Insulated Buildings

- Air Barriers
  - Fundamental to good building performance
  - Function of leakage and humidity ratio
  - Highly dependent on execution

- Requirements for Air Barriers
  - Impermeable to air flow
  - Continuous over the entire building envelope
  - Able to withstand forces acting on it
  - Durable over the life of the building

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Moisture Control in Insulated Buildings

- Vapor Diffusion Retarders
  - Important, but frequently overstated
  - Function of material properties and vapor pressure
  - Primarily dependent on design and materials
- Requirements for Vapor Diffusion Retarders
  - Low permeability
  - Full coverage, but not necessarily continuous
  - Durable over the life of the building

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Material Permeability

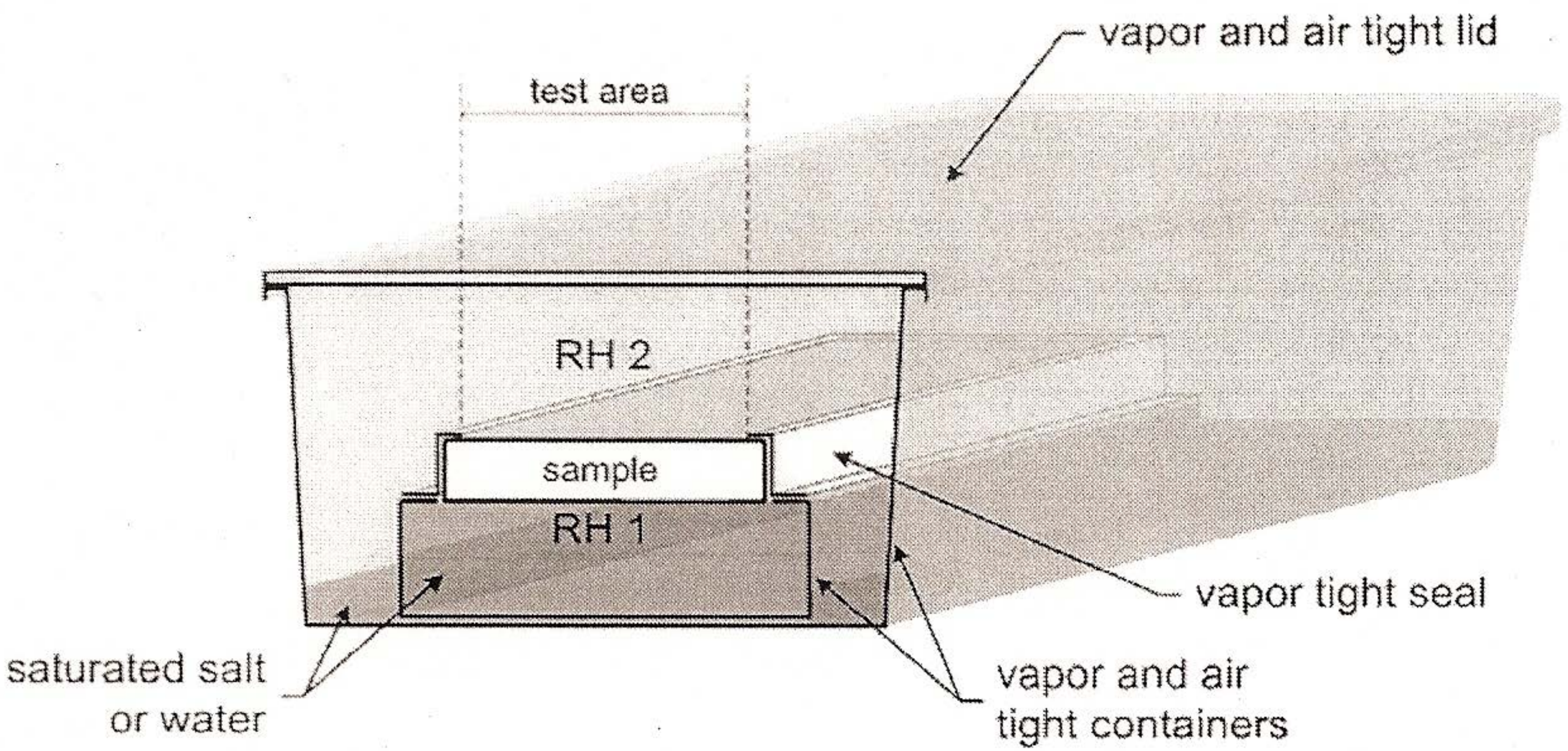

Figure 8.29: Test apparatus for measuring vapor permeance

Source: Straube & Burnett, Building Science for Building Enclosures, Chapter 8

Material Permeability

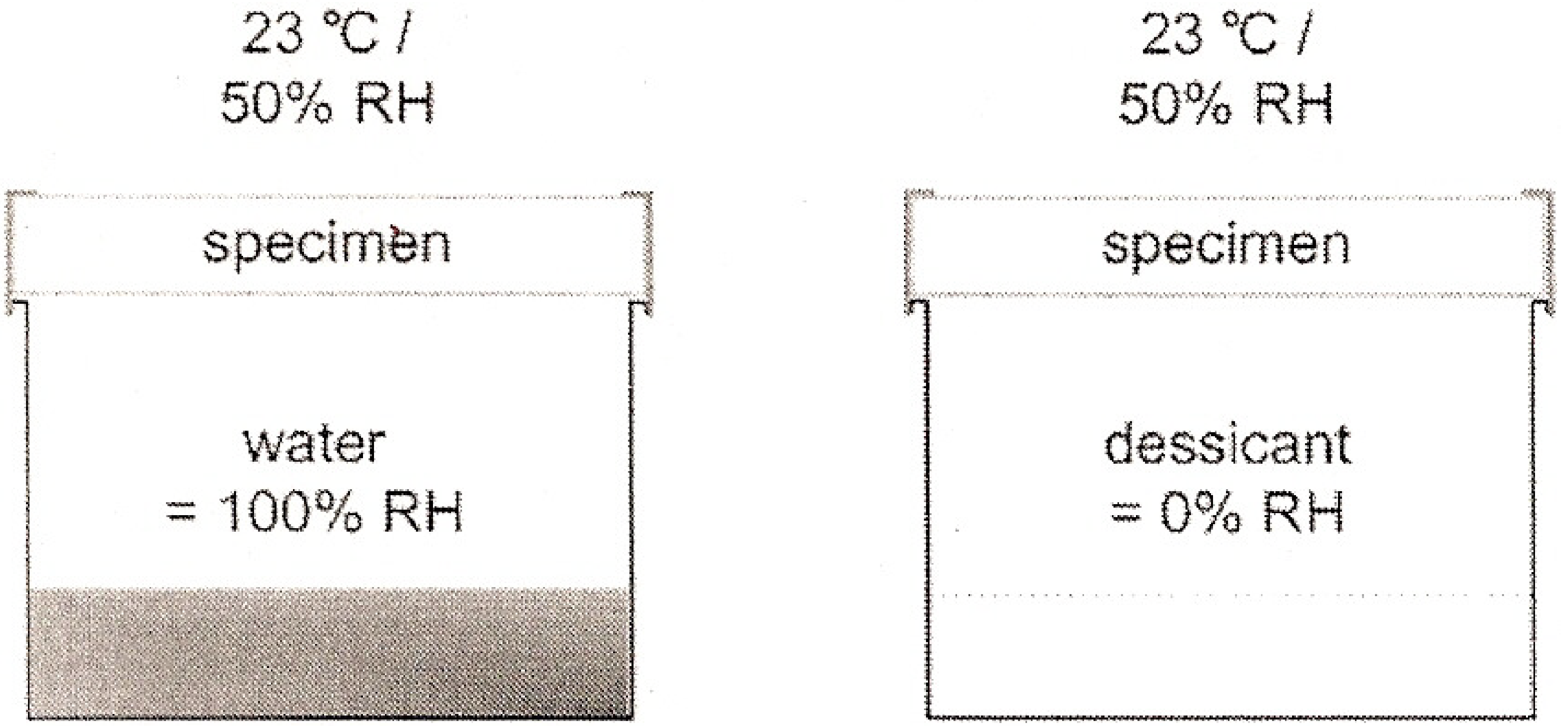

Figure 8.30: Wet cup and dry cup vapor permeance tests

Source: Straube & Burnett, Building Science for Building Enclosures, Chapter 8

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Material Permeability

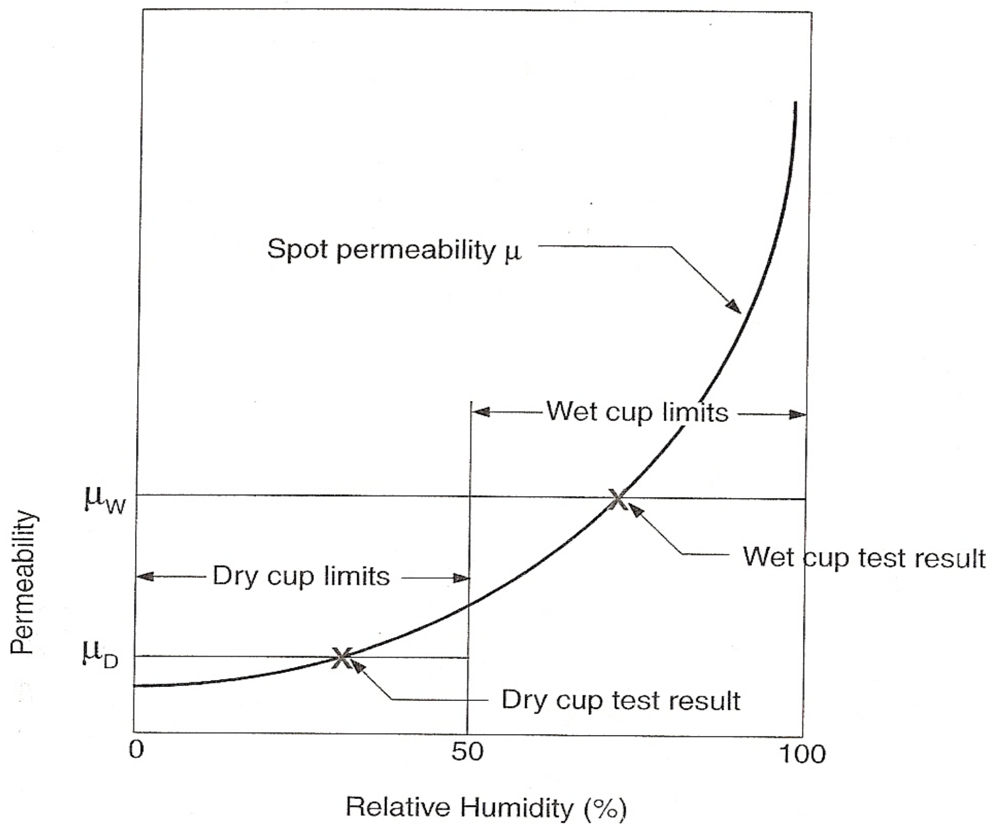

Figure III.3
Permeability vs. Relative Humidity

Source: Lstiburek, Builder's Guide for Cold Climates 2001

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Material Permeability

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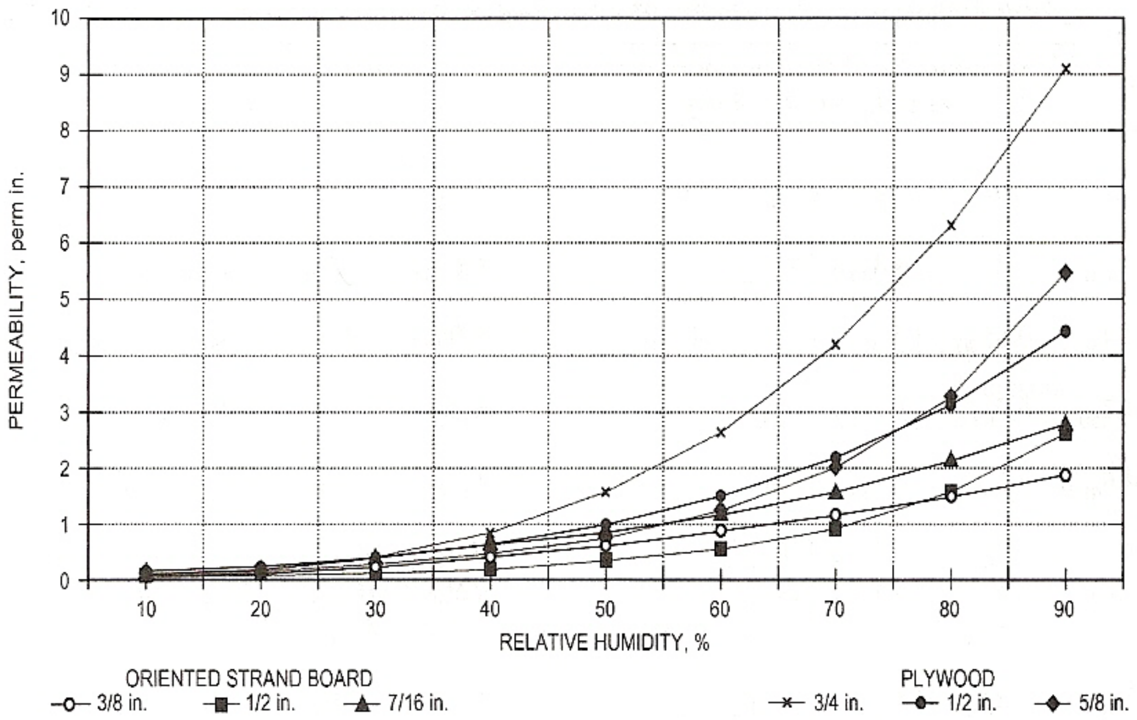

Fig. 7 Permeability of Wood-Based Sheathing Materials at Various Relative Humidities

Source: ASHRAE Handbook Fundamentals 2009, Chapter 26

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Material Permeability

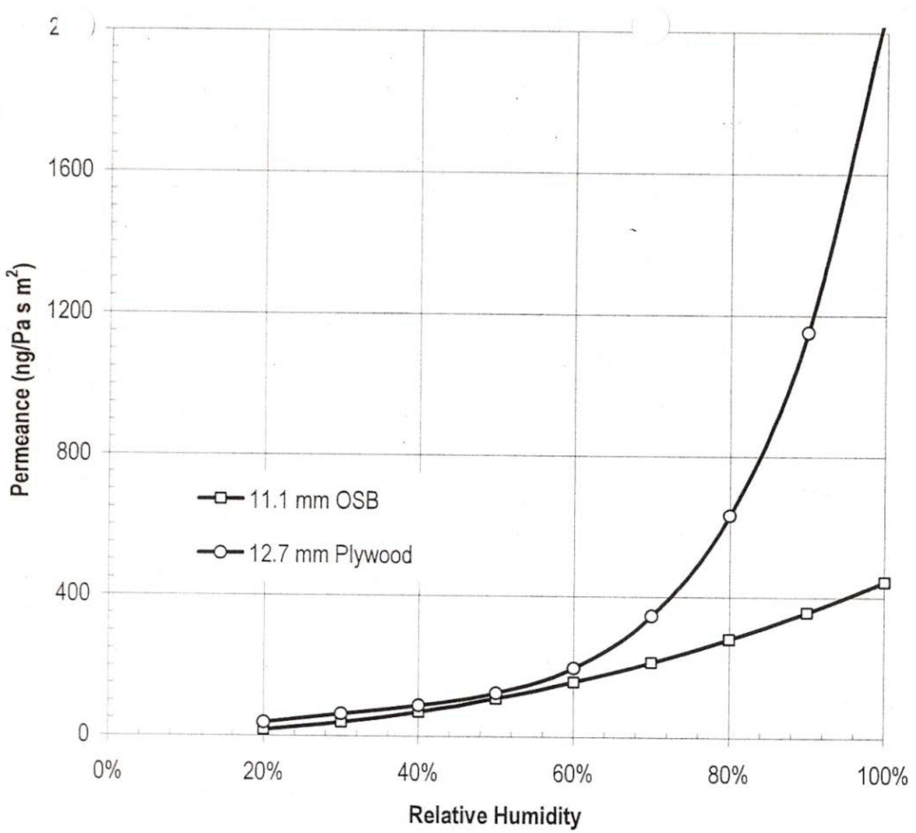

Figure 8.27: Vapor permeability test results for wood-based products as a function of RH [Kumaran et al 2002]

Source: Straube & Burnett, Building Science for Building Enclosures, Chapter 8

Condensation Potential

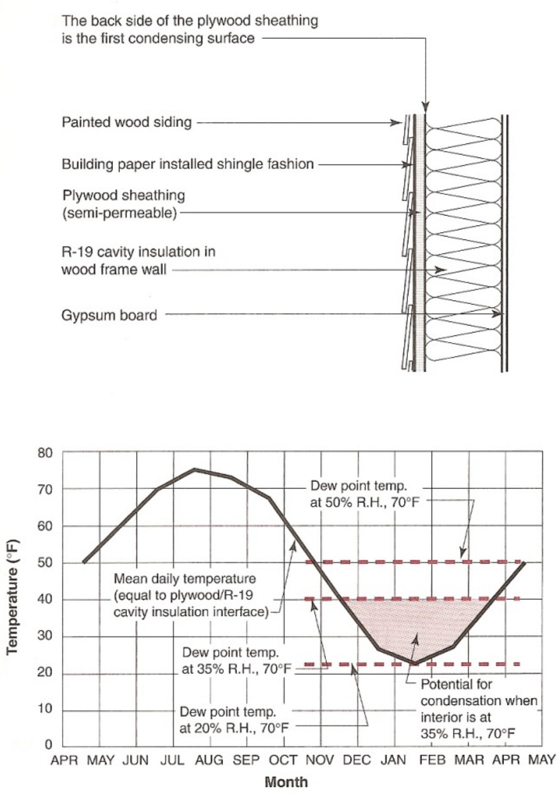

Figure III.9

Potential for Condensation in a Wood Frame Wall Cavity in Chicago, Illinois (Cold Climate)

- By reducing interior moisture levels, the potential condensation is reduced or eliminated
- No condensation occurs if interior moisture levels are maintained below 20% RH at 70°F

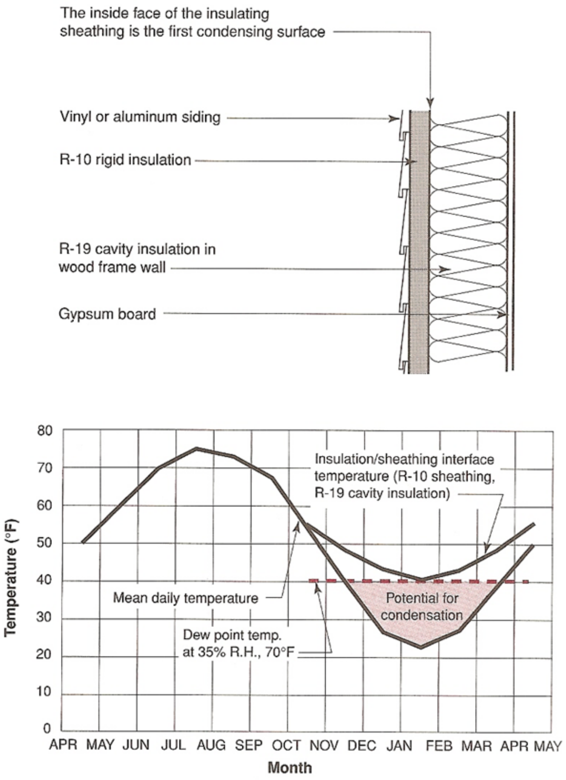

Figure III.10

Potential for Condensation in a Wood Frame Wall Cavity Without an Interior Vapor Diffusion Retarder in Chicago, Illinois

- The R-10 insulating sheathing raises the dew point temperature at the first condensing surface (cavity side of the foam sheathing) so that no condensation will occur when interior moisture levels are less than 35% relative humidity at 70°F

Source: Lstiburek, Builder's Guide for Cold Climates 2001

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Moisture Control in Insulated Buildings

Dew Point Calculation Method

- 1. Find temperature of each surface/interface
- 2. Find saturation vapor pressure for those temperatures
- 3. Calculate the vapor pressure drop
- 4. Compare saturation and calculated vapor pressures
- 5. Where calculated vapor pressure is greater than saturation, fix that surface at the saturation pressure
- 6. Recalculate the vapor pressure drops in two parts

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Example 1 - ASHRAE

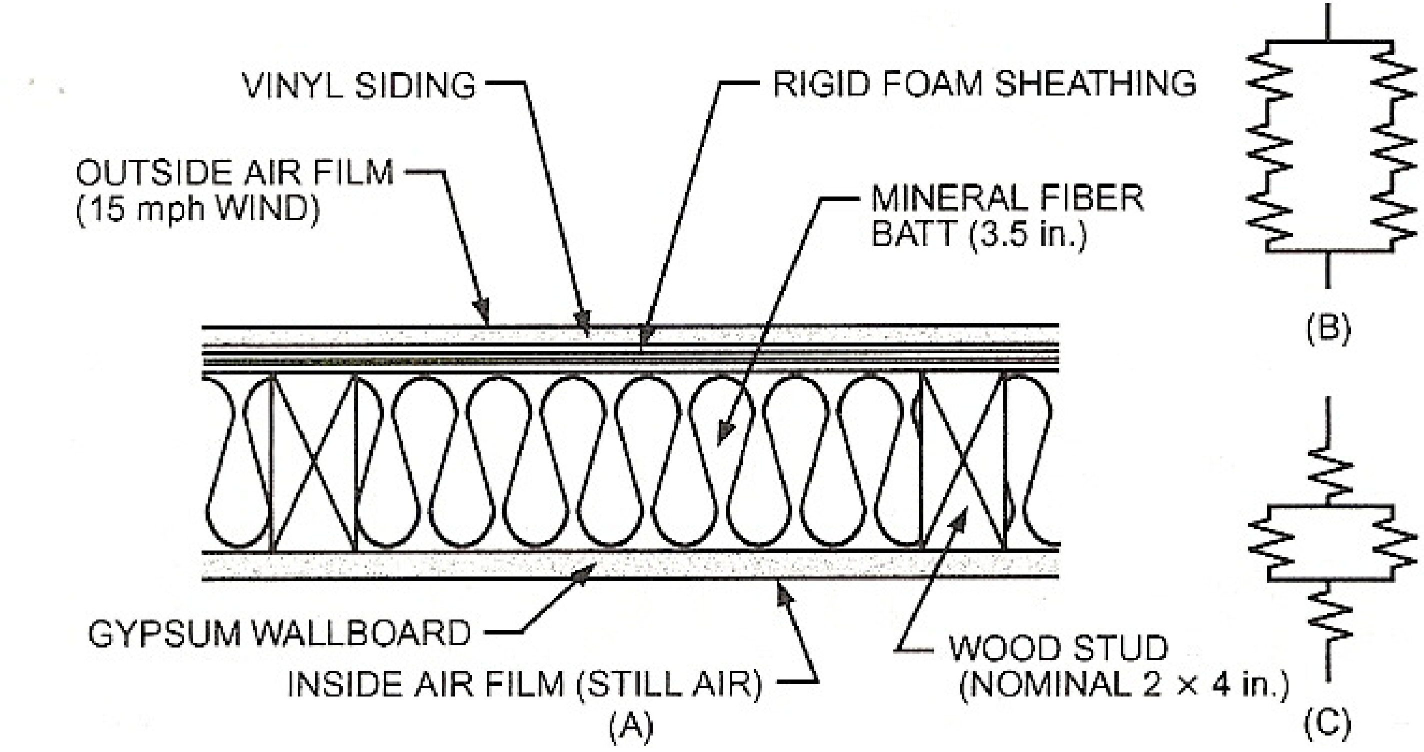

Fig. 3 (A) Wall Assembly for Example 3, with Equivalent Electrical Circuits: (B) Parallel Path and (C) Isothermal Planes

Source: ASHRAE Handbook Fundamentals 2009, Chapter 27

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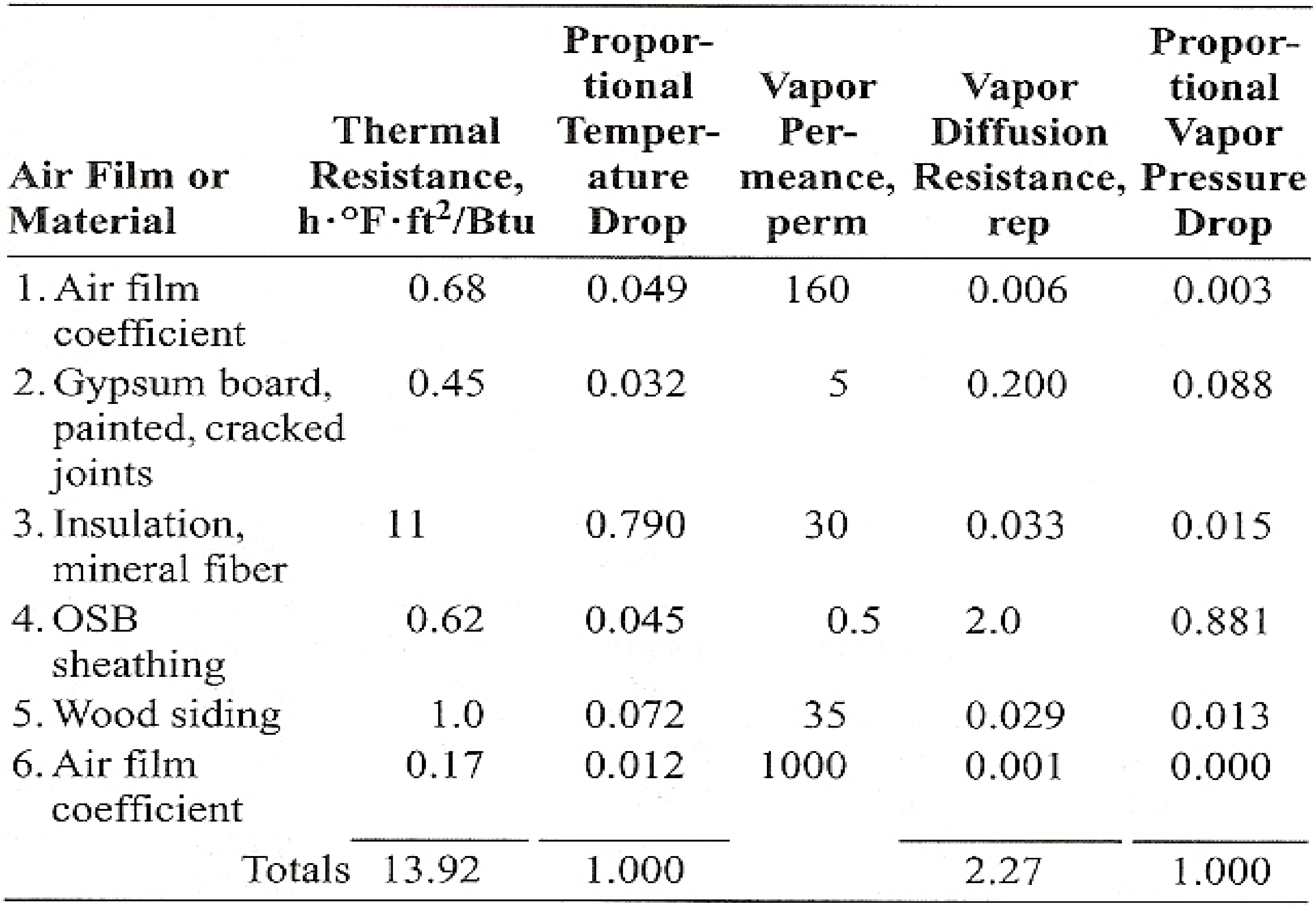
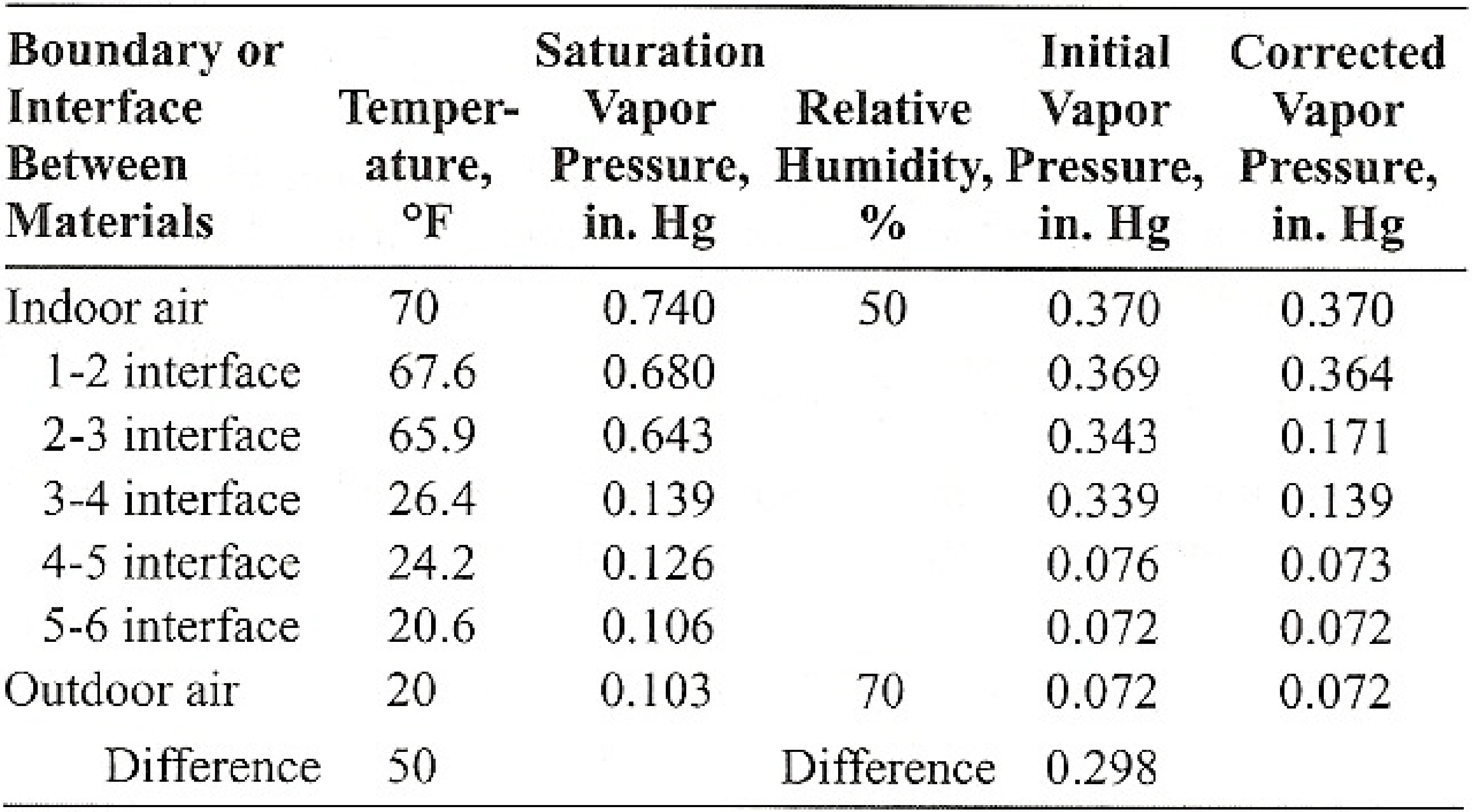


Air Film or Material	Thermal Resistance, h·°F·ft²/Btu	Proportional Temperature Drop	Vapor Permeance, perm	Vapor Diffusion Resistance, rep	Proportional Vapor Pressure Drop
1. Air film coefficient	0.68	0.049	160	0.006	0.003
2. Gypsum board, painted, cracked joints	0.45	0.032	5	0.200	0.088
3. Insulation,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

Source: ASHRAE Handbook Fundamentals, Chapter 27



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

Source: ASHRAE Handbook Fundamentals, Chapter 27

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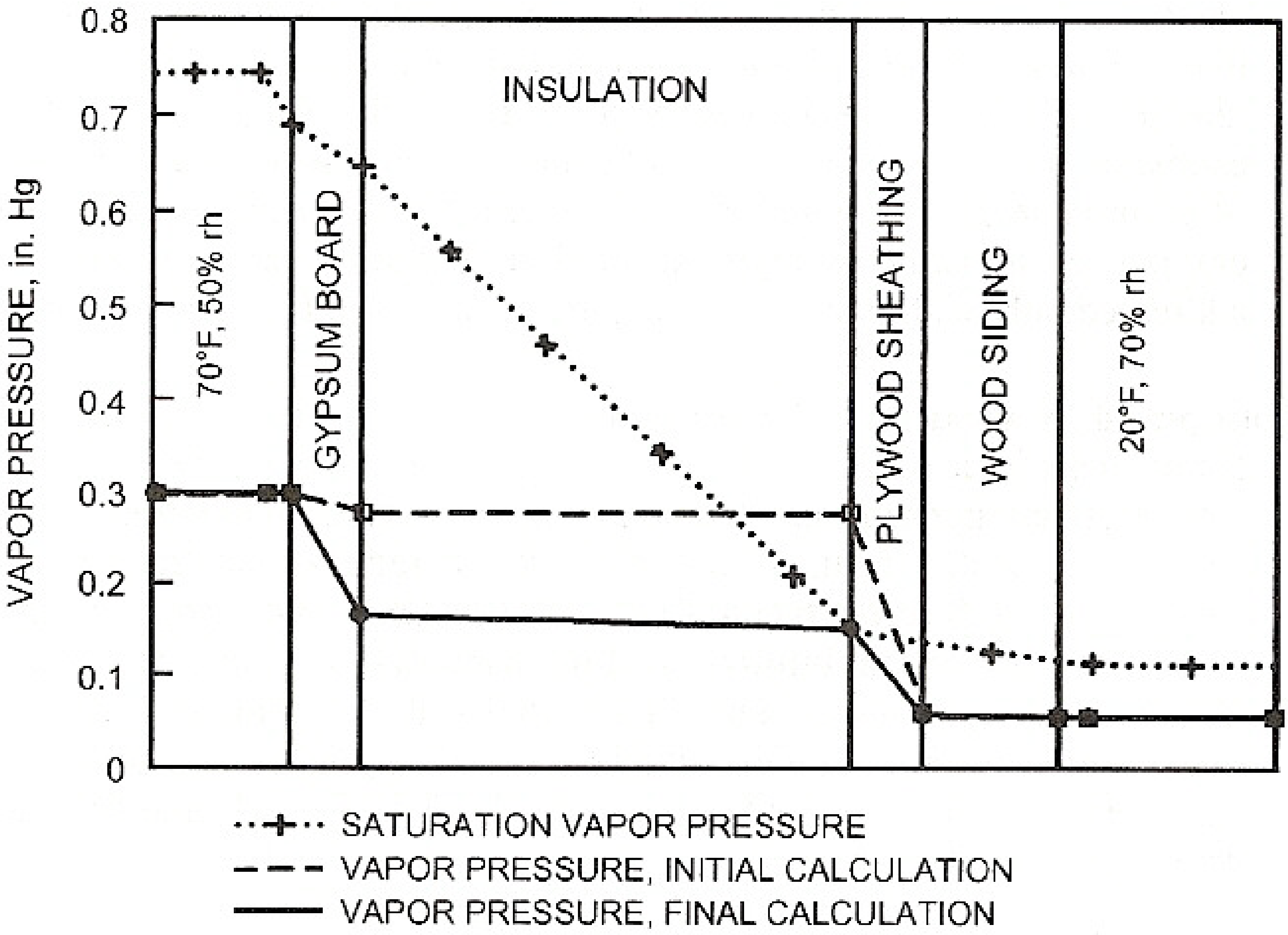
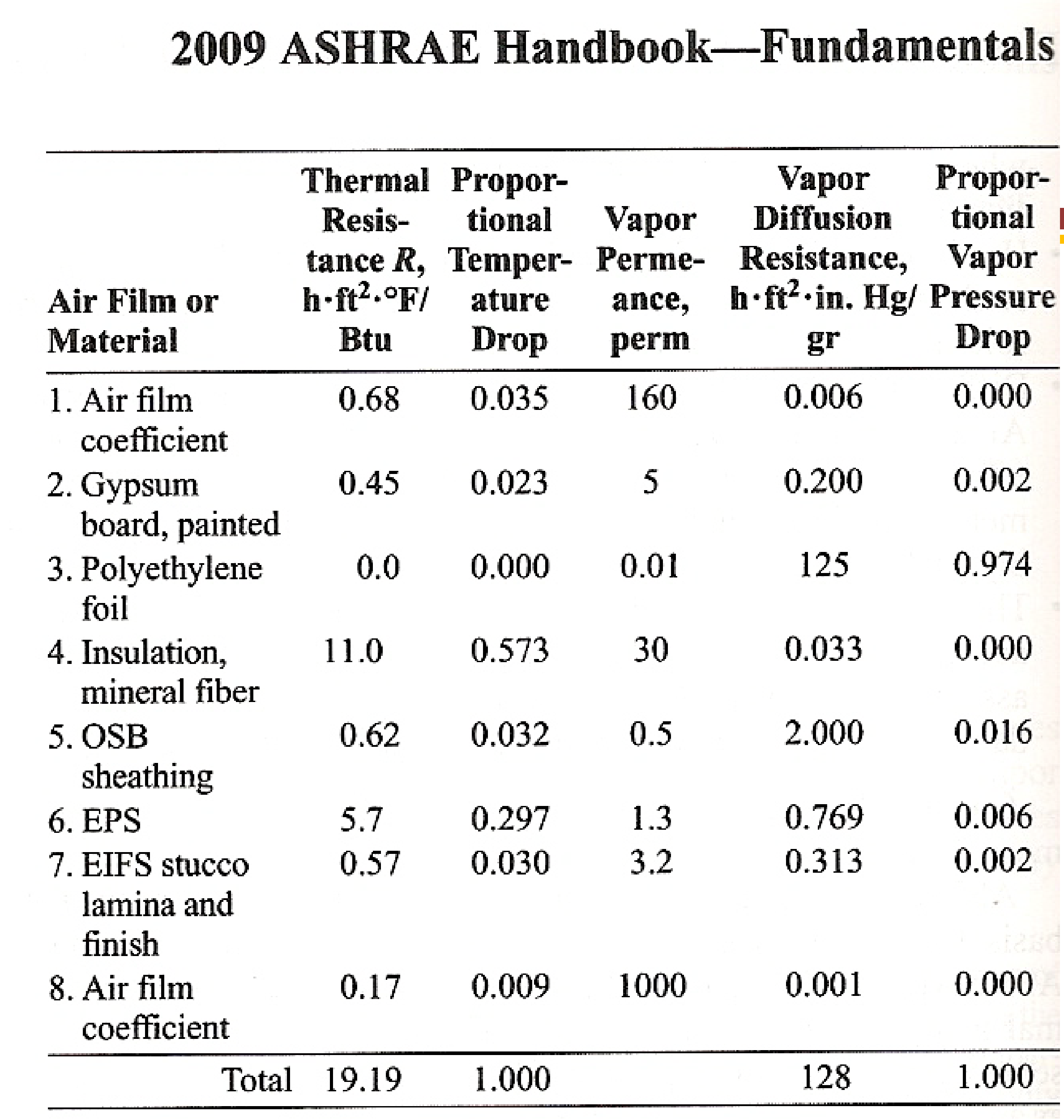


Fig. 12 Dew-Point Calculation in Wood-Framed Wall (Example 9)

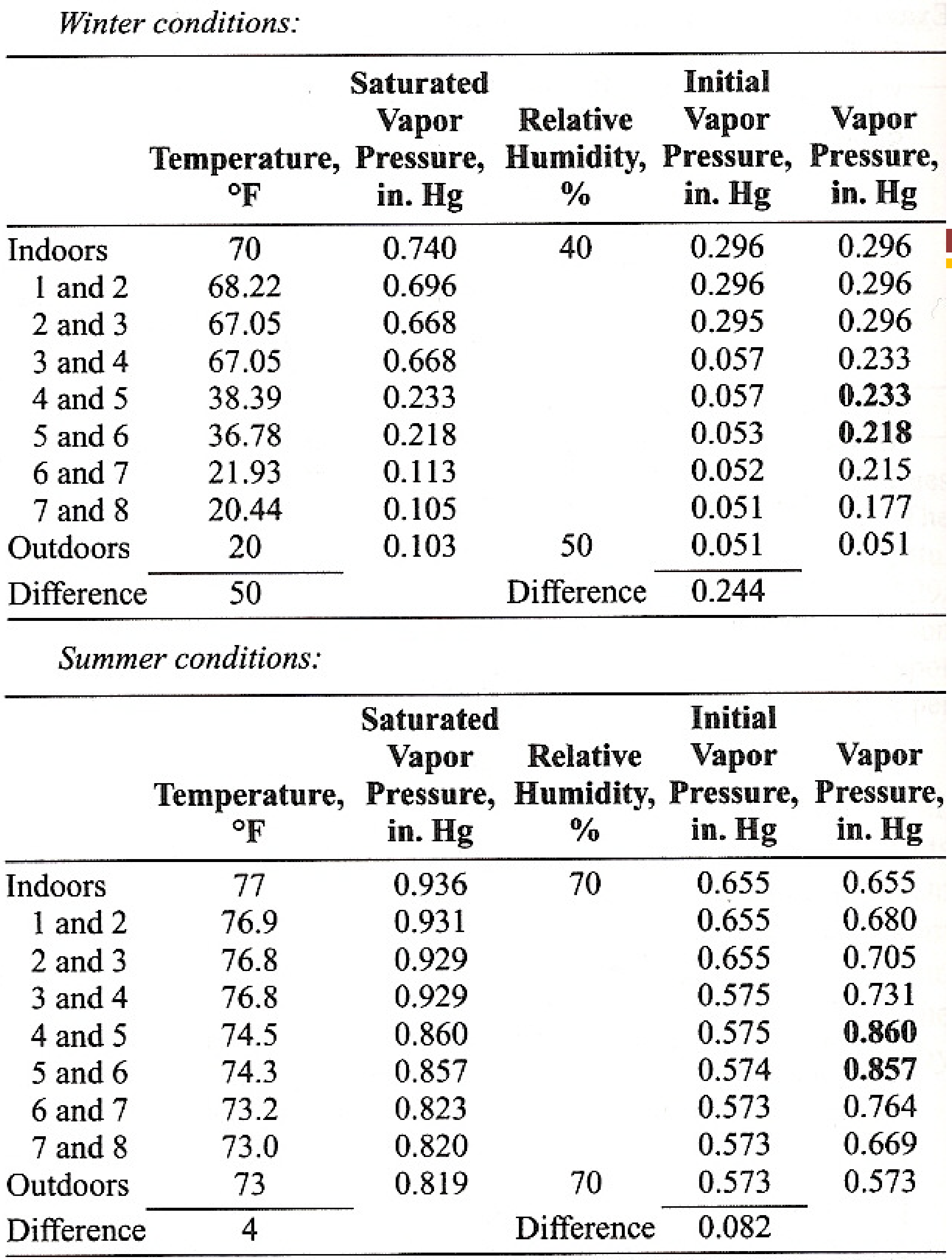
Source: ASHRAE Handbook Fundamentals, Chapter 27



2009 ASHRAE Handbook—Fundamentals

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

Source: ASHRAE Handbook Fundamentals 2009, Chapter 27



Winter conditions:

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

Summer conditions:

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

Source: ASHRAE Handbook Fundamentals, Chapter 27

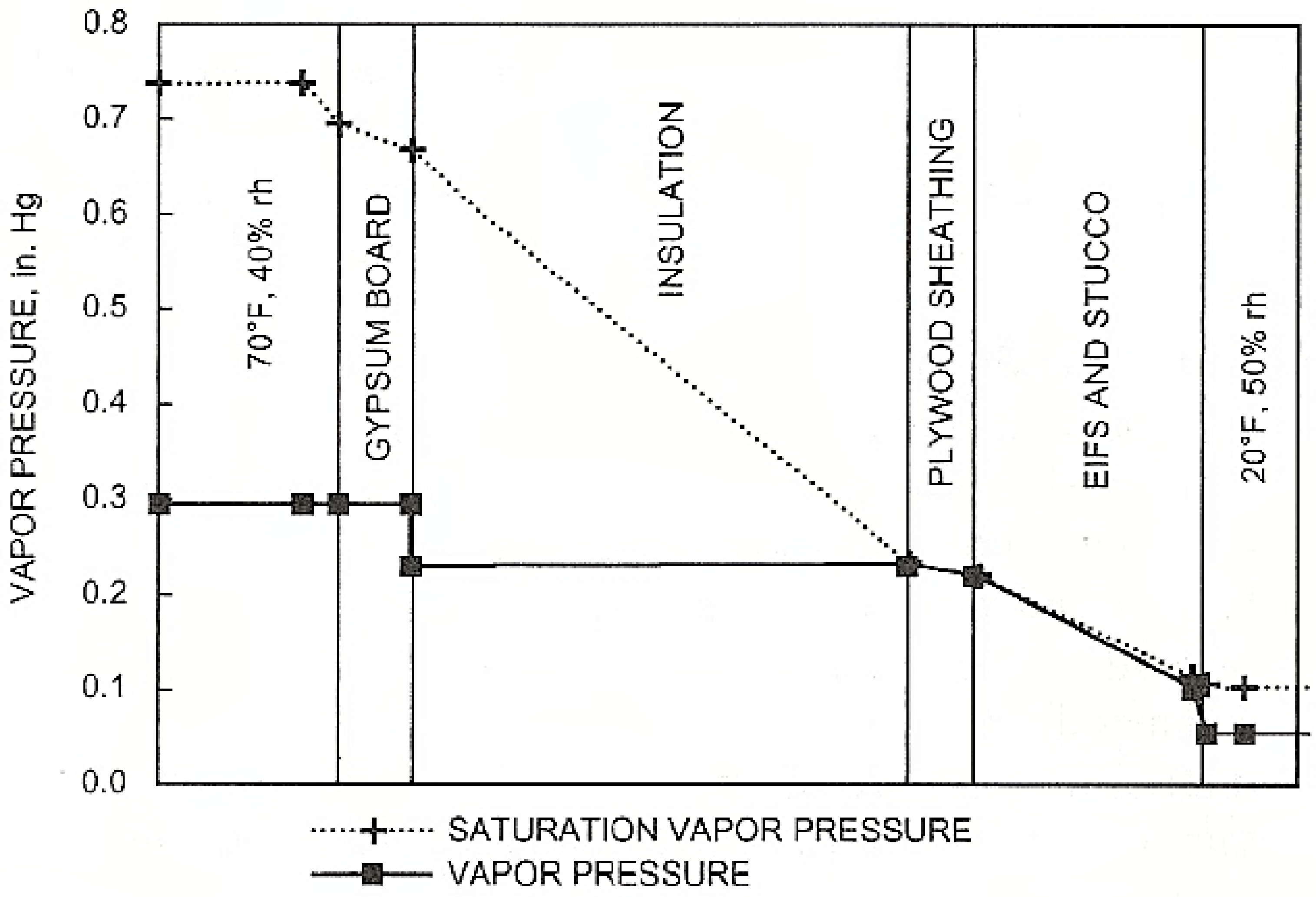


Fig. 13 **Drying Wet Sheathing, Winter (Example 10)**

Source: ASHRAE Handbook Fundamentals, Chapter 27.11

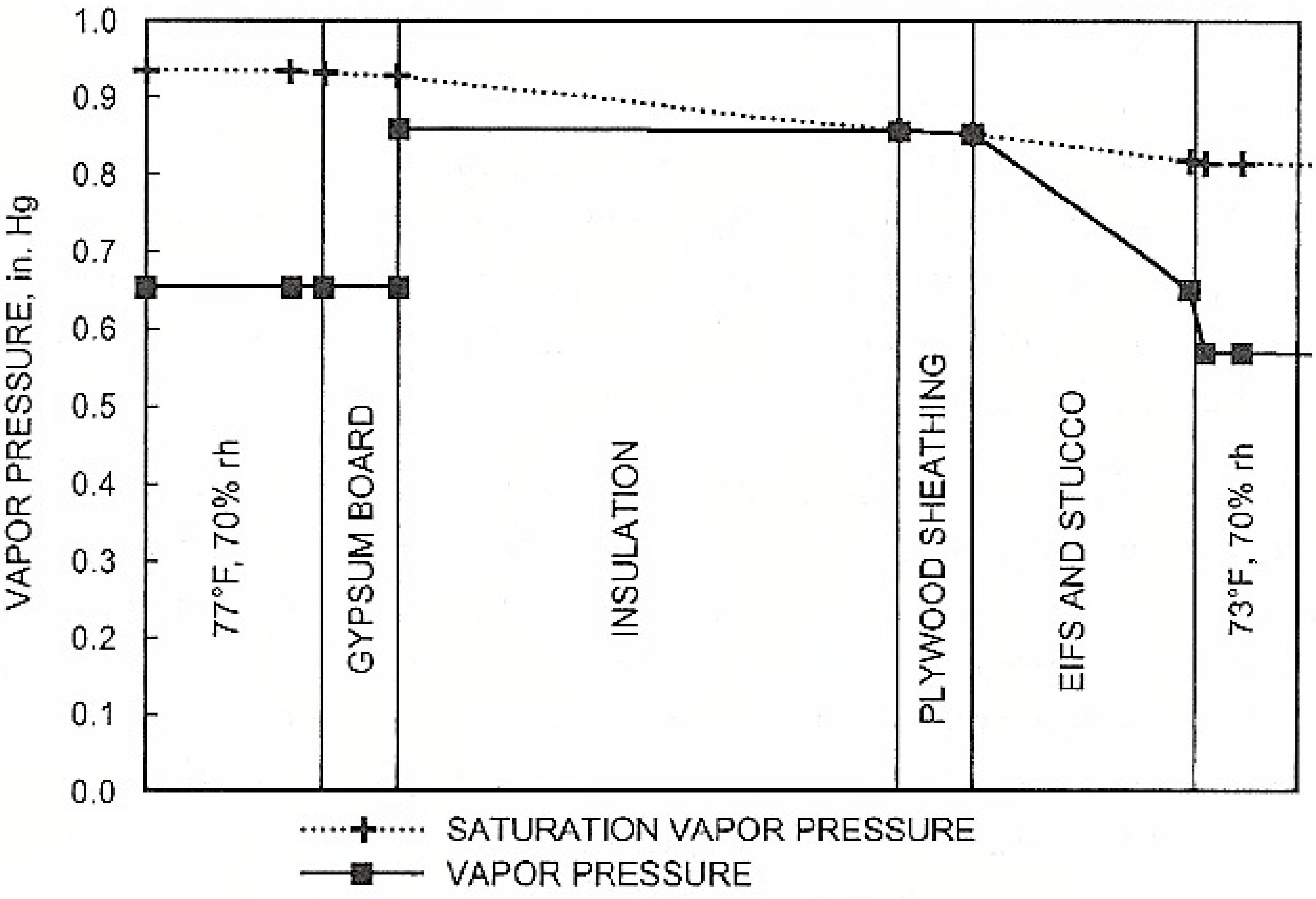


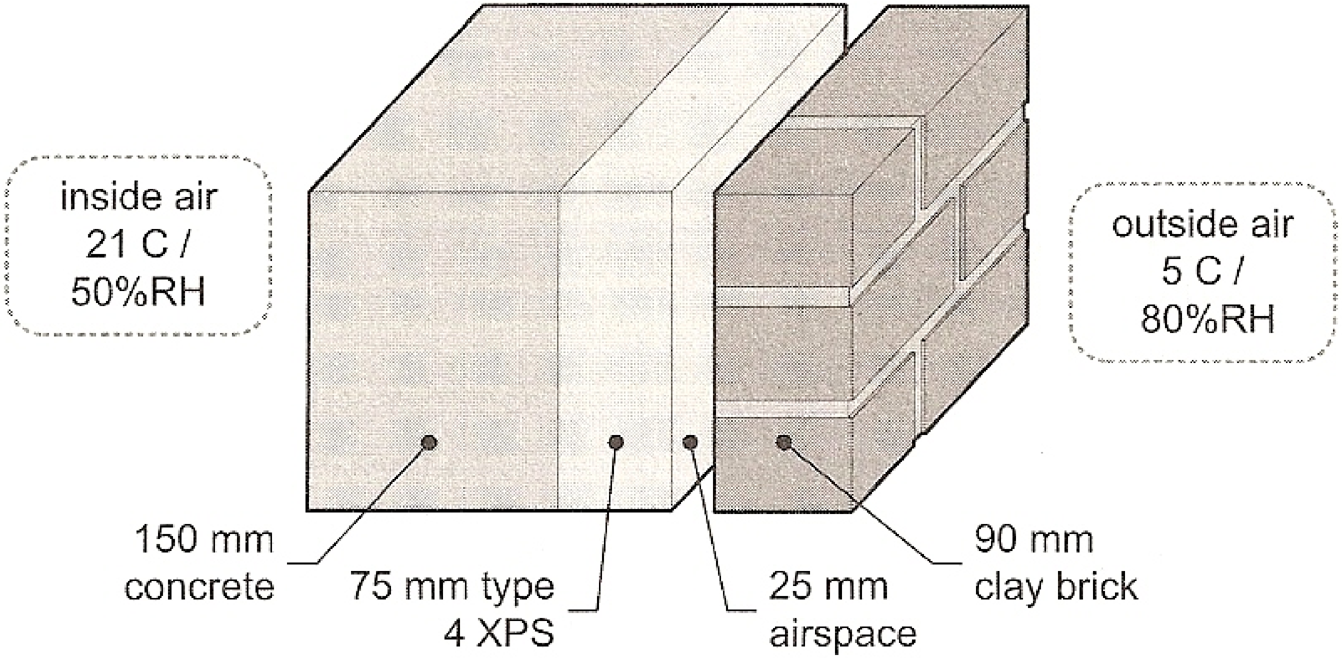
Fig. 14 Drying Wet Sheathing, Summer (Example 10)

Source: ASHRAE Handbook Fundamentals, Chapter 27.11

Example 2 - BSBE

6.5.1 Vapor pressure distribution

Example



Source: Straube & Burnett, Building Science for Building Enclosures, Chapter 6

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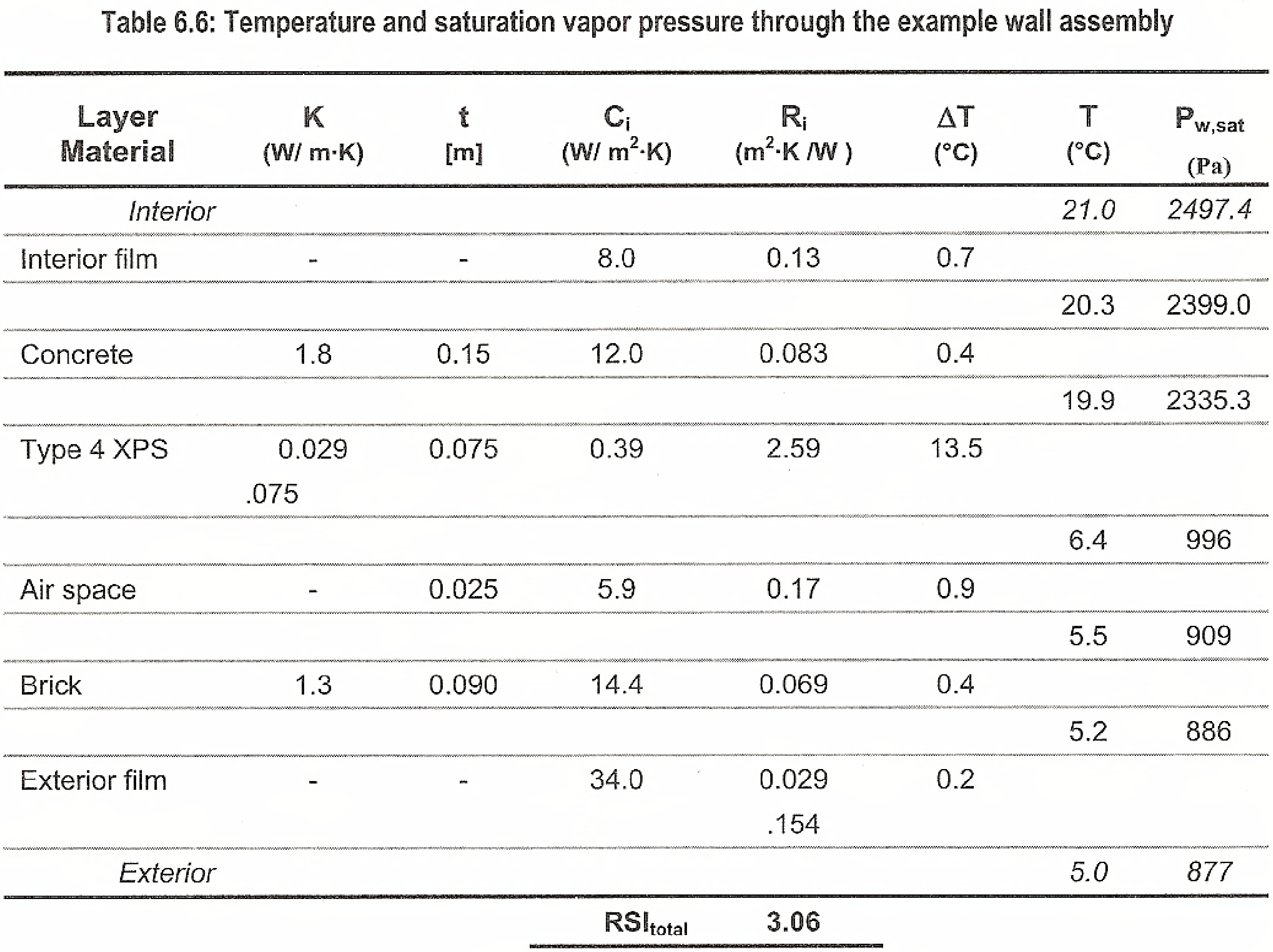

Table 6.6: Temperature and saturation vapor pressure through the example wall assembly

Layer Material	K (W/ m·K)	t [m]	C_i (W/ m^2·K)	R_i (m^2·K /W)	ΔT (°C)	T (°C)	$P_{w,sat}$ (Pa)
Interior						*21.0*	*2497.4*
Interior film	-	-	8.0	0.13	0.7		
						20.3	2399.0
Concrete	1.8	0.15	12.0	0.083	0.4		
						19.9	2335.3
Type 4 XPS	0.029 .075	0.075	0.39	2.59	13.5		
						6.4	996
Air space	-	0.025	5.9	0.17	0.9		
						5.5	909
Brick	1.3	0.090	14.4	0.069	0.4		
						5.2	886
Exterior film	-	-	34.0	0.029 .154	0.2		
Exterior						*5.0*	*877*
			RSI_{total}	3.06			

Source: Straube & Burnett, Building Science for Building Enclosures, Chapter 6

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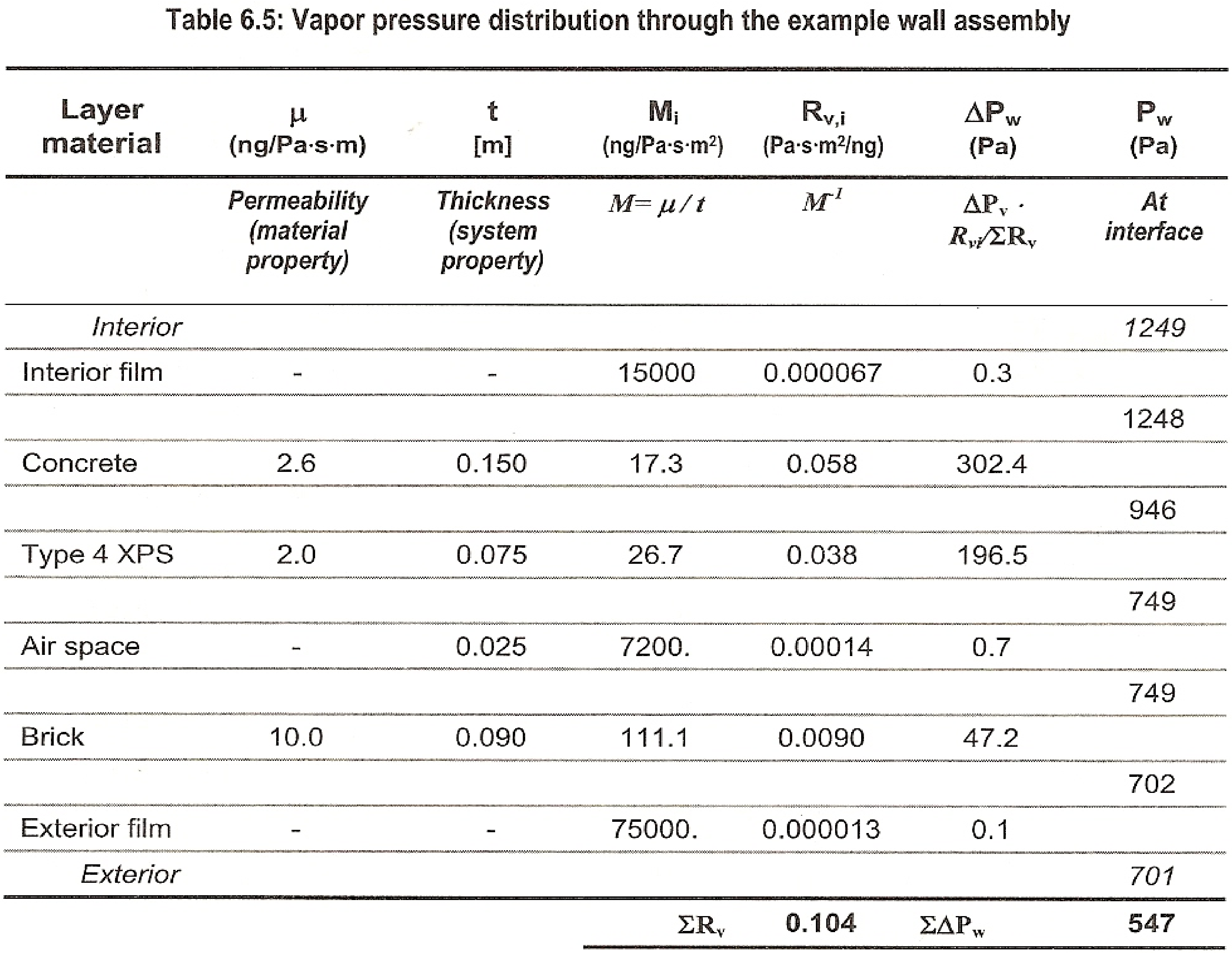
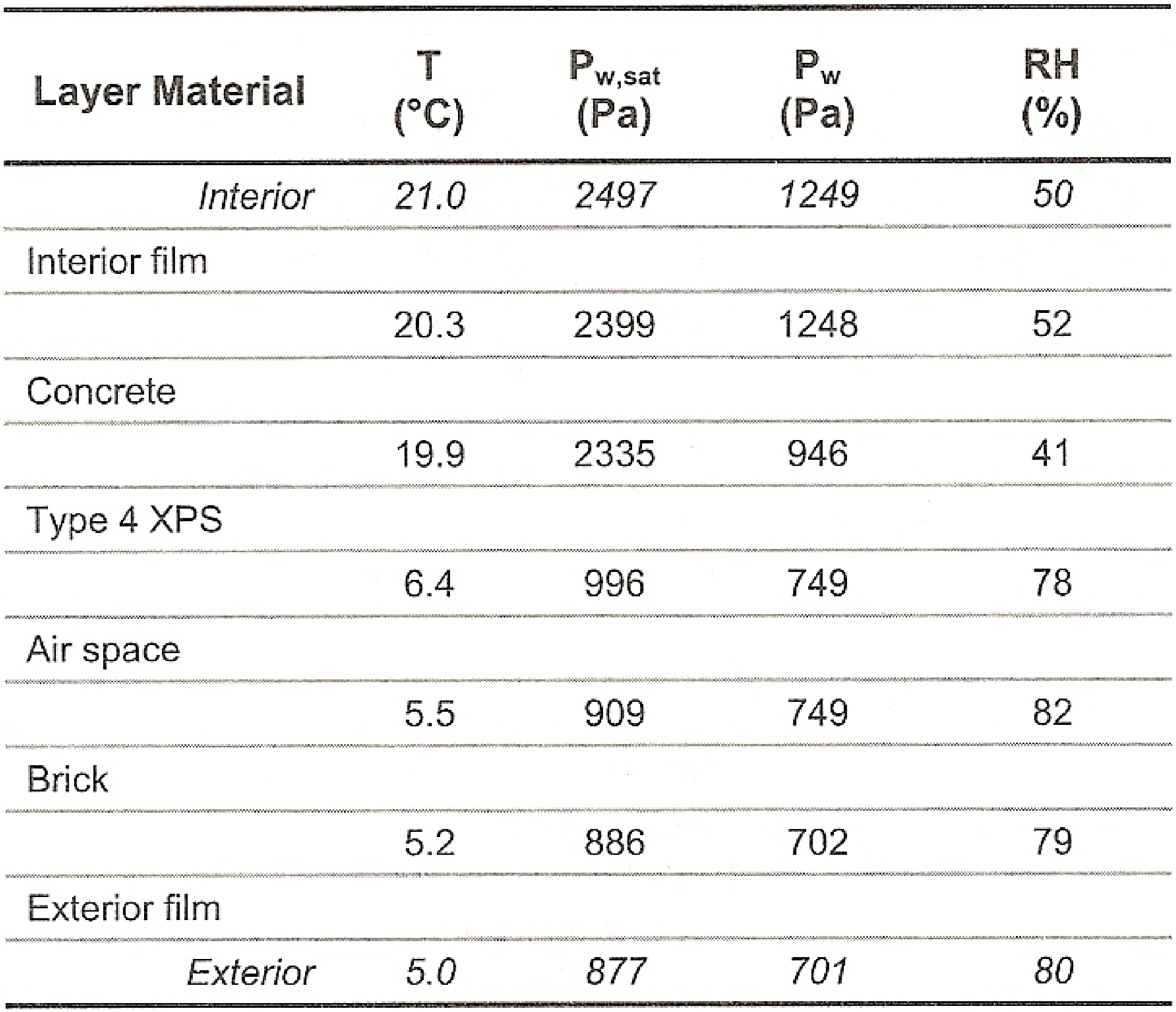


Table 6.5: Vapor pressure distribution through the example wall assembly

Layer material	μ (ng/Pa·s·m)	t [m]	M_i (ng/Pa·s·m^2)	$R_{v,i}$ (Pa·s·m^2/ng)	ΔP_w (Pa)	P_w (Pa)
	Permeability (material property)	*Thickness (system property)*	$M = \mu / t$	M^{-1}	$\Delta P_v \cdot R_{vi}/\Sigma R_v$	*At interface*
Interior						*1249*
Interior film	-	-	15000	0.000067	0.3	
						1248
Concrete	2.6	0.150	17.3	0.058	302.4	
						946
Type 4 XPS	2.0	0.075	26.7	0.038	196.5	
						749
Air space	-	0.025	7200.	0.00014	0.7	
						749
Brick	10.0	0.090	111.1	0.0090	47.2	
						702
Exterior film	-	-	75000.	0.000013	0.1	
Exterior						*701*
			ΣR_v	**0.104**	$\Sigma \Delta P_w$	**547**

Source: Straube & Burnett, Building Science for Building Enclosures, Chapter 6

Table 6.7: Temperature, saturation vapor pressure, vapor pressure, and RH



Layer Material	T (°C)	$P_{w,sat}$ (Pa)	P_w (Pa)	RH (%)
Interior	*21.0*	*2497*	*1249*	*50*
Interior film				
	20.3	2399	1248	52
Concrete				
	19.9	2335	946	41
Type 4 XPS				
	6.4	996	749	78
Air space				
	5.5	909	749	82
Brick				
	5.2	886	702	79
Exterior film				
Exterior	*5.0*	*877*	*701*	*80*

Source: Straube & Burnett, Building Science for Building Enclosures, Chapter 6

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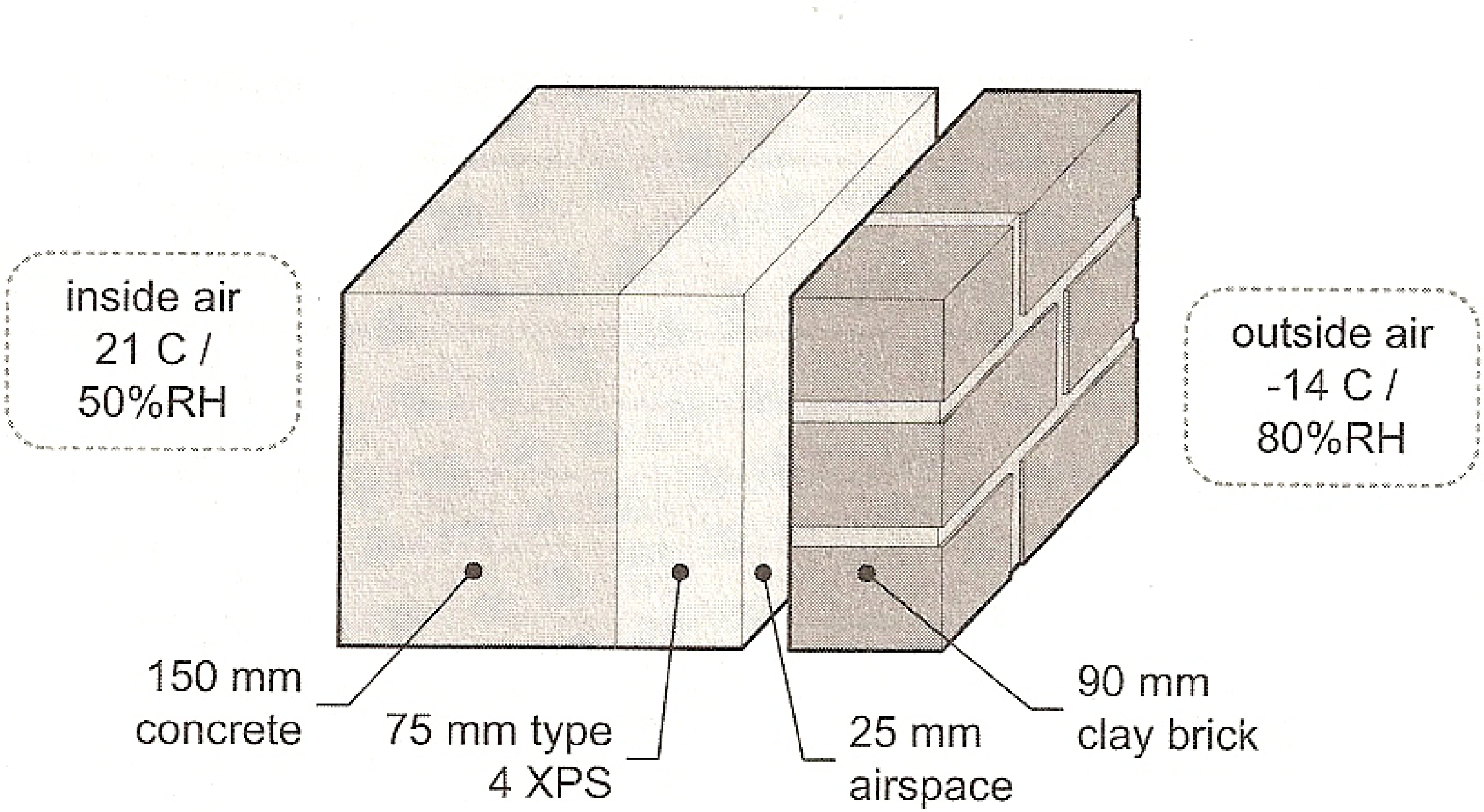
Example 3 - BSBE



Source: Straube & Burnett, Building Science for Building Enclosures, Chapter 6

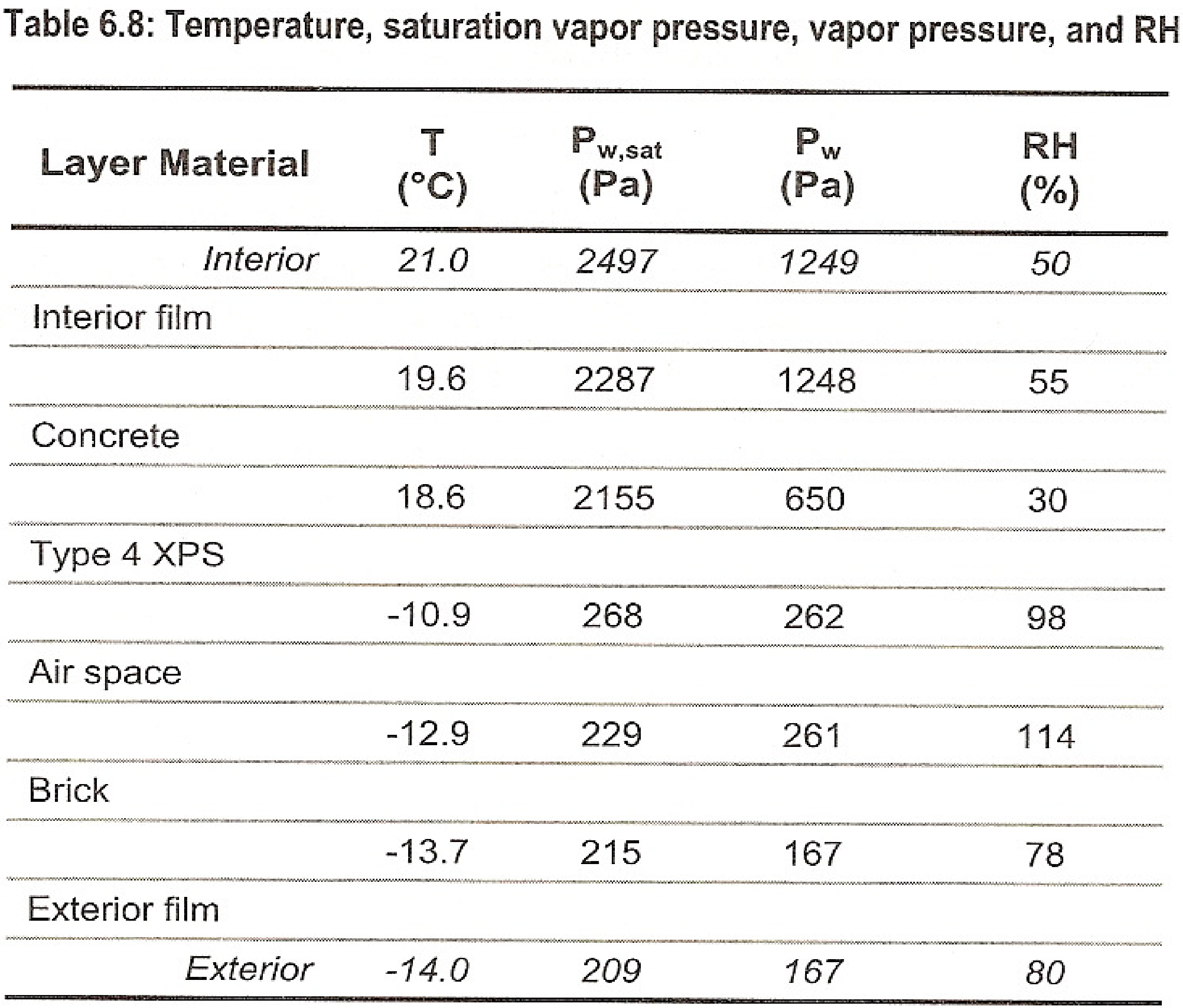


Table 6.8: Temperature, saturation vapor pressure, vapor pressure, and RH

Layer Material	T (°C)	$P_{w,sat}$ (Pa)	P_w (Pa)	RH (%)
Interior	*21.0*	*2497*	*1249*	*50*
Interior film				
	19.6	2287	1248	55
Concrete				
	18.6	2155	650	30
Type 4 XPS				
	-10.9	268	262	98
Air space				
	-12.9	229	261	114
Brick				
	-13.7	215	167	78
Exterior film				
Exterior	*-14.0*	*209*	*167*	*80*

Source: Straube & Burnett, Building Science for Building Enclosures, Chapter 6

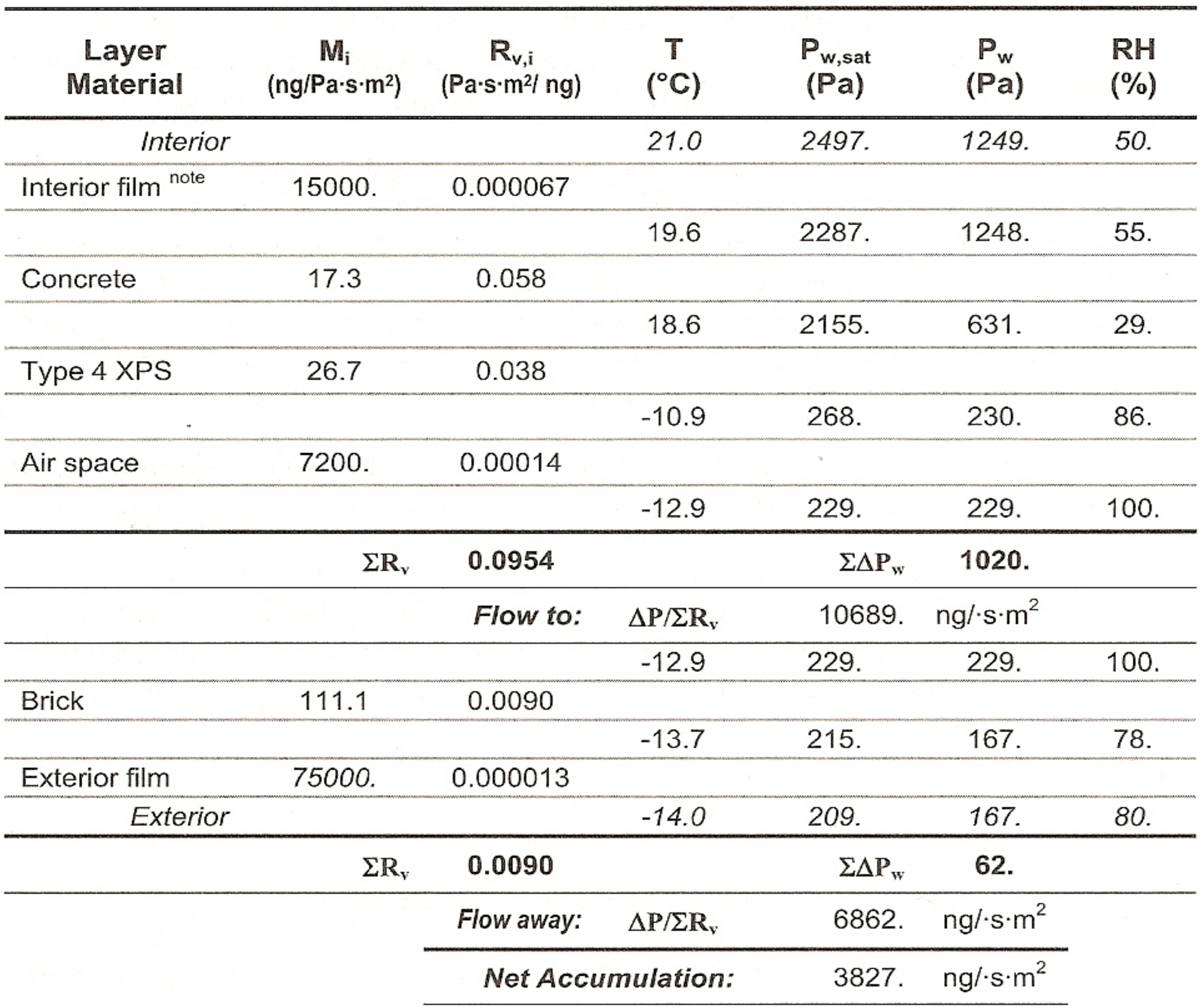


Table 6.9: Corrected vapor pressure distribution for a wall with condensation

Layer Material	M_i (ng/Pa·s·m²)	$R_{v,i}$ (Pa·s·m²/ ng)	T (°C)	$P_{w,sat}$ (Pa)	P_w (Pa)	RH (%)
Interior			*21.0*	*2497.*	*1249.*	*50.*
Interior film note	15000.	0.000067				
			19.6	2287.	1248.	55.
Concrete	17.3	0.058				
			18.6	2155.	631.	29.
Type 4 XPS	26.7	0.038				
			-10.9	268.	230.	86.
Air space	7200.	0.00014				
			-12.9	229.	229.	100.
	ΣR_v	**0.0954**		$\Sigma \Delta P_w$	**1020.**	
		Flow to:	$\Delta P/\Sigma R_v$	10689.	ng/·s·m^2	
			-12.9	229.	229.	100.
Brick	111.1	0.0090				
			-13.7	215.	167.	78.
Exterior film	*75000.*	0.000013				
Exterior			*-14.0*	*209.*	*167.*	*80.*
	ΣR_v	**0.0090**		$\Sigma \Delta P_w$	**62.**	
		Flow away:	$\Delta P/\Sigma R_v$	6862.	ng/·s·m^2	
		Net Accumulation:		3827.	ng/·s·m^2	

Source: Straube & Burnett, Building Science for Building Enclosures, Chapter 6

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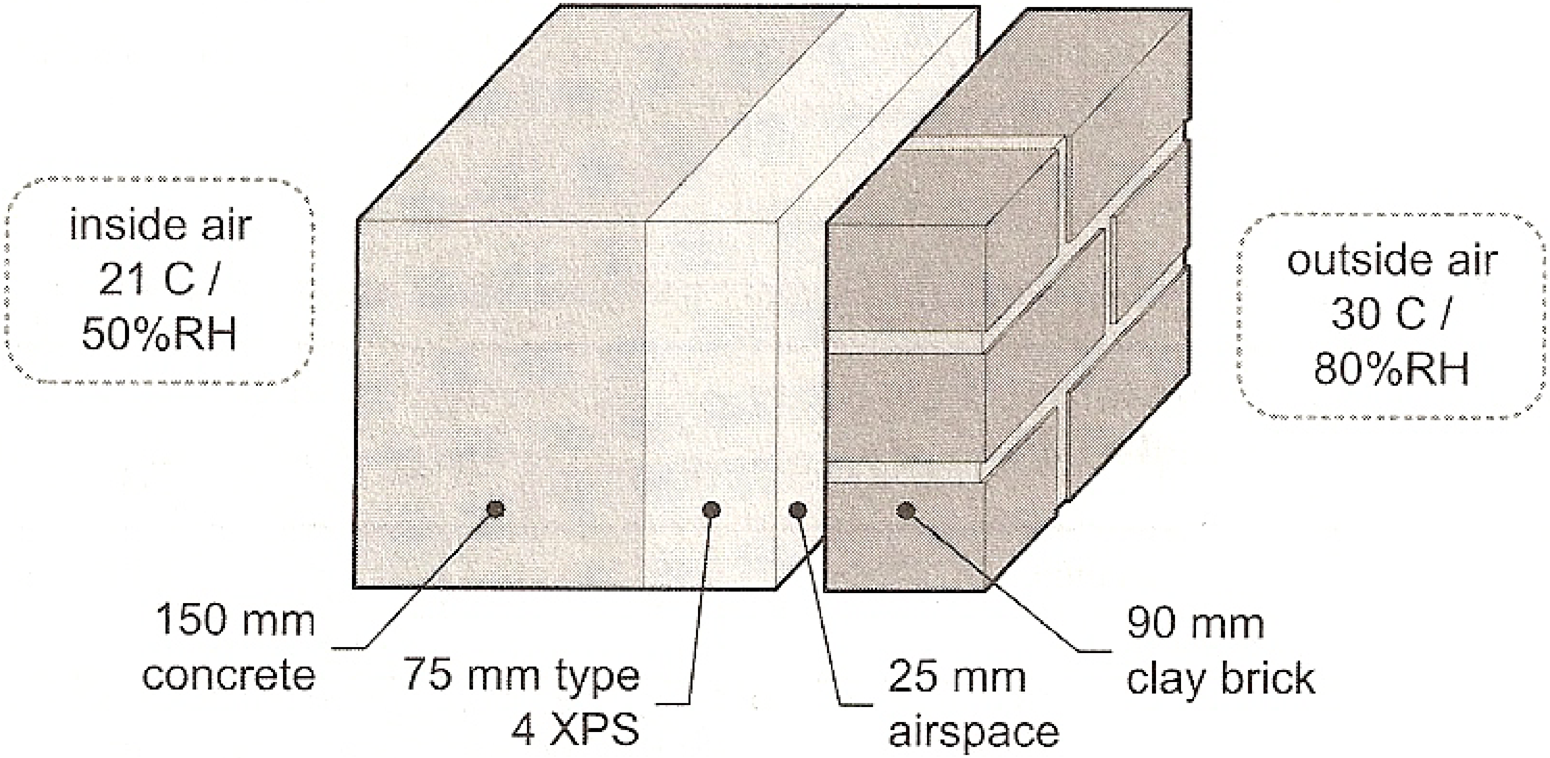
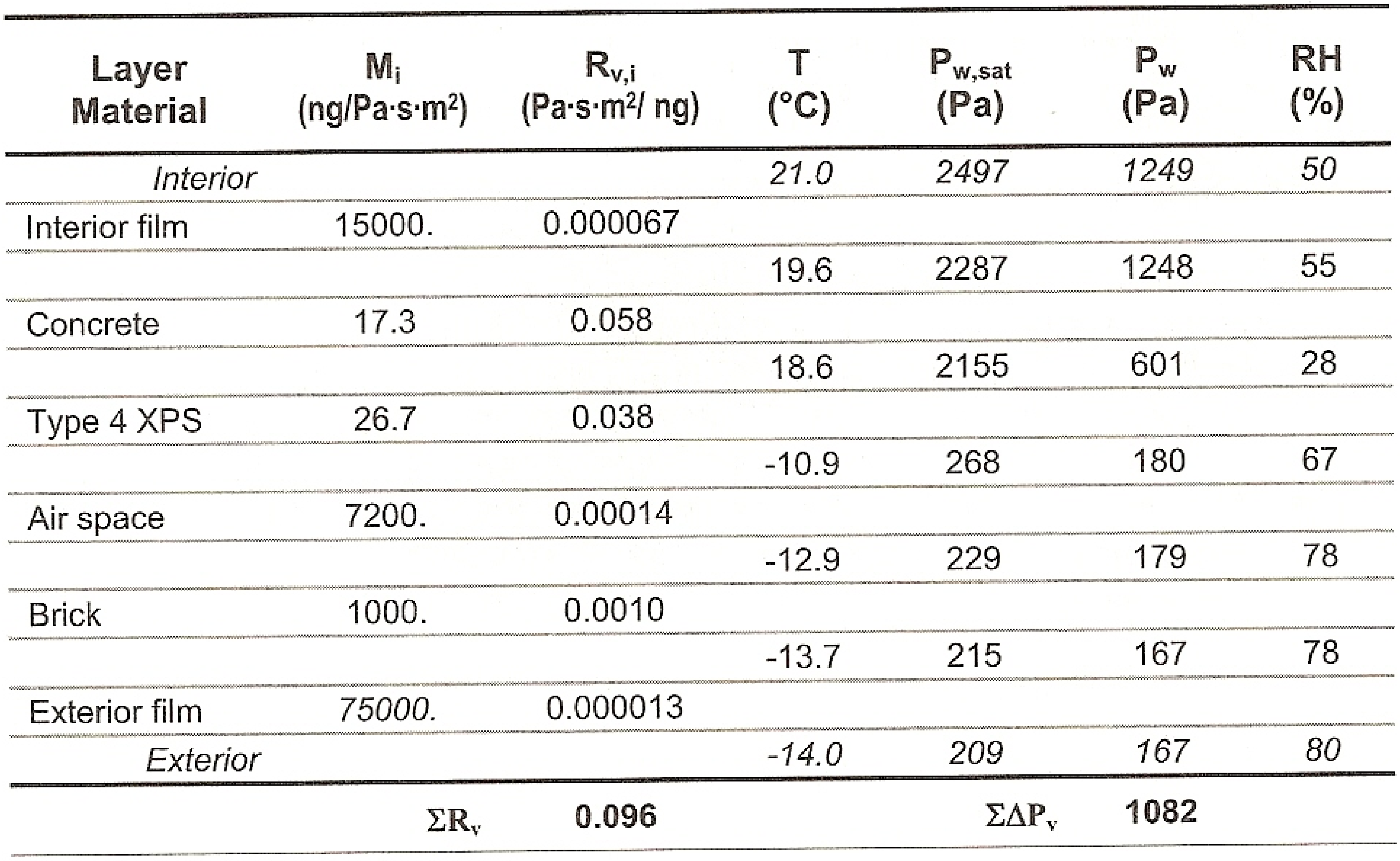


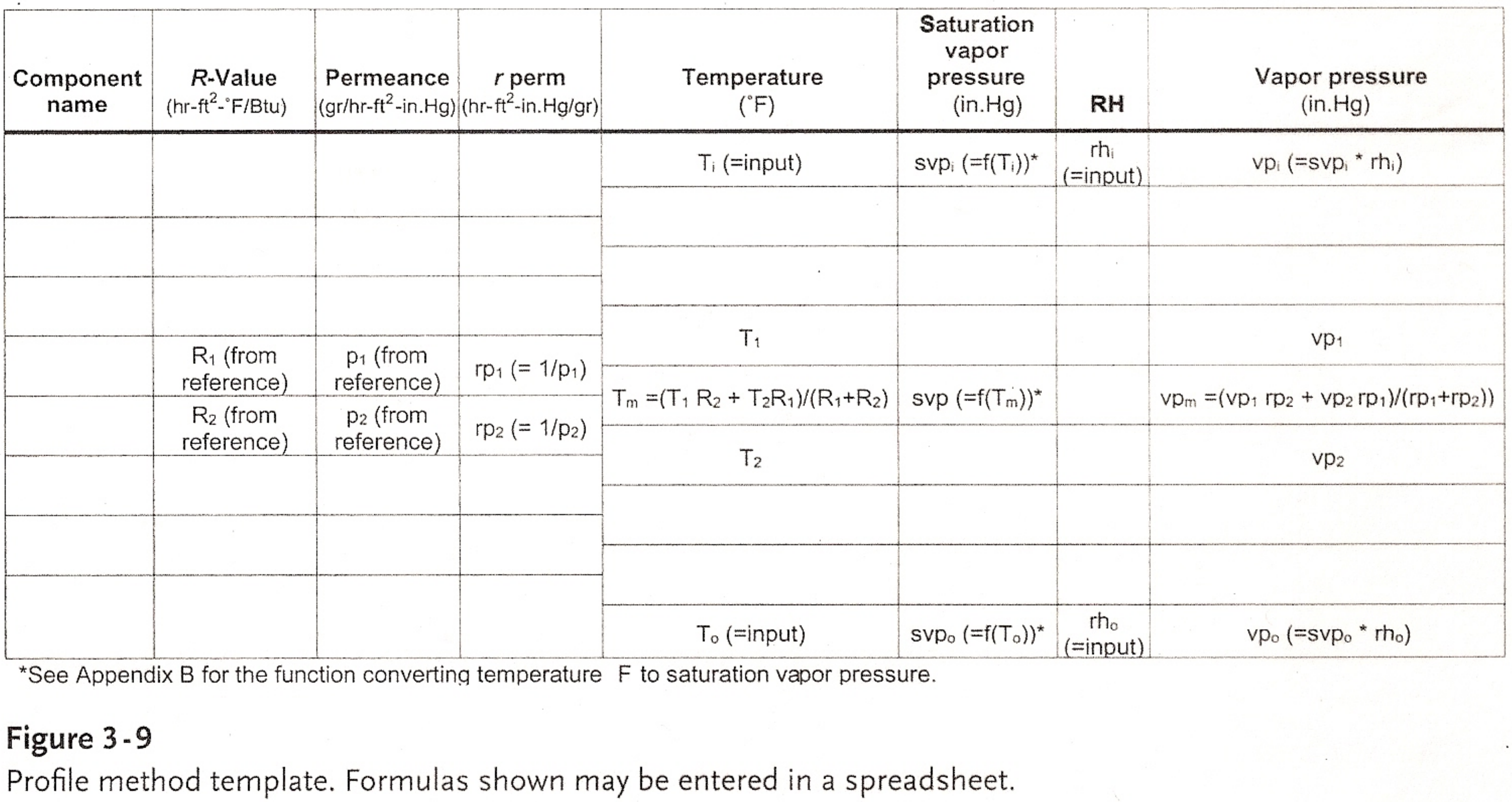
Source: Straube & Burnett, Building Science for Building Enclosures, Chapter 6

Table 6.10: Well-ventilated brick veneer



Layer Material	M_i (ng/Pa·s·m^2)	$R_{v,i}$ (Pa·s·m^2/ ng)	T (°C)	$P_{w,sat}$ (Pa)	P_w (Pa)	RH (%)
Interior			*21.0*	*2497*	*1249*	*50*
Interior film	15000.	0.000067				
			19.6	2287	1248	55
Concrete	17.3	0.058				
			18.6	2155	601	28
Type 4 XPS	26.7	0.038				
			-10.9	268	180	67
Air space	7200.	0.00014				
			-12.9	229	179	78
Brick	1000.	0.0010				
			-13.7	215	167	78
Exterior film	*75000.*	0.000013				
Exterior			*-14.0*	*209*	*167*	*80*
	ΣR_v	**0.096**		$\Sigma \Delta P_v$	**1082**	

Source: Straube & Burnett, Building Science for Building Enclosures, Chapter 6



Component name	*R*-Value (hr-ft^2-°F/Btu)	Permeance (gr/hr-ft^2-in.Hg)	*r* perm (hr-ft^2-in.Hg/gr)	Temperature (°F)	Saturation vapor pressure (in.Hg)	**RH**	Vapor pressure (in.Hg)
				T_i (=input)	svp_i (=f(T_i))*	rh_i (=input)	vp_i (=svp_i * rh_i)
				T_1			vp_1
	R_1 (from reference)	p_1 (from reference)	rp_1 (= $1/p_1$)				
				T_m =(T_1 R_2 + $T_2 R_1$)/(R_1+R_2)	svp (=f(T_m))*		vp_m =(vp_1 rp_2 + vp_2 rp_1)/(rp_1+rp_2))
	R_2 (from reference)	p_2 (from reference)	rp_2 (= $1/p_2$)				
				T_2			vp_2
				T_o (=input)	svp_o (=f(T_o))*	rh_o (=input)	vp_o (=svp_o * rh_o)

*See Appendix B for the function converting temperature F to saturation vapor pressure.

Figure 3-9

Profile method template. Formulas shown may be entered in a spreadsheet.

Source: Rose, Water in Buildings, Chapter 3

Moisture Control in Insulated Buildings

Mathematical Models

- Focus on transient models
  - transient physics
  - one or two dimensional
  - detailed material properties
  - hourly boundary conditions
  - surface conditions
  - building systems and subsystem effects

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In Summary

Questions and Discussion

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Next Class

- Moisture Control in Insulated Assemblies
  - Drying of assemblies
  - Rainwater deposition & control
  - Wall categorization

- Readings
  - HPE: Chapter 3.1

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