CAE 463/524
Building Enclosure Design
Spring 2014

Lecture 5: February 18, 2014
Finish complex conduction in building enclosures
Moisture flows

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Last time

- Complex conduction in enclosures
  - Parallel path
  - Isothermal
  - Thermal bridges: applications
  - THERM modeling
    - HW 2 assigned, due today

Today's objectives

- Finish complex conduction
  - Slab and below-grade wall/floor heat transfer
  - Save thermal mass for later

- Moisture in building enclosures

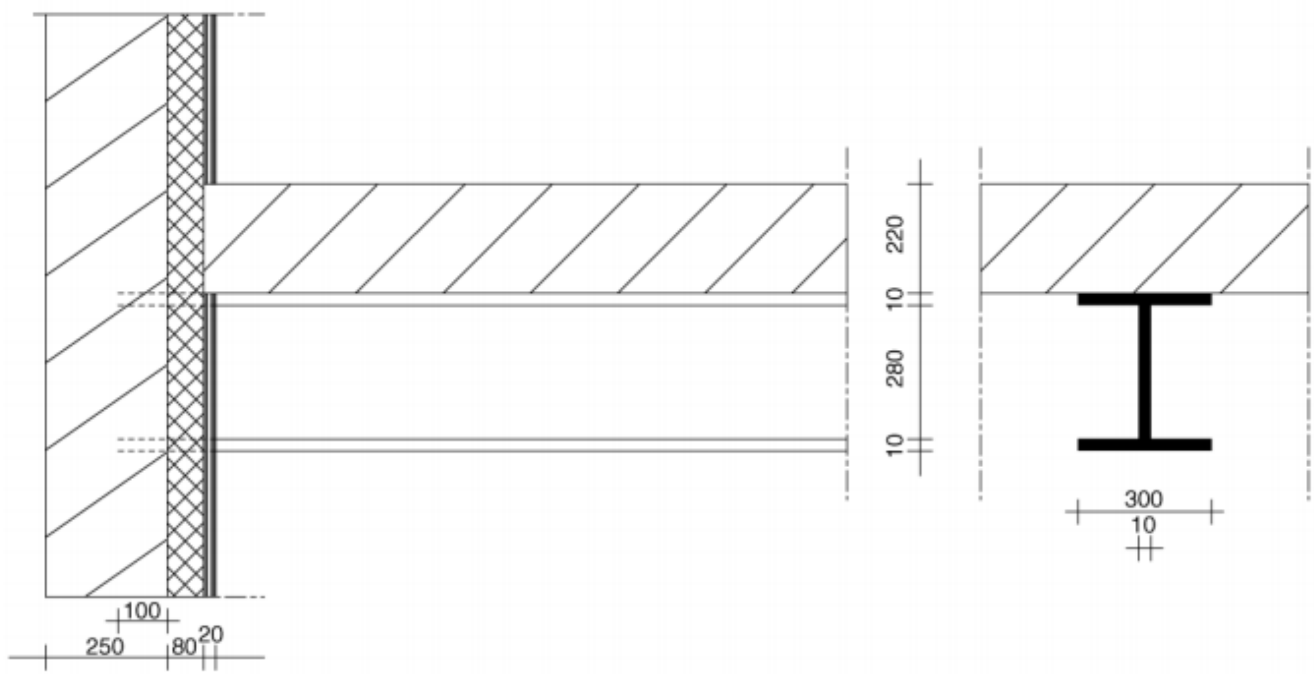
- Return HW 1 graded

COMPLEX CONDUCTION

Finishing up

Thermal analysis of these even more complex geometries

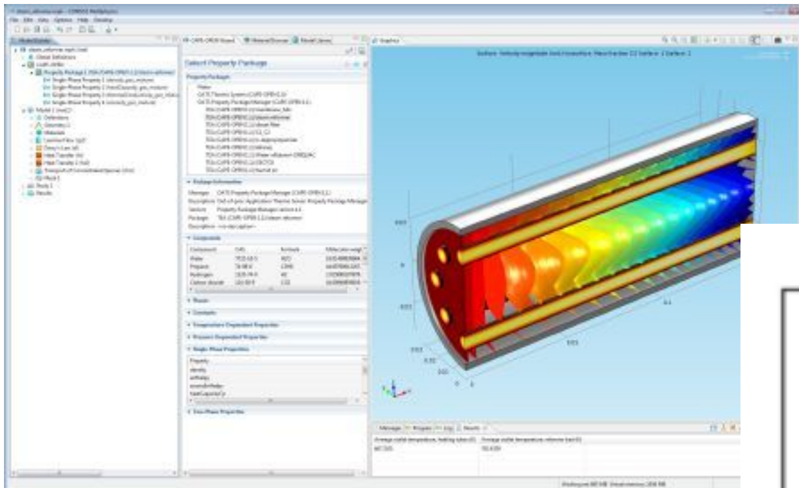
- How do we estimate U and R values for complex geometries and combinations of materials like this one?

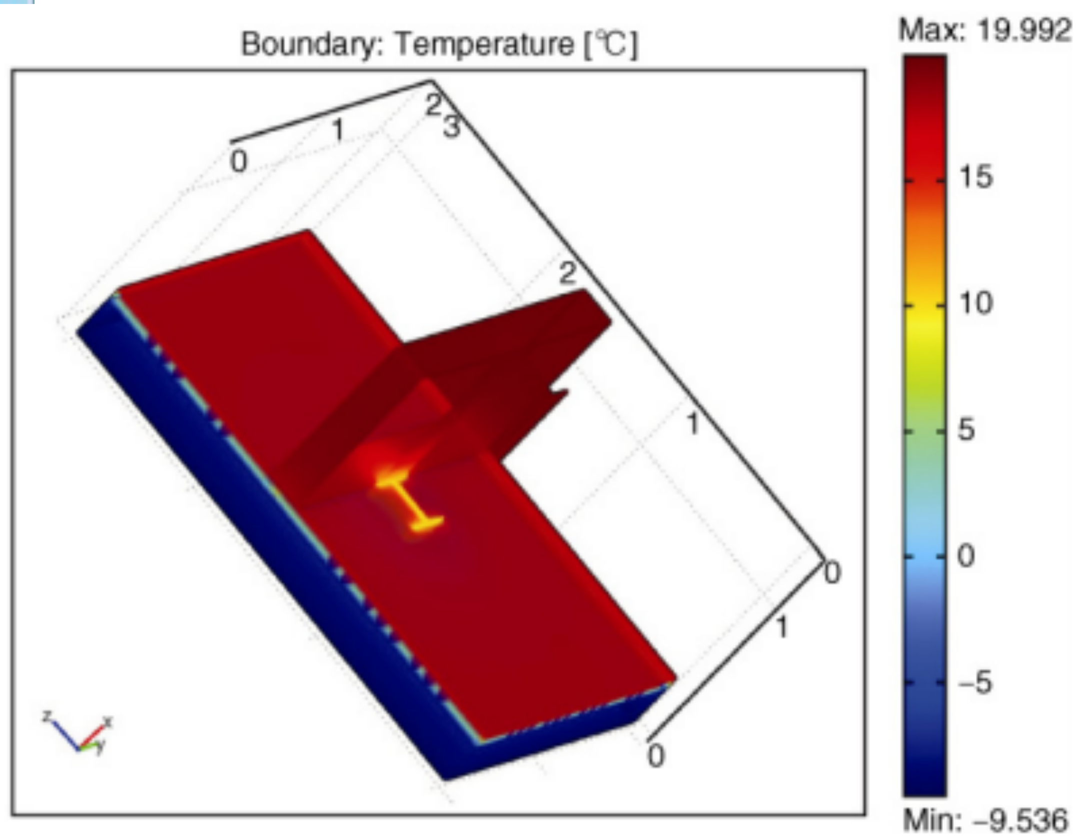


- Simple 1-D calculations can have significant errors
  - Hard (or impossible) to capture all phenomena
- Need to model 2-D or 3-D heat transfer using computer simulations

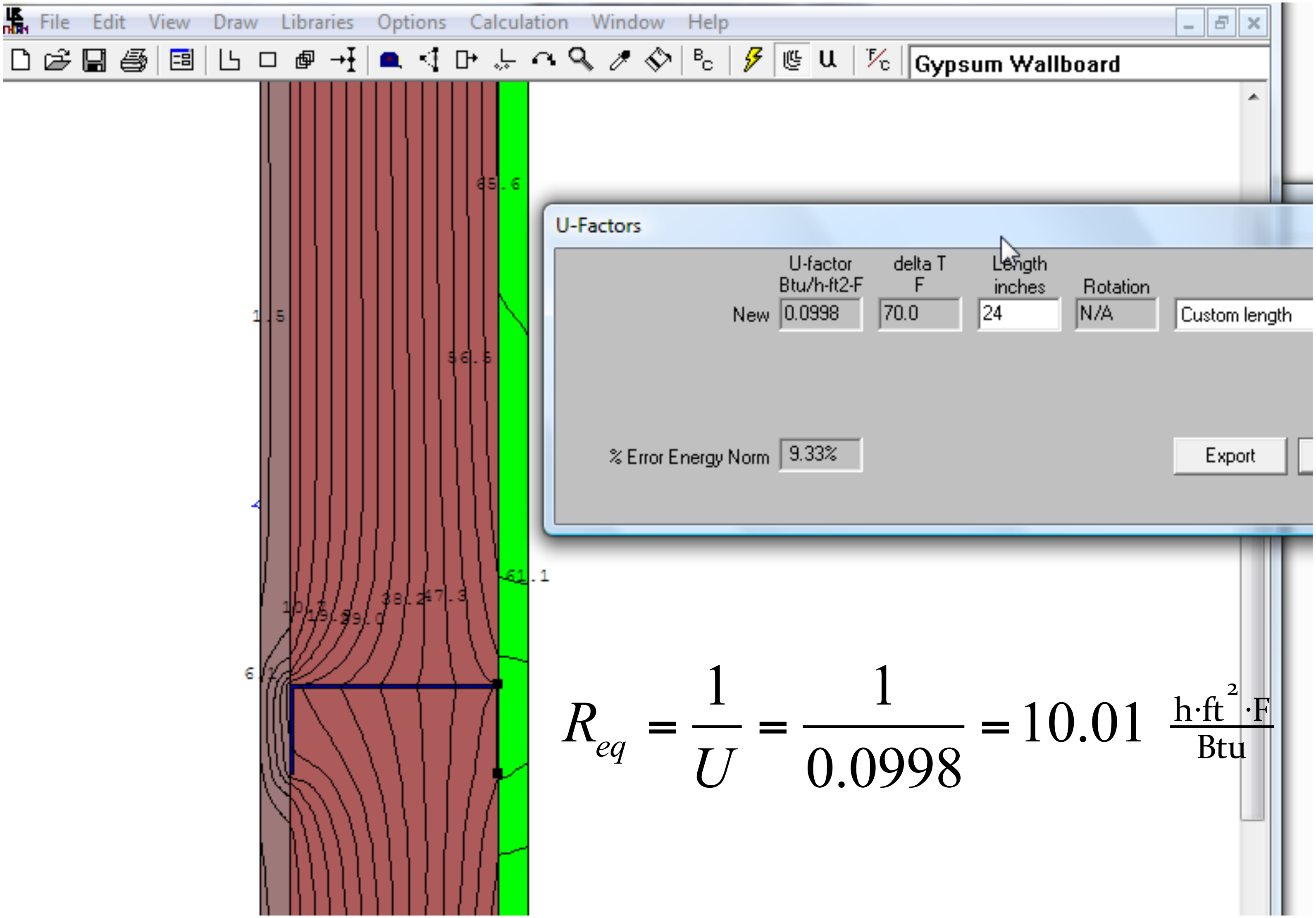
3-D solvers

- COMSOL finite element solver



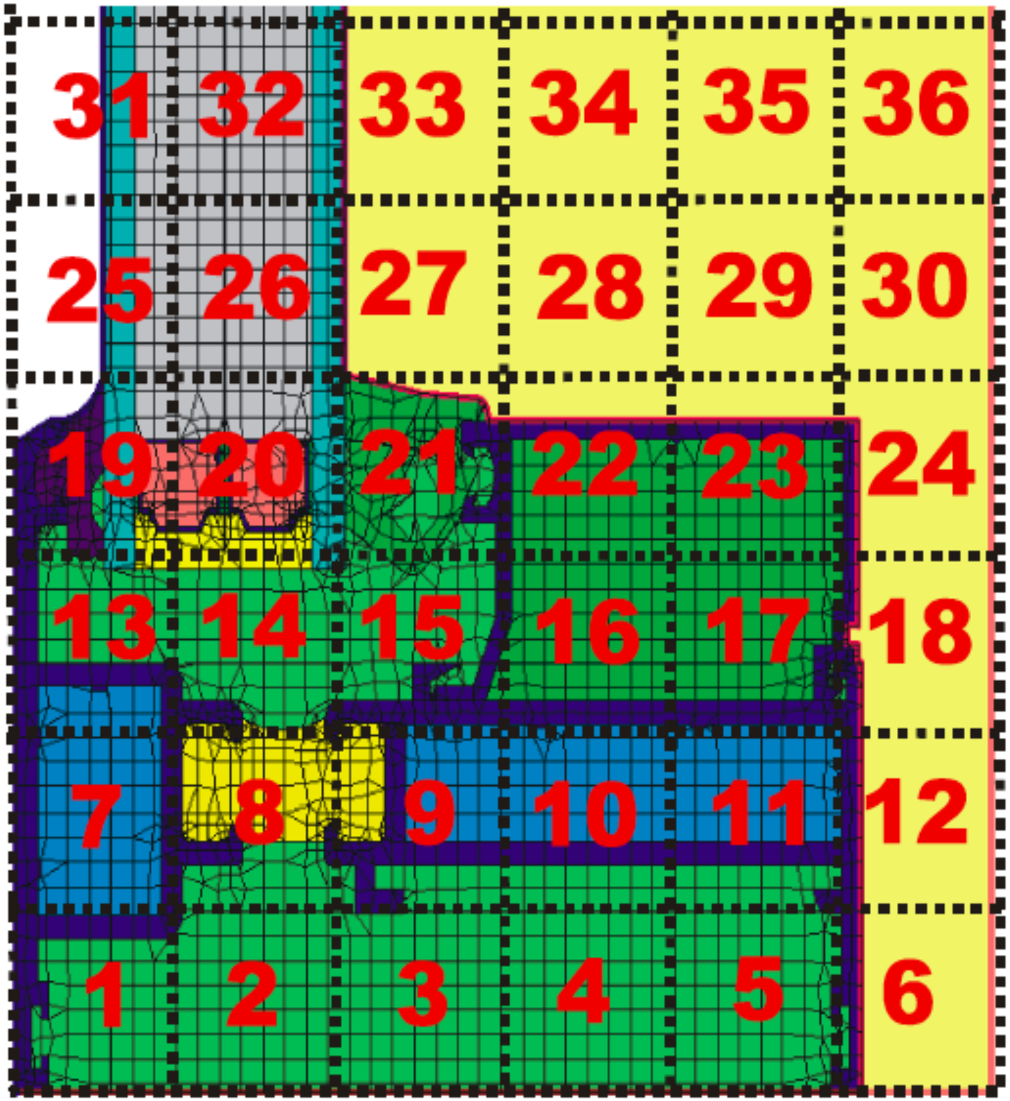


2-D Solver: THERM analysis of steel stud



$$R_{eq} = \frac{1}{U} = \frac{1}{0.0998} = 10.01 \ \frac{\mathrm{h \cdot ft^2 \cdot F}}{\mathrm{Btu}}$$

Grid for numerical solver



Governing equations for THERM

1-D Conduction

$$q_{cond} = -k\frac{dT}{dx} = -\frac{k}{L}dT$$

2-D Conduction

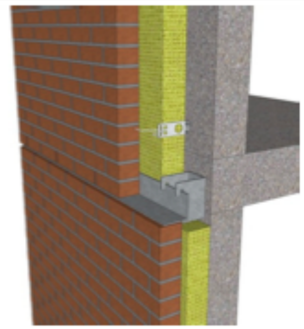
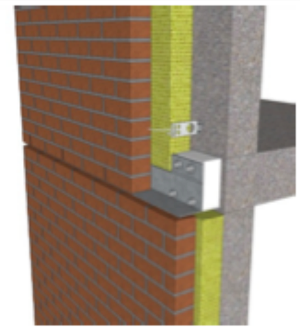
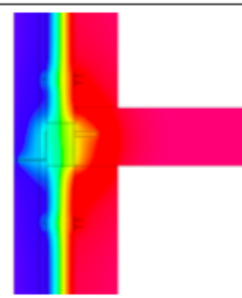
$$q_{cond} = -k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right)$$

- Energy balance at a surface of each discretized element is the same as previously, except the conduction term contains X and Y components

- Set boundary conditions on interior and exterior and the solver will compute temperature throughout assembly
  - Then it can calculate a U-value for the whole assembly

What you can do with THERM

Table 3: Summary of Nominal and Effective R-Values and U-values for Propriety Masonry Shelf Angle Support Options Showing Impact of Thermal Bridging

	Standoff Bracket	4-Bolt Cast-In
		
		
	shelf angle 4"x4"x1/4" outside insulation. Proprietary clip is ¼" thick steel, 4"x4"x1/4" 6 "lg C-section. Non-welded connection. .	Shelf angle 4"x4"x1/4" outside insulation. Pre-manufactured cast-in place thermal break connection with 4 stainless steel bolts attached to 7"x7"x 3/8" plate.
Nominal Insulation R-Value/U-Value	R-16.8 (RSI 2.95) U-0.060 (USI 0.339)	R-16.8 (RSI 2.95) U-0.060 (USI 0.339)
Effective Assembly R-Value/U-Value	R-14.9 (RSI 2.62) U-0.067 (USI 0.381)	R-16.4 (RSI 2.9) U-0.061 (USI 0.345)
Effective Reduction	16.4%	7%
Linear Transmission	ψ = 0.091 IP (0.158 SI)	ψ = 0.037 IP (0.064 SI)

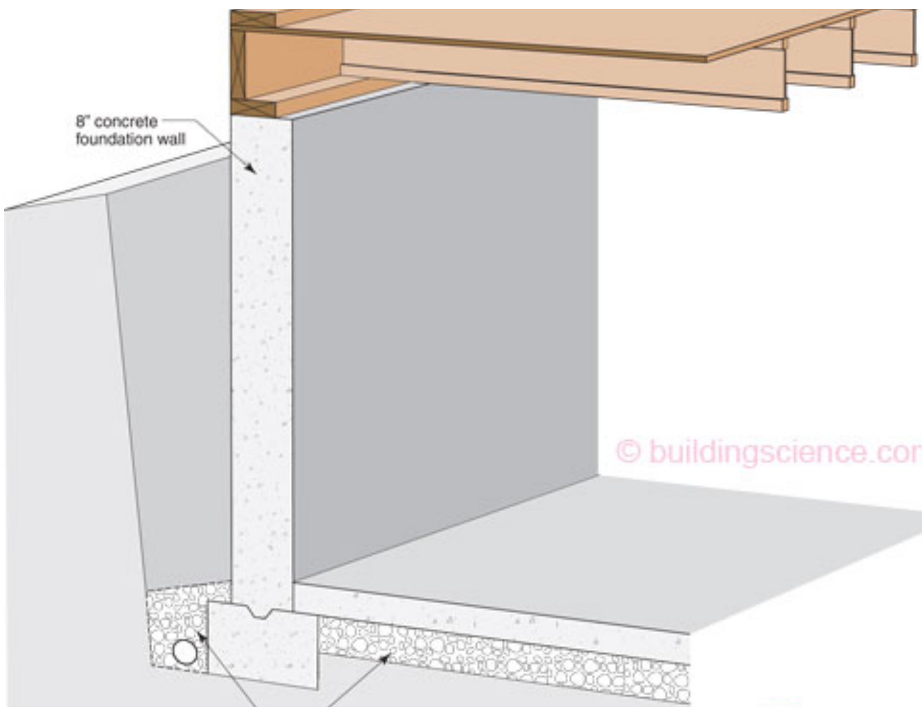
Finch et al. 2013, 12th Canadian Masonry Symposium

WRAPPING UP COMPLEX CONDUCTION

(1) Below-grade walls and floors
(2) On-grade heat transfer

Below-grade heat flow

- Where does heat flow?
  - Depends on surface and ground temperature distributions



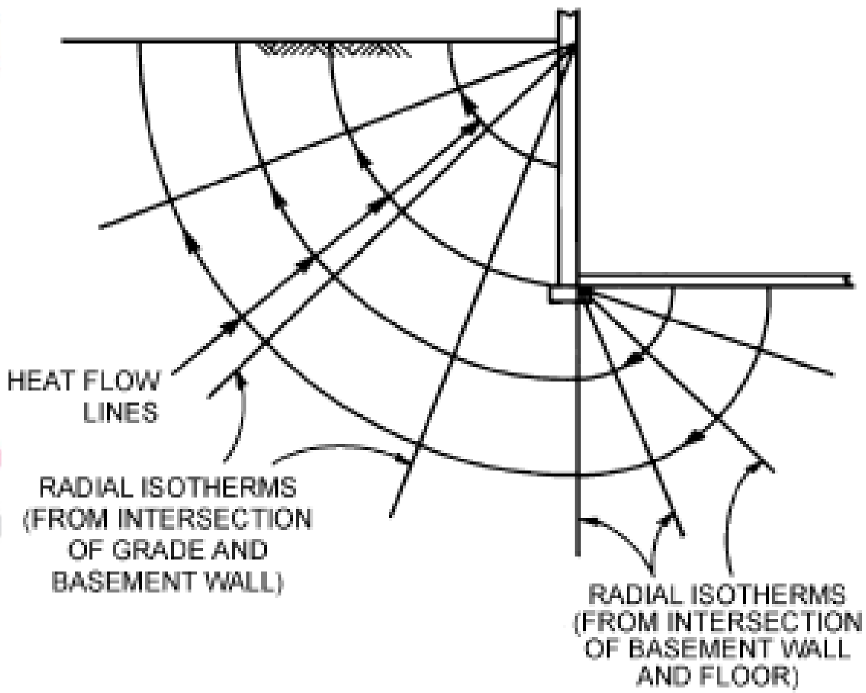
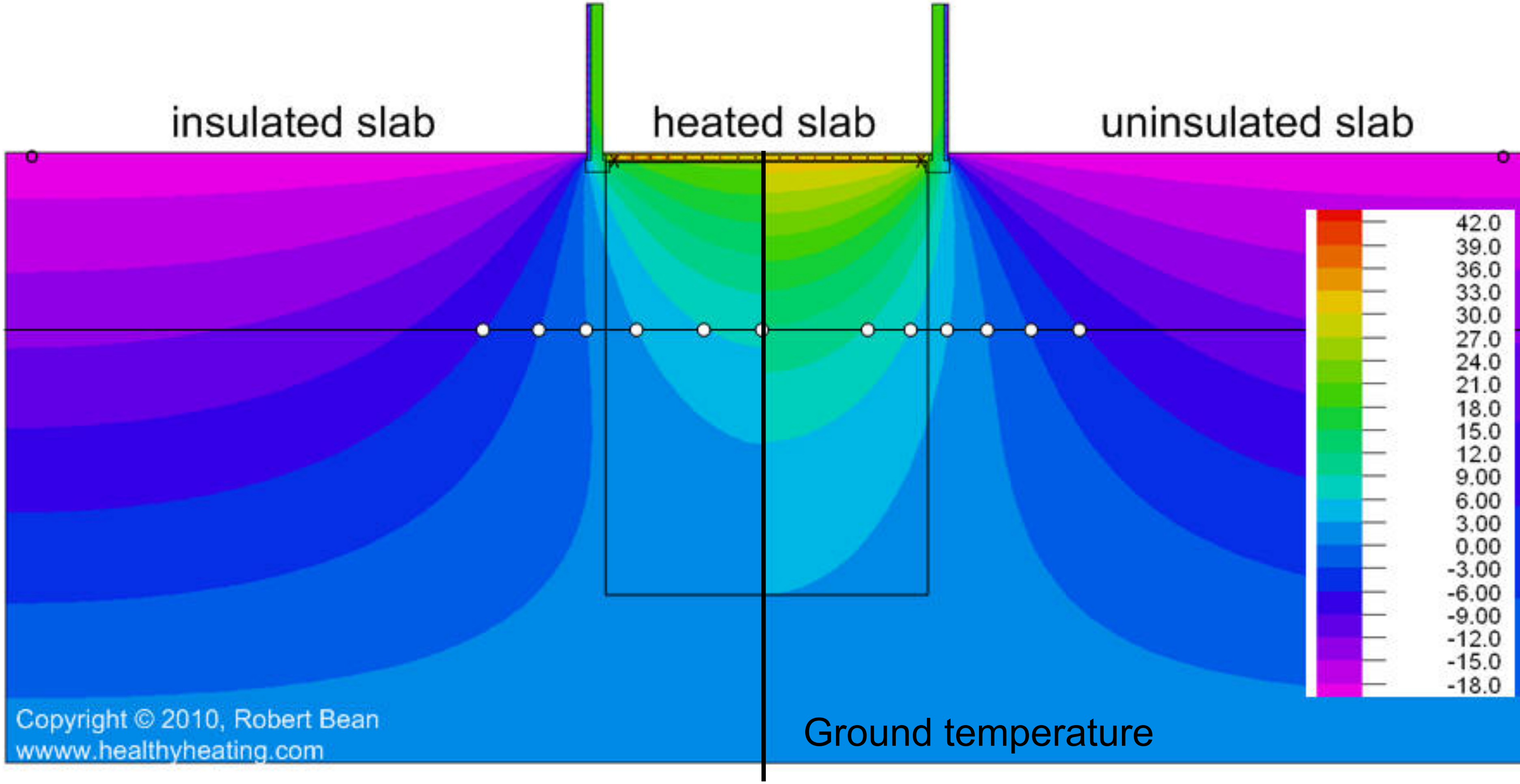


Fig. 4 Heat Flow from Basement

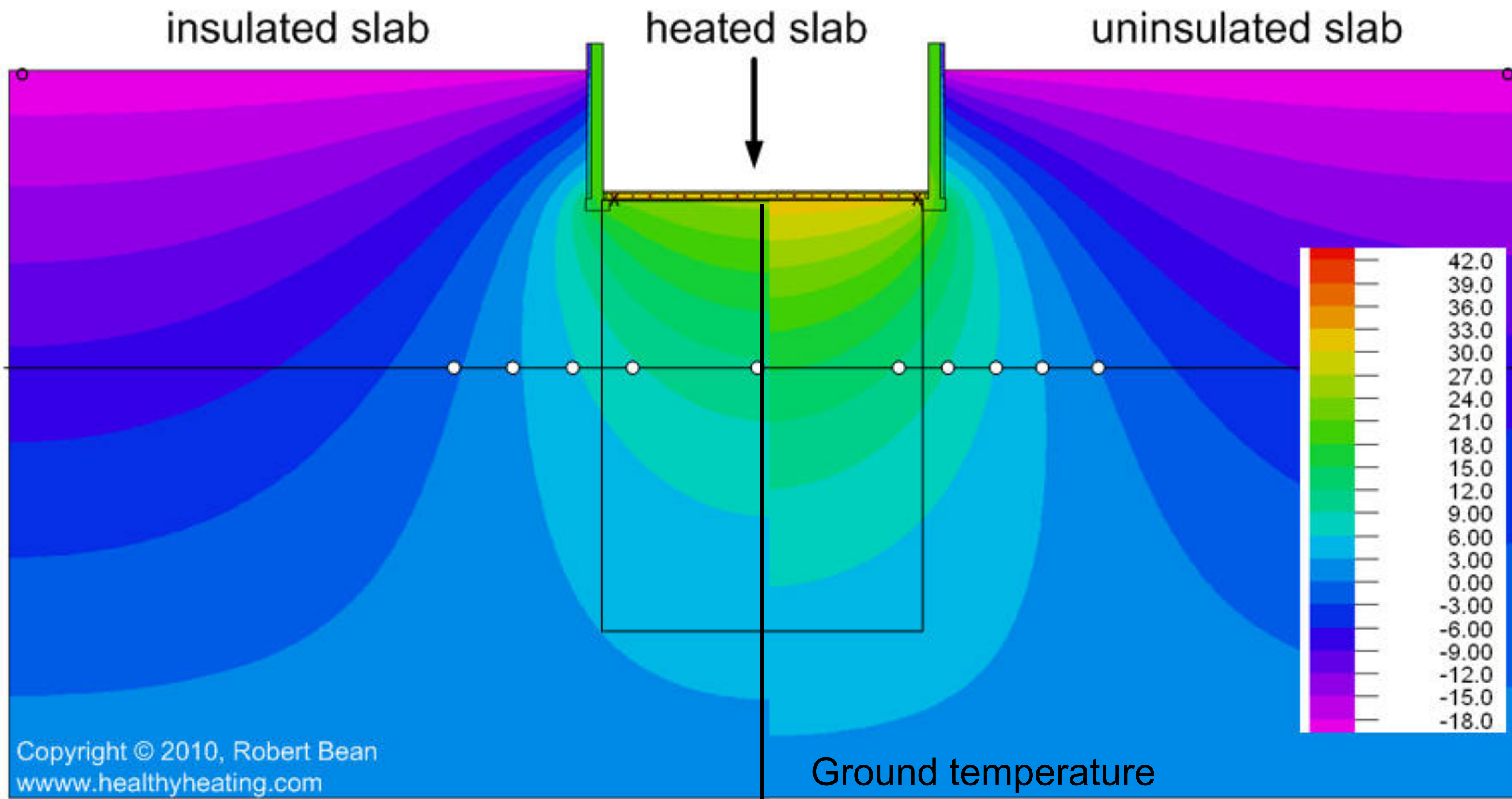
On-grade and below-grade heat transfer

- Often we have floors built directly on grade, in contact with the ground



On-grade and below-grade heat transfer

- Or we have walls and floors built below-grade, or “submerged” within the soil



Mean ground temperatures

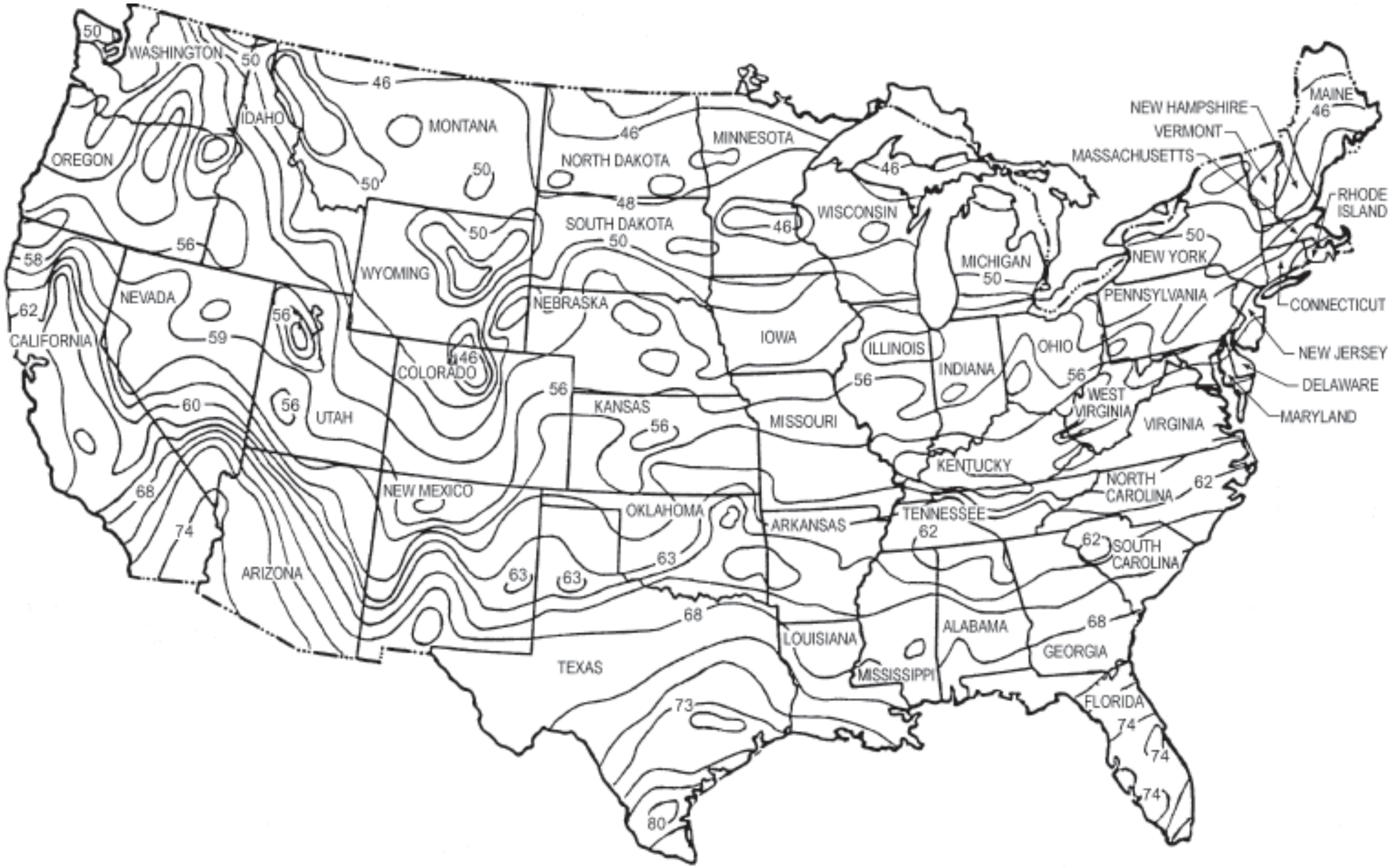
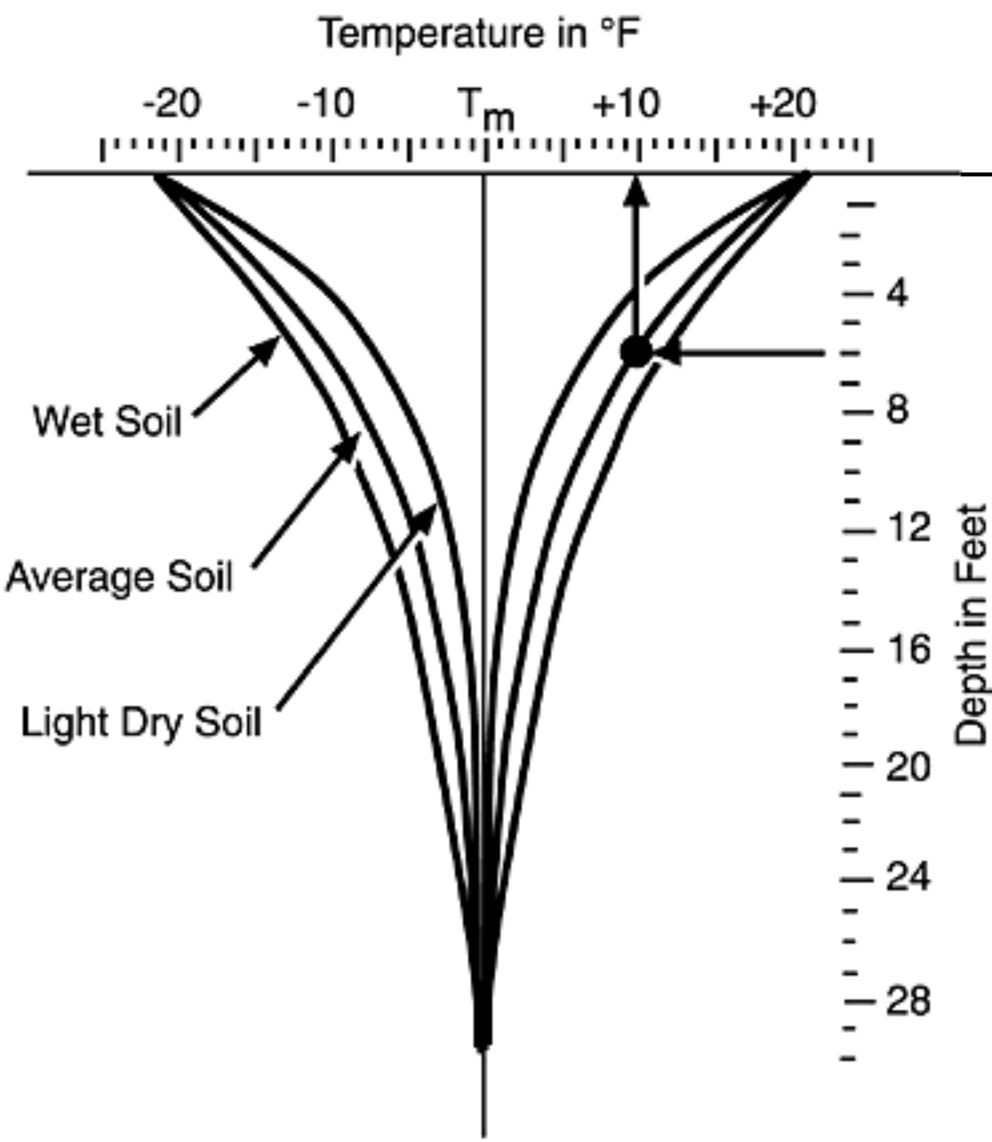
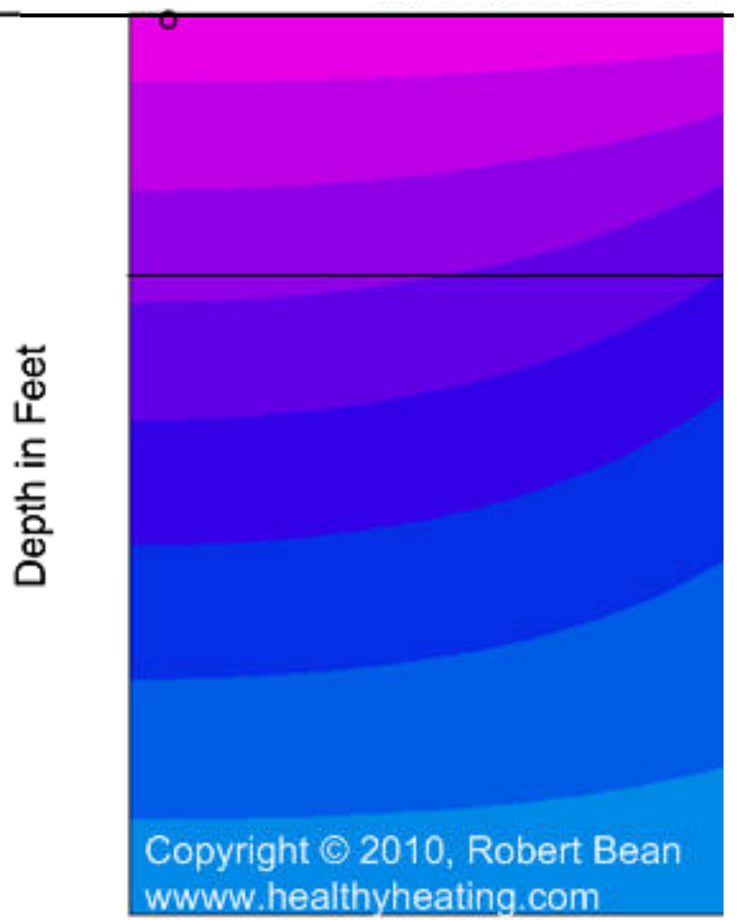


Fig. 17 Approximate Groundwater Temperatures (°F) in the Continental United States

Source: 2011 HVAC Apps Chapter 34, Figure 17

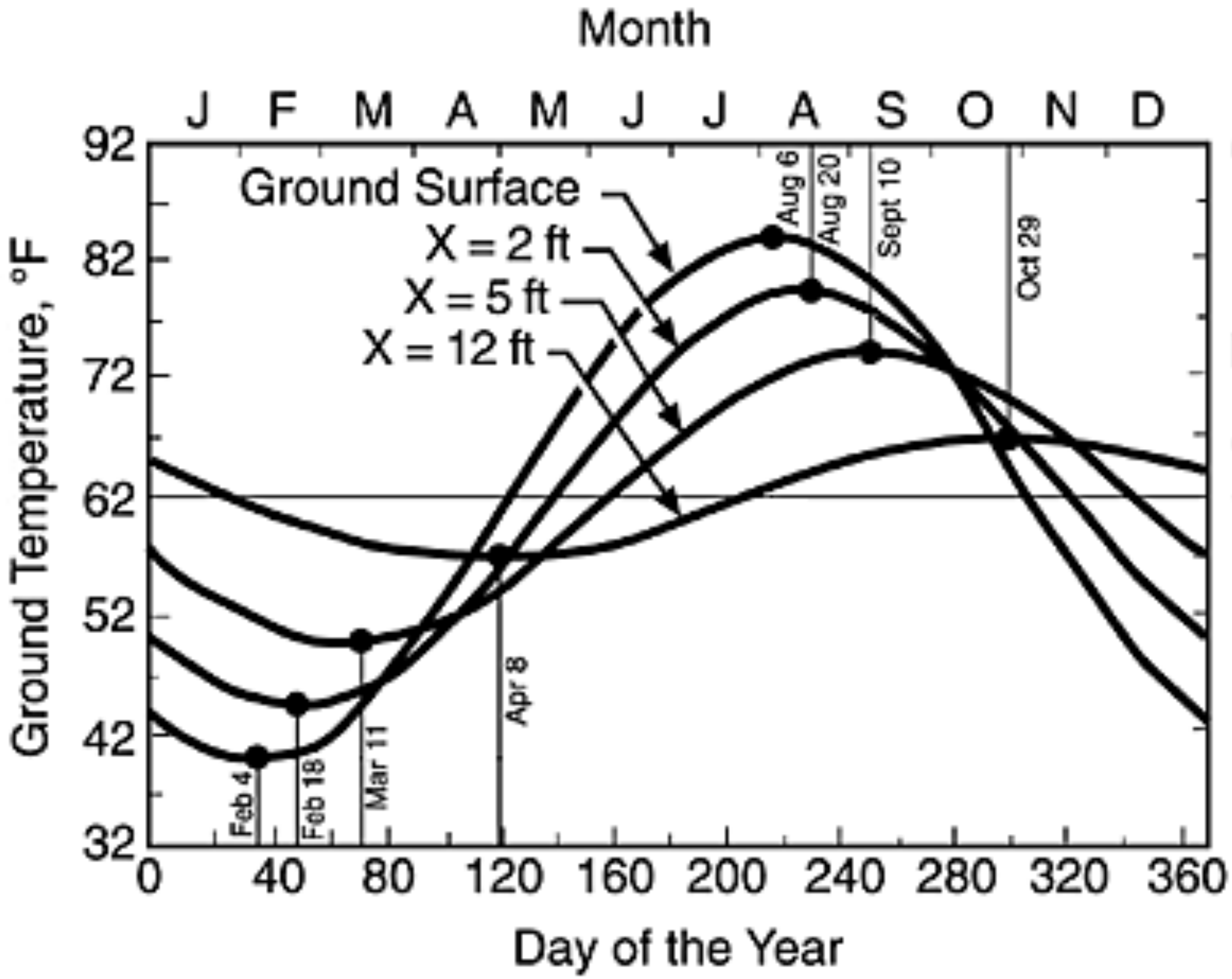
Ground temperatures vary with depth and soil moisture





Source: http://www.geo4va.vt.edu/A1/A1.htm

Ground temperatures also vary with season



Source: http://www.geo4va.vt.edu/A1/A1.htm

Design ground temperatures

- Design (worst-case) ground temperatures
  - Adjust mean ground temperature by a peak seasonal amplitude:

$$T_{gr} = T_{gm} - T_A$$

where

T_A = the ground temperature variation amplitude (right)

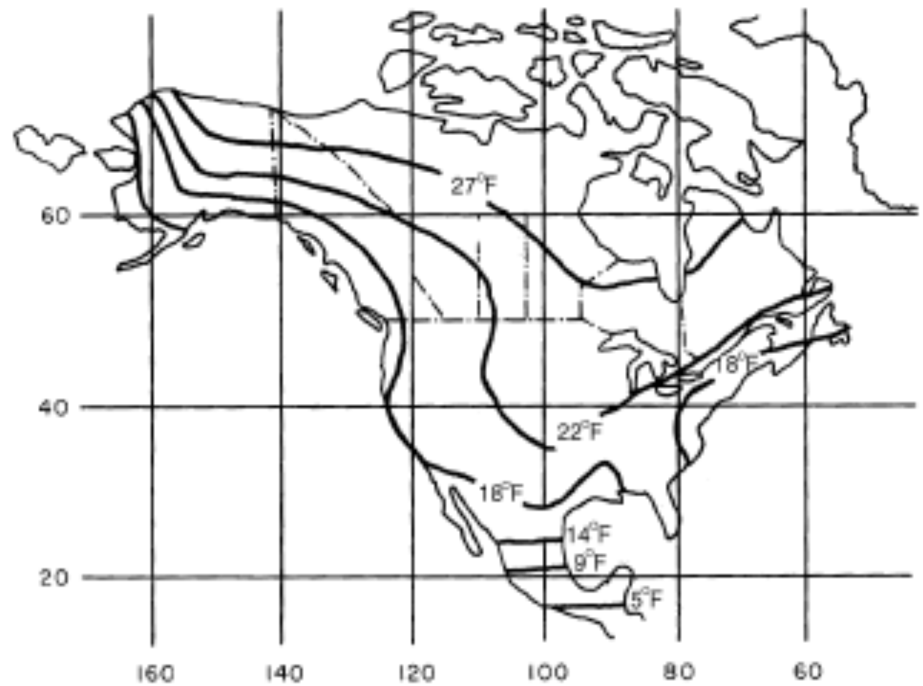
T_{gm} = mean ground temperature

*Note for Chicago:

$T_A \approx 22°F$ $T_{gm} \approx 54°F$

$T_{gr} \approx 54-22 = 32°F$

Alternatively, T_{gr} can be estimated as the mean air temperature in the coldest month



Ground Temp **Amplitude**, T_A

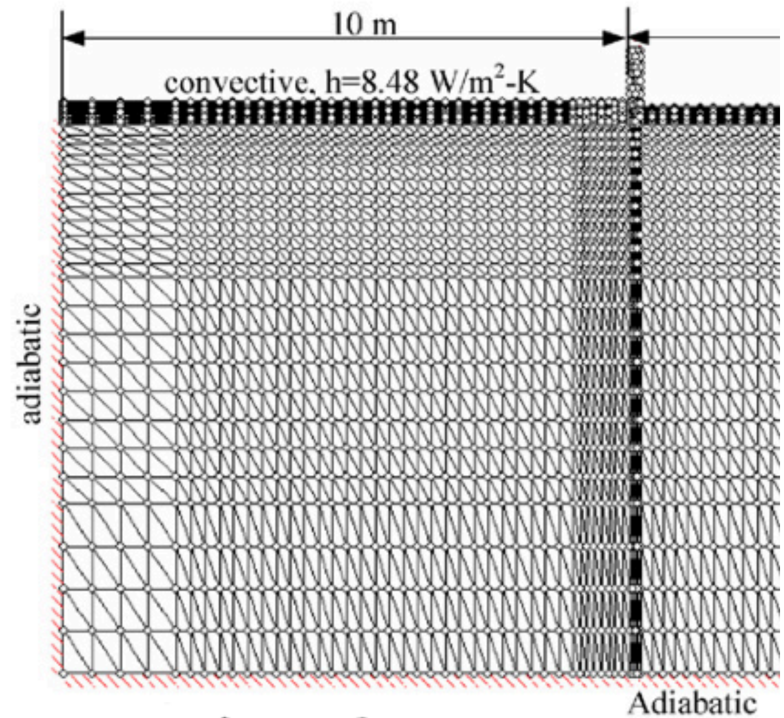
Source: 2005 ASHRAE Handbook Chapter, 29, Fig 2

Below-grade heat transfer

- Heat transfer through below-grade walls and floors
  - Conduction is truly 2-D or 3-D
  - 1-D modeling is not appropriate

- Heat transfer through walls
  - Between inside and surrounding soil
    - (not exterior air)
  - Depends on the wall area

- Heat transfer through the floor
  - Between inside and the soil below
  - Depends on the floor area



$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0$$

- ASHRAE HOF has some guidelines for transforming 2-D into 1-D

Below-grade heat transfer

$$Q = A U_{avg} (T_i - T_{gr}) \text{ [W]}$$

$$q = U_{avg} (T_i - T_{gr}) \text{ [W/m}^2\text{]}$$

where

A is the wall or floor area below grade [m^2] (analyze any wall portion above-grade in the normal way)

T_i is the below grade inside temp [K]

T_{gr} is the design ground surface temp [K]

U_{avg} is the average U factor for the below grade surface [W/(m^2K)] (see following slides)

Below grade depth parameters for estimating U value

z_1 = start of section to analyze

z_2 = end of section

z_f = bottom of floor

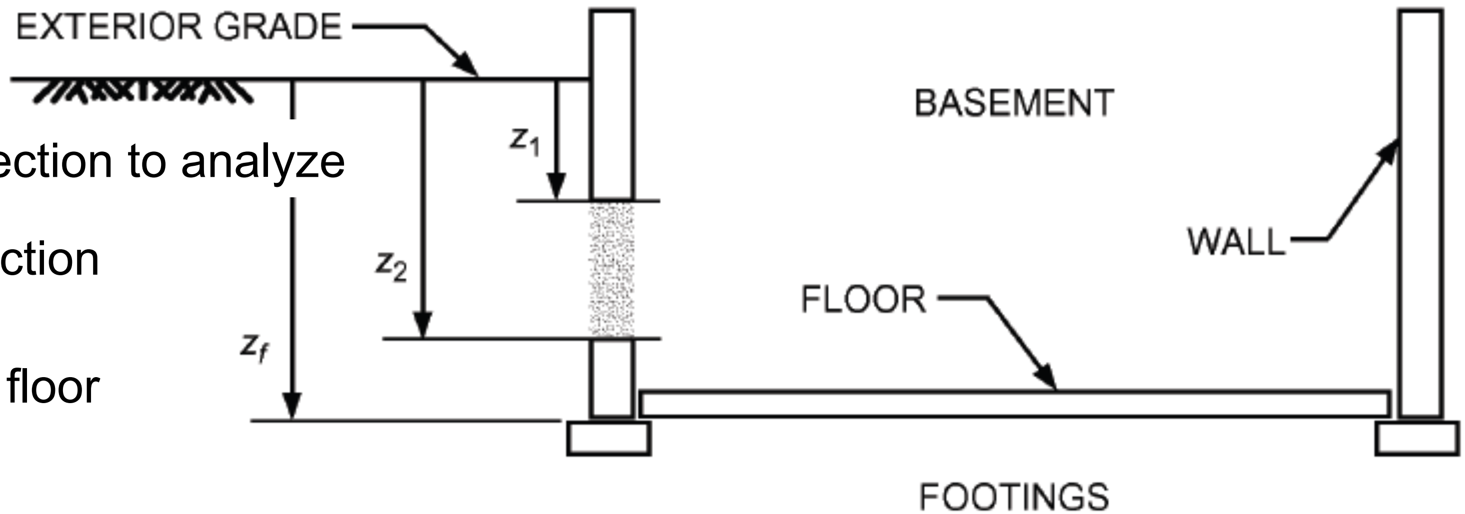


Fig. 14 Below-Grade Parameters

$U_{avg,bf}$ for below-grade floors

- For average below-grade floor value with a floor depth of height z_f from ground ("grade")

$$U_{avg,bf} = \frac{2k_{soil}}{\pi w_b} \times \left[\ln\left(\frac{w_b}{2} + \frac{z_f}{2} + \frac{k_{soil}R_{other}}{\pi}\right) - \ln\left(\frac{k_{soil}R_{other}}{\pi}\right)\right]$$

k_{soil} = soil thermal conductivity ≈ 1.4 W/mK
R_{other} = R value of floor + insulation + convection [m^2K/W]
w_b = shortest dimension of basement width [m]
z_f = floor depth below grade [m]

Pre-computed tables for $U_{avg,bf}$

Table 17 Average U-Factor for Basement Floors

z_f (depth of floor below grade), m	$U_{avg,bf}$, W/(m^2·K) — w_b (shortest width of basement), m: 6	7	8	9
0.3	0.370	0.335	0.307	0.283
0.6	0.310	0.283	0.261	0.242
0.9	0.271	0.249	0.230	0.215
1.2	0.242	0.224	0.208	0.195
1.5	0.220	0.204	0.190	0.179
1.8	0.202	0.188	0.176	0.166
2.1	0.187	0.175	0.164	0.155

Soil conductivity is 1.4 W/(m·K); floor is uninsulated. For other soil conductivities and insulation, use Equation (38).

- Assuming **un-insulated concrete** floor

$U_{avg,bw}$ for below-grade walls

$$U_{avg,bw} = \frac{2k_{soil}}{\pi(z_1 - z_2)} \times \left[\ln\left(z_2 + \frac{2k_{soil}R_{other}}{\pi}\right) - \ln\left(z_1 + \frac{2k_{soil}R_{other}}{\pi}\right)\right]$$

- k_{soil} = soil thermal conductivity ≈ 1.4 W/mK
- R_{other} = R value of wall, insulation and inside surface resistance [m^{2}K/W]
- z_1, z_2 = depths of top and bottom of wall segment under consideration [m]

Pre-computed tables for $U_{avg,bw}$

Table 16 Average U-Factor for Basement Walls with Uniform Insulation

Depth, m	$U_{avg,bw}$ from grade to depth, $W/(m^2 \cdot K)$ Uninsulated	R-0.88	R-1.76	R-2.64
0.3	2.468	0.769	0.458	0.326
0.6	1.898	0.689	0.427	0.310
0.9	1.571	0.628	0.401	0.296
1.2	1.353	0.579	0.379	0.283
1.5	1.195	0.539	0.360	0.272
1.8	1.075	0.505	0.343	0.262
2.1	0.980	0.476	0.328	0.252
2.4	0.902	0.450	0.315	0.244

Soil conductivity = 1.4 W/(m·K); insulation is over entire depth. For other soil conductivities and partial insulation, use Equation (37).

- Assuming **concrete** walls with **uniform insulation**

Below-grade example problem

Determine the heat flow, Q, through a basement enclosure

- Basement is 60 ft x 25 ft
- Walls are 5 ft below grade
  - Covered with R-4 (IP) insulation
  - Walls and floor are 6" concrete

Other information:

- k_{soil} = 0.8 Btu/(h ft^2 °F)
- R_{wall} = 4.0 (insul.) + 0.68 (convection) + 0.60 (6" concrete) = 5.28 (IP)
- R_{floor} = 0.61 (convection) + 0.6 (6" concrete) = 1.21 (IP)
- z_1 = 0, z_2 = 5 ft, z_f = 5 ft, w_b = 25 ft
- $A_{wall,bg}$ = 2*(5*25) + 2*(5*60) = 850 ft^2
- $A_{floor,bg}$ = 25*60 = 1500 ft^2
- Assume T_{in} = 65°F and T_{gr} = 40°F

Below-grade example problem

$$U_{avg,bw} = \frac{2(0.8)}{\pi(5-0)}\left[\ln\left(5+\frac{2(0.8)5.28}{\pi}\right)-\ln\left(0+\frac{2(0.8)5.28}{\pi}\right)\right] = 0.11 \ \frac{\text{Btu}}{\text{hr}\cdot\text{ft}^2\cdot{}^\circ\text{F}}$$

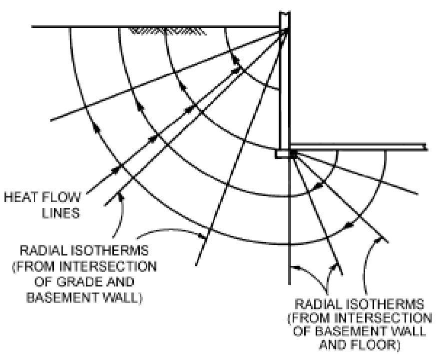


Fig. 4 Heat Flow from Basement

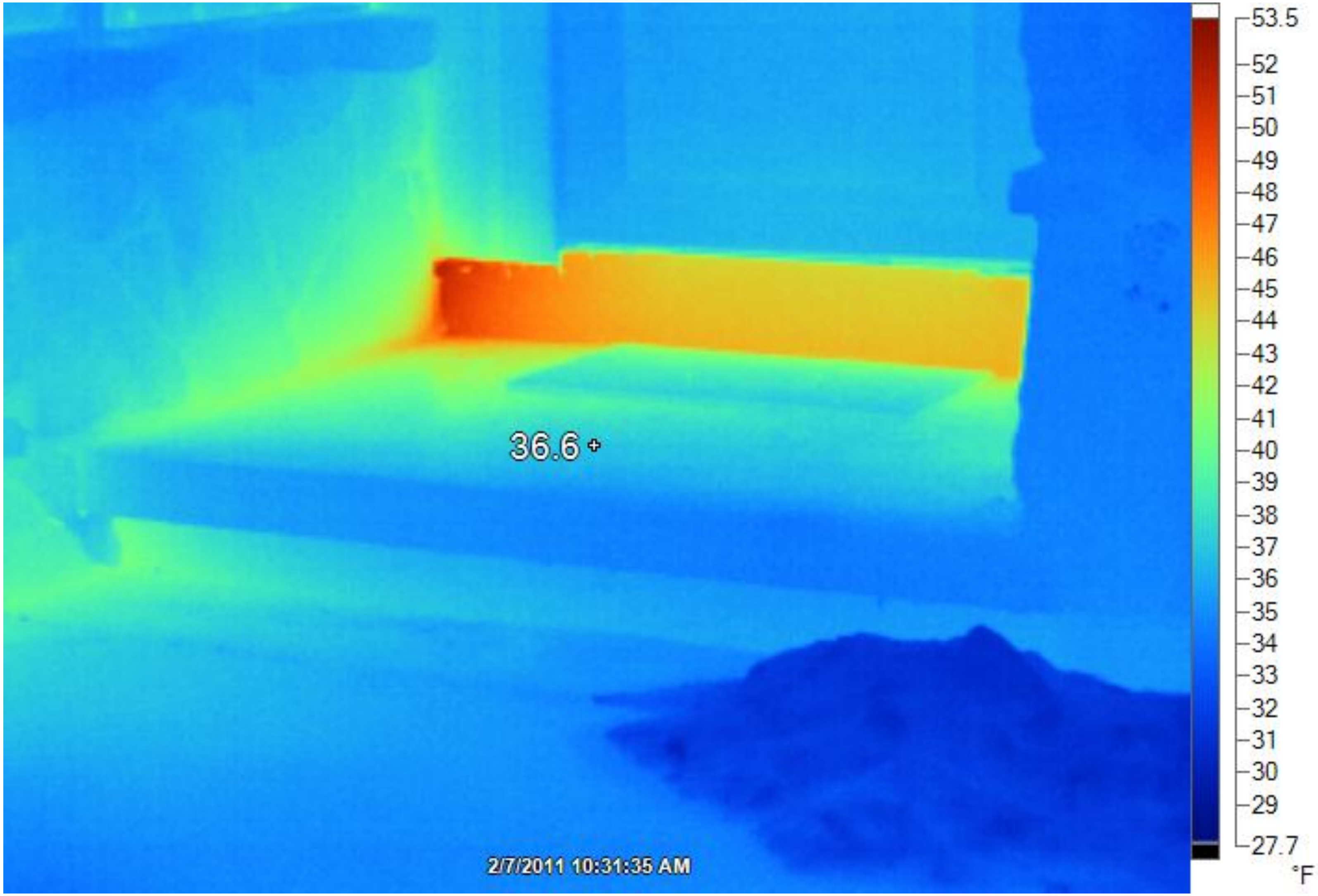
On-grade heat transfer

On-grade heat transfer

- Heat transfer for slab-on-grade floors
  - Concrete slabs can be heated or unheated
  - In either case:
    - Ground is often at a lower temperature than indoor air
      - Soil and concrete are fairly conductive
    - Perimeter can be exposed directly to outdoor air

  - It turns out that the perimeter is often most important for both energy and comfort
    - Need to insulate the perimeter

Slab-on-grade floors



Slab-on-grade floors

- Heat transfer through slab-on-grade floors
  - Function of perimeter of slab (not area)

$$Q = pF_p\left(T_i - T_o\right)$$

where T_i and T_o are the inside and outside temps [K]

p is the perimeter of the exposed floor surface [m]

F_p is the heat loss coefficient per unit length of perimeter [W/mK]

Design considerations

- To reduce heat transfer through slab on grade floors, we obviously need to:
  - Reduce the perimeter length, and/or
  - Decrease the heat loss coefficient, F_p

- Decreasing F_p is as simple as adding insulation to the foundation exterior
  - Typically no need to exceed $R = 8$ (IP)

Figure 3. Insulated Form Board Field Installation

Heat loss coefficient: F_p

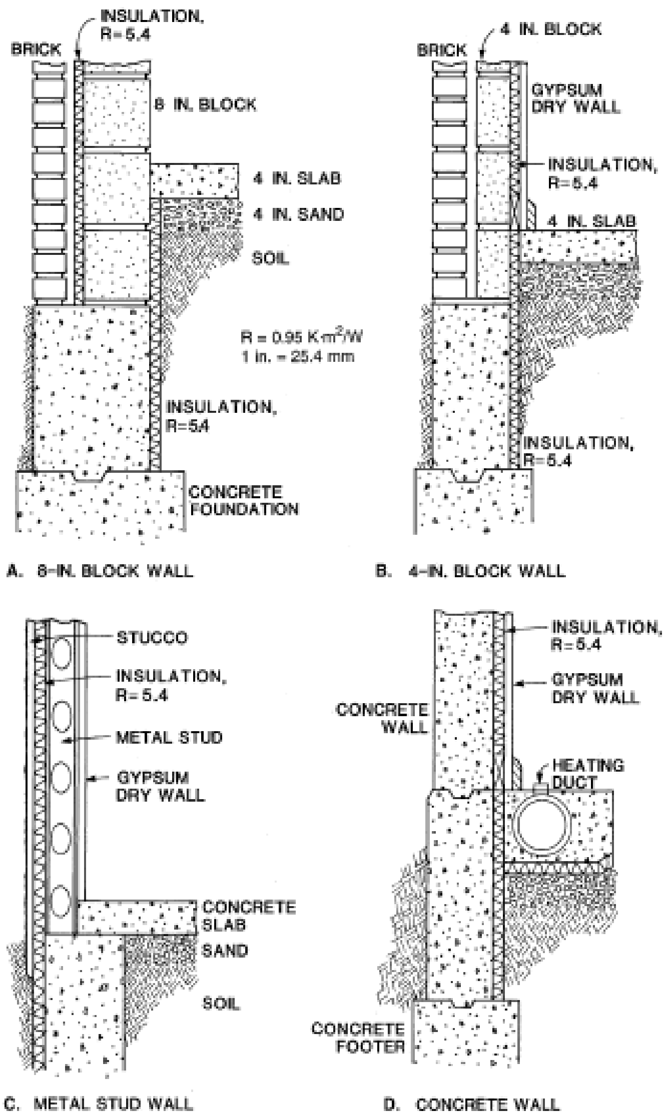


Fig. 8 Slab-on-Grade Foundation Insulation

Table 18 Heat Loss Coefficient F_p of Slab Floor Construction

Construction	Insulation	F_p, W/(m·K)
200 mm block wall, brick facing	Uninsulated	1.17
	R-0.95 (m^2·K)/W from edge to footer	0.86
4 in. block wall, brick facing	Uninsulated	1.45
	R-0.95 (m^2·K)/W from edge to footer	0.85
Metal stud wall, stucco	Uninsulated	2.07
	R-0.95 (m^2·K)/W from edge to footer	0.92
Poured concrete wall with duct near perimeter*	Uninsulated	3.67
	R-0.95 (m^2·K)/W from edge to footer	1.24

*Weighted average temperature of the heating duct was assumed at 43°C during heating season (outdoor air temperature less than 18°C).

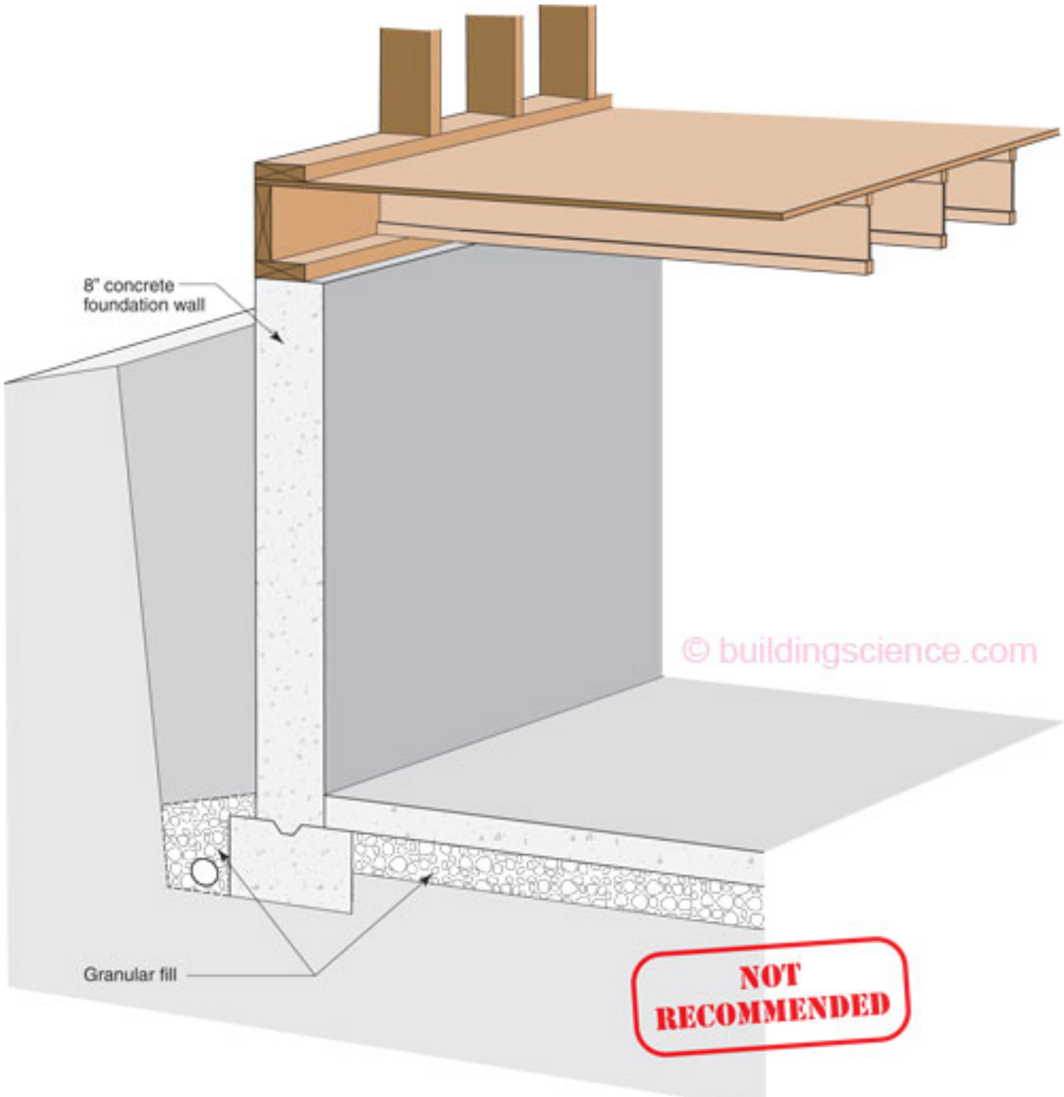
Using THERM for finding U_{avg}

- You can use THERM to model 2-D heat transfer but be careful …
  - Must create new convection boundary conditions for interior convection to/from floor
  - Must model a large area of soil around the foundation as a solid with adiabatic boundary conditions
  - Must model outside soil/air interface with new exterior convection

- Basement floor is a 3-D problem and so it cannot be easily modeled in THERM

Slab-on-grade and below-grade enclosures

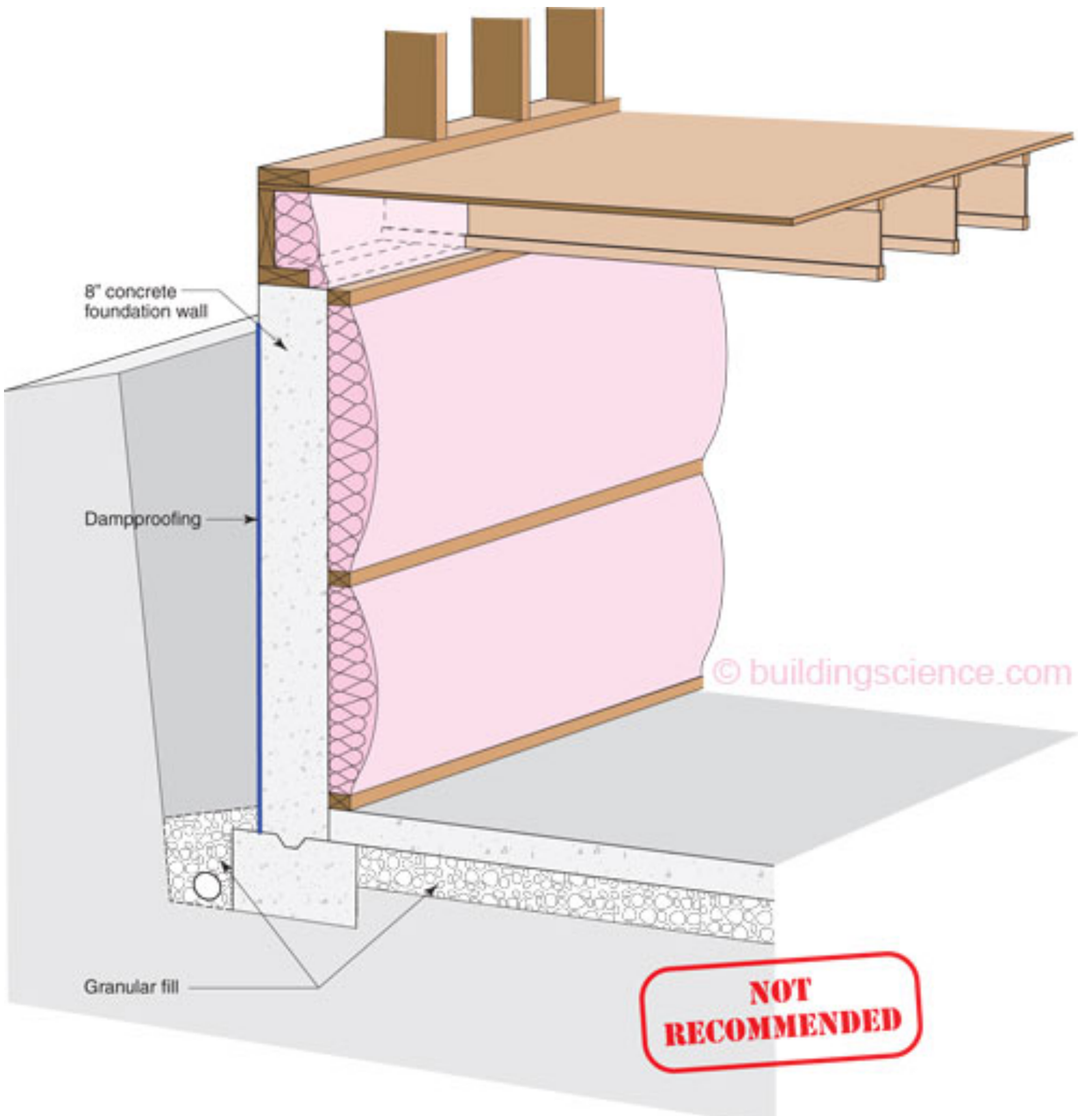
Uninsulated concrete foundation wall and slab



- No thermal control
- Not even allowed by code if basement is conditioned
- No moisture control
- Water vapor diffusion and capillary action are near-constant moisture sources

Slab-on-grade and below-grade enclosures

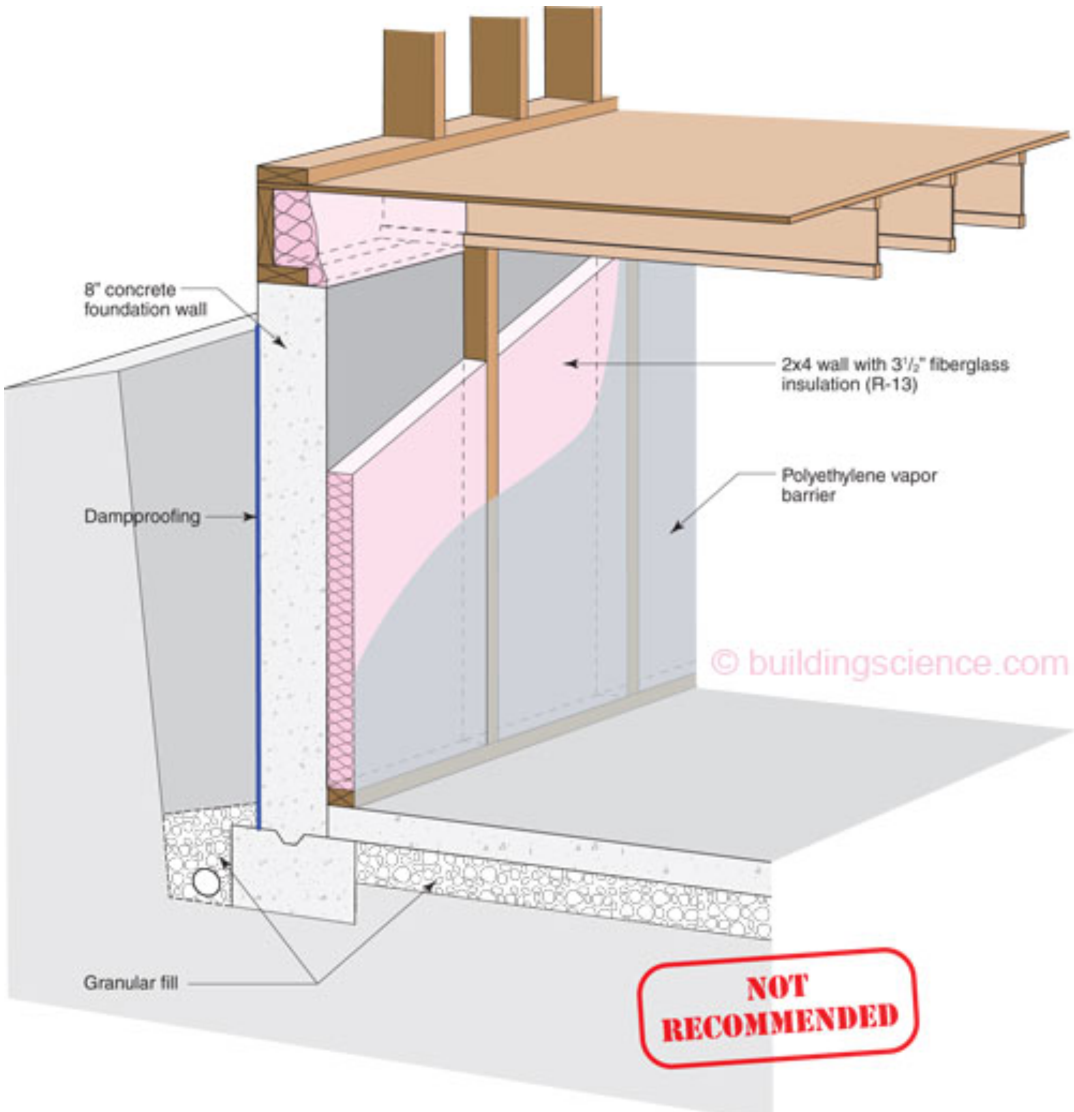
Code minimum R-10 (IP) continuous insulation in a framed wall



- Slab not insulated
- Better thermal control
- Inexpensive
- Sometimes wall insulation batt is covered with vapor barrier
- Moisture issues (batt is air and vapor permeable)
- High RH at concrete wall most of the year

Slab-on-grade and below-grade enclosures

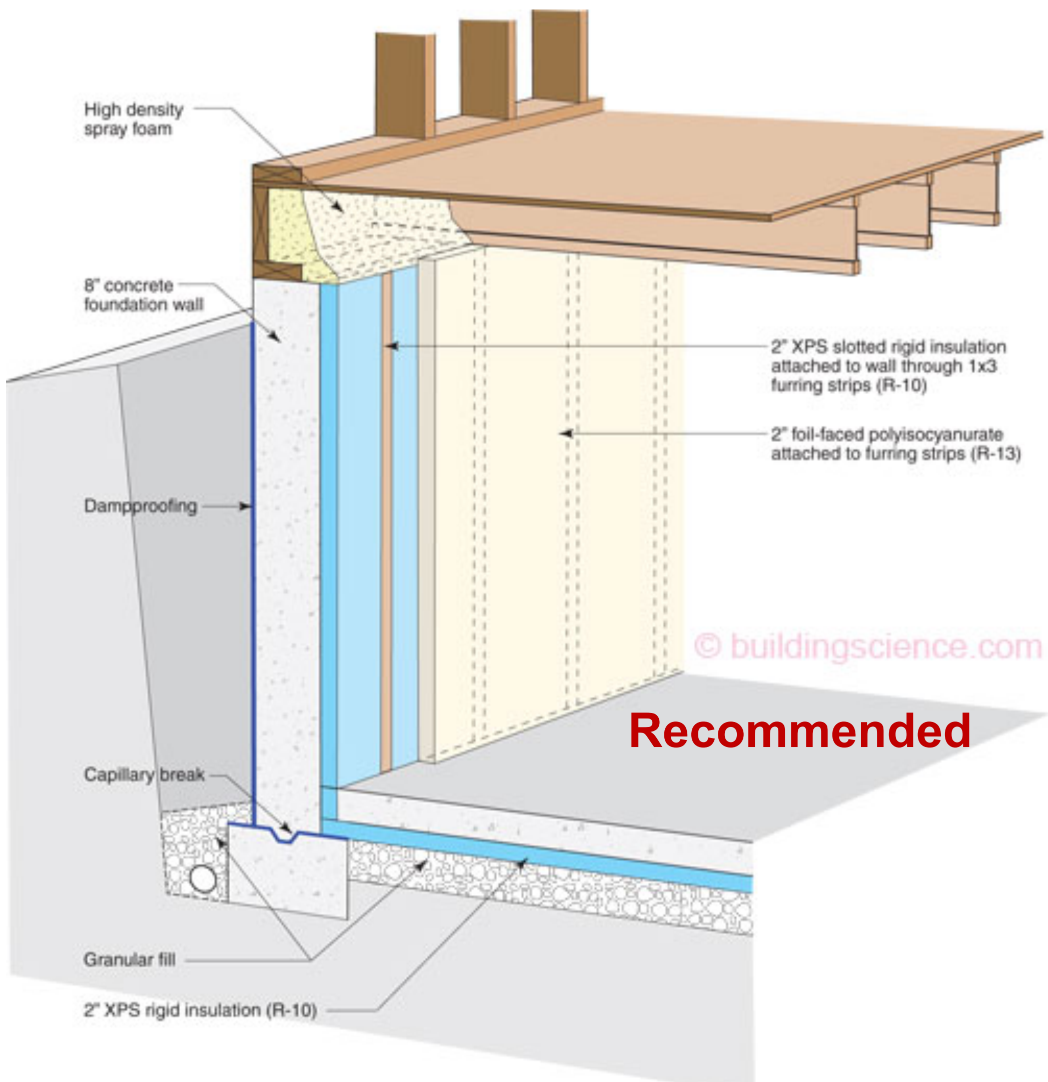
R-13 (IP) insulation in a 2x4 framed wall

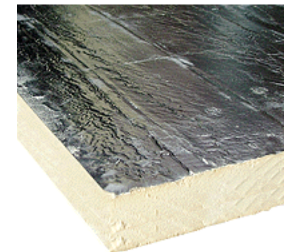


- Similar to last construction
- Moisture issues
- High RH at concrete wall most of the year
- Particularly a problem if there is any air leakage

Slab-on-grade and below-grade enclosures

2” XPS rigid insulation + 2” foil-face polyisocyanurate foam board

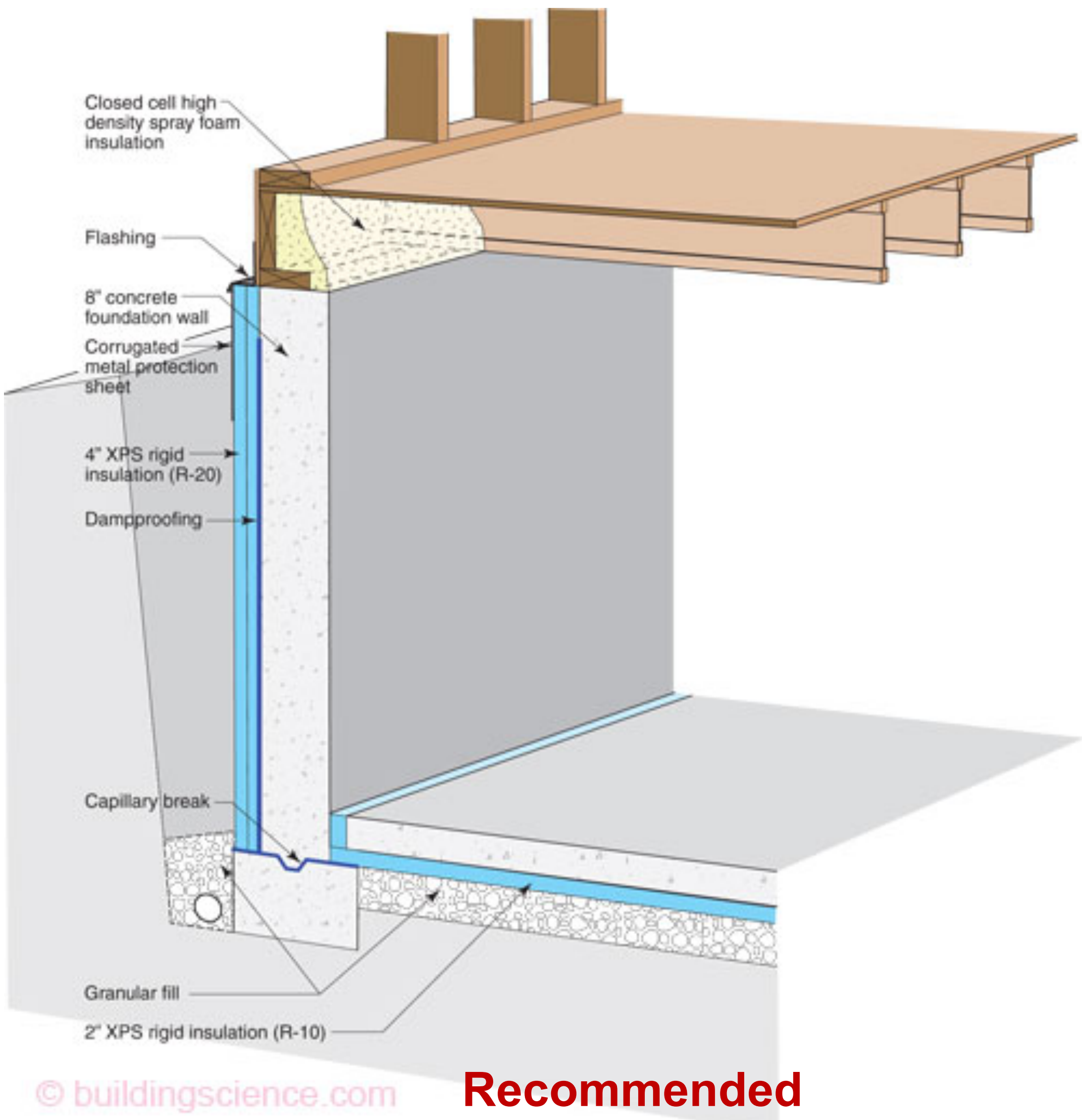




- Very good thermal control (R-23 walls)
- Water vapor diffusion is prevented
- Capillary action is prevented by the thermal/capillary break at the edge of the slab and top of footing

Slab-on-grade and below-grade enclosures

Rigid XPS exterior insulation



Recommended

- Very good thermal control (R-20 walls)
- Exterior insulation can be joined with first floor insulation
- Excellent resistance to vapor diffusion
- Capillary action is a potential problem (through the footing)
  - Need a break
- Exposed concrete provides moisture buffer after it dries
- May be hard to construct

MOISTURE FLOWS IN ENCLOSURES

Water vapor transport

- Moisture in air is one of the most important sources of wetting in buildings
  - Need to know to how to design and construct buildings that are safe from damage caused by water vapor and liquid water
  - Need to understand physics of water vapor and its:
    - Transport by diffusion and air movement (bulk convection)
    - Deposition by condensation
    - Removal by evaporation

- Most of notes today come from our textbook
  - Some also come from *Moisture Control Handbook: Princples and Practices for Residential and Small Commercial Buildings*, Listiburek and Carmody, Wiley, 1996, ISBN 0471318639.
  - Reduced version of this text is available as a DOE report:
    - http://www.ornl.gov/sci/roofs+walls/facts/moisture/Moisturehandbook2.pdf

Moisture management basics

- Moisture is involved in almost all performance problems or deterioration process that affect building enclosures
  - Leakage of water into the building
  - Freeze-thaw deterioration of concrete, stone, or masonry
  - Corrosion of metal components
  - Biological growth
    - Occupant health, structural integrity, and appearance
  - Chemical deterioration/dissolution of materials
  - Volume changes
    - Structural failure, cracking, degradation of appearance
  - Discoloration
    - Staining, dusting, irregular wetting

Moisture management basics

- For a moisture-related problem to occur, at least four conditions must be met
  - A moisture **source** must be available
  - There must be a **route** for moisture to travel
  - Three must be a **driving force** to cause moisture movement
  - The material(s) involved must be **susceptible** to moisture damage

- Address at least one of these can usually solve (or avoid) most problems

- More on moisture management later
  - For now, we will identify moisture problems and causes
  - Then learn the fundamentals/physics of moisture transport

Types of moisture failure

We use the term “failure” typically to include some level of
(a) material deformation or
(b) degradation of physical performance

that stem physical changes, chemical processes, and/or biological processes

Moisture can cause several types of failure:

- Structural failures from rot damage and freeze-thaw cycles
- Increased heat loss caused by moisture content in materials and airflow through moisture enhanced gaps
- Emission of volatile organic compounds (VOCs)
- Mold growth
- Insect problems

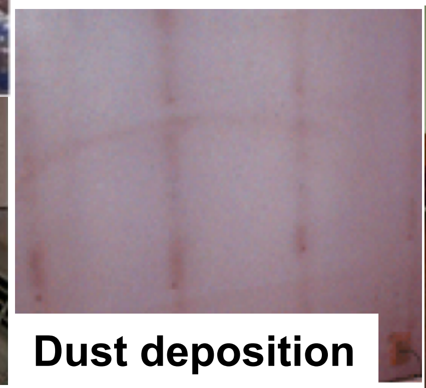
Examples of moisture problems


Freeze-thaw damage


Mold growth



Wood deformation: Shrinking, swelling


Dust deposition


Insects

Efflorescence

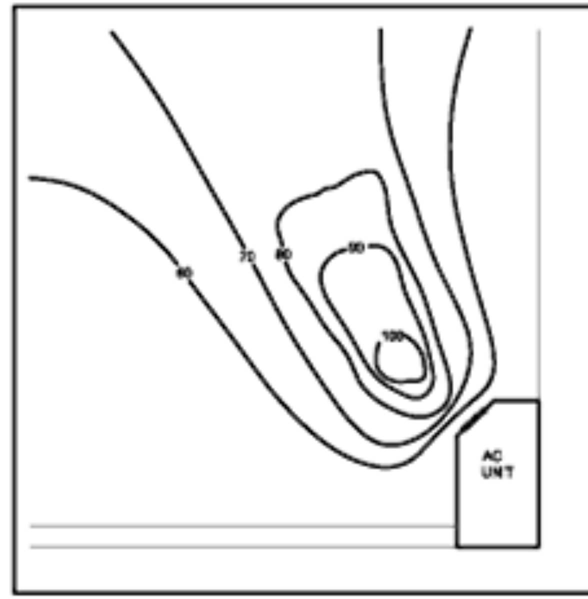

Rot


Corrosion

Moisture mapping

Condensation near an AC unit

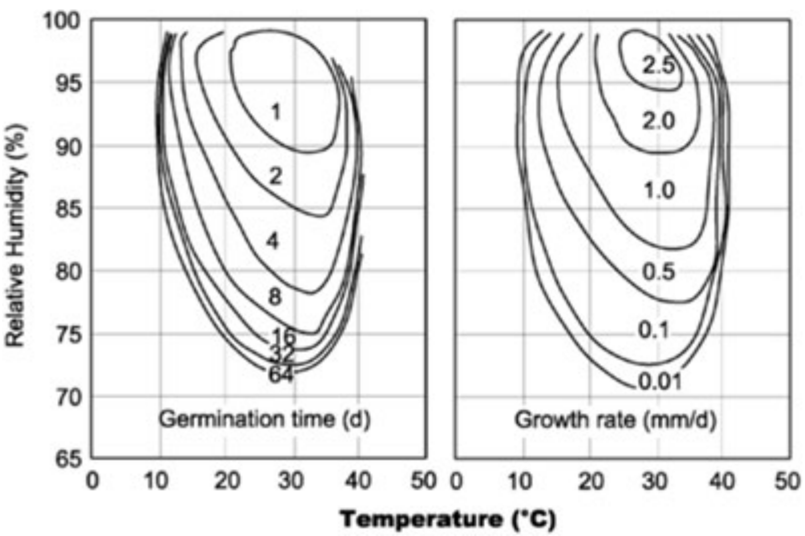
- A surface moisture meter was used to map out the condensation pattern on a wall

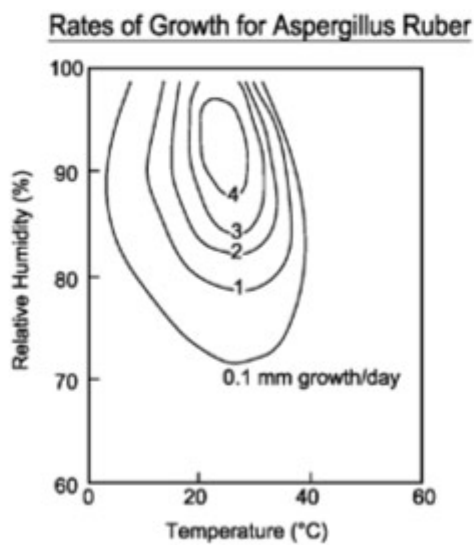


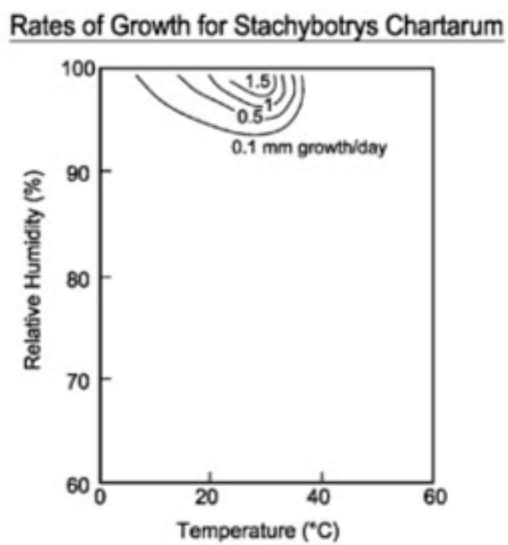
- When the wall paper was pulled back we see the mold growth that matches the condensation pattern

Mold growth requirements

- Typical 20-25°C room temperatures are often ideal for mold growth
  - Particularly if humidity is high (e.g., > 80%)







Moisture failure criteria

- Total water content of assembly
  – Does it increase over time?
- Moisture content in each component
  – Particularly critical wood components (should be less than 20%)
- Condensation potential
  – Surface temperatures lower than indoor air dewpoint?
  – If so, any air leak could cause condensation
  – No good guidelines on critical values
- Potential for mold growth
  – ASHRAE Standard 160: 30 day running average surface RH>80% when temperature is between ~40°F and ~100°F

Why wasn't moisture a problem before?

- In the past, enclosure materials could store a lot more moisture in their denser, more porous construction and thus dry slowly
  - e.g. brick and stone

- Enclosures used to lack moisture barriers
  - Few materials were good vapor barriers
  - So any moisture that did get to an internal wall surface could dry by diffusion and air motion to either the inside or outside

- Larger air leaks in older, leaker enclosures also allowed moisture in internal surfaces to dry to either the inside or the outside

Why moisture is a problem now

- Besides basic changes in wall construction from masonry to stud walls, there have been other changes in construction as well:

- Construction is more airtight
  - So any moisture that does get in cannot dry as easily

- Construction includes more materials that act as vapor barriers or at least have high vapor resistance
  - If vapor barrier is in the wrong spot it can cause condensation and limit drying
    - Latex paints
    - Foil coated insulation
    - Insulation in encapsulated in polyethelyne bags

Sources of moisture

- Water leakage
- Water penetration through joints and seams
- Convection of moist air through cracks (and condensation)
- Diffusion through structure
- Rising from damp ground

Moisture transport

Moisture enters a building in two forms:

- Liquid
- Vapor

We can break transport into three main categories:

- Condensed water infiltration (bulk liquid)
  - Infiltration of water in liquid form
- Moist air infiltration
  - Infiltration of water vapor in air that leaks into building
- Vapor diffusion
  - Infiltration of water vapor from high to low vapor pressure

Controlling Mode 1 (bulk liquid) differs from controlling Modes 2 and 3 (which involved water vapor)

- We will focus on water vapor first and bulk liquid water later

Water vapor transport

- Water vapor moves through the building enclosure in two primary modes
  - Diffusion
  - Bulk convection

- Combined transport of mass by diffusion and convection is called ***advection***

Water vapor transport: Diffusion

- Diffusion, like conduction, is mass/energy transport through a solid material, driven by a gradient

- Fick's Law:
  - Mass flow of water vapor dm_v/dt under a gradient in vapor pressure ∇p_w

$$\frac{dm_v}{dt} = -D\nabla p_w$$

where

$D =$ diffusivity

$p_w =$ vapor pressure (concentration)

$\nabla =$ divergent operator ($\partial/\partial x$, $\partial/\partial y$, $\partial/\partial z$)

Water vapor diffusion

- In one dimension, the difference in vapor pressure, dp_w, over a thickness x drives the rate of water vapor mass flow:

$$\frac{dm_v}{dt} = -\mu A \frac{dp_w}{dx}$$

where

$\frac{dm_v}{dt} =$ rate of water vapor mass flow [ng/s]

$A =$ area perpendicular to flow [m^2]

$\mu =$ average vapor permeability [ng/(m Pa s)]

$\frac{dp_w}{dx} =$ vapor pressure gradient [Pa/m]

Water vapor diffusion

- Assuming that vapor permeance (μ) does NOT vary with T/RH (it actually does), Fick's law can be written as:

$$\dot{M}_v = \frac{\mu}{L} A\left(p_{w,1} - p_{w,2}\right)$$

where

$\dot{M}_v$ = rate of water vapor mass flow [ng/s]

A = area perpendicular to flow [m^2]

μ = average vapor permeability [ng/(m Pa s)]

L = length of material [m]

$p_{w,i}$ = vapor pressure on either side of material [Pa]

$$\dot{m}_v = \frac{Q_v}{A} = \frac{\mu}{L}\left(p_{w,1} - p_{w,2}\right)$$

$\dot{m}_v$ = rate of water vapor mass flow per unit area [ng/s per m^2]

Water vapor diffusion

- We can rearrange terms just like in heat transfer:

$$\dot{m}_v = \frac{\dot{m}_v}{A} = \frac{\mu}{L}\left(p_{w,1} - p_{w,2}\right) = M\left(p_{w,1} - p_{w,2}\right) = \frac{1}{R_v}\left(p_{w,1} - p_{w,2}\right)$$

$$M = \frac{\mu}{L} \qquad \text{and} \qquad R_v = \frac{1}{M}$$

M = vapor permeance [ng/(s m^2 Pa)]

R_v = vapor resistance [(s m^2 Pa)/ng]

- *M* is analogous to *U*
- R_v is analogous to *R*

Water vapor diffusion: look familiar?

- Fick's law for diffusive vapor flow is the same as Fourier's Law for conductive heat flow

Table 6.1: Comparison of conductive heat flow and diffusive vapor flow

	Heat		Vapor	
Driving Potential	Temperature	t,T	Vapor Pressure	P_W
Measures	Conductivity	k, λ	Permeability	μ
	Conductance	C	Permeance	M
	Overall Transmittance	U	Overall Vapor Transmittance	V
	Resistance	R	Resistance	R_V
Flow	Heat flow	Q	Vapor Flow	Q_v
	Heat flux	q	Vapor flux	q_v
Single Layer	$\frac{\lambda}{l} \cdot \Delta t$ $= C \cdot \Delta t$ $= \Delta t / R$	q	$\frac{\mu}{l} \cdot \Delta P$ $= M \cdot \Delta P$ $= \Delta P / R_V$	i
Multi-Layer	$U \cdot \Delta t$		$V \cdot \Delta P$	

I prefer using:
$\dot{M}$
$\dot{m}$

Water vapor transport: Bulk convection

- The bulk convective flow of air can transport significant quantities of water vapor with it
  - Simple function of the flow rate of air
  - Remember the humidity ratio, $W = m_v/m_a$
  - If the rate of air movement is known:

$$\frac{dm_v}{dt} = \frac{dm_a}{dt} W$$

where

$\frac{dm_v}{dt}$ = rate of water vapor mass flow [kg_v/s]

$\frac{dm_a}{dt}$ = rate of air mass flow [kg_a/s]

W = humidity ratio [kg_v/kg_a]

Water vapor transport: convection

- Mass flow rate of convective water vapor movement

$$\dot{M}_{v,conv} = \rho_{air}\dot{V}_{air}W$$

  - Again, similar to bulk convective heat transfer
  - Mass flow rate of water vapor equals mass flow rate of air times humidity ratio

Key terms reference

Water vapor diffusion: movement under a pressure gradient of water vapor

Term	Symbol	Definition	SI Units	IP Units
Vapor flow	$\dot{M}_v$	Time rate at which water vapor moves	[ng/s]	[grains/hr]
Vapor permeability	μ	Rate of vapor flow through a unit thickness of material under a unit vapor pressure difference	[ng/(s m Pa)]	perm-inch [grain/(hr in Hg in)]
Vapor permeance	M	Permeability of a material for a given thickness	[ng/(s m^2 Pa)]	perm [grains/(hr ft^2 inHg)]
Vapor resistance	R_v	Resistance of a material for a given thickness	[(s m^2 Pa)/ng]	rep = 1/perm [(hr ft^2 inHg)/grain]

A note on the unit **perm**:
Materials in the US (IP units) are referred to by **perm** values
1 perm = 1 grain/(hr ft^2 inHg) → similar to a unit R value
1 perm = 57.2 ng/(s m^2 Pa)

Material moisture resistance properties

Table 7A Typical Water Vapor Permeance and Permeability Values for Common Building Materials[a]

Material	Thickness, mm	Permeance, ng/(s·m²·Pa)	Resistance[h], (TPa·m²·s)/kg	Permeability, ng/(s·m·Pa)	Resistance/m[h], (TPa·m·s)/kg
Construction Materials					
Concrete (1:2:4 mix)				4.7	0.21
Brick masonry	100	46[f]	0.022		
Concrete block (cored, limestone aggregate)	200	137[f]	0.0073		
Tile masonry, glazed	100	6.9[f]	0.14		
Asbestos cement board	3	220-458[d]	0.0017-0.0035		
With oil-base finishes		17-29[d]	0.0035-0.052		
Plaster on metal lath	19	860[f]	0.0012		
Plaster on wood lath		630[e]	0.0016		
Plaster on plain gypsum lath (with studs)		1140[f]	0.00088		
Gypsum wall board (plain)	9.5	2860[f]	0.00035		
Gypsum sheathing (asphalt impregnated)	13		29[f]	0.038	
Structural insulating board (sheathing quality)				29-73[f]	0.038-0.014
Structural insulating board (interior, uncoated)	13	2860-5150[f]	0.00035-0.00019		
Hardboard (standard)	3.2	630[f]	0.0016		
Hardboard (tempered)	3.2	290[f]	0.0034		
Built-up roofing (hot mopped)		0.0	∞		
Wood, sugar pine				0.58-7.8[f,b]	172.0-131
Plywood (douglas fir, exterior glue)	6.4	40[f]	0.025		
Plywood (douglas fir, interior glue)	6.4	109[f]	0.0092		
Acrylic, glass fiber reinforced sheet	1.4	6.9[f]*	0.145		
Polyester, glass fiber reinforced sheet	1.2	2.9[f]	0.345		
	L	M	R_v (strange units)	μ	

Material moisture resistance properties

Table 7A Typical Water Vapor Permeance and Permeability Values for Common Building Materials[a]

Material	Thickness, mm	Permeance, ng/(s·m²·Pa)	Resistance[h], (TPa·m²·s)/kg	Permeability, ng/(s·m·Pa)	Resistance/m[h], (TPa·m·s)/kg
Thermal Insulations					
Air (still)				174[f]	0.0057
Cellular glass				0.0[d]*	∞
Corkboard				3.0-3.8[d]	0.33-0.26
				14[e]	0.076
Mineral wool (unprotected)				245[e]	0.0059
Expanded polyurethane [R = 1.94 W/(m²·K)] board stock				0.58-2.3[d]	1.72-0.43
Expanded polystyrene—extruded				1.7[d]	0.57
Expanded polystyrene—bead				2.9-8.4[d]*	0.34-0.12
Phenolic foam (covering removed)				38	0.026
Unicellular synthetic flexible rubber foam				0.029[d]	34-4.61
Plastic and Metal Foils and Films[c]					
Aluminum foil	0.025	0.0[d]	∞		
Aluminum foil	0.009	2.9[d]	0.345		
Polyethylene	0.051	9.1[d]	0.110		2133
Polyethylene	0.1	4.6[d]	0.217		2133
Polyethylene	0.15	3.4[d]*	0.294		2133
Polyethylene	0.2	2.3[d]*	0.435		2133
Polyethylene	0.25	1.7[d]	0.588		2133
Polyvinylchloride, unplasticized	0.051	39[d]*	0.026		
Polyvinylchloride, plasticized	0.1	46-80[d]*	0.032		
Polyester	0.025	42[d]	0.042		
Polyester	0.09	13[d]	0.075		
Polyester	0.19	4.6[d]	0.22		
Cellulose acetate	0.25	263[d]	0.0035		
Cellulose acetate	3.2	18[d]	0.054		
	L	M	R_v (strange units)	μ	

Materials: Vapor barriers and vapor retarders

- Vapor retarders slow the rate of vapor diffusion
  - But does not prevent it

- General rules for vapor permeance are as follows:

Type	**Perms (IP units) [grains/(hr ft^2 inHg)]**	**SI units [ng/(s m^2 Pa)]**	**Example**
Class I vapor retarder Vapor barrier Vapor impermeable	0.1 or less	5.7	Foil Polyethylene
Class II vapor retarder Vapor semi-impermeable	0.1-1	5.7-57	Brick XPS
Class III vapor retarder Vapor semi-permeable	1-10	57-570	Poly-iso EPS
Vapor permeable NOT a vapor retarder	10+	570+	Gypsum board

Materials: Vapor barriers and vapor retarders

- Vapor retarders also need to satisfy some other requirements:
  - Mechanically strong
  - Adhesive
  - Elastic
  - Thermally stable
  - Fire resistant
  - Resistant to UV degradation
  - Easily applied and installed

- Very small punctures can lead to moist air leakage
  - Significantly increases overall permeance

Calculating steady state 1-D vapor flow

- Calculating vapor flow follows same general principles as calculating heat flow by conduction

- However, results of calculations tend to be much less accurate, for several reasons:
  - Values for vapor permeability (μ) are not always accurate
    - Also vary widely with moisture content and temperature
    - Variations of an order of magnitude are common for some materials
    - Extrapolating for different thicknesses also introduces inaccuracy
  - Moisture storage capacity for most building materials is large
    - Steady state conditions almost never occur in practice
    - Evaporation and desorption act as moisture sources and sinks
- Still important to understand vapor diffusion calculations
  - Helps identify potential condensation problems and understand how design decisions can impact potential moisture problems

Calculating steady state 1-D vapor flow

- Example problem: A 2 m wide, 3 m high, and 50 mm thick sheet of extruded polystyrene insulation material stands between indoor conditions of 24°C and 50% RH and exterior conditions of 35°C and 40% RH

- Calculate the following:
  - Vapor flow rate, $\dot{M}_v$
  - Vapor flux, $\dot{m}_v$
  - Vapor permeance, M
  - Vapor resistance, R_v

Example: Calculating steady state 1-D vapor flow

- First get p_{ws} for inside and outside conditions

Table 3 Thermodynamic Properties of Water at Saturation (*Continued*)

Temp., °C t	Absolute Pressure p_{ws}, kPa	Specific Volume, m^3/kg_w Sat. Liquid v_f	Specific Volume Evap. v_{fg}	Specific Volume Sat. Vapor v_g	Specific Enthalpy, kJ/kg_w Sat. Liquid h_f	Specific Enthalpy Evap. h_{fg}	Specific Enthalpy Sat. Vapor h_g	Specific Entropy, $kJ/(kg_w \cdot K)$ Sat. Liquid s_f	Specific Entropy Evap. s_{fg}	Specific Entropy Sat. Vapor s_g	Temp., °C t
0	0.6112	0.001 000	206.141	206.143	–0.04	2500.81	2500.77	–0.0002	9.1555	9.1553	0
1	0.6571	0.001 000	192.455	192.456	4.18	2498.43	2502.61	0.0153	9.1134	9.1286	1
2	0.7060	0.001 000	179.769	179.770	8.39	2496.05	2504.45	0.0306	9.0716	9.1022	2
3	0.7580	0.001 000	168.026	168.027	12.60	2493.68	2506.28	0.0459	9.0302	9.0761	3
4	0.8135	0.001 000	157.137	157.138	16.81	2491.31	2508.12	0.0611	8.9890	9.0501	4
5	0.8725	0.001 000	147.032	147.033	21.02	2488.94	2509.96	0.0763	8.9482	9.0244	5
6	0.9373	0.001 000	137.653	137.654	25.22	2486.57	2511.79	0.0913	8.9077	8.9990	6
7	1.0020	0.001 000	128.947	128.948	29.42	2484.20	2513.62	0.1064	8.8674	8.9738	7
8	1.0728	0.001 000	120.850	120.851	33.62	2481.84	2515.46	0.1213	8.8273	8.9488	8
9	1.1481	0.001 000	113.326	113.327	37.82	2479.47	2517.29	0.1362	8.7878	8.9240	9
10	1.2280	0.001 000	106.328	106.329	42.01	2477.11	2519.12	0.1511	8.7484	8.8995	10
11	1.3127	0.001 000	99.812	99.813	46.21	2474.74	2520.95	0.1659	8.7093	8.8752	11
12	1.4026	0.001 001	93.743	93.744	50.40	2472.38	2522.78	0.1806	8.6705	8.8511	12
13	1.4978	0.001 001	88.088	88.089	54.59	2470.02	2524.61	0.1953	8.6319	8.8272	13
14	1.5987	0.001 001	82.815	82.816	58.78	2467.66	2526.44	0.2099	8.5936	8.8035	14
15	1.7055	0.001 001	77.897	77.898	62.97	2465.30	2528.26	0.2244	8.5556	8.7801	15
16	1.8184	0.001 001	73.307	73.308	67.16	2462.93	2530.09	0.2389	8.5178	8.7568	16
17	1.9380	0.001 001	69.021	69.022	71.34	2460.57	2531.92	0.2534	8.4804	8.7338	17
18	2.0643	0.001 002	65.017	65.018	75.53	2458.21	2533.74	0.2678	8.4431	8.7109	18
19	2.1978	0.001 002	61.272	61.273	79.72	2455.85	2535.56	0.2821	8.4061	8.6883	19
20	2.3388	0.001 002	57.774	57.773	83.90	2453.48	2537.38	0.2964	8.3694	8.6658	20
21	2.4877	0.001 002	54.499	54.500	88.08	2451.12	2539.20	0.3107	8.3329	8.6436	21
22	2.6448	0.001 002	51.433	51.434	92.27	2448.75	2541.02	0.3249	8.2967	8.6215	22
23	2.8104	0.001 003	48.562	48.563	96.45	2446.39	2542.84	0.3390	8.2607	8.5996	23
24	2.9851	0.001 003	45.872	45.873	100.63	2444.02	2544.65	0.3531	8.2249	8.5780	24
25	3.1692	0.001 003	43.350	43.351	104.81	2441.66	2546.47	0.3672	8.1894	8.5565	25
26	3.3631	0.001 003	40.985	40.986	108.99	2439.29	2548.28	0.3812	8.1541	8.5352	26
27	3.5673	0.001 004	38.766	38.767	113.18	2436.92	2550.09	0.3951	8.1190	8.5141	27
28	3.7822	0.001 004	36.682	36.683	117.36	2434.55	2551.90	0.4090	8.0842	8.4932	28
29	4.0083	0.001 004	34.726	34.727	121.54	2432.17	2553.71	0.4229	8.0496	8.4724	29
30	4.2460	0.001 004	32.889	32.889	125.72	2429.80	2555.52	0.4367	8.0152	8.4519	30
31	4.4959	0.001 005	31.160	31.161	129.90	2427.43	2557.32	0.4505	7.9810	8.4315	31
32	4.7585	0.001 005	29.535	29.536	134.08	2425.05	2559.13	0.4642	7.9471	8.4112	32
33	5.0343	0.001 005	28.006	28.007	138.26	2422.67	2560.93	0.4779	7.9133	8.3912	33
34	5.3239	0.001 006	26.567	26.568	142.44	2420.29	2562.73	0.4915	7.8790	8.3713	34
35	5.6278	0.001 006	25.212	25.213	146.62	2417.91	2564.53	0.5051	7.8465	8.3516	35

Example: Calculating steady state 1-D vapor flow

- Then get p_w for indoor and outdoor conditions
  - Gives us the driving force

- Indoor @ 24°C and 50% RH:

$$p_{w,in} = \phi p_{ws,in} = 0.5(2985.3) = 1492.6 \text{ Pa}$$

- Outdoor @ 35°C and 40% RH:

$$p_{w,out} = \phi p_{ws,out} = 0.4(5627.8) = 2251.1 \text{ Pa}$$

Example: Calculating steady state 1-D vapor flow

$$\dot{M}_v = \frac{\mu}{L} A\left(p_{w,out} - p_{w,in}\right) = MA\left(p_{w,out} - p_{w,in}\right)$$

Need μ or M or extruded polystryene foam

Example: Calculating steady state 1-D vapor flow

Table 7A Typical Water Vapor Permeance and Permeability Values for Common Building Materials[a]

Material	Thickness, mm	Permeance, ng/(s·m²·Pa)	Resistance[h], (TPa·m²·s)/kg	Permeability, ng/(s·m·Pa)	Resistance/m[h], (TPa·m·s)/kg
Thermal Insulations					
Air (still)				174[f]	0.0057
Cellular glass				0.0[d*]	∞
Corkboard				3.0-3.8[d]	0.33-0.26
				14[e]	0.076
Mineral wool (unprotected)				245[e]	0.0059
Expanded polyurethane [R = 1.94 W/(m^2·K)] board stock				0.58-2.3[d]	1.72-0.43
Expanded polystyrene—extruded				1.7[d]	0.57
Expanded polystyrene—bead				2.9-8.4[d*]	0.34-0.12
Phenolic foam (covering removed)				38	0.026
Unicellular synthetic flexible rubber foam				0.029[d]	34-4.61
Plastic and Metal Foils and Films[c]					
Aluminum foil	0.025	0.0[d]	∞		
Aluminum foil	0.009	2.9[d]	0.345		
Polyethylene	0.051	9.1[d]	0.110		2133
Polyethylene	0.1	4.6[d]	0.217		2133
Polyethylene	0.15	3.4[d*]	0.294		2133
Polyethylene	0.2	2.3[d*]	0.435		2133
Polyethylene	0.25	1.7[d]	0.588		2133
Polyvinylchloride, unplasticized	0.051	39[d*]	0.026		
Polyvinylchloride, plasticized	0.1	46-80[d*]	0.032		
Polyester	0.025	42[d]	0.042		
Polyester	0.09	13[d]	0.075		
Polyester	0.19	4.6[d]	0.22		
Cellulose acetate	0.25	263[d]	0.0035		
Cellulose acetate	3.2	18[d]	0.054		
	L	M	R_v (strange units)	μ	

Example: Calculating steady state 1-D vapor flow

$$\dot{M}_v = \frac{\mu}{L} A\left(p_{w,out} - p_{w,in}\right) = MA\left(p_{w,out} - p_{w,in}\right)$$

$$\dot{M}_v = \frac{\mu}{L} A\left(p_{w,out} - p_{w,in}\right)$$

$$\dot{M}_v = \frac{1.7 \dfrac{\text{ng}}{\text{s}\cdot\text{m}\cdot\text{Pa}}}{0.05 \text{ m}} (2 \text{ m})(3 \text{ m})(2251.1 - 1492.6 \text{ Pa})$$

$$\dot{M}_v = 157768 \frac{\text{ng}}{\text{s}} = 157.768 \frac{\mu\text{g}}{\text{s}} = 0.157 \frac{\text{mg}}{\text{s}}$$

Is that a lot of water?

Example: Calculating steady state 1-D vapor flow

Is that a lot of water?

$$\dot{M}_v = 157768 \ \frac{\text{ng}}{\text{s}} = 157.768 \ \frac{\mu\text{g}}{\text{s}} = 0.157 \ \frac{\text{mg}}{\text{s}}$$

- In 1 hour, or 3600 seconds, that would mean ~565 mg of water vapor would be driven inward
- Density of water is ~0.622(1.2 kg/m^3) = ~0.746 kg/m^3

$$(565 \text{ mg})\left(\frac{\text{m}^3}{0.746 \text{ kg}}\right)\left(\frac{1 \text{ kg}}{1000 \text{ g}}\right)\left(\frac{1 \text{ g}}{1000 \text{ mg}}\right) = 0.000757 \text{ m}^3 \approx 0.8 \text{ L}$$

Example: Calculating steady state 1-D vapor flow

- Assume the insulation was adjacent to a 2 m x 3 m x 3 m space
  - Volume = 18 m^3 = 18,000 L

- Adding 0.8 L to 18,000 L would raise the water content of the room by about 0.005%

Is that a lot of water? No

Vapor diffusion through multiple layers

- Estimation method is called Glaser's method
  - Used since the 1930s
- Analogous to heat flow through multiple layers
- Two things to remember:
  - Vapor flux across the entire assembly must also pass through each layer (conservation of mass)
  - Sum of the **resistances** of each layer gives the total resistance
    - Do not add permeances
    - *Sound familiar?*

Vapor diffusion through multiple layers

- For any layer j:

$$\dot{M}_v = M_j A \Delta p_{w,j} = \frac{1}{R_{v,j}} A \Delta p_{w,j}$$

- For an assembly of n layers:

$$\dot{M}_v = A \frac{p_{w,interior} - p_{w,exterior}}{\sum_{j=0}^{n} R_{v,j}}$$

- Vapor transmittance of a system of n layers

$$M_{v,total} = \frac{1}{\sum_{j=0}^{n} R_{v,j}}$$

Vapor diffusion through multiple layers

- Vapor pressure drop across layer j:

$$\Delta p_{w,j} = \dot{M}_v R_{v,j}$$

- Combining equations:

$$\Delta p_{w,j} = \frac{p_{w,interior} - p_{w,exterior}}{\sum_{j=0}^{n} R_{v,j}} R_{v,j}$$

- Again: Doesn’t this look familiar?

Vapor diffusion through multiple layers

- A note on surface transfer coefficients
  - Remember that for heat transfer analysis we have to incorporate combined convective/radiative heat transfer coefficients into a “film” resistance
- For vapor transport, the convective mass transfer at exterior and interior surfaces is so high relative to vapor resistance that it can be ignored
  - No need for a “film resistance”
  - Equivalent permeance values (M)
    - Interior surfaces: 15000 ng/(Pa s m^2)
    - Still air spaces: 18000 ng/(Pa s m^2)
    - Exterior surfaces: 75000 ng/(Pa s m^2)
    - Compared to most building materials having 0-1000 ng/(Pa s m^2)

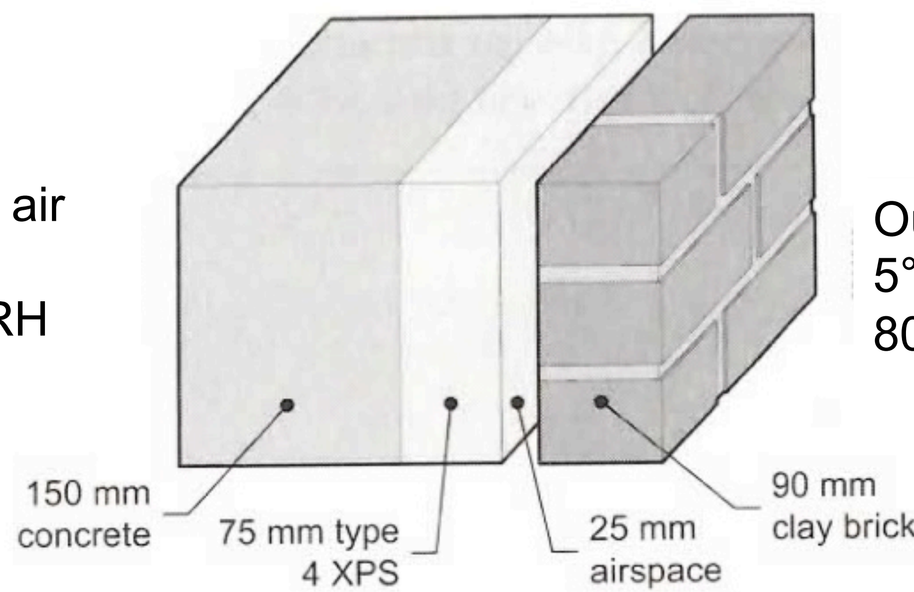
Glaser Method procedure

1. Break assembly into parallel paths
2. Find temp on all surfaces, T_j, of each path
3. Calculate saturation vapor pressure on all surfaces at the surface temp ($p_{ws,j}$ @ T_j)
4. Calculate interior and exterior vapor pressure from interior and exterior conditions
5. Estimate the vapor pressure, $p_{w,j}$, through the assembly assuming no condensation
6. Check if $p_{w,j} > p_{ws,j}$ at any location
   - If so then condensation occurs on that surface
7. If condensation occurs, set $p_{w,j} = p_{ws,j}$ and reanalyze

Example: Vapor diffusion through multiple layers

- Calculate vapor distribution through the wall assembly shown
  - Is condensation expected to occur anywhere in the assembly under the given conditions?

Inside air
21°C
50% RH



Outside air
5°C
80% RH

Example: Vapor diffusion through multiple layers

- Start by finding material properties

	Permeability	Thickness	Permeance	Resistance
	μ	L	M_j	$R_{v,j}$
Layer material	**ng/(Pa-s-m)**	**m**	**ng/(Pa-s-m^2)**	**(Pa-s-m^2)/ng**
Indoors				
Interior film			15000	0.000067
Concrete	2.6	0.15	17.3	0.058
XPS	2.0	0.075	26.7	0.0375
Air space		0.025	7200	0.00014
Brick	10	0.09	111	0.009
Exterior film			75000	0.000013
Outdoors				

Example: Vapor diffusion through multiple layers

- Calculate total vapor resistance (R_v)
  - R_v = sum of all R_j
- Calculate vapor pressure difference across each element

$$\Delta p_{w,j} = \frac{p_{w,interior} - p_{w,exterior}}{\sum_{j=0}^{n} R_{v,j}} R_{v,j}$$

- Calculate vapor pressure at each interface

$$p_{w,2} = p_{w,1} - \Delta p_{w,2-1}$$

Example: Vapor diffusion through multiple layers

- Need to determine vapor pressure and temperature at each interface in the assembly
  - p_{ws} at boundaries:
  - Indoor (21°C, 50%RH) → p_{ws} = 2488 Pa
    - p_w = 0.5(2488) = 1244 Pa

  - Outdoor (5°C, 80% RH) → p_{ws} = 873 Pa
    - p_w = 0.8(873) = 698 Pa

Example: Vapor diffusion through multiple layers

	Permeability	Thickness	Permeance	Resistance		
	μ	L	M_j	$R_{v,j}$	$\Delta P_{w,j}$	$P_{w,j}$
Layer material	**ng/(Pa-s-m)**	**m**	**ng/(Pa-s-m^2)**	**(Pa-s-m^2)/ng**	**Pa**	**Pa**
Indoors						1244
Interior film			15000	0.000067	0.3	
						1243.7
Concrete	2.6	0.15	17.3	0.058	301.7	
						942.0
XPS	2.0	0.075	26.7	0.0375	196.1	
						745.9
Air space		0.025	7200	0.00014	0.7	
						745.1
Brick	10	0.09	111	0.009	47.1	
						698.1
Exterior film			75000	0.000013	0.1	
Outdoors						698
			$R_{v,total}$	0.104		

Now we have the vapor pressure at each surface interface

Great! But not that helpful yet…

Example: Vapor diffusion through multiple layers

- Now estimate temperature distribution throughout assembly
  - We previously learned how to do this

	Conductivity, k	**Thickness, L**	**Conductance, U**	**Resistance, R**	**ΔT**	**T**
Layer material	**W/mK**	**m**	**W/m^2K**	**m^2K/W**	**°C**	**°C**
Indoors						21
Interior film			8.0	0.125		
					0.7	20.3
Concrete	1.8	0.15	12	0.083		
					0.4	19.9
XPS	0.029	0.075	0.39	2.564		
					13.5	6.4
Air space		0.025	n/a	0.17		
					0.9	5.5
Brick	1.3	0.09	14.4	0.069		
					0.4	5.2
Exterior film			34	0.029		
Outdoors					0.2	5.0
			R_{total} (m^2K/W)	3.04		
			U_{total} (W/m^2K)	0.33		

Example: Vapor diffusion through multiple layers

- Now, calculate saturation vapor pressure at each interface ($p_{w,s}$)
  - Remember: function of temperature only

$$\ln p_{ws} = C_8/T + C_9 + C_{10}T + C_{11}T^2 + C_{12}T^3 + C_{13}\ln T$$

where

$C_8 = -5.800\,220\,6\ \mathrm{E}{+}03$
$C_9 = 1.391\,499\,3\ \mathrm{E}{+}00$
$C_{10} = -4.864\,023\,9\ \mathrm{E}{-}02$
$C_{11} = 4.176\,476\,8\ \mathrm{E}{-}05$
$C_{12} = -1.445\,209\,3\ \mathrm{E}{-}08$
$C_{13} = 6.545\,967\,3\ \mathrm{E}{+}00$

Example: Vapor diffusion through multiple layers

- Saturation vapor pressure at each interface ($p_{w,s}$)

	Conductivity, k	Thickness, L	Conductance, U	Resistance, R	ΔT	T	T	$P_{w,sat}$
Layer material	**W/mK**	**m**	**W/m^2K**	**m^2K/W**	**°C**	**°C**	**K**	**Pa**
Indoors						21	294.2	2487.7
Interior film			8.0	0.125				
					0.7	20.3	293.5	2388.9
Concrete	1.8	0.15	12	0.083				
					0.4	19.9	293.1	2324.9
XPS	0.029	0.075	0.39	2.564				
					13.5	6.4	279.6	962.4
Air space		0.025	n/a	0.17				
					0.9	5.5	278.7	904.6
Brick	1.3	0.09	14.4	0.069				
					0.4	5.2	278.3	881.9
Exterior film			34	0.029				
Outdoors					0.2	5.0	278.2	872.5
			R_{total} (m^2K/W)	3.04				
			U_{total} (W/m^2K)	0.33				

Example: Vapor diffusion through multiple layers

- Will we have condensation?
  - Compare actual vapor pressure to saturation vapor pressure at each layer interface (p_w vs. $p_{w,s}$)

	Permeability	Thickness	Permeance	Resistance				
	μ	L	M_j	$R_{v,j}$	$\Delta P_{w,j}$	$P_{w,j}$	$P_{w,sat}$	RH
Layer material	**ng/(Pa-s-m)**	**m**	**ng/(Pa-s-m^2)**	**(Pa-s-m^2)/ng**	**Pa**	**Pa**	**Pa**	**%**
Indoors						1244	2487.7	50%
Interior film			15000	0.000067	0.3			
						1243.7	2388.9	52%
Concrete	2.6	0.15	17.3	0.058	301.7			
						942.0	2324.9	41%
XPS	2.0	0.075	26.7	0.0375	196.1			
						745.9	962.4	77%
Air space		0.025	7200	0.00014	0.7			
						745.1	904.6	82%
Brick	10	0.09	111	0.009	47.1			
						698.1	881.9	79%
Exterior film			75000	0.000013	0.1			
Outdoors						698	872.5	80%
			$R_{v,total}$	0.104				

No condensation under these conditions

Example: Vapor diffusion through multiple layers

- What happens if conditions change?
  - Interior stays same (21°C and 50% RH)
  - Exterior drops to -14°C and 80% RH

	Permeability	Thickness	Permeance	Resistance		
	μ	L	M_j	$R_{v,j}$	$\Delta P_{w,j}$	$P_{w,j}$
Layer material	**ng/(Pa-s-m)**	**m**	**ng/(Pa-s-m²)**	**(Pa-s-m²)/ng**	**Pa**	**Pa**
Indoors						1244
Interior film			15000	0.000067	0.7	
						1243.3
Concrete	2.6	0.15	17.3	0.058	595.6	
						647.7
XPS	2.0	0.075	26.7	0.0375	387.2	
						260.5
Air space		0.025	7200	0.00014	1.4	
						259.1
Brick	10	0.09	111	0.009	92.9	
						166.1
Exterior film			75000	0.000013	0.1	
Outdoors						166
			$R_{v,total}$	0.104		

Example: Vapor diffusion through multiple layers

- What happens if conditions change?
  - Interior stays same (21°C and 50% RH)
  - Exterior drops to -14°C and 80% RH

	Conductivity, k	Thickness, L	Conductance, U	Resistance, R	ΔT	T	T	$P_{w,sat}$
Layer material	**W/mK**	**m**	**W/m^2K**	**m^2K/W**	**°C**	**°C**	**K**	**Pa**
Indoors						21	294.2	2487.7
Interior film			8.0	0.125				
					1.4	19.6	292.7	2276.0
Concrete	1.8	0.15	12	0.083				
					1.0	18.6	291.8	2143.8
XPS	0.029	0.075	0.39	2.564				
					29.5	-10.9	262.2	266.7
Air space		0.025	n/a	0.17				
					2.0	-12.9	260.3	228.0
Brick	1.3	0.09	14.4	0.069				
					0.8	-13.7	259.5	213.6
Exterior film			34	0.029				
Outdoors					0.3	-14.0	259.2	207.8
			R_{total} (m^2K/W)	3.04				
			U_{total} (W/m^2K)	0.33				

Example: Vapor diffusion through multiple layers

- What happens if conditions change?
  - Interior stays same (21°C and 50% RH)
  - Exterior drops to -14°C and 80% RH

	Permeability	Thickness	Permeance	Resistance				
	μ	L	M_j	$R_{v,j}$	$\Delta P_{w,j}$	$P_{w,j}$	$P_{w,sat}$	RH
Layer material	ng/(Pa-s-m)	m	ng/(Pa-s-m^2)	(Pa-s-m^2)/ng	Pa	Pa	Pa	%
Indoors						1244	2487.7	50%
Interior film			15000	0.000067	0.7			
						1243.3	2276.0	55%
Concrete	2.6	0.15	17.3	0.058	595.6			
						647.7	2143.8	30%
XPS	2.0	0.075	26.7	0.0375	387.2			
						260.5	266.7	98%
Air space		0.025	7200	0.00014	1.4			
						259.1	228.0	114%
Brick	10	0.09	111	0.009	92.9			
						166.1	213.6	78%
Exterior film			75000	0.000013	0.1			
Outdoors						166	207.8	80%
			$R_{v,total}$	0.104				

Condensation will occur between air and brick
(RH > 100%)

Example: Vapor diffusion through multiple layers

- Now, RH can't technically be greater than 100%
- To continue the analysis, we would divide the wall into two sections
  - Analyze the sections independently
  - The reason is that if condensation occurs on a surface, some amount of moisture is removed at that interface
    - Assumption that mass flow in = mass flow out is **false**
    - Some vapor is removed (by conversion to condensate)
- Reality check:
  - Condensation plane will seldom be inside a highly porous material (i.e., not brick, stone, wood, or batt insulation)
  - As a general rule, the **condensation plane will usually be the next upstream-facing solid surface on the cold side of the dewpoint**
  - The condensation plane we pick will determine how we device the wall into two portions and continue

Example: Vapor diffusion through multiple layers

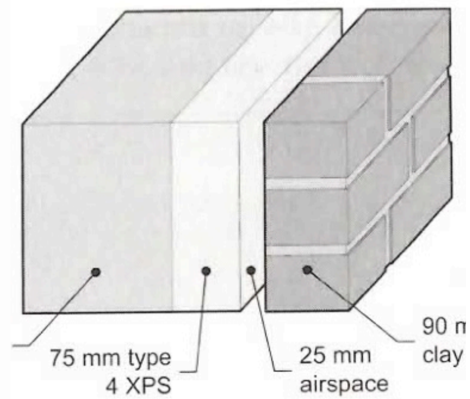
- Dividing a wall at the condensation plane

Procedure:

- Divide wall into two separate portions at the condensation plane
- Set the vapor pressure at the condensation plane equal to the saturation vapor pressure (RH = 100%)
  - This is more realistic and makes all calculations more accurate
- Analyze each portion of the divided wall separately using methods from previous example, but using the temperature and vapor pressure at the condensation plane as a boundary condition
  - For example: the interior portion of the divided assembly uses the vapor pressure at the condensation plane as the “exterior” vapor pressure

Example: Vapor diffusion through multiple layers

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·m²	
			-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·m²	
		Net Accumulation:		3827.	ng/·s·m²	



RH set to 100%

RH set to 100%

Example: Vapor diffusion through multiple layers

- What happened to the condensate?

ΣR_v	0.0954		$\Sigma \Delta P_w$	**1020.**
	Flow to:	$\Delta P / \Sigma R_v$	10689.	ng/·s·m^2

The vapor pressure difference from interior to edge of brick divided by the sum of the vapor resistances on this side of the wall division tells us the rate of inflow or outflow of vapor (inflow from interior to brick surface in this case)

- Similarly, on the other wall division:

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

Rate of outflow from brick surface to exterior

Example: Vapor diffusion through multiple layers

- The difference between the rate of vapor flow into the condensation plane and the rate of vapor flow away from the plane yields the net accumulation

ΣR_v	0.0090		$\Sigma \Delta P_w$	62.
	Flow away:	$\Delta P/\Sigma R_v$	6862.	$ng/\cdot s\cdot m^2$
	Net Accumulation:		3827.	$ng/\cdot s\cdot m^2$

- Net accumulation accounts for the rate of condensate formation
  - From vapor to liquid water
  - Net accumulation = 3827 ng/(s m^2) or 0.0137 grams per hr per m^2
    - This is not a lot of condensation
    - If conditions stayed the same for 24 hours, condensation due to vapor diffusion would make a layer of water ~1 µm thick (1 millionth of a meter)

Example: Vapor diffusion through multiple layers

- Even though vapor diffusion was low
  - What to do to prevent condensation under these conditions?
  - Look back at the table of materials
    - Brick, XPS, and concrete have the lowest permeance
    - What if we just add some ventilation to the brick cladding?

	Permeability	Thickness	Permeance	Resistance
	μ	L	M_j	$R_{v,j}$
Layer material	ng/(Pa-s-m)	m	ng/(Pa-s-m^2)	(Pa-s-m^2)/ng
Indoors				
Interior film			15000	0.000067
Concrete	2.6	0.15	17.3	0.058
XPS	2.0	0.075	26.7	0.0375
Air space		0.025	7200	0.00014
Brick	10	0.09	111	0.009
Exterior film			75000	0.000013
Outdoors				

Adding “weep holes” can increase permeance of brick cladding to **1000** ng/(Pa s m^2)

Example: Vapor diffusion through multiple layers

- Even though vapor diffusion was low
  - What to do to prevent condensation under these conditions?
  - Look back at the table of materials
    - Brick, XPS, and concrete have the lowest permeance
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	Permeability	Thickness	Permeance	Resistance
	μ	L	M_j	$R_{v,j}$
Layer material	ng/(Pa-s-m)	m	ng/(Pa-s-m^2)	(Pa-s-m^2)/ng
Indoors				
Interior film			15000	0.000067
Concrete	2.6	0.15	17.3	0.058
XPS	2.0	0.075	26.7	0.0375
Air space		0.025	7200	0.00014
Brick	10	0.09	1000	0.001
Exterior film			75000	0.000013
Outdoors				

Adding “weep holes” can increase permeance of brick cladding to **1000** ng/(Pa s m^2)

Example: Vapor diffusion through multiple layers

- Ventilated brick cladding eliminates condensation potential under these conditions

	Permeability	Thickness	Permeance	Resistance				
	μ	L	M_j	$R_{v,j}$	$\Delta P_{w,j}$	$P_{w,j}$	$P_{w,sat}$	RH
Layer material	**ng/(Pa-s-m)**	**m**	**ng/(Pa-s-m^2)**	**(Pa-s-m^2)/ng**	**Pa**	**Pa**	**Pa**	**%**
Indoors						1244	2487.7	50%
Interior film			15000	0.000067	0.7			
						1243.3	2276.0	55%
Concrete	2.6	0.15	17.3	0.058	645.1			
						598.2	2143.8	28%
XPS	2.0	0.075	26.7	0.0375	419.3			
						178.9	266.7	67%
Air space		0.025	7200	0.00014	1.6			
						177.3	228.0	78%
Brick	10	0.09	1000	0.001	11.2			
						166.1	213.6	78%
Exterior film			75000	0.000013	0.1			
Outdoors						166	207.8	80%
			$R_{v,total}$	0.096				

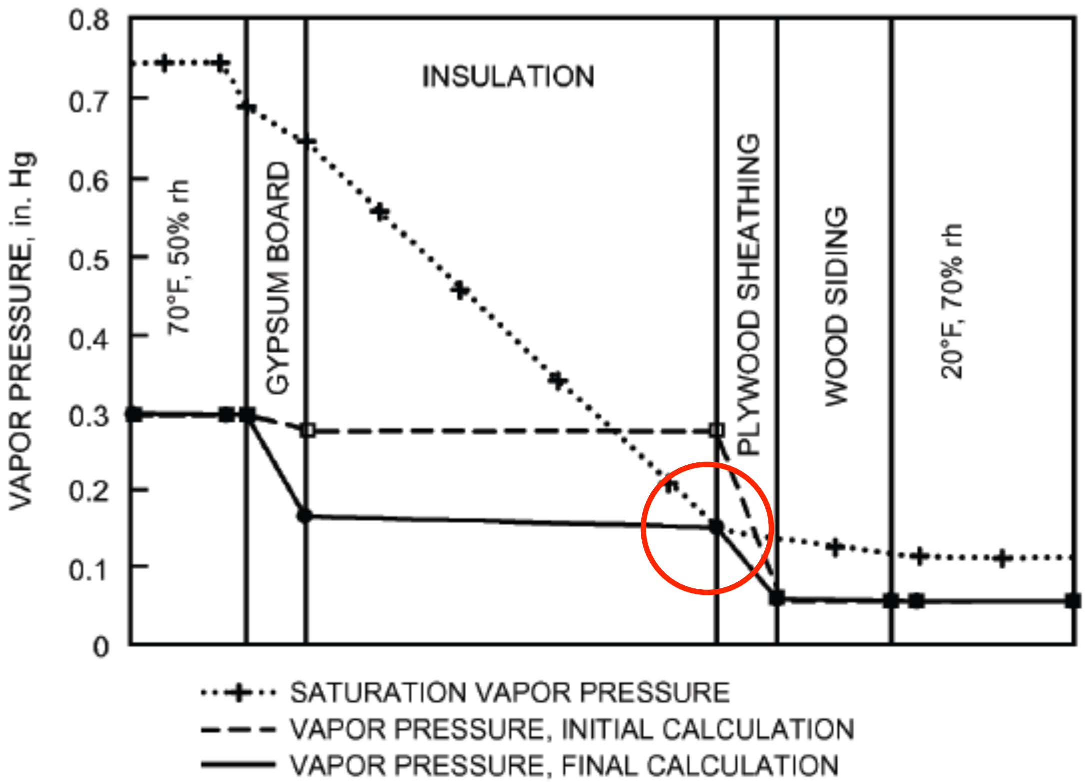
Vapor pressure diagrams

- We can plot the saturation vapor pressures and predicted vapor pressures on charts as a function of distance from the wall interior
  - Offers a way to interpret previous calculations graphically

- If the predicted pressure is above the saturation vapor pressure we will have condensation

- The ASHRAE handbook shows several examples of these charts

Vapor pressure diagrams

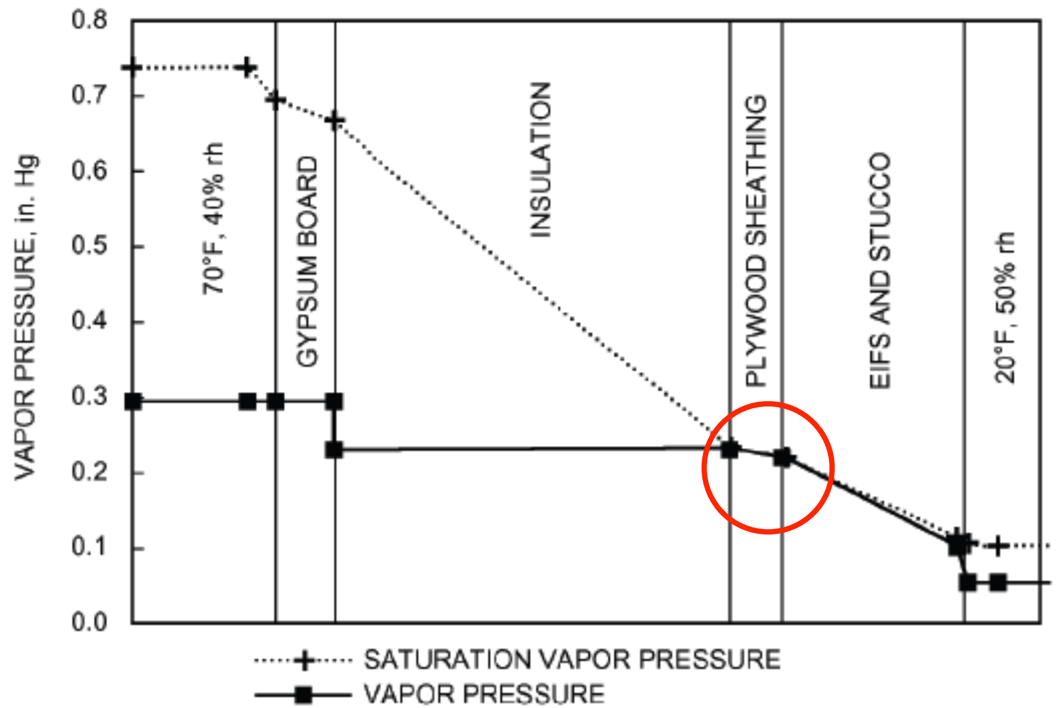


- Condensation is occurring between the insulation and the plywood
- Drying occurs to outside since it is lowest p_w

Vapor pressure diagrams

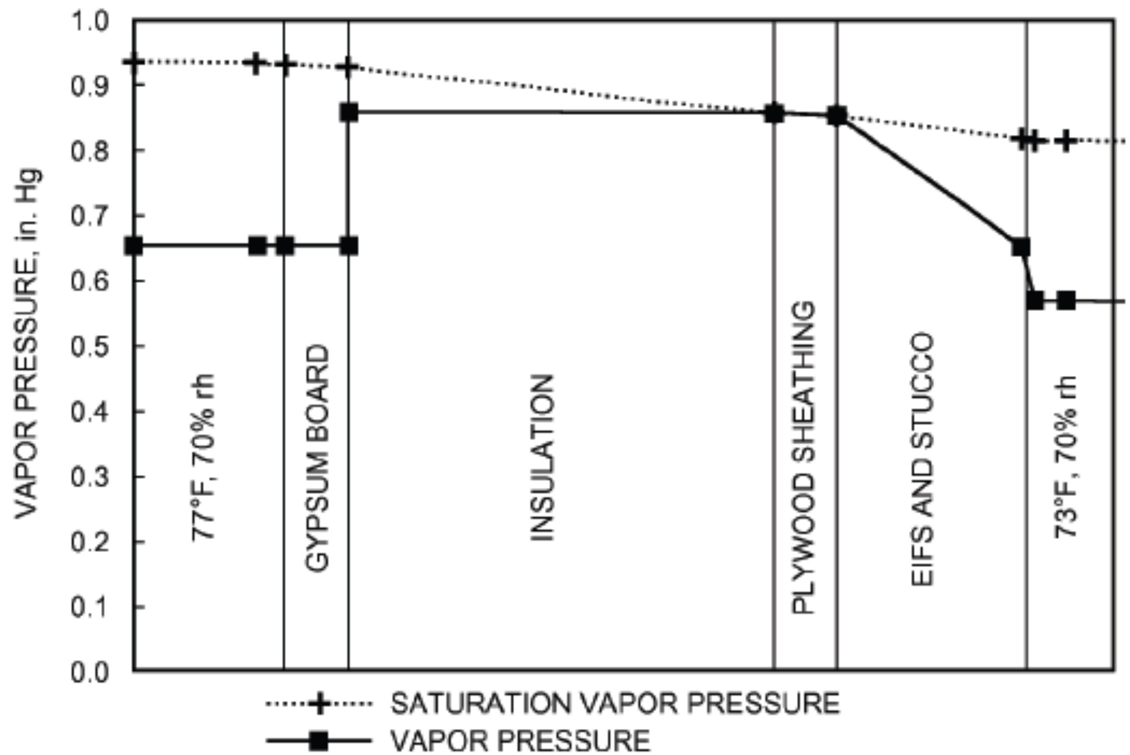
- Condensation between insulation and sheathing and possibly between sheathing and EIFS

- Drying occurs to outside



Vapor pressure diagrams

- Condensation on this sheathing can dry to either outside or inside



Bulk air movement and vapor transport

- Vapor diffusion is often a relatively small contributor to vapor transport
  - Bulk movement of air usually transports far more water vapor than diffusion

- The capacity of air to hold water vapor is high enough that bulk air movement can transport a significant amount of moisture
  - Forced or natural convection
  - When air comes in contact with enclosure surfaces, condensation will occur at those surfaces below the air's dew point temperature
    - We can attempt to calculate the quantity of condensation at surfaces

Bulk air movement and vapor transport

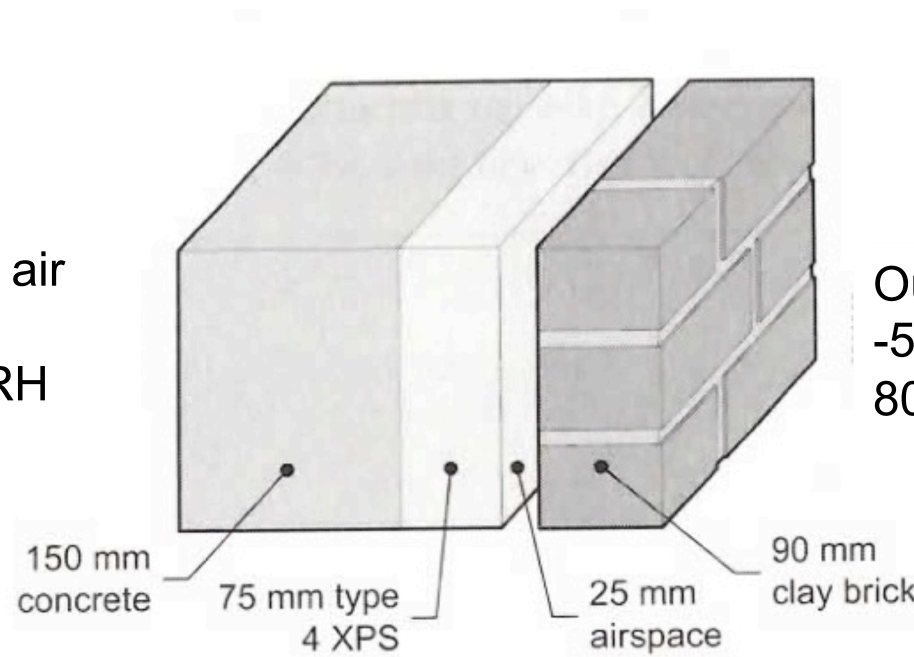
- Calculating the quantity of air leakage condensation in enclosures is difficult to do accurately
  - But given a flow rate, we can find the maximum amount of condensation that could occur

- We say “maximum amount” because several issues prevent easy and accurate calculation
  - Method assumes steady state diffuse (1-D) convection flow
  - Large flows of air will tend to alter temperatures near the actual flow path (i.e., if warm air entering an envelope actually warms the surface it’s passing over, less condensation than we predict will occur)
  - Some moist air will pass through the assembly without actually contacting the surface that we’re assuming condensation may be occurring
  - Flow through some enclosures is incredibly complex (think: flow through mineral fiber insulations – our 1-D steady state assumptions lead to inaccuracies)

Example: Bulk air movement and vapor transport

- Let's calculate the volume of condensation that would form if we had bulk air leakage through this assembly
  - Air leakage rate of 0.5 L per second per m^2 of exfiltration
    - Air moving from interior to exterior

Inside air
21°C
50% RH



Outside air
-5°C
80% RH

Example: Bulk air movement and vapor transport

- Method:
  1. Calculate temperature at every layer
  2. Calculate moisture content (i.e., humidity ratio) and dewpoint temperature of the interior or exterior air
  3. Calculate saturation vapor pressure of the first **upstream-facing** surface in the enclosure that is below the dewpoint temperature of the stream of air
  4. The maximum amount of condensate transported by bulk convection (and thus deposited on the condensation plane) is the moisture content of the indoor air minus the saturation moisture content of air at this particular layer

Example: Bulk air movement and vapor transport

1. Calculate temperature at every layer

	Conductivity, k	Thickness, L	Conductance, U	Resistance, R	ΔT	T	T	$P_{w,sat}$
Layer material	**W/mK**	**m**	**W/m^2K**	**m^2K/W**	**°C**	**°C**	**K**	**Pa**
Indoors						21	294.2	2487.7
Interior film			8.0	0.125				
					1.1	19.9	293.1	2328.9
Concrete	1.8	0.15	12	0.083				
					0.7	19.2	292.4	2228.0
XPS	0.029	0.075	0.39	2.564				
					21.9	-2.7	270.4	501.2
Air space		0.025	n/a	0.17				
					1.5	-4.2	269.0	449.6
Brick	1.3	0.09	14.4	0.069				
					0.6	-4.7	268.4	429.9
Exterior film			34	0.029				
Outdoors					0.3	-5.0	268.2	421.8
			R_{total} (m^2K/W)	3.04				
			U_{total} (W/m^2K)	0.33				

Example: Bulk air movement and vapor transport

2. Calculate moisture content and dewpoint temperature of the interior and exterior air

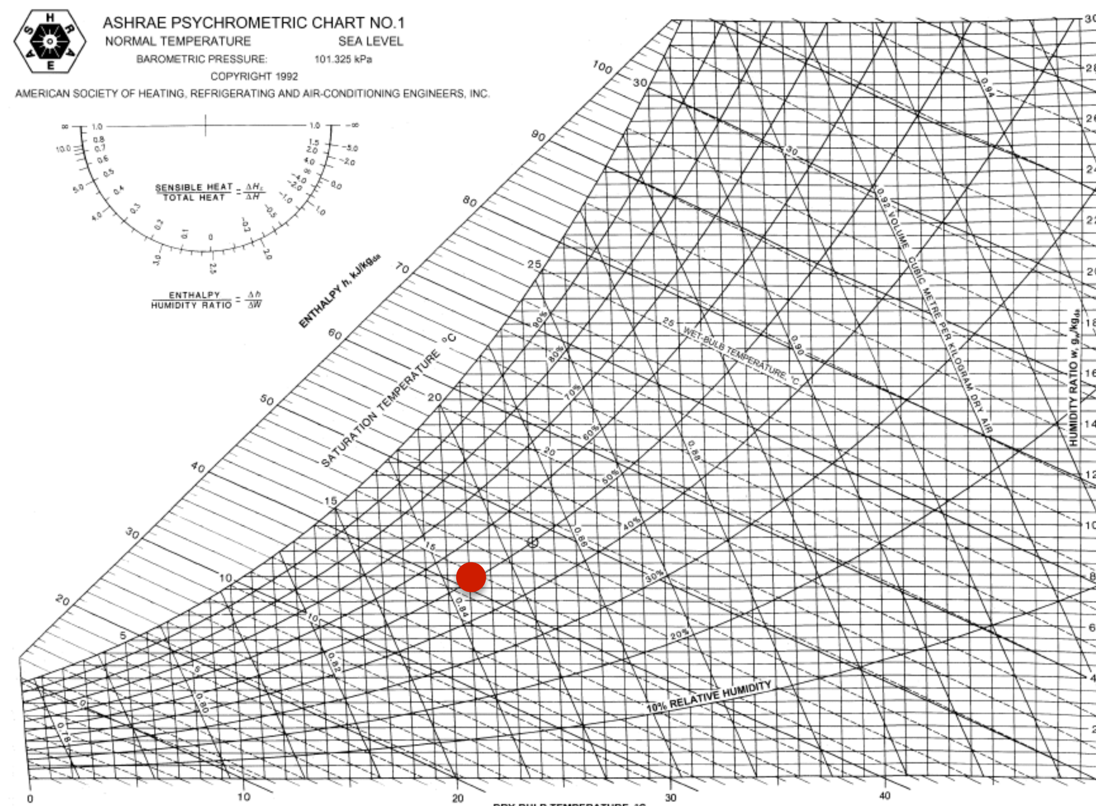
p_{ws} at boundaries:

Indoor (21°C, 50%RH) → p_{ws} = 2488 Pa

$p_w = 0.5(2488) = 1244$ Pa → $W_{surf} = 0.622p_w/(p_{total} - p_w)$

$W_{surf} = 0.622(1244)/(101325 - 1244) = 0.00773\ kg_w/kg_{da}$

$T_{dew\ point} = \sim 10.2°C$



Example: Bulk air movement and vapor transport

3. Calculate saturation vapor pressure of the first surface in the enclosure that is below the dewpoint of the stream of air (T_{dew} = 10.2°C)

	Conductivity, k	Thickness, L	Conductance, U	Resistance, R	ΔT	T	T	$P_{w,sat}$
Layer material	**W/mK**	**m**	**W/m²K**	**m²K/W**	**°C**	**°C**	**K**	**Pa**
Indoors						21	294.2	2487.7
Interior film			8.0	0.125				
					1.1	19.9	293.1	2328.9
Concrete	1.8	0.15	12	0.083				
					0.7	19.2	292.4	2228.0
XPS	0.029	0.075	0.39	2.564				
					21.9	-2.7	270.4	501.2
Air space		0.025	n/a	0.17				
					1.5	-4.2	269.0	449.6
Brick	1.3	0.09	14.4	0.069				
					0.6	-4.7	268.4	429.9
Exterior film			34	0.029				
Outdoors					0.3	-5.0	268.2	421.8
			R_{total} (m²K/W)	3.04				
			U_{total} (W/m²K)	0.33				

The exterior side of the XPS insulation is the first surface below dew point of air stream

BUT, remember our rule for the first "upstream-facing" solid surface

Upstream = inside ($p_{w,in} > p_{w,out}$) & XPS side faces out

Choose upstream-facing brick surface (T = -4.2 °C)

$p_{w,sat}$ = 450 Pa → W = 0.622(450)/(101325 – 450) = 0.00279 kg_w/kg_{da}

Example: Bulk air movement and vapor transport

4. Maximum amount of condensate transported by bulk convection and deposited on the condensation plane

Mass flow rate of vapor at 0.5 L/s per m^2, assuming density of air is ~1.2 kg/m^3:

$\dot{m}$ = 1.2 kg/m^3 * (0.5 L/s) (1 m^3 / 1000 L) per m^2

$\dot{m}$ = 0.0006 kg/s per m^2

Under ideal conditions, moisture will condense on the back of the brick at the following rate:

$(W_{in} – W_{sat,condensation\ plane}) * \dot{m}$ = (7.73 g/kg – 2.79 g/kg)*(0.0006 kg/s) per m^2

Condensation rate = 4.97×10^{-3} g/s per m^2

or Condensation rate = 17.9 g/hour per m^2

Remember: condensation rate due to **diffusion** in last example was: 0.0137 g/hr per m^2

Over 1000 times more condensation by bulk convection than by diffusion!

Bulk air movement and vapor transport

- Equivalent vapor permeance for various airflow rates:

Airflow rate (L/s per m^2)	Equiv. vapor permeance ng/(s m^2 Pa)
0.05	375
0.10	750
0.25	1875
0.50	3750
1.00	7500
3.00	22600

  - For comparison: vapor permeance of brickwork and wood siding is approximately 50 ng /(s m^2 Pa)
  - We will learn more about airflows in enclosures in a future lecture

Limitations of the Glaser Method

- Steady state calculations
  - Temperature and humidity are actually always changing

- Static material properties
  - We cannot easily vary material properties (which vary with RH) without recalculating

- Does not take moisture storage into account
  - Porous materials like wood and masonry can hold very large amounts of water

- These are pretty huge limitations!

Advanced “hygro-thermal” analysis

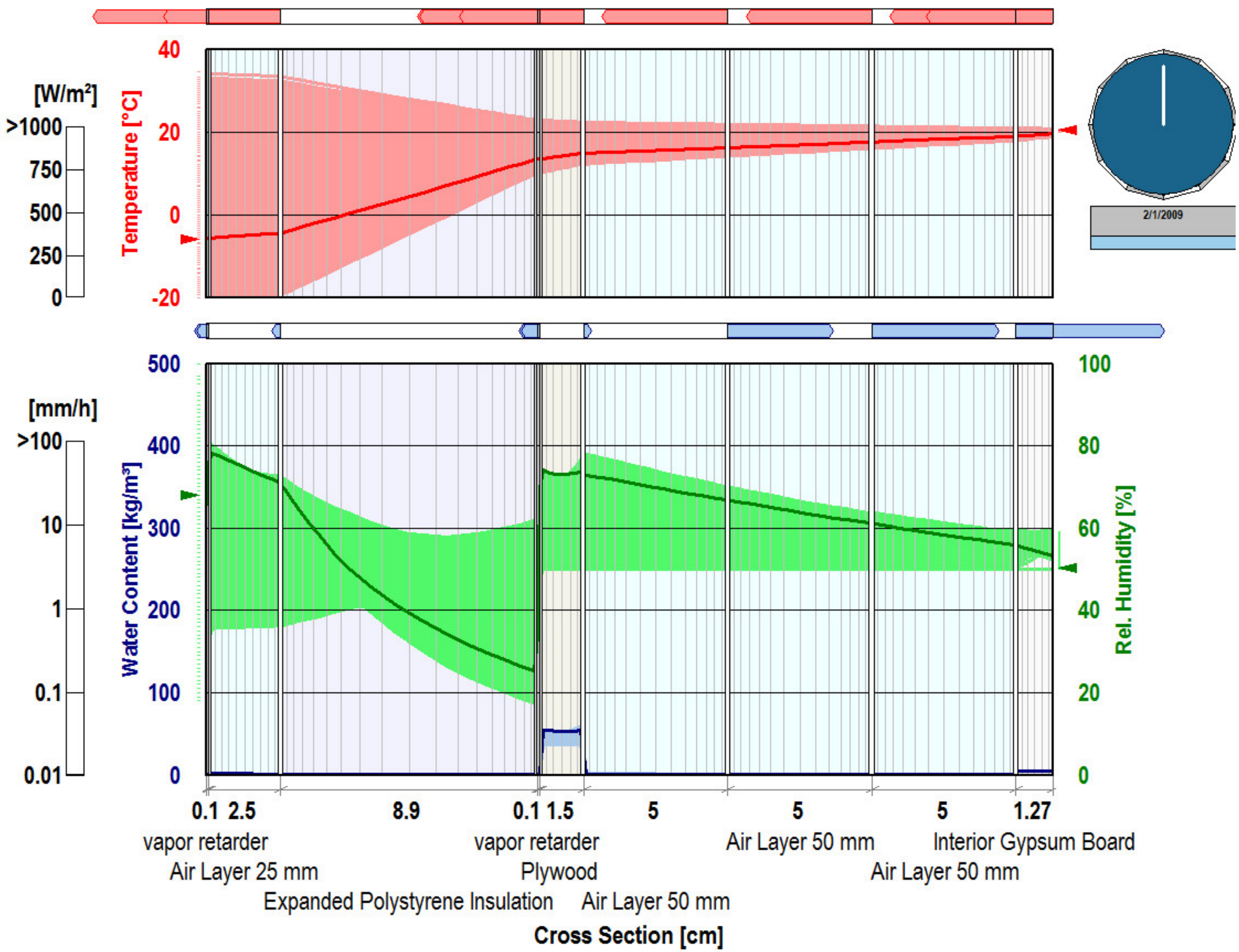
- A more complete analysis will find temperature, heat flow, moisture flow and moisture diffusion with changing interior and exterior conditions
  – Including changing material properties
  – Including thermal and moisture storage

- We call this hygrothermal analysis
  – There are free software packages available to do this
  – The most popular is WUFI
  – http://www.wufi-pro.com/

WUFI

- WUFI applies a limited finite element analysis to walls and roofs
  - **WUFI** stands for **W**ärme- **U**nd **F**euchtetransport **I**nstationär (Transient heat and moisture transport)
  - Assumes homogenous layers and only 1-D heat transfer
- Thermal and vapor diffusion are calculated
  - Includes solar radiation and real time-varying weather data
- Moisture transport by air infiltration can be added
- Liquid transport and by capillary suction can be included as well

WUFI



[W/m²]
>1000
750
500
250
0
Temperature [°C]
40
20
0
-20
2/1/2009
[mm/h]
>100
10
1
0.1
0.01
Water Content [kg/m³]
500
400
300
200
100
0
Rel. Humidity [%]
100
80
60
40
20
0
0.1 2.5 8.9 0.1 1.5 5 5 5 1.27
vapor retarder
Air Layer 25 mm
Expanded Polystyrene Insulation
vapor retarder
Plywood
Air Layer 50 mm
Air Layer 50 mm
Air Layer 50 mm
Interior Gypsum Board
Cross Section [cm]

WUFI

- The commercial version of WUFI is available at http://www.wufi-pro.com/ at a cost of €1950 ≈ $2600

- A free limited version is available from Oak Ridge National Lab (ORNL) who helped support development
  - WUFI Light or WUFI ORNL
  - http://www.ornl.gov/sci/ees/etsd/btric/wufi/
  - You can get a free copy but you have to register (free)
    - Only WUFI Light seems to work
  - **Demo film:** http://www.hoki.ibp.fhg.de/wufi/Movie/Movie_Pro_E/Movie_Pro_E.htm

WUFI

- You will use both WUFI and our hand-calculation methods in the next homework