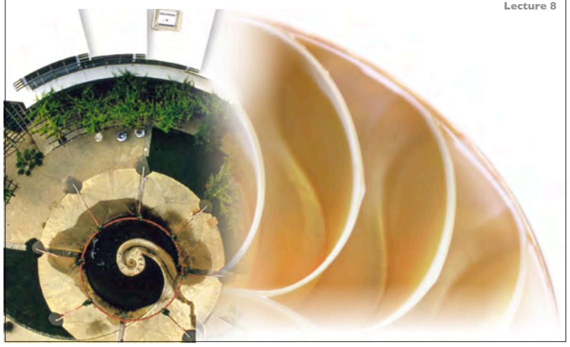
Whole Building Heat Transfer
Part 2

ARCH 331/431 Spring 2008
Lecture 8



announcements 4/24/08

A3: Envelope Heat Transfer

References: Available by this weekend (course website)

Due next week

Lecture: Tonight, 6:30 in Kane Hall, Room 210

Lars Gemzøe Architect MAA,Associate Partner, Gehl Architects, Copenhagen, Denmark

Global Green: A lecture/panel series showcasing Danish and Pacific Northwest Sustainable Planning and Design: "PLACES FOR PUBLIC LIFE:WINNING BACK PUBLIC SPACE AROUND THE WORLD."

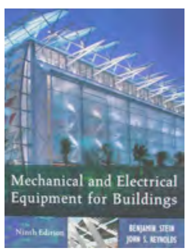
Assigned Readings by Section (not page)

ON RESERVE
caup library

9th Edition

Chapter 4

Thermal Properties of Building and Insulations Materials (beginning on page 147)



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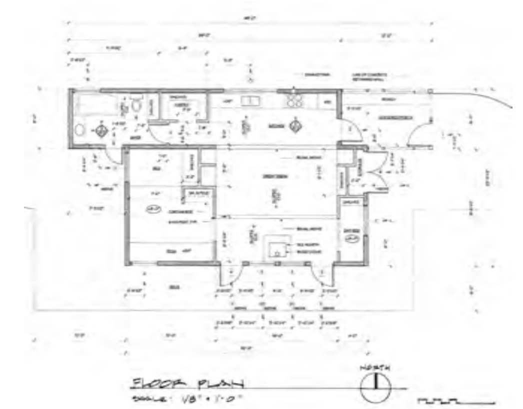
Appendix E

Thermal Properties of Materials and Assemblies (beginning on page 1547)



1. ENVELOPE UA

U x A
BTU/hr ft² °F x ft²

2. INFILTRATION "UA"

VHC_{air} x Volume x ACH
018 BTU/ft³ °F x ft³ x no./hr

3. PERIMETER "UA"

F x P
(BTU/hr ft °F) x (ft)

STEP 1: Envelope Heat Transfer Coefficient (UA conduction)

Building Element Orientation	Building Element Element	U-value BTU/hr ft² °F	Area ft²	U x Area BTU/hr °F	Description
South	Door C				
	Window D				
	Door 4				
	Windows E (2)				
	Door 5				
	Walls				
East	Window C				
	Doors 6				
	Door 2				
	Walls				
North	Windows A (3)				
	Window B				
	7 Window				
	8 Window				
	3 Door				
	Walls				
West	Window C				
	Ceiling/Roof				
			UA conduction		

STEP 2: Infiltration Heat Loss ("UA" infiltration)

Volumetric Heat Capacity (Air) 0.0 BTU/ft³ °F
Building Volume (ft³) ft³
Air Changes per Hour (ACH) ACH

"UA" infiltration = VHC x Volume x ACH 0.0 BTU/hr °F

STEP 3: Perimeter Heat Loss ("UA" perimeter)

Heat loss coefficient (F) BTU/hr °F ft
Length of building perimeter (P) ft³

"UA" perimeter = F x P 0.0 BTU/hr °F

Determining UA

Step 1: The Building Envelope (conductive heat transfer)

$$Q = UA_{envelope} \times \Delta T$$

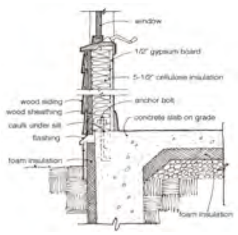
Q = Heat loss or gain (Btu/h)
U = conductance (Btu/h sf °F)
A = area (sf)
$\Delta T = T_{outside} - T_{inside}$ (°F)

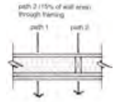
U ~ C (conductance)
C = 1/R (resistance)

Finding UA is a process of finding the R-values of each layer of the building envelope

SERIES HEAT TRANSFER

	k conductivity BTU - in / hr ft² °F	C Conductance BTU / hr ft² °F	R Resistance hr ft² °F / BTU	Path 1 (insulation) hr ft² °F / BTU	Path 2 (framing) hr ft² °F / BTU
outside air film					
1/2" wood siding		1.24			
1/2" medium density particleboard					
5-1/2" fiberglass batt insulation					
5-1/2" wood framing (Douglas Fir)					
1/2" gypsum board					
Inside Air Film					
			R total		
				x 85%	x 15%
			Paths 1 & 2		
			Overall R-value of Walls & Ceiling		
			Overall U-value of Walls & Ceiling		





PARALLEL HEAT TRANSFER

STEP 1: Envelope Heat Transfer Coefficient (UA conduction)

Building Element Orientation	Element	U-value BTU/hr ft² °F	Area ft²	U x Area BTU/hr °F	Description
South	Door C				
	Window D				
	Door 4				
	Windows E (2)				
	Door 5				
	Walls				
East	Window C				
	Doors 6				
	Door 2				
	Walls				
North	Windows A (3)				
	Window B				
	7 Window				
	8 Window				
	3 Door				
	Walls				
West	Window C				
	Ceiling/Roof				
			UA conduction		

Determining UA

Step 2: Infiltration (convective heat transfer)

$$Q = .018 \times V_{air} \times ACH \times \Delta T$$

Q = heat loss or gain

.018 = volumetric heat capacity of air (BTU/ft³ °F)

ACH = air changes per hour

V_{air} = volume of air (ft³)

ΔT = $T_{inside} - T_{outside}$

STEP 2: Infiltration Heat Loss ("UA" infiltration)

Volumetric Heat Capacity (Air)	0.018	BTU/ft³ °F
Building Volume (ft³)	9216	ft³
Air Changes per Hour (ACH)	1.30	ACH
"UA" infiltration = VHC x Volume x ACH	216	BTU/hr °F

Farnsworth House
UA_{ref}

Farnsworth House Heat Transfer Coefficient (UA conduction)

Building Element Orientation	Element	U-value BTU/hr ft² °F	Area ft²	U x Area BTU/hr °F	Description
South	Walls, Doors and Windows	1.124	384	432	
				0	
East	Walls, Doors and Windows	1.124	192	216	
				0	
North	Walls, Doors and Windows	1.124	384	432	
				0	
West	Walls, Doors and Windows	1.124	192	216	
				0	
Ceiling/Roof		0.158	1152	182	
				0	
Floor		0.112	1152	129	
				0	
			UA conduction =	1606	BTU/hr °F

STEP 2: Infiltration Heat Loss ("UA" infiltration)

Volumetric Heat Capacity (Air)	0.018	BTU/ft³ °F
Building Volume (ft³)	9216	ft³
Air Changes per Hour (ACH)	1.30	ACH
"UA" infiltration = VHC x Volume x ACH	216	BTU/hr °F

STEP 3: Perimeter Heat Loss ("UA" perimeter)

Heat loss coefficient (F)	na	BTU/hr °F ft
Length of building perimeter (P)	na	ft³
"UA" perimeter = F x P	na	BTU/hr °F
$UA_{reference}$	1822	BTU/hr °F

Note:
Step 3, "$UA_{perimeter}$" is not applicable since the Farnsworth House is not built with the floor in contact with the earth.

*If the Farnsworth House was built with a slab-on-grade or a basement condition, the **Perimeter Heat Loss** would have to be considered (Step 3) as follows:*

Step 3: Perimeter

for slab-on-grade or basement conditions - not applicable to the Farnsworth House

$$Q = F \times P \times \Delta T$$

F = empirically derived constant (Table E.11, pg. 1582)

P = length of perimeter (ft)

ΔT = $T_{inside} - T_{outside}$

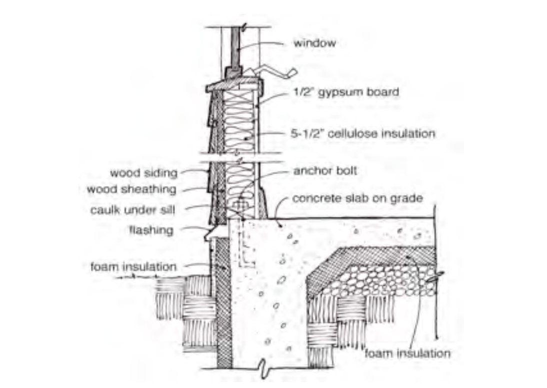


Table E.12

TABLE E.12 Heat Flow Coefficients (F_2) for Slab-on-Grade Floors with Various Insulation Strategies

R-Value, Position, and Width (or Depth) of Insulation	F_2 (Btu/h ft °F)	F_2 (W/m K)
Uninsulated slab	0.73	1.26
R-5 (SI: R-0.88) Horizontal insulation, 2 ft (0.6 m), no thermal break	0.70	1.21
R-10 (SI: R-1.76) Horizontal insulation, 2 ft (0.6 m), no thermal break	0.70	1.21
R-15 (SI: R-2.64) Horizontal insulation, 2 ft (0.6 m), no thermal break	0.69	1.19
R-5 (SI: R-0.88) Horizontal insulation, 4 ft (1.2 m), no thermal break	0.67	1.16
R-10 (SI: R-1.76) Horizontal insulation, 4 ft (1.2 m), no thermal break	0.64	1.11
R-15 (SI: R-2.64) Horizontal insulation, 4 ft (1.2 m), no thermal break	0.63	1.09
R-5 (SI: R-0.88) Vertical insulation, 2 ft (0.6 m)	0.58	1.00
R-10 (SI: R-1.76) Vertical insulation, 2 ft (0.6 m)	0.54	0.93
R-15 (SI: R-2.64) Vertical insulation, 2 ft (0.6 m)	0.52	0.90
R-5 (SI: R-0.88) Vertical insulation, 4 ft (1.2 m)	0.54	0.93
R-10 (SI: R-1.76) Vertical insulation, 4 ft (1.2 m)	0.48	0.83
R-15 (SI: R-2.65) Vertical insulation, 4 ft (1.2 m)	0.45	0.78
R-10 (SI: R-1.76) Fully insulated slab (insulated under entire slab as well as around edge)	0.36	0.62

Source: Super Good Cents Heat Loss Reference, Vol. 1, Ecotope Group, for Bonneville Power Administration, 1988.
Insulation is extruded polystyrene, R = 5.0 h ft² °F/Btu-in. (SI: R = 34.7 m K/W).
Soil conductivity is 0.75 Btu/h ft °F (1.30 W/K m).
No thermal break at edge of slab, where so indicated. If a thermal break is provided with horizontal insulation, use the corresponding value for vertical insulation.
Values assume an unheated slab (as per data in Table A-16 of ANSI/ASHRAE/IESNA Standard 90.1-2001, *Energy Standard for Buildings Except Low-Rise Residential Buildings*); F_2 values increase substantially when slab is heated.

Table E.11

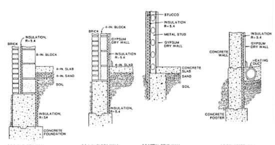
TABLE E.11 Heat Loss Coefficients (F_2) for Slab-on-Grade Floors

		Btu/h °F ft Perimeter Degree Days (65°F base)			W/K m Perimeter Degree Days (18°C base)		
Construction[a]	Insulation	2950	5350	7433	1640	2970	4130
(a) Block wall, 8 in. (200 mm), brick facing	Uninsulated	0.62	0.68	0.72	1.07	1.17	1.24
	Insulated from edge to footer: R-5.4 h ft² °F/Btu (SI: R-0.95 m² K/W)	0.48	0.50	0.56	0.83	0.86	0.97
(b) Block wall, 4 in. (100 mm), brick facing	Uninsulated	0.80	0.84	0.93	1.38	1.45	1.61
	Insulated from edge to footer: R-5.4 h ft² °F/Btu (SI: R-0.95 m² K/W)	0.47	0.49	0.54	0.81	0.85	0.93
(c) Metal stud wall, stucco	Uninsulated	1.15	1.20	1.34	1.99	2.07	2.32
	Insulated from edge to footer: R-5.4 h ft² °F/Btu (SI: R-0.95 m² K/W)	0.51	0.53	0.58	0.88	0.92	1.00
(d) Poured concrete wall with duct near perimeter[b]	Uninsulated	1.84	2.12	2.73	3.18	3.67	4.72
	Insulated from edge to footer, and 3 ft. [910 mm] under floor slab R-5.4 h ft² °F/Btu (SI: R-0.95 m² K/W)	0.64	0.72	0.90	1.11	1.24	1.56

Source: Reprinted with permission of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. from 2001 *ASHRAE Handbook—Fundamentals*. The SI units for F_2 shown in the last three columns were appended to the ASHRAE I-P data by the authors.
[a]See Fig. E.1 for illustrations of the listed constructions.
[b]Weighted average temperature of heating duct was assumed to be 110°F (43°C) during the heating season (outdoor air temperature less than 65°F [18°C]).
Note: To use this table:

$$q = F_2 P \Delta t$$

where
q = heat loss through perimeter (Btu/h or W)
F_2 = heat loss coefficients from above
P = perimeter of exposed slab edge (ft or m)
Δt = temperature difference between indoor and outdoor air (°F or °C).
Do not assume additional losses from the slab to the earth below. Heat gains are assumed to be nonexistent.



STEP 3: Perimeter Heat Loss ("UA" perimeter)

Heat loss coefficient (F)	0.36	BTU/hr °F ft
Length of building perimeter (P)	127.0	ft³
"UA" perimeter = F x P	**46**	BTU/hr °F

Farnsworth House
UA_{ref}

Farnsworth House Heat Transfer Coefficient (UA conduction)

Building Element: Orientation	Building Element: Element	U-value BTU/hr ft² °F	Area ft²	U x Area BTU/hr °F	Description
South	Walls, Doors and Windows	1.124	384	432	
				0	
East	Walls, Doors and Windows	1.124	192	216	
				0	
North	Walls, Doors and Windows	1.124	384	432	
				0	
West	Walls, Doors and Windows	1.124	192	216	
				0	
Ceiling/Roof		0.158	1152	182	
				0	
Floor		0.112	1152	129	
				0	
			UA conduction =	**1606**	BTU/hr °F

STEP 2: Infiltration Heat Loss ("UA" infiltration)

Volumetric Heat Capacity (Air)	0.018	BTU/ft³ °F
Building Volume (ft³)	9216	ft³
Air Changes per Hour (ACH)	1.30	ACH
"UA" infiltration = VHC x Volume x ACH	**216**	BTU/hr °F
$UA_{reference}$	**1822**	BTU/hr °F

Winter Hourly Heat Loss

Predicting Building Heat Loss Under Worst Case (Winter Design) Conditions:

$$Q_{losses} = UA_{ref} \times \Delta T$$

$$\text{Rate of Fuel Use} = \frac{UA_{ref} \times \Delta T}{V \times \text{Efficiency}}$$

Fuel	Heating Value (V)	Typical Efficiency (%)
No. 2 oil:	141,000 BTU/gal	75
Natural Gas	1,050 BTU/ft³	75
Propane	2,500 BTU/ft³	75
Electricity	3413 BTU/kW	100

Winter Hourly Heat Loss

Predicting Building Heat Loss Under Worst Case (Winter Design) Conditions:

Chicago Design Conditions	
Winter Design Temp. (97.5%)	-4°F
HDD65°F	6013
Summer Design Temp. (2.5%)	89/74

Furnace (heating plant capacity) Sizing:

Q_{losses} = $UA_{ref} \times \Delta T$ = 1822 BTU/hr °F × (68° - (-4°))
Q_{losses} = **131,184 BTU/hr**

Rate of Fuel Consumption:

Rate of Fuel Use = 131,184 BTU/hr / (1050 BTU/ft³ x .75)
Rate of Fuel Use = **167 ft³/hr** (natural gas)

Seasonal Heating Calculations

Predicting Annual Purchased Heating

$$E = \frac{(UA)\,(DegreeDays)\,(24\ hr)}{(AFUE)\ \ (V)}$$

Some Typical Values for Annual Fuel Utilization Efficiency:

Type of Furnace	AFUE
Natural Gas, natural-draft w/standing pilot	64.5%
Natural Gas, fan-assisted combustion	80.0%
Oil, standard w/improved heat transfer	76.0%

Seasonal Heating Calculations

Predicting Annual Purchased Heating

$$E = \frac{(1822\ BTU/hr\ {}^\circ F)\ (6013\ {}^\circ F\ days)\ (24\ hrs/day)}{(.80)\ (1{,}050\ BTU/ft^3)}$$

E = **313,020 ft³** natural gas per year

Farnsworth House UA_{ref}

AS BUILT

Farnsworth House Heat Transfer Coefficient (UA conduction)

Building Element: Orientation	Element	U-value BTU/hr ft² °F	Area ft²	U x Area BTU/hr °F	Description
South	Walls, Doors and Windows	1.124	384	432	
				0	
East	Walls, Doors and Windows	1.124	192	216	
				0	
North	Walls, Doors and Windows	1.124	384	432	
				0	
West	Walls, Doors and Windows	1.124	192	216	
				0	
Ceiling/Roof		0.158	1152	182	
				0	
Floor		0.112	1152	129	
				0	
			UA conduction =	1606	BTU/hr °F

STEP 2: Infiltration Heat Loss ("UA" infiltration)

Volumetric Heat Capacity (Air)	0.018	BTU/ft³ °F
Building Volume (ft³)	9216	ft³
Air Changes per Hour (ACH)	1.30	ACH

"UA" infiltration = VHC x Volume x ACH — **216** BTU/hr °F

$UA_{reference}$ **1822** BTU/hr °F

Farnsworth House UA_{ref}

AFTER RENOVATIONS

Farnsworth House Heat Transfer Coefficient (UA conduction)

Building Element: Orientation	Element	U-value BTU/hr ft² °F	Area ft²	U x Area BTU/hr °F	Description
South	Walls, Doors and Windows	**0.038**	384	15	
				0	
East	Walls, Doors and Windows	**0.038**	192	7	
				0	
North	Walls, Doors and Windows	**0.038**	384	15	
				0	
West	Walls, Doors and Windows	**0.038**	192	7	
				0	
Ceiling/Roof		0.158	1152	182	
				0	
Floor		0.112	1152	129	
				0	
			UA conduction =	355	BTU/hr °F

STEP 2: Infiltration Heat Loss ("UA" infiltration)

Volumetric Heat Capacity (Air)	0.018	BTU/ft³ °F
Building Volume (ft³)	9216	ft³
Air Changes per Hour (ACH)	0.51	ACH

"UA" infiltration = VHC x Volume x ACH — **85** BTU/hr °F

$UA_{reference}$ **439** BTU/hr °F

439 BTU/hr °F
vs.
1822 BTU/hr °F

76% improvement

Balance Point Temperature

Thermal Equilibrium between Inside and Outside

$Q_{in} = Q_{out}$
$Q_{gains} = Q_{losses}$

$Q_{gains} = Q_{free} + Q_{purchased} = Q_{losses}$

Q_{free} = people + lights + equipment (and sun!)
$Q_{purchased}$ = purchased heat (boiler, furnace, etc.)

$Q_{losses} = UA \times (T_{in} - T_{outside}) = UA \times \Delta T$

Balance Point Temperature:

$T_{balance\ point} = T_{in} - Q_{gains} / UA$

Determine Internal Loads

PEOPLE • LIGHTS • **EQUIPMENT**
ENVELOPE • INFILTRATION

F.3 ESTIMATING SUMMER HEAT GAINS MEEB 10th, pg. 1610

TABLE F.3 Approximate Summer Heat Gains from Occupants, Equipment, Lighting, and Envelope

Part A. Internal Heat Sources—People and Equipment

	Area per Person		Sensible Heat Gain (Btu/h ft² of Floor Area)			Sensible Heat Gain (W/m² of Floor Area)		
Function	ft²	m²	People	Equipment	Total	People	Equipment	Total
Office, U.S.	180–100	16.7–9.3	1.3–2.3	0.4–1.1	1.7–3.4	4.1–7.3	1.2–3.4	5.3–10.7
Office, Europe			1–1.6	2.2–4.2	3.2–5.8	3–5	7–13.1	10–18.1
School: elementary, U.S.	100–20	9.3–1.9	2.3–11.5	0–0.6	2.3–12.1	7.3–36.3	0–2.0	7.3–38.3
Schools, Europe			3.8–8.0	0–0.6	3.8–8.6	12–25.2	0–2.0	12.0–27.2
School: secondary, college	150–100	13.9–9.3	1.7–2.6	0–0.6	1.7–3.2	5.4–8.2	0–2.0	5.4–10.2
Health care								
Sleeping (hospital)	240	22.3	0.9	0.6	1.5	2.8	2.0	4.8
In-patient (clinic)	120	11.1	1.9	Varies	1.9+	6.0	Varies	6.0+
Assembly: fixed seats	15	1.4	14.0	—	14.0	44.2	—	44.2
standing space, concentrated use	15–7	1.4–0.7	21.0–45.0	0–0.5	21.0–45.5	66.3–142.0	0–1.6	66.3–143.6
Restaurant								
Fast food: dining area	15	1.4	17	3.4	20.4	53.6	10.7	64.3
Kitchen, refrigeration				17.1	17.1		54.0	54.0
Sit-down: dining area	25	2.3	10.2	5.1	15.3	32.2	16.1	48.3
Kitchen, refrigeration				7.2	7.2		22.7	22.7
Mercantile: street floor	50–30	4.7–2.8	6.3–10.5	3.4	9.7–13.9	19.9–33.1	10.7	30.6–43.8
Other sales floors	60–50	5.6–4.7	5.3–6.3	3.4	8.7–9.7	16.7–19.9	10.7	27.4–30.6
Shopping center, Europe			3.2	0.3–1.3	3.5–4.5	10	1.0–4.0	11.0–14.0
Warehouse	1000–300	92.9–27.9	0.4–1.2	—	0.4–1.2	1.3–3.8	—	1.3–3.8
Hotels, nursing homes	300–200	27.9–18.6	0.8–1.2	3.4	4.2–4.6	2.5–3.8	10.7	13.2–14.5
Apartments	300–200	27.9–18.6	0.8–1.2	See note g	See note g	2.5–3.8	See note g	See note g

Determine Interal Loads

PEOPLE • **LIGHTS** • EQUIPMENT
ENVELOPE • INFILTRATION

MEEB 10th, pg. 1610

Part B. Internal Heat Sources—Electric Lighting

	Sensible Heat Gain (Btu/h ft² of Floor Area)			Sensible Heat Gain (W/m² of Floor Area)		
Function	DF<1	1<DF<4	DF>4	DF<1	1<DF<4	DF>4
Office	5.1	2.0	0.5	16.1	6.3	1.6
School, elementary	6.3–6.8	2.5–2.7	0.6–0.7	19.9–21.5	7.9–8.5	1.9–2.2
School, secondary, college	6.3–6.8	2.5–2.7	0.6–0.7	19.9–21.5	7.9–8.5	1.9–2.2
Health care						
Sleeping (hospital)	6.8	2.7	0.7	21.5	8.5	2.2
In-patient (clinic)	6.8	2.7	0.7	21.5	8.5	2.2
Assembly	3.8	1.5	0.4	12.0	4.7	1.3
Restaurants	6.3	2.5	0.6	19.9	7.9	1.9
Mercantile	5.1–6.8	2.0–2.7	0.5–0.7	16.1–21.5	6.3–8.5	1.6–2.2
Warehouse	2.4	1.0	0.2	7.6	3.2	0.6
Hotels, nursing homes	6.8	2.7	0.7	21.5	8.5	2.2
Apartments	Up to 6.8	Up to 2.7	Up to 0.7	Up to 21.5	Up to 8.5	Up to 2.2