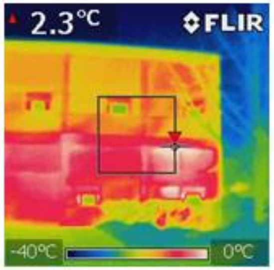
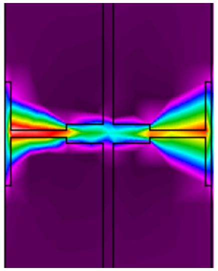
CAE 331/513
Building Science
Fall 2017





November 14, 2017
Heating load calculations

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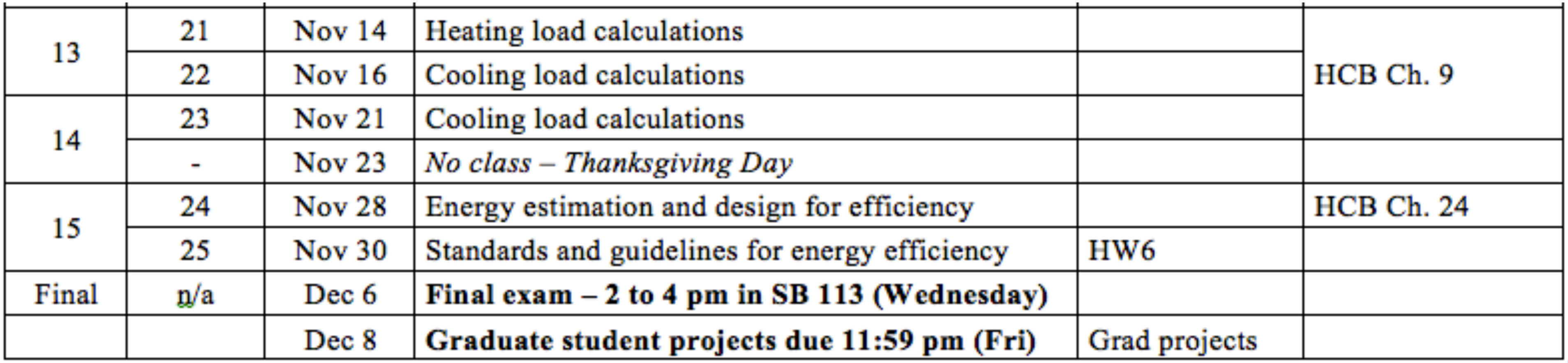
Schedule update



13	21	Nov 14	Heating load calculations		HCB Ch. 9
	22	Nov 16	Cooling load calculations		
14	23	Nov 21	Cooling load calculations		
	-	Nov 23	*No class – Thanksgiving Day*		
15	24	Nov 28	Energy estimation and design for efficiency		HCB Ch. 24
	25	Nov 30	Standards and guidelines for energy efficiency	HW6	
Final	n/a	Dec 6	**Final exam – 2 to 4 pm in SB 113 (Wednesday)**		
		Dec 8	**Graduate student projects due 11:59 pm (Fri)**	Grad projects	

- HW 6 (heating and cooling load calculations) is now due Thurs Nov 30
- Graduate student final projects originally due Thurs Nov 30 at 11:59 pm
  - Now due Fri Dec 8 at 11:59 pm
- Final exam is Wednesday December 6, 2-4 PM, SB 113

Last time

- Natural ventilation and infiltration
  - Finish natural ventilation today

Natural ventilation strategies

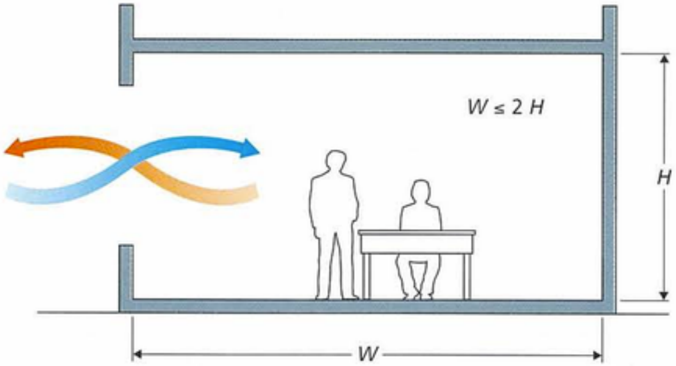


Figure 2.18 Single sided ventilation, single opening

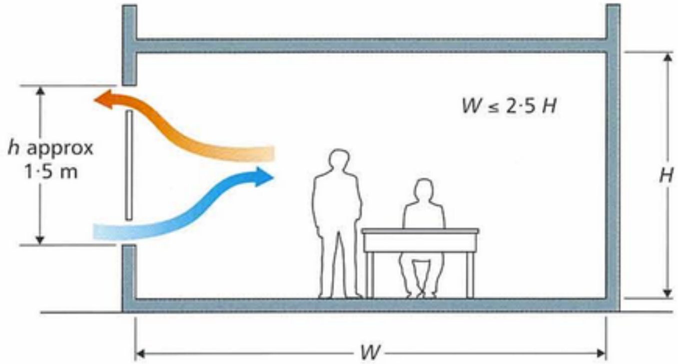


Figure 2.19 Single sided ventilation, double opening

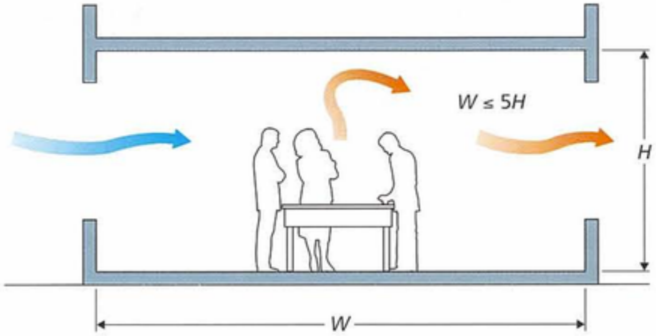


Figure 2.20 Cross ventilation

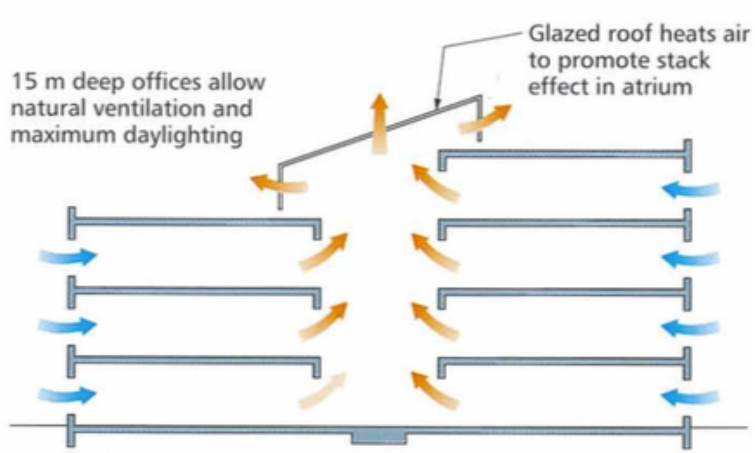


Figure 2.25 Atrium stack ventilation (Barclaycard Headquarters)

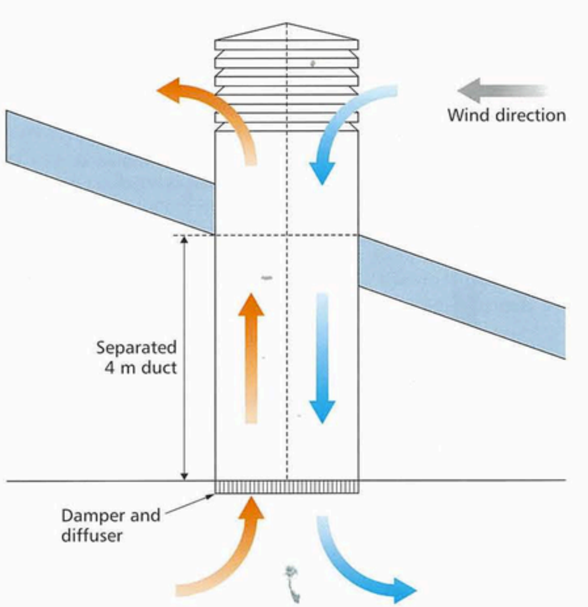


Figure 2.22 Roof-mounted ventilator

Natural ventilation equations

- Airflow caused by wind only

$$\dot{V} = C_v A U$$

$\dot{V}$ = airflow rate, m^3/s

C_v = effectiveness of openings, dimensionless

[C_v = ~0.5-0.6 for perpendicular winds and ~0.25-0.35 for diagonal winds]

A = free area of inlet openings, m^2

U = wind speed, m/s

Natural ventilation equations

- Airflow caused by thermal forces (buoyancy) only

$$\dot{V} = C_D A \sqrt{2g\left(H_{NPL} - H\right)\left(\frac{T_{in} - T_{out}}{T_{in}}\right)}$$

$\dot{V}$ = airflow rate, m^3/s
C_D = discharge coefficient for opening, dimensionless
A = cross-sectional area of opening, m^2
H_{NPL} = height of neutral pressure level above reference plane, m
H = height of point of opening, m
T_{out} = outdoor air temperature, K
T_{in} = indoor air temperature, K
g = acceleration due to gravity, 9.81 m/s^2

Note: If $T_{in} < T_{out}$, replace T_{in} with T_{out} and vice versa

Wind-driven natural ventilation example

- Consider the first floor of a house with two windows: one is 1 m^2 in area and orientated 20 degrees away from the normal of the prevailing wind direction and another is 1.5 m^2 in area on the opposite side of the room.

- If the local wind velocity is 6 m/s, determine the amount of ventilation air flowing into the room when both windows are wide open.
  - You can neglect infiltration due to stack effect since the indoor and outdoor temperatures are essentially the same
  - Assume an opening effectiveness of 0.6

- If the volume of the house is 360 m^3 (same as the last example), what is the air exchange rate?

When you have unequal inlet and outlet areas

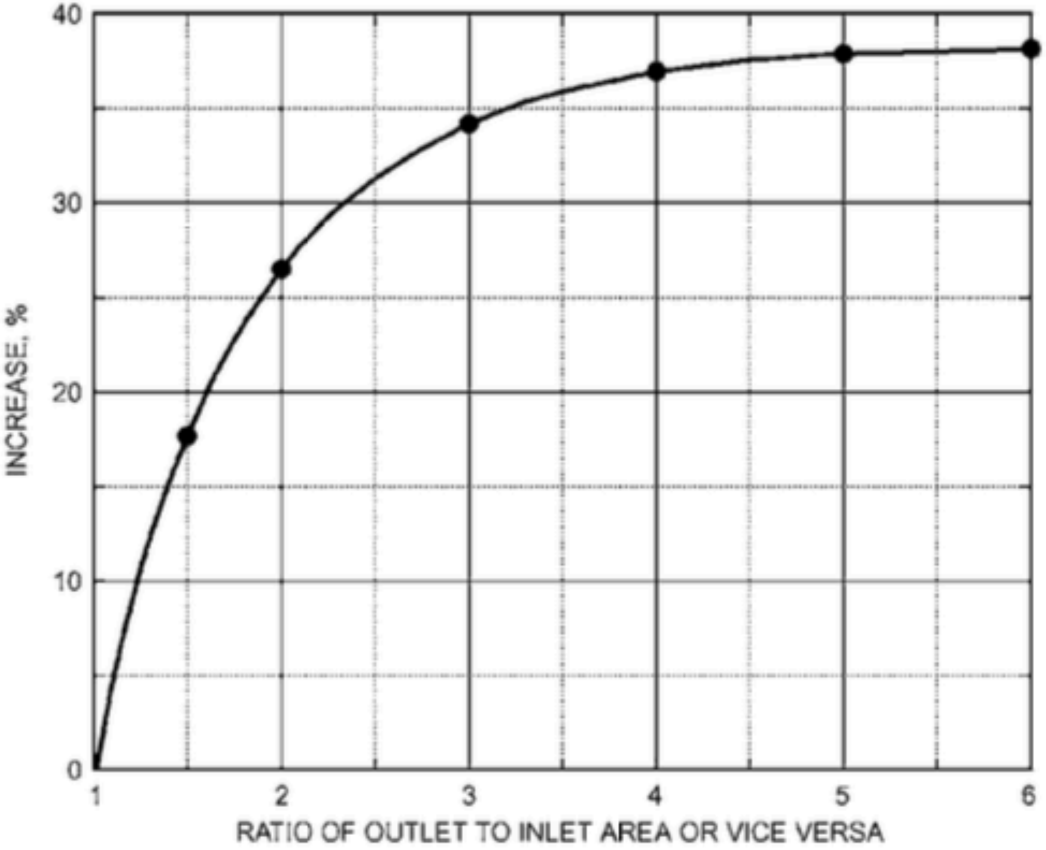


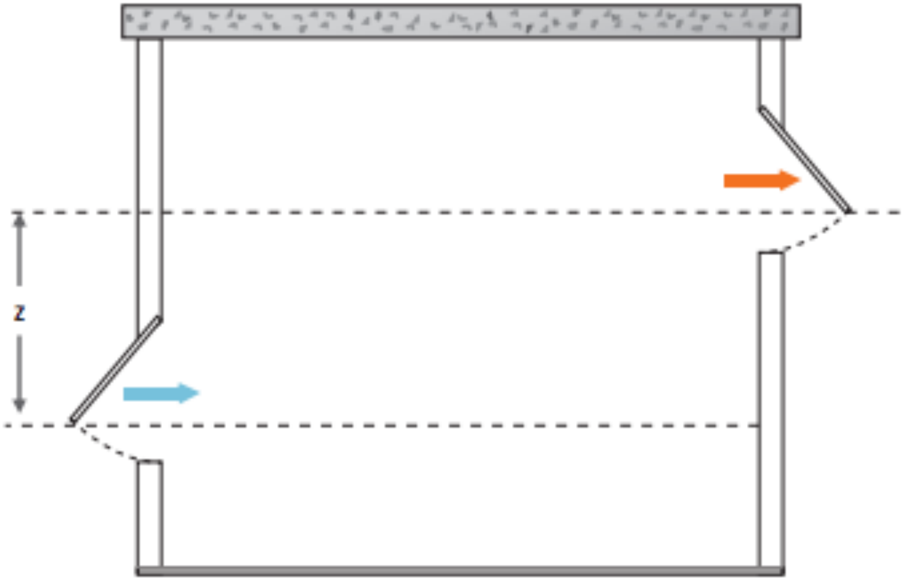
Fig. 8 Increase in Flow Caused by Excess Area of One Opening over the Other

Buoyancy-driven natural ventilation example

- Consider a 10 meter high atrium with openings to the outside at ground level and at roof level. The inside temperature is maintained at 25ºC and the outdoor temperature is 10ºC.

- Estimate the natural ventilation airflow rate due to stack effect pressure differences only if the area of both openings is 0.25 m^2

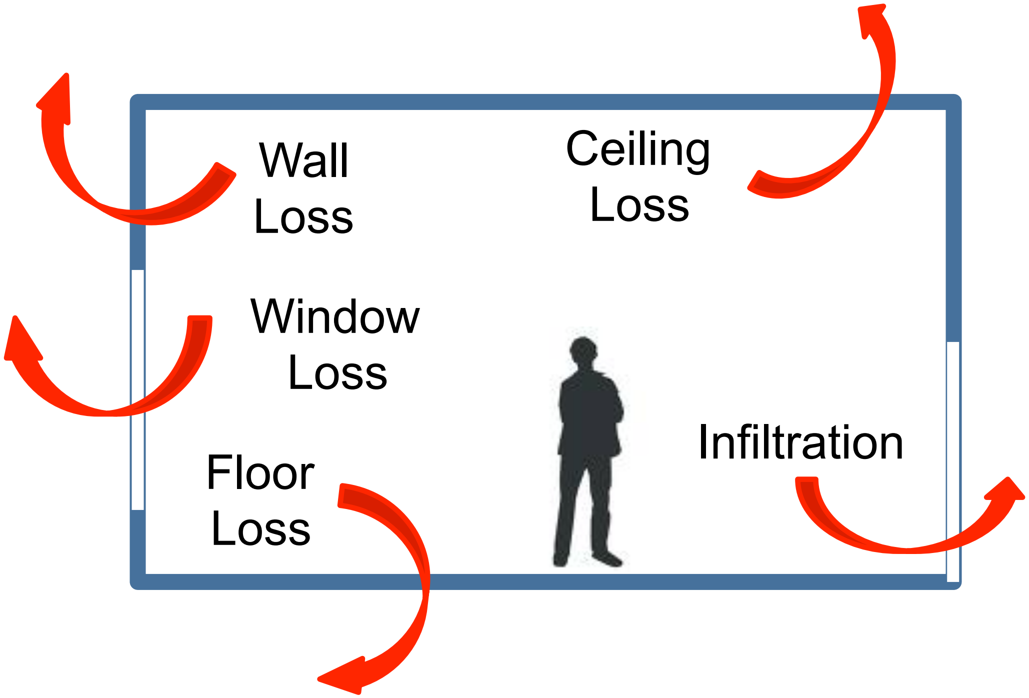
- If the volume of the house is 360 m^3 (same as the last example), what is the air exchange rate?



HEATING AND COOLING LOADS

Heating and cooling load calculations

- We've dealt with individual modes of heat transfer all year
- We need to know how all of the heat gains and losses in a building add up to affect thermal comfort, equipment size, and energy requirements



Heating and cooling load calculations

- When we use HVAC systems to maintain comfortable indoor conditions, we need to know what the **“peak loads”** for both heating and cooling are in order to design and select equipment

- The peak load tells you the maximum amount of energy that would realistically be required to supply to (or extract from) the conditioned space

- Peak loads occur at **“design conditions”**

- We estimate this peak load using a **“heat balance”** on the space in question

DESIGN CONDITIONS

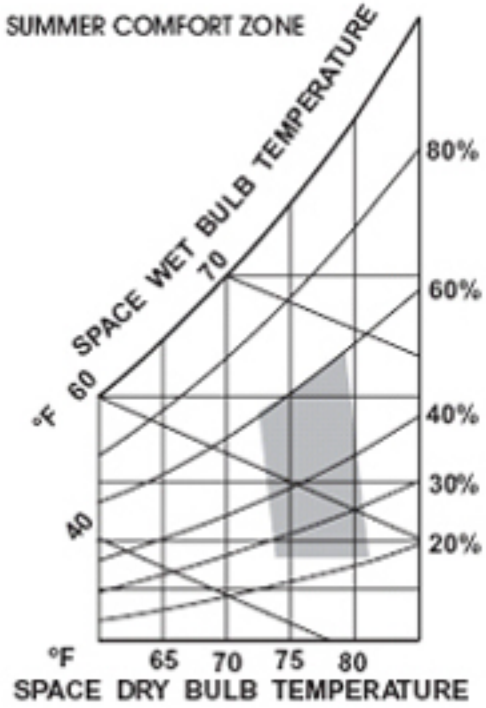
Design conditions

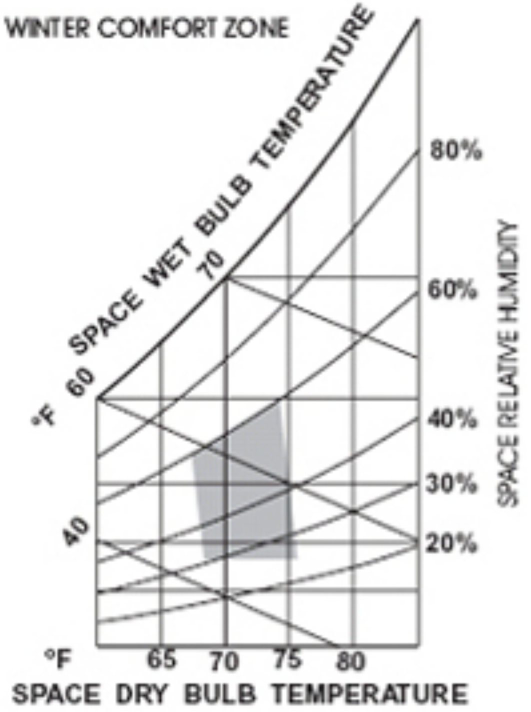
- When sizing a system to provide heating or cooling, we need to size it for worst case conditions
  - Or more accurately, ***nearly*** worst case conditions
    - If equipment is too small, it won't meet the load
    - If equipment is too large, it will have high upfront costs and may run at very low efficiency most of the time (remember: low efficiency at low part load ratio)

- So we choose extreme (or *nearly* extreme) design conditions on which to base heating and cooling load calculations
  - These are based on different levels of probability of occurrence

Indoor design conditions

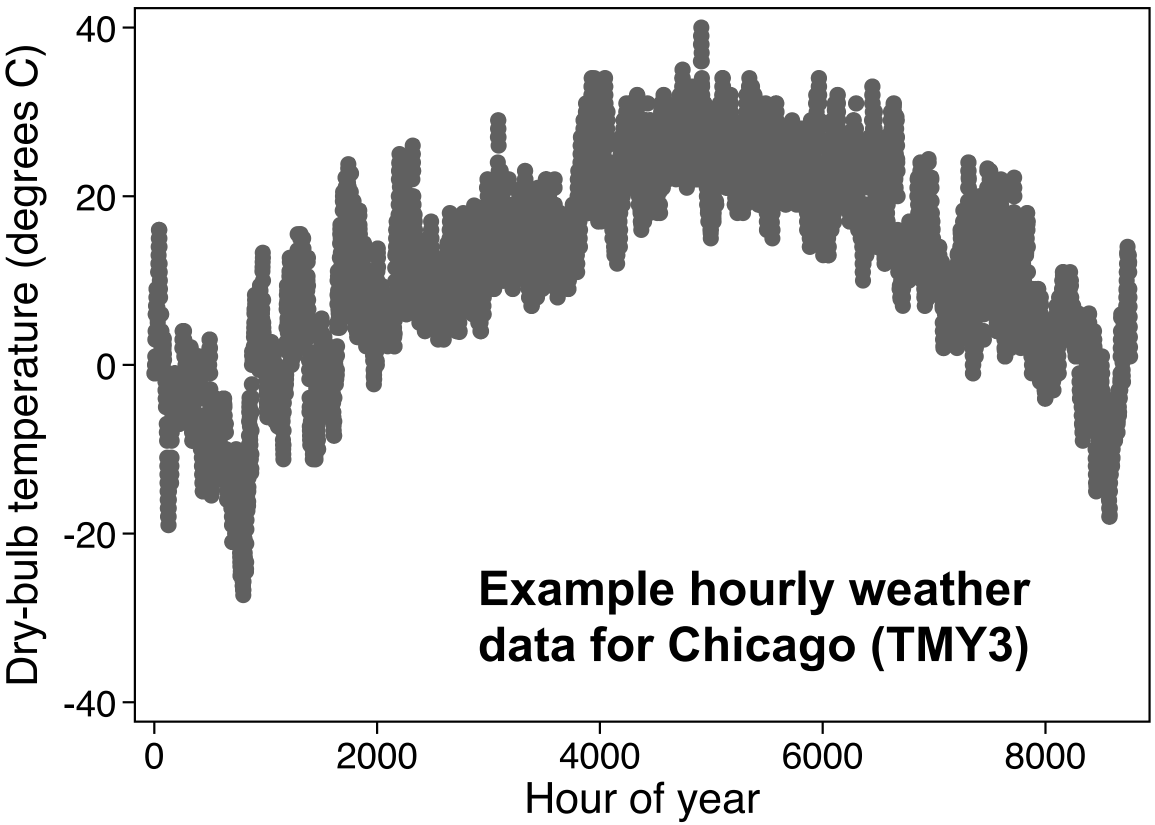
- <u>Indoor design conditions</u> are typically in the middle of the ASHRAE comfort zone for the appropriate season
  - Such as:
    - 76°F (24.4°C) and 40% RH in summer
    - 72°F (22.2°C) and 40% RH in winter





Outdoor design conditions

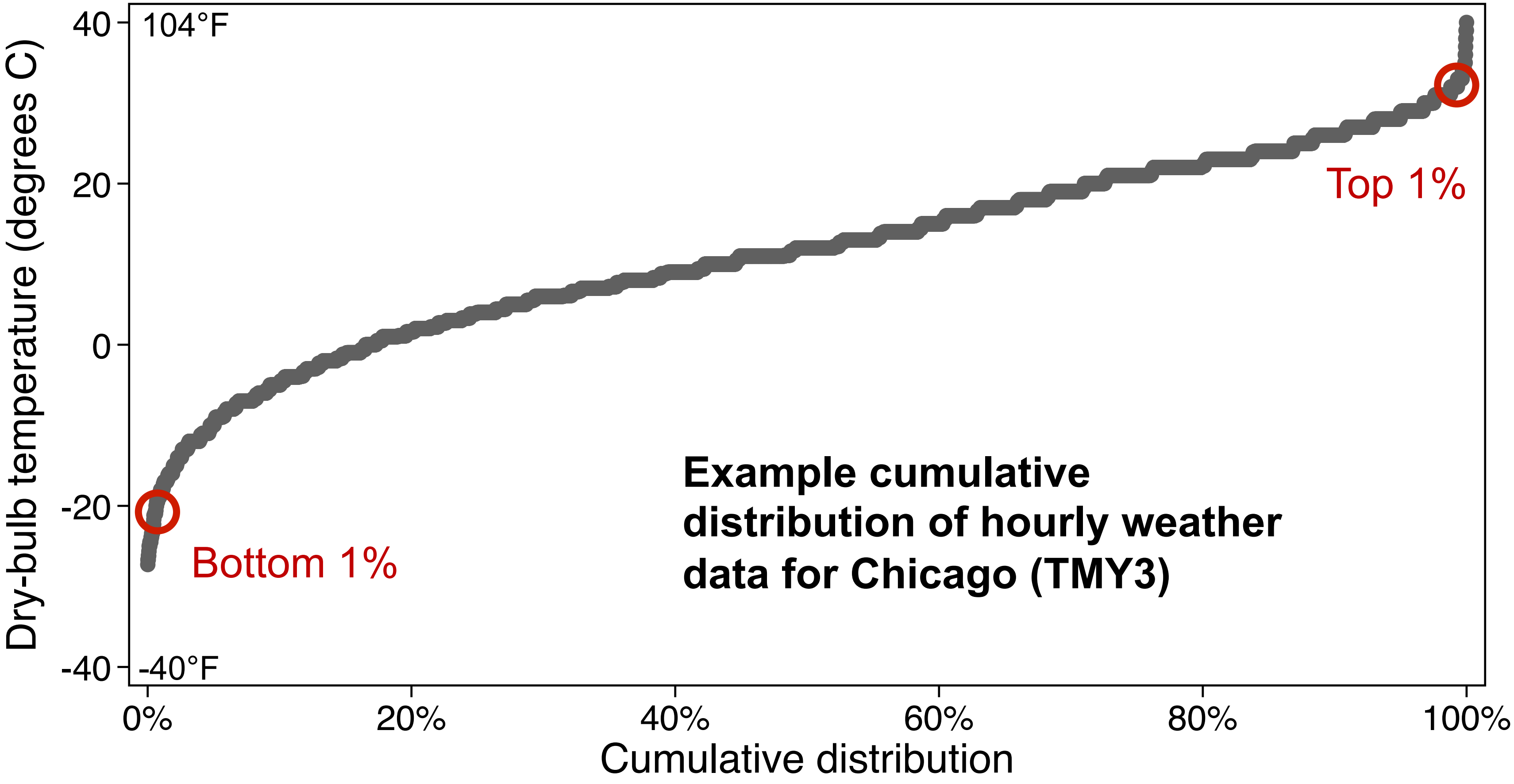
- Outdoor design conditions are not usually the coldest or hottest conditions ever measured, but are usually obtained from statistical summaries of long term measurements



http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/

Outdoor design conditions

We use statistical distributions of outdoor weather conditions to give us design conditions



Example cumulative distribution of hourly weather data for Chicago (TMY3)

http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/

Outdoor design conditions

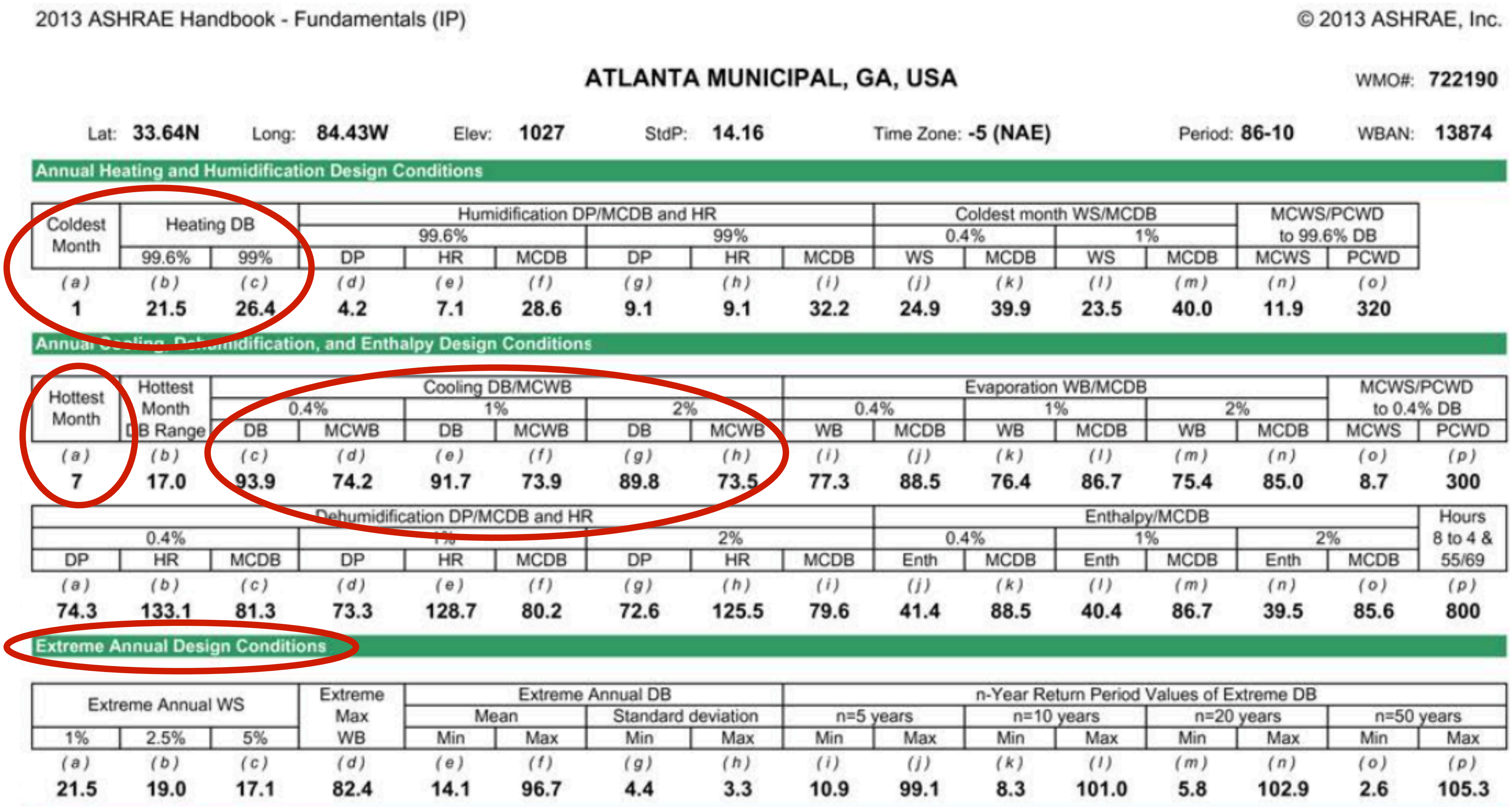
- ASHRAE has compiled decades of weather data for many cities
  - Available in the ASHRAE Handbook of Fundamentals Chapter 13

- ASHRAE lists the 99% and 99.6% cold temperatures for winter design conditions
  - Also the mean wind speed and prevailing direction

- Summer design conditions: Top 2%, 1%, or 0.4% in dry bulb temperature (DBT)
  - You have discretion in picking which percentile
  - Typically: 99% or 99.6% in either direction

- The idea is that the air temperature is colder than the 99% value for about 88 hours per year and colder than the 99.6% for about 35 hours per year

ASHRAE outdoor design conditions



2013 ASHRAE Handbook - Fundamentals (IP)

ATLANTA MUNICIPAL, GA, USA

WMO#: **722190**

Lat: **33.64N** Long: **84.43W** Elev: **1027** StdP: **14.16** Time Zone: **-5 (NAE)** Period: **86-10** WBAN: **13874**

Annual Heating and Humidification Design Conditions

Coldest Month	Heating DB		Humidification DP/MCDB and HR						Coldest month WS/MCDB				MCWS/PCWD to 99.6% DB	
			99.6%			99%			0.4%		1%			
	99.6%	99%	DP	HR	MCDB	DP	HR	MCDB	WS	MCDB	WS	MCDB	MCWS	PCWD
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)
1	21.5	26.4	4.2	7.1	28.6	9.1	9.1	32.2	24.9	39.9	23.5	40.0	11.9	320

Annual Cooling, Dehumidification, and Enthalpy Design Conditions

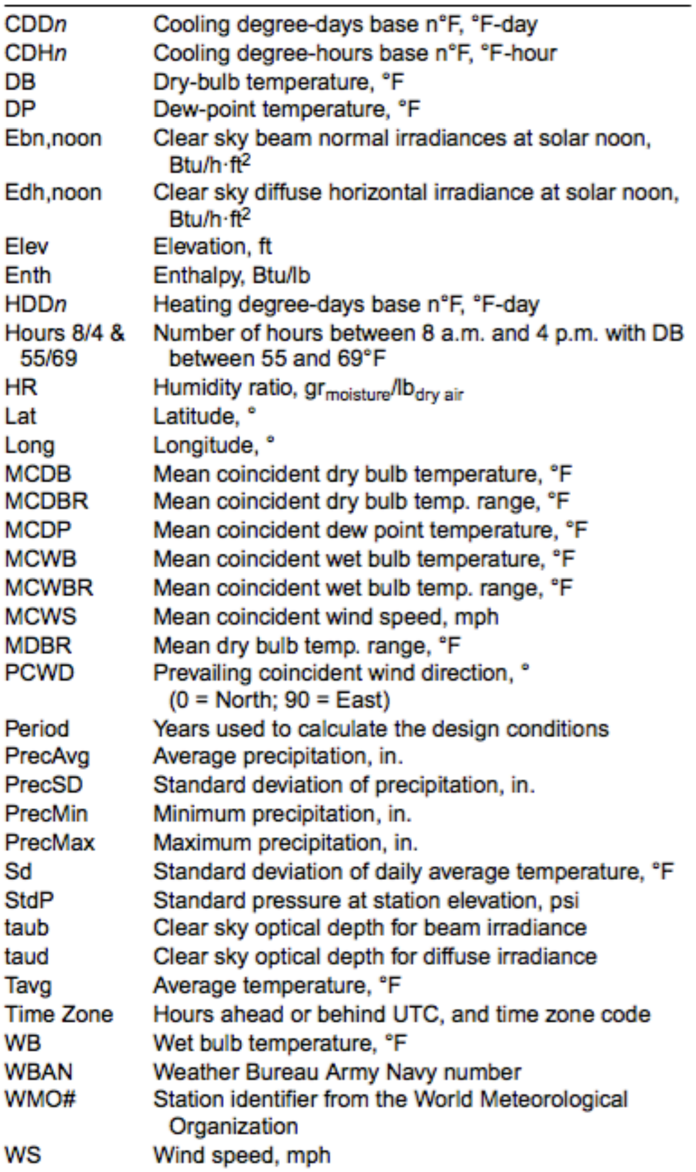
Hottest Month	Hottest Month DB Range	Cooling DB/MCWB						Evaporation WB/MCDB						MCWS/PCWD to 0.4% DB	
		0.4%		1%		2%		0.4%		1%		2%			
		DB	MCWB	DB	MCWB	DB	MCWB	WB	MCDB	WB	MCDB	WB	MCDB	MCWS	PCWD
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)
7	17.0	93.9	74.2	91.7	73.9	89.8	73.5	77.3	88.5	76.4	86.7	75.4	85.0	8.7	300

Dehumidification DP/MCDB and HR									Enthalpy/MCDB						Hours 8 to 4 & 55/69
0.4%			1%			2%			0.4%		1%		2%		
DP	HR	MCDB	DP	HR	MCDB	DP	HR	MCDB	Enth	MCDB	Enth	MCDB	Enth	MCDB	
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)
74.3	133.1	81.3	73.3	128.7	80.2	72.6	125.5	79.6	41.4	88.5	40.4	86.7	39.5	85.6	800

Extreme Annual Design Conditions

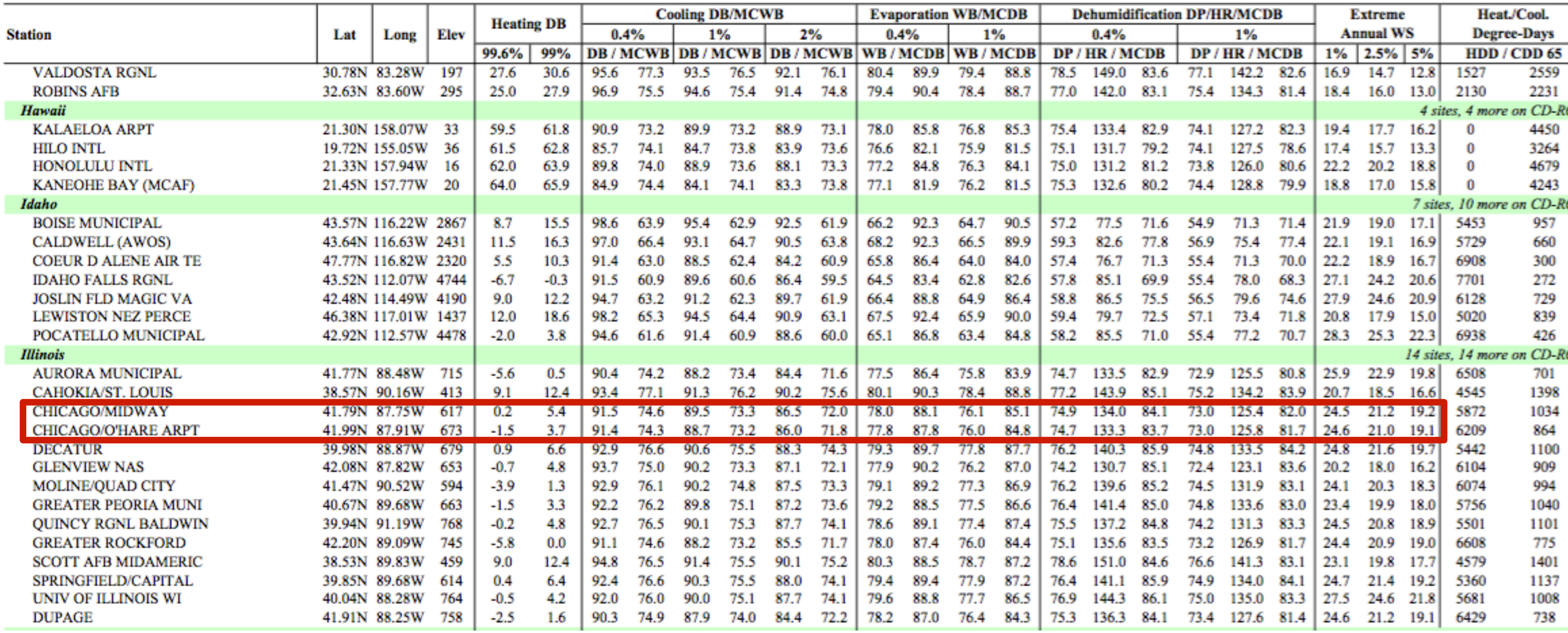
Extreme Annual WS			Extreme Max WB	Extreme Annual DB				n-Year Return Period Values of Extreme DB							
				Mean		Standard deviation		n=5 years		n=10 years		n=20 years		n=50 years	
1%	2.5%	5%		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)
21.5	19.0	17.1	82.4	14.1	96.7	4.4	3.3	10.9	99.1	8.3	101.0	5.8	102.9	2.6	105.3

ASHRAE outdoor design conditions



CDD*n*	Cooling degree-days base n°F, °F-day
CDH*n*	Cooling degree-hours base n°F, °F-hour
DB	Dry-bulb temperature, °F
DP	Dew-point temperature, °F
Ebn,noon	Clear sky beam normal irradiances at solar noon, Btu/h·ft^2
Edh,noon	Clear sky diffuse horizontal irradiance at solar noon, Btu/h·ft^2
Elev	Elevation, ft
Enth	Enthalpy, Btu/lb
HDD*n*	Heating degree-days base n°F, °F-day
Hours 8/4 & 55/69	Number of hours between 8 a.m. and 4 p.m. with DB between 55 and 69°F
HR	Humidity ratio, $gr_{moisture}/lb_{dry\ air}$
Lat	Latitude, °
Long	Longitude, °
MCDB	Mean coincident dry bulb temperature, °F
MCDBR	Mean coincident dry bulb temp. range, °F
MCDP	Mean coincident dew point temperature, °F
MCWB	Mean coincident wet bulb temperature, °F
MCWBR	Mean coincident wet bulb temp. range, °F
MCWS	Mean coincident wind speed, mph
MDBR	Mean dry bulb temp. range, °F
PCWD	Prevailing coincident wind direction, ° (0 = North; 90 = East)
Period	Years used to calculate the design conditions
PrecAvg	Average precipitation, in.
PrecSD	Standard deviation of precipitation, in.
PrecMin	Minimum precipitation, in.
PrecMax	Maximum precipitation, in.
Sd	Standard deviation of daily average temperature, °F
StdP	Standard pressure at station elevation, psi
taub	Clear sky optical depth for beam irradiance
taud	Clear sky optical depth for diffuse irradiance
Tavg	Average temperature, °F
Time Zone	Hours ahead or behind UTC, and time zone code
WB	Wet bulb temperature, °F
WBAN	Weather Bureau Army Navy number
WMO#	Station identifier from the World Meteorological Organization
WS	Wind speed, mph

Outdoor design conditions for Chicago?



Station	Lat	Long	Elev	Heating DB		Cooling DB/MCWB						Evaporation WB/MCDB				Dehumidification DP/HR/MCDB						Extreme Annual WS			Heat./Cool. Degree-Days	
						0.4%		1%		2%		0.4%		1%		0.4%			1%							
				99.6%	99%	DB / MCWB		DB / MCWB		DB / MCWB		WB / MCDB		WB / MCDB		DP / HR / MCDB			DP / HR / MCDB			1%	2.5%	5%	HDD / CDD 65	
VALDOSTA RGNL	30.78N	83.28W	197	27.6	30.6	95.6	77.3	93.5	76.5	92.1	76.1	80.4	89.9	79.4	88.8	78.5	149.0	83.6	77.1	142.2	82.6	16.9	14.7	12.8	1527	2559
ROBINS AFB	32.63N	83.60W	295	25.0	27.9	96.9	75.5	94.6	75.4	91.4	74.8	79.4	90.4	78.4	88.7	77.0	142.0	83.1	75.4	134.3	81.4	18.4	16.0	13.0	2130	2231
Hawaii																									*4 sites, 4 more on CD-R*	
KALAELOA ARPT	21.30N	158.07W	33	59.5	61.8	90.9	73.2	89.9	73.2	88.9	73.1	78.0	85.8	76.8	85.3	75.4	133.4	82.9	74.1	127.2	82.3	19.4	17.7	16.2	0	4450
HILO INTL	19.72N	155.05W	36	61.5	62.8	85.7	74.1	84.7	73.8	83.9	73.6	76.6	82.1	75.9	81.5	75.1	131.7	79.2	74.1	127.5	78.6	17.4	15.7	13.3	0	3264
HONOLULU INTL	21.33N	157.94W	16	62.0	63.9	89.8	74.0	88.9	73.6	88.1	73.3	77.2	84.8	76.3	84.1	75.0	131.2	81.2	73.8	126.0	80.6	22.2	20.2	18.8	0	4679
KANEOHE BAY (MCAF)	21.45N	157.77W	20	64.0	65.9	84.9	74.4	84.1	74.1	83.3	73.8	77.1	81.9	76.2	81.5	75.3	132.6	80.2	74.4	128.8	79.9	18.8	17.0	15.8	0	4243
Idaho																									*7 sites, 10 more on CD-R*	
BOISE MUNICIPAL	43.57N	116.22W	2867	8.7	15.5	98.6	63.9	95.4	62.9	92.5	61.9	66.2	92.3	64.7	90.5	57.2	77.5	71.6	54.9	71.3	71.4	21.9	19.0	17.1	5453	957
CALDWELL (AWOS)	43.64N	116.63W	2431	11.5	16.3	97.0	66.4	93.1	64.7	90.5	63.8	68.2	92.3	66.5	89.9	59.3	82.6	77.8	56.9	75.4	77.4	22.1	19.1	16.9	5729	660
COEUR D ALENE AIR TE	47.77N	116.82W	2320	5.5	10.3	91.4	63.0	88.5	62.4	84.2	60.9	65.8	86.4	64.0	84.0	57.4	76.7	71.3	55.4	71.3	70.0	22.2	18.9	16.7	6908	300
IDAHO FALLS RGNL	43.52N	112.07W	4744	-6.7	-0.3	91.5	60.9	89.6	60.6	86.4	59.5	64.5	83.4	62.8	82.6	57.8	85.1	69.9	55.4	78.0	68.3	27.1	24.2	20.6	7701	272
JOSLIN FLD MAGIC VA	42.48N	114.49W	4190	9.0	12.2	94.7	63.2	91.2	62.3	89.7	61.9	66.4	88.8	64.9	86.4	58.8	86.5	75.5	56.5	79.6	74.6	27.9	24.6	20.9	6128	729
LEWISTON NEZ PERCE	46.38N	117.01W	1437	12.0	18.6	98.2	65.3	94.5	64.4	90.9	63.1	67.5	92.4	65.9	90.0	59.4	79.7	72.5	57.1	73.4	71.8	20.8	17.9	15.0	5020	839
POCATELLO MUNICIPAL	42.92N	112.57W	4478	-2.0	3.8	94.6	61.6	91.4	60.9	88.6	60.0	65.1	86.8	63.4	84.8	58.2	85.5	71.0	55.4	77.2	70.7	28.3	25.3	22.3	6938	426
Illinois																									*14 sites, 14 more on CD-R*	
AURORA MUNICIPAL	41.77N	88.48W	715	-5.6	0.5	90.4	74.2	88.2	73.4	84.4	71.6	77.5	86.4	75.8	83.9	74.7	133.5	82.9	72.9	125.5	80.8	25.9	22.9	19.8	6508	701
CAHOKIA/ST. LOUIS	38.57N	90.16W	413	9.1	12.4	93.4	77.1	91.3	76.2	90.2	75.6	80.1	90.3	78.4	88.8	77.2	143.9	85.1	75.2	134.2	83.9	20.7	18.5	16.6	4545	1398
CHICAGO/MIDWAY	41.79N	87.75W	617	0.2	5.4	91.5	74.6	89.5	73.3	86.5	72.0	78.0	88.1	76.1	85.1	74.9	134.0	84.1	73.0	125.4	82.0	24.5	21.2	19.2	5872	1034
CHICAGO/O'HARE ARPT	41.99N	87.91W	673	-1.5	3.7	91.4	74.3	88.7	73.2	86.0	71.8	77.8	87.8	76.0	84.8	74.7	133.3	83.7	73.0	125.8	81.7	24.6	21.0	19.1	6209	864
DECATUR	39.98N	88.87W	679	0.9	6.6	92.9	76.6	90.6	75.5	88.3	74.3	79.3	89.7	77.8	87.7	76.2	140.3	85.9	74.8	133.5	84.2	24.8	21.6	19.7	5442	1100
GLENVIEW NAS	42.08N	87.82W	653	-0.7	4.8	93.7	75.0	90.2	73.3	87.1	72.1	77.9	90.2	76.2	87.0	74.2	130.7	85.1	72.4	123.1	83.6	20.2	18.0	16.2	6104	909
MOLINE/QUAD CITY	41.47N	90.52W	594	-3.9	1.3	92.9	76.1	90.2	74.8	87.5	73.3	79.1	89.2	77.3	86.9	76.2	139.6	85.2	74.5	131.9	83.1	24.1	20.3	18.3	6074	994
GREATER PEORIA MUNI	40.67N	89.68W	663	-1.5	3.3	92.2	76.2	89.8	75.1	87.2	73.6	79.2	88.5	77.5	86.6	76.4	141.4	85.0	74.8	133.6	83.0	23.4	19.9	18.0	5756	1040
QUINCY RGNL BALDWIN	39.94N	91.19W	768	-0.2	4.8	92.7	76.5	90.1	75.3	87.7	74.1	78.6	89.1	77.4	87.4	75.5	137.2	84.8	74.2	131.3	83.3	24.5	20.8	18.9	5501	1101
GREATER ROCKFORD	42.20N	89.09W	745	-5.8	0.0	91.1	74.6	88.2	73.2	85.5	71.7	78.0	87.4	76.0	84.4	75.1	135.6	83.5	73.2	126.9	81.7	24.4	20.9	19.0	6608	775
SCOTT AFB MIDAMERIC	38.53N	89.83W	459	9.0	12.4	94.8	76.5	91.4	75.5	90.1	75.2	80.3	88.5	78.7	87.2	78.6	151.0	84.6	76.6	141.3	83.1	23.1	19.8	17.7	4579	1401
SPRINGFIELD/CAPITAL	39.85N	89.68W	614	0.4	6.4	92.4	76.6	90.3	75.5	88.0	74.1	79.4	89.4	77.9	87.2	76.4	141.1	85.9	74.9	134.0	84.1	24.7	21.4	19.2	5360	1137
UNIV OF ILLINOIS WI	40.04N	88.28W	764	-0.5	4.2	92.0	76.0	90.0	75.1	87.7	74.1	79.6	88.8	77.7	86.5	76.9	144.3	86.1	75.0	135.0	83.3	27.5	24.6	21.8	5681	1008
DUPAGE	41.91N	88.25W	758	-2.5	1.6	90.3	74.9	87.9	74.0	84.4	72.2	78.2	87.0	76.4	84.3	75.3	136.3	84.1	73.4	127.6	81.4	24.6	21.2	19.1	6429	738

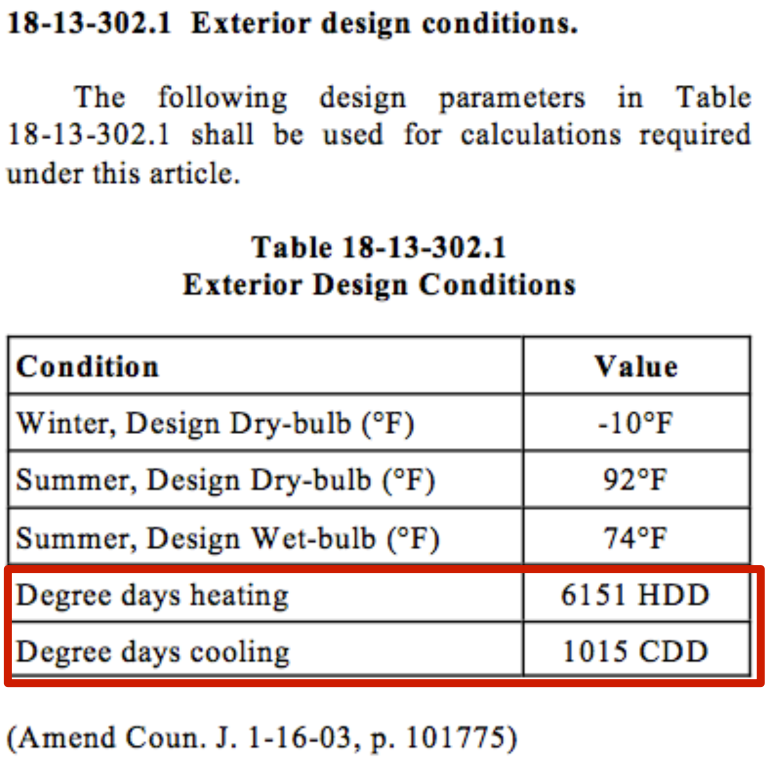
The winter 99% dry bulb temperature is 3.7°F at O'Hare and the 99.6% dry bulb temperature is -1.5°F

The summer 1% dry bulb temperature is 88.7°F at O'Hare and the 0.4% dry bulb temperature is 91.4°F

City of Chicago requirements for design conditions

- The City of Chicago Building code has required design conditions that differ slightly from ASHRAE
  - Section 18-13-302.1

- Winter Design Condition: T_{db} = -10°F
- Summer Design: T_{db} = 92°F, T_{wb} = 74°F
- The maximum allowable interior design temperature is 72°F for heating and 75°F for cooling
- Local codes supersede ASHRAE



18-13-302.1 Exterior design conditions.

The following design parameters in Table 18-13-302.1 shall be used for calculations required under this article.

Table 18-13-302.1
Exterior Design Conditions

Condition	**Value**
Winter, Design Dry-bulb (°F)	-10°F
Summer, Design Dry-bulb (°F)	92°F
Summer, Design Wet-bulb (°F)	74°F
Degree days heating	6151 HDD
Degree days cooling	1015 CDD

(Amend Coun. J. 1-16-03, p. 101775)

What is this?

A note on “degree-days”

- The energy use of a building is directly related to the **temperature difference between outdoor and indoor air**
- Heating equipment is assumed to run when the outdoor temperature drops below the “balance temperature”
  - The **balance temperature** is the outdoor air temperature at which the internal heat gains balance the heat loss to the outside
  - This is **less than** the interior temperature set point
  - The amount of time that this situation occurs is described by:
    - **Heating Degree Days**
- Cooling equipment is assumed to run when the outdoor temperature is above the balance temperature
  - The balance temperature might not be the same for heating and cooling because the interior temperature, interior heat gain, and building heat loss usually differ in summer and winter
  - The amount of time that this situation occurs is described by:
    - **Cooling Degree Days**

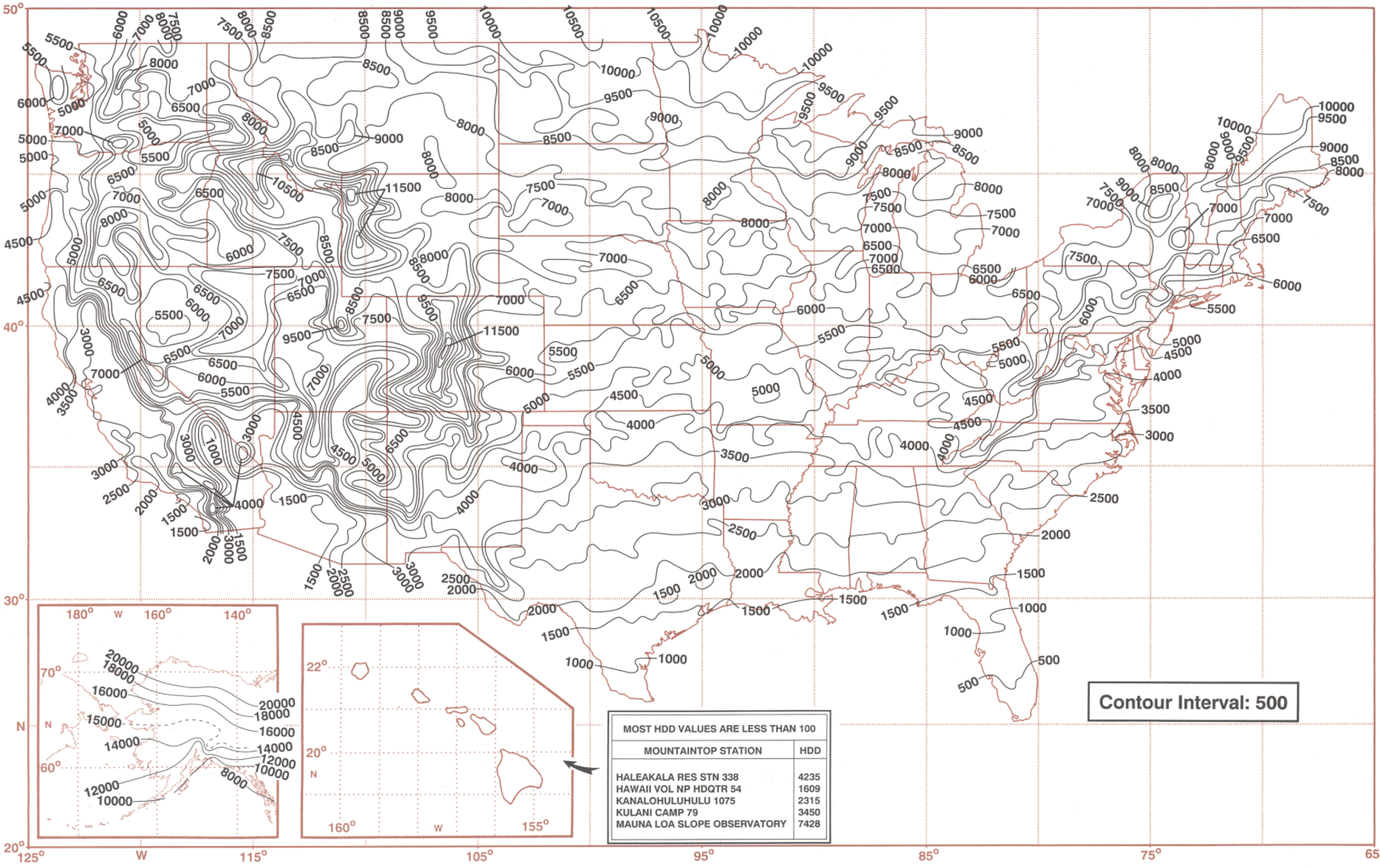
Selecting a base temperature

- HDD_{65F} and CDD_{65F} are common HDD/CDD levels that are used regularly in industry (both with a base of 65°F)

$$HDD = \int [T_{bal} - T_{out}(t)]dt \quad \text{when} \quad T_{out} < T_{bal}$$

$$CDD = \int [T_{out}(t) - T_{bal}]dt \quad \text{when} \quad T_{out} > T_{bal}$$

HDD$_{65F}$ maps

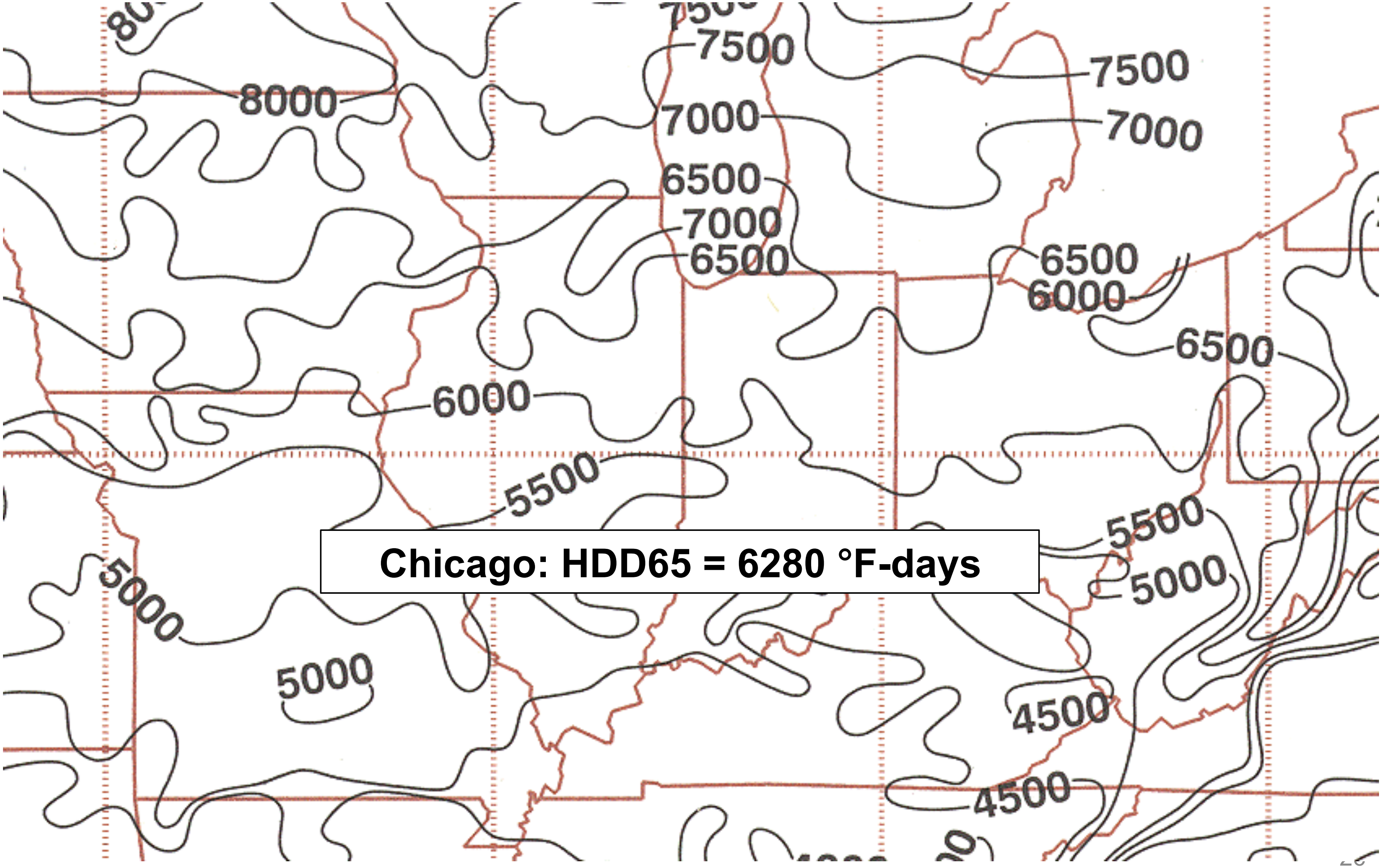


ANNUAL HEATING DEGREE DAYS

BASED ON NORMAL PERIOD 1961-1990

MOST HDD VALUES ARE LESS THAN 100	
MOUNTAINTOP STATION	HDD
HALEAKALA RES STN 338	4235
HAWAII VOL NP HDQTR 54	1609
KANALOHULUHULU 1075	2315
KULANI CAMP 79	3450
MAUNA LOA SLOPE OBSERVATORY	7428

HDD$_{65F}$ maps

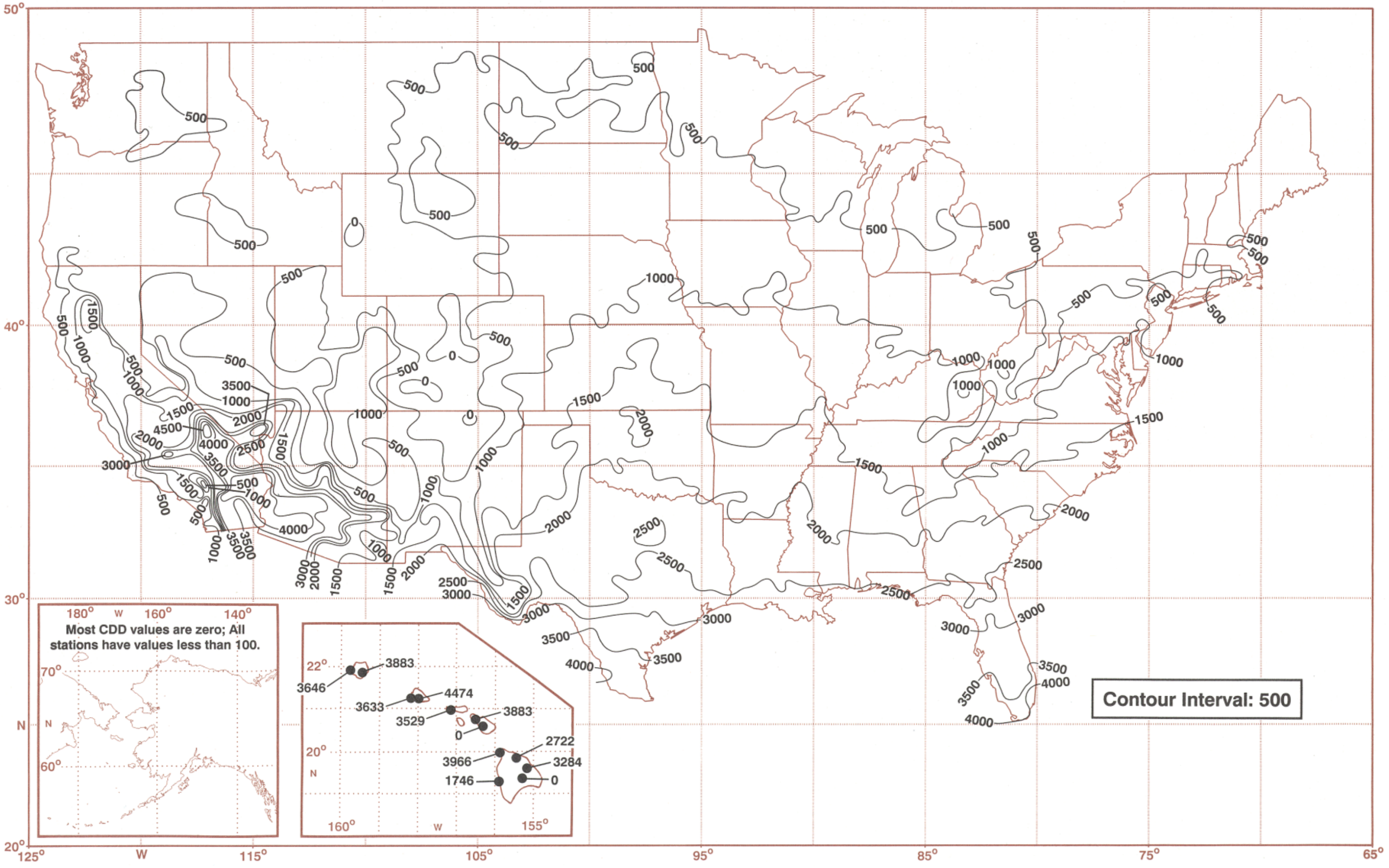


Chicago: HDD65 = 6280 °F-days

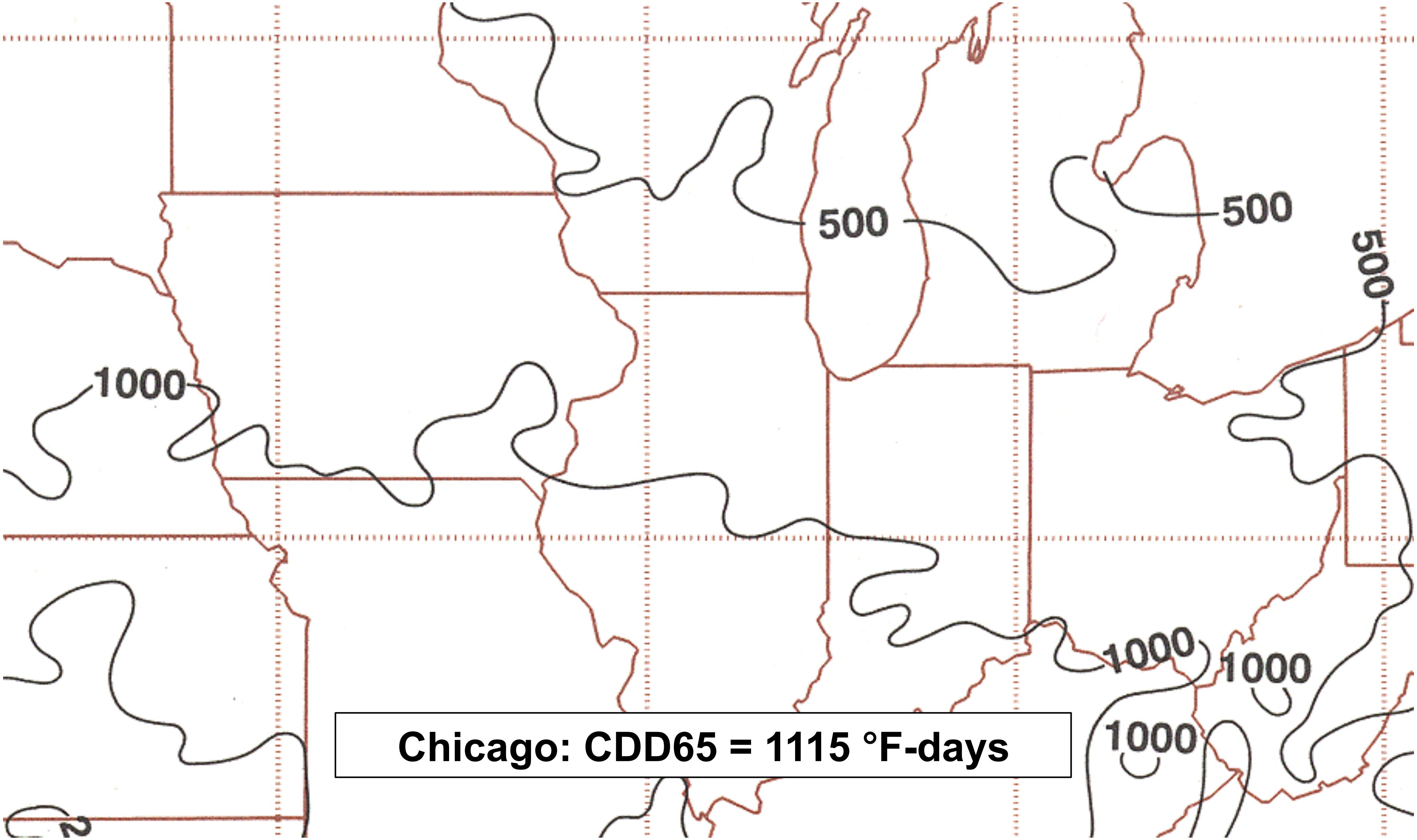
CDD$_{65F}$ maps

ANNUAL COOLING DEGREE DAYS

BASED ON NORMAL PERIOD 1961-1990



CDD_{65F} maps

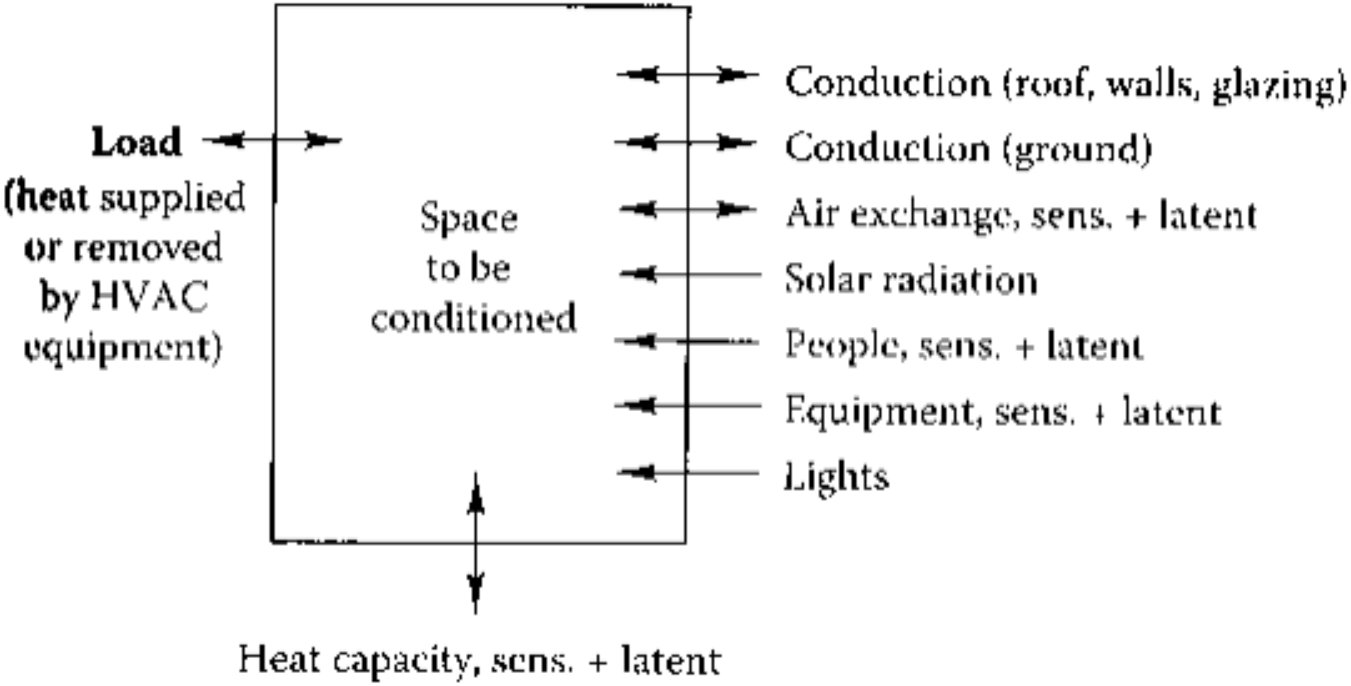


Chicago: CDD65 = 1115 °F-days

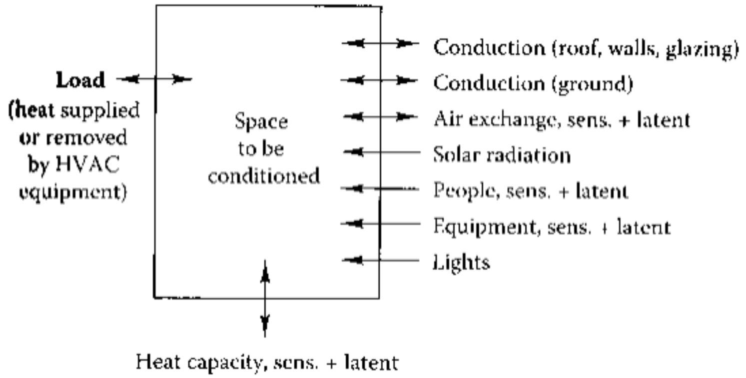
LOAD CALCULATION PROCEDURES

Heat balance

- For either heating or cooling loads at design conditions, we can calculate a "heat balance" on a building/space/zone in question



Sensible heat balance: Total sensible load



$$Q_{sensible\,load} =$$

$$Q_{envelope\,transmission} + Q_{air\,exchange} - Q_{solar} - Q_{people} - Q_{equipment} - Q_{lights} \pm Q_{storage}$$

Q is positive (+) when there is a heating load (cold outside)

- Need to add heat to stay comfortable

Q is negative (-) when there is a cooling load (hot outside)

- Need to remove heat to stay comfortable

$Q_{storage}$ accounts for thermal mass of a building (i.e., storage)

Units: BTU/hr or W

Sensible heat losses and gains

Envelope transmission:

$$Q_{envelope\,transmission} = \sum UA(T_{in} - T_{out})$$

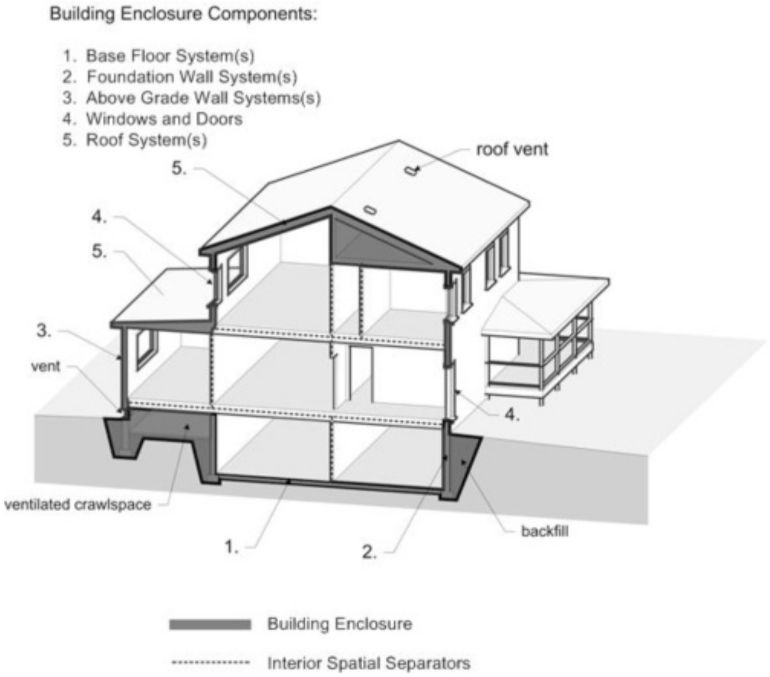
Air exchange:

$$Q_{air\,exchange} = \dot{V}_{OA}\rho_{OA}C_{p,air}(T_{in} - T_{out})$$

U = overall heat transfer coefficient for walls, roof, ceiling, floor, glazing, etc. [BTU/hr·ft^2·°F] or [W/m^{2}K]
A = area of walls, roof, ceiling, floor, glazing, etc. [ft^2] or [m^2]
T_{in} = indoor air design temperature [°F] or [K]
T_{out} = outdoor air design temperature [°F] or [K]
$\dot{V}_{OA}$ = volumetric flow rate of outdoor air due to air exchange [ft^3/hr] or [m^3/s]
ρ_{OA} = density of outdoor air [lb/ft^3] or [kg/m^3]
$C_{p,air}$ = specific heat capacity of air [BTU/lb·°F] or [J/kg]

Total heat transmission coefficient: Envelope + air exchange

- We can also lump conduction and air exchange together to define a total building heat transfer coefficient, K_{total}:



$$K_{total} = \sum UA + \dot{V}_{OA}\rho_{OA}C_{p,air}$$

$$\sum UA = (UA)_{walls} + (UA)_{windows} + (UA)_{doors} + (UA)_{roof} + (UA)_{floor}$$

$$Q_{envelope\,transmission} + Q_{air\,exchange} = K_{total}(T_{in} - T_{out})$$

Heat gains

$$Q_{gains} = Q_{solar} + Q_{light} + Q_{equip} + Q_{occ}$$

Typical heat gains include:

- Solar gains through windows (always positive, or 0 at night)
- Heat gains from occupants, lights, and equipment (internal gains)
  - Motors, copiers, computers, appliances, etc.
  - We need to know their scheduling (when they are off and on) as well as their magnitude
- Internal heat gains are heat sources on the inside of the building
  - These are all always positive (+), meaning they always add heat to the interior of the building
  - Internal heat gains can affect both heating and cooling loads

Heat gains from lighting

- Lights are often a major internal heat load component
  - This is changing as lighting efficiency increases
- Lights contribute to heat gain through convection and radiation
  - Function of total wattage and how much they are used

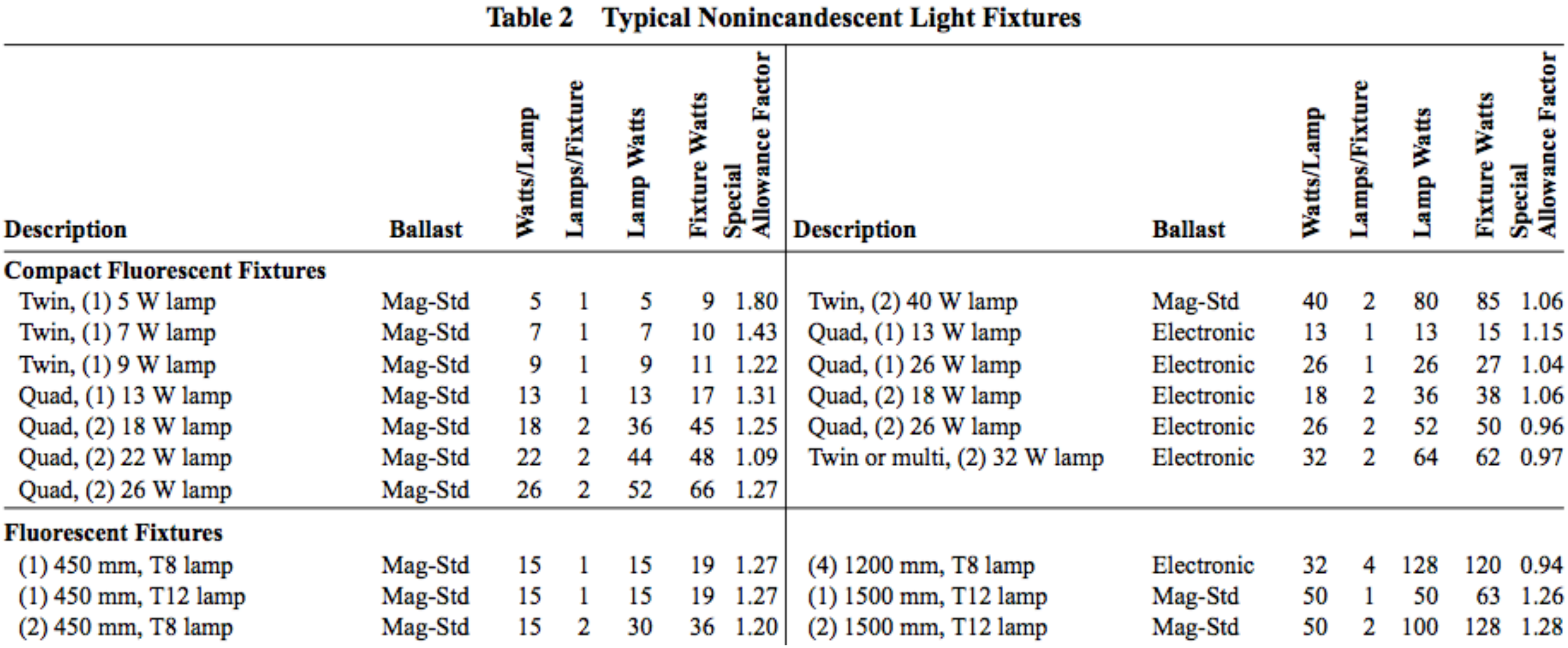
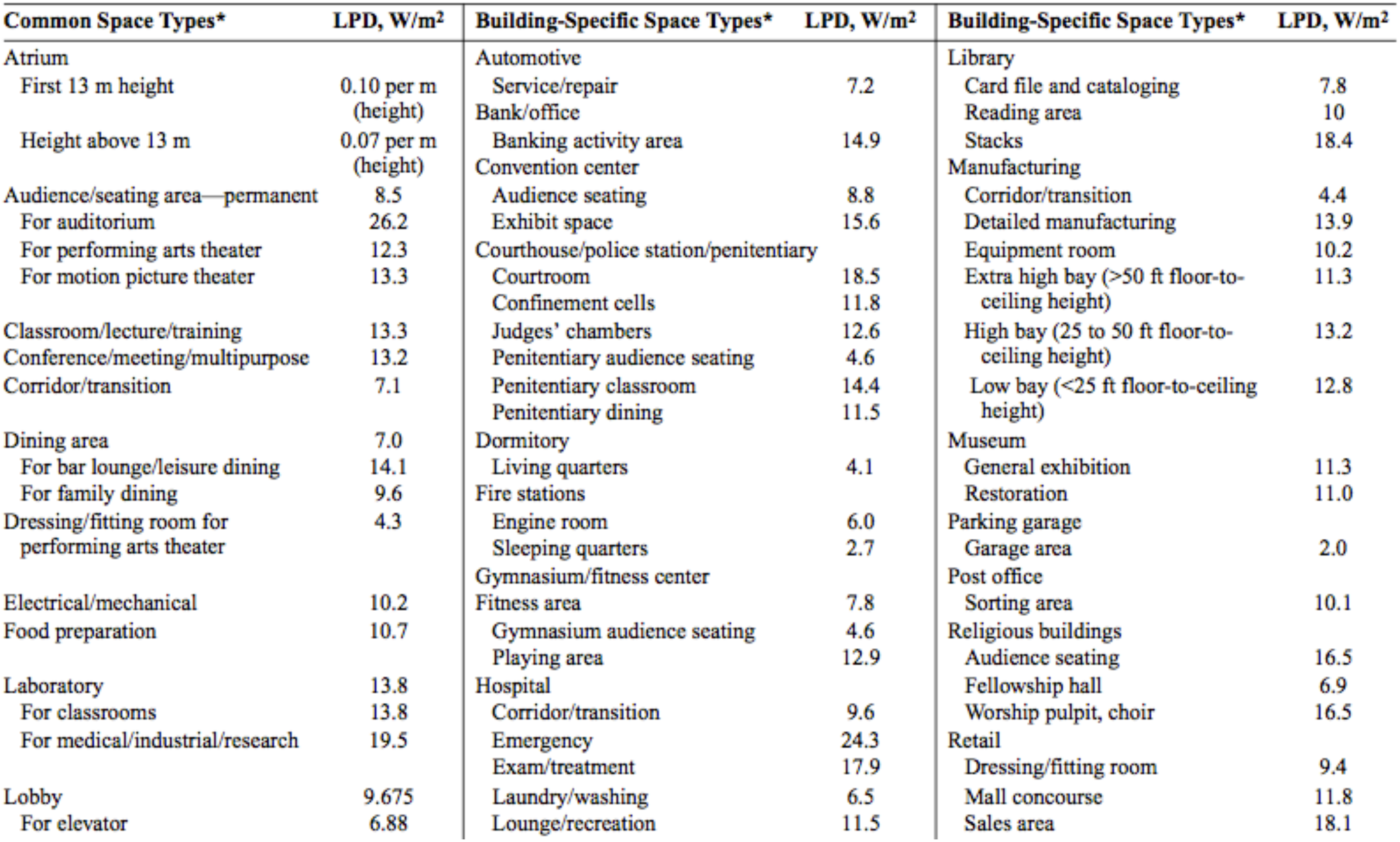


Table 2 Typical Nonincandescent Light Fixtures

Description	Ballast	Watts/Lamp	Lamps/Fixture	Lamp Watts	Fixture Watts	Special Allowance Factor
Compact Fluorescent Fixtures						
Twin, (1) 5 W lamp	Mag-Std	5	1	5	9	1.80
Twin, (1) 7 W lamp	Mag-Std	7	1	7	10	1.43
Twin, (1) 9 W lamp	Mag-Std	9	1	9	11	1.22
Quad, (1) 13 W lamp	Mag-Std	13	1	13	17	1.31
Quad, (2) 18 W lamp	Mag-Std	18	2	36	45	1.25
Quad, (2) 22 W lamp	Mag-Std	22	2	44	48	1.09
Quad, (2) 26 W lamp	Mag-Std	26	2	52	66	1.27
Twin, (2) 40 W lamp	Mag-Std	40	2	80	85	1.06
Quad, (1) 13 W lamp	Electronic	13	1	13	15	1.15
Quad, (1) 26 W lamp	Electronic	26	1	26	27	1.04
Quad, (2) 18 W lamp	Electronic	18	2	36	38	1.06
Quad, (2) 26 W lamp	Electronic	26	2	52	50	0.96
Twin or multi, (2) 32 W lamp	Electronic	32	2	64	62	0.97
Fluorescent Fixtures						
(1) 450 mm, T8 lamp	Mag-Std	15	1	15	19	1.27
(1) 450 mm, T12 lamp	Mag-Std	15	1	15	19	1.27
(2) 450 mm, T8 lamp	Mag-Std	15	2	30	36	1.20
(4) 1200 mm, T8 lamp	Electronic	32	4	128	120	0.94
(1) 1500 mm, T12 lamp	Mag-Std	50	1	50	63	1.26
(2) 1500 mm, T12 lamp	Mag-Std	50	2	100	128	1.28

Heat gains from lighting

- You can also use typical “**lighting power densities**” for different kinds of spaces



Common Space Types*	LPD, W/m²	Building-Specific Space Types*	LPD, W/m²	Building-Specific Space Types*	LPD, W/m²
Atrium		Automotive		Library	
First 13 m height	0.10 per m (height)	Service/repair	7.2	Card file and cataloging	7.8
		Bank/office		Reading area	10
Height above 13 m	0.07 per m (height)	Banking activity area	14.9	Stacks	18.4
		Convention center		Manufacturing	
Audience/seating area—permanent	8.5	Audience seating	8.8	Corridor/transition	4.4
For auditorium	26.2	Exhibit space	15.6	Detailed manufacturing	13.9
For performing arts theater	12.3	Courthouse/police station/penitentiary		Equipment room	10.2
For motion picture theater	13.3	Courtroom	18.5	Extra high bay (>50 ft floor-to-ceiling height)	11.3
		Confinement cells	11.8		
Classroom/lecture/training	13.3	Judges’ chambers	12.6	High bay (25 to 50 ft floor-to-ceiling height)	13.2
Conference/meeting/multipurpose	13.2	Penitentiary audience seating	4.6		
Corridor/transition	7.1	Penitentiary classroom	14.4	Low bay (<25 ft floor-to-ceiling height)	12.8
		Penitentiary dining	11.5		
Dining area	7.0	Dormitory		Museum	
For bar lounge/leisure dining	14.1	Living quarters	4.1	General exhibition	11.3
For family dining	9.6	Fire stations		Restoration	11.0
Dressing/fitting room for performing arts theater	4.3	Engine room	6.0	Parking garage	
		Sleeping quarters	2.7	Garage area	2.0
		Gymnasium/fitness center		Post office	
Electrical/mechanical	10.2	Fitness area	7.8	Sorting area	10.1
Food preparation	10.7	Gymnasium audience seating	4.6	Religious buildings	
		Playing area	12.9	Audience seating	16.5
Laboratory	13.8	Hospital		Fellowship hall	6.9
For classrooms	13.8	Corridor/transition	9.6	Worship pulpit, choir	16.5
For medical/industrial/research	19.5	Emergency	24.3	Retail	
		Exam/treatment	17.9	Dressing/fitting room	9.4
Lobby	9.675	Laundry/washing	6.5	Mall concourse	11.8
For elevator	6.88	Lounge/recreation	11.5	Sales area	18.1

Heat gains from equipment

- Equipment and appliances also add heat to the indoor air

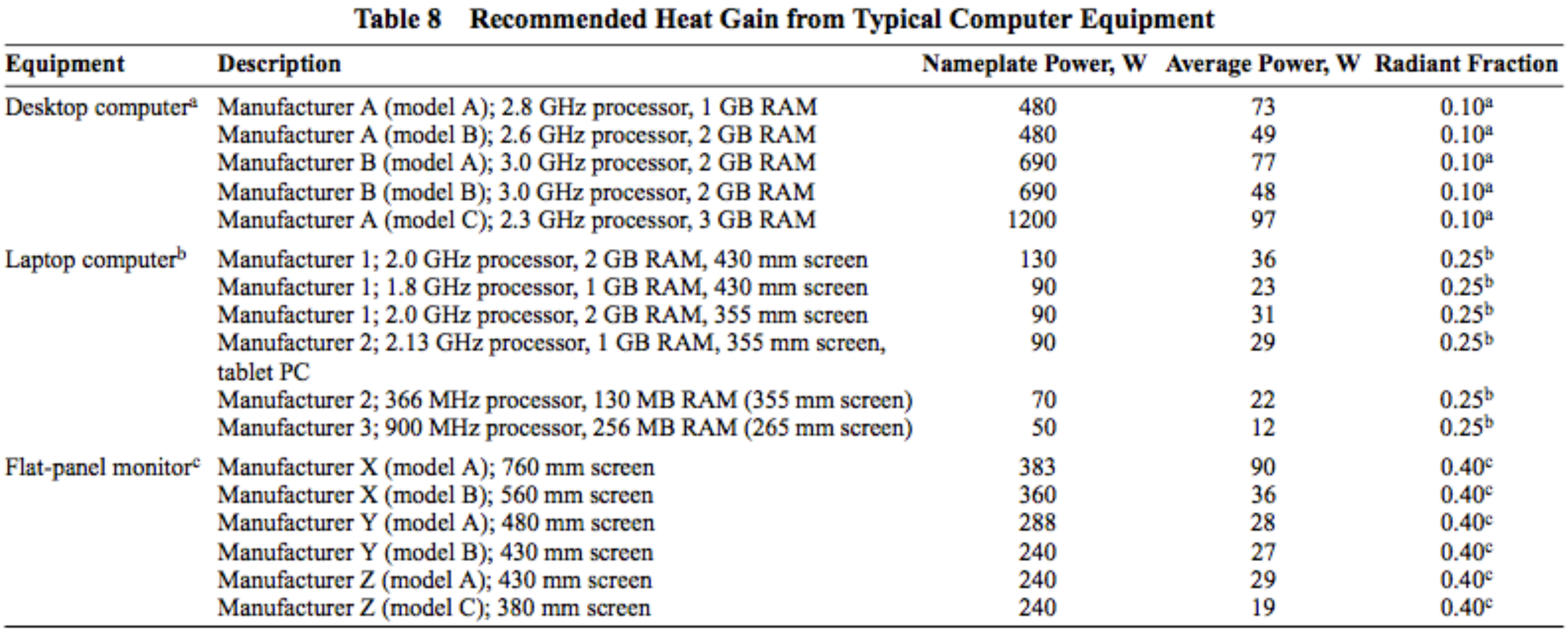


Table 8 Recommended Heat Gain from Typical Computer Equipment

Equipment	Description	Nameplate Power, W	Average Power, W	Radiant Fraction
Desktop computer[a]	Manufacturer A (model A); 2.8 GHz processor, 1 GB RAM	480	73	0.10[a]
	Manufacturer A (model B); 2.6 GHz processor, 2 GB RAM	480	49	0.10[a]
	Manufacturer B (model A); 3.0 GHz processor, 2 GB RAM	690	77	0.10[a]
	Manufacturer B (model B); 3.0 GHz processor, 2 GB RAM	690	48	0.10[a]
	Manufacturer A (model C); 2.3 GHz processor, 3 GB RAM	1200	97	0.10[a]
Laptop computer[b]	Manufacturer 1; 2.0 GHz processor, 2 GB RAM, 430 mm screen	130	36	0.25[b]
	Manufacturer 1; 1.8 GHz processor, 1 GB RAM, 430 mm screen	90	23	0.25[b]
	Manufacturer 1; 2.0 GHz processor, 2 GB RAM, 355 mm screen	90	31	0.25[b]
	Manufacturer 2; 2.13 GHz processor, 1 GB RAM, 355 mm screen, tablet PC	90	29	0.25[b]
	Manufacturer 2; 366 MHz processor, 130 MB RAM (355 mm screen)	70	22	0.25[b]
	Manufacturer 3; 900 MHz processor, 256 MB RAM (265 mm screen)	50	12	0.25[b]
Flat-panel monitor[c]	Manufacturer X (model A); 760 mm screen	383	90	0.40[c]
	Manufacturer X (model B); 560 mm screen	360	36	0.40[c]
	Manufacturer Y (model A); 480 mm screen	288	28	0.40[c]
	Manufacturer Y (model B); 430 mm screen	240	27	0.40[c]
	Manufacturer Z (model A); 430 mm screen	240	29	0.40[c]
	Manufacturer Z (model C); 380 mm screen	240	19	0.40[c]

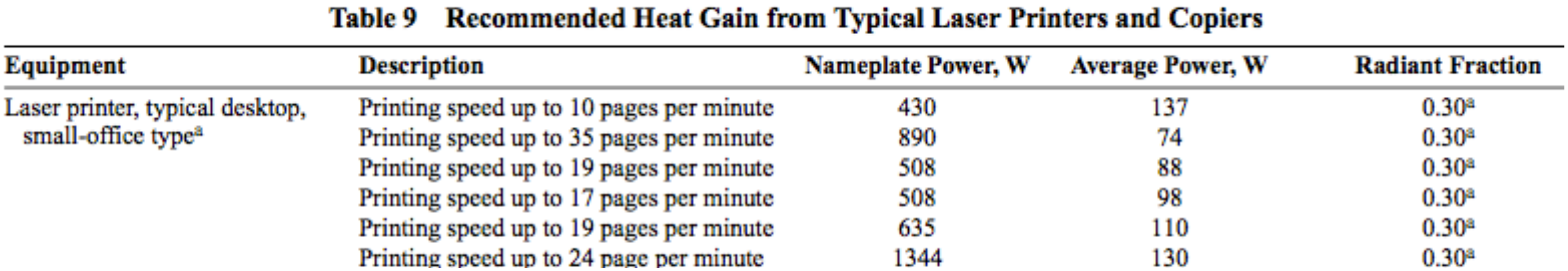


Table 9 Recommended Heat Gain from Typical Laser Printers and Copiers

Equipment	Description	Nameplate Power, W	Average Power, W	Radiant Fraction
Laser printer, typical desktop, small-office type[a]	Printing speed up to 10 pages per minute	430	137	0.30[a]
	Printing speed up to 35 pages per minute	890	74	0.30[a]
	Printing speed up to 19 pages per minute	508	88	0.30[a]
	Printing speed up to 17 pages per minute	508	98	0.30[a]
	Printing speed up to 19 pages per minute	635	110	0.30[a]
	Printing speed up to 24 page per minute	1344	130	0.30[a]

Heat gains from people

- Representative heat gains for people performing different activities are listed in the ASHRAE Handbook of Fundamentals
  - Need to keep the latent load separate from the sensible load

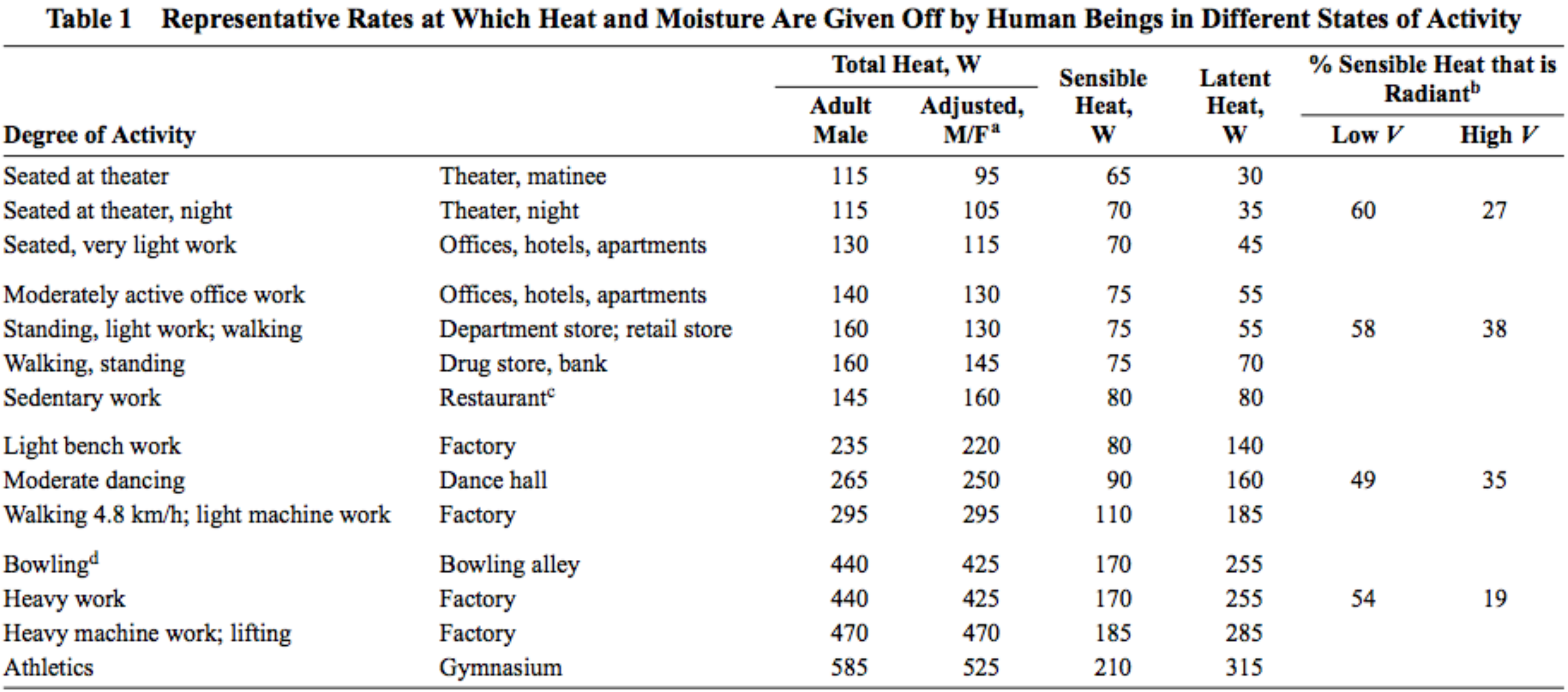
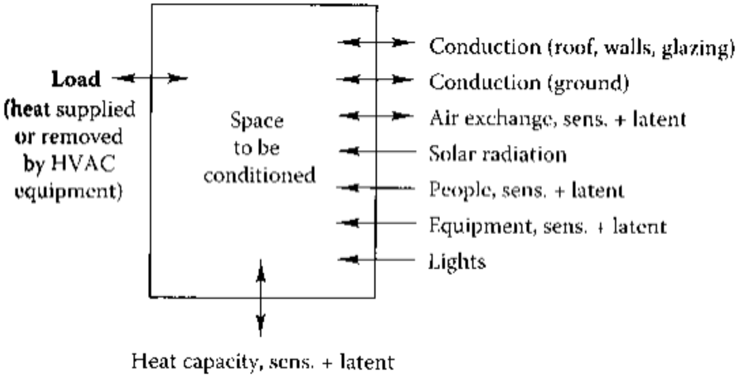


Table 1 Representative Rates at Which Heat and Moisture Are Given Off by Human Beings in Different States of Activity

		Total Heat, W				% Sensible Heat that is Radiant[b]	
Degree of Activity		Adult Male	Adjusted, M/F[a]	Sensible Heat, W	Latent Heat, W	Low *V*	High *V*
Seated at theater	Theater, matinee	115	95	65	30	60	27
Seated at theater, night	Theater, night	115	105	70	35		
Seated, very light work	Offices, hotels, apartments	130	115	70	45		
Moderately active office work	Offices, hotels, apartments	140	130	75	55	58	38
Standing, light work; walking	Department store; retail store	160	130	75	55		
Walking, standing	Drug store, bank	160	145	75	70		
Sedentary work	Restaurant[c]	145	160	80	80		
Light bench work	Factory	235	220	80	140	49	35
Moderate dancing	Dance hall	265	250	90	160		
Walking 4.8 km/h; light machine work	Factory	295	295	110	185		
Bowling[d]	Bowling alley	440	425	170	255	54	19
Heavy work	Factory	440	425	170	255		
Heavy machine work; lifting	Factory	470	470	185	285		
Athletics	Gymnasium	585	525	210	315		

Latent heat gains (moisture)



- Mainly due to:
  - Air exchange
  - Equipment (kitchen/bathroom)
  - Occupants
  - Humidification requirements

$$Q_{latent} = Q_{latent,air} + Q_{latent,occ} + Q_{latent,equip}$$

$$Q_{latent,air\,exchange} = \dot{m}_{w,OA} h_{fg} = \dot{V}_{OA} \rho_{OA} (W_{in} - W_{out}) h_{fg}$$

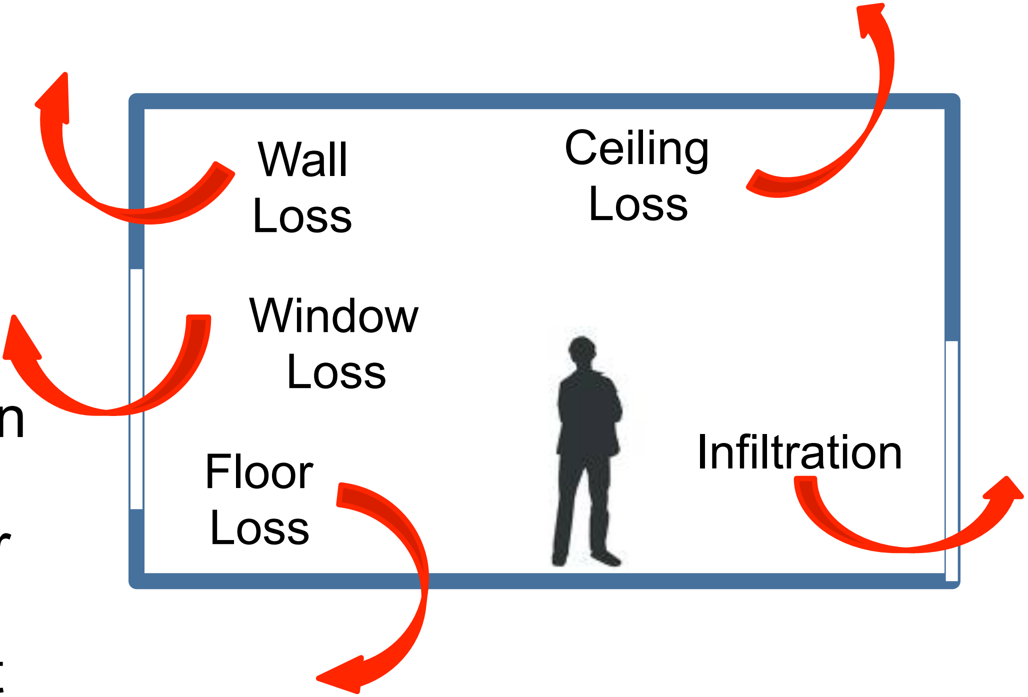
W_{in} = indoor design humidity ratio [$\mathrm{lb_w/lb_{da}}$] or [$\mathrm{kg_w/kg_{da}}$]
W_{out} = outdoor design humidity ratio [$\mathrm{lb_w/lb_{da}}$] or [$\mathrm{kg_w/kg_{da}}$]
h_{fg} = latent heat of vaporization of water [BTU/lbw] or [$\mathrm{J/kg_w}$]

Heating load calculation procedures

The peak heating load is simple and relies only on:

Overall envelope transmission and **infiltration**

- Transmission load (enclosure losses) is the heat lost to the outside through the building enclosure
  - Roof, walls, floor, windows
- Infiltration load (or ventilation load) is the heat required to warm up the cold outside air that leaks into the building through cracks or is brought in via ventilation



Heating load calculation procedures

- Heating load calculations are based on instantaneous heat losses
  - The maximum heating load should occur before sunrise on the coldest days of the year

- Therefore, we assume that:
  - All heating losses are instantaneous heating loads
    - We ignore any effects of thermal storage
  - Solar heat gains and internal loads are usually not taken into account except for those internal loads that continuously release heat inside the conditioned space during the whole heating season
  - The only latent load (*if any*) is that which is required to evaporate liquid water for maintaining adequate humidity

Heading load calculation procedures

1. Define your design conditions (T_{in} and T_{out})
2. Define the building envelope that separates conditioned (i.e., heated) space from unconditioned space
3. Determine the envelope and air exchange heat transmission coefficient (K_{total})
4. Determine any indoor heat sources present at the time of the peak load, e.g., people, equipment, lights, etc. (Q_{gains})
5. Calculate the instantaneous heat load using:

$$Q_{heating\,load} = K_{total}(T_{in} - T_{out}) - \sum Q_{gains}$$

$$Q_{heating\,load} = (\sum UA + \dot{V}_{OA}\rho_{OA}C_{p,air})(T_{in} - T_{out}) - \sum Q_{gains}$$

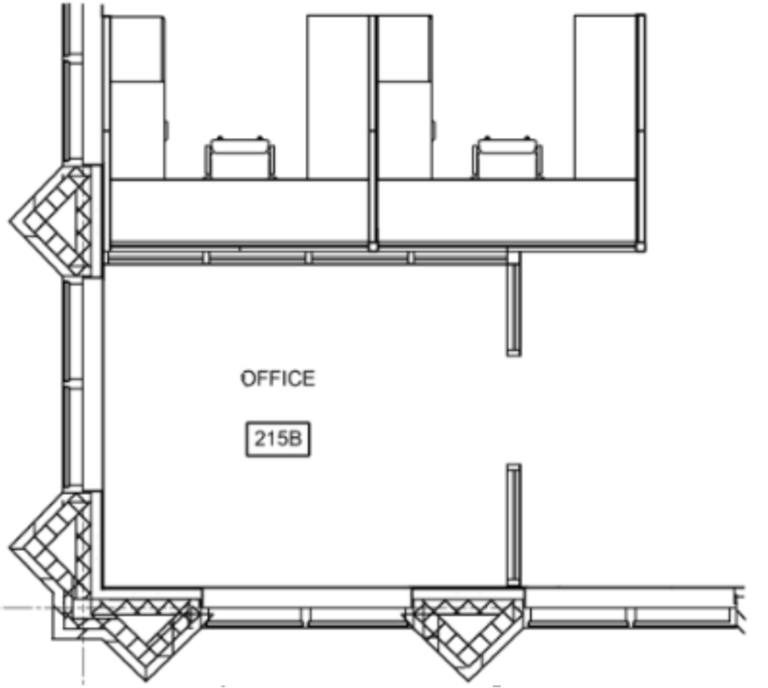
Heating load calculations

Example (SI units):

- Find the design heat load for a 12 m x 12 m x 2.5 m building with an insulated R-4.2 m^2K/W flat roof and R-2.5 m^2K/W walls
  - Double glazed windows (U = 3 W/m^2K) cover 20% of the walls
  - The air exchange rate is 0.5 per hour
  - Ignore floor heat transfer
  - Design conditions of -10°C outside and 22°C inside
  - Internal gains = 1 kW
  - Assume all R values and U values already include film resistances

Heating load calculations (single zone – IP units)

Calculate the peak heating load for the office room shown here (at 99.6%):



South exposure: Orientation = 30° east of true south
Window area = 40 ft^2
Spandrel wall area = 60 ft^2
Brick wall area = 60 ft^2

West exposure: Orientation = 60° west of south
Window area = 40 ft^2
Spandrel wall area = 60 ft^2
Brick wall area = 40 ft^2

Location: Atlanta, GA, 2nd floor of a two-story building,
Enclosure: 2 vertical exterior exposures and a flat roof above
Area: 130 ft^2
Ceiling height: 9 ft
Floor: Carpeted 5 inch concrete slab on metal deck above conditioned space
Roof: Flat metal deck with rigid closed cell polyisocyanurate foam insulation (R=30 hr-ft^2-°F/BTU)
Spandrel wall: Bronze tinted glass, opaque, backed with air space and rigid fiberglass insulation. Total U-value of 0.077 BTU/hr-ft^2-°F
Insulated brick wall: Brick with continuous exterior insulation and interior fiberglass batt insulation. Total U = 0.08 BTU/hr-ft^2-°F).
Infiltration: 1 air change per hour during peak heating
Window U values: Double glazed ¼” bronze tinted with 1/2” air space. Total U = 0.56 BTU/hr-ft^2-°F.
Occupancy: None during peak heating
Lighting: None during peak heating
Indoor design conditions: 72°F for heating

Heating load calculations (single zone – IP units)

2013 ASHRAE Handbook - Fundamentals (IP)

ATLANTA MUNICIPAL, GA, USA

WMO#: **722190**

Lat: **33.64N** Long: **84.43W** Elev: **1027** StdP: **14.16** Time Zone: **-5 (NAE)** Period: **86-10** WBAN: **13874**

Annual Heating and Humidification Design Conditions

Coldest Month	Heating DB		Humidification DP/MCDB and HR						Coldest month WS/MCDB				MCWS/PCWD to 99.6% DB	
			99.6%			99%			0.4%		1%			
	99.6%	99%	DP	HR	MCDB	DP	HR	MCDB	WS	MCDB	WS	MCDB	MCWS	PCWD
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)
1	21.5	26.4	4.2	7.1	28.6	9.1	9.1	32.2	24.9	39.9	23.5	40.0	11.9	320

Annual Cooling, Dehumidification, and Enthalpy Design Conditions

Hottest Month	Hottest Month DB Range	Cooling DB/MCWB						Evaporation WB/MCDB						MCWS/PCWD to 0.4% DB	
		0.4%		1%		2%		0.4%		1%		2%			
		DB	MCWB	DB	MCWB	DB	MCWB	WB	MCDB	WB	MCDB	WB	MCDB	MCWS	PCWD
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)
7	17.0	93.9	74.2	91.7	73.9	89.8	73.5	77.3	88.5	76.4	86.7	75.4	85.0	8.7	300

Dehumidification DP/MCDB and HR									Enthalpy/MCDB						Hours 8 to 4 & 55/69
0.4%			1%			2%			0.4%		1%		2%		
DP	HR	MCDB	DP	HR	MCDB	DP	HR	MCDB	Enth	MCDB	Enth	MCDB	Enth	MCDB	
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)
74.3	133.1	81.3	73.3	128.7	80.2	72.6	125.5	79.6	41.4	88.5	40.4	86.7	39.5	85.6	800

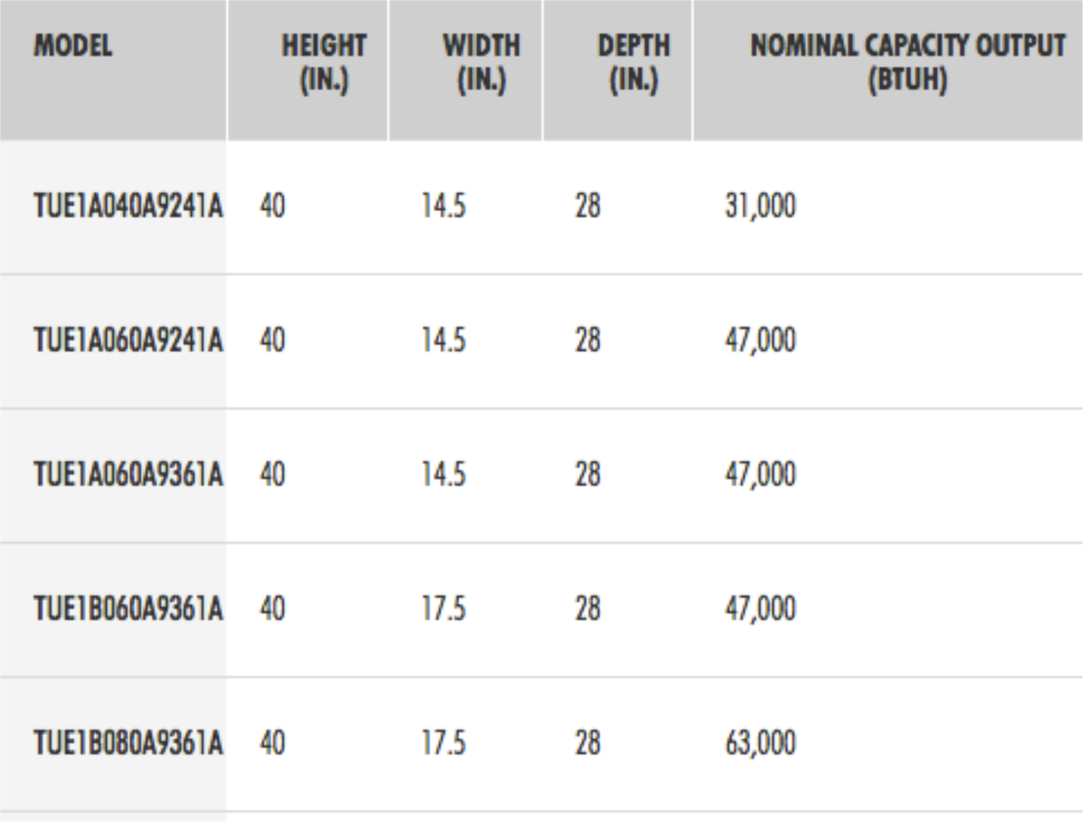
Extreme Annual Design Conditions

Extreme Annual WS			Extreme Max WB	Extreme Annual DB				n-Year Return Period Values of Extreme DB							
				Mean		Standard deviation		n=5 years		n=10 years		n=20 years		n=50 years	
1%	2.5%	5%		Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)	(l)	(m)	(n)	(o)	(p)
21.5	19.0	17.1	82.4	14.1	96.7	4.4	3.3	10.9	99.1	8.3	101.0	5.8	102.9	2.6	105.3

Selecting equipment

- Once you know your design heating load, you can select equipment

$$Q_{h,\max} = 4406 \text{ BTU/hr} = 4.4 \text{ kBTU/hr}$$



MODEL	HEIGHT (IN.)	WIDTH (IN.)	DEPTH (IN.)	NOMINAL CAPACITY OUTPUT (BTUH)
TUE1A040A9241A	40	14.5	28	31,000
TUE1A060A9241A	40	14.5	28	47,000
TUE1A060A9361A	40	14.5	28	47,000
TUE1B060A9361A	40	17.5	28	47,000
TUE1B080A9361A	40	17.5	28	63,000

Selecting equipment