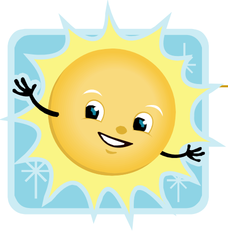
Green Buildings:
Solar Design and Heat Loss



Acknowledgment:
Lecture prepared with able assistance from
Harold (JJ) Johnson, TA in Fall 2006

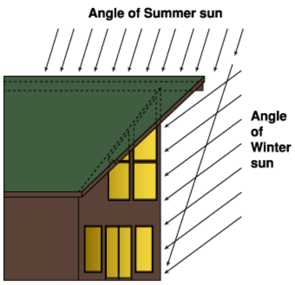
http://www.london-se1.co.uk/news/imageuploads/1158238970_80.177.117.97.jpg

---

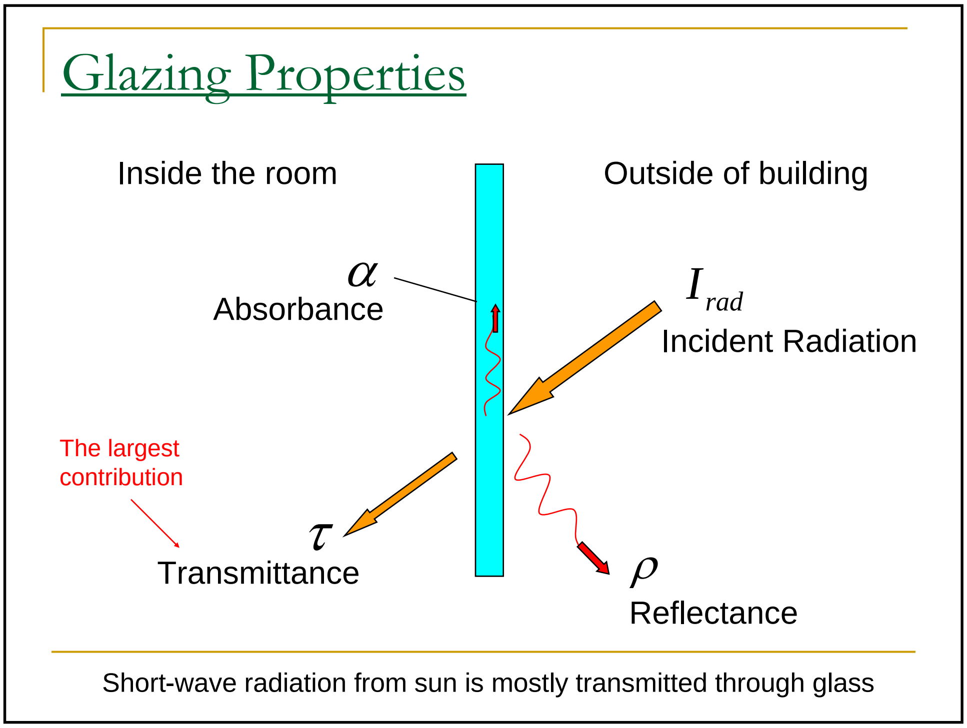
Solar Radiation Basics

- Direct solar gain
- Glazing properties
- Heat loss pathways
- Degree days
- Angle of incidence

(http://www.iron-to-live-with.com/apartment/source/4.html)



(http://solar.steinbergs.us/solar.html)



Glazing Properties

Inside the room

Outside of building

α
Absorbance

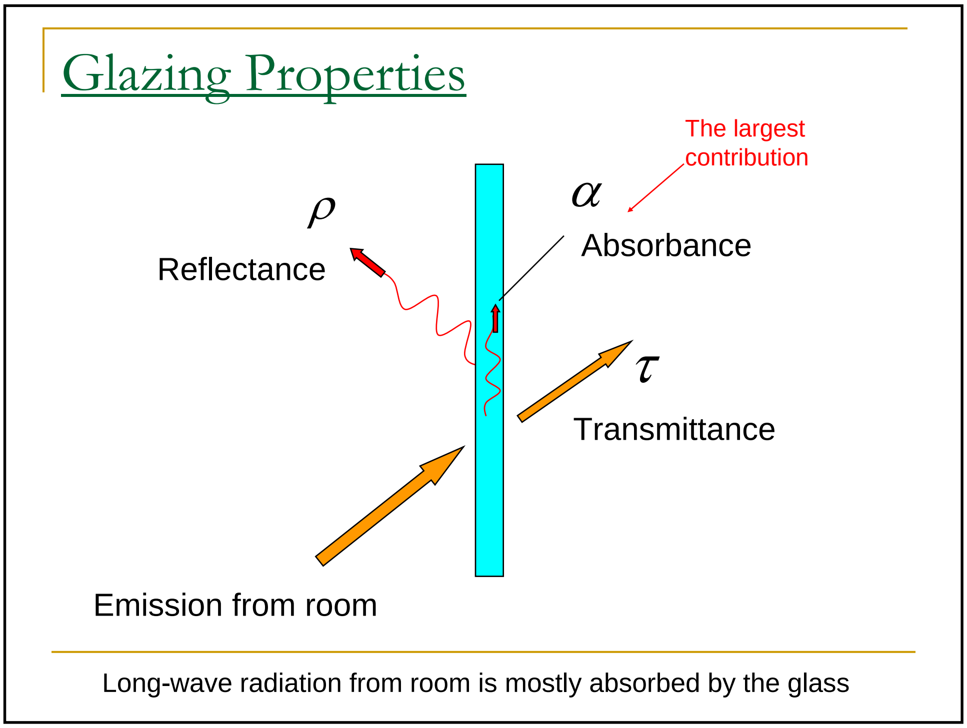
I_{rad}
Incident Radiation

The largest contribution

τ
Transmittance

ρ
Reflectance

Short-wave radiation from sun is mostly transmitted through glass



Glazing Properties

The largest contribution

ρ
Reflectance

α
Absorbance

τ
Transmittance

Emission from room

Long-wave radiation from room is mostly absorbed by the glass

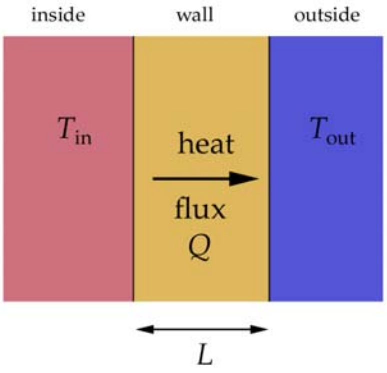
Heat Loss Pathways

- **Conduction**
  - Transfer of heat from warmer molecules to adjacent cooler molecules, without material transfer
- **Convection**
  - Movement of a fluid from one location to another. Heat is being transported as warm fluid goes to cool spots.
- **Radiation**
  - Emission of electromagnetic waves. Infrared rays carry heat.

Conduction

Heat flux proceeds by transfer of molecular agitation from more agitated (warmer) molecules to adjacent, less agitated (cooler) molecules.

$$\text{heat flux} = \text{conductivity} \times (\text{temperature gradient})$$



$$q_c = K\frac{\Delta T}{L} = K\frac{T_{in}-T_{out}}{L}$$

$$q_c = U\,(T_{in}-T_{out})$$

per unit area

Multiply by area and sum over all surfaces of the building (walls, windows, doors and roof):

$$Q_c = (T_{in}-T_{out})\times\underbrace{\sum_i (A_i\times U_i)}_{\text{Heat Load }(HL)}$$

The Heat Load is a characteristic of the building and can be calculated once and for all.

Convection - Ventilation

Heat flux proceeds by movement of a fluid from one location to another.
Warm air escapes through cracks or when a door is open, and colder air flows in to take its place. This is convection by infiltration.

In larger buildings, forced ventilation is necessary to keep the air fresh.

$$\text{Heat flux} = \text{Heat capacity of air} \times \frac{\text{change of volume}}{\text{time}} \times \Delta\text{Temperature}$$

$$Q_v = H_{air}\frac{dV}{dt}(T_{in} - T_{out}) \quad \text{with} \quad H_{air} = 0.018\ \text{Btus/(ft}^3 \times {}^{\text{o}}\text{F)}$$

$$Q_v = \underbrace{0.018 \times N_{air\ exchanges} \times V_{room}}_{\text{Air ventilation/infiltration } (AV)} \times (T_{in} - T_{out})$$

where $N_{\text{air exchanges}}$ = number of volume exchanges per time, such as 2 times in 3 hours.

Radiation

Heat flux proceeds by emission and absorption of electromagnetic waves
(in infrared range for common room and external temperatures)

$$\begin{aligned} q_r &= e \times \sigma \times \left(T_{in}^4 - T_{out}^4\right) \\ &\approx 4e \times \sigma \times T_{in}^3 (T_{in} - T_{out}) \end{aligned}$$

where $e = \text{emissivity } (\leq 1)$

$$\sigma = 5.67 \times 10^{-8}\ \text{W/(m}^2 \times \text{K}^4) = 1.712 \times 10^{-9}\ \text{BTUs/(ft}^2 \times \text{hr} \times {}^{\text{o}}\text{F}^4)$$

and T = absolute temperature

Multiply by area through which radiation occurs (mostly windows and hot surfaces exposed to the outside) and sum over these surfaces:

$$Q_r = (T_{in} - T_{out}) \times \underbrace{\sum_i 4 e_i \sigma A_i T_{in}^3}_{\text{Radiation Factor } (RF)}$$

Summing up the various heat flows

This makes the number of energy needed to keep the building warm on a per-time basis (BTUs per hour) when the desired indoor temperature is T_{in} and the outside temperature happens to be T_{out}.

$$\begin{aligned} Q_{net} &= Q_{conduction} + Q_{ventilation} + Q_{radiation} \\ &= (T_{in} - T_{out}) \times (HL + AV + RF) \end{aligned}$$

(on per-hour basis)

Assuming that we wish to keep the same indoor T_{in} throughout the year, we can determine the annual heat demand by integrating this expression over time, namely summing over the days of the year:

$$Q_{annual} = \sum_{i=1}^{365} [T_{in} - T_{out}(\mathrm{day}_i)] \times (24\,\mathrm{hours}) \times (HL + AV + RF)$$

The components HL, AV and RF are properties of the building and do not depend on the day of the year. Only the first factor depends on the daily outdoor temperature; it can be separated by defining

$$\mathrm{Degree\text{-}days} = \sum_{i=1}^{365} \left[T_{in} - T_{out}(\mathrm{day}_i) \right]$$

Thus: $$Q_{annual} = (\mathrm{Degree\text{-}days}) \times (24\,\mathrm{hours}) \times (HL + AV + RF)$$

Example

For Lebanon, NH during 2006:

January:	1162
February:	1179
March:	1028
April:	587
May:	276
June:	60
July:	0
August:	34
September:	171
October:	529
November:	660
December:	1013
TOTAL:	**6,699 Degree-days**

Assuming:
Indoor temperature of 65ºF

(http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/cdus/degree_days/)

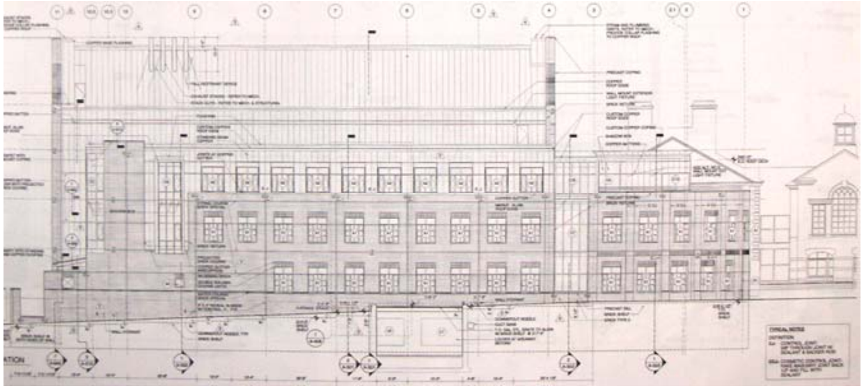
Case Study:

(Photo by Douglas Fraser)

MacLean Engineering Sciences Center

Dartmouth College, Hanover, NH

Elevation Drawings



First, determine surface area of glazing and wall areas
Then, find out the *R*-values of windows, walls and roof.

Heat Loss Calculations – Conduction

- Annual conduction heat loss:

  Q = (U-value) x (Surface areas) x (Degree-days)

		Area (ft^2)	R-value	U-value	Heat Loss (BTUs)
South	Windows	2660	7	0.14	61,094,880
	Walls	8988	20	0.05	72,252,734
East	Windows	1678	7	0.14	38,540,304
	Walls	2738	20	0.05	22,010,234
West	Windows	1224	7	0.14	28,112,832
	Walls	3192	20	0.05	25,659,850
North	Windows	578	7	0.14	13,275,504
	Walls	1000	20	0.05	8,038,800
Top	Roof	15300	30	0.033	81,995,760
					350,980,898

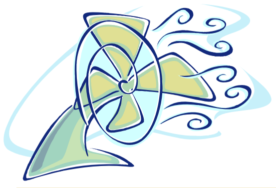
For 6,699 Degree-days (2006 value)

Heat Loss Calculations – Convection

- Heat demand due to ventilation:
  - MacLean has two separate forced-air units
    - Office air handling unit – 48,000 cfm w/ minimum 20% outdoor air
    - Laboratory air system – 18,500 cfm w/ 100% outdoor air
      - Energy recovery wheel – 76% total enthalpy efficiency

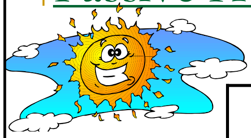
$$Q = (\text{Heat capacity of air}) \times (\text{Volume per time}) \times (\text{Degree-days})$$

$$= (0.018) \times (\#\,\text{ft}^3/\text{min of fresh air}) \times (1440\,\text{min}/\text{day}) \times (6{,}699) \times (1 - \%\text{ energy recovery})$$



Offices	flowrate	48,000	ft³/min
	% outdoor air	20	%
	% recovery	0	%
	Heat needed	1,666,925,568	BTUs
Laboratories	flowrate	18,500	ft³/min
	% outdoor air	100	%
	% recovery	76	%
	Heat needed	770,953,075	BTUs
	TOTAL	2,437,878,643	BTUs

Passive Heat Sources: 1 – Solar Gain



		EAST	SOUTH	WEST	NORTH	% sun
Heat received from sun on clear day, in BTUs/(ft^2.day)	Sep	787	1,344	787	0	57%
	Oct	623	1,582	623	0	55%
	Nov	445	1,596	445	0	46%
	Dec	374	1,550	374	0	46%
	Jan	452	1,626	452	0	46%
	Feb	648	1,642	648	0	55%
	Mar	832	1,388	832	0	56%
	Apr	957	976	957	0	54%
	May	1,024	716	1,024	0	57%
Net solar radiation	BTUs/ft^2	100,020	195,115	100,020	0	
Window area	ft^2	1,678	2,660	1,224	578	
Total per side	10^6 BTUs	167.83	519.01	122.42	0.00	
Building total	10^6 BTUs		**809.26**			

(Solar Heat Gain Factors and Cloudiness Factors from "The Passive Solar House" by James Kachadorian, 1997)

Passive Heat Sources: 2 – Body Heat

http://www.landinst.com/infrared/latest/images/body_temperature.jpg

Fact:

A human person emits 520 BTUs per hour in the course of normal activities.

Assumptions:

- 150 people inside MacLean Building during a typical workday
- 9-hour workday
- 213 workdays in the year (discounting week-ends and holidays)

Calculation:

$$\text{Heat from people} = \frac{520\ \text{BTUs}}{\text{person} \times \text{hour}} \times 150\ \text{persons} \times \frac{9\ \text{hours}}{\text{day}} \times \frac{213\ \text{days}}{\text{year}}$$

$$= 149.53 \times 10^6\ \text{BTUs/year}$$

Energy Balance

- Heat gains – Heat losses = Heat surplus/deficit

Solar gain:	+ 809.26
Body heat:	+ 149.53
Conduction losses:	– 350.98
Convection losses:	– 2,437.88
	– 1,830.07

in million BTUs per year

Economic and Environmental Impacts

http://news.umr.edu/images/Coalplant_f.jpg

- Heating cost:
  - 3412 BTU/kWh
  - $0.14 per kWh
- CO_2 emissions
  - 0.68 lbs of CO_2 per kWh
- Totals:
  - (1,830.07 x 10^6 BTUs/yr) / (3412 BTUs/kWh) = 536,363 kWh/yr
  - 536,363 kWh x 0.14 $/kWh = $75,091
  - 536,363 kWh x 0.68 lbs CO_2/kWh = 364,727 lbs CO_2
  - 364,727 lbs CO_2 = driving from Hanover to Seattle 385 times

Alternative Design – 1

- Cost/benefit of replacing half the windows in the atrium with insulation

		Area	R-value	U-value	Heat Loss
South	Windows	2,660	7	0.14	61,094,880
	Walls	8,988	20	0.05	72,252,734
East	Windows	1,278	7	0.14	29,353,104
	Walls	3,138	20	0.05	25,225,754
West	Windows	824	7	0.14	18,925,632
	Walls	3,592	20	0.05	28,875,370
North	Windows	578	7	0.14	13,275,504
	Walls	1,000	20	0.05	8,038,800
Top	Roof	15,300	30	0.033	81,995,760
	Degree-days	6,699		TOTAL	339,037,538
				Savings	3.4%

Conduction heat loss is reduced from 350.98 million BTUs to 339.04 million BTUs.

However, solar gain is also reduced by 80.02 million BTUs.

Overall, net energy loss of 68.08 million BTUs.

Conclusion: **Keep the windows!** They act as a greenhouse.

Alternative Design – 2

- Benefit of installing R-5 curtains for nighttime use

R = 7 for window + 1 for air layer + 5 for curtain = 13 total

		Area	*R*-value	*U*-value	Heat Loss
South	Windows	2,660	13	0.077	32,897,243
	Walls	8,988	20	0.05	72,252,734
East	Windows	1,678	13	0.077	20,752,471
	Walls	2,738	20	0.05	22,010,234
West	Windows	1,224	13	0.077	15,137,679
	Walls	3,192	20	0.05	25,659,850
North	Windows	578	13	0.077	7,148,348
	Walls	1,000	20	0.05	8,038,800
Top	Roof	15,300	30	0.033	81,995,760
	Degree-days	6,699		TOTAL	285,893,120
				Savings	18.5%

Conduction heat loss reduced from 350.98 million BTUs to 285,89 million BTUs, with no reduction in solar gain.

Overall, annual savings of 65.09 million BTUs = 19,076 kWh = $2,671.

Conclusion: **Curtains will probably be too expensive to justify savings, unless they also serve an aesthetic purpose.**

Alternative Design – 3

- Benefit of atrium connecting Cummings and MacLean *vs*. open air between them

		Area	R-value	U-value	Heat Loss
South	Windows	2,660	7	0.14	61,094,880
	Walls	8,988	20	0.05	72,252,734
East	Windows	**1,278**	7	0.14	29,353,104
	Walls	2,738	20	0.05	22,010,234
West	Windows	**824**	7	0.14	18,925,632
	Walls	3,192	20	0.05	25,659,850
North	Windows	**1,300**	7	0.14	29,858,400
	Walls	**10,348**	20	0.05	83,185,502
Top	Roof	15,300	30	0.033	81,995,760
	Degree-days	6,699		TOTAL	424,336,097
				Loss	**20.9%**

If the atrium did not connect the two buildings, conduction losses would increase from 350.98 million to 424.34 million BTUs, per year (= 21,499 kWh/year = $3,010/year).

But, we would save having to heat the atrium, we would have to shovel snow, *etc*.

Green Design Case Study

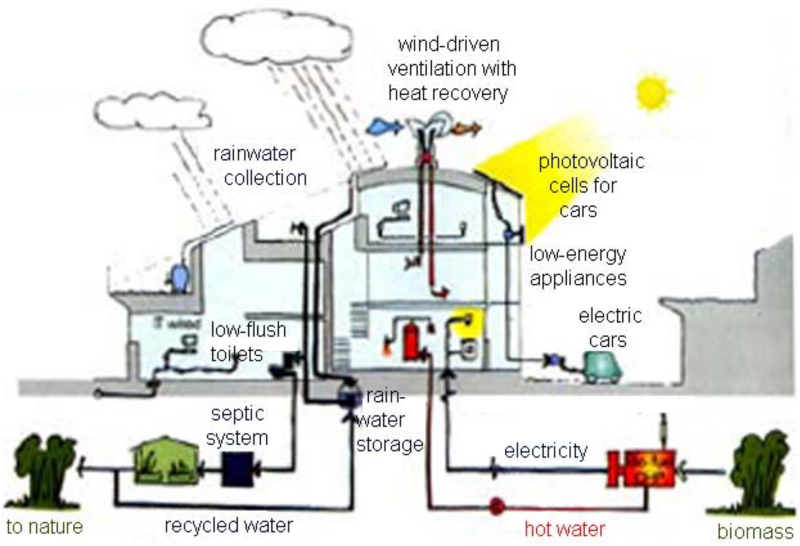
Hackbridge, Sutton, UK
(http://www.zedfactory.com/bedzed/bedzed.html)

Bennington Zero Energy Development (BedZED)

BedZED Goals

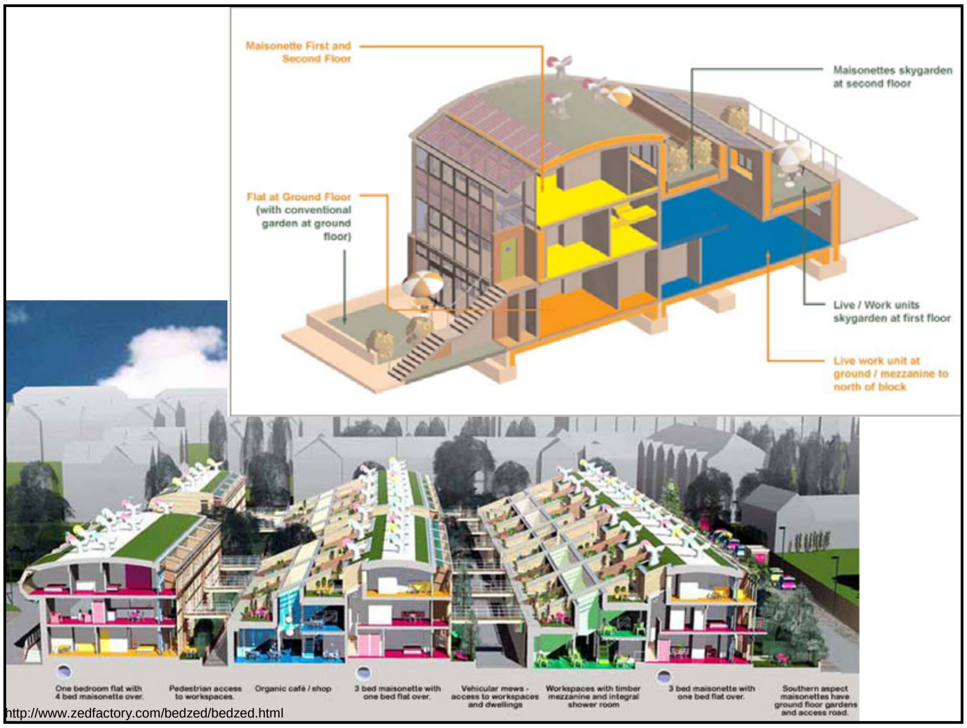
BedZED was developed

- “to be a carbon neutral residential and commercial development with a mixture of work spaces and residential units occupying an area of reclaimed brownfield land”,
- to provide “affordable, attractive, and environmentally responsible housing and workspace”,
- to address environmental, social, and economic needs,
- to reduce energy, water, and car use.



Green Design Features

- Renewable materials, low embodied energy
- Energy efficient lighting and appliances
- Passive solar heat, natural lighting
- Combined heat and power plant (CHP) – biomass fuel
- Photovoltaic cells
- Rainwater harvesting and greywater recycling
- Electric cars and access to public transportation
- Natural ventilation heat recovery



http://www.zedfactory.com/bedzed/bedzed.html

http://www.bioregional-reclaimed.com/BEdZED%20case%20study.htm