LCCSS.org or sustainableloudoun.org

Theoildrum web site has some of Will’s articles on passive solar

Passive Solar Design and Retrofit

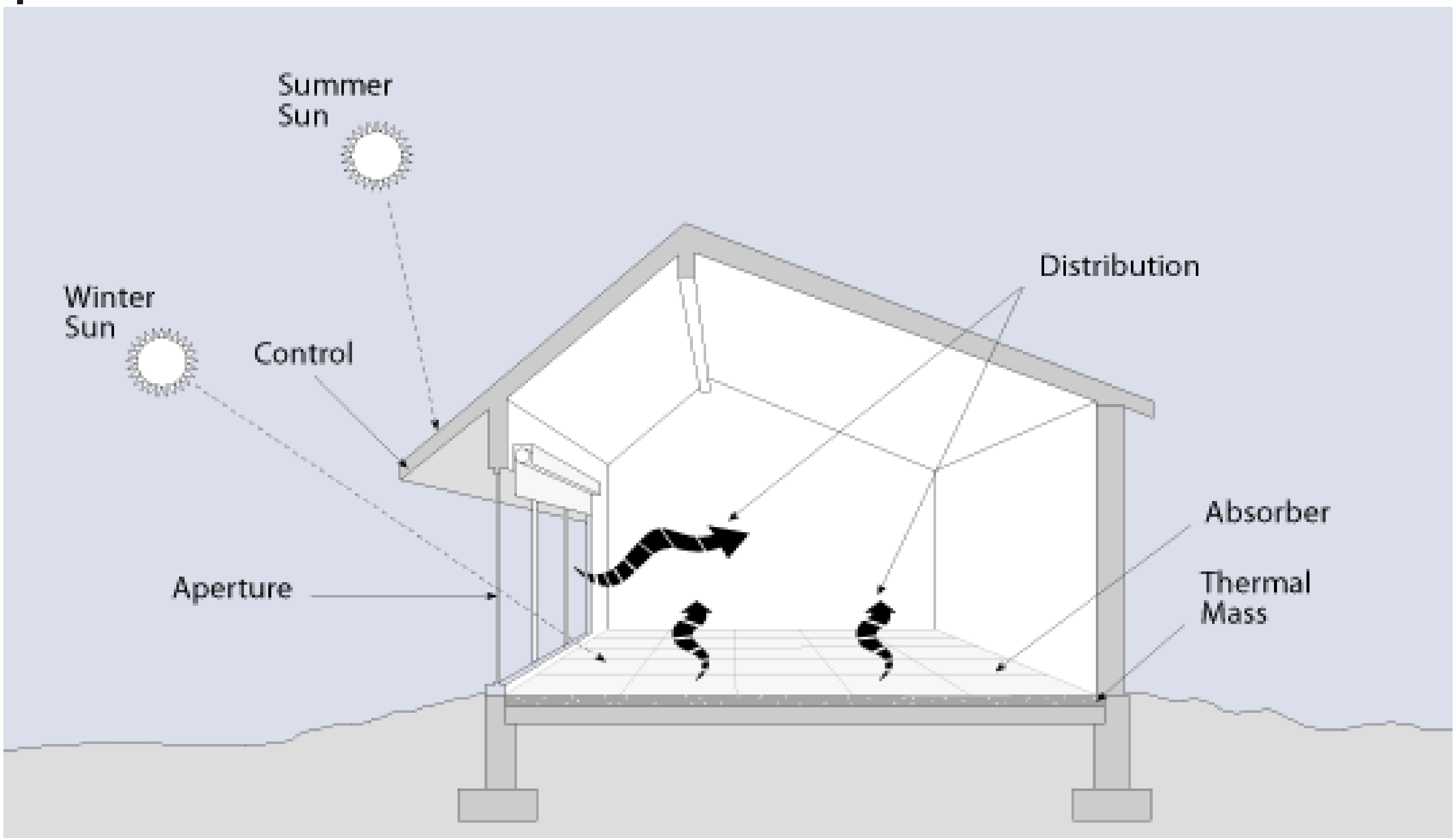
William Stewart
Sustainable Loudoun

May 7, 2009

What is Passive Solar?

- Passive solar design refers to the use of the sun's energy for the
  - heating and cooling of living spaces, and
  - heating of water
- Passive solar in ancient history
  - Socrates noted “In houses that look toward the south, the sun penetrates the portico in winter.”
  - Greek playwright Aeschylus stated only primitives and barbarians "lacked knowledge of houses turned to face the winter sun”.

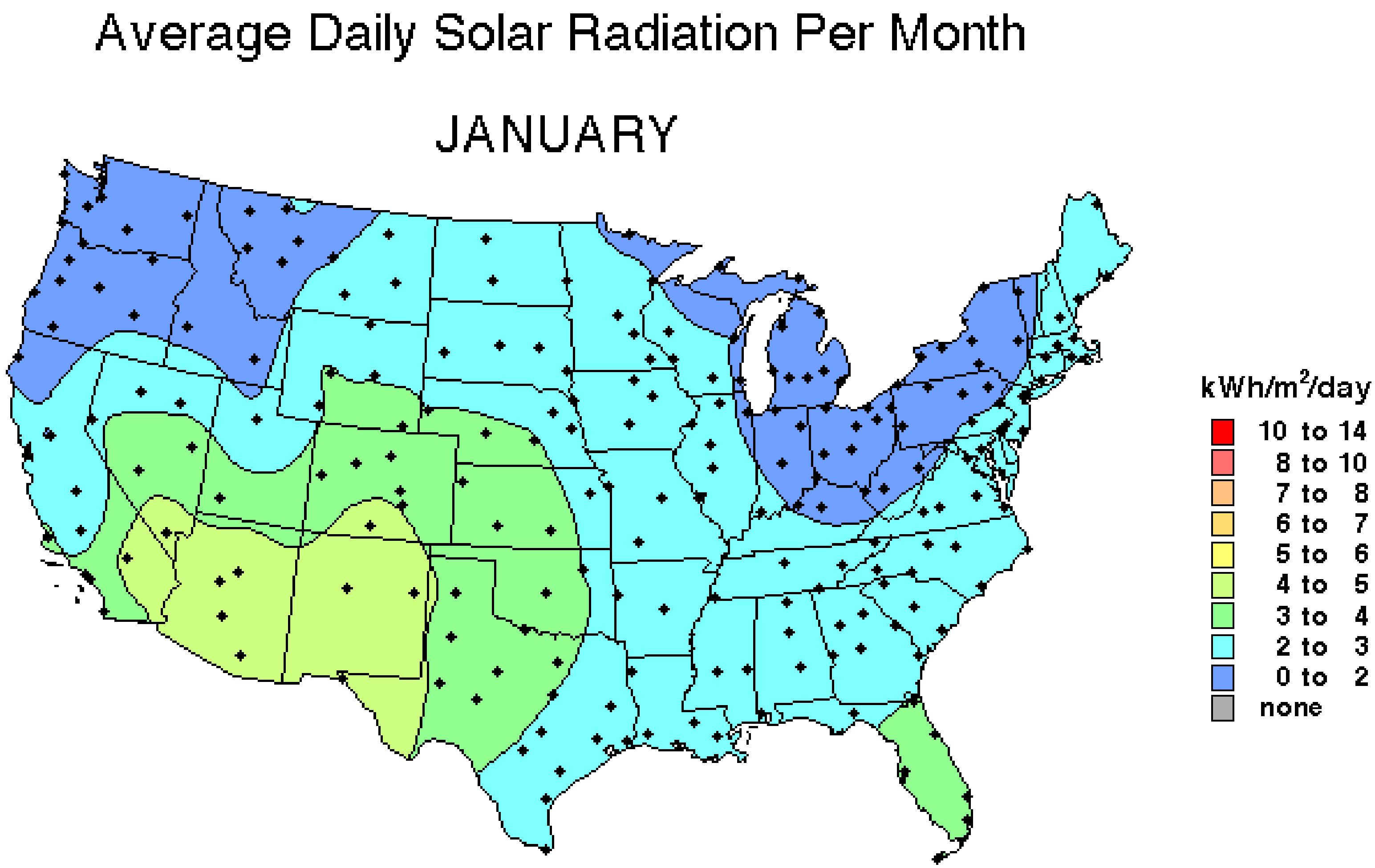
Main Elements of Passive Solar



Where can we use Passive Solar?

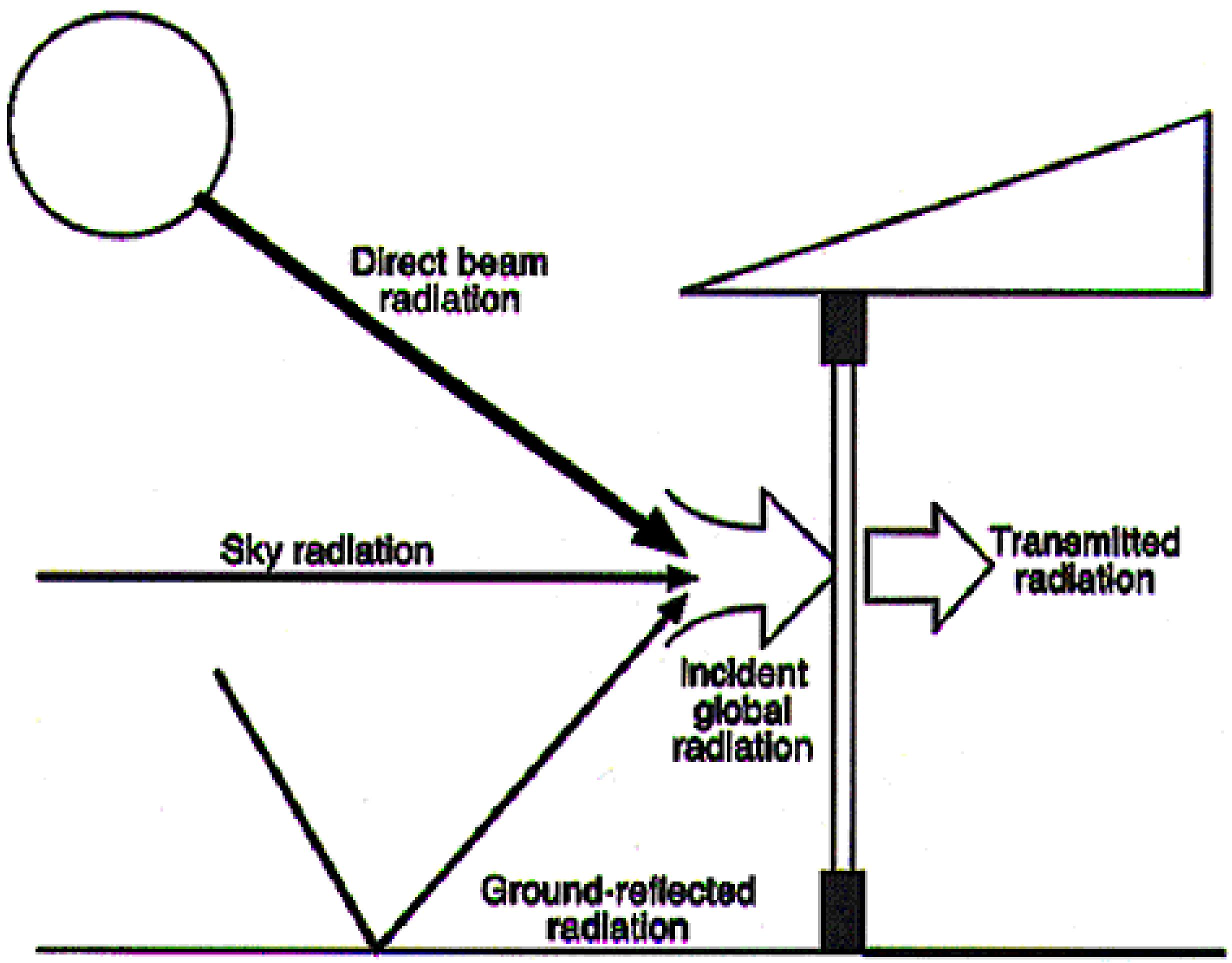
- In areas without frequent winter overcast (e.g., Seattle doesn't qualify)
- In buildings with sufficient insulation and insignificant infiltration
  - If a house is drafty and/or poorly insulated, those aspects must be corrected before passive solar can be effective

Where is Passive Solar heating viable?



http://www.nrel.gov/rredc/solar_data.html

Aperature: Sources



Thermal Balance: Heat Loss

- On average, daily solar input must be at least as much as daily building heat loss at desired temp.
- Qloss = (Σ(UA)n + Cv)(ti - to)

where:

Qloss = BTU/hr or kW

U = 1/R-value (*conduction*, see R-values of common materials)

A = area (ft2 or m2)

n = exterior building surfaces (all walls, windows, ceilings, floors)

Cv = infiltration losses (see Architect's Handbook) [1]

ti = desired indoor temperature

to = outdoor temperature, normally the coldest in the 97.5 percentile (2.5% of the time is colder)

Thermal Balance: Solar Heat Gain

- $Q_{gain} = (\Sigma((Q_{insolation} + Q_{diffuse} + Q_{reflected})A)_n SHGC + Q_{other}$

where:

Q_{gain} = BTU/day or kWh/day

$Q_{insolation}$ = BTU/ft2/day or kWh/m2/day from table in Part 1

$Q_{diffuse}$ = (normally a part of the empirical insolation data, more at NREL)

$Q_{reflected}$ = insolation energy x surface reflectivity (rough estimate, more at NREL)

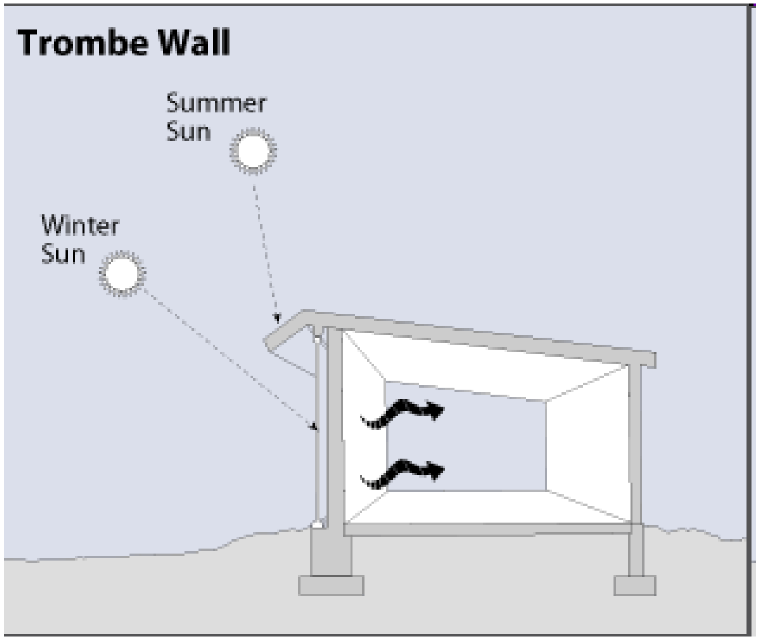
n = each window facing the equator (cooling calculations must account for east and west windows)

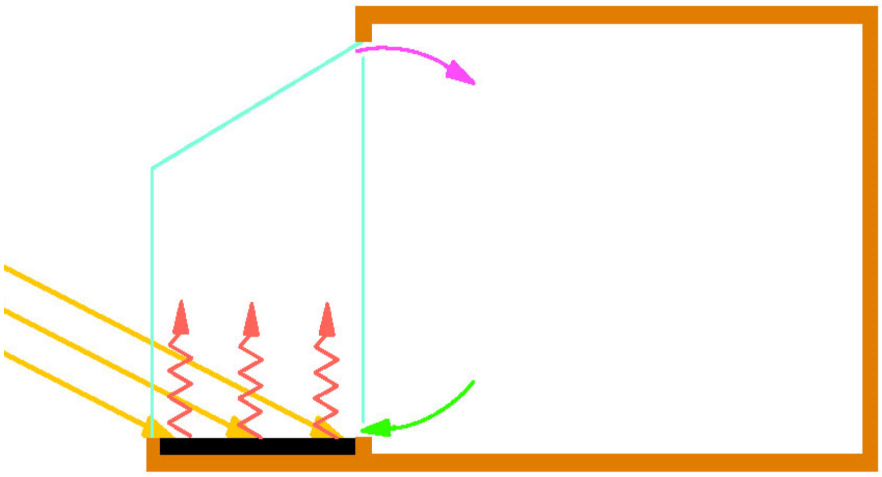
SHGC = Solar Heat Gain Coefficient

Q_{other} = Heat from people and various powered devices inside the insulated shell [2]

Basic Design Types: Space Heating

- Direct Gain: Sunlight shines into and warms the living space.
- Indirect Gain: Sunlight warms thermal storage (e.g., Trombe Wall), which then warms the living space.
- Isolated Gain: Sunlight warms another room (sunroom) and convection brings the warmed air into the living space.

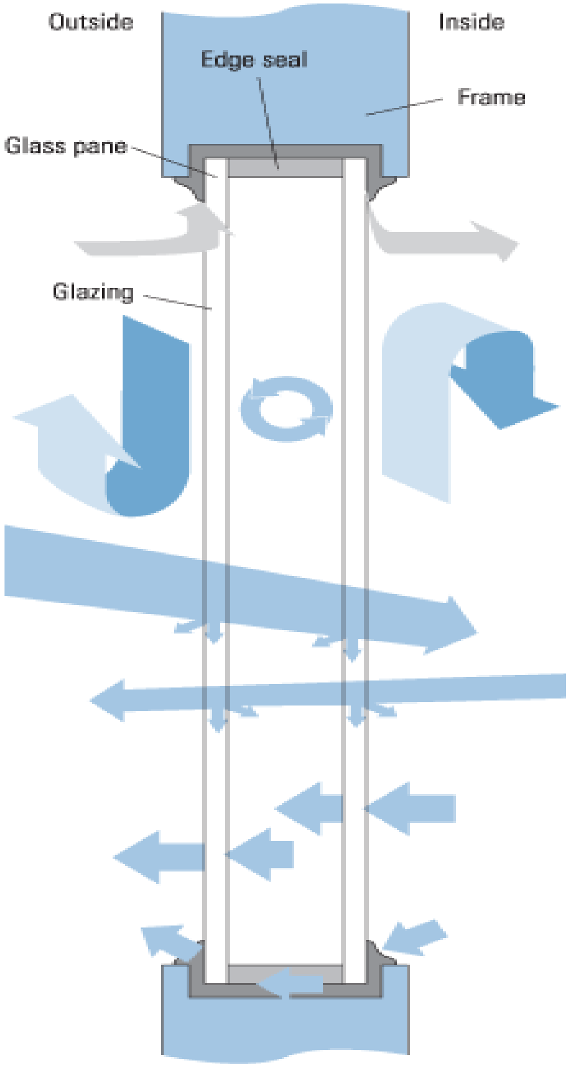




Isolated Gain: Sunspace

Other Design Types

Aperature: Windows



Infiltration
Air leaks around the frame, around the sash, and through gaps in movable window parts. Infiltration is foiled by careful design and installation (especially for operable windows), weather stripping, and caulking.

Convection
Convection takes place in gas. Pockets of high-temperature, low-density gas rise, setting up a circular movement pattern. Convection occurs within multiple-layer windows and on either side of the window. Optimally spacing gas-filled gaps minimizes combined conduction and convection.

Radiation
Radiation is energy that passes directly through air from a warmer surface to a cooler one. Radiation is controlled with low-emissivity films or coatings.

Conduction
Conduction occurs as adjacent molecules of gases or solids pass thermal energy between them. Conduction is minimized by adding layers to trap air spaces, and putting low-conductivity gases in those spaces. Frame conduction is reduced by using low-conductivity materials such as vinyl and fiberglass.

Courtesy: E SOURCE

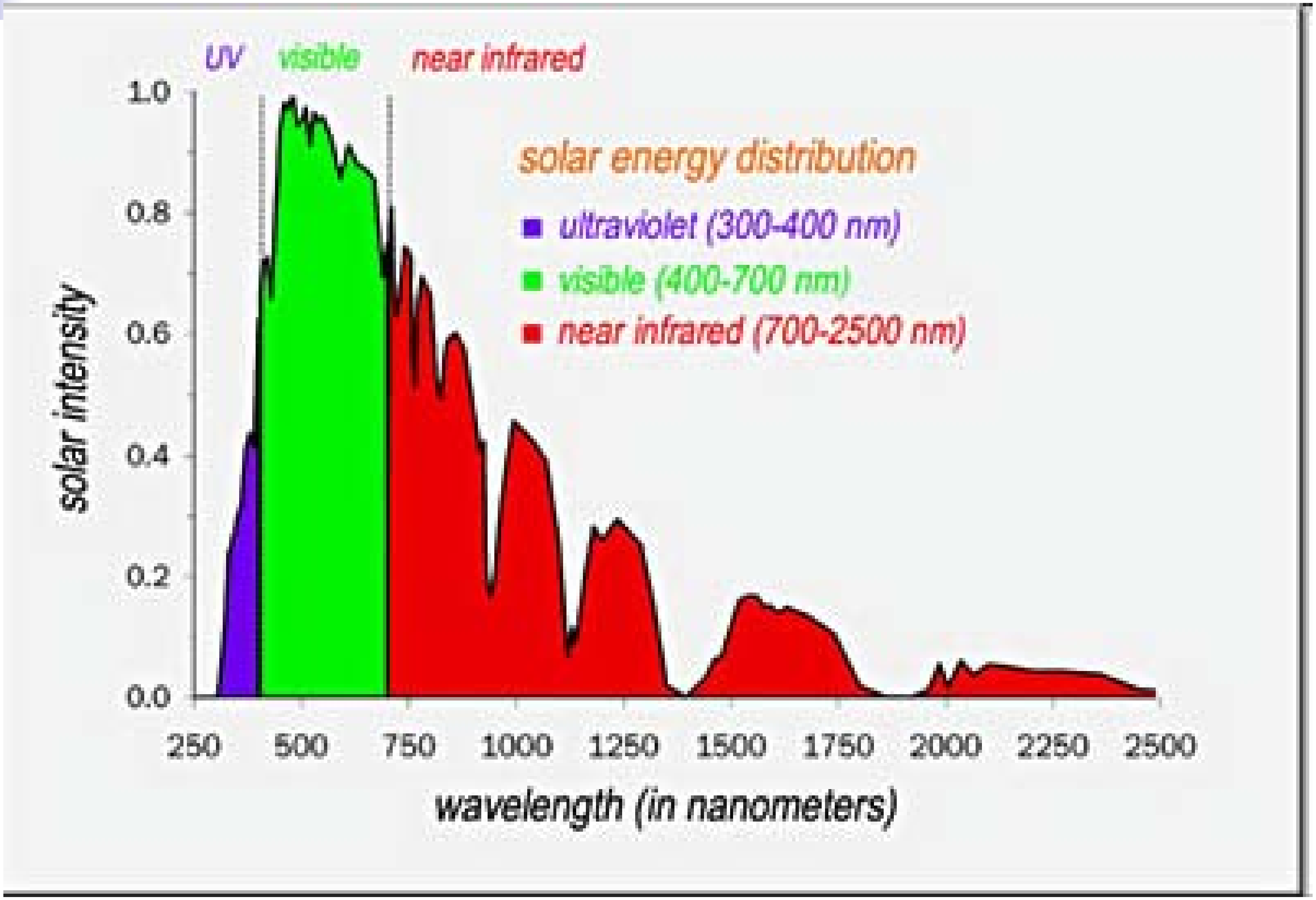
Windows: SGHC vs U-factor

Strive for the combination of the lowest U-factor and highest SHGC

SAMPLE WINDOW PRODUCTS

Manufacturer	Frame Type	Glass Type	U-factor	SHGC
default	Metal, operable	Clear single-pane	1.28	.80
default	Metal, operable	Clear dual-pane	.87	.70
Rylock	Metal slider	Clear dual-pane	.75	.67
default	Nonmetal, operable	Clear dual-pane	.60	.65
Milgard	Vinyl slider	Hard coat Low E	.42	.58
Milgard	Fiberglass slider	Soft coat Low E	.38	.34
Anderson	Wood double-hung	Soft coat Low E	.35	.34
Marvin	Wood slider	Soft coat Low E	.39	.30

Solar Energy Distribution



Absorber

- A surface that converts light energy into thermal energy

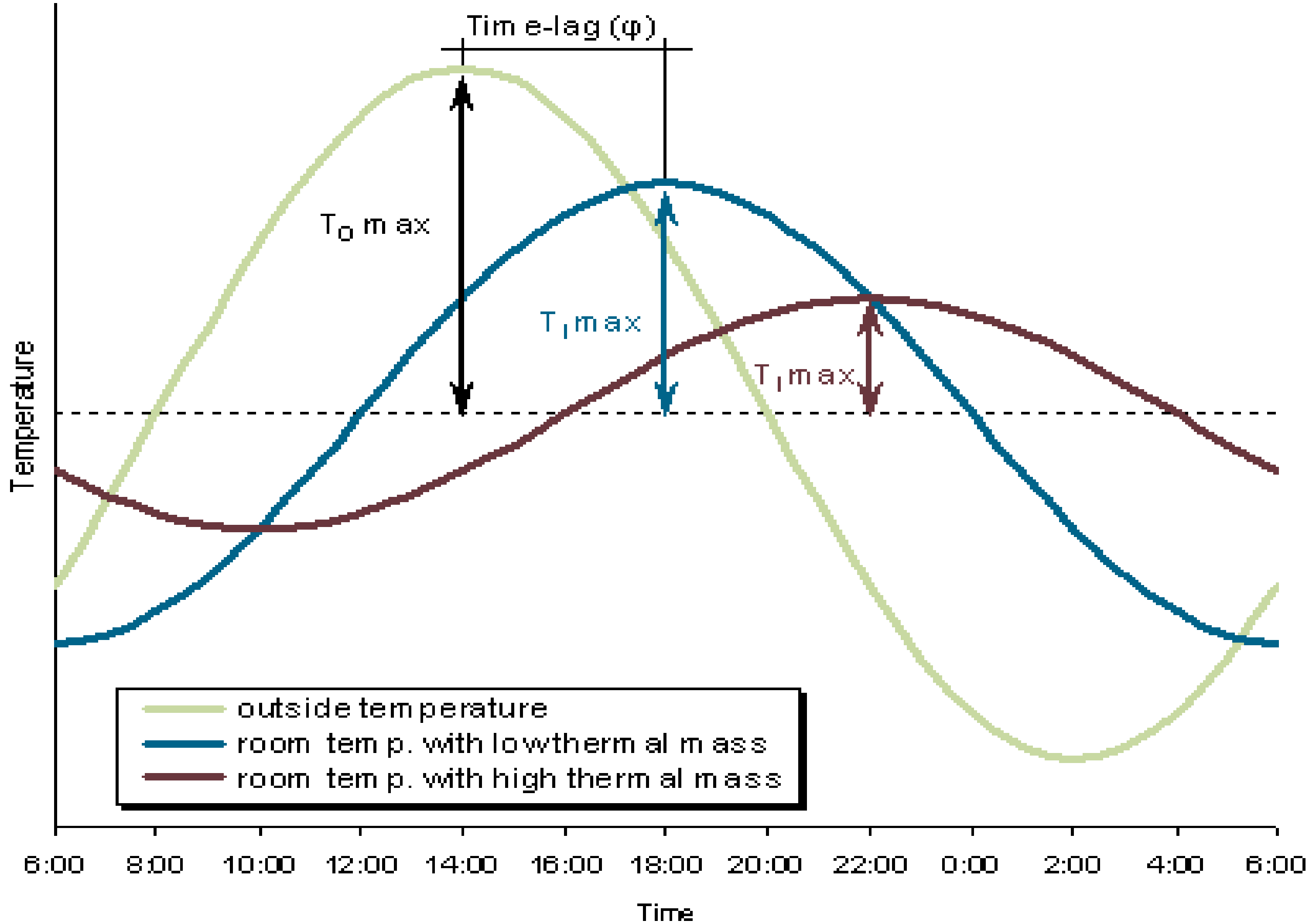
Table 1 - Absorptivity and Emissivity of Common Materials[3][4]

Material	**Absorptivity**	**Emissivity**
White tile/stone/paint	0.30 - 0.50	0.85 - 0.95
Unfinished concrete	0.65	0.87
Red brick/stone/paint	0.65 - 0.80	0.85 - 0.95
Flat black paint	0.96	0.87
Copper Oxide	0.90	0.17
Black nickel	0.90	0.08
Black chrome-coated copper foil	0.95	0.11

Thermal Storage Mass

- Stores thermal energy collected during the day for use later (i.e., night or succeeding cloudy days)
- Two main types
  - Sensible: Stores/releases energy proportional to temperature rise
  - Latent: Stores/releases energy at a phase change temperature

Storage Mass Time Lag



Thermal Time Constant

- Definition: The thermal inertia of the building taking into consideration the building's insulating properties.
- The greater the time constant, the slower and more even the diurnal temperature changes

Latent Thermal Storage Mass: Materials

Material	**Specific Heat** (**c**) BTU/(lb F)	**Density** (**ρ**) lb/ft^3	**Thermal Conductivity** (**k**) BTU/(hr F ft)	**Thermal Resistivity** (**r**) (hr F ft)/BTU	**Heat Capacity** (**β**) BTU/(ft^3 F)	**Embodied Energy** BTU/lb
Water (still)	1	64	0.35[1]	2.94[1]	64	0 (add energy to pump)
Face Brick ASTM C 216	0.24	130	0.76	1.32	31.2	~1075[2]
Building Brick ASTM C 62	0.22	120	0.47	2.13	26.4	~1075[2]
Concrete (light)	0.22	125	0.833	1.2	27.5	~400[3]
Concrete (heavy)	0.24	150	1.33	.75	36	~400[3]
Granite	0.20	165	1 - 2.3	0.43 - 1	33	(energy to extract and haul)
Wallboard (gypsum)	0.26	50	0.093	10.81	13	1935
Straw bale	0.32	5.2 - 8.3	~0.057	~17.4	1.65 - 2.63	56 - 103
Fiberglass batts	0.23	0.65	0.027	37.5	0.15	12,000
Cellulose batts	0.46	~4.4	~0.0275	~37	~1.9	~200
Air (80F, dry)	0.24	0.0624	0.017[1]	58.8[1]	0.0149	0

Thermal Mass Rules of Thumb

- Masonry and concrete floors, walls and ceilings to be used for heat storage should be a minimum of 4 inches thick.
- A number of small windows to admit sunlight in patches gives better control re: overheating.
- Use light colored surfaces (non-thermal mass storage walls, ceilings, floors) to reflect sunlight to thermal storage mass elements.
- Thermal storage mass elements (floors, walls, ceilings) should be dark in color.
- Masonry floors used for thermal mass should not be covered with wall-to-wall carpeting.
- The most favorable storage occurs when each square foot of sunlight is spread (diffused) over a nine square foot area of storage surface.
- The most efficient way to increase heat storage capacity is to increase the storage surface area and the distribution of sunlight rather than the thickness of the storage mass.

From the Arizona Solar Center

Thermal Time Constant Calculations

- $TTC_A = R_{os} + Q_A R$ [11]
  where:
  $Q_A = c*d*\rho$ (specific heat * d * density)
  d = thickness (in the same units as in density and area)
  $R = d/k$
  R_{os} = resistance of outside still air film (neglible in a breeze)

- For a composite surface of multiple layers, starting from the outside layer as "1";
  $TTC_A = Q_A1(Ros + 0.5R1) + Q_A2(Ros + R1 + 0.5R2) + Q_A3(Ros + R1 + R2 + 0.5R3) \ldots$ [13]

More Thermal Time Constant

- To determine the TTC of a surface area;

  TTCs = As * TTCs [14]

  where:

  As = area of surface

- For *n* external surfaces in the building;

  TTCext. surfaces = ΣTTCs/Atotal [14][15]

- To take into account any other interior thermal mass (e.g., partition walls, standing water walls, insulated masonry slab, etc), we can approximate the overall effective thermal mass;

  TTCtotal = TTCext. surfaces + ΣMiβi/kidiρi

  where:

  M = mass of individual interior objects *i*

Diurnal Heat Constant

- $DHC_{surface} = F1s$ [12]

  where: (checkmark is symbol for square root in simple html)

  $F1 = \sqrt{(\cosh 2x - \cos 2x)(\cosh 2x + \cos 2x)}$

  $x = d\sqrt{\pi\rho c/Pk}$

  $s = \sqrt{Pk\rho c/2\pi}$

  P = period (24 hours)

- The overall DHC of a building is the summation the DHC values of each surface in contact with the interior air;
- $DHC_{total} = \Sigma DHC_{surface}A_{surface}$ [12]

Heat Balance: Daily swings

- ΔT (swing) = $0.61Q_{gain}/DHC_{total}$ [12]

  where:

  ΔT (swing) = the difference between the minimum and maximum interior temperatures.

  Qgain = the daily building energy gain calculated previously

- To design for a number of cloudy days, change the value of P (for example, to have sufficient thermal mass for 3 heavily cloudy days, P = 3)

Location of Mass and Insulation

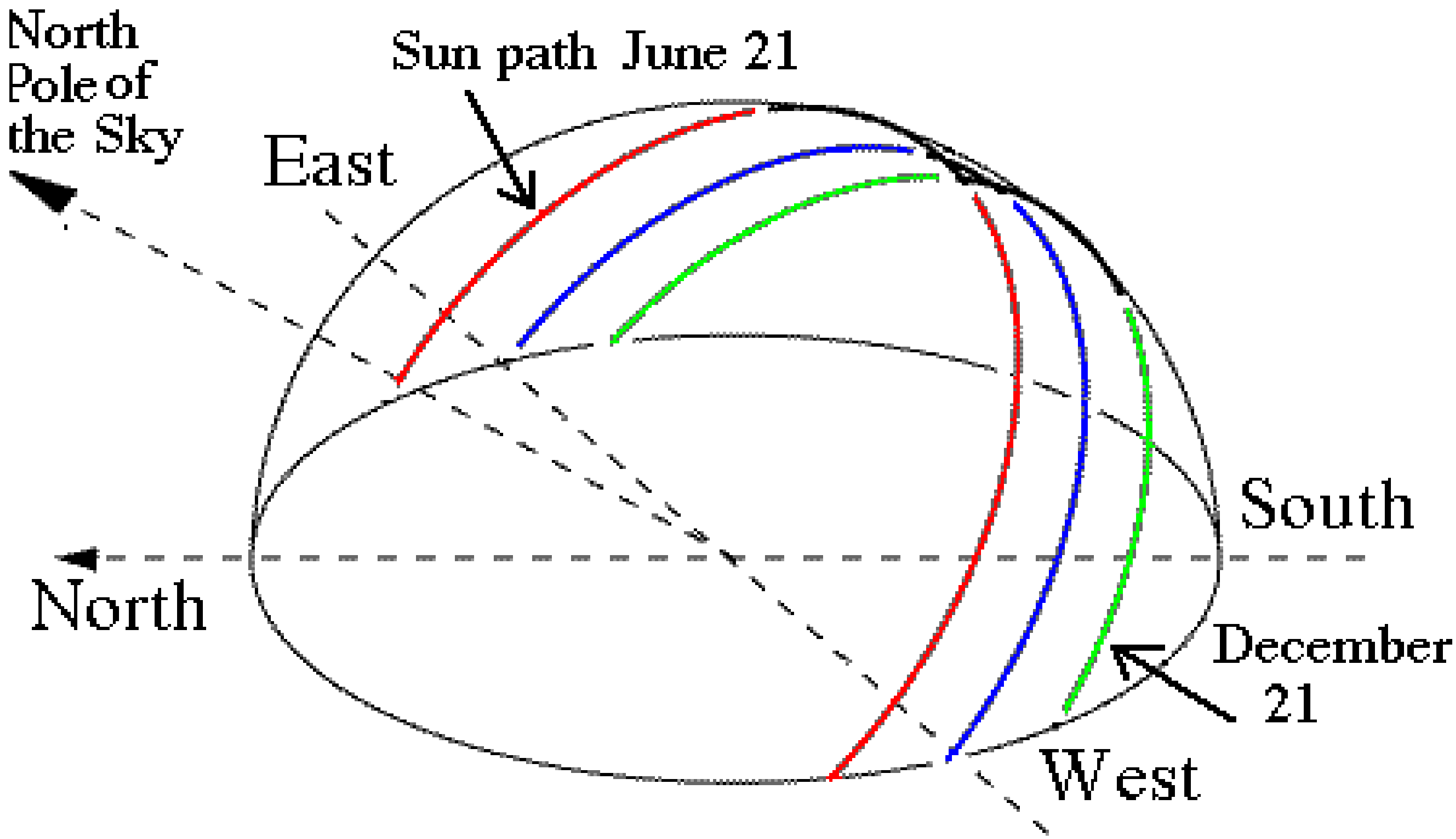
- **High insulation, low thermal mass**: Results in a low TTC and low DHC, so while the heat loss across highly insulated surfaces is low, there is still higher levels of heat loss through windows. The internal temperature is subject higher daily swings without thermal mass and such a building is a poor candidate for passive solar heating or cooling.

- **External insulation, internal thermal mass**: A high TTC and high DHC, providing a moderation of the indoor temperature during the winter and summer from winter solar gain and summer night time flushing.

- **Internal insulation, external thermal mass**: A low TTC and low DHC, providing very little temperature moderation. The internal temperature is subject higher daily swings and such a building is a poor candidate for passive solar heating or cooling.

- **Internal and external insulation, encased thermal mass**: Common with insulating concrete forms (ICF), provides a medium-high TTC, but a low DHC, so while it is somewhat effective for moderating temperatures generally, this approach does not store heat from passive solar insolation, nor does it cool off on summer nights with cool air flushing.

Controls: Determining Sun Angles



Controls: Shading Techniques

- Overhangs
- Fins
- External Shades
- Internal Shades
- Daylighting Considerations

Controls: Overhangs

- Permanent vs. adjustable vs. removeable
- Three main parameters
  - Overhang depth
  - Height above window
  - Window height

Controls: Overhang variations

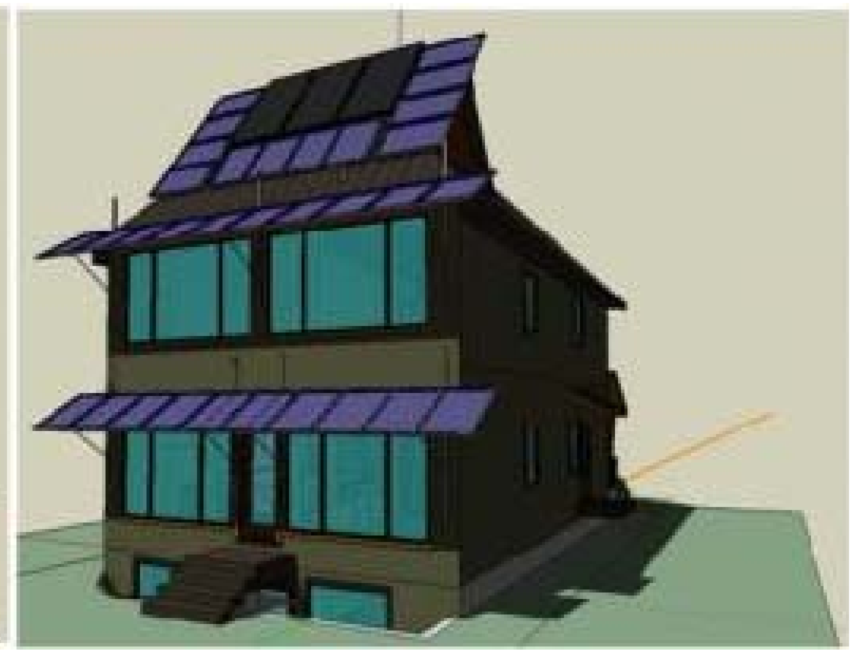
Cantilevered

Multi-Story, External Support

Overhangs: Combined with other systems

- Photovoltaic panels can be overhangs

Winter



Summer

Controls: Fins

- Prevent unwanted insolation in morning and evening

Controls: Daylighting considerations

Overhangs doubling as light shelves

Light distribution from light shelves

Controls: External Shades

Controls: External Shades (cont)

Motorized External Shades

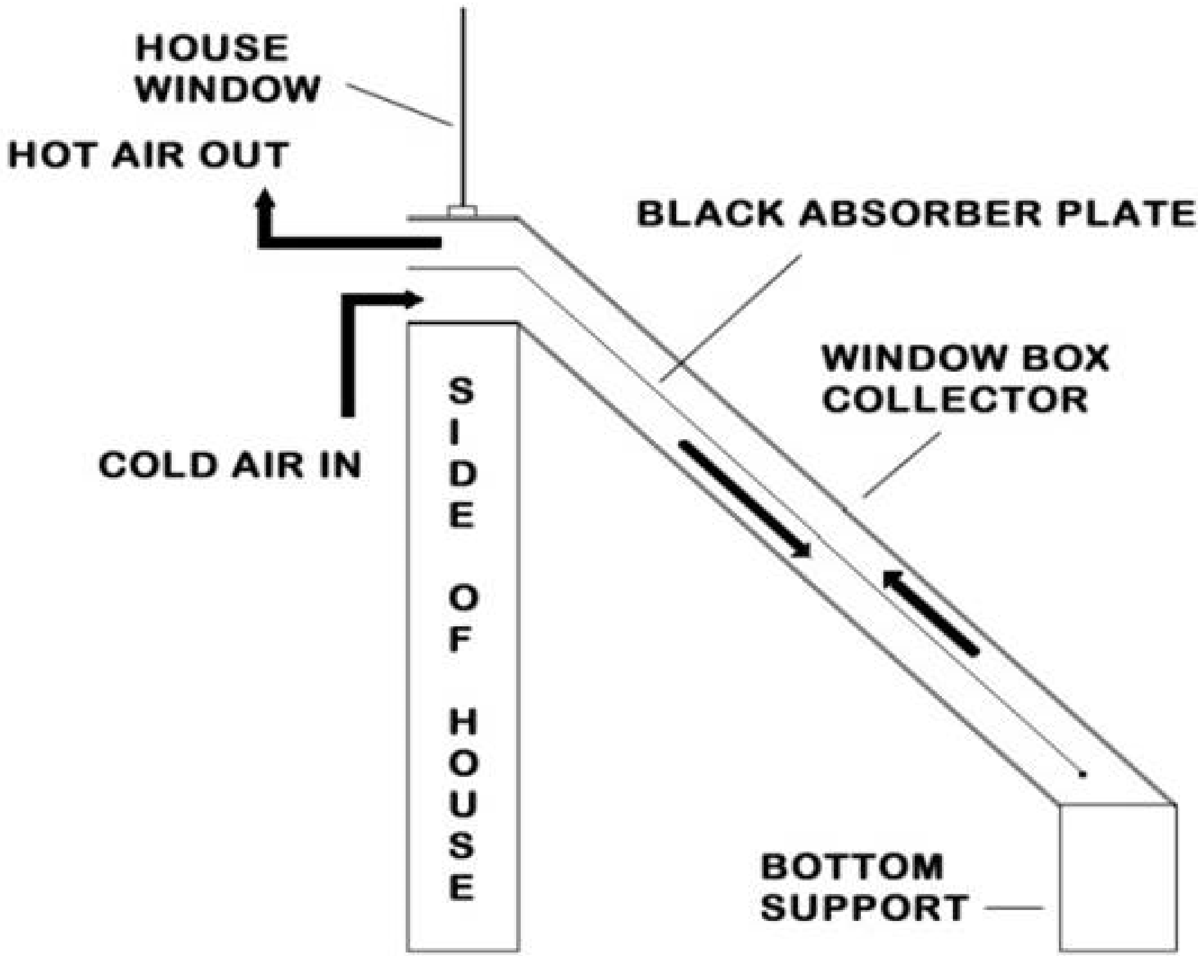
Controls: Internal Shades

Insulating shades add R-Value

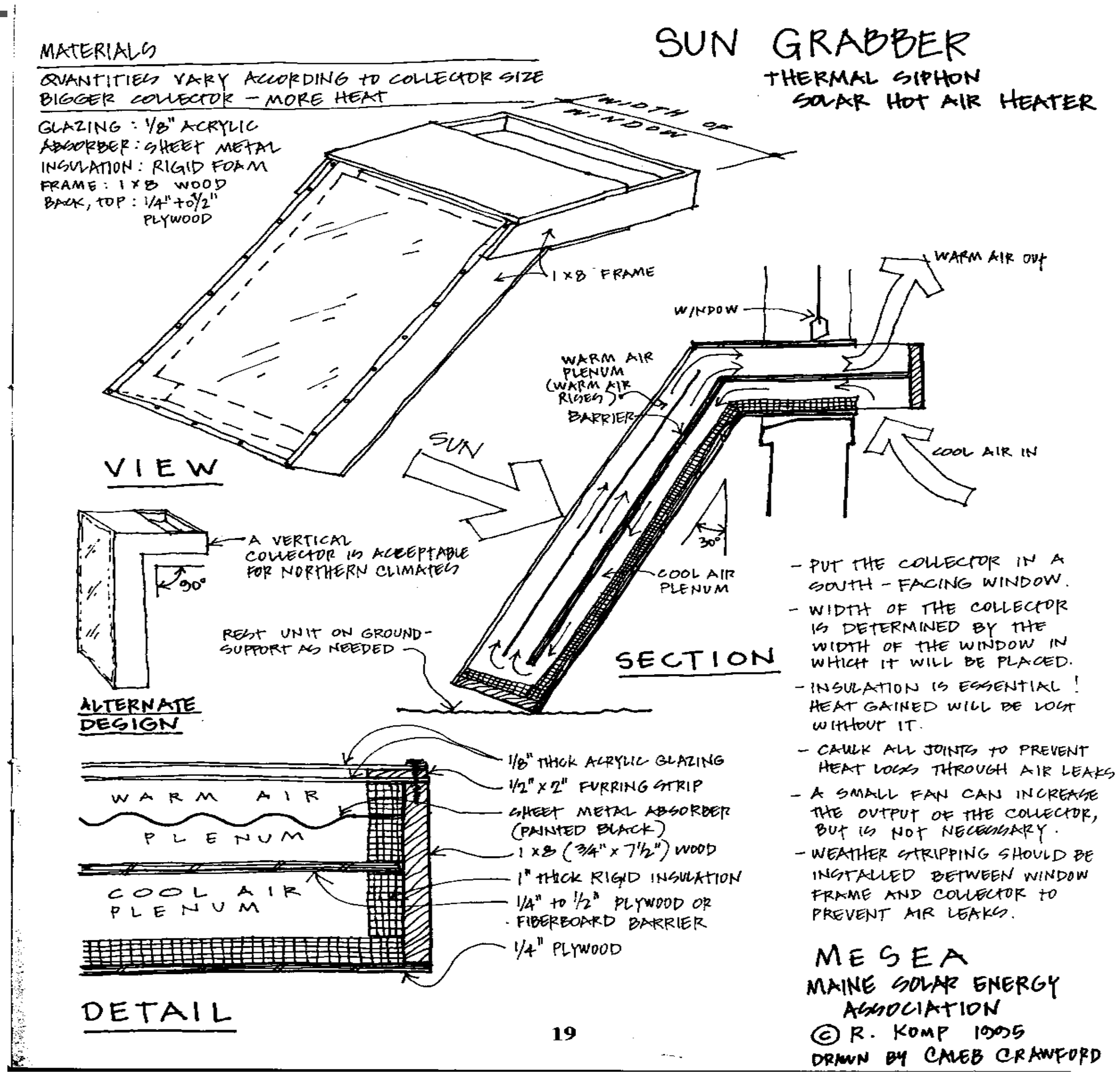
Retrofit: What are the options?

- Do It Yourself
  - Solar windowbox
  - Wall collector
- Renovation
- Excellent source of plans
  - www.build-it-solar.com

Retrofit: Solar Windowbox

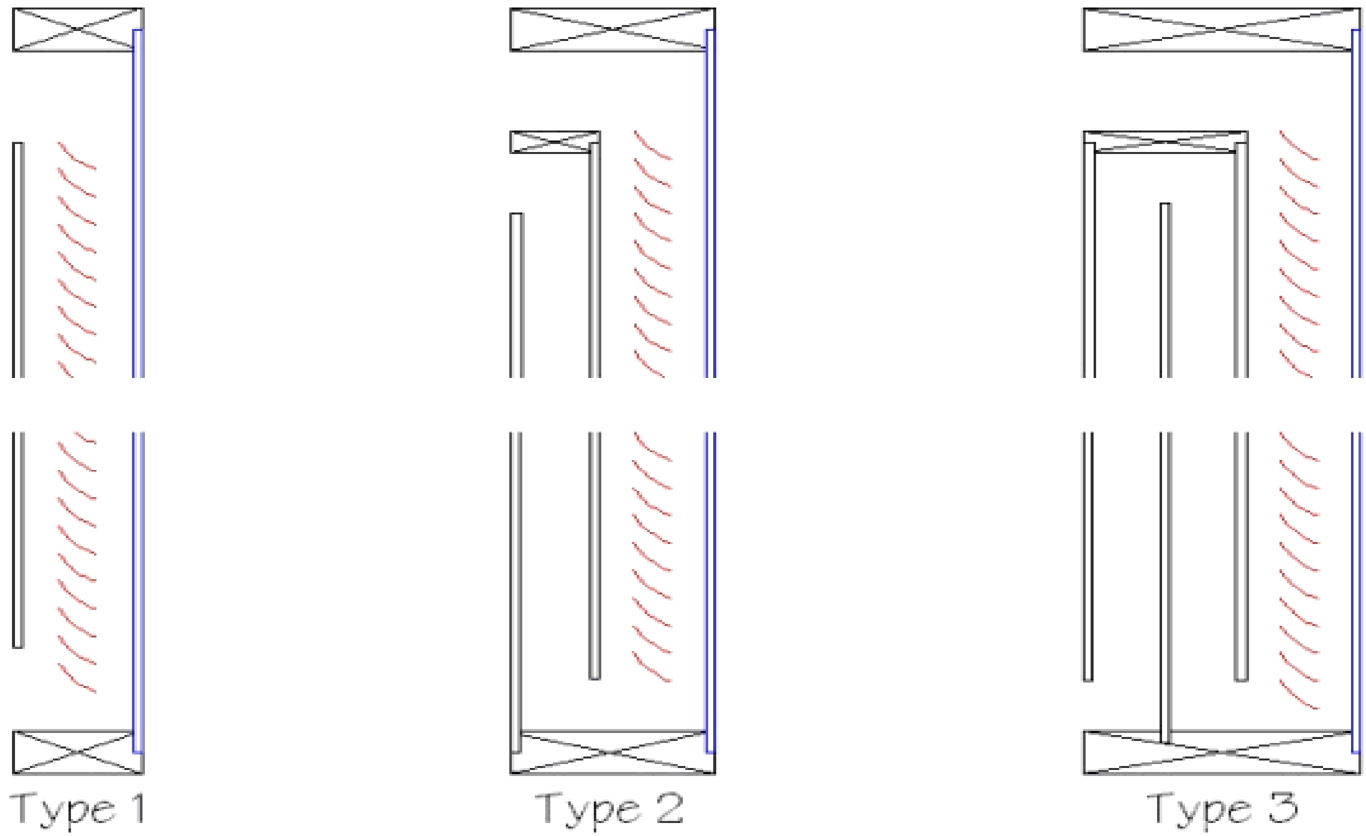


Solar Windowbox Plans



Retrofit: Wall Mount

Retrofit: Wall Mount
Preventing Night-time Thermosiphon



Retrofit: Renovation

References

- 1. David Kent Ballast, Architect's Handbook of Formulas, Tables, and Mathematical Calculations, Prentice Hall, 1988
  2. Kissock, J, Internal Heat Gains and Design Heating & Cooling Loads, University of Dayton Lecture
  3. Michael J. Crosbie, The Passive Solar Design and Construction Handbook, John Wiley and Sons, 1998
  4. John Little, Randall Thomas, Design with Energy: The Conservation and Use of Energy in Buildings, Cambridge University Press, 1984
  5. Passive Solar Heating and Cooling, Arizona Solar Center
  6. Jeff Vail, Annualized Geo-Solar, JeffVail.net
  7. K. Darkwa *, J.-S. Kim, Dynamics of energy storage in phase change drywall systems, Wiley, 2005
  8 Jo Darkwa, Mathematical Modelling and Simulation of Phase Change Drywalls for Heating Application in a Passive Solar Building, AIAA, 2005
  9. Warszawski, Abraham, Industrialized and Automated Building Systems, Taylor & Francis, 1999
  10. US Department of Defense, Passive Solar Buildings, Unified Facilities Criteria, UFC 3-440-03N, 2004
  11. F. Bruckmeyer, The Equivalent Brick Wall, *Gesunheitsingenieur*, 63(6), 1942, pg 61-65
  12. J. Douglas Balcomb, Passive Solar Buildings, MIT Press, 1988
  13. M. Hoffman, M. Feldman, Calculation of the Thermal Responses of Buildings by the Total Time Constant Method, Building and Environment, Vol 16, No. 2, pg 71-85, 1981
  14. Givoni, Baruch, Climate Considerations in Building and Urban Design, John Wiley and Sons, 1998 pg. 115-147
  15. Høseggen, Rasmus, Dynamic use of the building structure - energy performance and thermal environment, Norwegian University of Science and Technology, 2008
  16. Bruce Haglund, Kurt Rathmann, Thermal Mass in Solar and Energy-Conserving Buildings (.pdf), University of Idaho