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Lecture 1: Introduction to Passive solar buildings

- INTRODUCTION
  - Passive solar energy is an excellent idea to heat, cool and light the living room based on the structure of our buildings.
  - Passive solar energy is used to distribute heat or cool through wise selection of building materials.
  - Passive solar energy will provide inexpensive sustainable alternatives for heating and cooling of home.

    - Passive solar system is used to "collect, store and distribute thermal energy"-by means of conduction, convection and radiation.
    - Decrease the amount of money that we spend on energy.
    - The exploitation and misuse of natural resources rapidly depleting the Non-renewable energy resources.
    - Passive solar energy buildings considerably reduce the usage of Non-renewable energy resources.

- Reasons for Passive solar system
  - Passive solar system meets the minimum requirements.
  - Active solar system produces the greenhouse gases such as (CO_2).
  - Active solar energy is expensive and more equipment are needed for installation.

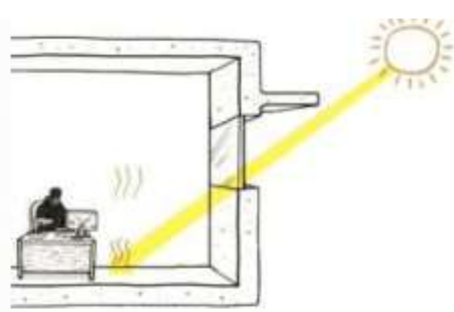
- PASSIVE SOLAR HEATING
  - Passive solar heating happens when sunlight strikes an object and that object absorbs the heat.
  - Effective when the windows are oriented correctly

  - Perfect orientation is south.
  - By installing high performance windows with insulated frames, multiple glazing, low-e-coatings we may reduce the heat loss by 50 to 75 percent

- PASSIVE SOLAR COOLING
  - Buildings are designed to retain cooling and drew the heat air away.
  - The shading device is fixed and this was achieved by natural vegetation and using special glazing in windows.
  - The shading device can reduce solar gains up to 90%

- MATERIALS REQUIRED
  - Acrylic glasses or panels is enough to observe the heat from the sunlight ,used as windows and doors
  - Normal concrete was just enough to make the thermal mass, these are act as a absorber.

Acrylic panel

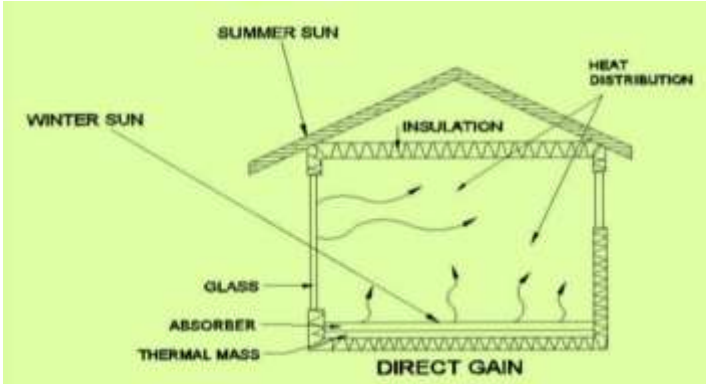


Sunlight hits the concrete

❖ CATEGORIES OF PASSIVE SOLAR ENERGY

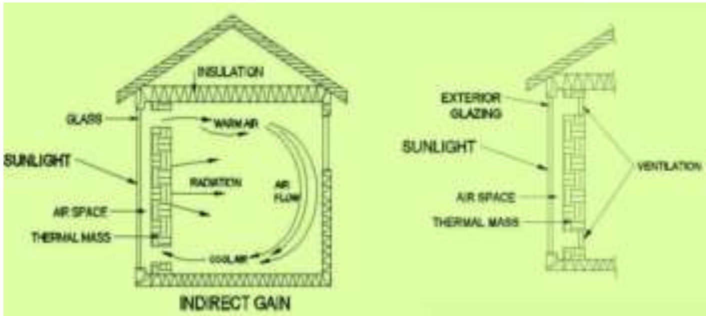
➢ **Direct gain method**

Direct gain method is the simplest method where the space of the building is directly heated by sunlight.



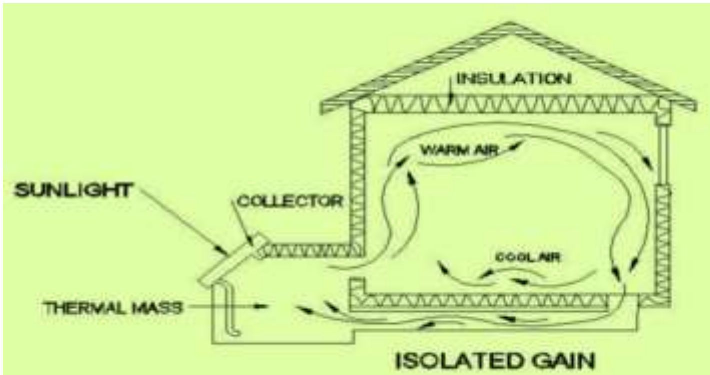
➢ **Indirect gain method**

For indirect gain, sunlight is often received by a south facing wall, and as air moves internal space the heat moves through the living room.

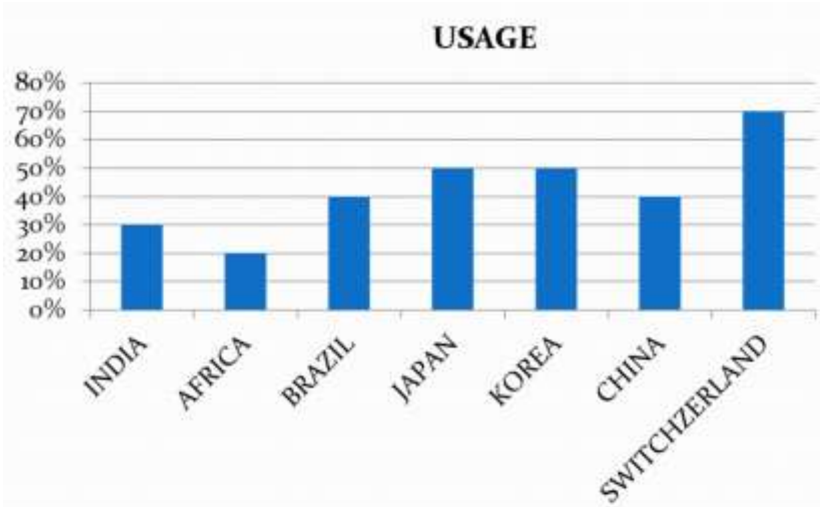


➢ **Isolated gain method**

Isolated gain method contains solar collection, thermal storage that is separated from actual living space.



❖ USAGE AMONG COUNTRIES



❖ ADVANTAGES

- Mainly it provides perfect temperature and it is renewable energy resource.
- Its cost of installation is lower than active solar energy resources.
- And it is eco-friendly due to the eradication of greenhouse effect.
- Less or zero usage of conventional equipment.

❖ FUTURE TRENDS

- The design of passive solar buildings based on the materials is available today and will consistent for next several decades.
- Many obstacles due to over exploitation of non- renewable resources may be eradicated by using this energy.

Lecture 2: Solar Radiations

What Is Solar Radiation?

- Solar radiation is the energy that comes from the Sun.
- This radiation is generated from nuclear fusion reactions that occur in the solar nucleus.
- Nuclear radiation produces electromagnetic radiation at various frequencies or wavelengths. Electromagnetic radiation propagates in space at the speed of light.

What Is the Solar Constant?

- The solar constant is the amount of energy received in the form of solar radiation per unit time and unit area.
- The solar constant is measured in the outer part of the Earth's atmosphere in a plane perpendicular to the rays of the sun. The results of its measurement by satellites give an average value of 1366 W / m^2.

Types of Solar Radiation

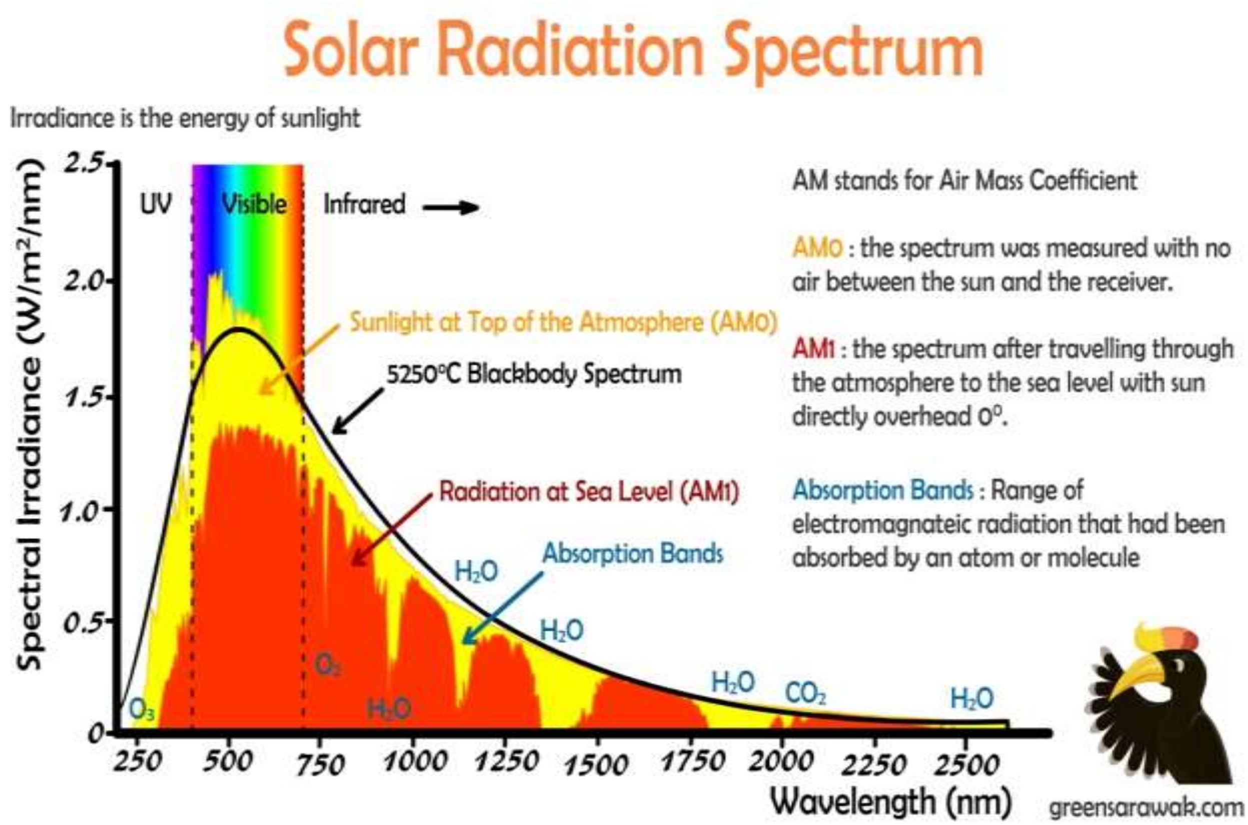
- The sun's radiation contains three types of rays with ratios:

49% are infrared (IR) rays that provide heat.

43% are visible rays (VI) that provide light.

7% are ultraviolet (UV) rays.

1% are other types of lightning.



- **Ultraviolet (UV) rays are subdivided into three types:**
  - Ultraviolet A or UVA: They easily pass through the atmosphere, reaching the entire earth's surface.
  - Ultraviolet B or UVB: Short wavelength. It has greater difficulty to cross the atmosphere. They reach the equatorial zone more easily than at high latitudes.
  - Ultraviolet C or UVC: Short wavelength. They do not pass through the atmosphere. They are absorbed by the ozone layer.

Characteristics of Solar Radiation

- Solar radiation is distributed over a wide spectrum of non-uniform amplitude with the typical shape of a bell.
- The radiation maximum is focused on the band of radiation or visible light with a peak at 500 nm outside the Earth's atmosphere according to Wien's law, which corresponds to the cyan green color.
- The photosynthetically active radiation band oscillates between 400 and 700 nm, corresponds to the visible radiation and is equivalent to 41% of the total radiation.

- Within photosynthetically active radiation are sub-bands with radiation:
- blue-violet (400-490 nm)
- green (490-560 nm)
- yellow (560-590 nm)
- orange red (590-700 nm)

When crossing the atmosphere the solar radiation is subjected to phenomena of reflection, refraction, absorption and diffusion by the various atmospheric gases to a variable degree depending on the frequency.

How Does Solar Radiation Spread in the Atmosphere and on the Surface of the Earth?

- Due to the characteristics of the Earth's atmosphere, solar radiation undergoes certain alterations to cross it and reach the surface.

Radiation Balance

- On average, the Earth receives 1,366 W / m² (solar constant) from the Sun.
- This is related to the thresholds of the atmosphere and the plane perpendicular to the incoming solar rays:
- The solar radiation in Earth hits a spherical cap for 1,440 minutes each day, decreasing by 75%. The atmosphere in turn filters the rays of the Sun to a certain extent, as each body does, causing:

- A reflection and a back-scattering of rays, due to their albedo, to clouds and atmospheric gases themselves.

- An absorption that causes an increase in temperature, as a result of which it emits radiation in any direction according to Wien's law. However, this absorption is modest in the visible light band, making it transparent to direct sunlight.
- Approximately half of the solar radiation passes through the atmosphere without alteration. Called net radiation.
- Half of the net radiation finally contributes to the evaporation of the water masses; therefore, the available solar energy is approximately a quarter of the total emitted energy

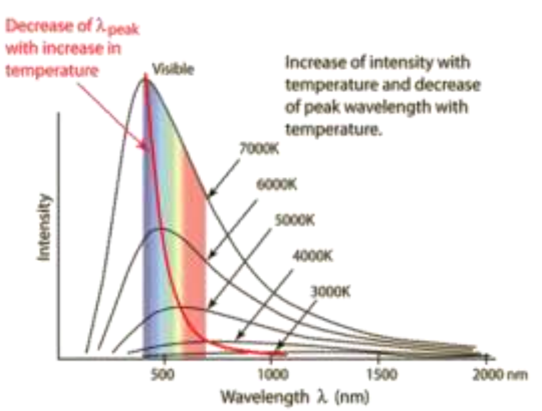
Wien Displacement Law

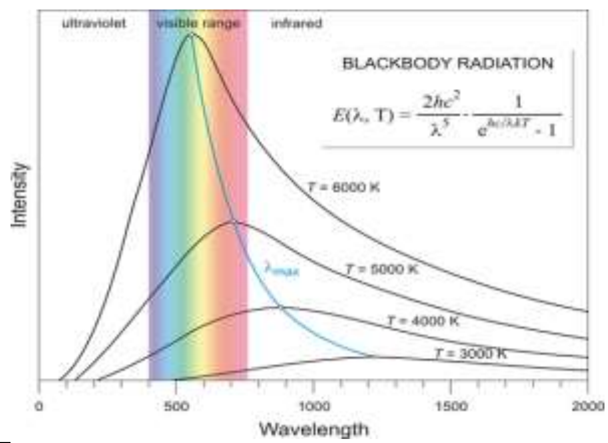
- *The black body radiation curve for different temperatures peaks at a wavelength inversely proportional to the temperature.*

$$\lambda_{max} = b/T$$

Where:

- λ_{max}: The peak of the wavelength
- b: Wien's displacement constant. ($2.9*10^{(-3)}$ m K)
- T: Absolute Temperature in Kelvin.





Examples1: If the temperature of a black body radiator is 127K, what is its peak of radiation?

Answer:

The peak is found with the formula:

$$\lambda_{max} = b/T$$

then,

$$\lambda_{max} = \frac{2.9 \times 10^{-3}}{127} = 0.022 \times 10^{-3} m = 22 \mu m$$

Examples2: A star has a surface temperature of 10000K. At what wavelength will this star emit most of its light?

Answer:

Most of the wavelength is found with the formula:

$$\lambda_{max} = b/T$$

$$\lambda_{max} = \frac{2.9 \times 10^{-3}}{10000} = 0.00029 \times 10^{-3} m = 0.29 \mu m$$

❖ Diffuse Solar Radiation

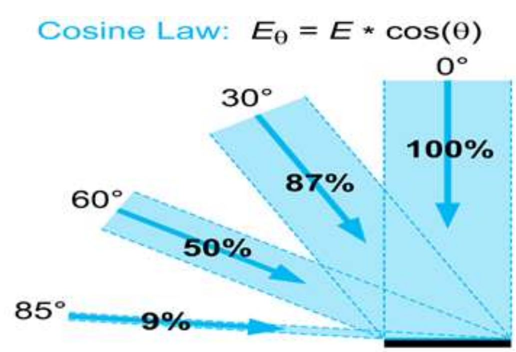
- Diffuse radiation is also called indirect radiation.
- Diffuse radiation represents the portion of solar radiation that has hit at least one particle of atmospheric gases by changing the angle of incidence and that, however, reaches the ground because it is directed at it.
- the Rayleigh scattering of the blue component of solar radiation is responsible for the blue color of the sky. A part of the diffuse radiation is back towards, the space.

❖ Incident Solar Radiation

- Incident solar radiation is that radiation that has encountered any obstacle to which it has delivered all or part of its energy.
- According to Lambert's law, the amount of radiation hitting the surface unit is proportional to the cosine of the angle of incidence.
- The maximum amount of incident solar radiation is obtained with perpendicular incidence, since the angle increases

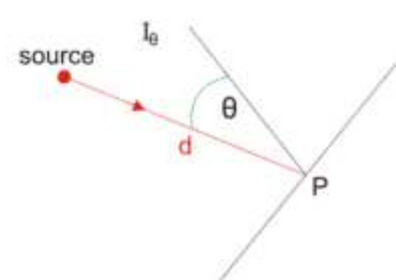
Lambert's Cosine Law

- the radiant intensity or luminous intensity observed from an ideal diffusely reflecting surface or ideal diffuse radiator is directly proportional to the cosine of the angle θ between the direction of the incident light and the surface normal



$$E_\theta = E\cos\theta$$

$$E = \frac{I}{d^2}$$



- Where, I is the luminous intensity of the source in the direction of the illuminated point,
- θ is the angle between the normal to the plane containing the illuminated point and the line joining the source to the illuminated point, and
- d is the distance to the illuminated point.
- **Irradiance** is the radiant flux received by the detector area. The unit of **irradiance** is W/m^2

- By definition the luminous flux received by unit area of the detector is called **Illuminance**.
  Its unit is Lux or Lumen per sq. meter (lm/sq. m).

❖ Reflected Solar Radiation

- Reflected solar radiation is the part of incident solar radiation reflected from the earth's surface due to the albedo effect.
- *Albedo can be defined as a way of quantifying how much radiation is reflected from the surface. It is a comparison between the reflection radiations from the surface to the amount of radiation that hits it.*
- The albedo is the reflection coefficient c. Values for c are generally between 0 and 1 or expressed as a percentage. It is given by the relationship between the radiant energy reflected from a surface with respect to the incident energy. Earth has an average value of 40% (c = 0.4).

❖ Absorbed Solar Radiation

- After deducting all losses due to reflection and backscatter from the Earth's atmosphere and surface, the remaining incident solar radiation is absorbed by the Earth's surface and therefore contributes to its warming, in a variable way depending on the latitude and the type of surface.

Summery

- Solar radiation is the energy that comes from the Sun.
- Nuclear reactions occur in the solar nucleus, releasing a large amount of energy. This energy travels to Earth through electromagnetic waves: solar radiation.
- Solar radiation is divided into mainly three types of rays:

1. Infrared (IR) rays. They provide heat.
2. Visible rays (VI). They provide light.
3. Ultraviolet (UV) rays. They are the ones that have the most influence on human health.

Lecture 3: Passive solar design

❖ Passive solar building

- The main concept of passive solar buildings is its building elements i.e. the windows, walls and the floors are made able to collect solar energy and store them. This energy is then used in the winter for warmth and used to reject the heat during the summer seasons.
- The buildings convert the solar energy into useful energy without the help of any other mechanical or electrical systems.

❖ Principles of passive solar buildings

1. The first principle is based on the route of the sun in different seasons. The sun in winter will be traveling in a lower route compared to summer.
2. In winter, the south direction faced glass will help in energy absorption and storage in the building.
3. The location of thermal mass in a position enabling easy absorption of solar energy later would help in the easy release of the same energy during evening time.
4. The direct sun can be resisted by overhanging elements as shown in the figure below. These are also called control elements.
5. Proper insulation enables warmth in winter and coolness in summer.

Elements Considered for Passive Solar Building Construction.

The main elements considered are:

1. Room types, internal doors, walls and furniture in buildings and their placement.
2. The Equator faced orientation for the building
3. Building dimension extension in east-west direction
4. Window size fixed to get adequate solar in winter and shade in summer.
5. Windows in the west are avoided.
6. Use of thermal mass like floors or walls

Performance of Passive Solar Building

The efficiency of passive solar buildings depends upon the following factors:

1. The site climate conditions.
2. The building system adopted.
3. The building design criteria.
4. The building size.

Benefits of Passive Solar Buildings

- **The benefits of passive solar building systems are as follows:**

1. The building interior is bright – The interior of the building would be filled with sufficient light. This is due to the transmission of visible light frequencies. The system is designed such a way that the control of glare and over lighting is kept in mind.
2. The ultraviolet energy is blocked – The direct ultraviolet rays are harmful. The passive solar building system has the advantage of blocking almost 99.9% of the ultraviolet radiation energy. Preventing this would save the interior fabrics as well as decor and make them long lasting.
3. Summer is made cooler and comfortable – It keeps the interior cool during the hot season. This would obviously reduce cooling energy costs. This would give a low solar gain coefficient value (SHGC).
4. Winter made warmer

Positives of Passive Solar Systems

1. **It is environmentally friendly.**

When homeowners harness the power of the sun, they don't have to rely too much on fossil fuels. As a result, they can greatly help in saving the earth's non-renewable energy resources and reducing greenhouse gasses in the atmosphere.

2. **It can help homeowners save money.**

Passive solar energy uses an energy source that occurs naturally, is almost always available and, more importantly, is free for all. Because of these, homeowners who use passive solar energy can enjoy low utility bills and have more savings in the long run.

3. **It doesn't require expensive equipment.**

Compared to the equipment needed in active solar energy (such as solar panels, inverters, wires, and other types of equipment and materials), the materials required in passive solar energy is relatively cheap. This is great for homeowners who want to create an eco-friendly home but don't have a large budget.

Negatives of Passive Solar Systems

1. **It can be expensive as a whole.**

As mentioned above, passive solar energy requires less expensive materials. However, homeowners must take note that adapting a house to fit a passive solar energy system can be costly. This is particularly true if they have to knock down interior and exterior walls to facilitate proper heat distribution and make extensive renovations to incorporate heat-absorbing materials in their home.

2. **It is dependent on location.**

Not all passive solar energy systems are ideal for every place. A system that works well in Florida, for instance may not be ideal for those who live in Texas and California. Because of this, homeowners will have to do extensive research or even hire a passive solar energy expert, who'll help them create the right design for their home.

3. **It may not be able to cover the home's heating and cooling needs.**

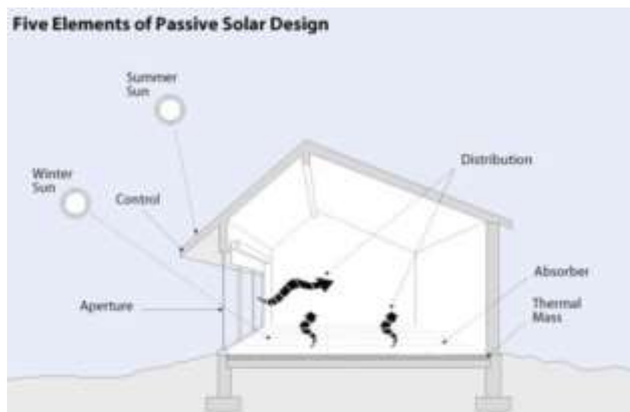
For those who live in northern regions with harsh winters, passive solar energy will not be enough to provide all their heating needs. Because of this, they'll need to supplement it with other energy sources like coal, petroleum, and natural gas. For those who live in southern climates, passive solar energy may cause too much heat to enter their homes (especially during hot summers) and make it difficult for them to stay cool.

Passive Solar Design

Passive solar design refers to the use of the sun's energy for the heating and cooling of living spaces by exposure to the sun. When sunlight strikes a building, the building materials can reflect, transmit, or absorb the solar radiation. In addition, the heat produced by the sun causes air movement that can be predictable in designed spaces. These basic responses to solar heat lead to design elements, material choices and placements that can provide heating and cooling effects in a home

Elements of Passive Solar Design

- A complete passive solar design has five elements:



1. **Aperture/Collector:** The large glass area through which sunlight enters the building. The aperture(s) should face within 30 degrees of true south and should not be shaded by other buildings or trees from 9a.m. to 3p.m. daily during the heating season.
2. **Absorber:** The hard, darkened surface of the storage element. The surface, which could be a masonry wall, floor, or water container, sits in the direct path of sunlight. Sunlight hitting the surface is absorbed as heat.
3. **Thermal mass:** Materials that retain or store the heat produced by sunlight. While the absorber is an exposed surface, the thermal mass is the material below and behind this surface.
4. **Distribution:** Method by which solar heat circulates from the collection and storage points to different areas of the house. A strictly passive design will use the three natural heat transfer modes- conduction, convection and radiation- exclusively. In some applications, fans, ducts and blowers may be used to distribute the heat through the house.
5. **Control:** Roof overhangs can be used to shade the aperture area during summer months. Other elements that control under and/or overheating include electronic sensing devices, such as a differential thermostat that signals a fan to turn on; operable vents and dampers that allow or restrict heat flow; low-emissivity blinds; and awnings.

Lecture 4: Passive solar system Direct Gain

Solar Energy System or Solar Power System is a stand-alone system, entirely powered by solar energy to harness different types of energies.
Solar Energy Systems are characterized as either Passive Solar or Active Solar depending on the way they capture, convert and distribute solar energy.

- Active Solar Energy Systems include the use of photovoltaic panels and solar thermal collectors to harness the energy.
- Passive Solar Energy Systems include orienting a building to the Sun, selecting materials with favorable thermal mass or light dispersing properties, and designing spaces that naturally circulate air.

Passive Solar Energy Systems

Ancient people used passive solar energy systems. They build their houses out of stone or clay, which absorbed the sun's heat during the day and stayed warm after dark, providing heat throughout the night.
Builders today use similar methods for passively capturing solar energy. For example, they construct houses with large double- or triple-paned windows that get direct sunlight to capture and magnify the sun's warmth. The effect is similar to but more powerful than what happens to your car on a sunny day: The air inside becomes much warmer than the air outside because the windows let in the sun's energy and trap it, gradually raising the temperature.

Other effective methods of passive solar energy capture include using stone flooring and walls with thick insulation to keep the energy in buildings. With carefully placed windows and other architectural techniques, passive solar energy systems can be an effective way to heat buildings.

Active Solar Energy Systems

Active Solar Energy Systems use the same principles as passive systems except that they use a fluid (such as water to absorb the heat) and some electrical or mechanical equipment (such as pumps and fans) to increase the usable heat in a system.
A solar collector positioned on the roofs of buildings heats the fluid and then pumps it through a system of pipes to heat the whole building.

Photovoltaic Cells, or Solar Panels, are slightly more involved than active solar energy systems. They convert sunlight to electricity by using thin sheets of silicon. These thin sheets are inexpensive and can be added to roof tiles.

People in remote areas such as mountain tops and islands often use photovoltaic cells to generate electricity in their homes and businesses.

This figure illustrates how solar panels capture sunlight and generate electricity.

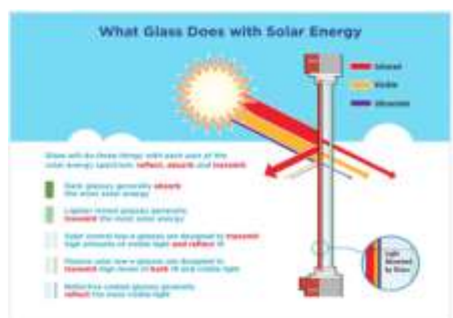
Passive Solar system

- Passive solar heating is defined as using solar energy striking windows, skylights, greenhouses, clerestories, and mass walls in order to provide heating for a house.
- Generally, such solar collection occurs passively, without the extensive use of pumps or fans typically used in active solar collector systems.
- Because heating is needed only over the colder part of the year (Sept. to May), passive solar design must also eliminate unwanted solar heat gains during the summer.
- The use of techniques to eliminate solar gains and to cool a house with the use of active systems is often referred to as passive cooling

Types of Passive Systems

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

Direct Gain Systems



- **Direct Gain.** Sunlight incident on transparent surfaces allows the energy to enter the living space directly
- South facing windows thus form the basis for the simplest type of solar heating system.
- With some simple guidelines, this design is the cheapest and best way to incorporate solar into a house.

❖ Glass will do 3 things with each part of the solar energy spectrum; Reflect, Absorb, and Transmit.

- Dark glasses generally absorb the most solar energy.
- Lighter tinted glasses generally transmit the most solar energy.
- Solar control low e-glasses are designed to transmit high amounts of visible light and reflect IR.
- Passive solar low-e glasses are designed to transmit high levels of both IR and visible light.
- Reflective coated glasses generally reflect most of the visible light.

✓ Direct Gain Passive Solar Design

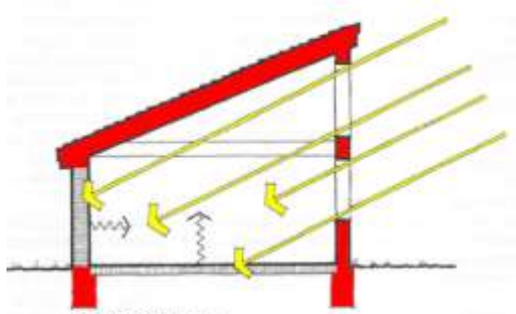


FIG. 19a. Direct Gain

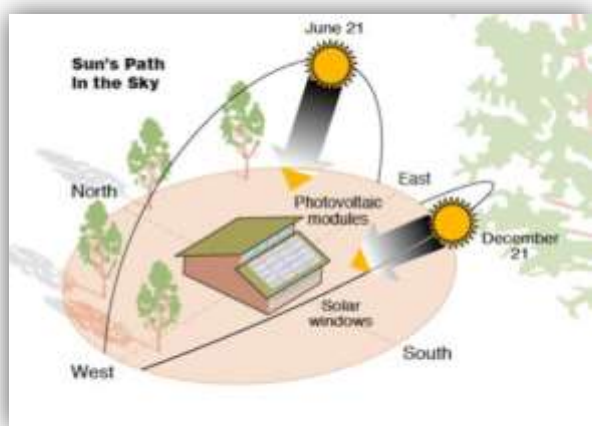
- Surfaces should be generally facing south (to within 20 degrees)
- Overhangs should prevent unwanted summer gains (2 ft typical at 40 degrees latitude)
- Window area should be 8-12% of the house floor area if no extra thermal mass is added
- This amount of passive solar gain should provide no more than 40-50% of the yearly heating load
- More area may be possible if additional thermal mass is added.

✓ Direct Gain Rules:

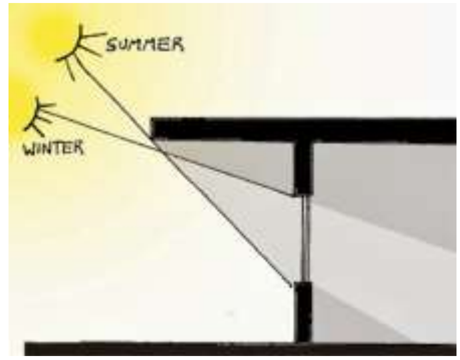
1. Mass Distribution: spread it around evenly; 6 times glazing area (3X minimum)
2. Mass Thickness: thin and spread out better than thick. More than 4" for masonry or concrete not useful
3. Color: Floors dark to absorb more heat, walls and ceilings lighter to reflect light.
4. Surface Covering: insulated coverings (i.e. Rugs) greatly decrease performance of thermal mass
5. Concrete Block Masonry: If used, a high density with cores filled with grout
6. Floor Materials: Concrete or brick preferred. If insulating under, at least 4" thick (100mm). More than 6" (150mm) not useful.
7. Limits on Direct Gain Glazing Area: South facing glazing limited to prevent large temperature swings. 7% of floor area for low mass buildings, 13% of floor area for high mass buildings.
8. Glazing orientation: Vertical facing due south preferred. Vertical easiest to build, and easiest to shade in summer. Performance penalty for 15degrees off due south is 10% and for 30 degrees is 20% loss; so within 15 degrees recommended.
9. Night insulation: Really helpful but can be very costly.
10. Thermal Insulation: Insulation located OUTSIDE the thermal mass.

❖ The Sun's Seasonal Path

- **This path is hemisphere and latitude dependent.**



✓ Overhangs on the South Side

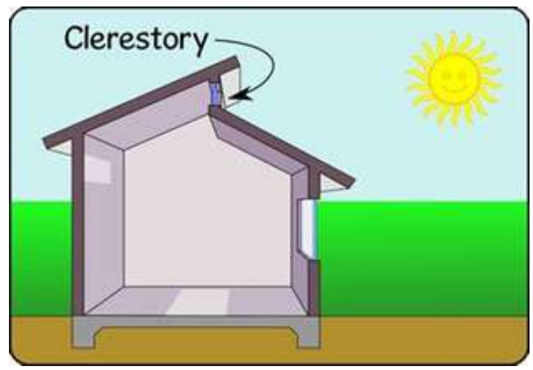


- Overhangs are important parts of passive solar heating and natural cooling.
- Roof overhang are determined by orientation of the house to the sun.
- ➢ During the Summer the Sun travels closer to earth.
- ➢ During the Winter the Sun is farther away and lower in the sky.
- Extended roof overhang:

A. Keeps the hot afternoon Sun from entering the house via the bank of west windows

B. while allowing the warming winter sun to bring warmth into the house.

✓ Clerestory is also direct gain



- Two alternatives to standard windows are clerestory windows – those high-up windows that sit between two levels of external roofing – and skylights. They both have their uses in passive solar design, though you have to be careful with their effects on light and heating.
- Because they are placed high up compared to other windows, clerestories can deliver sunlight far deeper into a living space than normal vertical glazing.
- Their main function is twofold:

1. They deliver extra daylighting.
2. They provide a method of heating thermal mass in north walls which would normally be in shade.

❖ Benefits of Clerestory windows :

- ➢ They allow a lot more light into the building, while reducing glare and improving privacy.
- ➢ They increase solar gain in the living space and particularly in thermal mass placed on the north side of the home.
- ➢ They are a great choice if the bottom-story windows are obstructed by trees, neighboring homes or other structures.
- ➢ They add to the overall aesthetic of the home.

❖ Disadvantages of Clerestory windows :

- ➢ The extra light extends into the night, as clerestories capture street lighting, ambient light from neighbors' homes and even moonlight. This can make them a bad choice in sleeping areas.
- ➢ They provide another exit for the home's stored heat – and since they're high up, they are closer to the warmest air in the space.

- They are extremely difficult to shade, which means they generally remain uncovered at all times, thus increasing heat loss. You may need to install expensive powered shutters to reduce the losses.
- They require very high ceilings compared to most homes, which means the living space contains a lot more air to heat. Vaulted ceilings always make home heating more difficult.

❖ Skylights

- Skylights are very popular in many homes as a means of bringing extra light into a space, especially an attic... but they come at the price of potential overheating in the warmer seasons.
- The big problem with skylights placed for solar gain rather than daylighting (so those on a south-facing roof) is that they don't capture much of the winter sun's energy unless the roof is very steep. On a shallow or flat roof, skylights will generate intense solar gain in summer, when it is least needed, and do little except provide a bit of extra light in winter.
- Even on a steep roof, skylights are an uncomfortable choice:

For example, they are extremely hard to waterproof, insulate, and shade. With heat escaping through the skylight via air filtration and the possibility of rain leaking in, they can be an expensive option to maintain. And the harder it is to operate a shade (in summer, for instance), the less likely you are to operate the mechanism, so you end up with overheated rooms.

- If you are thinking of installing skylights primarily for the extra daylighting, but want to keep most of the solar gain, you should consider tube skylights. These are special tubes which extend from the roof down into the ceiling. They have a light-gathering lens on the relatively small exterior end and are surfaced with reflective material which directs a massive amount of light into the home below.
- The light is diffuse but brings most of its heat energy with it, without exposing the home so badly to unwanted solar gain in summer. The interior end of a solar tube looks like a ceiling lamp.

Lecture 5: Passive solar system indirect Gain

Indirect Gain Passive Solar

Indirect Gain: means the method of passive-solar heating in which solar radiation is collected within a space that can be thermally separated from a building's occupied space. Indirect-gain systems include attached-sunspaces, and trombe walls (thermal storage walls).

The single most widely applicable passive solar design option is indirect gain passive solar. The option works in every climate and every location, from the hottest and sunniest to the coldest and darkest.

"Indirect gain passive solar" translates into thermal storage walls (or Trombe walls).

- BENEFITS of INDIRECT GAIN SYSTEM

1. Flexible system
2. Multi-story uses
3. Easy control of Heat loss and heat gain

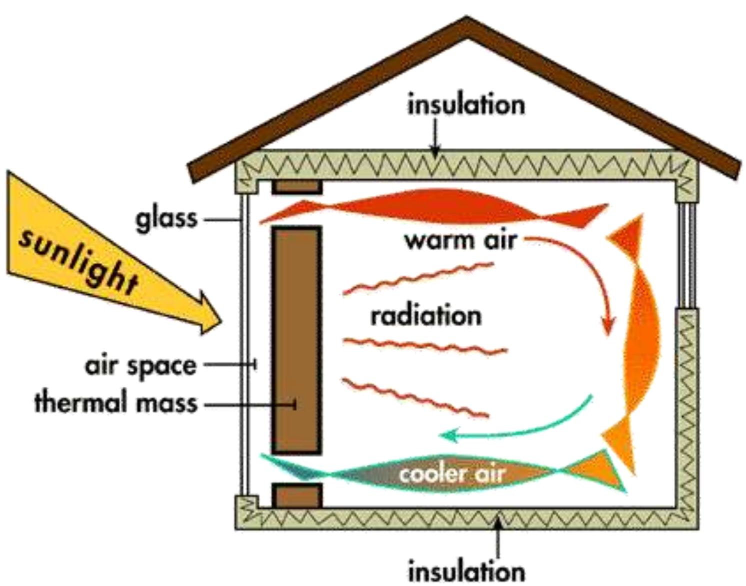
- **There are three types of Indirect Gain Systems:**
    1. Trombe Walls
    2. Roof Ponds
    3. Thermosiphon

1. Trombe Walls

These walls are made from dense or earthen materials such as rammed earth, poured concrete, or concrete blocks.

A pane of clear glass is fixed to the wall, about 3-6 inches away from the surface, which allows the sun's light to penetrate and heat the wall. The energy generated is either stored in the wall or escapes into the air between the wall and the glass, heating the air. The warm air either vents out to the sides or can be captured and directed.

Trombe walls are designed for night heating.



- They absorb the sun's warmth and are built so that the stored heat being taken in on the outside reaches the interior surface at sunset, or soon afterwards.
- As the inside of the home cools, the wall starts to release its heat and extends the comfortable warm period into the night.
- The amount of time it takes for the heat to get from the outside to the inside depends on the wall thickness, density and design, and ranges from a few hours to an entire day.
- Most Trombe walls are between 8 and 18 inches thick, though some are as thin as 6 inches and some as thick as 24 inches.
- Thicker walls take longer to transfer the heat from outside but they also maintain a more stable interior surface temperature. Trombe walls can hold windows, the same as any other wall.

Mass Wall: Materials vs. Thickness

MATERIAL	DENSITY (lb/df)	THICKNESS (inches)
Concrete	140	8 - 24
Concrete masonry (concrete blocks)	130	7 - 8
Clay brick	120	7 - 16
Light Weight Concrete Masonry	110	6 - 12
Adobe	100	6 - 12

- Trombe walls must be designed to prevent overheating. This is usually achieved with overhangs, though some people choose to install movable, insulated panels that cover the glass. The rigid foam panel option is more flexible, as it can also be used to prevent nighttime heat losses, especially in cold climates, though it requires a bit of physical effort from the homeowner.

One final note on thermal walls: many people are reluctant to install them because they think the walls will look ugly. The truth is that, from a distance, they look just like any other solar glazing. It's only when you get up close that you notice there's a wall behind the glass. They can contain windows, so it's not like living in a prison cell, and the interior can be covered with attractive plaster or stucco without significantly reducing heat transfer.

❖ PROS OF THERMAL MASS WALL (TROMBE)

- Simple and relatively effective
- Good for privacy
- Good for where you do not want daylight or view
- Makes good use of existing wall space
- Thermal mass is prevented from receiving direct sunlight while absorbing the heat in the room, helping to keep the temperature cooler.
- Free heating once installed
- The heat that gradually migrates through wall is low grade but effective radiant inside at night

❖ CONS OF THERMAL MASS WALL (TROMBE)

- Must be carefully designed
- More expensive to install, because of the cost of materials and the structural modifications required.
- Usually requires heavy masonry construction
- Problems with reverse heat loss in the winter
- Problems with moisture and cleaning
- Can feel enclosed
- Usually dark colored masonry

2. **Roof Ponds**

The roof pond is a system that passively incorporates water elements to passively cool and heat the building.

- The system comprises of 4 parts which are
  1. the pond support,
  2. water container,
  3. pond cover, and
  4. A spraying system.

The pond support element should possess high thermal conductivity. The pond support can be either metal or reinforced slab with the metal having higher thermal connectivity.

- The roof pond can be applied in three different methods.
  1. Dry (water is contained in plastic bags),
  2. wet (the plastic bags are sprayed or flooded),
  3. Open (water is contained within the parapet).

- **Cooling Cycle**

During day-time in the summer, it is vital to protect the pond from solar radiation. This can be done through covering the pond with a reflective cover, to reflect the solar radiation off. Spraying the pond or the protective cover can further enhance the functionality of the system as it will further cool down through evaporation.

Whereas, during night time the pond cools the spaces below through long wave radiation to the atmosphere, making interior spaces cooler.

- **Heating Cycle**

The roof pond being exposed during the day absorbs heat through solar radiation and transfers it into the interior of the house, thus, passively warming it up. During night time, a protection cover can be placed over the pond to prevent heat loss.

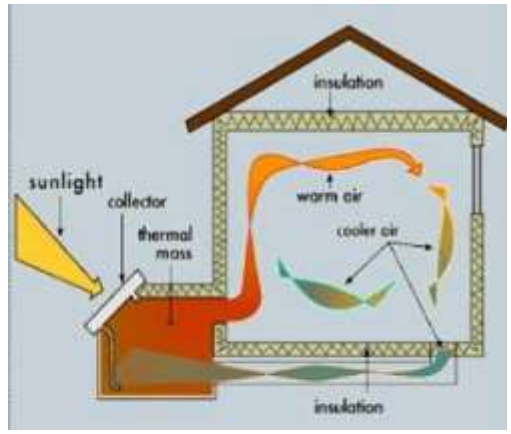
❖ PROS OF ROOF POND SYSTEMS

- Very efficient and economic.
- Can provide passive cooling in summer.
- Higher overall heat capacity and a potential translucency that lets diffused light into the space.
- Best for cooling in low humidity climates but can be modified to work in high humidity climates.

❖ CONS OF ROOF POND SYSTEMS

- Extra structural costs.
- The system does not guarantee sufficient advantages at high latitudes because of the reduced solar radiation intercepted by the horizontal plane.
- Require somewhat elaborate drainage systems, movable insulation to cover and uncover the water at appropriate times, and a structural system to support up.
- Only effective for heating at mid-latitudes, in moderate to temperate climates. Roof ponds are usually installed more for their passive cooling effects, with any heating potential simply being a bonus.

3. Thermosiphon

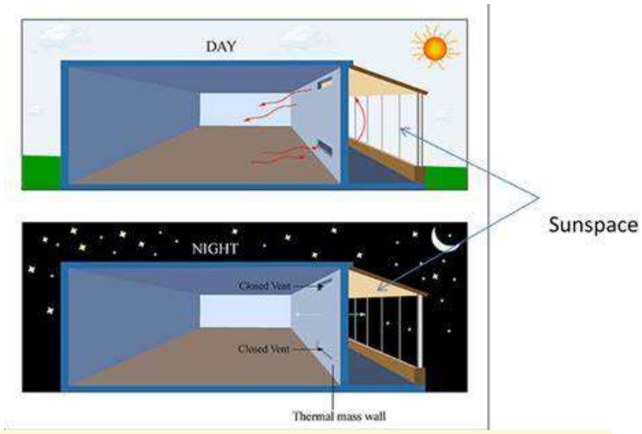


- Use the same materials as direct gain system but thermal mass is placed between the sun and the space to be heated.
- Use flat plate collectors.
- Solar heat is transferred to the thermal mass where it is absorbed.
- The hot air rises and enters room through ventilation at the bottom of the walls.
- Convection brings the heat into room and cool air down to ducts at the bottom to be sent back to the thermal mass where it is heated again and circulated.
- During the hot summer season, the process is reversed, so since the thermal mass is not in direct sunlight, it absorbs heat from inside the room and radiates out.
- It is very effective as it usually takes around 6-8 hours for the heat energy of the thermal to totally dissipate, so it can supply heat to the home throughout the night.

Lecture 6: Passive solar system isolated Gain

A sunspace is also known as isolated gain passive solar. A sunspace serves three main functions.

- They can offset the energy required to heat the home,
- provide a place to grow plants, and
- be a wonderful room to enjoy.



Typically a sunspace is a separate room on the south side of the house. It needs to contain thermal mass in the floor, and/or in the walls between the sunspace and the living space. The sunspace is connected to the main living spaces with doors and/or windows that can be closed off during the night, isolating it during cold nights. A sunspace can perform better than direct and indirect passive solar as long as the thermal mass is sized sufficiently. Since the sunspace can be isolated from the rest of the home, temperature fluctuations can be more easily managed. By isolating the sunspace with doors and windows you have more control of the transfer of heat than the other systems. It is generally the more expensive system to build.

In an isolated gain system solar radiation is captured in a separate, glazed, otherwise unheated space and then transferred to the living space. Atriums and attached greenhouses are examples of isolated gain. Solar greenhouses are the most practical method for retrofitting existing housing with passive solar heating and are the usual way of employing isolated gain.

A greenhouse is advantageous for three reasons.

1. First, the solar heat can be stored without having unsightly or bulky masonry or water tanks in the living areas, and the heat can be distributed effectively to where it is needed. This distribution is done by vents and ducts.
2. Second, the greenhouse provides additional living space.
3. Third, the greenhouse can serve as a buffer between the living space and the outdoor, thus reducing heat losses.

❖ Cooling

Although our main objective in passive solar design is to heat a house, for the house to be livable, it will also require some type of cooling. The effectiveness of passive cooling depends on how well heat gain is controlled and on adequate ventilation. Ventilation removes heat generated inside the house—for example by the people living there. Moving air also feels more comfortable than still air. Heat can be kept out by shading the collection area with overhangs or vegetation.

Moveable insulation can be used to reduce heating through windows. House design can promote natural ventilation. Such design requires a clear path for summer breezes and use of the chimney effect to pull cooler air into the house. The chimney effect is produced by warm air rising and flowing out of the house, as smoke rises and flows out of a chimney. Traditional housing in the

Middle East and in West Africa has made remarkably effective use of natural ventilation for centuries.

❖ Energy efficiency first

Before you decide to add a sunspace to your existing home or new house design, remember that energy efficiency is the most cost-effective strategy for reducing heating and cooling bills.
If its primary function will be heating, a sunspace with sloped glazing, few plants, little thermal mass, and insulated, unglazed end walls will get very hot on sunny winter days. In practice, sunspaces are rarely built to serve only as heaters, because there are less expensive ways to provide solar heat.
If the space will be a greenhouse, plants need fresh air, water, lots of light, and protection from extreme temperatures. Greenhouses consume energy through the growth processes of plants and the evaporation of water -- one pound of evaporating water uses about 1,000 Btu that would otherwise be available as heat. Plants require overhead glazing, which complicates construction and maintenance, and glazed sidewalls, which are net heat losers. The bottom line is that a sunspace designed as an ideal agricultural environment is unlikely to have much energy left over for supplementary space heating.
Most people want to use the sunspace as a year-round living area, in which case it should have minimum glare, only moderate humidity, and comfortable temperatures. Carefully sized thermal mass and energy-efficient windows that are well-shaded in the summer will improve comfort by stabilizing temperature extremes.

❖ Orientation and Glazing

Ideally, the sunspace should face due south, but 30 degrees east or west of due south will provide about 90% of the maximum static solar collection potential. The optimum orientation will depend on site-specific and local landscape features.
The angle and type of sunspace window glazing will be important to the performance of the sunspace.

- sloped glazing
  - Collects more heat in the winter,
  - Loses more heat at night,
  - can be covered with snow in the winter, and
  - Will cause overheating in warmer weather.
- Vertical glazing
  - Maximizes heat gain in the winter, when the angle of the sun is low and you need the heat most, and
  - Easier to shade and produces less heat gain as the sun rises toward its summer zenith.
  - less expensive than sloped glazing,
  - easier to install and insulate, and
  - Not as prone to leaking, fogging, breaking and other glazing failures. Vertical glazing is also often
  - More aesthetically compatible with the design of existing homes.
  - A well-designed overhang may be all that is necessary to shade vertical glazing in the summer.

Placing windows in the east and west walls is not recommended for sunspaces, but if it’s necessary the east side is preferable to the west. The sunlight entering east-facing glazing occurs early in the day and is less likely to cause unwanted solar gain in the summer than afternoon sunlight. Solid insulated sidewalls are preferable, and will reduce unwanted solar gain and nighttime heat loss.

❖ Heat Distribution and Control

Operable vents at the top of the sunspace where temperatures are the highest and at the bottom where temperatures are the lowest can circulate warm air into the house. They can be operated manually or with thermostatically controlled motors that open and close them automatically. Warm air can also move through doors, vents, or open windows between the sunspace and the interior living space.

❖ Window Types and Technologies

Many features and technologies make windows more energy efficient and improve the durability, aesthetics, and functionality. When selecting new windows consider the following:

- the frame materials,
- the glazing or glass features,
- gas fills and spacers, and
- The type of operation.

Frames

Improving the thermal resistance of the frame can contribute to a window's overall energy efficiency, particularly its U-factor (The U-factor is the overall heat transfer coefficient; it describes the rate at which heat will be transferred through the structure.). There are advantages and disadvantages to all types of frame materials, but vinyl, wood, fiberglass, and some composite frame materials provide greater thermal resistance than metal.

Aluminum or Metal Frames

Although very strong, light, and almost maintenance free, metal or aluminum window frames conduct heat very rapidly, which makes metal a very poor insulating material. To reduce heat flow and the U-factor, metal frames should have a thermal break -- an insulating plastic strip placed between the inside and outside of the frame and belt.

Composite Frames

Composite window frames consist of composite wood products, such as particleboard and laminated strand lumber, and some are mixed with polymer plastics. These composites are very stable, they have the same or better structural and thermal properties as conventional wood, and they have better moisture and decay resistance.

Fiberglass Frames

Fiberglass window frames are dimensionally stable and have air cavities that can be filled with insulation, giving them superior thermal performance compared to wood or uninsulated vinyl.

Vinyl Frames

Vinyl window frames are usually made of polyvinyl chloride (PVC) with ultraviolet light (UV) stabilizers to keep sunlight from breaking down the material. Vinyl window frames do not require painting and have good moisture resistance. The hollow cavities of vinyl frames can be filled with insulation, which makes them thermally superior to standard vinyl and wood frames.

Wood Frames

Wood window frames insulate relatively well, but they require regular maintenance, although aluminum or vinyl cladding reduces maintenance requirements. Metal clad wood frames may have slightly lower thermal performance.

Glazing or Glass

In addition to choosing a frame type, you will need to consider what type of glazing or glass you should use to improve your home's energy efficiency. Based on various window design factors such as window orientation, climate, building design, etc., you may even want to choose different types of glazing for different windows throughout your home.

Below are some of the coatings and technologies you may find when shopping for windows:

Insulation

Insulated window glazing refers to windows with two or more panes of glass. To insulate the window, the glass panes are spaced apart and hermetically sealed, leaving an insulating air space. Insulated window glazing primarily lowers the U-factor, but it also lowers the SHGC (**Solar Heat Gain Coefficient**).

Low-Emissivity Coatings

Low-emissivity (low-e) coatings on glazing or glass control heat transfer through windows with insulated glazing. Windows manufactured with low-e coatings typically cost about 10% to 15% more than regular windows, but they reduce energy loss by as much as 30% to 50%.

A low-e coating is a microscopically thin, virtually invisible, metal or metallic oxide layer deposited directly on the surface of one or more of the panes of glass. The low-e coating lowers the U-factor of the window, and different types of low-e coatings have been designed to allow for high solar gain, moderate solar gain, or low solar gain. Although low-e coatings are usually applied during manufacturing, some are available for do-it-yourselfers. These films are inexpensive compared to total window replacements, last 10 to 15 years without peeling, save energy, reduce fabric fading, and increase comfort.

Spectrally Selective Coatings

A special type of low-e coating is spectrally selective, filtering out 40% to 70% of the heat normally transmitted through insulated window glass or glazing while allowing the full amount of light transmission.

Spectrally selective coatings are optically designed to reflect particular wavelengths, but remain transparent to others. Such coatings are commonly used to reflect the infrared (heat) portion of the solar spectrum while admitting more visible light. They help create a window with a low U-factor and SHGC but a high VT.

Computer simulations have shown that advanced window glazing with spectrally selective coatings can reduce the electric space cooling requirements of new homes in hot climates by more than 40%.

Gas Fills and Spacers

Gas fills between glazing layers minimize heat transfer between the interior and exterior of the window. Argon or krypton is the gases typically used; both are inert, non-toxic, clear, and odorless.

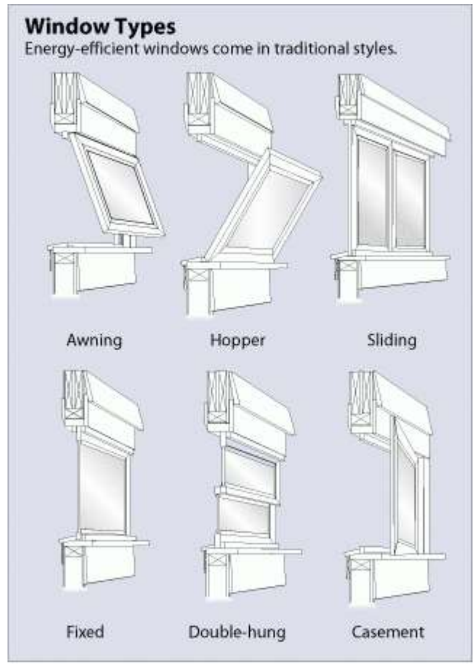
Krypton can be used when the space between glazing layers must be thin—about ¼ inch. It has better thermal performance than argon but is also more costly.

Argon can be used when the spacing can be a bit larger—1/2 inch. Sometimes it is mixed with krypton to keep cost low while increasing thermal performance.

Spacers are used to keep the layers of glazing the correct distance apart. In addition, they provide accommodation for thermal expansion and pressure differences, while also preventing moisture and gas leaks.

Operating Types

Another important consideration is how the windows operate, because some operating types have lower air leakage rates than others, which will improve your home's energy efficiency. Traditional operating types include:



- Awning. Hinged at the top and open outward. Because the sash closes by pressing against the frame, they generally have lower air leakage rates than sliding windows.
- Hopper. Hinged at the bottom and open inward. Like both awning and casement, they generally have lower air leakage rates because the sash closes by pressing against the frame.
- Single- and double-sliding. Both sashes slide horizontally in a double-sliding window. Only one sash slides in a single-sliding window. Like single- and double-hung windows, they generally have higher air leakage rates than projecting or hinged windows.
- Fixed. Fixed panes that don't open. When installed properly they're airtight but are not suitable in places where window ventilation and egress is desired.
- Single- and double-hung. Both sashes slide vertically in a double-hung window. Only the bottom sash slides upward in a single-hung window. These sliding windows generally have higher air leakage rates than projecting or hinged windows.
- Casement. Hinged at the sides. Like awning windows, they generally have lower air leakage rates than sliding windows because the sash closes by pressing against the frame.

Lecture 7: Cooling Load Estimation (1)

Principles of Heat Transfer

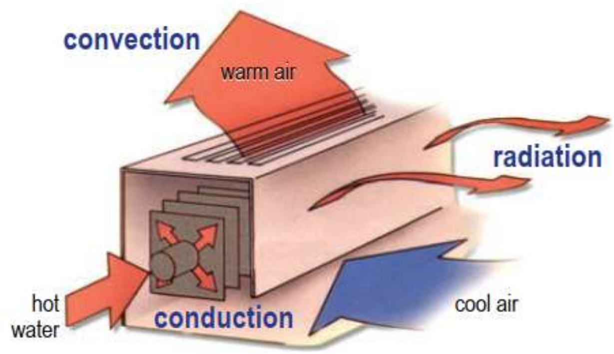
- Heat energy cannot be destroyed.
- Heat always flows from a higher temperature substance to a lower temperature substance.
- Heat can be transferred from one substance to another.

- Heat energy cannot be destroyed; it can only be transferred to another substance.

To produce cooling, heat must be removed from a substance by transferring the heat to another substance. This is commonly referred to as the principle of "conservation of energy." Ice cubes are typically placed in a beverage to cool it before being served. As heat is transferred from the beverage to the ice, the temperature of the beverage is lowered. The heat removed from the beverage is not destroyed, but instead is absorbed by the ice, melting the ice from a solid to a liquid.

- Heat energy naturally flows from a higher-temperature substance to a lower-temperature substance, in other words, from hot to cold. Heat cannot naturally flow from a cold substance to a hot substance. Consider the example of the beverage and the ice cubes. Because the temperature of the beverage is higher than the temperature of the ice cubes, heat will always flow from the beverage to the ice cubes.
- Heat energy is transferred from one substance to another by one of three basic processes: conduction, convection, or radiation.

Methods of Heat Transfer

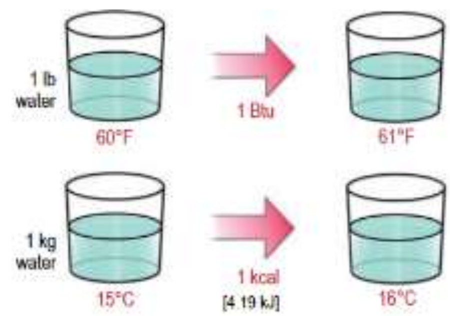


The device shown is a baseboard convector that is commonly used for heating a space. It can be used to demonstrate all three processes of transferring heat.

Hot water flows through a tube inside the convector, warming the inside surface of the tube. Heat is transferred, by conduction, through the tube wall to the slightly cooler fins that are attached to the outside surface of the tube. Conduction *is the process of transferring heat through a solid*. The heat is then transferred to the cool air that comes into contact with the fins. As the air is warmed and becomes less dense, it rises, carrying the heat away from the fins and out of the convector. This air movement is known as convection current. Convection *is the process of transferring heat as the result of the movement of a fluid*. Convection often occurs as the result of the natural movement of air caused by temperature (density) differences.

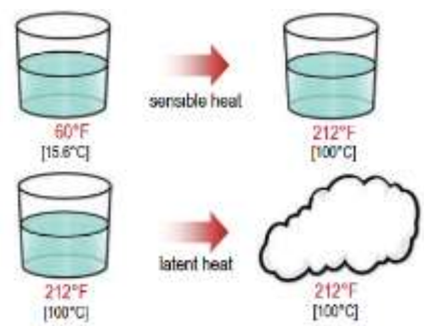
Additionally, heat is radiated from the warm cabinet of the convector and warms cooler objects within the space. Radiation *is the process of transferring heat by means of electromagnetic waves, emitted due to the temperature difference between two objects*. An interesting thing about radiated heat is that it does not heat the air between the source and the object it contacts; it only heats the object itself.

Measuring Heat Quantity



The unit for measuring the quantity of heat is the British Thermal Unit (Btu). The *Btu* is defined as the quantity of heat energy required to raise the temperature of 1 lb. of water 1°F.
Similarly, in the Système International (SI) system, heat quantity can be expressed using the unit kilojoule (kJ). A kcal is defined as the amount of heat energy required to raise the temperature of 1 kg of water 1°C. One kcal is equal to 4.19 kJ.
In heating and cooling applications, however, emphasis is placed on the rate of heat transfer, that is, the quantity of heat that flows from one substance to another within a given period of time. This rate of heat flow is commonly expressed in terms of Btu/hr.—the quantity of heat, in Btu, that flows from one substance to another during a period of 1 hour.
Similarly, in the SI system of units, the rate of heat flow is expressed in terms of kilowatts (kW). One kW is equivalent to 1 kJ/sec. One kilowatt describes the quantity of heat, in kJ, that flows from one substance to another during a period of 1 second. Finally, the rate of heat flow may often be expressed in terms of watts (W). One kW is equivalent to 1000 W.

Sensible versus Latent Heat



The process of comfort heating and air conditioning is simply a transfer of energy from one substance to another. This energy can be classified as either sensible or latent heat energy.
Sensible heat *is heat energy that, when added to or removed from a substance, results in a measurable change in dry-bulb temperature.*
Changes in the latent heat content of a substance are associated with the addition or removal of moisture.
Latent heat *can also be defined as the "hidden" heat energy that is absorbed or released when the phase of a substance is changed.* For example, when water is converted to steam, or when steam is converted to water.

- **Dry/Wet bulb temperature of air**

The temperature of the air measured by the ordinary thermometer is called as the dry bulb temperature of air, commonly referred as DBT. When ordinary thermometer is exposed to the atmosphere, it indicates the dry bulb temperature, which is nothing but the atmospheric temperature.
The more is the moisture or water vapor content of the air more is the wet bulb temperature. Thus the wet bulb temperature indirectly indicates the moisture content present in the air or we can say that it is affected by the relative humidity of the air.

Heat Generated by People

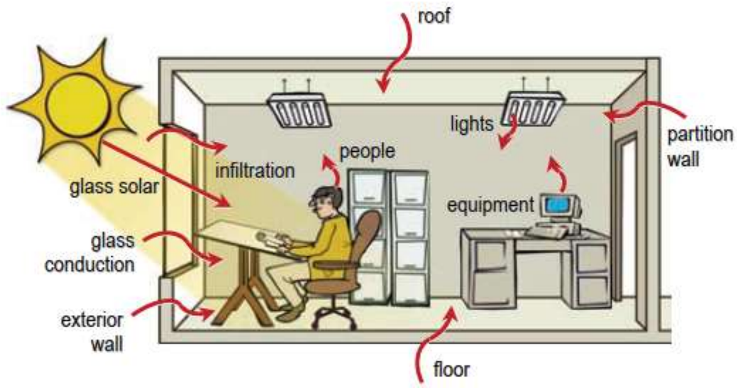
The necessity for comfort air conditioning stems from the fact that the metabolism of the human body normally generates more heat than it needs. This heat is transferred by convection and radiation to the environment surrounding the body. The average adult, seated and working, generates excess heat at the rate of approximately 450 Btu/hr [132 W]. About 60% of this heat is transferred to the surrounding environment by convection and radiation, and 40% is released by perspiration and respiration.

As the level of physical activity increases, the body generates more heat in proportion to the energy expended.

❖ Cooling Load Estimation

The selection of Heating, Ventilating, and Air Conditioning (HVAC) system components and equipment should always be based on an accurate determination of the building heating and cooling loads.

- During this lecture we will estimate the cooling loads for a single space in a single-story office building.



The Cooling Load Temperature Difference/Solar Cooling Load/ Cooling Load Factor (CLTD/SCL/CLF) load estimation method, used here, is a simplified hand calculation procedure developed long ago by ASHRAE. Because of its simplicity, it is the most common method used for basic instruction on estimating cooling loads.

➤ Cooling Load Components

The space cooling load *is the rate at which heat must be removed from a space in order to maintain the desired conditions in the space, generally a dry-bulb temperature and relative humidity.* The cooling load for a space can be made up of many components, including:

- Conduction heat gain from outdoors through the roof, exterior walls, skylights, and windows. (This includes the effects of the sun shining on these exterior surfaces.)
- Solar radiation heat gain through skylights and windows.
- Conduction heat gain from adjoining spaces through the ceiling, interior partition walls, and floor.
- Internal heat gains due to people, lights, appliances, and equipment in the space.
- Heat gain due to hot, humid air infiltrating into the space from outdoors through doors, windows, and small cracks in the building envelope.

In addition, the cooling coil in the building HVAC system has to handle other components of the total building cooling load, including:

- Heat gain due to outdoor air deliberately brought into the building for ventilation purposes.
- Heat generated by the fans in the system and possibly other heat gains in the system.

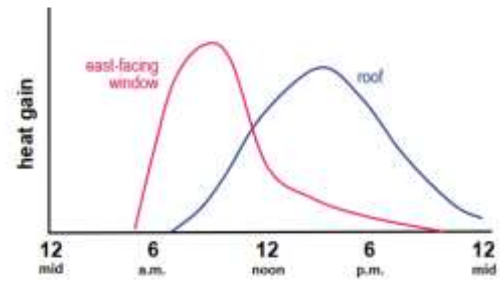
Cooling Load Components

cooling load components	sensible load	latent load	space load	coil load
conduction through roof, walls, windows, and skylights	✓		✓	✓
solar radiation through windows, skylights	✓		✓	✓
conduction through ceiling, interior partition walls, and floor	✓		✓	✓
people	✓	✓	✓	✓
lights	✓		✓	✓
equipment/appliances	✓	✓	✓	✓
infiltration	✓	✓	✓	✓
ventilation	✓	✓		✓
system heat gains	✓			✓

Assume that the space has no plenum (the space between the ceiling and roof). Therefore, all of the heat gain due to the roof and

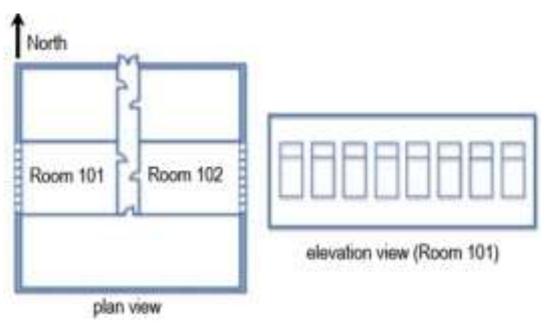
lighting affects the space directly.
These load components contribute sensible and/or latent heat to the space. Conduction through the roof, exterior walls, windows, skylights, ceiling, interior walls, and floor, as well as the solar radiation through the windows and skylights, all contributes only sensible heat to the space. The people inside the space contribute both sensible and latent heat. Lighting contributes only sensible heat to the space, while equipment in the space may contribute only sensible heat (as is the case for a computer) or both sensible and latent heat (as is the case for a coffee maker). Infiltration generally contributes both sensible and latent heat to the space.
The cooling coil has to handle the additional components of ventilation and system heat gains. Ventilation contributes both sensible and latent heat to the coil load. Other heat gains that occur in the HVAC system (from the fan, for example) generally contribute only sensible heat.

- Time of Peak Cooling Load



One of the more difficult aspects of estimating the maximum cooling load for a space is determining the time at which this maximum load will occur. This is because the individual components that make up the space cooling load often peak at different times of the day, or even different months of the year.
For example, the heat gain through the roof will be highest in the late afternoon, when it is warm outside and the sun has been shining on it all day. Conversely, the heat gain due to the sun shining through an east-facing window will be highest in the early morning when the sun is rising in the east and shining directly into the window.

- Example Office Space (Room 101)



Room 101 is the space that we will use as an example throughout this lecture. The windows face west and the solar heat gain through these windows will peak in the late afternoon when the sun is setting and shining directly into the windows. Because of this, we will assume that the maximum cooling load for our example space occurs at 4 p.m. For this example, the following criteria will be used as a basis for estimating the space cooling and heating loads.

- Floor area = 45 ft. × 60 ft. [13.7 m × 18.3 m].
- Floor-to-ceiling height = 12 ft. [3.7 m] (no plenum between the space and roof.
- Desired indoor conditions = 78ºF [25.6ºC] dry-bulb temperature, 50% relative humidity during cooling season; 72ºF [22.2ºC] dry-bulb temperature during heating season.
- West-facing wall, 12 ft. high × 45 ft. long [3.7 m × 13.7 m], constructed of 8 in. [203.2 mm] lightweight concrete block with aluminum siding on the outside, 3.5 in. [88.9 mm] of insulation, and ½ in. [12.7 mm] gypsum board on the inside.
- Eight clear, double-pane (¼ in. [6.4 mm]) windows mounted in aluminum frames. Each window is 4 ft. wide × 5 ft. high [1.2 m × 1.5 m].
- Flat, 45 ft. × 60 ft. [13.7 m × 18.3 m] roof constructed of 4 in. [100 mm] concrete with 3.5 in. [90 mm] insulation and steel decking.

- Space is occupied from 8:00 a.m. until 5:00 p.m. by 18 people doing moderately active work.
- Fluorescent lighting in space = 2 W/ft^2 [21.5 W/m^2].
- Computers and office equipment in space = 0.5 W/ft^2 [5.4 W/m^2], plus one coffee maker.

In order to simplify this example, we will assume that, with the exception of the west-facing exterior wall, room 101 is surrounded by spaces that are air conditioned to the same temperature as this space.

Outdoor Design Conditions

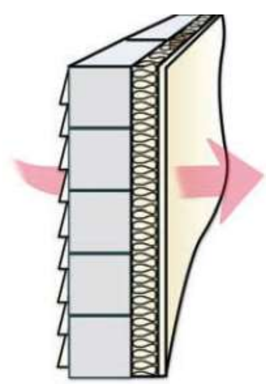
Earlier we discussed the indoor conditions required for thermal comfort. The next step toward estimating the cooling load of a space is to determine the highest, frequently-occurring outdoor air temperature. In the summer, for example, when the temperature outside is high, heat transfers from outdoors to indoors, thus contributing to the heat gain of the space.

Obviously, HVAC systems would be greatly oversized if cooling load calculations were based on the most extreme outdoor temperature ever recorded for the location. Instead, outdoor design temperatures are based on their frequency of occurrence.

0.4%		1%		2%	
DB	WB	DB	WB	DB	WB
95°F [35°C]	76°F [25°C]	93°F [34°C]	75°F [24°C]	90°F [32°C]	74°F [23°C]

The table shows the cooling outdoor design conditions for our example, includes three columns of dry-bulb temperatures and corresponding wet-bulb temperatures. The first column heading, 0.4%, means that the dry-bulb temperature exceeds 95ºF [35ºC] for only 0.4% of all of the hours in an average year (or 35 hours). Also, 76ºF [25ºC] is the wet-bulb temperature that occurs most frequently when the dry-bulb temperature is 95ºF [35ºC]. The second column heading, 1%, means that the temperature exceeds 93ºF [34ºC] for only 1% of all of the hours in an average year (or 87.6 hours). When the dry-bulb temperature is 93ºF [34ºC], the wet-bulb temperature that occurs most frequently is 75ºF [24ºC]. For our example, we will use the more severe 95ºF [35ºC] dry bulb and 76ºF [25ºC] wet bulb for the outdoor design conditions.

Heat Conduction through Surfaces



Conduction is the process of transferring heat through a solid, such as a wall, roof, floor, ceiling, window, or skylight. Heat naturally flows by conduction from a higher temperature to a lower temperature. Generally, when estimating the maximum cooling load for a space, the temperature of the air outdoors is higher than the temperature of the air indoors.

We will focus on the most common conduction heat gains to a space: through the roof, external walls, and windows.

Conduction through a Shaded Wall

Assume that the surface is completely shaded at all times. With this assumption, the amount of heat transferred through the surface is a direct result of the temperature difference between the space and outdoors.

The amount of heat transferred through a shaded exterior surface depends on the area of the surface, the overall heat transfer coefficient of the surface, and the dry-bulb temperature difference from one side of the surface to the other.

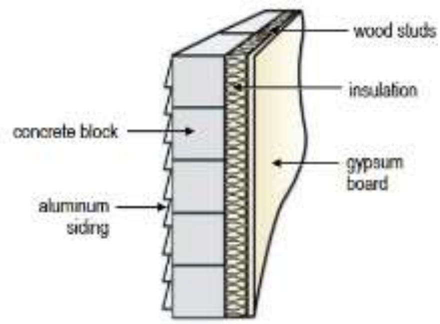
The equation used to predict the heat gain by conduction is:

$$Q = U \times A \times \Delta T$$

Where,
Q = heat gain by conduction, Btu/hr. [W]
U = overall heat-transfer coefficient of the surface, Btu/hr. • ft^2 • °F [W/m^2 • °K]
A = area of the surface, ft^2 [m^2]
ΔT = dry-bulb temperature difference across the surface, ºF [°C]
In the case of a shaded exterior surface, this temperature difference is the design outdoor dry-bulb temperature (T_o minus the desired indoor dry-bulb temperature (T_i).

U-factor

The U-factor is the overall heat transfer coefficient; it describes the rate at which heat will be transferred through the structure. Walls and roofs are typically made up of layers of several materials. The U-factor for a specific wall or roof is calculated by summing the thermal resistances (R-values) of each of these layers and then taking the inverse.



The wall in our example space is comprised of:

- aluminum siding (R = 0.61 ft^2 • hr. • ºF/Btu [0.11 • m^2 • ºK/W])
- 8 in. [200 mm] lightweight concrete block (R = 2.0 [0.35])
- 3.5 in. [90 mm] of fiberglass insulation (R = 13.0 [2.29])
- ½ in. [12.7 mm] gypsum board (R = 0.45 [0.08])

Additionally, there is a film of air on the outside surface of the wall (R = 0.25 [0.044], assuming air moving at 7.5 mph [12 km/hr.] during the summer) and another film of air on the inside surface of the wall (R = 0.68 [0.12], assuming still air).

U-factor for Example Wall

thermal resistance (R)		
$R_{outdoor\text{-}air\ film}$	0.25	[0.04]
R_{siding}	0.61	[0.11]
$R_{concrete\ block}$	2.00	[0.35]
$R_{insulation}$	13.00	[2.29]
$R_{gypsum\ board}$	0.45	[0.08]
$R_{indoor\text{-}air\ film}$	0.68	[0.12]
R_{total}	16.99	[2.99]

$$U = \frac{1}{R_{total}}$$

$$U = 0.06\ \text{Btu/hr}\cdot\text{ft}^2\cdot{}^\circ\text{F}$$

$$[\,U = 0.33\ \text{W/m}^2\cdot{}^\circ\text{K}\,]$$

The U-factor of this wall is calculated by adding the thermal resistances of each of these layers and then taking the inverse.

$$U = \frac{1}{R_{\substack{outdoor\\air\ film}} + R_{siding} + R_{\substack{concrete\\block}} + R_{insulation} + R_{\substack{gypsum\\board}} + R_{\substack{indoor\\air\ film}}}$$

$$U = \frac{1}{0.25 + 0.61 + 2.0 + 13 + 0.45 + 0.68} = \frac{1}{16.99} = 0.06\ \text{Btu/hr} \bullet \text{ft}^2 \bullet {}^\circ\text{F}$$

$$\left[U = \frac{1}{0.04 + 0.11 + 0.35 + 2.29 + 0.08 + 0.12} = \frac{1}{2.99} = 0.33\ \text{W/m}^2 \bullet {}^\circ\text{K}\right]$$

The U-factor of the roof in our example is calculated in a similar manner.

$$U = \frac{1}{R_{\substack{outdoor \\ air\ film}} + R_{\substack{built\ up \\ roofing}} + R_{insulation} + R_{\substack{lightweight \\ concrete}} + R_{\substack{metal \\ decking}} + R_{\substack{indoor \\ air\ film}}}$$

$$U = \frac{1}{0.25 + 0.33 + 13 + 3.12 + 0 + 0.92} = \frac{1}{17.62} = 0.057\ Btu/hr \bullet ft^2 \bullet {}^\circ F$$

$$\left[U = \frac{1}{0.04 + 0.06 + 2.29 + 0.54 + 0 + 0.16} = \frac{1}{3.09} = 0.323\ W/m^2 \bullet {}^\circ K\right]$$

Conduction heat gain through the west-facing wall (assume shaded at all times):

- $Ufactor = 0.06\ Btu/hr \bullet ft^2 \bullet {}^\circ F\ [0.33\ W/m^2 \bullet {}^\circ K]$
- $Total\ area\ of\ wall + windows = 12\ ft \times 45\ ft = 540\ ft^2\ [3.7\ m \times 13.7\ m = 50.7\ m^2]$
- $Area\ of\ windows = 8\ windows \times (4\ ft \times 5\ ft) = 160\ ft^2\ [8 \times (1.2\ m \times 1.5\ m) = 14.4\ m^2]$
- $Net\ area\ of\ wall = 540 - 160 = 380\ ft^2\ [50.7 - 14.4 = 36.3\ m^2]$
- $\Delta T = outdoor\ temperature\ (95^\circ F\ [35^\circ C]) - indoor\ temperature\ (78^\circ F\ [25.6^\circ C])$

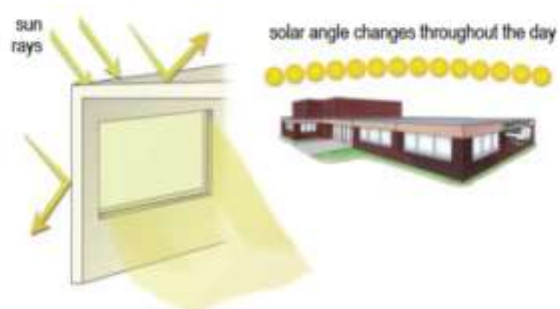
$$Q = U \times A \times \Delta T$$

$$Q = 0.06 \times 380 \times (95 - 78) = 388\ Btu/hr$$

$$[Q = 0.33 \times 36.3 \times (35 - 25.6) = 113\ W]$$

- **Sunlit Surfaces**

Radiant heat is similar to light, in that it travels in a straight line and can be reflected from a bright surface. Both light and radiant heat can pass through a transparent surface (such as glass), yet neither can pass directly through an opaque or non-transparent surface (such as a brick wall). When the sun's rays strike an opaque surface a certain amount of radiant heat energy is transferred to that surface, resulting in an increase in the surface temperature. The amount of heat transferred depends primarily on the color and smoothness of the surface, and the angle at which the sun's rays strike the surface.

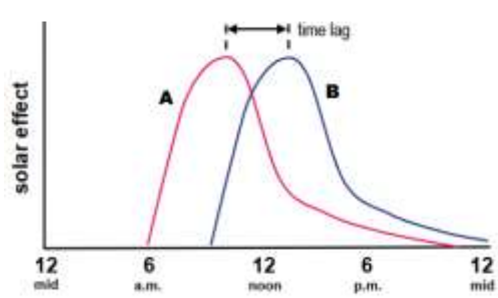


When the sun's rays strike the surface at a 90º angle, the maximum amount of radiant heat energy is transferred to that surface. When the same rays strike that same surface at a lesser angle, less radiant heat energy is transferred to the surface. The angle at which the sun's rays strike a surface depends upon the latitude, the time of day, and the month of the year. Due to the rotation of the earth throughout the day, and the earth orbiting the sun throughout the year, the angle at which the sun's rays strike a surface of a building is constantly changing. This varies the intensity of the solar radiation on an exterior surface of a building, resulting in a varying amount of solar heat transferred to the surface throughout the day and throughout the year.

- **Time Lag**

Time lag is the time required for heat to be transferred through a structure into the space.

The walls and roof that make up a building's envelope have the capacity to store heat energy. This property delays the heat transfer from outdoors to the space.



Curve A shows the magnitude of the solar effect on the exterior wall. Curve B shows the resulting heat that is transferred through the wall into the space. This delay in the heat gain to the space is the time lag. The magnitude of this time lag depends on:

- The materials used to construct the particular wall or roof.
- Their capacity to store heat.

Conduction through Sunlit Surfaces

A factor called the cooling load temperature difference (CLTD) is used to account for the added heat transfer due to the sun shining on exterior walls, roofs, and windows, and the capacity of the wall and roof to store heat. The CLTD is substituted for ΔT in the equation to estimate heat transfer by conduction.

$$Q = U \times A \times CLTD$$

This particular table includes CLTD factors for a west-facing wall similar to the type used in our example building. It should be noted that the data in this table are based on the following assumptions:

- 78ºF [25.6ºC] indoor air
- 95ºF [35ºC] maximum outdoor air
- Average outdoor daily temperature range of 21ºF [11.7ºC]
- 21st day of July
- 40º north latitude
- Dark-colored surface

CLTD Factors for West-Facing Wall

hour	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
CLTD (°F)	35	30	25	21	17	14	11	8	7	6	6	7	8	10	12	16	22	30	37	44	48	48	45	41
CLTD (°C)	19	17	14	12	9	8	6	4	4	3	3	4	4	6	7	9	12	17	21	24	27	27	25	23

The wall in our example, at 4 p.m. (Hour 17 in this table), the CLTD for a west-facing wall of this type is 22ºF [12°C]. This means that, even though the actual dry-bulb temperature difference is only 17ºF (95ºF – 78ºF) [9.4ºC (35ºC – 25.6ºC)], the sun shining on the outer surface of this wall increases the "effective temperature difference" to 22ºF [12ºC].

Notice that the CLTD increases later in the day, and then begins to decrease in the evening as the stored heat is finally transferred from the wall into the space.

Using CLTD instead of ΔT, we will determine the heat gain, by conduction, through the west-facing wall and the roof. The U-factors are the same as those calculated on Figure 20.

- Conduction heat gain through the west-facing sunlit wall:
  - $Ufactor = 0.06\ Btu/hr \bullet ft^2 \bullet °F\ [0.33\ W/m^2 \bullet °K]$
  - $Net\ area\ of\ wall = 380\ ft^2\ [36.3\ m^2]$
  - $CLTD_{hour=17} = 22ºF\ [12°C]$

$$Q = 0.06 \times 380 \times 22 = 502\ Btu/hr$$

$$[Q = 0.33 \times 36.3 \times 12 = 144\ W]$$

The roof in our example building is based on assumptions similar to the CLTD table for walls. At Hour 17, the CLTD for a flat roof of this type is 80ºF [44°C].

- Conduction heat gain through the roof
  - $Ufactor = 0.057\ Btu/hr \bullet ft^2 \bullet °F\ [0.323\ W/m^2 \bullet °K]$
  - $Area\ of\ roof = 45\ ft \times 60\ ft = 2{,}700\ ft^2\ [13.7\ m \times 18.3\ m = 250.7\ m^2]$
  - $CLTD_{hour=17} = 80ºF\ [44°C]$

$$Q = 0.057 \times 2{,}700 \times 80 = 12{,}312\ Btu/hr$$
$$[Q = 0.323 \times 250.7 \times 44 = 3{,}563\ W]$$

- **U-factors for Windows**

Estimating the heat gain by conduction through a window is very similar to walls and roofs.
The windows in our example are double-pane windows with a ¼-inch [6.4 mm] air space between the panes. Assuming that the windows are fixed (not operable), with aluminum frames and a thermal break, the U-factor is 0.63 Btu/hr. • ft^2 • °F [3.56 W/m^2 • °K].
Using this U-factor, we will determine the heat gain, by conduction, through the eight west-facing windows.

U-factors for Windows

	fixed frames, vertical installation		
	aluminum without thermal break	aluminum with thermal break	wood/vinyl
single glazing			
1/8 in. [3.2 mm] glass	1.13 [6.42]	1.07 [6.07]	0.98 [5.55]
double glazing			
1/4 in. [6.4 mm] air space	0.69 [3.94]	0.63 [3.56]	0.56 [3.17]
1/2 in. [12.8 mm] air space	0.64 [3.61]	0.57 [3.22]	0.50 [2.84]
1/4 in. [6.4 mm] argon space	0.66 [3.75]	0.59 [3.37]	0.52 [2.98]
1/2 in. [12.8 mm] argon space	0.61 [3.47]	0.54 [3.08]	0.48 [2.70]
triple glazing			
1/4 in. [6.4 mm] air spaces	0.55 [3.10]	0.48 [2.73]	0.41 [2.33]
1/2 in. [12.8 mm] air spaces	0.49 [2.76]	0.42 [2.39]	0.35 [2.01]
1/4 in. [6.4 mm] argon spaces	0.51 [2.90]	0.45 [2.54]	0.38 [2.15]
1/2 in. [12.8 mm] argon spaces	0.47 [2.66]	0.40 [2.30]	0.34 [1.91]

CLTD factor for glass is also based on similar assumptions as the CLTD tables for walls and roofs. At Hour 17, the CLTD for a glass window is 13ºF [7°C].

- Conduction heat gain through the west-facing windows:

$Ufactor = 0.63\ Btu/hr \bullet ft^2 \bullet °F\ [3.56\ W/m^2 \bullet °K]$

$Total\ area\ of\ glass = 8\ windows \times (4\ ft \times 5\ ft) = 160\ ft^2$

$[8 \times (1.2\ m \times 1.5\ m) = 14.4\ m^2]$

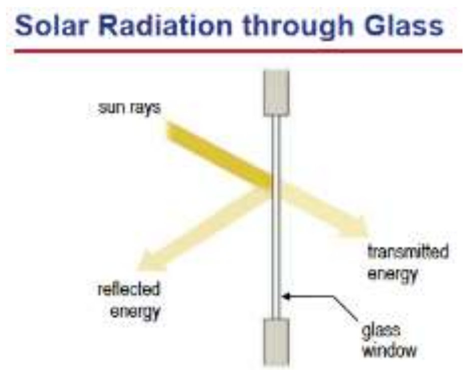
$CLTD_{hour=17} = 13ºF\ [7°C]$

$$Q = 0.63 \times 160 \times 13 = 1{,}310\ Btu/hr$$
$$[Q = 3.56 \times 14.4 \times 7 = 359\ W]$$

Lecture 8: Cooling Load Estimation (2)

- **Solar Radiation through Glass**

Previously, we estimated the heat transferred through glass windows by the process of conduction. A large part of the solar heat energy that shines on a window or skylight is radiated through the glass and transmitted directly into the space. The amount of solar heat radiated through the glass depends primarily on



- The reflective characteristics of the glass.
- The angle at which the sun's rays strike the surface of the glass.
- ✓ While glass windows of double- or triple-pane construction do an excellent job of reducing heat transfer by conduction, they do not appreciably reduce the amount of solar radiation directly into a space. To limit the amount of solar radiation entering the space, heat-absorbing glass, reflective glass, or internal or external shading devices can be used.

The equation used to predict the solar heat gain through glass is:

$$Q = A \times SC \times SCL$$

where,

„ Q = heat gain by solar radiation through glass, Btu/hr. [W]
„ A = total surface area of the glass, ft^2 [m^2]
„ SC = shading coefficient of the window, dimensionless
„ SCL = solar cooling load factor, Btu/hr. • ft^2 [W/m^2]

- The solar cooling load (SCL) factor is used to estimate the rate at which solar heat energy radiates directly into the space, heats up the surfaces and furnishings, and is later released to the space as a sensible heat gain. Similar to CLTD, the SCL factor is used to account for the capacity of the space to absorb and store heat.

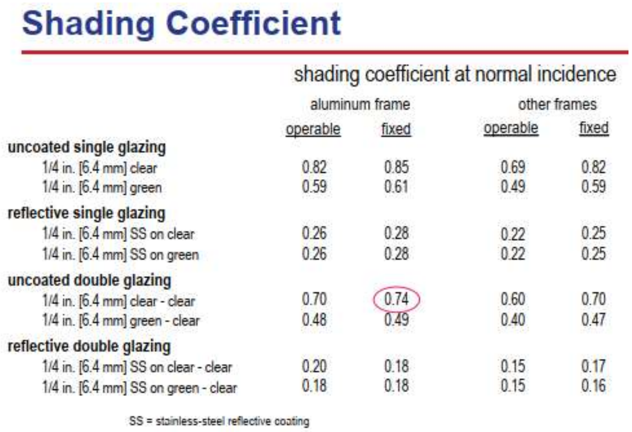
The value of SCL is based on several factors,

Solar Cooling Load Factor

- Direction that the window faces.
- Time of day.
- Month.
- Latitude.
- Construction of interior partition walls.
- Type of floor covering.
- Existence of internal shading devices.

The space in our example is based on the 21st day of July and 40º north latitude. At Hour 17, the SCL for the west-facing windows in our example space is 192 $Btu/hr \bullet ft^2$ [605 W/m^2].

- Shading Coefficient (SC) is an expression used to define how much of the radiant solar energy, that strikes the outer surface of the window, is actually transmitted through the window and into the space. The shading coefficient for a particular window is determined by comparing its reflective properties to a standard reference window. The table on this slide includes shading coefficients for common window systems. When the value for the shading coefficient decreases, more of the sun's rays are reflected by the outer surface of the glass.


Shading Coefficient

	shading coefficient at normal incidence			
	aluminum frame		other frames	
	operable	fixed	operable	fixed
uncoated single glazing				
1/4 in. [6.4 mm] clear	0.82	0.85	0.69	0.82
1/4 in. [6.4 mm] green	0.59	0.61	0.49	0.59
reflective single glazing				
1/4 in. [6.4 mm] SS on clear	0.26	0.28	0.22	0.25
1/4 in. [6.4 mm] SS on green	0.26	0.28	0.22	0.25
uncoated double glazing				
1/4 in. [6.4 mm] clear - clear	0.70	0.74	0.60	0.70
1/4 in. [6.4 mm] green - clear	0.48	0.49	0.40	0.47
reflective double glazing				
1/4 in. [6.4 mm] SS on clear - clear	0.20	0.18	0.15	0.17
1/4 in. [6.4 mm] SS on green - clear	0.18	0.18	0.15	0.16

SS = stainless-steel reflective coating

The windows in our example space are constructed of two panes of ¼-inch [6.4 mm] clear glass with an air space between the panes. The glass is mounted in an aluminum frame and the windows are fixed (not operable). The SC for this type of window is 0.74.

Solar radiation heat gain through the windows on the west-facing wall:

„ $Total\ area\ of\ glass = 8\ windows \times (4\ ft \times 5\ ft) = 160\ ft^2\ [8 \times (1.2\ m \times 1.5\ m) = 14.4\ m^2]$

„ $SC = 0.74$

„ $SCL_{hour=17} = 192\ Btu/hr \bullet ft^2\ [605\ W/m^2]$

$$Q = 160 \times 0.74 \times 192 = 22{,}733\ Btu/hr$$

$$[Q = 14.4 \times 0.74 \times 605 = 6{,}447\ W]$$

- Shading Devices

Installing internal shading devices, such as venetian blinds, curtains, or drapes, can reduce the amount of solar heat energy passing through a window. The effectiveness of these shading devices depends on their ability to reflect the incoming solar radiation back through the window, before it is converted into heat inside the space. Light-colored blinds or drapes lined with light-colored materials, therefore, are more effective than dark-colored shading devices. The type of internal shading device used affects the shading coefficient of the window-and-shading-device combination.

External shading devices, such as overhangs, vertical fins, or awnings, can also reduce the amount of solar heat energy passing through a window. They can be used to reduce the area of the glass surface that is actually impacted by the sun's rays.

- **Internal Heat Gains**

The next component of the space cooling load is the heat that originates within the space. Typical sources of internal heat gain are people, lights, cooking processes, and other heat-generating equipment, such as motors, appliances, and office equipment. While all of these sources contribute sensible

heat to the space, people, cooking processes, and some appliances (such as a coffee maker) also contribute latent heat to the space.

- Heat Generated by People

People generate more heat than is needed to maintain body temperature. This surplus heat is dissipated to the surrounding air in the form of sensible and latent heat. The amount of heat released by the body varies with age, physical size, gender, type of clothing, and level of physical activity.

The heat gains are adjusted to account for the normal percentages of men, women, and children in each type of space.

Heat Generated by People

level of activity	sensible heat gain	latent heat gain
moderately active work (office)	250 Btu/h [75 W]	200 Btu/h [55 W]
standing, light work, or walking (store)	250 Btu/h [75 W]	200 Btu/h [55 W]
light bench work (factory)	275 Btu/h [80 W]	475 Btu/h [140 W]
heavy work (factory)	580 Btu/h [170 W]	870 Btu/h [255 W]
athletics (gymnasium)	710 Btu/h [210 W]	1,090 Btu/h [315 W]

The equations used to predict the sensible and latent heat gains from people in the space are:

$$Q_S = number\ of\ people \times sensible\ heat\ gain/person \times CLF$$
$$Q_L = number\ of\ people \times latent\ heat\ gain/person$$

Where,

- Q_S = sensible heat gain from people, Btu/hr. [W]
- Q_L = latent heat gain from people, Btu/hr. [W]

CLF = cooling load factor, dimensionless

The cooling load factor (CLF) is used to account for the capacity of the space to absorb and store heat. Some of the sensible heat generated by people is absorbed and stored by the walls, floor, ceiling, and furnishings of the space, and released at a later time. Similar to heat transfer by conduction through an external wall, the space can therefore experience a time lag between the time that the sensible heat is originally generated and the time that it actually contributes to the space cooling load. For heat gain from people, the value of CLF depends on

1) The construction of the interior partition walls in the space,
2) The type of floor covering,
3) The total number of hours that the space is occupied, and
4) The number of hours since the people entered the space.

CLF Factors for People

total hours in space	hours after people enter space: 1	2	3	4	5	6	7	8	9	10	11	12
2	0.65	0.74	0.16	0.11	0.08	0.06	0.05	0.04	0.03	0.02	0.02	0.01
4	0.65	0.75	0.81	0.85	0.24	0.17	0.13	0.10	0.07	0.06	0.04	0.03
6	0.65	0.75	0.81	0.85	0.89	0.91	0.29	0.20	0.15	0.12	0.09	0.07
8	0.65	0.75	0.81	0.85	0.89	0.91	0.93	0.95	0.31	0.22	0.17	0.13
10	0.65	0.75	0.81	0.85	0.89	0.91	0.93	0.95	0.96	0.97	0.33	0.24

The table to the right shows that one hour after people enter the space, 35% (1– 0.65) of the sensible heat gain from the people is absorbed by the surfaces and furnishings in the space, and 65% is the actual cooling load in the space. Following the table to the right, however, you see that, as the people are in the space for a longer period of time, the surfaces and furnishings of the space can no longer absorb as much heat, and they release the heat that was absorbed earlier in the day. For example, if the people enter the space at 8 a.m. and remain for a total of 8 hours, at 2 p.m. (6 hours after entering) 91% of the sensible heat gain from the people is seen as a cooling load in the space. Only 9% is absorbed by the surfaces and furnishings of the space.

If the space is not maintained at a constant temperature during the 24-hour period, however, the CLF is assumed to equal 1.0. Most air-conditioning systems designed for non-residential buildings either shut the system off at night or raise the temperature set point to reduce energy use. Thus, it is uncommon to use a CLF other than 1.0 for the cooling load due to people.
Determine the internal heat gain from people in our example space. Based on the table, people participating in moderately active office work generate 250 Btu/hr. [75 W] sensible heat and 200 Btu/hr. [55 W] latent heat.

Internal heat gain from people:

$Number\ of\ people = 18$

$Sensible\ heat\ gain/person = 250\ Btu/hr\ [75\ W]$

$Latent\ heat\ gain/person = 200\ Btu/hr\ [55\ W]$

$CLF = 1.0\ (because\ the\ space\ temperature\ set\ point\ is\ increased\ at\ night)$

$Q_S = 18\ people \times 250\ Btu/hr\ per\ person \times 1.0 = 4{,}500\ Btu/hr$

$[Q_S = 18\ people \times 75\ W\ per\ person \times 1.0 = 1{,}350\ W]$

$Q_L = 18\ people \times 200\ Btu/hr\ per\ person = 3{,}600\ Btu/hr$

$[Q_L = 18\ people \times 55\ W\ per\ person = 990\ W]$

Heat Gain from Lighting

Heat generated by lights in the space is a significant contribution to the cooling load. For example, a 120-watt light fixture generates 410 Btu/hr. [120 W] of heat—approximately the same amount of heat gain generated by an average office worker.
The equation used to estimate the heat gain from lighting is:

$$Q = watts \times 3.41 \times ballast\ factor \times CLF$$
$$[Q = watts \times ballast\ factor \times CLF]$$

Where,
Q = sensible heat gain from lighting, Btu/hr. [W]
Watts = total energy input to lights, W
3.41 = conversion factor from W to Btu/hr. (when using I-P units)
Ballast factor = 1.2 for fluorescent lights, 1.0 for incandescent lights
CLF = cooling load factor, dimensionless
Similar to the sensible heat gain from people, a cooling load factor (CLF) can be used to account for the capacity of the space to absorb and store the heat generated by the lights. If the lights are left on 24 hours a day, or if the air- conditioning system is shut off or set back at night, the CLF is assumed to be equal to 1.0.
Next, determine the internal heat gain from lighting in our example space.

Internal heat gain from lighting:

$Amount\ of\ lighting\ in\ space = 2\ W/ft^2\ [21.5\ W/m^2]$

$Floor\ area = 45\ ft \times 60\ ft = 2{,}700\ ft^2\ [13.7\ m \times 18.3\ m = 250.7\ m^2]$

$Total\ lighting\ energy = 2\ W/ft^2 \times 2{,}700\ ft^2 = 5{,}400\ W$

$[21.5\ W/m^2 \times 250.7\ m^2 = 5{,}400\ W]$

$Ballast\ factor = 1.2\ (fluorescent\ lights)$

$CLF = 1.0\ (because\ the\ space\ temperature\ set\ point\ is\ increased\ at\ night)$

$$Q = 5{,}400 \times 3.41 \times 1.2 \times 1.0 = 22{,}097\ Btu/hr$$
$$[Q = 5{,}400 \times 1.2 \times 1.0 = 6{,}480\ W]$$

Heat Generated by Equipment

Using this table, we estimate that the coffee maker contributes 3,580 Btu/hr. [1,050 W] of sensible heat and 1,540 Btu/hr. [450 W] of latent heat to our example space. Additionally, we are told that there are 0.5 W/ft^2 [5.4 W/m^2] of computers and other office equipment in the space (floor area = 2,700 ft^2 [250.7 m^2]).

Therefore, the internal heat gain from computers and office equipment is:

Heat Generated by Equipment

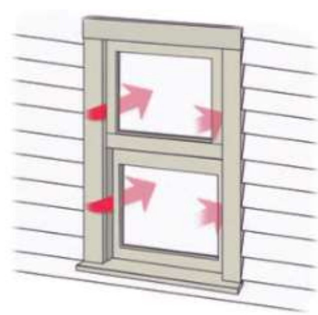
equipment	sensible heat gain	latent heat gain
coffee maker	3,580 Btu/h [1,050 W]	1,540 Btu/h [450 W]
printer (letter quality)	1,000 Btu/h [292 W]	
typewriter	230 Btu/h [67 W]	

$$Sensible\ heat\ gain\ =\ 0.5\ W/ft^2\ \times\ 2{,}700\ ft^2\ \times\ 3.41\ Btu/hr/W\ =\ 4{,}604\ Btu/hr.$$

$$[5.4\ W/m^2\ \times\ 250.7\ m^2\ =\ 1{,}354\ W]$$

Similar to the sensible heat gain from people and lighting, tables of cooling load factors (CLF) can be used to refine this estimate. The CLF is assumed to be equal to 1.0. In our example, the CLF is 1.0 because the space temperature set point is increased at night.

Infiltration



In a typical building, air leaks into or out of a space through doors, windows, and small cracks in the building envelope. Air leaking into a space is called infiltration. During the cooling season, when air leaks into a conditioned space from outdoors, it can contribute to both the sensible and latent heat gain in the space because the outdoor air is typically warmer and more humid than the indoor air. There are three methods commonly used to estimate infiltration airflow.

- Air change method
- Crack method
- Effective leakage-area method

The air change method is the easiest, but may be the least accurate of these methods. It involves estimating the number of air changes per hour that can be expected in spaces of a certain construction quality. Using this method, the quantity of infiltration air is estimated using the equation:

$$infiltration\ airflow\ =\ (volume\ of\ space\ \times\ air\ change\ rate)\ \div\ 60$$

$$[infiltration\ airflow\ =\ (volume\ of\ space\ \times\ air\ change\ rate)\ \div\ 3{,}600]$$

Where,

Infiltration airflow = quantity of air infiltrating into the space, cfm [m^3/s]
Volume of space = length × width × height of space, ft^3 [m^3]
Air change rate = air changes per hour
60 = conversion from hours to minutes
3,600 = conversion from hours to seconds

The crack method is a little more complex and is based upon the average quantity of air known to enter through cracks around windows and doors when the wind velocity is constant. The effective leakage-area method takes wind speed, shielding, and “stack effect” into account, and requires a very detailed calculation.

The table below includes estimates for infiltration using the air change method. Assuming that the space in our example is of average construction and kept at a positive pressure relative to the outdoors, we estimate 0.3 air changes/hr. of infiltration.

$$Volume\ of\ space = 45\ ft \times 60\ ft \times 12\ ft = 32{,}400\ ft^3$$
$$[13.7\ m \times 18.3\ m \times 3.7\ m = 927.6\ m^3]$$

Neutral pressure, poor construction	1.0
Neutral pressure, average construction	0.6
Neutral pressure, tight construction	0.3
Pressurized, poor construction	0.5
Pressurized, average construction	0.3
Pressurized, tight construction	0.0

$$Infiltration\ air\ flow = \frac{32400 \times 0.3}{60} = 162\ cfm$$

$$Infiltration\ air\ flow = \frac{927.6 \times 0.3}{3600} = 0.077\ m^3/s$$

The equation used to estimate the sensible heat gain from infiltration is:

$$Q_s = 1.085 \times airflow \times \Delta T$$
$$Q_s = 1210 \times airflow \times \Delta T$$

„ Q_S = sensible heat gain from infiltration, Btu/hr. [W]
„ 1.085 [1,210] = product of density and specific heat, Btu • min/hr. • ft^3 • ºF [J/m^3 • ºK]
„ Airflow = quantity of air infiltrating the space, cfm [m3/s]
„ ΔT = design outdoor dry-bulb temperature minus the desired indoor dry-bulb temperature, ºF [ºC]

The equation used to estimate the latent heat gain from infiltration is:

$$Q_L = 0.7 \times airflow \times \Delta W$$
$$Q_L = 3010 \times airflow \times \Delta W$$

Where,
„ Q_L = latent heat gain from infiltration, Btu/hr. [W]
„ 0.7 [3,010] = latent heat factor, Btu • min • lb./hr. • ft3 • gr [J • kg/m3 • g]
„ Airflow = quantity of air infiltrating the space, cfm [m3/s]
„ ΔW = design outdoor humidity ratio minus the desired indoor humidity ratio, grains of water/lb. of dry air [grams of water/kg of dry air]

Heat gain from infiltration:

„ Infiltration airflow = 162 cfm [0.077 m^3/s]
- Outdoor conditions: 95ºF [35ºC] dry bulb and 76ºF [25ºC] wet bulb results in Wo = 105 grains of water/lb. dry air [15 grams of water/kg dry air]
- Indoor conditions: 78ºF [25.6ºC] dry bulb and 50% relative humidity results in Wi = 70 grains of water/lb. dry air [10 grams of water/kg dry air]

$$Q_S = 1.085 \times 162 \times (95 - 78) = 2{,}988\ Btu/hr.$$
$$[Q_S = 1{,}210 \times 0.077 \times (35 - 25.6) = 876\ W]$$

$$Q_L = 0.7 \times 162 \times (105 - 70) = 3{,}969\ Btu/hr$$
$$[Q_L = 3{,}010 \times 0.077 \times (15 - 10) = 1{,}159\ W]$$

Realize that 1.085 and 0.7 [1,210 and 3,010] are not constants, but are derived from properties of air at "standard" conditions (69°F [21°C] dry air at sea level).
Air at other conditions and elevations will cause these factors to change.

- Density = 0.075 lb./ft^3 [1.2 kg/m^3]
- Specific heat = 0.24 Btu/lb. • °F [1,004 J/kg • °K]
- Latent heat of water vapor = 1,076 Btu/lb. [2,503 kJ/kg]
- 0.075 × 0.24 × 60 min/hr. = 1.085 [1.2 × 1,004 = 1,210]

$$\frac{0.075 \times 1076 \times 60 min/hr}{7000\ grains/lb} = 0.7 \left[\frac{1.2 \times 2503 \times 1000 J/kJ}{1000\ g/kg} = 3010\right]$$

This completes the estimation of the components of the cooling load for the space.

In addition to these space cooling loads, there are other loads that affect the cooling coil in the building HVAC system. These include the load of the outdoor air, deliberately brought into the building for ventilation purposes, and heat generated by the fans in the system. These loads are added to the space load to determine the total cooling load for the building. Estimating these additional components is necessary to properly size the cooling coil for the system.

Summary of Space Cooling Loads

space load components	sensible load Btu/hr [W]	latent load Btu/hr [W]
conduction through roof	12,312 [3,563]	
conduction through exterior wall	502 [144]	
conduction through windows	1,310 [359]	
solar radiation through windows	22,733 [6,447]	
people	4,500 [1,350]	3,600 [990]
lights	22,097 [6,480]	
equipment	8,184 [2,404]	1,540 [450]
infiltration	2,988 [876]	3,969 [1,159]
total space cooling load	**74,626 [21,623]**	**9,109 [2,599]**

- ## Ventilation

Outdoor air is often used to dilute or remove contaminants from the indoor air. The intentional introduction of outdoor air into a space, through the use of the building's HVAC system, is called ventilation.

It is common to introduce outdoor air through the HVAC system, not only to meet the ventilation needs, but also to maintain a positive pressure (relative to the outdoors) within the building. This positive pressure reduces, or may even eliminate, the infiltration of unconditioned air from outdoors. To pressurize the building, the amount of outdoor air brought in for ventilation must be greater than the amount of air exhausted through central and local exhaust fans.

- ### Outdoor Air Requirements

The amount of outdoor air required for a space is often prescribed by local building codes or industry standards.

In our example, calculating the required quantity of outdoor air involves multiplying the number of people in the space by the 20 cfm (cubic feet per minute) [0.01 m^3/s] of outdoor air required per person in an office space.

Outdoor Air Requirements

type of space	outdoor air (per person)	outdoor air (per ft^2 [m^2])
auditorium	15 cfm [0.008 m^3/s]	
classroom	15 cfm [0.008 m^3/s]	
locker rooms		0.5 cfm [0.0025 m^3/s]
office space	20 cfm [0.01 m^3/s]	
public restrooms	50 cfm [0.025 m^3/s]	
smoking lounge	60 cfm [0.03 m^3/s]	

$$ventilation\ airflow = 18\ people \times 20\ cfm/person = 360\ cfm$$
$$[ventilation\ airflow = 18\ people \times 0.01\ m^3/s/person = 0.18\ m^3/s]$$

The sensible and latent loads from ventilation are calculated using the same equations as for infiltration:

$$Q_S = 1.085 \times airflow \times \Delta T$$
$$[Q_S = 1{,}210 \times airflow \times \Delta T]$$

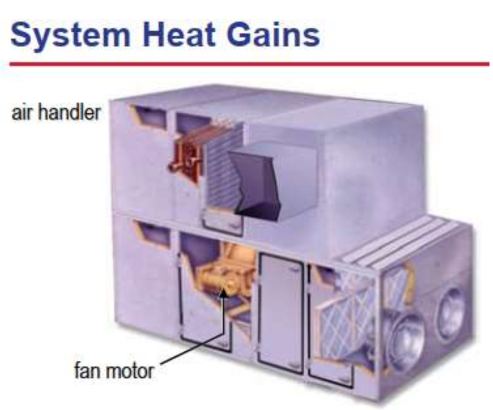
$$Q_L = 0.7 \times airflow \times \Delta W$$
$$[Q_L = 3{,}010 \times airflow \times \Delta W]$$

Cooling load due to the conditioning of ventilation air:
„ Ventilation airflow = 360 cfm [0.18 m^3/s]
„ Outdoor conditions: To = 95ºF [35ºC], Wo = 105 grains of water/lb. dry air [15 grams of water/kg dry air]
„ Indoor conditions: Ti = 78ºF [25.6ºC], Wi = 70 grains of water/lb. dry air [10 grams of water/kg dry air]

$$Q_S = 1.085 \times 360 \times (95 - 78) = 6{,}640\ Btu/hr$$
$$[Q_S = 1{,}210 \times 0.18 \times (35 - 25.6) = 2047\ W]$$

$$Q_L = 0.7 \times 360 \times (105 - 70) = 8{,}820\ Btu/hr$$
$$[Q_L = 3{,}010 \times 0.18 \times (15 - 10) = 2{,}709\ W]$$

System Heat Gains



There may be others sources of heat gain within the HVAC system. One example is the heat generated by fans. When the supply fan, driven by an electric motor, is located in the conditioned airstream, it adds heat to the air.

Heat gain from a fan is associated with three energy conversion losses. Fan motor heat is due to the energy lost in the conversion of electrical energy (energy input to the motor) to mechanical energy (rotation of the motor shaft). It is dissipated as heat from the motor and is represented by the inefficiency of the motor.

$$fan\ motor\ heat\ gain = power\ input\ to\ motor \times (1 - motor\ efficiency)$$

If the fan motor is also located within the conditioned airstream, such as inside the cabinet of an air handler, it is considered an instantaneous heat gain to the airstream. If it is located outside the conditioned airstream, it is considered a heat gain to the space where it is located.

Fan-blade heat gain is due to the energy lost in the conversion of mechanical energy to kinetic energy (moving of the air). It is dissipated as heat from the fan blades, it is considered an instantaneous heat gain to the airstream, and it is represented by the inefficiency of the fan.

$$fan\ blade\ heat\ gain = power\ input\ to\ fan \times (1 - fan\ efficiency)$$

Finally, the remaining (useful) energy input to the fan, the energy used to pressurize the supply duct system, is eventually converted to heat as the air travels through the ductwork. For simplicity, most designers assume that this heat gain occurs at a single point in the system, typically at the location of the fan.

$$duct\ friction\ heat\ gain = power\ input\ to\ fan \times fan\ efficiency$$

- Heat Gain in Ductwork

Another source of heat gain in the system may be heat that is transferred to the conditioned air through the walls of the supply and return ductwork. For example, if the supply ductwork is routed through an unconditioned space, such as a ceiling plenum or an attic, heat can be transferred from the air surrounding the duct to the supply air. For the example used in this clinic, we will assume that fan heat gains and other system heat gains are negligible.

❖ Summary of Cooling Loads

In summary, the total cooling load for our example space is made up of the following components:

- Conduction heat gain from outdoors through the roof and west-facing exterior wall and windows
- Solar radiation heat gain through the west-facing windows
- Internal heat gains from people, lights, office equipment, and a coffee maker in the space
- Heat gain due to hot, humid air infiltrating into the space from outdoors

Summary of Cooling Loads

	sensible load Btu/hr [W]	latent load Btu/hr [W]
conduction through roof	12,312 [3,563]	
conduction through exterior wall	502 [144]	
conduction through windows	1,310 [359]	
solar radiation through windows	22,733 [6,447]	
people	4,500 [1,350]	3,600 [990]
lights	22,097 [6,480]	
equipment	8,184 [2,404]	1,540 [450]
infiltration	2,988 [876]	3,969 [1,159]
total space cooling load	**74,626 [21,623]**	**9,109 [2,599]**
ventilation	6,640 [2,047]	8,820 [2,709]
total coil cooling load	**81,266 [23,670]**	**17,929 [5,308]**

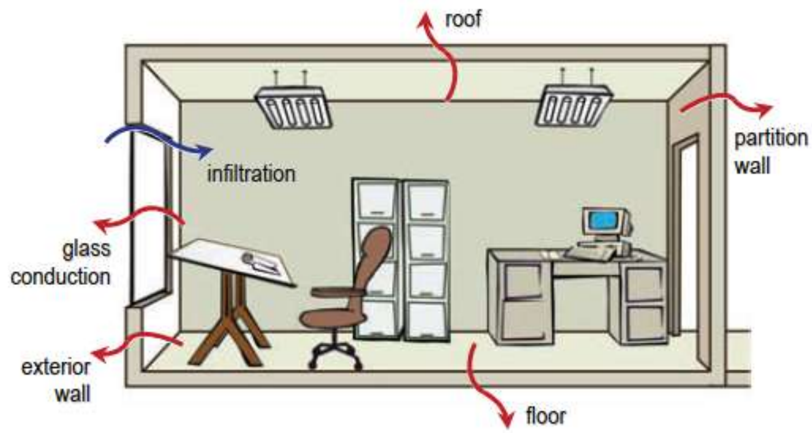
In addition, the cooling coil in the building HVAC system has to cool the outdoor air that is deliberately brought into the building for ventilation purposes.

Lecture 9: Heating Load Estimation

❖ Heating Load Estimation

The space heating load is the rate at which heat must be added to a space in order to maintain the desired conditions in the space, generally a dry-bulb temperature. During this lecture, we will estimate the heating load for the same office space that was used for the example in lecture 7.

Heating Load Components



In general, the estimation of heating loads assumes worst-case conditions for the space. The winter design outdoor temperature is used for determining the conduction heat loss through exterior surfaces. No credit is given for heat gain from solar radiation through glass or from the sun's rays warming the outside surfaces of the building. Additionally, no credit is given for internal heat gains due to people, lighting, and equipment in the space.

The heating load for a space can be made up of many components, including:

- Conduction heat loss to the outdoors through the roof, exterior walls, skylights, and windows.
- Conduction heat loss to adjoining spaces through the ceiling, interior partition walls, and floor.
- Heat loss due to cold air infiltrating into the space from outdoors through doors, windows, and small cracks in the building envelope.

In addition, the heating coil in the building HVAC system has to heat up the outdoor air that is deliberately brought into the building for ventilation purposes.

Outdoor Design Conditions

Similar to the cooling-design outdoor conditions discussed at the beginning of lecture 7, heating-design outdoor conditions for many locations can be found in the 1997 ASHRAE Handbook—Fundamentals.

For our example, we will use the more severe 2°F [-16.7°C] dry-bulb temperature for the outdoor design conditions.

Conduction through Surfaces

The amount of heat loss through a roof, an exterior wall, or a window depends on

1. the area of the surface,
2. the overall heat transfer coefficient of the surface,
3. the dry-bulb temperature difference from one side of the surface to the other.

The equation used to predict the heat loss by conduction is:

$$Q = U \times A \times \Delta T$$

Where,

Q = heat loss by conduction, Btu/hr. [W]

U = overall heat-transfer coefficient of the surface, Btu/hr. • ft^2 • °F [W/m^2 • °K]
A = area of the surface, ft^2 [m^2]
ΔT = desired indoor dry-bulb temperature (Ti) minus the design outdoor dry-bulb temperature (To), ºF [°C]
The U-factors for the roof, wall, and windows will be slightly different during the winter than during the summer. This is due to a change in the outside surface resistance (R = 0.17 versus 0.25 [R = 0.03 versus 0.044]) that is caused by a difference in wind conditions from summer to winter. For simplicity, we will ignore this minor difference and use the U-factors calculated in lecture 7 for the roof, wall, and windows of our example space. Also, realize that in our example the desired indoor dry-bulb temperature during the heating season is 72ºF [22.2°C], different than during the cooling season.

- Conduction heat loss through the west-facing wall:

U-factor for wall = 0.06 Btu/hr. • ft^2 • °F [0.33 W/m^2 • °K]
Net area of wall = 380 ft^2 [36.3 m^2]
ΔT = indoor temperature (72ºF [22.2ºC]) – outdoor temperature (2ºF [16.7ºC])

$$Q = 0.06 \times 380 \times (72 - 2) = 1{,}596\ Btu/hr.$$
$$[Q = 0.33 \times 36.3 \times (22.2 - (-16.7)) = 466\ W]$$

- Conduction heat loss through the roof:

U-factor for roof = 0.057 Btu/hr. • ft^2 • °F [0.323 W/m^2 • °K]
Area of roof = 2,700 ft^2 [250.7 m^2]
ΔT = 70ºF [38.9ºC]

$$Q = 0.057 \times 2{,}700 \times 70 = 10{,}773\ Btu/hr.$$
$$[Q = 0.323 \times 250.7 \times 38.9 = 3{,}150\ W]$$

- Conduction heat loss through the west-facing windows:

U-factor for window = 0.63 Btu/hr. • ft^2 • °F [3.56 W/m^2 • °K]
Total area of glass = 160 ft^2 [14.4 m^2]
ΔT = 70ºF [38.9ºC]

$$Q = 0.63 \times 160 \times 70 = 7{,}056\ Btu/hr.$$
$$[Q = 3.56 \times 14.4 \times 38.9 = 1{,}994\ W]$$

Infiltration and Ventilation

Similar to the cooling season, during the heating season, air may leak in from outdoors through doors, windows, and small cracks in the building envelope. It contributes to the sensible heat loss of the space because the outdoor air is typically colder than the indoor air. Additionally, the outdoor air during the heating season is generally drier than the indoor air. If the building requires humidification, infiltration of cold, dry outdoor air adds to the humidification load. This lecture, however, will only focus on the sensible heat loss due to infiltration and its effect on sizing the sensible heating equipment in the HVAC system.
The equation used to calculate the sensible heat loads due to infiltration and ventilation is the same as shown in lecture 7&8:

$$Q_S = 1.085 \times airflow \times \Delta T$$
$$[Q_S = 1{,}210 \times airflow \times \Delta T]$$

Where,
Q_S = sensible heat load due to infiltration or ventilation, Btu/hr. [W]
1.085 [1,210] = product of density and specific heat, Btu • min/hr. • ft^3 • ºF [J/m^3 • ºK]
Airflow = infiltration or ventilation airflow, cfm [m^3/s]
ΔT = desired indoor dry-bulb temperature minus the design outdoor dry-bulb temperature, ºF [ºC]
Sensible heat loads due to infiltration and the conditioning of ventilation air:

- Infiltration airflow = 162 cfm [0.077 m^3/s]
- Ventilation airflow = 360 cfm [0.18 m^3/s]
- Outdoor dry-bulb temperature: 2ºF [-16.7ºC]
- Indoor dry-bulb temperature: 72ºF [22.2ºC])

Infiltration:

$$Q_S = 1.085 \times 162 \times (72 - 2) = 12{,}304\ Btu/hr.$$
$$[Q_S = 1{,}210 \times 0.077 \times (22.2 - (-16.7)) = 3{,}624\ W]$$

Ventilation:

$$Q_S = 1.085 \times 360 \times 70 = 27{,}342\ Btu/hr.$$
$$[Q_S = 1{,}210 \times 0.18 \times 38.9 = 8{,}472\ W]$$

Summary of Heating Loads

Again, the estimation of heating loads assumes worst-case conditions for the space. No credit is given for solar effects or internal heat gains. The total heating load for our example space is made up of the following components:

- Conduction heat loss through the roof and the west-facing exterior wall and windows.
- Cold air infiltrating into the space from outdoors.

Summary of Heating Loads

	sensible load Btu/hr [W]
conduction through roof	10,773 [3,150]
conduction through exterior wall	1,596 [466]
conduction through windows	7,056 [1,994]
infiltration	12,304 [3,624]
total space heating load	**31,729 [9,234]**
ventilation	27,342 [8,472]
total coil heating load	**59,071 [17,706]**

In addition, the heating coil in the building HVAC system must warm the outdoor air that is deliberately brought into the building for ventilation purposes.
This total heating load, 59,071 Btu/hr. [17,706 W], is used to size the heating coils in the HVAC system. For buildings in cold climates, many system designers choose to apply an additional safety factor to the estimated heating load. This is not the case with the cooling load. The reason

for this additional concern is that the danger of under sizing the heating system may lead to frozen and/or broken water pipes that can cause extensive damage to the building.