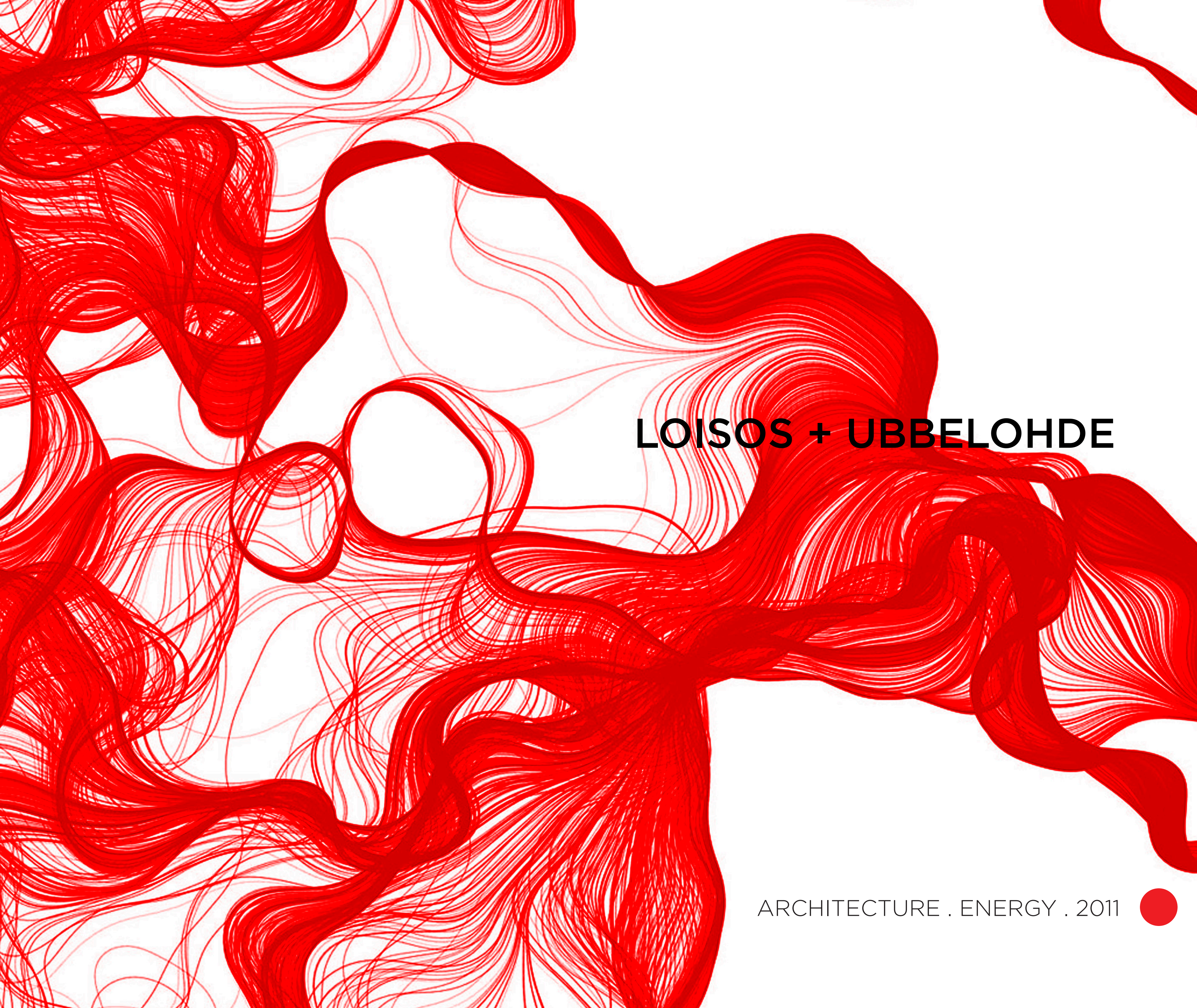

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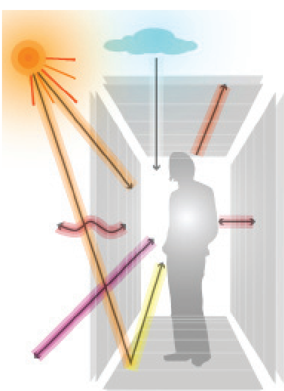
energy • comfort • cost

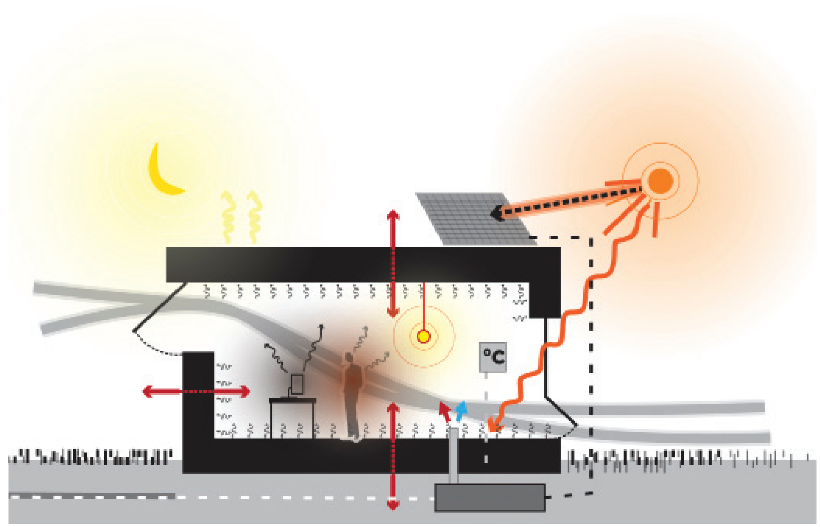
Like a second layer of clothing, architecture is the filter between the ambient environment and the individual. Energy continually flows in and out of a building as light, heat, air, moisture, and sound. When this ambient energy is useful, such as the sun's rays on a cold day, the architectural envelope can allow energy into the building to make the occupants more comfortable. When the energy is not useful, such as the sun's rays on a hot day, the envelope can exclude this energy. When useful ambient energy is not available, such as daylight disappearing with the sunset, we need to rely on stored energy which is most commonly fossil fuels. However, architecture should not rely on stored energy through ignorance or lack of care in the design. A high-performance building that is tuned to maximize the opportunities presented by the ambient environment will reduce energy dependence on the grid and improve occupant comfort.

Our approach to low-energy building design is a three-pronged one: (1) design an envelope that is closely tuned to the climate and building use, (2) supplement ambient energy inputs with efficient machines, and (3) supply energy for those machines with renewable sources. This approach suggests that light and thermodynamics are not only a way of understanding building performance, but an architectural palette that organizes space, exploiting the complex interactions among people, materials, energy, and the environment. High performance design is not only matter organizing energy, but also energy organizing matter.



Architecture as mediator between climate and people

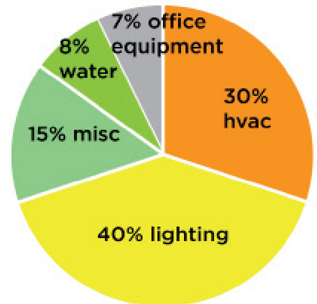
Any energy system can be analyzed in terms of the source, filter, and receptor. For instance, the source of a daylight system is the sun's radiation in the visible spectrum, the filter is a combination of the atmosphere and the architecture, and the receptor is the building occupant. By understanding all components of an energy system we can track how energy flows into and out of a building and design the architecture as a high performing filter.



Energy Systems: climate, envelope, machines, renewables

The climate in which a building is located dictates the availability of ambient energy. Air temperature, humidity, wind speed and direction, illumination, and solar radiation are the primary climatic variables that affect building energy. Climate data,called Typical Meteorological Year (TMY) data, is used in standard practice. These data describe twelve "typical" months aggregated into a year through analysis of measured hourly data and published by reliable organizations. These are not averages; they show actual local weather events such as rainstorms, fog, heat storms, and cold spells. TMY data is currently available for over 2100 international locations.

Daylight is a crucial climatic component and the ways that architecture filters it have far-reaching implications for energy use and occupant comfort. Electric lighting can account for over 40% of the energy consumed by buildings. In all climates daylight is available from the sun and the skydome and can be taken advantage of, lighting interior spaces so that electric lights can be kept off during daylight hours. However, daylight is highly variable and always in flux, making it one of the most provocative aspects of the ambient environment to capture and exploit. Designing for daylight shapes the plan and section of the building. Thin floor plates, such as the 16.5 m width of the NASA Sustainability Base keep workstations near windows. High ceilings with the window head at 3.5 m throw daylight far into the the floor. Skylights light the center of the top floor that is farthest from the curtainwalls. Annual daylight autonomy of this building, a measure of when the electrical lights are turned off during daytime, reaches nearly 100% for most of the workstations.



Typical distribution of energy use in a commercial building.

After daylight, much of the mediation or filtering of the ambient environment that impacts energy use concerns thermal conditions. Temperature, humidity, temperature of the surrounding surfaces and air speed are the primary environmental variables that affect human comfort. The clothing level and metabolism of the occupant also plays a role in thermal comfort. Equally important, but more difficult to account for are the age, gender, psychology of the occupant. Research has shown that people will feel comfortable under a wider range of conditions if they feel that they have control of their environment. This is also true if they are in a naturally ventilated space rather than an air-conditioned one as long as they are habituated to that climate.

Perhaps the most fundamental, and the most commonly misunderstood, variable of human comfort is temperature and how we feel hot or cold. There are three kinds of heat transfer – conduction, convection, and radiation - and we experience each of these differently.

Conductive transfer occurs through direct heat transfer between two surfaces that are touching. When you stand on a cold stone floor with bare feet, heat transfers from your feet to the floor. Since very little of our body usually physically touches a building, conductive transfer contributes very little to thermal comfort in a regular day.

Convective transfer occurs between a surface and a fluid medium like air or water. When you are standing in a building, air constantly moves across your skin and transfers heat to or from it. Indoor dry bulb temperature or air temperature is the most common way we understand whether we will feel hot or cold through convective transfer.

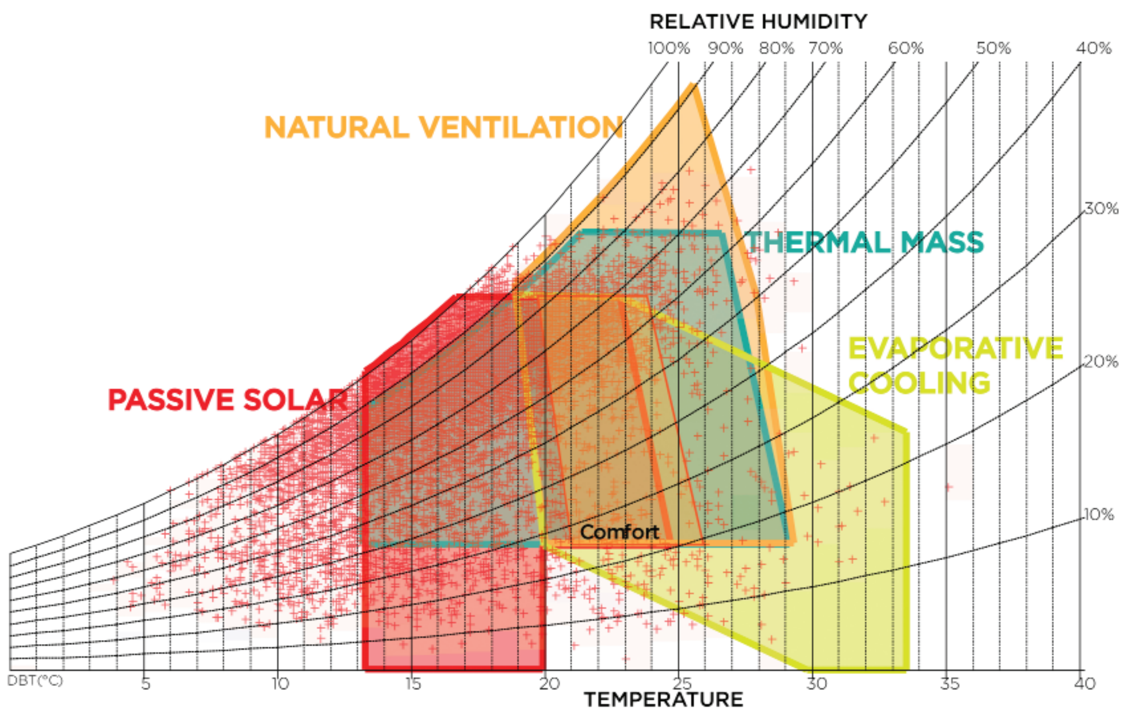
Radiative heat transfer is a powerful but little recognized factor in our thermal comfort. This transfer occurs through the exchange of infrared electromagnetic radiation between our bodies and surrounding surfaces. All surfaces emit infrared radiation, including our own bodies, and warmer surfaces always radiate to cooler ones. Human bodies are extremely sensitive to this heat transfer. When we feel that we are radiating to a cooler surface, we feel cooler than the air temperature around us, while when we are receiving radiation from a warmer surface we feel wamer than the air temperature around us. The exchange is constant and varies based on the surface temperature and view angle of one surface to another. To the extent that our bodies “see” more of the wall than the ceiling while we are standing upright, the wall will have more of an influence on our sense of being warm of cool.

This means that the surface temperature of the walls can actually have as much of an influence on our thermal comfort as the temperature of the air. A metric known as "operative temperature" is the average of the air temperature and mean radiant temperature in a space. Operative temperature is often misunderstood or ignored by air conditioning specialists but it is crucial to an accurate understanding of occupant comfort.

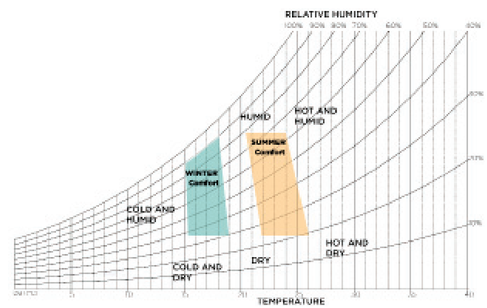
To establish the operative temperature, humidity, and air speed (and thereby start to define occupant comfort), we can define the role of the building in filtering the ambient environment. There are only five methods by which heat can flow through the building envelope and each is associated with a strategy for climatic mediation, or "filter":

Filter	Heat Flow / Storage
Insulation	Conduction
Ventilation	Convection
Glass and Shade	Radiation (light and heat)
Evaporation / Dessication	Latent Heat
Thermal Mass	Thermal Capacity

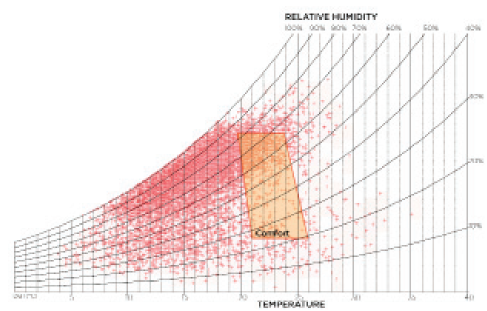
These filters or strategies for mediation can be combined to reject, accept, or store ambient energy. They are the fundamental palette of the building envelope and the principal arena of design for the



Psychrometric-Bioclimatic Chart showing regions where architectural filters could potentially reduce energy use.



Psychrometric Chart with winter (left) and summer (right) comfort zones for Los Angeles.

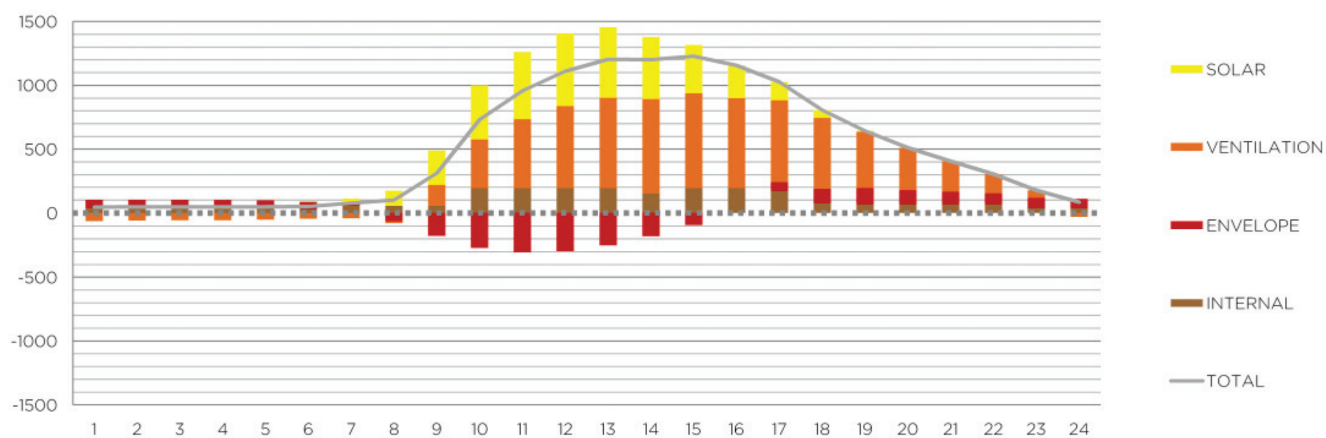


Psychrometric Chart with average annual comfort zone and hourly data plotted.

architect. The Global Ecology Center at Stanford University illustrates these ideas clearly. Windows provide bilateral daylighting to the offices and laboratory floors, supplementing conference rooms with skylights to bring daylight into the center of the building. Insulation in the walls, roof, and floor traps cool air in the building. Operable windows allow cross ventilation in the mornings and then prevent hot air from entering as the day heats up. Exterior horizontal shades over the windows prevent direct sun from radiantly heating up the space. Sprinklers evaporatively cool intake air on hot, dry days. Finally, polished concrete on the ground floor provides a large amount of thermal mass that stores heat and stays cool during the hot afternoons.

The psychrometric-bioclimatic chart relates external variables of temperature, humidity, and air speed to architectural filters and occupant comfort. The chart defines a zone bounded by operative temperature and relative humidity in which most people will feel comfortable for a given air speed, metabolic rate, and clothing level. It also locates regions of the chart wherein the proper application of specific architectural strategies will likely result in comfort conditions. For instance, 30°C and 30% humidity is outside of the comfort zone, but by ventilating the space and increasing air speed the operative temperature can be brought into the comfort zone. The chart shows that if ventilation is not a viable option for a particular building, high thermal mass, evaporative cooling, or air conditioning may be. By plotting the temperature and humidity of a given ambient environment on a psychrometric-bioclimatic chart, the designer can get a quick picture of the design palette to be considered.

This picture can be further refined by considering the thermal loads on the building. While the filters we just discussed modulate the energy flows from the ambient environment, energy can also be generated from within:



Summer Design Day Loads

External Loads (climate-dependent)

Radiation	sun (gain), night sky (loss)
Conduction	temp difference across envelope (gain or loss)
Convection	air infiltration / ventilation (gain or loss)
Latent Heat	humidity (gain or loss)

Internal Loads (program-dependent)

People	heat and humidity gain
Lights	heat gain
Equipment	heat gain (sometimes humidity gain)

Whereas external loads add or subtract heat to a space, internal loads can only add heat. The balance between the two is so critical that we characterize buildings accordingly as externally-dominated buildings or internally-dominated buildings in order to understand the general exchange of energy between the indoor and outdoor environments. In externally-dominated buildings such as houses, heat gain and loss through the envelope are more influential than gains from people, lights, and equipment. In internally-dominated buildings such as large offices, internal gains generally overwhelm any gains or losses through the envelope. However, even in internally-dominated buildings external conditions can dominate the conditions next to the envelope.

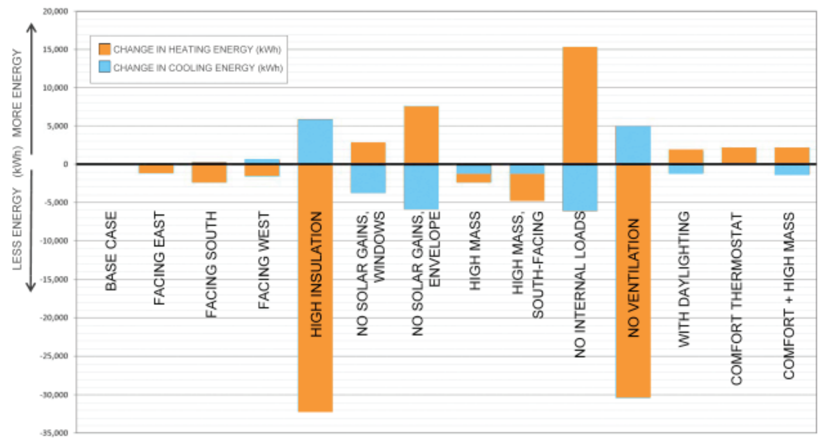
Most of our work analyzing building performance begins with the fundamental questions we have just outlined:

What is the climate?
What is the program?
What (and when) are the external loads and site energy resources?
What (and when) are the internal loads and programmatic needs?

These questions help us explore the most interesting question:

How should this building filter the environment?

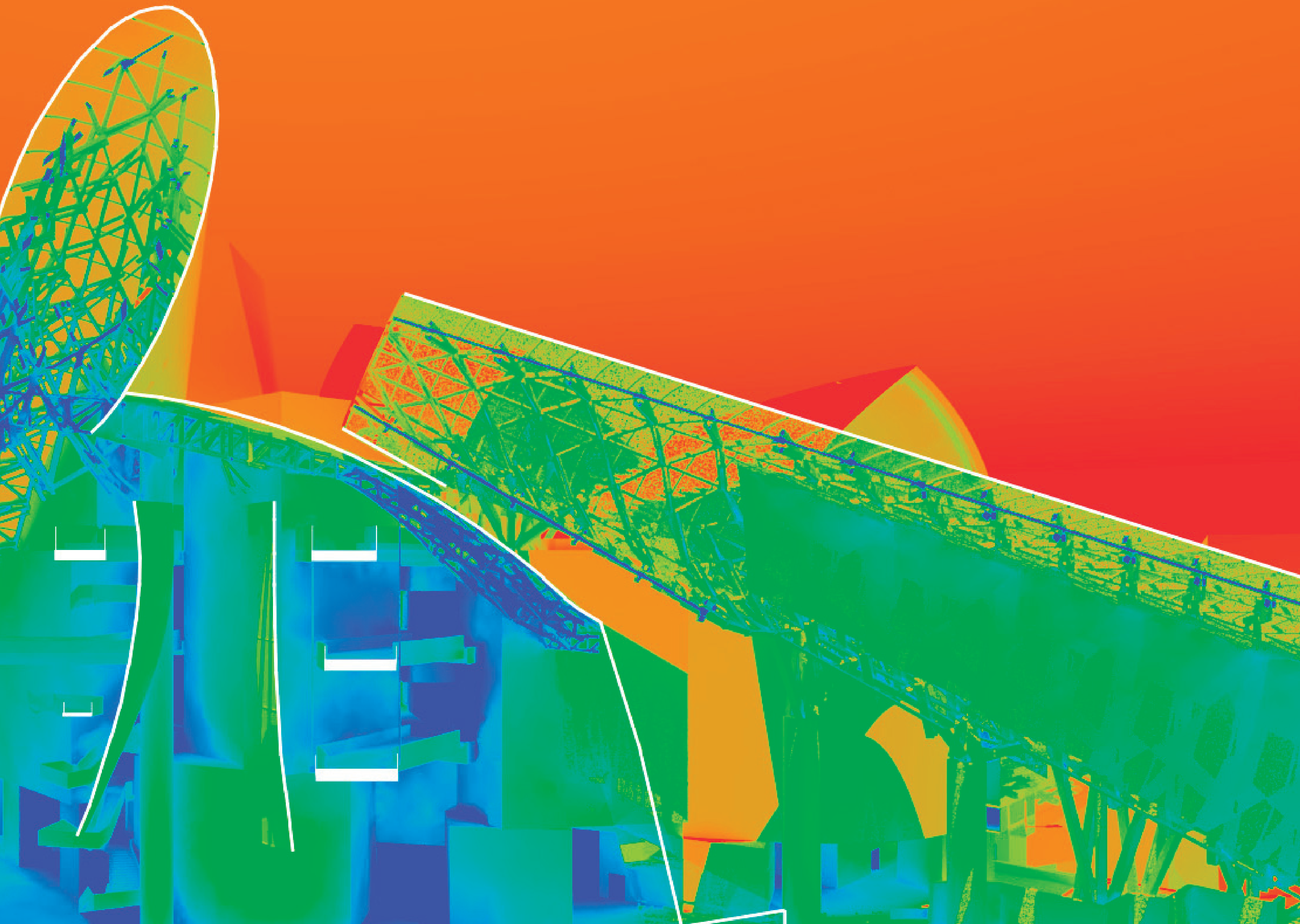
Parametric analysis can quickly point us in the right direction. By changing one variable at a time – insulation, solar heat gain, ventilation, evaporation, and mass – we can identify a suite of effective characteristics for the design. It is important to note that, like any part of architectural design, this is not a deterministic process. Aesthetics, constructability, structure, weatherproofing… all of the systems that go into a structure are highly reciprocal and contingent.



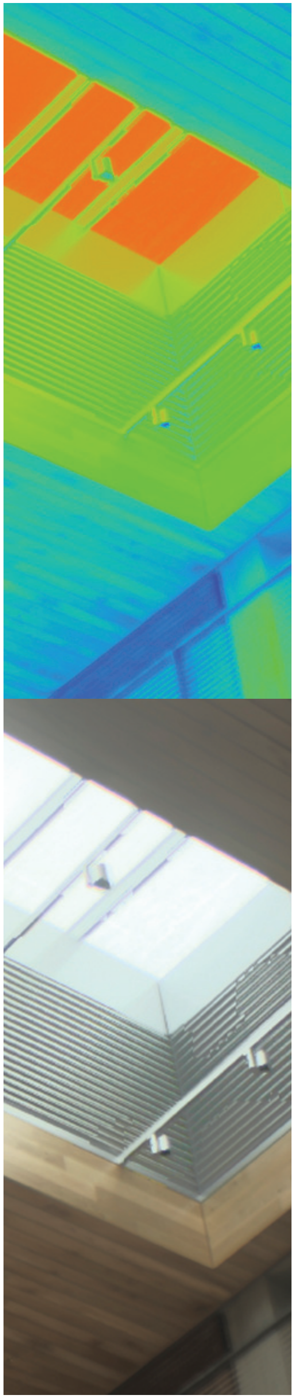
Elimination Parametrics illustrates the impact of different architectural filters on energy use for a given building.

While it is true that high performance buildings generally cost more than badly performing buildings, it is not true that high performance buildings need be expensive, especially when considering long-term finances. The approach we will outline in this workshop - optimize envelope, reduce machines, generate energy with renewables – is another way of saying, "use available materials and energy wisely, eliminate materials and energy you don't need, and plan for the future." Simple and inexpensive elements such as insulation, shading devices, good glass, operable windows, and thermal mass can go a long way toward filtering enough ambient energy so that supplementary energy doesn't have to be generated. As the financial, political, and environmental cost of fossil fuels continues to climb, the price of renewable energy is certain to fall. In the meantime, the less energy a building needs to generate, the less its finances are subject to the exigencies of the market.

day one: light

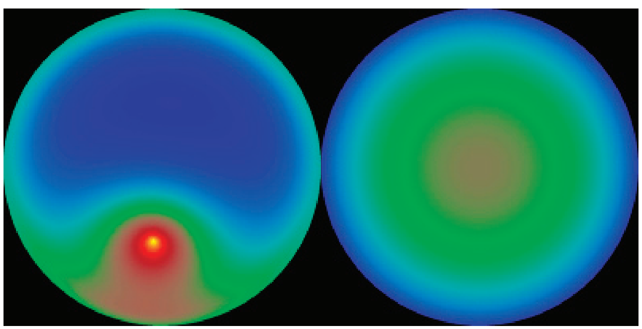


daylighting



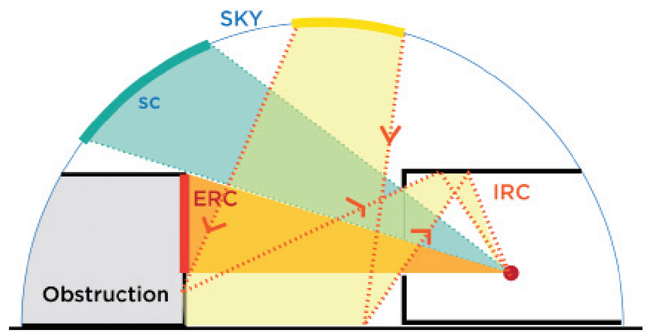
Like other energy systems, all lighting involves a source, a filter, and a receptor. For daylighting, the receptor is the human eye, the source is the sun, and the filter consists of four parts: the atmosphere or sky component (SC), the exterior reflected component (ERC), the glass, and the interior reflected component (IRC).

What is the difference between light from the sun and light from the sky?
When the visible spectrum of electromagnetic waves reaches the earth's atmosphere from the sun, some of this light is reflected, some is transmitted, and some is absorbed and then re-radiated. Light is absorbed in the atmosphere in three ways: by gas, by moisture, or by particulates such as pollen, dust, soot, etc. Light absorbed by the gasses appears to us as blue, light absorbed by moisture appears as white or gray (clouds), and light absorbed by particulates has variable color but often appears as green or brown (smog). For daylighting, direct beam from the sun is extremely bright and has "warm" colors - yellow and red. Light from the blue sky (opposite the sun on a clear day) is relatively dark and very "cool." Light from clouds and particulates is bright and "cool-neutral."



Sky brightness distribution on a clear day (left) and overcast day (right). The deep blue sky opposite the sun on a clear day is darker than any part of the sky on an overcast day.

Should I design for an overcast or clear sky?
While some climates have one predominant sky condition, it is important to design for the range of the sky conditions a site will experience over a year. For example, designing for clear skies only will mean that electric lights are used far more than necessary on overcast days. Since the position of the sun under clear skies changes daily and seasonally, designing for the motion of the sun is part of effective daylighting design.



Daylight System: Sky Component (SC), Externally Reflected Component (ERC) and Internally Reflected Component (IRC)

What affect will the building across the street have on daylight in my building?
The exterior reflected component (ERC) of the daylight system consists of the contribution of light reflected off of exterior materials. This includes the building across the street, the opposite hillside, the garden the snow and thepavement outside the window as well as the tree in front of the window. the full daylight system includes these surfaces that act to filter light from the sun.

What kind of glass should we specify?
Like the atmosphere, glass reflects, absorbs, and transmits light. Clear, single-pane glass has a visible transmittance of about 90% (Tvis = 0.90). Some tinted

lu·mi·nance/'loomənəns/

the intensity of light emitted from a surface per unit area in a given direction; surface brightness

glasses have a transmittance as low as 5% (Tvis = 0.05). Spectrally selective, high performance clear glass generally has a Tvis around 0.60. It is important that the glass find the correct balance between light and heat transmissionfor the climate and building use. This will be discussed in the section on radiation, but for daylighting we generally need the glass to be as visually transmissive as possible.

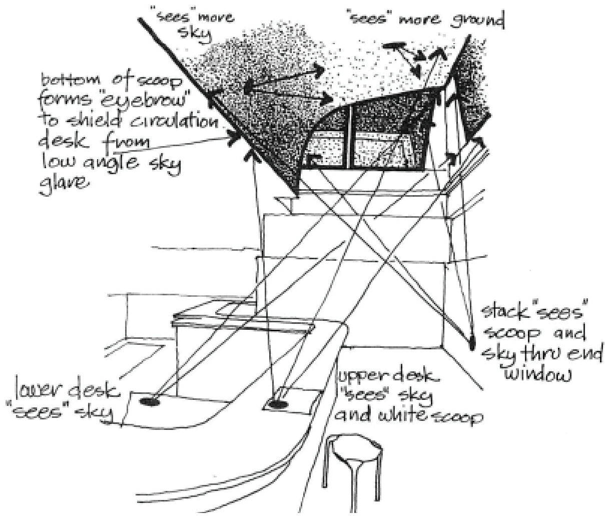
Should translucent glass be sandblast, film, or frit?
Translucent glass introduces irregularities that cause light to scatter internally instead of being transmitted through the glass along a straight, collimated path. When light hits translucent glass, the glass becomes a bright surface but not all of this light is transmitted to the interior space. Large expanses of translucent glass can be a source of glare, particularly when they are exposed to direct sunlight.

Sandblasted, acid-etched, or cast glass (such as channel glass), scatter light unevenly so that the incident light is transmitted in greater proportion to the scattered light. Applied films differ by manufacturer, but can be engineered to diffuse the light more evenly. Composite glass products, such as Solera or Okalux, use an interlayer of fiberglass or plastic to produce almost perfectly-diffuse light patterns that minimize bright spots.

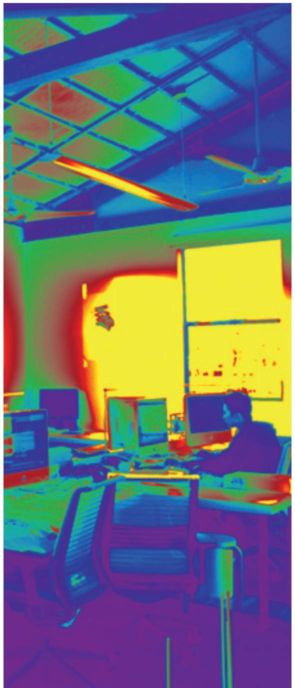
Frit is an opaque ceramic coating on the surface of the glass. When located on the outer pane of glass, frit is an effective method of reducing solar radiation, but it also reduces light transmission. Because frit is opaque, it will not produce a translucent surface but small frit patterns can achieve visual privacy while still allowing light transmission. A white frit often produces an uncomfortable brightness similar to sandblasted glass when in direct sun.

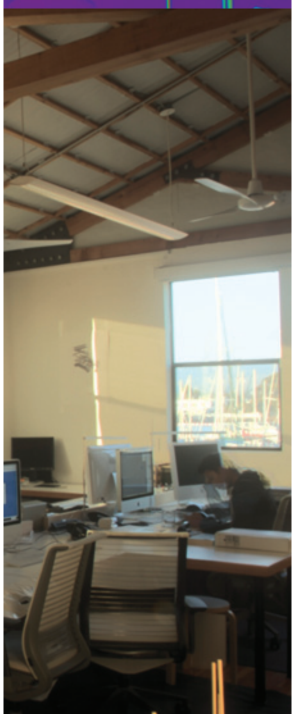
What interior finishes should we choose?
The last element of the daylight system is the interior reflected component (IRC). The interior of a building is like a light fixture for the daylight. Interior geometry, surface reflectance, and color will impact the amount and quality of light that reaches an occupant's eyes. Lighter color values reflect more light and create less visual contrast between the exterior and interior environments.

How deep should the building be? How high should the ceiling be?
The total amount of light at a point is the sum of the light received from all surfaces the point sees. The light received varies with the angle of view so that a surface perpendicular to the point will contribute more light than an equally bright surface at a low angle. The floor adjacent to a window will see primarily the ceiling inside the building and the sky outside the building. The walls of the interior and the buildings across the street will contribute



This analysis of Aalto's Rovaniemi Library shows the impact of view angle and surface brightness to illumination levels. From Moore 1985, 44.





daylighting

some but less reflected light to that point on the floor. The floor farther from the window sees less of the bright sky and is therefore darker. In sum, the height of the window header, the height of the ceiling, and the distance from the window to the point being illuminated are critical factors. The maximum useful daylighting results from high ceilings, high window heads and narrow floor plates.

How big should skylights be?

Because the sky is usually the brightest source of daylight, skylights do not have to be large to be effective. As a general rule of thumb, a skylight area about 5% of the floor area is sufficient to daylight a space with good energy efficiency. For more visually intense spaces, such as art studios and for places with high latitudes and cloudy skies 10% is good. However, skylight efficacy is heavily dependent on the glazing, as well as the depth, shape, and color of the skylight well. Splayed openings with matte white materials are most effective at delivering diffuse light over larger areas. Deep, vertical wells with dark materials will create pools of daylight illuminating the areas directly underneath them. Light-colored walls located underneath skylights will re-reflect the light to the rest of the space.

How can I avoid glare in a daylighted space?

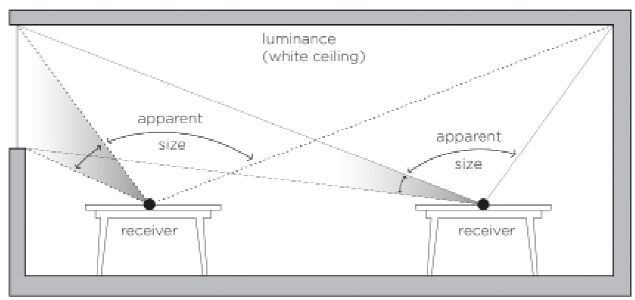
Visual comfort depends primarily on two conditions: quantity of light falling on a point (illuminance) and brightness of surfaces in the visual field (luminance). Most codes, guidelines, and lighting professionals concern themselves primarily with illuminance values, but the relative brightness of surfaces within the field of view contributes just as much to our visual comfort. Excessive contrast between adjacent surfaces causes glare, especially when those surfaces take up a large portion of our visual field. Because direct sun light is so much brighter than sky light, direct beam in a space can also cause discomfort glare.

Where in the wall should I place a punched window?

For both skylights and windows, washing large surfaces such as ceilings and walls produces gradual gradients of light that: (a) allow the eye to transition from brighter to darker regions of a room, and (b) effectively re-reflect the daylight to the rest of the room. If the wall is not deep enough for a sill or sloped jam to create a gradient, placing the window next to a perpendicular wall reduces glare and increases useful illumination.

How deep should overhangs be to provide visual comfort?

A clear day and an overcast day have very different distributions of sky brightness. On a clear day the sun and the area around it are the brightest regions, the area in the sky opposite the sun is the darkest region, and the horizon is somewhere between the two. On a uniformly overcast day the horizon is the darkest region of the sky and the brightness gradually increases up to the zenith, immediately overhead.



View to the sky is a key influence on illuminance levels.

il·lu·mi·nance/i'loomənəns/

the luminous flux incident on unit area of a surface

When there are unimpeded views to the sky from a building interior, the brightness of the sky can be uncomfortable, especially the region around the sun on a clear day and the high sky on an overcast day. Overhangs act like the brim of a hat, obscuring views to these bright regions of the sky and providing a transitional gradient from a darker interior to a brighter exterior. Overhangs can also control direct sun which can be a source of visual discomfort. Optimal overhang depth depends on latitude, orientation, and window height. As a general rule, overhangs with a depth equal to one third or one half the height of the window will provide some high sky glare protection and some control for direct solar radiation.

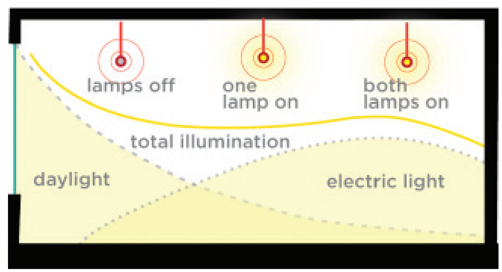
Do I really need shades on the north?
Shading strategies vary by latitude and climate, but in temperate northern latitudes, north facades will receive direct sun on summer mornings and afternoons. Vertical fins are effective for cutting this sun. Operable diffusing shades are useful on high north windows to control sky glare under certain overcast or hazy sky conditions.

Do I really need operable shades?
Overhangs are a static solution to a dynamic phenomenon. No overhang will block all of the potential sky glare all of the time, and it will rarely block all of the direct sun all of the time. For these reasons, operable shades (either interior or exterior) that provide fine-tuned control of the luminous environment are an important component of a daylighted space.

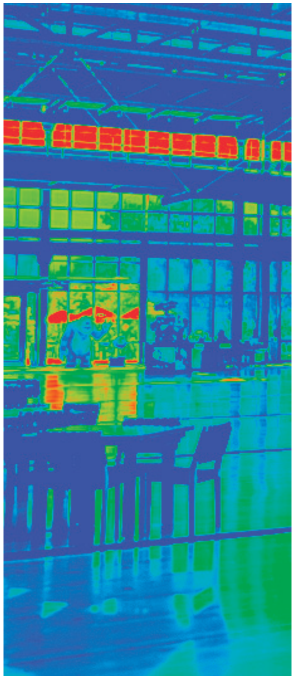
What if we can't afford motorized shades?
Controlling operable shades is another matter. Building occupants tend to reliably lower or close shades when they need to, but they rarely open them when no longer needed. This reduces available daylight and undermines the daylight system. When automatic controls fall outside of a building budget, manually controlled shades must be vigilantly retracted.

Is a light shelf effective?
The primary purpose of a light shelf is to reduce light levels closest to the window so that there is less contrast between perimeter and inboard spaces. The secondary purpose is to reflect light back up onto the ceiling reducing the contrast ratios between the ceiling and the sky outside. This reflection is most effective when the light shelf can see the sun or very bright portions of the sky.

How should we zone the electric lighting for energy efficiency?
Daylighting only reduces energy use if electric lights can be turned off. The amount of useful daylight will fluctuate throughout the day and year so electric light must be zoned such that fixtures in the daylight zone can be turned off when not needed. In deep spaces, the design might require two or three daylight zones that fluctuate depending on daylight penetration. If the lighting controls are a distraction to occupants they will be overridden, so electric lighting design must anticipate the visual effect of turning some lights off while other lights are on. The most effective daylight control installations are never noticed by the occupants. This usually requires a continuous dimming system which also maximizes energy savings. Using photosensors, light fixtures can be programmed to gradually respond to fluctuations in daylight.



Maintaining design illuminance with electric light switching in layered zones

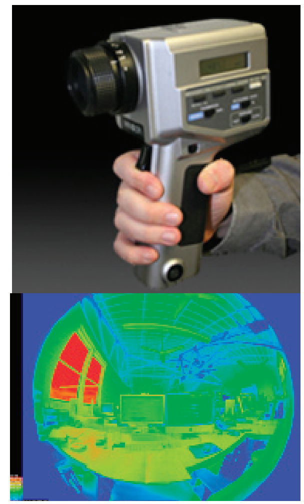


tools and software

How to measure the amount of light falling on a surface?
An illuminance meter (or photometer) measures the amount of light at a location. Units are in Lux (SI). By blacking out the white globe while turning the device on, it automatically calibrates the 0 light level. Position the device on or next to a surface and take a measurement. The device "sees" a half-hemisphere, so make sure that there are no unusual obstructions in the way of the light (including your body). Illuminance values are commonly given as a range of minimum light levels suitable for a particular activity (i.e. walking, reading, cooking). For instance, IES recommends horizontal illuminance values of 200-500 lux for visual tasks of high contrast or large size. Using an illuminance meter is a good way of checking your experience against such standards.

How to measure surface brightness?
A luminance meter measures the surface brightness at a certain point. Units are in candelas / m2 (SI) also call nits. Turn the device on, sight through the viewfinder and point the trigger to get a luminance value. Surface brightness is most useful when comparing the ratio of brightness between adjacent regions of the visual field. For instance, a computer display emits about 150 cd/m2 whereas the blue sky emits about 3000 cd/m2. This results in a 20:1 brighness ratio that can be uncomfortable when the eye has to adjust quickly between them.

Luminance meters are relatively expensive, but there is a lower cost way of measuring surface brightness. All you need is a digital camera and a Mac computer. Photosphere (www.anyhere.com) is freeware for the Mac OS that processes High Dynamic Range (HDR) photographs and allows you to retrieve surface brightness for any pixel on the image. To take an HDR photo, you must "bracket" an image by taking a series of 5-10 photographs at different exposures (i.e. +2.0, +1.5, +1.0, +0.5, 0, -0.5, -1.0, -1.5, -2.0). Make sure to hold the camera still or use a tripod so the compiled image registers. Using Photosphere you can then compile the photos into an HDR image and calibrate your camera using a luminance meter. Click on a pixel to get the surface brightness.



Using a luminance meter and HDR photography to measure surface brightness.

How to determine where and when there will be direct sun on a site?
Figuring out a site's access to sun helps to not only understand daylight potential, but also potential solar heat gain, and PV energy generation potential. The most useful and accurate tool is a fisheye camera coupled with a sunpath overlay. The view through a full fisheye lens is a half-hemisphere, so by pointing it straight up at the sky's zenith, the 360-degrees of the horizon is located around the outer circumference of the image. Since a fisheye view is dependent on a particular spot, it is a good idea to take photos at the extents of a site, such as the four corners and see how solar access changes. When setting up the camera on site: use a level to ensure the camera is pointing straight up, use a compass to note a landmark from which you can get a bearing for north-south alignment, and duck down below the lens when you take the picture. The software SunPath allows you to overlay a sunpath diagram over your photo. Check the image by comparing the position of the sun on the solar path to the time you

took the photo. There may not be an exact time correlation because of the differences between local time and solar time, but the sunpath should be accurate to within 1/2 hour.

There are other tools that do substantially the same thing. The Solmetric Suneye combines the fisheye lens and the sunpath overlay in one device. iPhone Sun Seeker and SunTraker are apps that use the iPhone camera to define where the sun will appear in relation to the horizon.

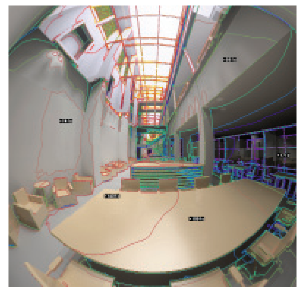
How to determine direct beam penetration and size shading devices?
Many digital modeling programs, such as Google Sketchup and Autodesk 3D Studio Max, allow the user the ability to control the sun's position by time, date, and latitude. Such programs do not necessarily render daylight correctly, though they are good tools for understanding the patterns of direct sun into a building. By modeling a building and looking at the extremes of the year (December 21 and June 21 in the morning, noon, and afternoon) you can get a good sense of how direct sun will interact with the architecture. Parametric modeling through informed trial and error is an excellent method for balancing aesthetics, constructability, and shade in the early design stages.

Fisheye photograph with sun-path overlay

How to determine daylight availability?
There are a few climate analysis tools that can quickly tell you the annual sky conditions for a site using Typical Meteorological Year (TMY) data. Autodesk Ecotect Weather Tool and Climate Consultant are two of the best. (See resources on the next page for references.) Since TMY data gives the sky conditions for all 8,760 hours of the year, it is important to graphically visualize this data in a way that is useful. You should decide what works for you, but the idea is to be able to tell how much of the year the skies are clear, partly cloudy, or overcast. Are there certain sky conditions that dominate certain seasons? It's always useful to compare data from a place you know well to a new site so that you have a point of reference.

Physical model used to predict daylight quality

How to determine quality and quantity of daylight?
Accurately predicting the quality or quantity of daylight in a space requires some time and expertise. Each part of the daylight system, from sky conditions and neighboring buildings, to interior materials and geometry must be carefully constructed, either physically or digitally. Physical daylight models are the most accessible and immediate path for many designers. A daylight model differs from a conventional architectural model in that it is light-tight and the materials used in the model closely simulate the reflectances and textures of the proposed design. A daylight model can be tested for light quality under analagous sky conditions as the proposed building. The quantity of light can be measured using illuminance sensors.

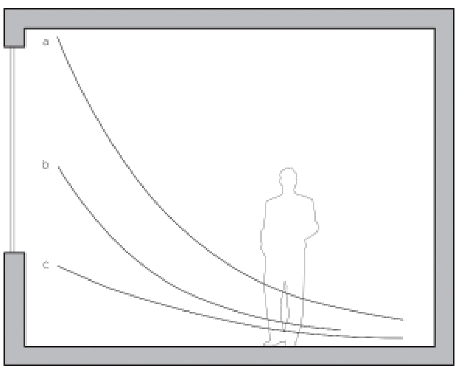


Iso-illuminance rendering of Radiance daylight calculation

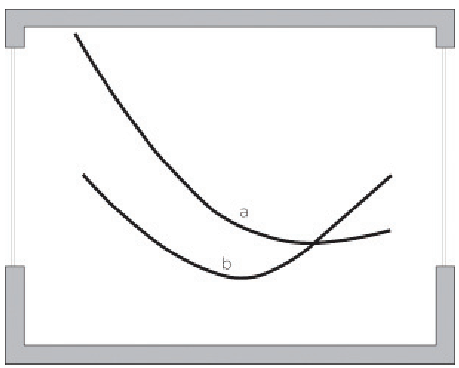
The accuracy of a digital daylight model depends on the expertise of the modeler and the type of modeling engine being used. Most daylight software uses highly simplified algorithms to predict light behavior and accuracy suffers, especially when complex geometry or lighting situations are considered. We use Radiance, a research-grade simulation engine that is extremely accurate when used correctly. While it is processor intensive and requires extensive expertise, it is unparalleled in predicting the quality and quantity of light in a space.

resources and rules of thumb

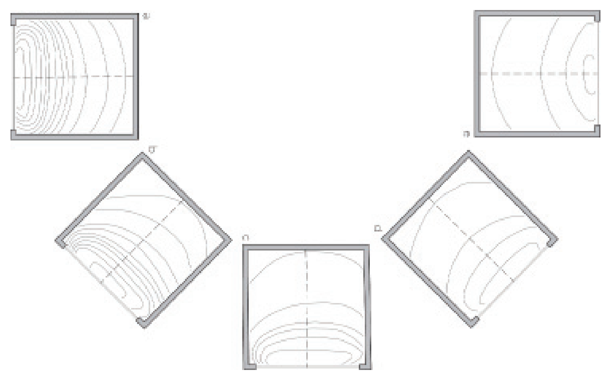
- Higher window head heights will light the ceiling more and allow daylight deeper into a space.
- Ceiling brightness has the biggest affect on desk illumination because horizontal surfaces “see” primarily ceiling.
- Sloping the ceiling away from the fenestration area will help increase the surface brightness of the ceiling further into a space.
- Overcast skies are brighter than clear, north skies.
- Luminance contrast ratios greater than 20:1 in the visual field of a daylighted space will likely result in glare. In electrically lighted spaces ratios of 10:1 are preferred.
- In a room that is lit by a punched window on one side, the darkest surface is the wall with the window and the brightest surface is the view out the window itself. Placing the window next to a perpendicular wall or canting the wall next to the window jamb will help the eye transition.
- Horizontal shading devices are more effective than vertical ones on south, east and west facades. To block all direct beam on an east or west facade while still allowing daylight, requires an operable shade.
- North facades will receive direct sun on summer mornings and afternoons. Vertical fins are effective for cutting this sun.
- As a general rule, overhangs with a depth equal to one third or one half the height of the window will provide some high sky glare protection and some control for direct solar radiation.
- The primary purpose of a light shelf is to reduce light levels closest to the window so that there is less contrast between perimeter and in-board spaces. The secondary purpose is to reflect light back up onto the ceiling. This reflection is most effective when the light shelf can see the sun or very bright portions of the sky.
- As a general rule of thumb, a skylight area about 5% of the floor area is sufficient to daylight a space with good energy efficiency. For more visually intense spaces, such as art studios and for places with high latitudes and cloudy skies 10% is good.



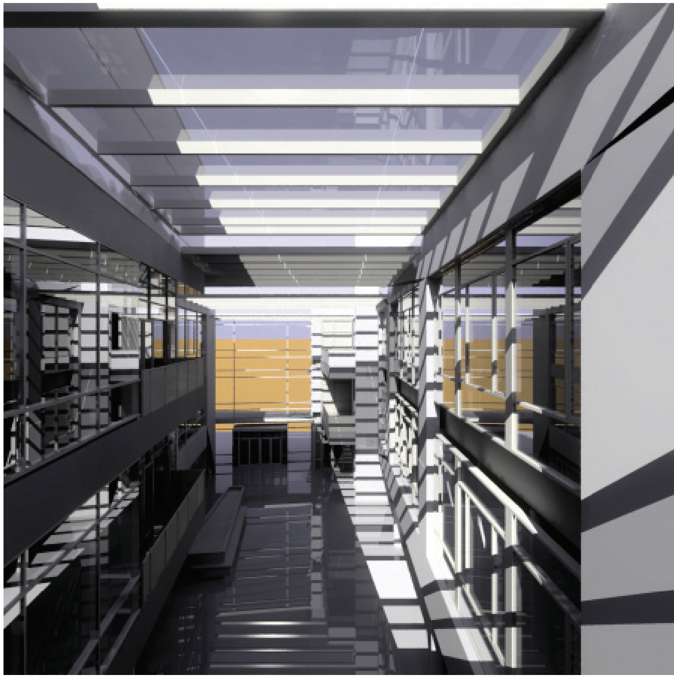
Daylight in a unilaterally lit room with window facing: (a) the sun, (b) overcast sky, (c) away from the sun. From Robbins 1986, 70.



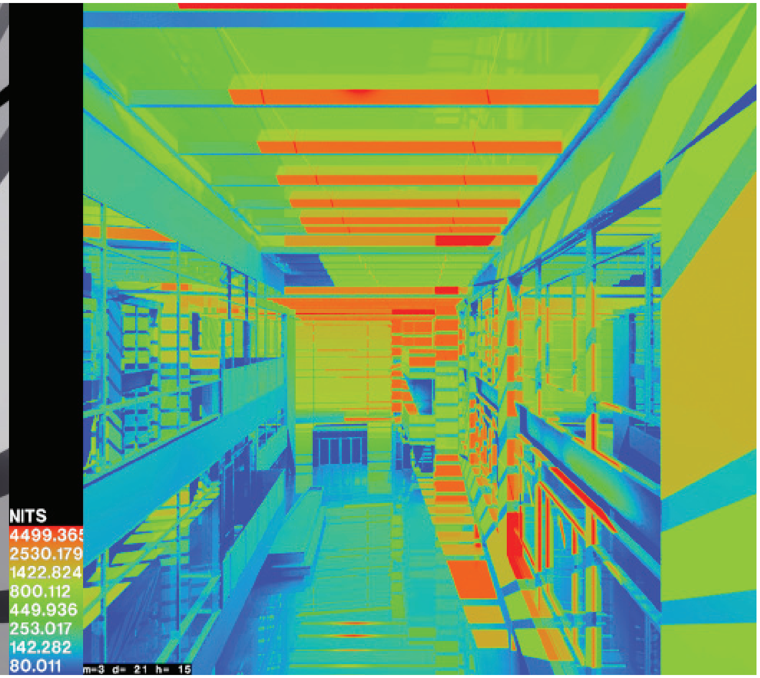
Daylight in a bilaterally lit room on a: (a) clear day and (b) overcast day. From Robbins 1986, 81.



Iso-illuminance plan of a daylit room rotated to face: (a) the sun, (b) 45°, (c) 90°, (d) 135°, (e) 180°. From Robbins 1986, 77.



Radiance rendering post-processed with human visual response algorithm.



False color luminance rendering.

Books

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Daylight Design of Buildings by Nick Baker and Koen Steemers,London: James and James, 2002
Daylighting Performance of Buldings, edited by Marc Fontoynont. Brussels: James and James, 1999.
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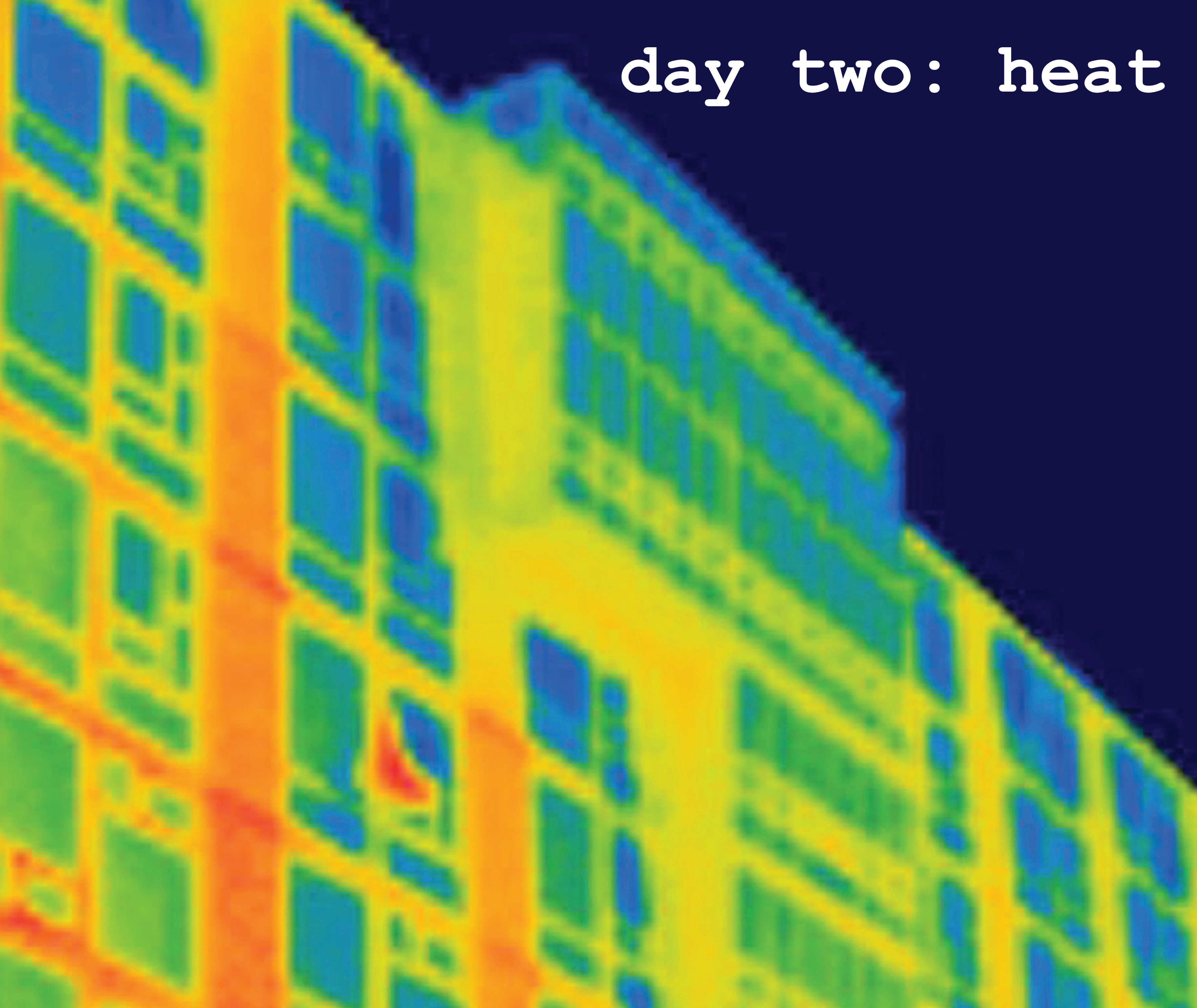
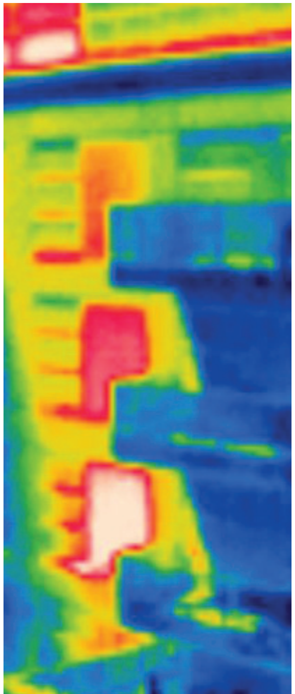
Daylighting by Hopkinson, R. G., Petherbridge, P., and Longmore, J. London, England: University College, 1966.

Websites

Daylight in Buildings: A Source Book on Daylighting Systems and Components (gaia.lbl.gov/iea21)
Lawrence Berkeley Lab Daylighting Information (windows.lbl.gov/daylighting/Default.htm)
eLAD An eLearning platform for commercial building daylighting and lighting systems (elad.lbl.gov/index.php/Body_of_Knowledge)
Whole Building Design Guide (www.wbdg.org/resources/daylighting.php)
Autodesk Ecotect Analysis (www.autodesk.com): Weather Tool climate analysis software bundled with Ecotect
Climate Consultant (www.energy-design-tools.aud.ucla.edu): Climate analysis freeware
Radiance (radsite.lbl.gov/radiance): Main portal for Radiance software including freeware and tutorials
DIVA (www.diva-for-rhino.com): Radiance plug-in for Rhino

day two: heat





sun / shade / surface

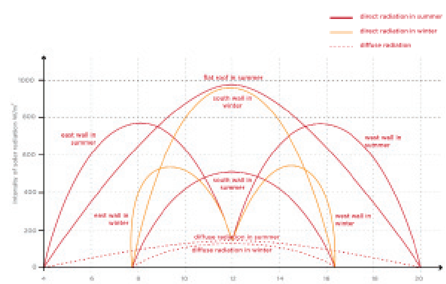
The way the building envelope reflects, transmits, absorbs, and stores radiation is a major determinant of occupant comfort and energy use. In buildings we usually encounter radiant effects in three ways: as direct solar radiation, as radiation to or from internal surfaces, and as radiant losses to the night sky. Shortwave radiation from the sun can be useful energy when the interior is too cold or it can be stored in thermal mass to be used later. In buildings that overheat, whether due to internal gains or a warm climate, solar radiation needs to be shaded.

Does it matter if my shades are on the interior or exterior?
Glass transmits radiant heat and traps air. The combination of the two contributes to the "greenhouse effect," a phenomenon that describes why glass buildings heat up in the sun. Interior shades reflect a portion of the solar radiation that hits them, but this energy is largely reflected back into the space by low-e glass. Interior shades can help to trap heat near the window, but the heat is in the space and adds to the cooling load. The only way to exclude this energy is to prevent the solar radiation from entering in the first place. This can be done by changing the properties of the glass, applying films or coatings to the glass, or shading the glass on the exterior.

Do I really need exterior shading devices?
Exterior shading devices are highly effective at blocking solar radiation and can provide visual comfort benefits, but they are not the only means of doing so. The glass itself can reduce solar radiation through the use of tinting, films, deposits or ceramic frits.

How do I select the right glass?
Tinted glass, films that darken the glass and ceramic frit all decrease the transmission of solar radiation (reduce the Solar Heat Gain Coefficient, SHGC) and also reduce the Tvis of the glass, possibly reducing daylight performance. Spectrally selective glass is designed with films or deposits that transmit a higher ratio of visible light to heat than the other glass types (sometimes called the Coolness Index Ke or Efficacy Factor). Clear 1/8" glass has an SHGC of 0.9 (90% transmissive to solar radiation). Clear, spectrally selective glass can transmit 60% of the radiation in the visible spectrum while transmitting only 30% (SHGC=0.3) of the infrared radiation that causes heat.

Are overhangs only useful on the south?
Allowing the right amount of solar radiation into a building entails an iterative process of "tuning" the building for daylight, shade, and sun in response to the climate and considering the interior uses. Generally speaking, horizontal shades are effective on south-facing facades, with latitude and seasonal shading considerations helping to determine the depth. Vertical fins are often effective on north-facing facades so that low-angle morning and evening summer sun is not admitted. Horizontal overhangs are effective on east- and west-facing facades at cutting mid-day sun, but they are less effective when the sun is lower in the sky (closer to

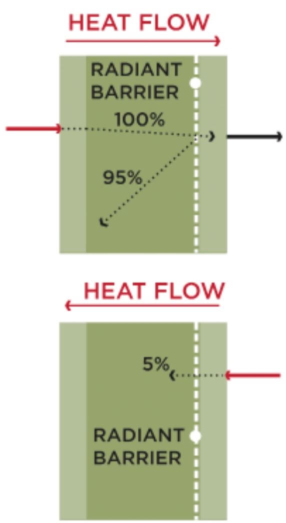


Intensity of solar radiation on south, east, and west walls in summer and winter.

sunrise or sunset). At these times, operable devices are often the most effective.

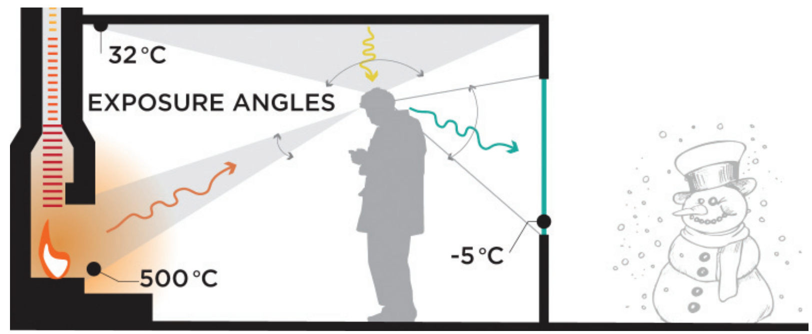
Does it matter what my floor surface is?
Apart from the sun, material surfaces - walls, floors, and ceilings - are the primary architectural elements that heat or cool people by radiation. All objects are constantly emitting electromagnetic waves and the magnitude of heat transfer between two objects depends on six factors: unobstructed line of sight, surface temperature difference, distance, exposed surface area, relative angle, and surface emissivity. Any surface that is exposed to direct sun and has high thermal capacity (stone, concrete etc) will absorb the energy and release it after the sun passes.

How does the surface temperature affect me?
Long wave radiation is often difficult to understand because we cannot see it or touch it. A person will lose heat to any surface that is cooler than the skin and gain heat from any surface that is warmer. As we know from sitting next to a campfire on a cold night, this phenomenon occurs regardless of the intervening air temperature. In terms of building, if the mean radiant temperature (MRT) of the surface is warmer than we are, we will feel comfortable even if the air temperature is cool. The reverse is also true, which explains the feeling of well being when we walk into a stone cathedral on a hot summer day; the stones are cooler than we are and we feel the heat radiating from our skin to the stones, keeping us cool in spite of warm air temperatures.



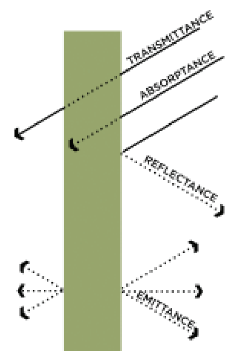
Radiant barriers reflect heat from the outside (above) and emit little heat from the inside (below).

Do I need a radiant barrier?
Most objects are very good emitters of radiation. Dark, matte surfaces such as asphalt or cast iron emit radiation readily. Light, matte surfaces such as white plaster or unfinished pine have lower emissivity. Specular (shiny) materials such as polished aluminum or stainless steel emit very little radiation. This is why stainless steel teakettles are more effective than cast iron ones at keeping water hot - almost all of the thermal radiation is reflected by the shiny surface back to the water. This is also why radiant barriers are made of mylar or aluminum foil - the specular surface essentially reflects heat. If we are trying to keep a space warm, we will place the radiant barrier facing into the room; if we are trying to keep a space cool, we will face it outwards. The specular face of a radiant barrier must face an air gap to be effective because if it touches a solid object, heat will flow by conduction through the assembly rather than being reflected out by radiation.

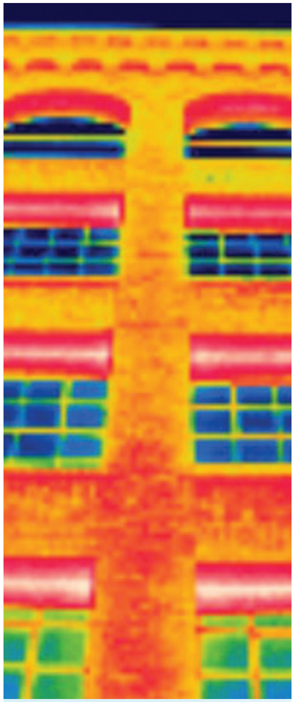


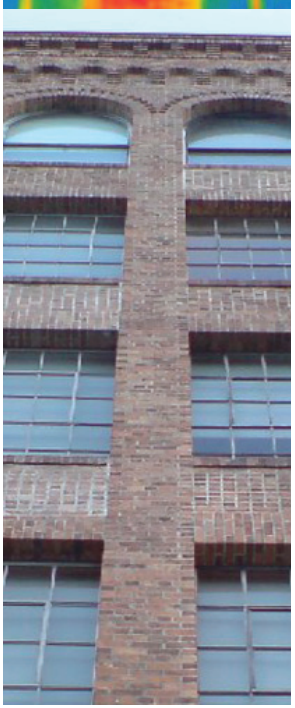
The radiant heat transfer depends on line of sight, surface temperature, distance, surface area, angle, and emissivity. Adapted from Lechner 2009, 48.

What is low-e glazing?
Low-e (low-emissivity) glass has a radiant barrier of very fine metal sputter-coated onto the glass surface in order to lower the transfer of radiant heat. Low-e glass will help to keep heat in a building once the sun has come through the window and is widely used in cold climates and residences to reduce heat loss through glass.



Longwave radiation is transmitted, reflected, absorbed, and then emitted from all materials.

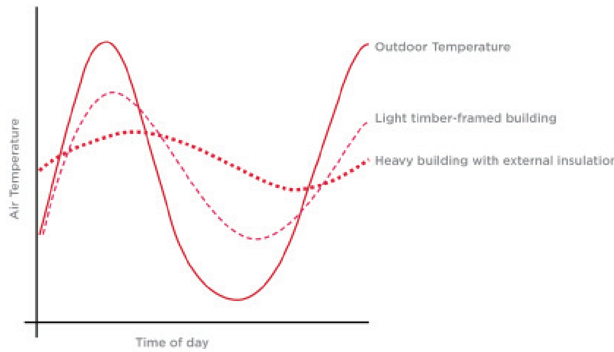




thermal mass

How does thermal mass store heat?
Heat capacity is a material property that is a form of energy storage. Heat is transferred to the surface of a material and is then conducted from the warmed surface to the cooler interior of the material. When the surface becomes warmer than other objects in the room it radiates heat to them. Stored heat from the warmer interior is then conducted to the cooler surface. The time that this takes depends on the heat capacity of the material, the thickness of the material, the surface area exposed to the room and the temperature difference between the room and the surface. Materials such as concrete or stone are thermally massive because they have a high heat capacity whereas wood and plastic are not able to store heat for very long.

How does thermal mass keep people comfortable?
Massive materials act as a thermal flywheel, dampening extremes through absorption and emission. This typically happens on a daily basis in climates with noticeable temperature differences between day and night. As temperatures rise during the day, the mass absorbs the heat keeping the space cool. As temperatures decrease at night, the mass releases the stored heat keeping the space warmer than outside. When designed properly, mass can be a thermal stabilizer for a building.

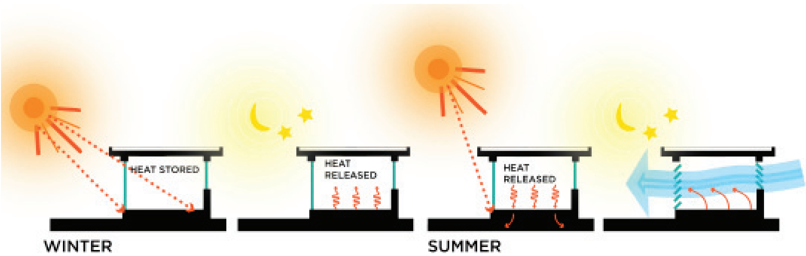


Can thermal mass work on an annual cycle to balance out winter cold and summer heat?
In a space built of thick stone like a Gothic cathedral, there is so much mass that the middle of the stone walls assumes the average annual outside temperature. In the morning, sun begins to warm the outside surface of the stone but the inside is still cool. By late afternoon, the stone has only warmed up slightly. During the evening it loses this heat through convection to the cool air and radiation to the night sky. Like a large ship sailing on the open sea, any changes in core temperature happen very slowly. In a Mediterranean climate such as Italy's, stone cathedrals remain relatively comfortable all year long at 16°C with no supplementary energy inputs. In England, however, where the average annual temperature is 10°C, the mass is a liability during the cold, damp winters.

A stone cathedral's thermal mass dampens the ambient temperature swings.

heat ca·pac·i·ty / hēt kə'pasitē' /

the heat required to raise the temperature of a mass by a given amount



The diurnal and annual cycles of well-designed thermal mass.

Does a thermally massive building need air conditioning?
Air conditioning works by lowering the air temperature and the relative humidity inside a sealed building. If the building thermal mass can be kept cooler than the outside air temperature, the air temperature may not need to be conditioned. If the surfaces around you are cool, you can still feel comfortable in a space with relatively warm air temperature.. Without the thermal mass, the surfaces would heat up along with the air, and the resultant operative temperature (Mean Radiant Temperature + Air Temperature) would be uncomfortable, necessitating air conditioning. If air conditioning is used in a thermally massive building, energy is first used to lower the temperature of the mass, and then to keep the air temperature lower so it will initially use more energy than a lighter weight air-conditioned building, but depending on the rest of the building envelope it may or may not use more energy over the long term.

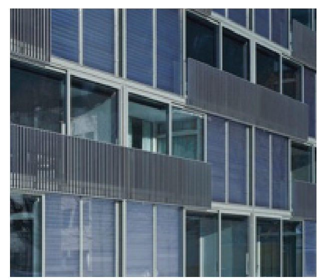
Is the ground a useful source of heat capacity?
For most soil types, the ground assumes the average annual outside temperature at a depth of 2-12 feet below the surface. Coupling a building to the ground will "borrow" the soil as thermal mass. Underground buildings, earth berms, and grass roofs dampen the diurnal and seasonal effects of outside air temperature on the building interior. In a temperate climate, when a conditioned building is coupled to the ground, the soil immediately under the building will warm to the average indoor temperature. As long as the house is consistently conditioned, this thermal bubble will remain. When coupling a building's interior space with the ground it is important to know what the average ground temperature is to ensure that the spaces remain within the comfort zone.

Do thermally massive buildings require insulation?
Massive materials are not good insulators. In a heated building, heat will conduct through massive materials to the outside if they are not insulated. The mass effect works primarily through radiant exchange, so the mass must be on the inside of the building envelope, in direct view of the occupants, to be effective.

What happens if the mass absorb or emits too much heat?
In warmer climates or in buildings with high internal gains, thermal mass can become too warm for comfort. In many climates, allowing outside night air to convect heat away from the mass ("night ventilation") is sufficient to recharge the mass for the next day. When massive construction becomes too cold for comfort, it can be warmed with passive solar gain. If either of these envelope-oriented solutions are insufficient, the mass can be mechanically cooled using hydronic tubes or forced air.

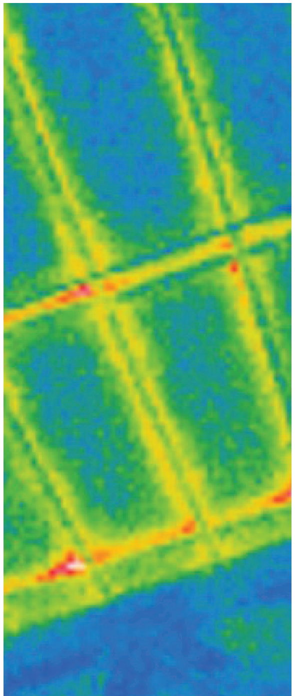
Are there any light-weight approaches to achieving thermal mass?
Instead of using the density of the material to store heat, phase change materials (PCM)use the change in phase between solids and liquids to store energy. As ice melts to become water, it absorbs heat even though it does not change temperature. When water turns to ice, it loses heat, but again remains at 0°C. Whereas the ice changes phase at 0°C, salt hydrates and paraffins can be engineered to change phase at comfort temperatures, such as 22°C. By absorbing or releasing heat, the material is maintaining a constant surface temperature that is radiating to the occupant and the rest of the room.

PCM technology has been slow to develop but it is gradually gaining momentum in Europe. BASF manufactures a paraffin-impregnated gypsum board. Delta makes a salt hydrate PCM that is encapsulated in translucent polycarbonate that changes translucency as it melts and solidifies.



PCM-integrated facade changes translucency as the salt hydrate changes state. This phase change stores energy.

insulation

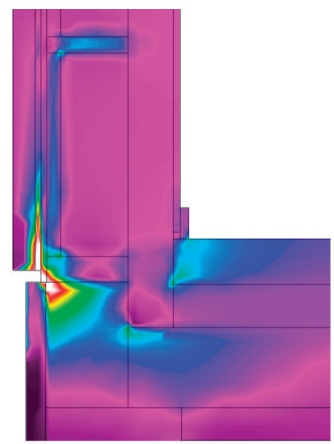


Insulation is an architectural filter between the temperature inside and outside a building. Every material has some resistance to heat transfer and building insulation values are simply a measure of how quickly heat transfers through the envelope. A building can be thought of as a leaking thermos. In designing the envelope, the architect is strategically determining how much, and where, the thermos leaks.

How much insulation do we need?
No matter how much insulation there is, the building is always transferring heat through the envelope as long as the inside and outside temperatures are different. The rate of transfer or leakage depends on the resistance of the materials to heat flow, the surface area, and temperature difference. With more insulation the building transfers less heat. With less envelope area the building transfers less heat. And with a smaller temperature difference the building transfers less heat. So the amount of insulation that is necessary depends on the building form as well as the climate. In temperate climates, 15cm of fiberglass wall insulation and 30cm of roof insulation is a good place to start. Higher insulation levels will generally offer greater interior comfort and energy savings.

Do we need more insulation in the walls or roof?
The amount of insulation that is desired also depends on where the heat is coming from. Solar radiation is much hotter than the outside air temperature, so roof insulation tends to be more important than wall insulation in sunny climates and in low latitudes where the sun is overhead much of the day. In a cold climate heat generated inside a building rises and roof insulation levels tend to be higher in order to keep that heat in. In multi-story buildings, wall area is far greater than roof area so the wall insulation is a higher priority.

Do we need to insulate under the floor?
The ground is an interesting thermal component of heat transfer. Unlike the air, the ground remains thermally stable throughout the year - it usually maintains the average annual temperature with little variation. Under a building with a slab on grade, the ground will stay at the same relatively constant temperature at which the interior of the building is kept. Very little heat flows in either direction, and insulation does not provide significant benefit. Because the thermal bubble forms underneath the floor, the sides do not benefit from the steady state even if they are in contact with the earth. As a result, underground walls and slab edges need to be insulated, though generally not to the degree required of above-ground walls and floors.



Thermal flux analysis through stud wall and slab shows thermal bridge at joint

Does framing or stud spacing really matter for insulation levels?
Like a thermos, the ideal thermal envelope for a building would be a continuous wrapper of insulation with no penetrations. Each penetration through the thermal envelope represents an increase in leakage. Insulating materials such as foams and fibers are rarely structural and structural materials such as wood, steel, and concrete are not very resistive to heat flow. Therefore, buildings by their composite nature

have variable insulation levels and create thermal bridges - extremes of localized heat flow caused by conductive materials.

These thermal bridges need to be designed to prevent excessive thermal leakage. With the same thickness of insulation, a wall with studs 40 cm on center has a lower R-value than a wall with studs 60 cm on center. With stud framing 40 cm on center, the studs make up 15% of the wall. With studs 60 cm on center, they make up 10% of the wall. Using a higher insulation value in the cavities between studs will compensate for this "framing factor" in terms of overall energy going in and out of the envelope, but there may still be localized conditions of thermal transfer that can cause condensation or comfort problems.

How can we avoid growing mold inside assemblies?
It is not just where thermal bridges occur, but the degree of bridging that is important. For instance, wood studs are about three times less resistant to heat flow than fiberglass insulation, so they form a significant thermal connection through the envelope. Steel studs are 1,500 times less resistant to heat flow than wood and in a cold climate rapidly conduct heat from inside to outside. Not only is this a large energy leak, but it is a point of potential condensation. Condensation is likely to form on cold steel studs, and moist conditions are a good breeding environment for mold spores. To address this, we can insulate more to prevent thermal bridges, ventilate the surface where moisture is likely to collect, or reduce the amount of moisture that reaches the cold surface.

What kind of insulation should we use?
Ideally insulation should be a continuous surface on the exterior of the building structure. Rigid insulation is designed for this and also has more resistance to heat transfer per cm of thickness than batt or loose insulation. Batt insulation is used in composite walls where there are cavities. For example, wood and steel framing readily accepts batt insulation between the structural members. Higher performing walls and roofs will have both batt insulation between the structural members and rigid insulation continuous outside the structural members. Batt and loose fill insulation such as cellulose and recycled blue jeans work well in spaces such as attics.

Can we reduce insulation by installing a radiant barrier?
Radiant barriers help resist heat transfer by radiation, but cannot resist heat transfer through conduction as insulation can. Both are necessary for a wall or roof to resist heat transfer, keep occupants comfortable, and reduce energy use.

While conventional glazing does not insulate well, high-tech plastics and films have much potential. Photo courtesy of Nic Lehoux.

How insulative is an all-glass building?
Glass transfers heat far more effectively than opaque building materials and assemblies, and glazing is typically the largest thermal leak in the building envelope. Conductive heat transfer can only be managed by capturing air or dense gas between two or more panes of glass. Highly insulative glass assemblies tend to be 25-40mm thick, making it difficult to detail elegant all-glass facades, but research into alternatives holds promise for thinner high performing units. Emerging technologies such as insulated translucent glazing and high-performance plastics, hold promise for admitting light while reducing heat flow.

How much glass should we use?
The performance challenge for any building envelope in any climate is achieving a balance among the sometimes competing concerns of solar radiation, daylight, ventilation, and insulation. We have found that as the ratio between glass and opaque wall increases, the room for error decreases. With care and studied practice almost anything is possible.

tools and software

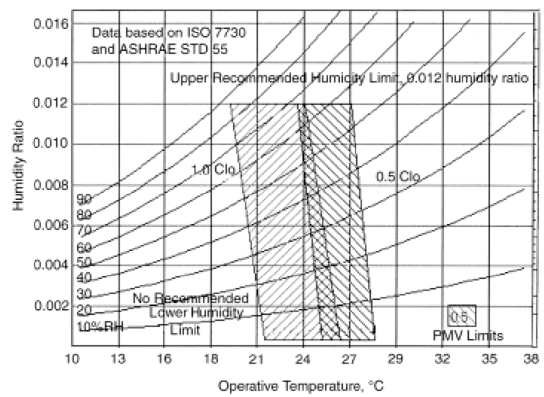
How to measure thermal comfort?

There are four environmental variables that contribute to human comfort. Each one can be measured with the following tools:

Air Temperature	Thermometer
Humidity	Hygrometer
Radiant Temperature	Infrared Thermometer
Air Speed	Anemometer

The thermometer and hygrometer require no specialized knowledge to use. Depending on the sensitivity of the meter, reaction time can vary. By cupping the meter in your hand you can get a good idea how fast the meter reacts to humidity and temperature changes in the environment.

To use an infrared (IR) thermometer, point the device at the surface you want to measure and pull the trigger until a temperature registers. Some IR thermometers allow you to select the emissivity of the surface and others default to ϵ=0.95, which is a common value for materials. Mean radiant temperature is a complex calculation, but taking an average of the walls, ceiling, and floor is a useful approximation. Be sure to bias the calculation towards the surfaces that are closer to you. Air speed measurements will be discussed on Day 3.

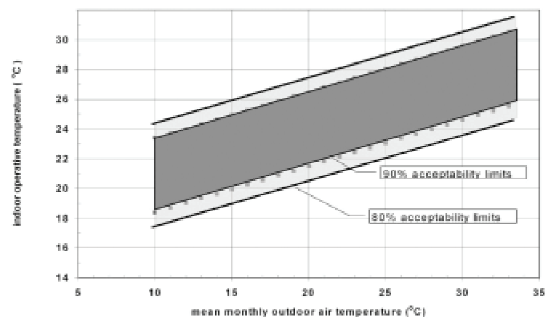


ASHRAE-55 comfort chart for conditioned buildings

What do my measurements mean for comfort?

Typical comfort criteria used by mechanical engineers specifies that fully mixed air should be between 18°C and 22°C, and between 40% and 60% relative humidity. These criteria assume that the room's mean radiant temperature is the same as the air temperature and that there is no discernable air movement.

More sophisticated comfort criteria specify an *operative temperature*. Operative temperature is a weighted average between the mean radiant temperature (MRT) and the air temperature. In low mass buildings the MRT will be equal to the air temperature. In high mass buildings you will see substantial differences.



ASHRAE-55 adaptive comfort chart for naturally conditioned spaces.

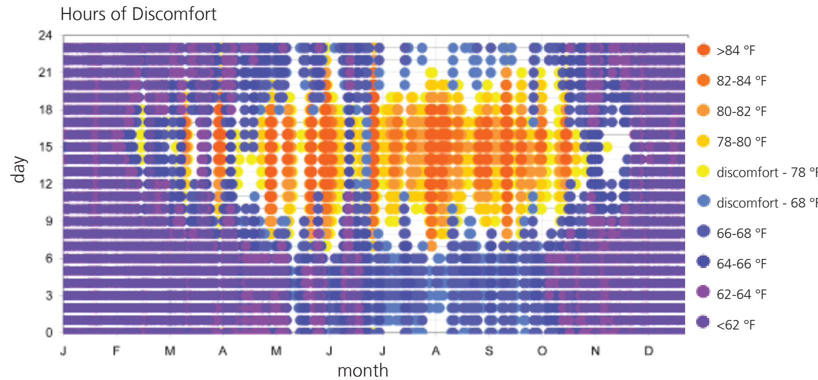
The ASHRAE-55 adaptive comfort standard gives a range of operative temperatures between 19°C and 28°C for conditioned buildings. Adaptive comfort standards for unconditioned buildings give a larger range between 17°C and 32°C that depends on occupants' habituation to the local climate.

How to predict thermal comfort potential for a climate?
The four primary climatic variables of air temperature, solar radiation, humidity, and wind can be analyzed together to see what kind of filter the architecture must form between it and the occupants. Ecotect Weather Tool and Climate Consultant, mentioned on Day 1, are excellent tools for such analysis.

How to predict thermal comfort potential of a site?
Microclimatic effects and localized conditions can have a significant influence on thermal comfort. In Day 1 we discussed tools related to solar access and geometry. In addition to those, we analyze a particular site for access to wind and water. When there are significant differences between a site and the closest climate data, we either set up a weather station on site if there is enough time to collect useful data, or we normalize TMY data for local conditions using specialized software called Meteonorm.

How to predict the amount of energy needed to keep a space comfortable?
All energy simulation software attempts to quantify energy demand in some fashion. The sophistication of the calculation engines and algorithms vary from rules of thumb to steady state to physically accurate interactions. This represents a broad spectrum of accuracy and complexity. When simulating energy use it is therefore important to understand the limitations and assumptions of the model because there are many "black box" energy programs that have insufficient documentation to ascertain their liabilities. Some commonly used software include: Ecotect, HEED, DOE-2, eQuest, TRNSYS, IES Virtual Environments, and EnergyPlus.

How to predict thermal comfort in a non-conditioned space?
It is one thing for software to report how much energy machines are

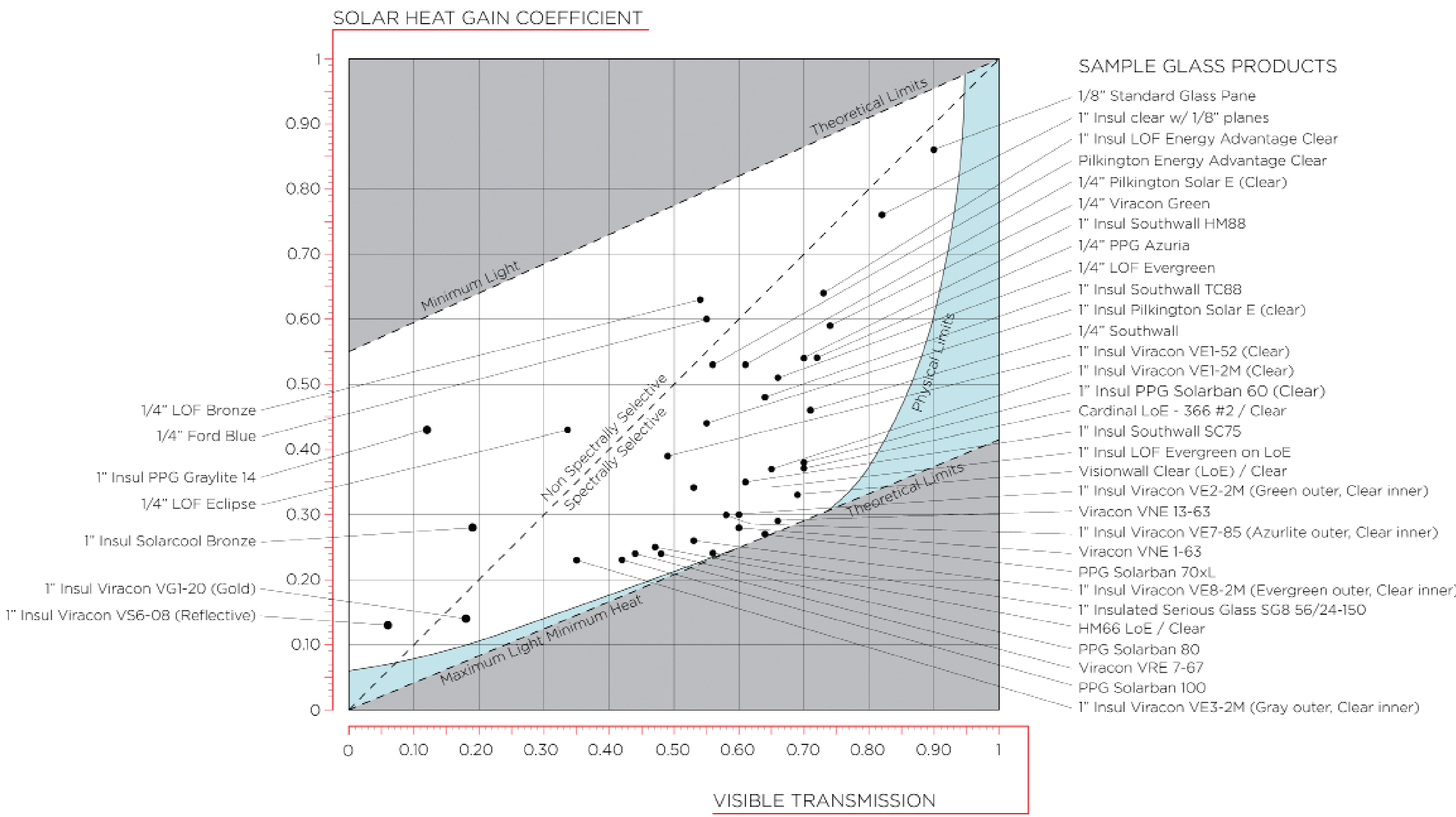


Simulation of occupant comfort in an unconditioned building in a cold climate.

using in a building, but it is quite another to report how an occupant is likely to feel. Few simulation programs accurately predict thermal comfort because it is difficult to simulate either the contribution of thermal mass to the thermodynamics of a building envelope or to the occupants therein. EnergyPlus is a simulation engine developed by the US Department of Energy that works from fundamental physical principles to simulate all of the thermodynamic exchanges that occur between the climate, a building, and an occupant. EnergyPlus is open source software, which means that it is transparently coded, but it also means that there are several third-party interfaces to the engine, including IDF Editor, Open Studio for Sketchup, Comfen, and Design Builder.

How to predict thermal bridging and moisture migration?
The complex interactions between heat and moisture within envelope assemblies directly influence energy consumption but are beyond the scope of what energy programs typically simulate. Analysis of thermal bridging and condensation require specialized software when trying to predict the performance of unusual interactions. THERM is software that calculates two-dimensional heat-transfer effects in building assemblies by modeling local temperature patterns. WUFI is software that allows realistic calculation of not only heat flow but also moisture transport through assemblies. It uses actual weather data and actual material properties of vapor diffusion and liquid transport.

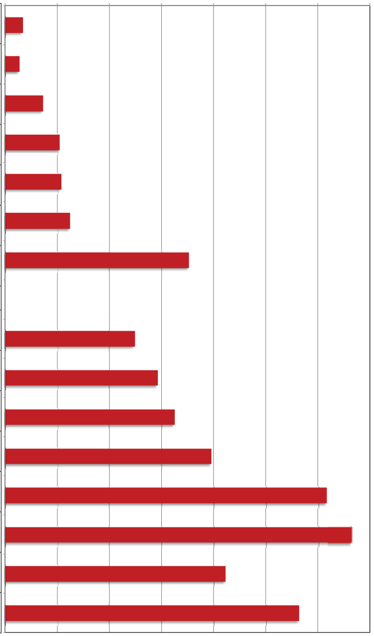
resources and rules of thumb

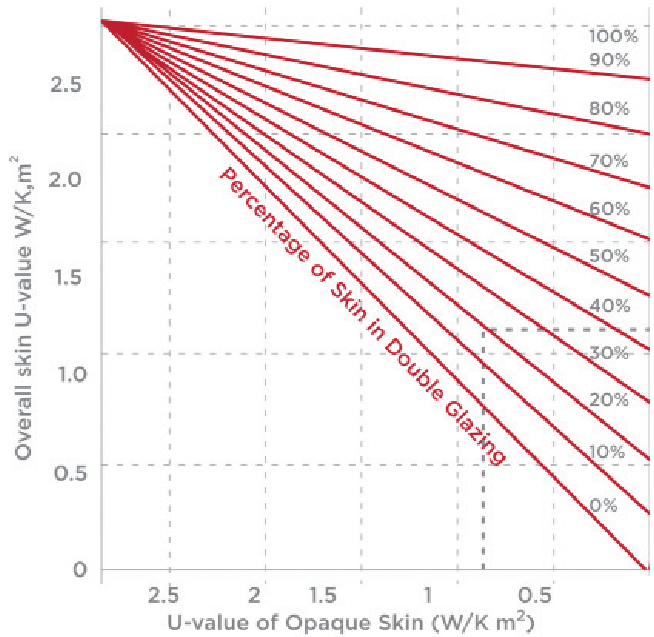


Common glass types organized by relationship between heat and light transmission

R Value (SI) by Assembly

300mm concrete	0.17
1-pane glass, alum frame	0.14
2-pane glass, wood frame	0.36
2-pane, low-e, argon, wood frame	0.52
3-pane glass, wood frame	0.53
25mm Fiberglass	0.62
25mm Aerogel	1.76
50x100 metal stud @ 400	1.24
50x100 metal stud @ 600	1.47
50x150 metal stud @ 400	1.63
50x150 metal stud @ 600	1.98
50x150 wood stud @ 400	3.08
50x150 wood stud @ 600	3.33
50x100 metal stud @ 400 w/ 25mm ext rigid	2.11
50x100 metal stud @ 400 w/ 50mm ext rigid	2.82





Relationship of glazing to opaque envelope for insulation performance. Adapted from Brown 2001, 47.

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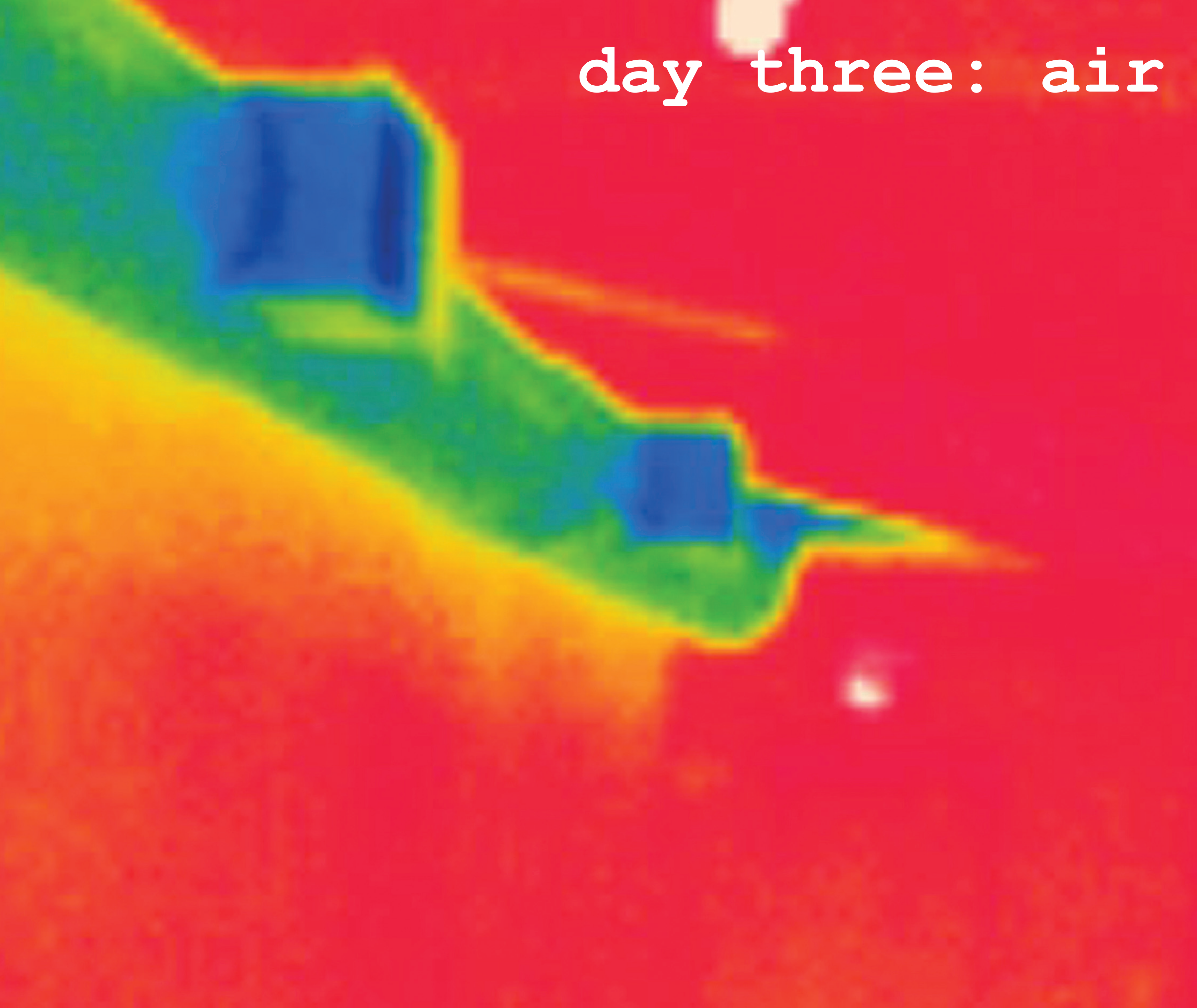
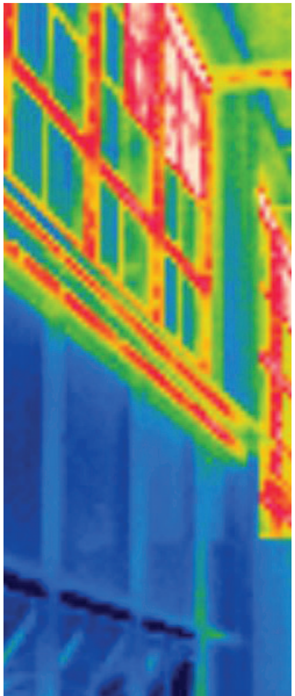
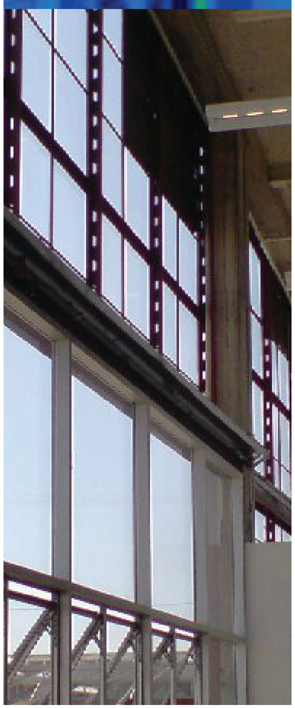
COMFEN (windows.lbl.gov/software/comfen/comfen.html)


day three: air





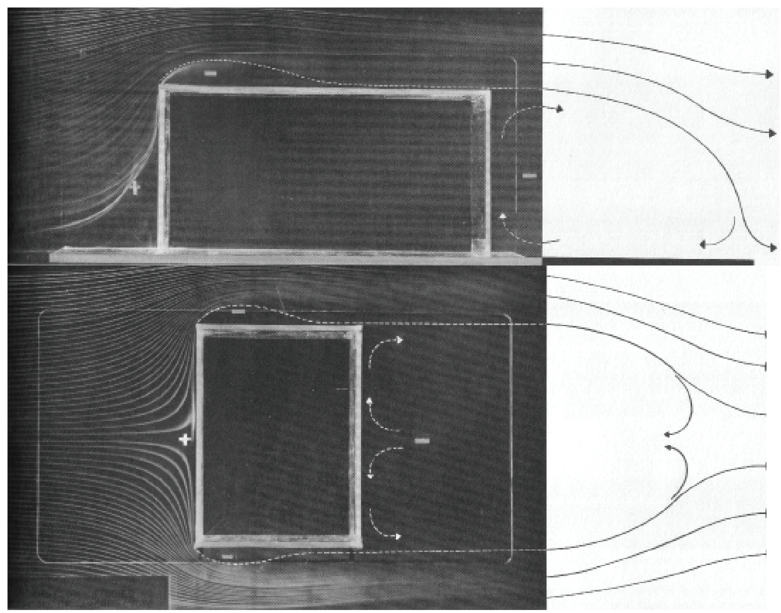
ventilation

What drives natural ventilation? Is it heat or wind?
Air moves by pressure differences. These differences can be induced by wind or heat. As air cools it becomes denser and sinks, displacing warmer air which, in turn, rises. Pressure-driven air movement is the result of a force (such as a fan or the wind) creating positive pressure on the windward side and negative pressure, or suction, on the leeward side. Both of these mechanisms commonly take place in buildings, although some strategies rely on one method over the other. In either case, the architectural envelope can filter the ambient air to control ventilation rates.

Is ventilation for fresh air the same as for cooling?
Ventilation is the term used for both providing fresh air and providing cooler air to the interior. Air needs to be exhausted because CO_2 accumulates in an occupied space. Codes (such as ASHRAE 62.2) require a minimum ventilation rate that varies by building type. For most types, a barely perceptible ventilation rate of 7-9 L/s is required. As air is exhausted, either naturally or mechanically, fresh air must take its place and so there needs to be a clear path for its entry into the building. When outside air is introduced for cooling, it replaces the interior air that has warmed up and needs to be exhausted. This kind of ventilation for cooling can be driven by wind, heat or mechanically by fans. Whole-building fans use one-tenth the energy of mechanical air-conditioning systems.

How do ceiling fans cool if they don't provide fresh air?
Air moving across the skin causes localized evaporation, which can have a cooling effect of 2-4°C. This results in perceptible cooling even though the air temperature in the room has not dropped. The cooler the air that moves across your skin, the faster the heat exchange can happen and the faster you will feel cooled down. Ceiling fans use a small percentage of the energy used by mechanical air-conditioning systems and are often helpful in supplementing air conditioning for comfort.

How big should my window openings be for cross ventilation?
Wind causes a positive pressure on the windward side and a negative pressure on the leeward side of buildings. To equalize pressure, fresh air will enter any windward open-



Wind tunnel test of a model in section and plan showing regions of positive and negative pressure. From Olgyay 1963, 103.

con•vec•tion/kən'vekSHən/

the movement caused within a fluid by the tendency of hotter and therefore less dense material to rise, and colder, denser material to sink under the influence of gravity, which consequently results in transfer of heat.

ing and be exhausted from any leeward opening. In summer, wind is used to supply as much fresh air as possible while in winter, ventilation is normally reduced to levels sufficient to remove excess moisture and pollutants. The volume of airflow depends on the smaller of the two apertures and the outdoor wind speed and direction. Ventilation inlets should be oriented perpendicular to prevailing winds, and the building should have a narrow floor plate that is generally no more than 50'. Interior partitions can block cross ventilation so they need to be studied to keep the path from inlet to outlet open to the air flow.

How fast does the wind have to be blowing for effective ventilation?
Not all natural ventilation depends on wind movement. Buoyancy ventilation may be temperature-induced (stack ventilation) or humidity induced (cool tower). The rate of stack ventilation depends on the smallest of the inlet, throat and outlet areas, the vertical distance between inlet and outlet, and the temperature differential between the indoor air at the bottom of the stack and the air leaving the top of the stack.

How can we use buoyancy to our advantage?
Even without full ventilation, the natural buoyancy of warm air can help increase comfort. In rooms with a high enough ceiling (generally over 10') hot air will stratify out of the occupied zone. If this bubble of hot air is not exhausted it will start to warm the ceiling and will radiate heat back down to the occupants, but the hot air cannot transfer heat to the occupants as long as the air is not being mixed. See "Machines" for a full discussion of displacement air.

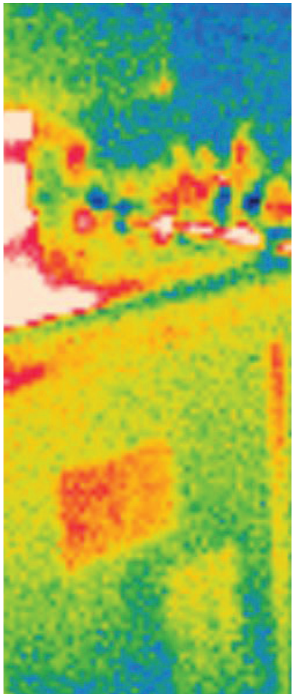
Is it possible to naturally ventilate if outdoor air is warmer than indoor air?
The density of air depends on temperature and humidity (cool air is heavier than warm air at the same humidity and dry air is heavier than humid air at the same temperature). In a cool tower, the cool air supply to the space is pressurized by weight of the column of cool air above it. Cool tower ventilation is only effective where outdoor humidity is low. Cool tower ventilation rates depend on the smallest

Thermal stack used to ventilate a classroom in Los Angeles. Image courtesy of Daly Genik Architects.

of the inlet, throat and outlet areas, the vertical distance between inlet and outlet, and the temperature and humidity of outdoor air.

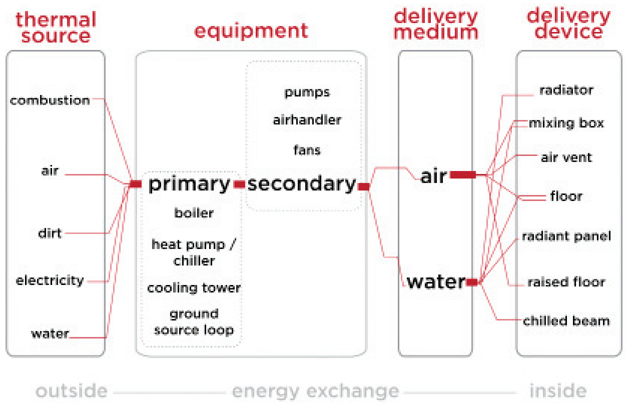
Do double-skin facades make sense?
As a vented cavity to protect shading devices from the elements, double-skin facades have their place. However, if the cavity is not sufficiently vented the trapped bubble of hot air transfers heat to the inside. In cold climates, this strategy makes sense, particularly if the hot air is distributed to the parts of the building that most need the energy. In temperate climates and warm climates this hot air can be a liability if it is not thoroughly and immediately vented. In hot climates, double-skin facades can be effective as a waste air plenum to exhaust stale air as a thermal buffer against an inhospitable climate.

What is the difference between infiltration and ventilation?
Gaps between materials can result in unintended air movement through the envelope. Tightly-constructed buildings typically have an infiltration rate of 0.5 air changes per hour (ACH) whereas poorly-constructed buildings can allow 2 ACH or more. As opposed to operable windows or dampers, leaks do not allow occupant control. These leaks move unwanted air, carrying heat and moisture, through the building. Infiltration is a large energy sink, particularly in cold climates.



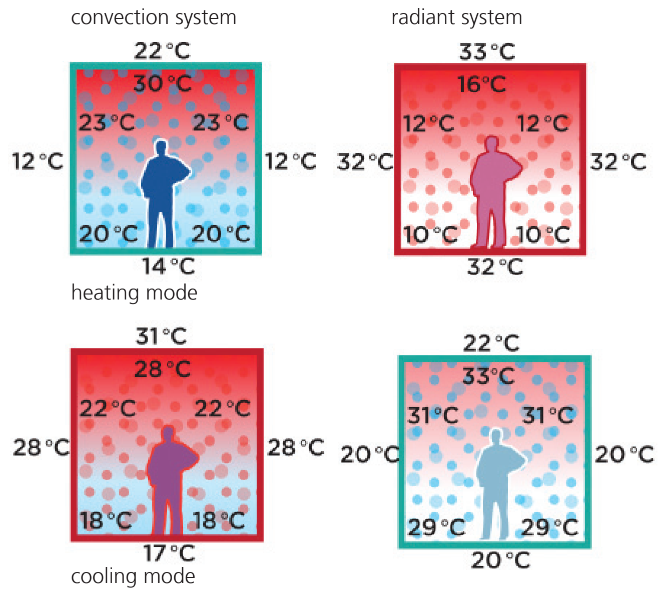
machines

Machines, by which we mean mechanical systems or HVAC (heating, ventilating and air conditioning) equipment, supply or extract energy to make a space comfortable. Because machines are expensive and typically require energy from the grid, we see them as a supplement to the primary energy-balancing mechanism of the building, the architectural filters. Therefore, machines should be as efficient as possible in using fuel or electricity to condition the space. The way in which conditioning is delivered should be comfortable, without drafts or uncontrolled cooling or overheating. Most importantly, the aesthetic impact of the machines should be consistent with the architectural intention, both within the space and on the building envelope.



The fundamental components of a heating or cooling system.

Does the building need to be sealed to be energy efficient?
Many mechanical engineers prefer sealed buildings because they are easier to control, to balance and to deliver the controlled range of temperature and humidity. However if exterior conditions are comfortable and natural ventilation can be used, it will be more energy



Air-based systems require extreme air-supply (hot in winter, cold in summer) which consumes more energy and less comfortable. Adapted from Moe 2010, 76.

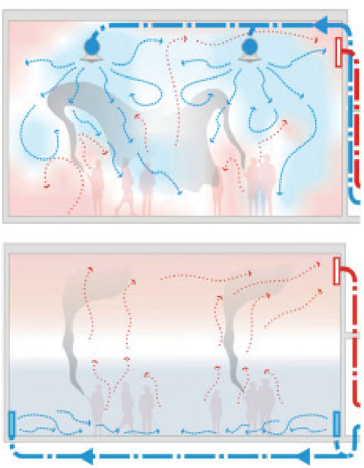
efficient to open the building during those times and to turn off the mechanical system. This building is then considered a mixed-mode building. As codes adjust to pressure from architects and owners, naturally-ventilated and mixed-mode buildings are gradually becoming the norm.

Is thermal comfort different in a sealed building as opposed to a mixed mode building?
The prevailing comfort standards used by mechanical engineers (ISO 7730 and ASHRAE 55) define a range of temperatures and humidity levels at which most people say they are comfortable. The standards assume static indoor conditions that are common to mechanically conditioned buildings, regular business clothes and behavior. Research has shown that people describe

radiant and convection systems

a broader range of comfort conditions when the building is open to natural ventilation, not sealed for conditioning. The Adaptive Comfort Standard takes into account not only the air temperature, but also the temperature of surrounding surfaces (Mean Radiant Temperature) and accounts for variations in air movement, clothing and metabolic levels, and seasonal expectations.

Will I need a cooling tower on the roof?
In broad terms, mechanical systems move heat into or out of the building, depending on what conditions are required inside. To cool a building, heat is gathered from the interior and dumped outside. It can be dispersed into air (cooling tower or condenser), water (hydrothermal exchange), or the ground (geothermal exchange).To heat a building, you can burn a fuel (boiler or furnace) or use electrical resistance. You can also use a heat pump in reverse to move heat from the outside to the inside. Similar to cooling, the heat pump can use air, water, or earth as a medium for heat exchange. The question of which system is most efficient and effective involves a complex balance among the relative need for heating, cooling, dehumidification, and the scale of energy that needs to be moved.



Mixed-air supply (above) vs. Displacement cooling (below)

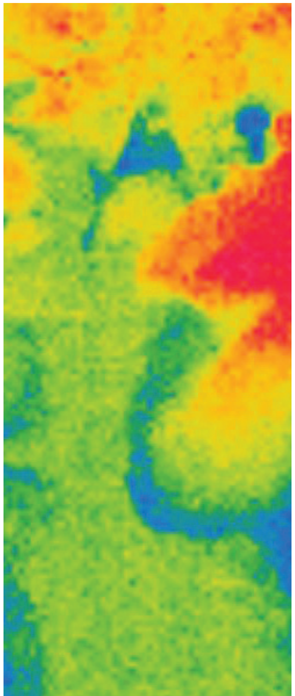
How do you choose between an air system and radiant system?
Each system has some advantages, some disadvantages and both have important architectural impacts. Compared with radiant systems, air systems have a larger capacity for cooling, a faster response time to changing loads, they tend to be less expensive and they supply ventilation air along with conditioning air in the same system. Radiant systems are typically more energy efficient, they are quiet, they work better with natural ventilation and they provide greater comfort with a more gentle failure mode.

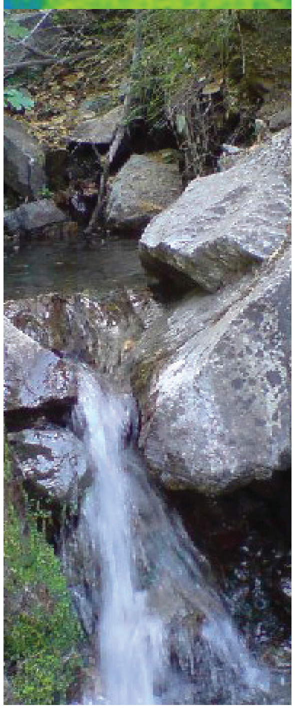
What is the difference between using ducts in the ceiling and underfloor air distribution (UFAD)?
From ducts in the ceiling you need enough velocity to mix the air and deliver it to the occupant which means more fan power, more noise and the potential for drafts with little occupant control. Delivering air from the floor, the air is delivered at a higher temperature for cooling, which means greater energy savings in cooling the air, and a lower velocity which means reduced fan power. With UFAD the occupant has greater personal control of air delivery through the floor vents which they can reach. UFAD systems are typically more expensive and require a raised floor of 30-50 cm.

What is displacement air?
This is a low energy, air based system that delivers air through registers in the floor or walls. It works by delivering low velocity conditioned air at the floor level, creating a horizontal laminar flow of cool air. When the flow reaches a person, the person's body heat creates a plume of air that rises to the ceiling, drawing the cooler air around them. This cools the occupants directly and uses the natural buoyancy of hot air to deliver the stale air to a high level exhaust.

What types of radiant systems are possible?
Radiant heating can be provided by running hot water or steam through radiators (usually wall mounted or floor mounted), ceiling mounted panels, tubes in the floor or ceiling slab, or tubes installed under a concrete slab or wood floor. Ceiling panels and slabs also work for radiant cooling provided by running chilled water through the panels or tubes.

What are the limits to using radiant systems?
The heating applications of radiant systems are mostly limited by the slower response time compared to air systems. They are inappropriate for spaces with rapidly changing loads, such as spaces that will be occupied for a few hours such as auditoria. Radiant systems also tend to have a limited cooling capacity. If the floor is too cool, discomfort from cold feet might happen. The cool temperature of the floor has to remain above the wet-bulb temperature to avoid condensation which limits use in climates with high humidity.





machines

How does ventilation (fresh air supply and used air exhaust) work with radiant systems?
For buildings with operable windows fresh air and exhaust air are handled by natural ventilation. In cold climates, trickle vents allow slightly tempered outside air directly to the room without creating cold drafts and without mechanical assistance. For large buildings, ventilation air can be supplied in ducts, but because it is only fresh air and not conditioning the space, the ducts can be 25-30% the size of a full air system. Ventilation air also uses less fan power and has fewer restrictions on the placement of registers.

What is a chilled beam?
A chilled beam consists of a hydronically cooled surface, usually shaped like a deep beam, mounted in a ceiling cove. The chilled beam uses convective air flow instead of fan power to deliver cooled air to the room below. They can deliver higher levels of cooling than radiant panels or surfaces, but require close coordination of other ceiling systems such as lighting, sprinklers and structure.

Are heat exchangers energy efficient?
Heat exchangers use a temperature differential to transfer heat from one stream of air or water to another stream. This enables the mechanical system to capture rather than waste the energy that was originally used to condition the water or air.

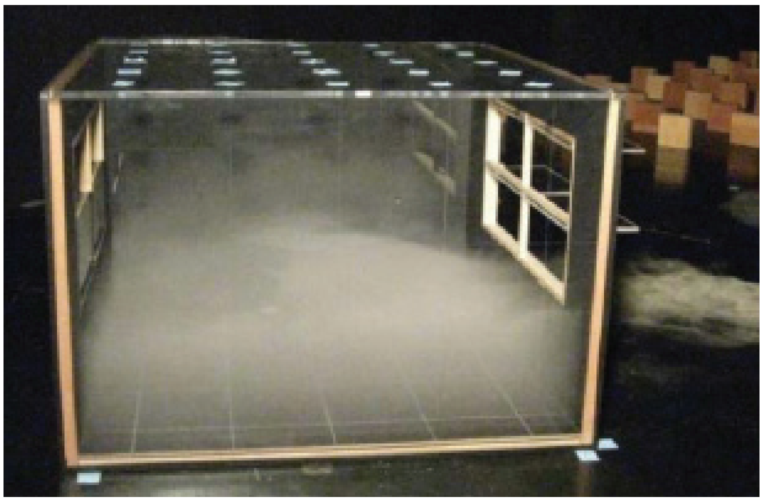
Is air conditioning the only way to deal with high humidity in warm climates?
There are currently two ways used to extract moisture from the air. The first is to cool the air below dew point (wet bulb temperature) which condenses the moisture into water. The air is then reheated and becomes drier since it is carrying less water vapor. This is how compressors deliver cooler, dry air in air conditioned buildings. The cycle takes a lot of energy and requires a sealed building to contain the conditioned air. The second method is to use a desiccant a material with the unique property of absorbing water vapor from the air. The challenge with desiccants is providing a large enough surface area to absorb enough moisture and that they need to be heated in order to recharge them. The reheating often involves the use of fossil fuels, but can also be accomplished with solar panels if there is sufficient solar radiation available.

Can evaporative coolers be used instead of compressor-based air conditioners?
Evaporative cooling is based on the process of changing liquid water into vapor. In the change of state from liquid to gas, the water takes up heat from the air and the temperature of the air drops while the relative humidity of the air rises with the increase in water vapor being held in the air. In humid climates, the capacity of the air to absorb water vapor is limited, so the cooling effect from evaporation is also limited. However, in dry climates with low relative humidity, evaporative cooling can be an effective replacement for air conditioning and requires significantly less energy. Evaporative cooling can be delivered through a direct evaporative cooler which adds water vapor directly to the air in the room. Direct evaporative coolers use energy to pump the water and fans to move air through a wetted medium. Cool towers introduce water at the top of a chimney and the cooler moist air falls via gravity down the chimney into the space with no fan assist. Indirect evaporative coolers use evaporation to cool air which is then run through a heat exchanger with the room air to cool it down.

tools and software

How to measure air speed in a building?
Air speed is measured with an anemometer and the units are meters per second or kilometers per hour. Wind vane type meters have lower sensitivity than do hot wire type meters. To get an accurate reading place the device perpendicular to the flow of air. Most air sources are variable, particularly at lower velocities, so take multiple readings over a period of several seconds until you find a concensus air speed.

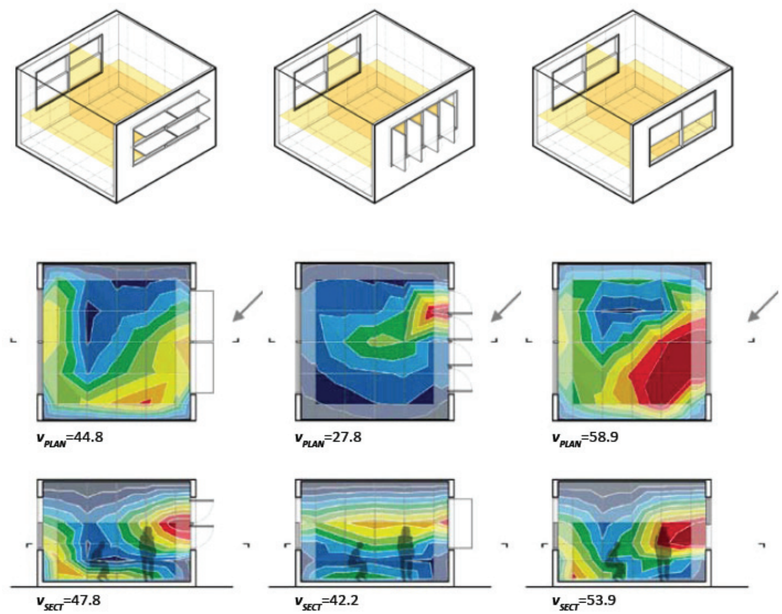
See Day 2 for other thermal comfort measurements: thermometer, hygrometer, radiant thermometer, IR camera. See Day 2 for climate and site analysis, energy modeling, and comfort modeling.



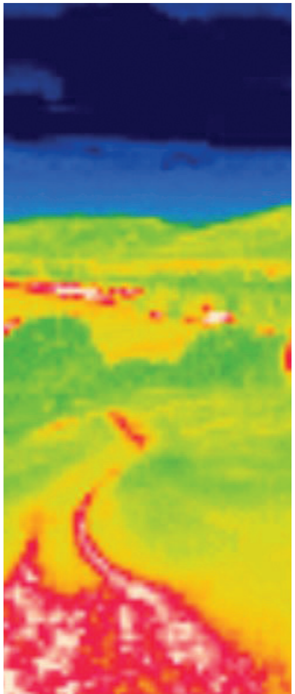
Model being tested in a boundary-layer wind tunnel. Image courtesy of P.W. Hildebrand.

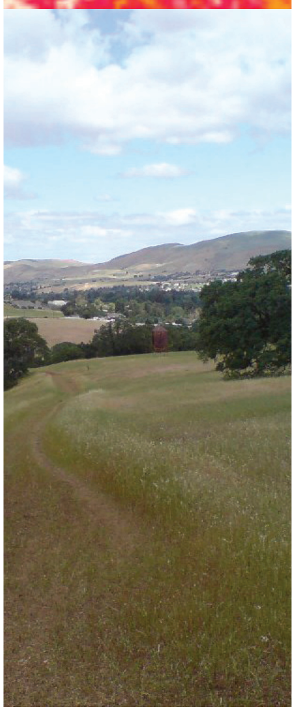
How to predict air movement?
Wind tunnels are laboratory scale facilities that generate a known air stream for use with physical models. While many wind tunnels are used to study the aerodynamics of aircraft, cars and space vehicles, the flow patterns of wind and air around and within buildings require a boundary layer wind tunnel to simulate the turbulence of the earth's surface. Wind tunnels can generate data for the velocity, direction of flow and pressure variations in and around buildings. They also enable visualization of the flow patterns but cannot easily model thermally driven air movement such as stack ventilation.

Computational fluid dynamics (CFD) uses algorithms and calculations to simulate situations that involve fluid flows, including the flow of air. CFD analysis is increasingly used to study complex air flows and thermally driven air movement in and through building components (such as double skin facades) and urban spaces between and around buildings. While CFD offers some advantages compared to wind tunnel testing and simplified rules of thumb, there remain many problems with the ability of the computer power to handle the complex conditions of architecture. CFD validation still requires wind-tunnel data and this is likely to be the case for the foreseeable future.



Iterative testing of facade design for cross ventilation. Image courtesy of P.W. Hildebrand.





resources and rules of thumb

- Ventilation requires nearly 75% less air volume to be delivered than thermal conditioning.

- When occupants control their environments they have a greater range of tolerance for temperature and humidity variation.

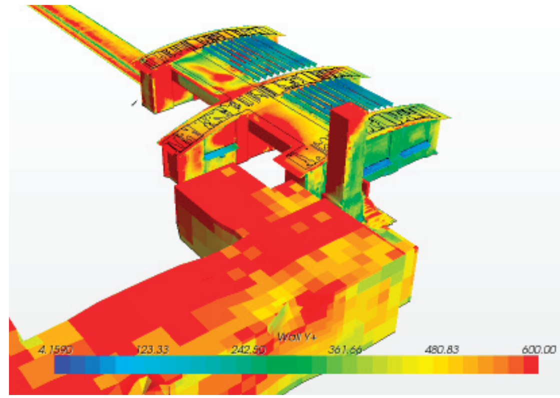
- Air speed thresholds for conditioned and naturally-ventilated buildings:

0.20 mps barely noticeable
1.00 mps upper limit for air-conditioned space, good for natural ventilation in hot/dry climates
2.00 mps natural ventilation in hot/humid climates
4.60 mps gentle breeze outdoors

- Air movement against the skin, even when it's warm air, can have a cooling effect of 2-4°C.

- Ventilation inlets should be oriented perpendicular to prevailing winds.

- The more the architecture and the envelope create comfortable conditions for the occupants, the less mechanical equipment is needed. This results in a lower first cost for the machines and the energy to operate the building is reduced, resulting in a smaller carbon footprint.



CFD analysis of wind pressures on a bus and ferry terminal.

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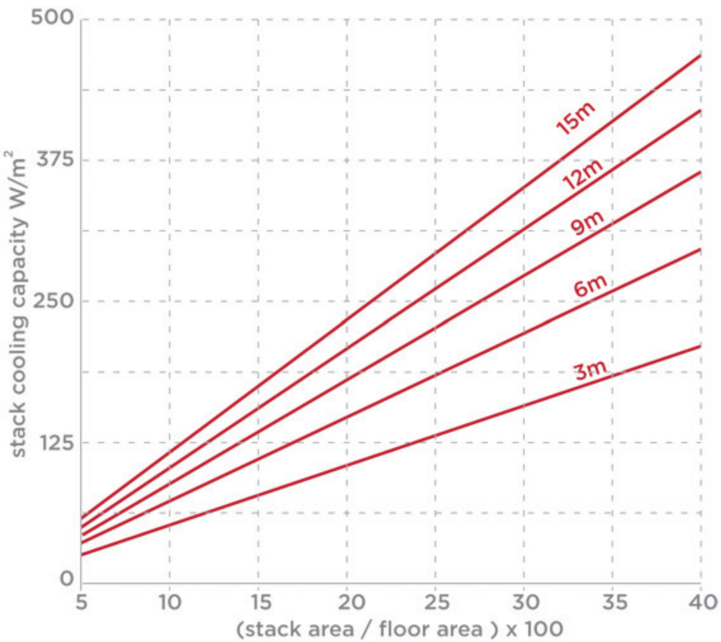
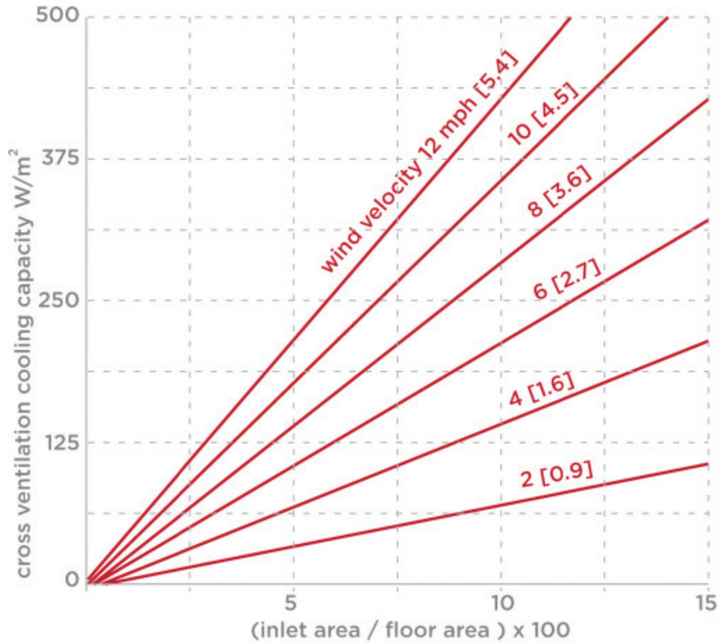
Books

Architectural Aerodynamics by R.M. Aynsley, W. Melbourn, and B.J. Vickery. London: Applied Science Publishers,1977
Natural Ventilation in Buildings: A Design Handbook by Francis Allard and Mat Santamouris, (Best (Buildings, Energy and Solar Technology))
Moving Air for Comfort by Ed Arens et al. Original Citation: ASHRAE Journal, May 51 (25), 8 – 18, 2009 1. Can be downloaded: escholarship.org/uc/item/6d94f90b
High-Performance Building by Vidar Lerum. Hoboken, N.J. : John Wiley & Sons, 2008



Cooling capacity of stack ventilation dependent on stack area, floor area being cooled, and height of stack. Adapted from Kwok 2007, 147.



Cooling capacity of cross ventilation dependent on inlet area, floor area being cooled, and wind velocity. Adapted from Kwok 2007, 147.

equation for stack ventilation cooling

qV = 1.2 V dT
= 1.2 (0.65 A √ (9.81 h (Tin - Tout) / Tin)) Tin - Tout

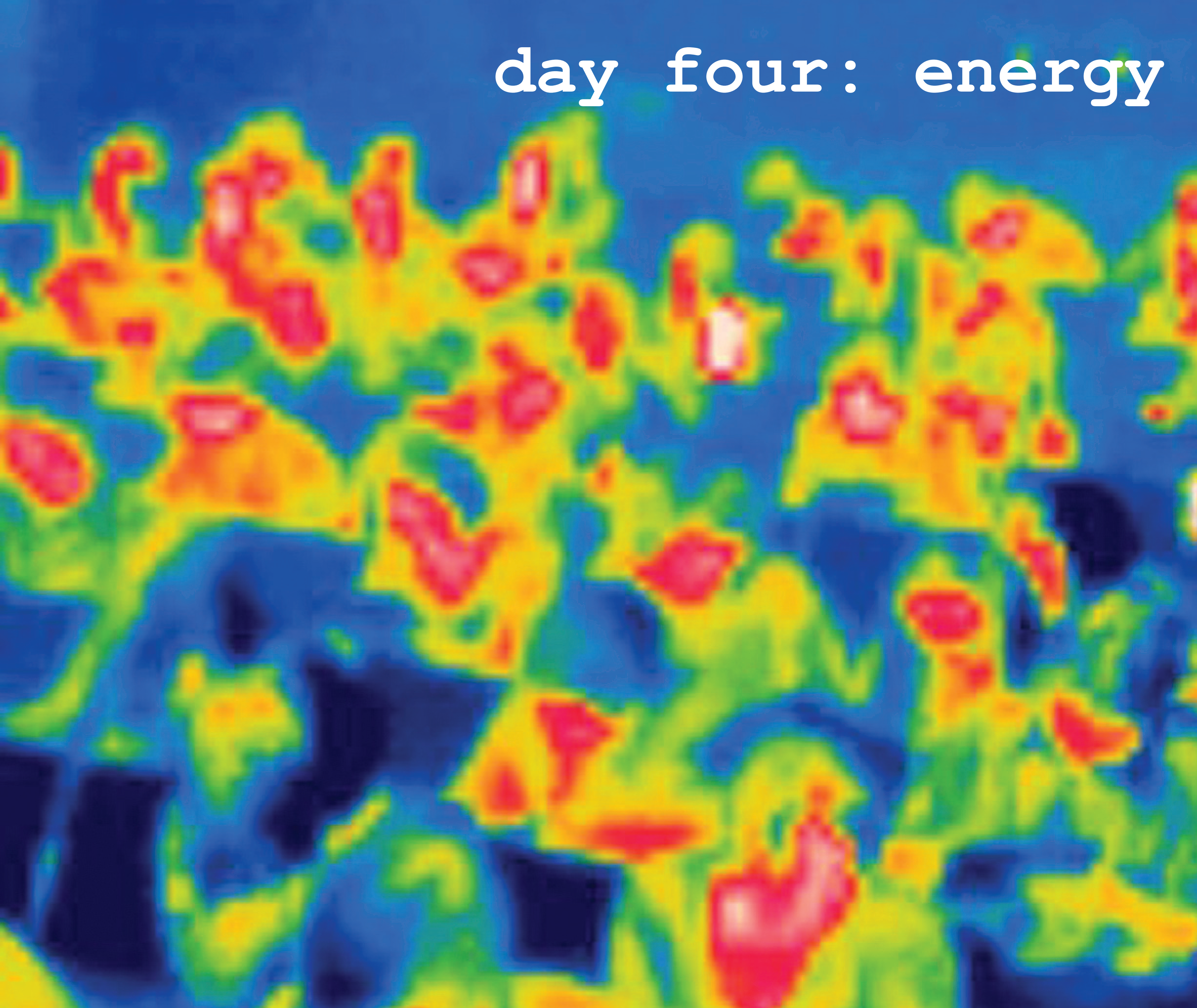
qV = energy loss
V = flow rate (L/s) = K A √ (g h (Tin – Tout) / Tin)
K = discharge coefficient = 0.65
A = smallest area of inlet, throat, outlet (m2)
g = gravitational constant = 9.81 m/s2
h = height from inlet to outlet (m)
Tin = interior temperature (°K)
Tout = outside temperature (°K)
dT = Tin – Tout (°K)
* outside temp must be less than inside

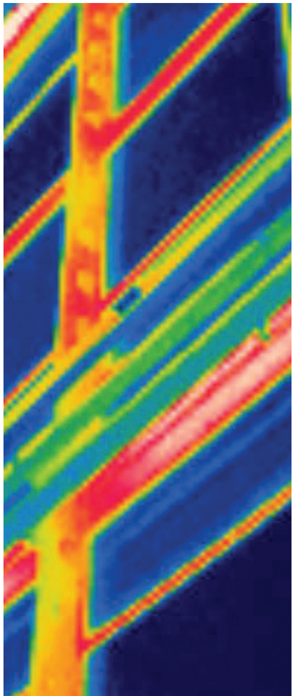
equation for cross ventilation cooling

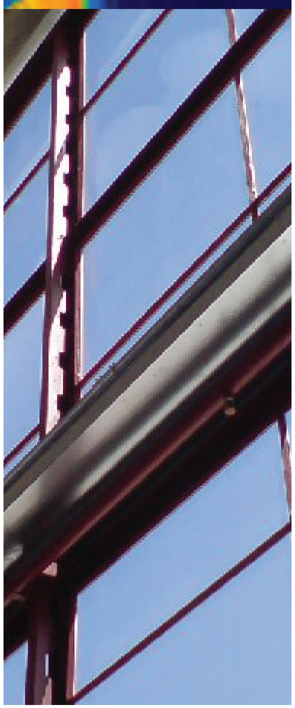
qV = 1.2 V dT
= 1.2 (1000 Cv A v) (Tin - Tout)

qV = energy loss
V = flow rate (L/s) = 1000 Cv A v
Cv = wind direction relative to bldg
* 0.50 – 0.60 (perpendicular); 0.25 – 0.35 (diagnol)
A = smaller of inlet or outlet area (m2)
* must account for window operation
v = velocity of air (m/s)
dT = (Tin – Tout)
* outside temp must be less than inside

day four: energy



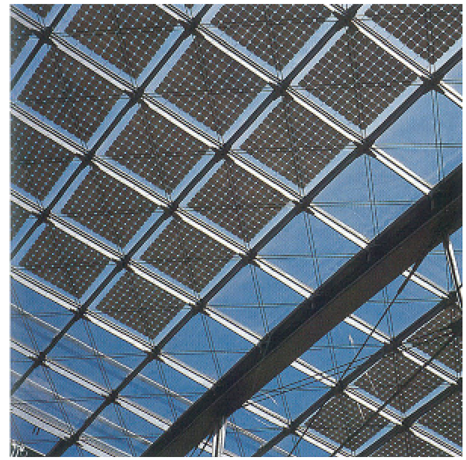




renewable energy

Renewable energy should be considered supplementary to an effective envelope and efficient mechanical systems. Once the loads are reduced by the architecture and the machines that address these loads are efficient, the energy that is required is minimized and the economics of renewable sources begin to make sense. Renewable site energy sources presently include sun and wind. Some few sites with streams or rivers may have the potential for small-scale hydro, but these are unusual. Using the sun, photovoltaic panels (PV's) deliver electricity and solar thermal collectors deliver hot water. Wind turbines use site wind to generate electricity.

What kind of PV is the most efficient?
Crystalline photovoltaic cells, both mono-crystalline and poly-crystalline, yield the most energy per unit area. Thin film PV's, available on either glass or a flexible substrate, produce approximately 25% of the energy for the same unit area compared with crystalline. Flexible thin film PV's are considerably less expensive, though, so they are less expensive per watt generated as long as area is not an issue. Thin film PV's are also much more shade tolerant than crystalline. The most efficient PV today is gallium arsenide, which are so expensive they are primarily used in space.



Building-Integrated PV modules that are sandwiched between two pieces of glass. From Schittich 2003, 31.

What is the optimal orientation and tilt for the PV panels?
This is based on a number of factors: the latitude, the daily patterns of clouds or fog, and the season and time of day you most need the electricity. For example, at 38 degrees North, a 30-degree tilt off the horizon is optimal when facing south for annual production (see the graph on the following page). However if you need more electricity in the summer or in the afternoon the optimal tilt and orientation will be different.

Can the PV panels be horizontal or vertical?
Sometimes the optimal tilt or the optimal orientation does not work with the aesthetics of the building design. PV panels can be mounted in almost any orientation with the understanding that you will lose generating efficiency. With horizontal panels you will lose efficiency during winter generation and gain some during summer. Over the year, at 38°N, you lose approximately 13% efficiency by laying the panels flat instead of mounting them at 30°.

Mounting PV panels vertically tends to have a larger impact on efficiency (as much as 40% loss in annual production when oriented south at 38°N). However, vertical panels can serve double duty as an integral part of a curtain wall or as a shading screen that is generating electricity as well as shading. This double use can de-emphasize the efficiency of production in tradeoff with an architectural element that would be paid for anyway.

Do PV panels have to be black or purple-blue?
No, the black and purple-blue color is usually a coating applied to the cells to increase efficiency. Some manufac-

turers are producing red, green, silver and gold cells as well. The loss in efficiency may be less important than the improved aesthetic contribution, as the color may allow applications where the blue / black cells would not be acceptable, such as vertical applications.

What happens if a tree, a roof parapet, a chimney or a nearby building shades some of the panels?
For crystalline cells, the PV array is usually wired in strings, which are then wired in series. This means that shade on one panel or part of a panel will radically reduce energy production for the entire string of panels. One solution is to design the circuits to recognize predictable shade patterns so that the minimal number of panels are affected. Another is to use micro-inverters so each panel can produce electricity independently. A third solution for shaded locations with sufficient area is to use the thin film technology that is tolerant of partial shade on the array.

Does it make sense to use a wind turbine for a single building?
Yes if you have good wind resource, can find an appropriate location on site, and the turbine noise will not be objectionable. Wind turbines are manufactured at many scales, from domestic to utility scale and for various wind speeds. The selection of the appropriate turbine for the project is crucial.

What kind of wind should there be on site to consider using wind power?
Clear, non-turbulent steady air is ideal. Gusts of high wind velocity and long periods of calm are both less than optimal for electrical generation.

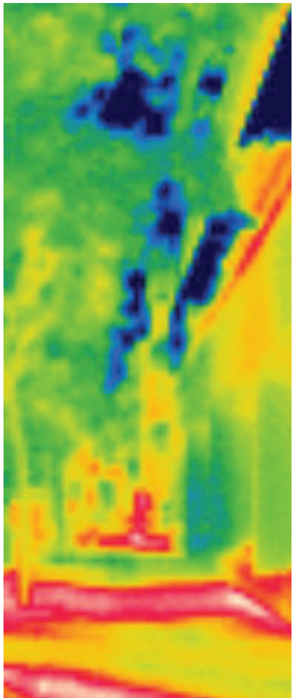
Does the project have to be in the countryside to use wind as a renewable resource?
It is often easier to have good conditions for wind availability in a rural or suburban site or at the seashore, but wind turbines are increasingly being developed for urban sites. Many of these are smaller in scale and designed to be mounted on a building with minimal vibration and noise generation.

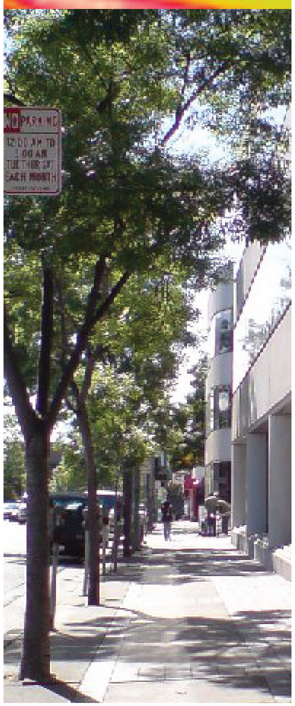
Are storage batteries necessary for PV or wind generated electricity?
If the system can be connected to the electrical grid, no storage is necessary on site unless it is desirable to have a UPS system (Uninterrupted Power Supply) that can be charged by the PV array or a wind turbine. If the building is not grid connected and the site energy is the only electrical supply, a storage system will make sure there is electricity when it is not being generated on site. This would be during overcast hours and at night for the PV system and during period of calm for the wind system. Battery storage technologies are still expensive, bulky and are manufactured with toxic materials that will need special handling when discarded.

Is it worth considering solar thermal collectors for hot water and if so, how large an array will I need?
Solar thermal collectors (as compared with solar electric photovoltaic cells) are a widespread, well understood, use of the sun to deliver domestic hot water, to heat water for swimming pools, and to supplement the hot water for radiant heating systems. Solar thermal typically takes up much less space than solar electric panels and usually requires a back-up system such as an electric or gas water heater for cloudy and rainy days. Solar thermal can provide a significant reduction in energy costs for a building that uses hot water.

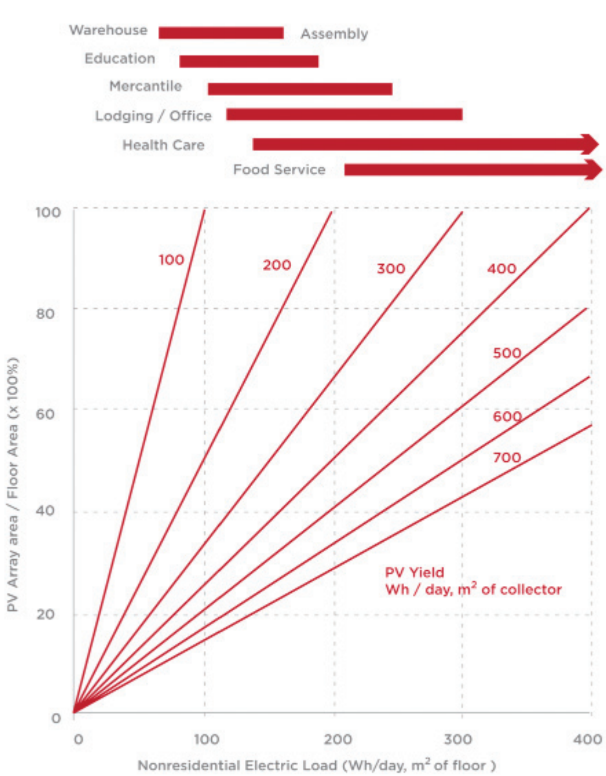
Does solar thermal have to be an ugly box on the roof?
While the most basic solar thermal collectors is a fairly simple glass covered black box, newer highly efficient evacuated tubes are more transparent and have some flexibility in both location and orientation, as long as the tubes receive sunshine and deliver heated water to a manifold for collection. While these are currently marketed as a utilitarian equipment, the potential exists to make them very good looking.

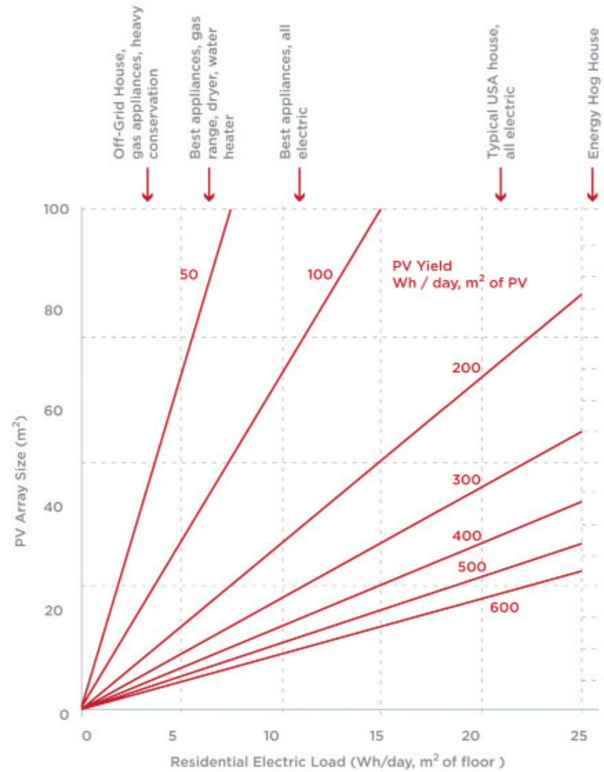

Building-Integrated evacuated tube collectors form guardrails. From Schittich 2003, 29.



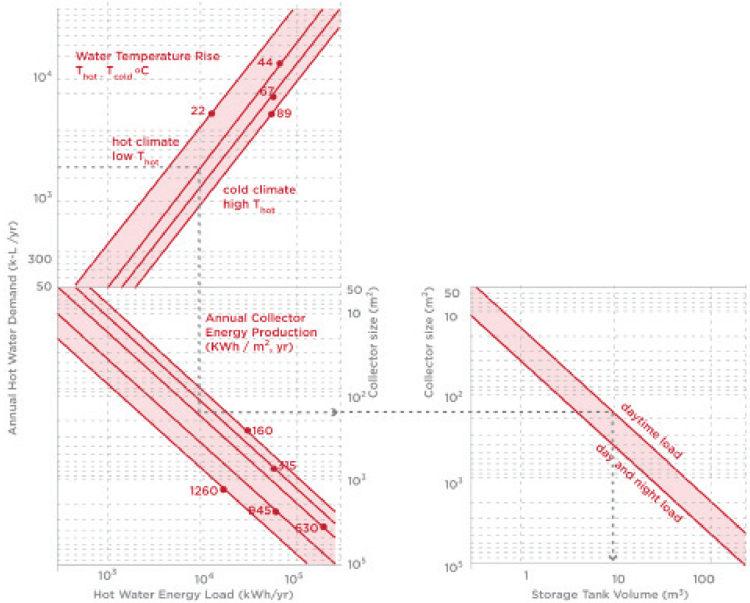


resources and rules of thumb

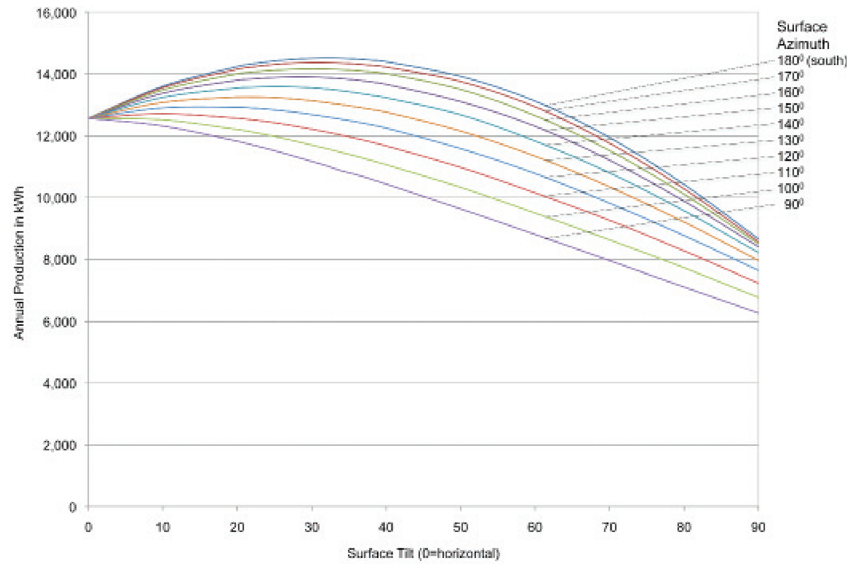




Adapted from Brown 2001, 224.



Solar Hot Water Collector Sizing. Adapted from Brown 2001, 236.



10kW (100 m²) PV Performance, 38°N Latitude

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Wind Energy Explained: Theory, Design and Application by J. F. Manwell et al. Chichester ; New York : Wiley, c2002
Solar domestic water heating by Chris Laughton. London: Earthscan, 2010

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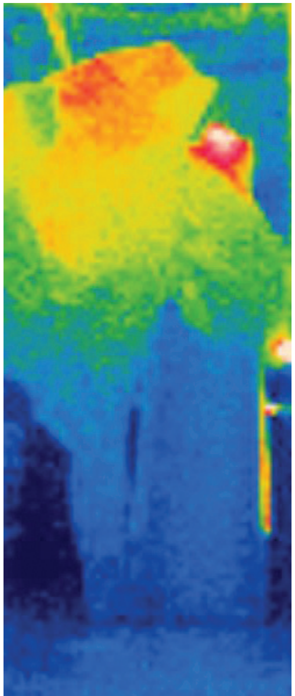
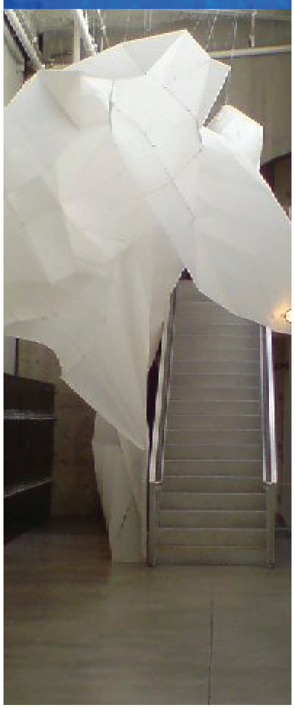
PV Watts (www.nrel.gov/rredc/pvwatts/): Photovoltaic sizing and output prediction software
International wind resource maps (www.nrel.gov/wind/international_wind_resources.html)
Hot Water Solar Evacuated Tube Collectors (greenterrafirma.com/evacuated_tube_collector.html)
Meteonorm (/meteonorm.com/products/software/): Weather data including solar radiation for any site worldwide





integration

In the normal architectural process, issues such as mechanical systems and thermal performance of the envelope are left until the design is developed enough that consultants can size and specify materials and machines. This seems to serve the architects well in that they are left alone to generate a design scheme and form without being constrained by technical concerns and engineers who say no. This also serves the consultants well in that they only have to run the energy models and other simulations once, which is usually what their fee can cover. This process often does not serve the performance of the building well in terms of energy efficiency, comfort or ecological performance. Firstly because possibilities of generating the design moves to be intrinsically high performance become closed out early in the process, and because the creative potential embedded in that technical knowledge is ignored, leaving the consultants to provide the best normative solutions they can to a project already conceived.

One way of addressing this is to develop a creative dialogue at the beginning of the design process; not to give the engineers and consultants the keys to the design car, but rather to let their conceptual understanding provoke and inform the design possibilities.

Integrated design process has come to be the recognized term for a design process that includes technical knowledge early in the design process. It has been adopted with particular passion by those in the sustainable design community as a means to include ecological considerations, understandably because so many early decisions impact the sustainable performance of the building. Along with the good idea of engaging everyone with useful knowledge early, it has also unfortunately come to mean a single all day meeting with everyone at the table going through a tedious checklist, not a design brainstorming session with key players at the table.

BIM is another aspect of the integrated design process that the profession seems to imagine guarantees smooth inclusion of simulations and sustainable knowledge. In our experience, BIM so far is a production management tool and has little if anything to do with generative information in the design process. Books of design guidelines for energy efficiency are similar. Our best performing buildings break the rules.

The third ubiquitous trend in approaching integrated design process is to ask the architect to become proficient with simplified simulation tools so that they can generate technical evaluations of their early design ideas without having to work with consultants. While we would never try to keep a designer from becoming smarter about their design, we are worried about the simplifications inherent in this type of software or design tool. In order to make them easy to learn and useful while design ideas are developing, many assumptions are embedded in the default settings. We advocate the use of advanced simulation tools early in the process rather than elementary tools that often oversimplify complex phenomenon and disguise the true potential of a design.

There are analytical tools that can make the design team smarter in advance of designing: site, climate, program. Site solar analysis tells you whether shading will even be necessary at the skin. A close look at historic buildings might help you overcome some commonly accepted guidelines. Climate analysis tells you whether mass might be helpful, leading to a set of thick walls and new ideas of heaviness, or whether stack ventilation will be a good option, leading to a tower for view as well as air. Sky analysis can tell you whether the color of light will be soft grey or a shocking yellow and blue. These are good things to know before you begin to design. We believe they open the door to invention.

There are also evaluative tools that can help you understand how a design proposition works. You can see the performance of a design or design alternatives in terms of sun, shade, daylight, sectional and plan organization, energy use, orientation, amount of glass, levels of insulation, programmatic organization etc. etc.

But in a successful design process, the evaluative tools cannot be put into practice without a design being proposed, which belongs with the architect. We have had clients ask us: what should the window to wall ratio be on this building? or what

level of insulation should I have in the roof? All before they start designing. This kind of information doesn't help before they have a design idea. We can only answer: we don't know - what are you trying to design and we'll see how it works.

To be effective, we need to work with architects who understand enough of the performance issues to be excited by the possibilities - even if just to ask us really difficult questions that may illuminate new ways of doing things. We are interested in thinking beyond the guidelines and conventional wisdom about finding new solutions.

In this way the technical understanding can open possibilities rather than be a set of constraints or rules that make boring architecture. In short, the laws of physics that determine the performance of architecture are at least as elegant as you want your architecture to be and should be put in service of that end.

As Professor Buntrock put it on the first morning, there was a flowering of structural invention following the Kobe earthquake. Fukushima has provided just such a catalyst to begin a flowering of energy invention from the most extraordinary architects in the world.

english-japanese dictionary

Aerodynamic(s)	空気力（学）	くうきりょく（ガク）
Aerogel	エアロゲル （透明断熱材）	
Air Conditioner	エア コン 空気調和器	 くうき ちょうわ き
Air distribution	空気分布	くうき ぶんぷ
Air duct	ダクト / 風道	かぜみち / ふうどう
Air handling unit	エア ハンドリングウニット	
Air motion	気動	きどう
Air supply	給気	きゅうき
Air temperature	気温	きおん
Anemometer	アネモメーター 風速計	 ふうそくけい
Artificial lighting	人工照明	じんこうしょうめい
Candela	カンデラ	
Central Heating	中央暖房	ちゅうおう だんぼう
Chilled water	冷水	れいすい
Clerestory	高窓	たかまど
Climatic chart	気候図	きこうず
Climatic region	気候区	きこうく
Comfort zone	快感帯	かいかんたい
Condensation	凝結 凝縮	ぎょうけつ ぎょうしゅく
Conditioned air	調和空気	ちょうわくうき
Conduction	伝導	でんどう
Convection	対流	たいりゅう
Cross ventilation	通風	つうふう
Daylight	昼光	ちゅうこう
Daylight factor	昼光率	ちゅうこうりつ

Dehumidification	減湿	げんしつ
Dew point temperature	露点温度	ろてんおんど
Double glazing	二層ガラス ペア ガラス	にそうガラス
Dry bulb temperature	乾球温度	かんきゅう おんど
Duct	ダクト	
Emissivity	輻射率	ふくしゃりつ
Energy	エネルギー	
Energy conservation	省エネルギー	しょうエネルギー
Exhaust air (gas)	排気	はいき
Existing conditions analysis	現況解析	げんきょう かいせき
Fan	送風機 / ファン	そうふうき
Field measuring	現場計量	げんばけいりょう
Floor heating	床暖房	ゆか だんぼう
Foot candle	フート キャンドル	
Geothermal energy	地熱エネルギー	ちねつエネルギー
Glare	グレア	
Heat capacity	熱容量	ねつようりょう
Heat exchange	熱交換	ねつこうかん
Heat gain	取得熱量	しゅとくねつりょう
Heating / heater	暖房	だんぼう
Heat pump	熱ポンプ / ヒート ポンプ	ねつポンプ
Heat transfer	熱移動	ねついどう
Hot air system	温風暖房	おんぷう だんぼう
Humid air	湿り空気	しめり くうき
Humidity	湿度	しつど
Illuminance	照度	しょうど
Illuminance distribution	照度分布	しょうど ぶんぷ

Insulation	断熱材料	だんねつ ざいりょう
Laminated glass	合わせガラス	あわせガラス
Latent heat (storage)	潜熱(蓄熱)	せんねつ(ちくねつ)
Lighting	照明	しょうめい
Luminance	輝度	きど
Luminance meter	輝時計	きとけい
Luminance ratio	輝度比	きどひ
Lux	ルクス	
Mean radiant temperature	平均輻射温度	へいきん ふくしゃ おんど
Mechanical ventilation	機械換気	きかいかんき
Mixed mode	混合モード	こんごう モード
Natural ventilation	自然換気	しぜん かんき
Negative pressure	負圧	ふあつ
Outdoor air	外気	がいき
Passive solar	パッシブ ソーラ	
Photometer	光度計	こうどけい
Photovoltaic cell (PV)	光電池	こうでんち / ピービー
Prevailing wind direction	最多風向	さいた ふうこう
Psychrometric chart	湿り空気線図	しめりくうきせんず
R-value	R値	アル あたい
Radiant energy	輻射エネルギー	ふくしゃエネルギー
Radiant heat	輻射熱	ふくしゃねつ
Relative humidity	相対湿度	そうたい しつど
Return air	返り空気 かえり くうき	レーターン エア
Saturated moist air	飽和湿り空気	ほうわ しめり くうき
Schematic diagram	系統図	けいとうず
Sensible heat	顕熱	けんねつ

Simulation	シミュレーション	
Sky brightness (or sky luminance)	天空輝度	てんくう きど
Solar altitude	太陽高度	たいよう こうど
Solar azimuth	太陽方位角	たいよう ほういかく
Solar radiation	日射	にっしゃ
Specific heat	定圧比熱 定容比熱	ていあつ ひねつ ていよう ひねつ
Sun path diagram	太陽位置図	たいよう いち ず
Temperature	温度	おんど
Thermal capacity	熱容量	ねつようりょう
Thermometer	温度計	おんどけい
True north	真北	まきた
True solar time	真太陽時	またいようじ
U value	U値	ユー あたい
Unit air conditioner	個別式空気調和器 (ユニット)エアコン	こべつしき くうき ちょうわき
Unit heater	個別式加熱器 (ユニット)ヒーター	こべつしき かねつき
Vapor barrier	防湿層	ぼうしつそう
Ventilation	換気	かんき
Watt	ワット	
Wet-bulb temperature	湿球温度	しっきゅう おんど
Wind tunnel / channel	風洞	ふうどう
Wind direction	風向	ふうこう
Window	窓	まど
Wind pressure	風圧	ふうあつ
Wind speed / velocity	風速	ふうそく

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