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Passive and Low Energy Cooling Survey

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Marc's other articles

This report documents a survey I made of passive and low energy cooling techniques. It begins with an overview of general cooling issues. The topics covered in the sections following are: comfort, psychrometrics, an overview of mechanical cooling, loads, climate data, distribution options, dehumidification, ventilative cooling, nocturnal ventilative cooling, radiant cooling, evaporative cooling, earth-coupled cooling, and combined system strategies.

Principal references were Passive Cooling, edited by Jeffrey Cook, and Passive and Low Energy Cooling of Buildings, by Baruch Givoni. Both books are primarily academic in nature, but Givoni in particular provides plenty of actual field data. These books don't necessarily represent the state-of-the-art: Cook was published in 1989, and Givoni in 1994. As we decide which direction to pursue, we will seek more current information. The physics are unlikely to change much, however.

The usual caveat applies: I am not expert in any of these applications, and all errors herein are mine.

1.0 Comfort

Buildings are cooled primarily to enhance human comfort. There is a range of what people actually define as comfortable, based on cultural expectations and clothing, as well as some rigorous scientific testing of human subjects. In the case of cooling, the task is to promote heat rejection at the skin surface. The body rejects heat by evaporation (sweat), convection (from moving air), and by radiation to cooler surfaces. It's worthwhile to distinguish between a strategy that cools the building and a strategy that cools the person directly. A ceiling fan is an example of the latter ñ the building doesn't get cooler by its operation (in fact, the temperature rises due to motor waste heat), but the effect of the moving air is to promote human heat rejection.

The variables influencing comfort are air temperature, radiant temperature of the surrounding surfaces, air speed (feet/minute, FPM), and relative humidity. Within limits, these can be traded off. John Spears presented a table at EEBA some years ago of equivalent comfort conditions:

Temperature, °F	RH, %	Air speed, fpm
76	45	20
76	80	250
72	80	20
80	20	20
80	45	500

You can see that higher temperatures may be accepted when the RH is lower and/or the air speed is higher.

There are clearly variations in what experts consider the human comfort envelope. ASHRAE limits air speed to 160 fpm, yet Givoni suggests that 400 fpm as a maximum. Europeans limit RH to 70% (in buildings in which it is controlled), and ASHRAE requires a maximum dewpoint of 62°F, which is a more stringent condition. (Dewpoint is related to an absolute moisture content of the air, not a relative moisture content, so a 62°F dewpoint translates to 70% RH at 72°F. The goal is still to keep interior conditions below 70% RH, to prevent mold growth.)

Radiant exchange between humans and their surroundings is a significant comfort determinant. Surrounding a person with surfaces that are cooler than the air temperature will increase comfort. This can be achieved either actively, with cooled radiant panels, or passively, with massive walls/floor/ceiling which are cooled in some way to below the typical occupied temperature.

2.0 Psychrometrics

Some definitions and relationships are necessary to go further. *Dry bulb temperature* (DB) is the temperature of the air that the thermometer measures. *Wet bulb temperature* (WB) is the temperature attained by a thermometer whose bulb is covered by a wetted wick placed in a moving airstream. The evaporation from the wick takes energy, so the WB will be below the DB except at 100% RH, when they are equal. The dryer the air (lower RH) at a given DB, the lower the WB. Evaporation occurs more readily at lower WB. *Dewpoint* is the temperature at which a given sample of moist air would be cooled to when it reaches 100% RH, called fully saturated. Cooling that air sample any further results in some of the water vapor condensing out as liquid. This is the primary strategy for effecting dehumidification. Air at 80°F DB and 50% RH has the same dewpoint as air at 96°F and 30% RH ñ about 60°F. Both conditions have the same moisture content, or *Humidity Ratio* (HR), which is measured in grains of moisture per pound of dry air (7000 grains = 1 pound.) *Relative Humidity* (RH) is the ratio of water vapor in a given air sample to the maximum water vapor that air could hold at saturation, which is defined as 100% RH. Dry air's ability to hold water vapor rises with an increase in temperature, so heating a given sample of air lowers the RH, and cooling it raises the RH. When this sample is cooled to 100% RH, the temperature of the sample is the dewpoint of the initial temperature/RH condition.

3.0 Conventional Mechanical Cooling Using Vapor Compression

In a conventional cooling system, air from the occupied zone passes through a cooling coil. As the air drops in temperature, it typically reaches its dewpoint. Some of the water vapor in the air begins to condense on the coil and drip off as condensate. The air continues to cool down along the saturation curve, remaining at or near 100%RH. When it leaves the coil, it is typically in the vicinity of 55°F DB, and close to 100%RH. Both *sensible* cooling (sensible heat is what is measured by temperature) and *latent* cooling (removal of moisture) have occurred. When the leaving air mixes with room air and is heated up to, say, 77°F, it will be at 45%RH. The room air is replaced by the cooled and dried air, so the room is both cooled and dehumidified.

Cooling is often measured in tons (12,000 Btu/hour). One ton of cooling is typically delivered with an airflow rate of about 400 cubic feet per minute (cfm). If the cooling air was delivered at 66°F DB instead of 55°F DB, it would take roughly double the air flow rate to deliver one ton of cooling.

The following systems are all versions of mechanical cooling using vapor compression:

Conventional room air conditioners package the compressor, the blower, the cooling coil, and the heat rejection coil into one unit. These units compromise a number of qualities ñ most notably noise and efficiency - for the advantages of packaging and low cost.

Ductless mini-split air conditioners have terminal units containing the cooling coil and the blower located in the space to be cooled, and a separate outdoor unit which has the heat rejection coil and the compressor. They are quieter and more efficient than room AC, and the terminal units can be located on interior walls or ceilings.

Split systems place the cooling coil and blower into a centrally located package, from which air is supplied to, and returned from, the space to be cooled. The compressor and heat rejection coil and its fan are located outdoors. This is the most common residential system. These systems can be quieter and more efficient than the systems mentioned above. The best current technology incorporates variable speed blower and a multispeed compressor to better match varying loads, and increase efficiency.

Packaged rooftop systems are the mainstay of the commercial world, especially in commercial low-rise buildings. A rooftop unit incorporates the compressor, the blower, the cooling coil, and the heat rejection coil and fan, and is located on a rooftop curb with ducts to the space emanating from the underside of the unit.

Chillers are used in large or complex buildings which demand many cooling zones. A chiller makes chilled water, often 45°F, that is circulated around the building to different types of terminal units. The chilled water is pumped through water coils in these units, which cool the room air circulating through them. Small chillers are typically air-cooled, larger ones are water-cooled, most commonly with cooling towers.

The conventional systems noted above are all adaptable to buildings which require zoning of cooling. Typical residential split systems are just one zone, but zoning capability exists with the state-of-the-art units. Conventional approaches are more likely to incorporate zoning than are the passive and low energy techniques that will be described in this document.

4.0 Loads

The cooling load of a building is made up of both sensible and latent heat sources. Sensible heat comes from solar gains through glass, and secondarily through the envelope; internal gains from lights, appliances, and people; and from infiltration and/or ventilation of outside air, if the exterior DB is above the interior DB. Latent heat comes from people and animal metabolism; plants; cooking; and from infiltration and/or ventilation of outside air, if the exterior dewpoint is above the interior dewpoint. Both sensible and latent heat can be stored in the building envelope surfaces, reducing peak loads. It is easier to control sensible heat loads (proper glazing placement, shading, type; efficient lights and appliances) than latent loads.

Loads are very sensitive to what the exterior conditions are, and what the interior setpoints are.

In a simple conventional cooling system, at a given entering air condition (air which is coming back from the room), a cooling coil operating at a given temperature will remove both sensible and latent heat, in a constant ratio. The ratio of sensible heat to total heat (sensible plus latent) is called the sensible heat ratio (SHR). Residential air conditioning systems are controlled purely on room temperature, a measure of sensible heat, and therefore RH is only changed as a byproduct, it is not controlled independently of temperature. Systems do exist which add this level of control, but they are uncommon and they add cost and complexity. If the SHR of the load, and the SHR of the coil are mismatched, then the room RH may settle at an undesirable level. This is particularly noticeable in humid climates in off-peak conditions. The exterior dewpoint is highest early in the morning, there may be no solar gains, and the exterior DB may be well within the comfort zone. The thermostat does not call for cooling, yet the house is too humid. So conventional systems are often compromising humidity control. Some houses have been built with a separate dehumidifier and sensible cooling system, to avoid this problem.

5.0 Climate

Across the United States, climates vary tremendously, from extremely dry climates to hot, humid climates. Dry climates present more cooling opportunities, as dehumidification may never be required. Climate data is presented by ASHRAE as Design Conditions, based on long term averages. The 0.4% Design Condition will show a DB number which will only be exceeded 0.4% of the hours in an average year (35 hours.) 1% and 2% conditions are also presented. The closest location to Martha's Vineyard for which this data is given is Otis AFB in East Falmouth. Some sample data follow:

.4%		1.0%		2.0%		
DB	MWB	DB	MWB	DB	MWB	
85	72	82	72	79	69	Otis AFB
91	73	87	71	84	70	Boston

MWB is Mean Coincident Wet Bulb temperature, which is the average WB experienced at the DB given. Note how Boston is hotter, but Falmouth is much more humid (WB is closer to DB).

ASHRAE data is intended primarily for use in sizing equipment, so it would be useful to have more data, broken down into bins (typically 5°F increments, telling how many hours per year fall into each bin) to really understand the nature of the cooling issues.

6.0 Distribution Options

Cooling can be provided to a space by means of convection (in this case, moving air) or radiation. Convection can be free convection, air moving under natural forces such as wind or the thermal stack effect, or it can be forced convection, in which a fan or blower moves the air.

Free convection is typically associated with open systems, that is, the air which is doing the cooling originates outdoors and replaces warm room air. Ventilation with outdoor air, nocturnal cooling with outdoor air, and some traditional designs with thermal chimneys and/or evaporative cooling, all rely on the warmer air rising due to density differences or wind pressures. Free convection is also present in radiant cooling systems, as any system which presents a surface cooler than the room air temperature will cool the air adjacent to itself, which will fall, setting up a free convection loop.

Forced convection cooling usually involves a blower. In open loop systems, such direct evaporative cooling, the blower(s) supply the cooled air to the space, and exhaust the room air outdoors. Another open loop forced convection system might use a blower to supply air from a network of earth tubes, and another blower to exhaust room air outdoors. Closed loop systems, such as conventional mechanical cooling, use the blower to circulate air over the cooling coil, to the room, and return room air back to the coil.

The air flow rate that is required in either free or forced convection is dependent on the size of the cooling load, and on the temperature differential between the room air and the supply air. In free convection systems, increasing air flow requires larger openings (such as windows), wind catching devices such as fins, or taller spaces to increase the chimney effect. Often in these systems there is little or no control of supply air temperature, and the temperature differentials are small, so flow rates need to be high. In forced convection systems, air flow rates are set by trading off blower size and horsepower, duct and register size, and temperature available from the cooling system. For example, a conventional compressor-based cooling system can easily produce 55°F air, much lower than the temperature available from an evaporative cooler. This permits smaller blower, ducts, and registers, so less power is consumed by the blower, and less space is required for the ducts. However, the evaporative cooler has no compressor, so it's overall power consumption is lower. Less air flow typically means less noise.

Forced convection systems can be ductless as well as ducted. Ductless systems include room air conditioners and ductless mini-splits. In commercial buildings, individual fan coils allow zoning and either minimal or no ductwork. (A fan coil is a packaged piece of equipment which combines a blower and a water-to-air coil that can be used for heating or cooling. A kickspace heater is a fan coil, heating-only because it has no provision for condensate collection.)

Radiant cooling is supplied to the space by placing cool surfaces in or around the space. These surfaces may be part of the structure, such as massive walls and ceilings which are cooled by nocturnal ventilation, and remain below the room air temperature throughout the day. As the sensible cooling loads are applied (solar, lights, appliances) the rise in space temperature is damped by the cooler mass. In some cases, solar loads may impinge on the walls directly, and be absorbed, bypassing the step of raising the air temperature. People surrounded by cooler surfaces have a higher net radiant heat loss, so they feel cooler.

Radiant cooling may also be provided by low-mass panels, through which chilled water is circulated. These panels are located on or in the ceiling (can be integrated in dropped ceilings) or can be located high on a wall. Radiant panels provide sensible cooling only. The chilled water temperature must be set so that the panel surface remains above the dewpoint of the air. It is also important that the panel surface not absorb water, so that mold growth will be unlikely. Commercially available radiant panels are metal, and expensive. You may recall we explored using low-cost plastic swimming pool absorbers at Stonyfield Farms as radiant panels. I envisioned a system there in which we ran the panels in the condensing mode, hanging them close to vertically so as to be able to collect condensate.

There is European technology which runs chilled water into terminal units which are shaped more like beams than panels. Delivery of cooling is by a combination of free convection and radiation. Some of these systems integrate the delivery of ventilation air, which has been deeply dehumidified so as to satisfy the latent cooling portion of the load.

There is one more commercially available which, like the radiant panels, is supplied with chilled water and delivers the cooling in both radiant and convective modes. It is called a valance convector, and it is comprised of a coil-like heat exchanger which is located in a metal valance, and installed high on a wall just below the ceiling. Chilled water is circulated to the coil, and cold air is generated and falls out of the valance, drawing warm air in at the top to replace it. This is a free convection process. The valance is designed as a condensate drip tray, and it must be connected to a drain. This feature allows both sensible and latent heat removal, unlike the radiant panels. Greg Allen designed a shop-fabricated version of this product for a 250 unit apartment complex in Canada.

Note that all of these active panel or convector systems require a source of chilled water, which may be a small chiller or water-to-water groundsource heat pump, but might also be a groundwater well.

7.0 Dehumidification

In the section above about psychrometrics, it became clear (I hope) that cooling a given sample of air below its dewpoint causes some of the water vapor contained in that air to condense on the cold surface, where it can be drained away as liquid. This process is dehumidification. As previously discussed, dehumidification is a byproduct of conventional cooling systems, which have coil temperatures well below the dewpoint of the desired room air temperature. As the temperature of the cooling coil rises, the ability of the system to remove moisture from the air drops off dramatically. A coil supplied with 60°F water will do virtually no dehumidification if the air passing over it is in the conventional comfort range. Passive systems have not traditionally been capable of producing low temperatures comparable to conventional mechanical systems, so in humid climates their ability to control RH has been weak.

One company (DEC) makes a compressor-based recuperative dehumidifier that incorporates a built-in heat recovery system. The use of heat exchange in this product substantially lowers the SHR, and consequently the amount of energy needed to remove a given amount of water vapor from the air. This product might conceivably be used in conjunction with a closed loop passive or low energy cooling system that was designed to only handle sensible heat removal.

The other approach to dehumidification is to use desiccants. These are materials that absorb water. They absorb the water passively, and then, in order to create a cyclic process that can continue to absorb water, they must be regenerated. Regeneration is simply heating the desiccant to drive off absorbed moisture.

In desiccant-based systems, it has been typical for some sensible heat to be added to the room air as the latent heat is removed, caused by some carryover of the regeneration heat. Configurations may exist in which this is not the case, but I am not aware of any that are commercially available.

Regeneration energy could come from solar input, and this has been done. Regeneration improves with increasing temperature, so it may make sense to look at vacuum tube absorbers for this task. Commercial desiccant systems use gas as the regen fuel. One product, developed with funding from the Gas Research Institute, packaged a small desiccant dehumidifier with a coil that used domestic hot water from a water heater to provide the regen heat. This product may not be currently available. John Spears has been using one in his home in MD in conjunction with a forced air-based cooling system using water from a domestic water well in a fan coil to provide sensible cooling.

8.0 Ventilative Cooling

Ventilative cooling is the strategy of using outdoor air to cool the building. It is only useful when the outdoor temperature is below the indoor temperature. This strategy combines the approaches of building cooling and people cooling, if the air velocities are high enough and are felt within the occupied zone. It is an applicable strategy to warm humid climates.

Openings in the buildings are usually windows and doors. Air movement can be provided by the wind, by the stack effect, or by a fan. Much work has been done analyzing the effects of different window placement and building design for maximizing air movement under the pressure of the wind. Some conclusions are:

- Cross ventilation is enhanced by an irregularly-shaped, spread-out building.
- Facing the building at an oblique angle to the prevailing wind is better than facing it directly perpendicular to the wind direction.
- Wing walls which protrude can act as scoops to enhance wind capture, and can also generate different pressures on the same side of a building, greatly increasing the air flow through the adjacent space compared to a building with a flat façade. Casement windows when open act as wing walls.
- Sizing the inlet area equal to the outlet area is best.
- Horizontally shaped windows (width greater than height) work better than vertical windows.
- Highest velocities are attained when windows and doors are unscreened, so one tactic is to do insect protection with a screened porch but leave the windows between the porch and house unscreened.

High and low openings can promote stack effect cooling, but the stack is weak in most places at night. Also wind velocities tend to drop off at night. Most discomfort in a continuously ventilated building occurs during the evening hours. Using a whole house fan to move enough air through the building is a viable alternative. Subrato Chandra of Florida Solar Energy Center (FSEC, where much of the best US research has been done on cooling) recommends 15 air changes per hour (ACH) for *building* cooling, but says that on the order of 60 ACH are required for people cooling, in order to get the velocities in the occupied zone up to 100-150 fpm.

FSEC states that well-designed buildings (low heat gain) are best closed up during the day and ventilated at night. This solution may violate RH limits, however, as the nocturnal ventilation will likely increase the moisture load of the house as it reduces the temperature. They suggest that night flushing of hollow thermal mass may provide the same cooling benefits without introducing the moisture ñ this is unclear to me, at least if the mass is masonry, which is highly hygroscopic.

Ceiling fans are a good choice in warm humid climates. They raise the comfort envelope several degrees, even at higher RH, by creating air velocities of 100-150 fpm, and the turbulent form of airflow is preferable over uniform air motion. Chandra showed an interesting scheme in which a ceiling fan was mounted below a flat ceiling with two long operable vents to the attic above. The vents are closed during the day, and opened at night, allowing the fan to pull cooler attic air into the space and circulate it. Data shows that, although the attic gets quite hot during the day, by 11 p.m. it is quite close to ambient temperature.

I believe that ceiling fans, as people coolers, should be controlled by occupancy sensors and/or timers ñ there's no benefit to running them when there are no people present.

9.0 Nocturnal Ventilative Cooling

Nocturnal ventilative cooling refers to the strategy of ventilating a building at night, when the ambient temperature is low, and closing it off from the outdoors during the daytime hours. It is most effective in high mass, well-insulated buildings with low internal heat gains. In dry climates, which often have high daily ambient temperature swings, this approach may provide excellent comfort with no additional energy input. Some guidelines are:

- Indoor minimum DB = Outdoor minimum DB + (0.35-0.45)Daily range
- Indoor maximum DB = Outdoor maximum DB - (0.35-0.45)Daily range
- Indoor daily range = (0.10-0.20) Outdoor daily range
- Works best in arid climates, daily range = 21-27°F, Outdoor minimum DB less than 68°F, Outdoor maximum DB less than 97°F.

Indoor average DB can be 4-5°F the same building if it was not ventilated at night. The nocturnal ventilation may be natural or supplemented by a fan.

10.0 Night Sky Radiational Cooling

The temperature of the sky is lower than the temperature of the earth's surface (at least in Martha's Vineyard), so there is a net radiant transfer to the sky. It is interesting to note that this radiant loss occurs 24 hours a day, not just at night, but it is offset by solar gain during the day. A clear sky is colder than a cloud-covered sky, so that night sky radiant cooling is far more effective under clear skies. The amount of heat that can be rejected overnight to a clear night sky from a building roof is about 200 BTU/sq.ft. This performance is quite modest ñ night sky radiant cooling as a primary strategy would be confined to fairly low heat gain buildings, typically of one story, in dry climates.

The simplest night sky radiant cooling system is a massive roof with movable insulation. The roof is covered with insulation during the day, and exposed at night. The mass needs to be in direct contact with the space below, because the temperature drops are small. The goal is to have the ceiling side of the roof be a few degrees below comfort temperature, so the roof can absorb heat from the space.

The most commonly known system of this type is the Skytherm system invented by Harold Hay. The roof deck is typically a metal deck, and water in large plastic bags, like water beds, are laid on the roof deck. Movable insulation can slide off the roof, and reveal the water bags to the night sky. Skytherm buildings have been monitored and are quite successful. The biggest problem has been to develop a robust system of movable insulation.

A more recent innovation is the Cool Roof system. This approach keeps the insulation in place, floating on top of a three inch layer of water, and sprays water at night over the insulation, where it loses heat by both evaporation and radiation. The water is cooled to as much as 8°F below the minimum night time DB. The building can be cooled by circulating air past the underside of the ceiling, or by using the water storage as chilled water for fan coils. This system, like the Skytherm, offers sensible cooling only. A more recent version eliminates the roof water storage entirely, and cools the floor slab with the water coming off the roof, or stores it in a tank for use in fan coils.

An insulated, high mass roof will begin the evening also being cooled by convection, as it typically begins the night warmer than the air.

An alternative approach is to make a light mass nocturnal radiator, such as a metal roof panel, and move air behind it. One way this has been implemented is to bring nocturnal ventilation air in via the gap below a nocturnal radiator, further depressing its temperature. In dry areas, this cooling benefit can be 5-9°F, in humid areas it will be lower, 3-5°F. If the night air is near saturation, some dehumidification may occur. Since a lightweight radiator quickly drops below the night time ambient DB, it can lose effectiveness if there is a breeze, since it will be heated by convection.

Lightweight nocturnal radiators can also be linked with thermal storage, such as a rock bed, and the air from the radiator, cooled below night time ambient, can cool the rock bed, which can be coupled to the building during the day to absorb heat.

Finally, unglazed solar collectors, such as pool collectors, can be used as night time radiators, and the water circulated back to a tank or to pipes cast into building mass.

11.0 Evaporative Cooling

Evaporative cooling takes advantage of the fact that it takes energy to change water from a liquid to a gas, around 1000 BTU/pound. This phase change energy must come from somewhere, and in air it comes from the sensible heat in the air, thereby lowering the temperature of the air.

Evaporative cooling techniques fall into two categories, direct evaporation and indirect evaporation. In direct evaporation, water is evaporated directly into the air that is circulated to the space being cooled. This raises the RH of the air (it actually raises RH two way ñ lowering temperature and adding moisture) and consequently of the space. Indirect evaporative approaches use evaporation to lower the temperature of some medium which is separated from the building air.

The most common direct evaporation system in the U.S. is the single stage direct evaporative cooler, or swamp cooler. Water is evaporated into the supply air stream, lowering its temperature and raising its RH. The DB of the outdoor supply air can be reduced by 60-80% of the DB ñ WB differential, so a low outdoor WB temperature is important to making this system work well. Air change rates are high in direct evaporative systems ñ 15-30 ACH. This can get velocities inside the space up high enough to provide people cooling in addition to space cooling.

Givoni describes a downdraft passive direct evaporative cooling tower by Cunningham and Thompson. This employed four wetted pads for outdoor air to flow through as the water evaporated, cooling the air to quite close to the outdoor WB. A thermal chimney also attached to the home provided additional pressure to drive the system, pulling warm air out of the home as the cooling tower dropped cool air in. Givoni reports that at an outdoor DB of 105°F and outdoor WB of 71°F, the air entering the house was 75°F. House DB was 78-82°F. The maximum suggested outdoor WB for this system to work is 71°F. This, like other direct evaporative systems, would not be successful in warm, humid climates, when the highest discomfort occurs when the RH (and WB) is high.

Givoni has an interesting twist on the evaporative downdraft cooling tower, in which he sprays water with a shower head down into the tower cavity. The water spray gives additional momentum to the supply air, and, since it is not circulated over pads, he says that brackish water or sea water can be used.

Indirect evaporation doesn't add moisture to the air. One way air is cooled by indirect evaporation is to use a flat plate air-to-air heat exchanger. The water is added to the exhaust air, just before it enters the heat exchanger, lowering its temperature. In the heat exchanger core, heat is transferred from the supply air to the cooled exhaust air, thereby cooling the supply air. Indirect machines typically are larger and use more power than direct evaporative machines. Multiple effect machines are possible, in which the first stage is indirect and the second stage is direct. Each stage adds power and complexity.

Indirect evaporation can also be employed in roof pond applications. As previously described in the radiant cooling section, a shaded roof pond will cool by evaporation, and the ceiling below is cooled by conduction to the roof pond. Monitored systems show that the ceiling temperature will be between 5-7°F above the average outdoor WB. Givoni suggests that buildings in climates with a maximum outdoor WB of 77°F or less can be cooled by roof pond systems.

One interesting variation on roof ponds, which are quite limiting architecturally, are ground-based ponds with floating insulation. Water is circulated at night over the insulation, where it cools by evaporation and radiation. The pond will track average weekly outdoor WB, maintaining a temperature about 2°F above this point. This water can be used in radiant systems or in fan coils, as long as the climate is dry enough to have a low outdoor WB.

12.0 Earth-coupled Cooling

The temperature of the earth ten feet or more deep is slightly above the average annual air temperature. This temperature can be further lowered by these techniques:

- mulching with pea stone or wood chips to a depth of at least four inches, and irrigating if necessary to provide moisture for evaporation. The mulch must be vapor permeable.
- Shading the earth's surface ñ one way is to raise the building above the ground on posts.

Cooling approaches include partial or full earth-sheltering of the building, and the use of earth tubes in either closed or open loops. It is also possible to have closed water loops in remote cooled soil storage, but it is unlikely to be worth much unless the soil is actively frozen during the winter, using the water-ice phase change to store "coolth." The basement walls of a building can also be used as an earth-air heat exchanger, with the understanding that condensation and biological growth could be present.

The surface temperature of the ground is dependent on color, vegetation, soil moisture, as well as soil conductivity and soil diffusivity. The net radiant flow is usually positive into the soil in the summer, but this can be reversed by shading. It is negative in the winter. The net convective heat flow is usually from the earth to the air, but this also reverses with shading, so it makes sense to minimize convection with a vapor permeable covering, such as the mulch described above. In arid desert regions, bare soil averages 9°F above the average air temperature. Vegetation shades the soil and also evapotranspirates, but this process cools the leaves, not the soil. Dense, low vegetation actually maintains air near saturation at the ground, which reduces evaporation from the soil. Water that percolates into the soil can raise or lower the soil temperature. Rain run-off from unshaded soil can raise the temperature of the shaded soil as it sinks in. If the soil is covered with pea stone, watering the stone at the end of the night can capture some of the radiant cooling stored by the stones.

There has been a fair amount of work done on earth tubes in the U.S. Givoni presents the results of several researchers. None of the research is performed on actual systems that are used to cool houses, but there is a fair amount of data on built systems, principally in the Midwest, a hot and humid summer climate. The system designs he reports on vary in size and layout ñ some have tubes in parallel terminating in a header, some used a radial pattern collecting in a central sump (to make moisture removal easier), some were only a single tube. All are open loop systems ñ inlet air comes form outdoors, and makes one pass through the earth tube exchanger. The interesting figure of merit that I calculated for six systems was Btu/hr/sq.ft. of tube wall area ñ the range was 7.83 to 12.38, averaging just over 10. This allows some initial scoping calculations of size that might be required in a home. There is clearly a dehumidification function being performed in these systems, and the the biological contamination issue is not explicitly addressed. Labs quotes from a DOE report, "Many authors remark that earth tubes provide an ideal environment for Legionella, Pseudomonas, and other harmful microorganisms."

Givoni concludes that tube lengths over 50 feet are unnecessary, which is interesting, given that most of the cases he describes used much longer tubes. It is important to design the system so as to minimize blower horsepower, which leads to more, shorter, larger diameter tubes. He notes that longer tubes of smaller diameter dehumidify better.

Labs quotes from the DOE report these following conclusions:

- small diameter tubes are more effective per unit area than large tubes
- long tube are unnecessary
- tubes should be placed as deeply as possible
- closed loop systems are more effective than open loop systems
- tube thermal resistance is immaterial ñ the ground thermal resistance dominates

Another form of earth-coupled cooling is to use a groundwater well as the source for cool water. On Martha's Vineyard, groundwater temperatures are likely to be above 50°F, which will make dehumidification difficult if used in the conventional manner by pumping the water through a water-to-air coil. If the water could be used directly in a surface that directly contacts the room air it is possible that sufficient dehumidification might be accomplished, otherwise, supplementary dehumidification would be required. The ground water temperature is quite adequate for sensible cooling, which could be delivered via fan coil or radiant panels.

The last earth-coupled strategy is to actually freeze a portion of ground during the winter and use that stored "coolth" to provide cooling in the cooling season. Givoni recommends that the minimum dimension of the size of the store is 50 feet, so that edge losses don't overcome the system. This strategy would not work well unless the store was isolated from moving ground water, which would be heating the store. My sense is that the Martha's Vineyard climate wouldn't have enough freezing degree days to do this strategy.

13.0 System Strategies

I believe that the first and fundamental decision that should be addressed is whether you are seeking *building* cooling or *people* cooling. Building cooling requires that the building be closed to the outdoors, so that the interior environment can be maintained at a point which is lower in temperature and humidity. With this criterion, any system designed is going to have to compete with conventional air conditioning in these ways:

- first cost
- performance
- compromise to the home's design

In the application you are most likely to encounter, the occupants are using the house as a summer home, and the cooling season is very short. This means that operating costs are very low with a conventional system, because the hours of operation are low ñ probably less than $200/year, so operating cost savings won't pay for much extra capital cost.

My sense of how people would operate cooling if they had it would be to generally keep the house open unless the weather got severe. This approach would drop their cooling load, and therefore cost of cooling, well below that which would be calculated by a thermal simulation.

If building cooling is the direction chosen, then distribution must be addressed next. The low energy methods outline in the discussion above all generate temperatures that are warmer than conventional air conditioning systems, which can easily run the cooling coil at 45°F. The implication of this is that an air-based distribution system will need to move more air for a given amount of cooling load if it is supplied with air from a non-conventional source. As an example, an indirect evaporative cooler on the market provides a nominal 10 tons of cooling and moves 10,000 cfm to do so. This yields 1000 cfm per ton, vs. 400 cfm per ton for conventional equipment. Total power use is lower, because there is no compressor, but blower power, noise, and duct size all are substantially increased. The approach you would take would be to focus serious attention on cooling load reduction, so that the cfm required would be similar to that required in a normal house with a conventional system.

Options for a building cooling system include:

Forced air options

- sensible cooling provided by a closed loop of earth tubes or groundwater/fan coil combination, and dehumidification provided by DEC recuperative dehumidifier or the

GRI-developed hot water-driven desiccant dehumidifier, or perhaps by a roof-integrated, solar regenerated desiccant system (if truly feasible)

In these systems, I think it would be relatively simple to provide multiple zones. The earth tube loop might be set up so that the output could be shunted to multiple zones. By only using the cooling needed, the rate of the heating up of the earth surrounding the tubes would be slowed. In the groundwater/fan coil system, each zone would have its own fan coil. There would be a question of how to duct dehumidified air to each zone.

Radiant options

- I don't feel that radiant panel cooling is a good choice in your houses, based solely on aesthetics. You would need hundreds of sq.ft. of panel (figure perhaps 30 Btu/hour/sq.ft.) to do a typical house, and they would be very visible. Ground water well would be the source of cool water for these panels, and they would be controlled to operate in the non-condensing mode.
- A much more radical option would take off from where we were at Stonyfield some years ago. We considered using Kalwall tubes with chilled water pumped through them in the cooling season to provide both sensible and latent cooling (and then pump warm water through ëem in the heating season. In both seasons, they would also absorb solar heat.) I could envision pumping ground water from a well through weird and wonderful metal sculptures that would be located in the space. A base would be required to catch and drain away condensate. The sculptures would need to have lots of surface area to make this work (hundreds of sq.ft..)

The systems envisioned above would be designed to function in a closed house.

People cooling focuses on extending the comfort envelope. The building remains open for at least part of the daily cycle.

Options include:

- One approach is a combination of daytime and nocturnal ventilation, which is fan-assisted in order to get good nocturnal building cool-down. In most cases, the house could be closed during the day, since it would be below outdoor ambient DB. The night time ventilation would provide the cooling. I feel that this is a marginal improvement over the do-nothing approach, since there is no humidity control, and in the worst cases the system doesn't provide enough comfort towards the end of the day. This approach could be augmented with ceiling fans to extend the comfort envelope.
- Another approach would be to accept the fact that the house will usually be open to the outdoors, and that ceiling fans will be used. The performance of the ceiling fans might be augmented in the worst conditions by some variation of Chandra's scheme of drawing air that is cooler than room air into the fan air flow. If air which is cooler and dryer than room air could be circulated by the ceiling fans, it might make people feel comfortable in a wider range of conditions. Grilles in the ceiling above the ceiling fan could be supplied with cool air via ductwork. This portion of the system would be operate as a second stage ñ the first stage is ceiling fan with no cool air supply. The cool air supply could be provided by a closed loop earth tube network or a fan coil supplied by a ground water well. The system would operate room-by-room based on manual-on occupancy sensors, which would keep energy use to a minimum. This

would be particularly beneficial in the earth tube version, because it would delay the heating up of the network.

Once again, this approach doesn't control humidity, it merely provides air movement and a sensation of cooler, dryer air to the occupants.

- Marc Rosenbaum

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