

# Compatibility Of Roofing Membranes With Roof Cooling Systems

By William Spencer

Besides moisture protection and long service life, an important attribute of a roofing system is its energy efficiency. In some cases, there is a tradeoff between energy efficiency and service life. In other cases, the two purposes are complementary. That is, an energy-efficient roofing system is also a long-lived roofing system.

Building Technology Associates, Oak Park, MI, tracks the life cycles of many roofing systems in their ROOFACTS database, and their data clearly show inverse correlation exists between insulation thickness and roof life cycle. As discussed earlier in an *RCI Interface* article<sup>1</sup>, "With insulation between the interior of a building and the roofing membrane, the roof doesn't benefit from the temperature stability of the building interior. It is subjected to various extremes of temperature." The extensive BTA data confirm that energy efficient insulation has a negative effect on the service life of roofing systems. Even without thermal cycling, high temperatures accelerate the aging of asphalt, coal tar pitch, synthetic, and polymer-modified bitumen roofing membranes, as described in another *Interface* article<sup>2</sup>.

Energy efficiency and life cycle influence each other in ways that are not obvious. The energy efficiency calculations may be relatively straightforward, but decisions about long-term effects on the roof life cycles require the judgment and expertise of a roofing professional. Sooner or later a roofing consultant will be asked to advise on practical methods to insulate and cool a particular building.

Evaporative cooling is a "lost technology" which is not widely applied and appears to run contrary to many common prejudices in building design philosophy. The basic principles have been well known for many decades<sup>3</sup>.

Recently, there has been a renewed interest in evaporative cooling as building owners look for ways to address special concerns and reduce energy costs. Articles on evaporative cooling have been appearing in trade magazines read by plant engineers and facilities managers<sup>4</sup>. These



**Figure 1:** Each low-voltage solenoid valve (24 VAC) controls the supply of water to 50-80 sprayheads, reaching 5,000-8,000 sq. ft. of roof. The 2-in. diameter mainline water supply rests on 6" x 6" plastic supports which are placed at 5' intervals.

(Photographs courtesy of Delta T Corp. / Sprinkool Systems, Lexington, KY.)

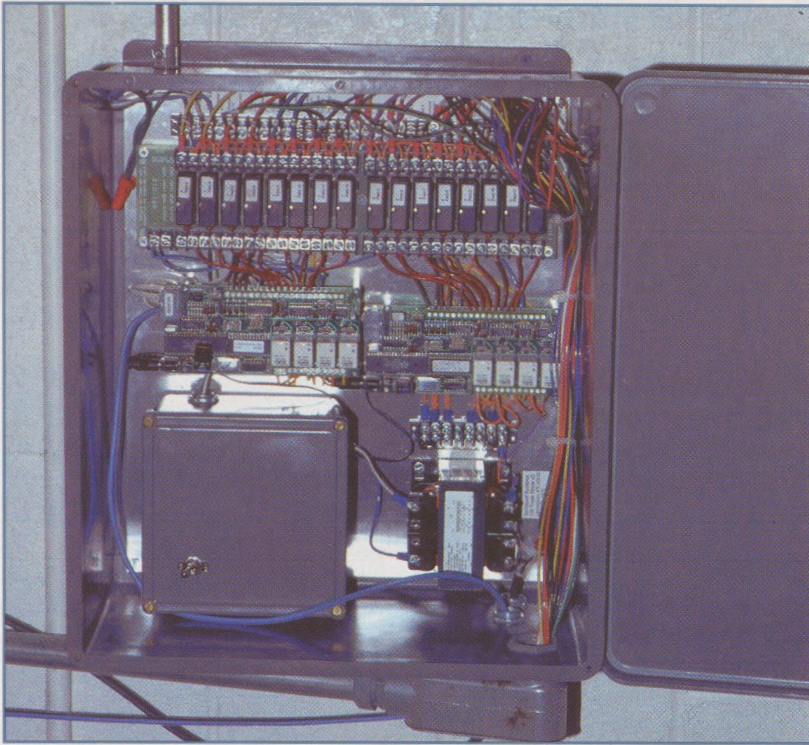
articles suggest that evaporative cooling can be part of an integrated systems approach to building energy efficiency.

This paper summarizes the basic principles, history, new technology, installed costs, operating costs and energy savings of evaporative cooling. The compatibility of evaporative cooling with roofing membranes is also addressed. Although various other approaches to cooling are examined and compared, the emphasis is on evaporative cooling. Radiative cooling and insulation have been surveyed in an *Interface* article by Patrick Downey, who points out that the "analysis of energy conservation in roofing design is complex and in its early stages of understanding"<sup>5</sup>.

## Summary of Cooling Processes:

### Radiation, Conduction and Convection

In general, roof surface temperature can be reduced by three types of heat transfer: conduction, radiation and con-



**Figure 2:** Optimizing water use requires state-of-the-art controls which monitor the temperature of the roof surface and determine the rate at which water is evaporated from the roof.

vection.

Newton was the first to investigate heat loss by a body in air. Newton's Law of Cooling states that the rate of loss of heat is proportional to the excess in temperature over the surroundings. (Heat lost or transferred/second =  $dQ/dt = k\Delta T = \Delta T/R$ , where  $\Delta T = (T_1 - T_2)$  is the temperature difference,  $k$  corresponds to the thermal conductance, and  $R$  corresponds to the thermal resistance). This law is accurate under conditions of forced convection and conduction, and it is approximate in still air for temperature differences of 10-20° C. Radiative heat transfer is more complex to model since it is governed by emissivity, absorptivity and reflection of various wavelengths of radiation at different temperatures.

### Conduction

An insulator blocks heat, it does not remove it. According to Newton's Law of Cooling, heat removal is proportional to the temperature difference across the roof interface. Paradoxically, by blocking heat transfer, insulators raise the roof surface temperature, thereby promoting heat transfer (i.e., both  $\Delta T$  and  $R$  are increased).

Obviously, this is not to say that insulators don't work. The point is that insulators can be made to work better and buildings can be made more energy efficient by reducing the " $\Delta T$ " (change in temperature) in Newton's Law of Cooling as well as by increasing the  $R$  values. The " $\Delta T$ " can be reduced dramatically by reducing the temperature of the external surface of the roofing system. Cutting the exterior-to-interior temperature difference in

half cuts the heat load in half, regardless of the insulating properties of the roof.

When the goal is to heat a building, more insulation is generally better but this strategy can backfire when the goal is to draw heat out of a building. In hot climates, less insulation and more conduction may be desirable. For example, highly insulated roofs on industrial plants and some commercial buildings can promote the "oven effect." If the processes and operations within a plant generate heat, then insulation can make cooling problems worse by retaining solar heat and process waste heat.

For example, nocturnal cooling can be important, especially in facilities that operate 24 hours a day. At dusk, when the roof temperature drops, a thick blanket of hot insulation is a barrier to removing the solar heat that accumulated during the day. The interior of a building would cool by natural means if not for the insulation.

In existing buildings, adding more insulation is not the only way to reduce air conditioning costs. Rather than tearing off a good roof to add more insulation, a balance between air conditioning and alternative cooling methods may be the best solution.

The purpose of insulators is to prevent heat conduction. Conversely, conduction can be promoted by using less insulation. The question, "What is the right amount of insulation?" can be rephrased as, "What is the right amount of conduction?"

### Radiation

The large surface area of a roof is well suited for use as a reflector of solar radiation, or, in the case of passive solar heating, as an absorber of solar radiation. Likewise, a roofing system can cool itself by emitting infrared radiation.

As mentioned, radiative cooling of roofs is a complex subject that has been surveyed elsewhere<sup>6</sup>. The theory of radiative heat transfer appears to be a formidable subject because it is based on black-body radiation, which physicists can only explain by using quantum mechanics theory. Nevertheless, theoretical results and experimental observations can be expressed in relatively simple terms which are easy to understand and have immediate applications.

For example, Stefan's Law describes radiative energy, or emissivity, as proportional to the fourth power of the absolute temperature of a body. A roof surface with high emissivity can significantly reduce the surface temperature of the roof. Internally, the ceiling of a building can also act as a heat radiator or absorber, warming or cooling the interior.

Albedo is the reflectance, or reflection factor. (The Latin word *albedo* literally means *whiteness*.) Albedo is not emittance, and the two terms should not be confused. Albedo is the ratio of the light reflected in all directions

from an object to the light incident on the object, especially a celestial body (e.g., a planet or moon). Emittance, on the other hand, is the temperature-dependent radiation of energy that is already contained within the object. A white object with a high albedo could still have a low emissivity, which means its surface properties inhibit black-body radiation. Hence, its surface temperature could rise significantly despite its white color. [Editor's note: See article, "Demonstrated Energy Savings of Cool Roof Coatings and Future Directions for Research," by Dr. Lisa M. Gartland, elsewhere in this issue for more on the concept of albedo.]

Radiative heat transfer effects should be included in any complete energy model of a building. Merik Inc. has developed software for modeling the combined effects of conductive and radiative heat transfer, allowing for such effects as surface color and insulation values<sup>7</sup>. The software also includes a database of average temperature and relative humidity for 1000 locations.

### Convection

Convection is accomplished by mass flow to and from the heat sources or sinks. When the goal is the removal of heat, convection is often more effective than either radiation or conduction. Forced-air convection includes passing



**Figure 3:** The lightweight piping network is supported every 40 in. by a polymer pipe stand that is sized to allow the pipe to move freely. During each misting cycle, no more water is misted than will evaporate in a short time; hence, standing water is avoided.

air through a plenum near the ceiling of a building, and installing fans or blowers on a roof, although the latter is not very effective. Haddock has recently reviewed the topic of venting as applied to metal roof systems<sup>8</sup>.

Evaporation is a form of convection, which occurs when the mass is input as a liquid and output as a gas. Energy is

absorbed in changing from liquid to gas, and the gas removes this energy from the heat source. Based on simple thermodynamics, evaporative cooling is highly effective in reducing the heat load on the building envelope, and it is most effective when most needed. A close look at the physics of evaporative cooling reveals why it is so effective. (See sidebar, "Principles of Evaporative Cooling".) First, however, the history of building design is reviewed with respect to cooling.

### History of Water-cooled Roofs

Roof cooling with water is not as widely used as it once was or could be. In the past forty years, building design philosophy has emphasized insulation and air conditioning and, hence, interest in evaporative cooling has waned, perhaps undeservedly. A brief synopsis of this aspect of building design history puts the present status of evaporative cooling in perspective.

Around the middle of this century, architects deliberately designed buildings to use ponded water to cool buildings. To appreciate why thousands of gallons of water were allowed to pond on a building, one must understand that efficient air conditioners and modern insulating materials, which we take for granted, did not exist at that time.

(The most common roof insulating material at that time was natural cork.)

Heating was manageable, but cooling the interiors of buildings presented a real challenge. Architects and engineers realized that cooling requirements could be greatly reduced by reducing the heat load coming through the roof—for example, by allowing water to collect on the roof. The ponded water was viewed as an insulator or thermal mass.

While water-cooled roofs kept buildings cool, advances in air conditioning and insulating materials offered other approaches to the cooling problem. Also, energy costs were low in the 1960s and early 1970s, so energy conservation and the expense of air conditioning were not issues.

Eventually, the practice of using water as an insulator fell out of favor. New buildings, designed with lightweight decks rather than concrete decks, were unable to bear the weight of ponded water. Water weighs about five pounds per inch per square foot, which means a 100,000 square foot roof with two inches of water would have an additional load of 1,000,000 pounds, or 500 tons. Also, modern insulating materials are so good today that few building designers would recommend using water as an insulator.

Today, few people perceive ponded water as an insulator, but evaporative cooling, which is essentially a revision of the old water cooling technology, is still valid when thoughtfully applied.

### Revised Technology

Evaporative cooling provides the benefits of ponding

without the disadvantages. The old water cooled technology provided fresh water to the roof as needed to keep the water at a constant level. In the revised technology of evaporation cooling, the sprinkler systems are carefully regulated to provide only a thin film of water (Figures 1 and 2). Hence, the loads on the roof are insignificant and there is very little runoff. Temperature sensors in contact with the roofing membrane control the valves of the sprinkler system.

According to Tom Goetz, Manager, Energy Management Solutions for the Mercantile Stores Company, Fairfield, OH, evaporative cooling systems are application-specific. Their economic success depends on the details of the application, e.g., climate, building type and local utility

can occur.

Any technology becomes more robust as it develops. The quality of evaporative cooling systems has improved



**Figure 4:** Each sprayhead cools about 100 sq. ft. of roof, leaving wide aisles accessible.

rates. Goetz describes the use of evaporative cooling as a fine art. While it can provide the equivalent of many tons of air conditioning, it requires an evaluation of the local setting and building application.

The main maintenance requirement is that the sprinkler systems must be purged of water using air compressors before the temperature drops below freezing. The maintenance requirements, however, are about the same as those for an air conditioning system. Newer systems include compressors for injecting air to purge the pipes of water before freezing

## Principles of Evaporative Cooling

It is worthwhile to re-examine the fundamentals of any developing technology in order to appreciate its application prospects. The basic physical principles of evaporative cooling have been well known for many years.

The kinetic (or mechanical) theory of heat was well established in the nineteenth century through the works of scientists such as Clausius (1822-88), Boltzmann (1831-79) and Maxwell (1844-1906). Temperature is really the "internal" kinetic energy of a solid, liquid or gas. There is no basis for temperature other than the kinetic energy of the molecules—that is, the "one-half mass times velocity squared" (i.e.,  $mv^2/2$ ) summated for all the molecules in the system.

What complicates this simple picture

is that the molecules move at various speeds. But that's exactly what makes evaporative cooling work. Some molecules move at three times the average speed, some at twice, some at half, and so on. A few molecules might briefly come to a complete stop as the result of a peculiar combination of random collisions. If one could take a "snapshot" of the molecules in a liquid and measure their individual velocities, one could plot the number of molecules for each speed range. The resulting histogram approximates what is known in physics as the Maxwell-Boltzmann distribution, which gives the distribution of kinetic energy for atoms in a "classical ideal equilibrium system." It applies exactly to systems where there are no interactions between the con-

stituents; for example, ideal gasses.

Although there are many differences between liquids and gasses, the root-mean-square velocities of molecules are the same in the liquid phase as in the gas phase at the same temperature (John W. Moore, *Kinetics and Mechanism*, John Wiley & Sons, New York, 1981, p. 237). Of course, since liquid water is many times more dense than water vapor, the molecules are closer together and collide much more frequently. (Interestingly, the "nearest neighbors" do not change very frequently.)

Consider a hypothetical distribution curve for water molecules on the surface of a thin film of water on a roof. When the water is heated, either directly by sunlight or from contact with the roof sur-

dramatically in recent years, as a result of advances in materials and design and the availability of low-cost computers. These two trends have increased system life cycles and efficiencies.

The first trend is toward better mechanical integrity of the system. For example, spray heads now include molded polymer filters that prevent minerals from clogging the orifice. ABS pipe supports are attached to the roof with a cement that is compatible with the membrane materials. They are oversized to allow for pipe expansion without placing stress on the roof membrane. The lightweight polymer pipes have replaced the copper pipes of previous designs (Figures 3 and 4).

The second trend is toward computer control of the system. The key to an effective system is misting only the amount of water that can quickly evaporate from the roof. A typical roof would be divided into zones of about 10,000 square feet each. Sensors in the roofing membrane provide detailed temperature data to a computer, which calculates the exact amount of misting required for each roof section.

In cost comparisons, a factor to consider is utility costs, i.e., electricity for air conditioning, compared to the water. Some utilities provide a discount for water that is not discharged into the sewage system.

As a "lost technology," evaporative cooling has not been intensively developed. Advances in sensors, programmable controllers, computerized maintenance management systems, proactive maintenance practices, plumbing materials and mechanical design could help to make evaporative cooling more practical. Better simulations and models of the building energy efficiency could be a factor

in helping designers better understand the benefits of energy-efficient buildings.

## Special Applications

An evaporative cooling system could correct a building design flaw. For example, an existing air conditioning system may prove insufficient in the summer months. Also, the adaptive reuse of a building could be made feasible through evaporative cooling. If space limitations do not allow for more tonnage of air conditioning, an evaporative cooling system could provide a solution.

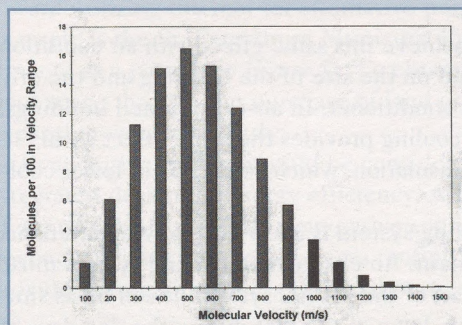
It can protect the roofing system from thermal shock in areas where sudden thunderstorms occur on hot summer days. The strains caused by sudden drops in temperature contribute to the aging of roofing membranes.

Note that buildings with or without insulation are candidates for evaporative cooling. Roof insulation results in higher roof temperatures, making an insulated building also a good evaporator.

Evaporation cooling is an adaptation of the water-based roof cooling systems of the 1950s to satisfy today's demand for energy-efficient cooling systems. Refined and brought under greater control, it can be workable technology in some circumstances. Many factors should be evaluated before deciding whether or not evaporative cooling makes sense for any particular building.

## Compatibility with Roofing Materials

Coal tar pitch was specified for the old-fashioned, water-cooled roofs, because it withstands ponded water. Coal tar pitch is completely insoluble in water. Roofing



For molecules on the surface of a film of water, if the number of molecules in each velocity range could be counted and plotted, the resulting histogram would approximately follow a Maxwell Distribution Curve. The velocities (or kinetic energy) would vary from 0 m/s to 1,000 m/s or more. When high energy molecules (shaded) break free from the surface or vaporize, the average temperature of the liquid decreases.

face, the distribution curve moves to the right; when the water cools, the distribution curve moves to the left.

Molecules at the surface of the film of

water break free from the liquid only if their velocity exceeds a certain escape velocity. At any instant (even well below the boiling temperature), a substantial fraction of the surface molecules can and do break free from the liquid. When these more energetic molecules evaporate, the average kinetic energy of the remaining water molecules decreases and the liquid cools. The curve moves to the left.

The heat of evaporation can be interpreted in terms of the shift in the distribution of velocities that occurs when the energetic molecules evaporate. Additional heat would be necessary to shift the curve back to its initial condition.

The term "latent" heat is sometimes used to describe the heat of evaporation. Latent means hidden. At the boiling point, heat can be added to the system without increasing the temperature.

The energy goes into breaking the cohesive bonds between the molecules in the liquid.

**The heat of evaporation of water is 540 cal / g = 2260 J/g = 2.14 BTU/g = 60.8 BTU/oz. = 6780 x 10<sup>-23</sup> Joules per water molecule.** The heat of condensation is the same. (Note that 1 cal = 4.184 J; 1 BTU = 1055 J; and 1 oz. = 28.35 g.)

The only other factor to keep in mind is that condensation and evaporation are in competition at the surface, so the temperature and humidity of the atmosphere are factors as well. If water molecules condense as frequently as they evaporate, then evaporative cooling cannot occur. It is rare that the relative humidity is so high that no evaporative cooling occurs.

Evaporative cooling, therefore, can be described in terms of a few key factors, including roof area, evaporation efficiency and the heat of evaporation of water. Roof temperature, heat load and humidity affect the rate of cooling.



**Figure 5:** This AlliedSignal roofing system, serving as a roof-top restaurant for the Municipal Pier, St. Petersburg, FL, is an example of an alternative use for roofs.

consultants and contractors are still likely to encounter buildings designed for the ponding of water. The long-term survival of these roofs serves as proof that an evaporative cooling system won't harm a coal tar roofing system.

The ponded water approach to thermal management was actively pursued for many decades, and, hence, a significant amount of field experience on such roofing systems has accumulated. A roof doesn't have to be dead level to enjoy the benefits of evaporative cooling. A roofing consultant should check with the manufacturers when using evaporative cooling on roofing systems made from materials other than coal tar pitch, to ensure that the warranty will still be valid. Many roofing systems are designed with a slope because they have to be. They won't stand up to ponded water or the conditions of evaporative cooling.

Some experts speculate that ponded water prolongs the life cycle of coal tar roofing systems, because it acts like an inverted roof (with insulation above the protective membrane) and so the roofing membrane is not subjected to temperature cycling extremes.

### Energy Savings and System Cost

The solar constant gives the rate at which energy arrives from the sun just outside the earth's atmosphere. It is equal to 434 BTU/sq. ft./hr.

It is interesting to compare the cooling of the Earth to a roof. On a global basis, about 50% is reflected back into space by clouds, about 15% is reflected by the surface, about 5.3% is absorbed by bare soil, about 1.9% by marine and plant life. Almost all of the remaining 27.8% is used to evaporate water. When the water condenses into clouds, it radiates this energy back into space<sup>9</sup>. Thus, the Earth relies on evaporative cooling in a big way; without it, temperatures would soar.

If the sun is directly overhead and there are no clouds, about 70% of the solar radiation will be incident on the

roof surface. This is about 302 BTU/sq. ft./hr. (or 952 W/m<sup>2</sup>). Even if 50% of this is reflected, the heat load is 15,100 BTU per square per hour (100 sq. ft.).

According to the manufacturer of one evaporative cooling system, misting rates are about 1 oz./sq. ft./hr.<sup>10</sup>. The evaporation of 1.5 gallons (128 oz. + 64 oz. = 192 oz.) of water will remove nearly 12,000 BTUs of heat from the roof, which is equivalent to one ton of air conditioning. According to these figures, one ounce of water will remove 31 BTUs of energy if it evaporates 100%. Such cooling power can reduce roof temperatures by 60 to 80° F on a hot summer day.

Removal of heat from the roof, of course, is not the same as removal of heat from the interior of the building. Evaporative cooling is said to lower the floor temperature of an unconditioned building by 7 to 10° F on a hot summer day.

Although not technically an insulating system, the effect of evaporation can be compared with the equivalent insulation that would be needed to produce the same temperature drop. On hot days, when the insulation is needed most, a roof cooling system can be functionally equivalent to R-70+ insulation. It can lower temperatures inside the building day and night for a cost of about \$0.0025 per month per square foot, which is about \$25 per month per 100 squares (10,000 sq. ft.). This cost could be compared with the cost of producing an equivalent temperature drop using conventional HVAC systems. Since roof cooling systems are most effective under conditions in which HVAC systems are most overworked, they are an important candidate technology for energy-efficient building design.

The cost to achieve this same effect with air conditioning would depend on the size of the building and the efficiency of the air conditioner. In air-conditioned buildings, the evaporative cooling provides the same effect as an additional R-70 insulation, which can result in lower cooling costs.

Ideally, a roofing system is a low-cost, low-maintenance building component. An evaporative cooling system must be considered part of the HVAC system. It can be as simplistic as a hosing down of the roof during the dog days of July, or it can be as complex as a carefully designed roof cooling system that turns on only when its use will impact the air conditioning costs and that achieves close to 100 percent evaporation rates.

Note that evaporation is not limited to daylight hours or when the sun is shining. It can be used to draw heat out of the building at night and on overcast days as well.

Rapid evaporation eliminates the solar heat which would otherwise be making its way into the building. The water need not serve as a thermal mass or insulator; its only function is evaporative cooling. Hence, all that is needed is a thin film that wets the roof surface.

## Smart Use of Energy

Energy efficiency means doing more with less. If a technology offers the same or better result and can be achieved with less energy and at lower cost, then that technology will be adopted as building owners strive to lower operating expenses.

Energy conservation measures are encouraged through programs such as the U.S. EPA Energy Star program<sup>11</sup>, whose purpose is to promote energy efficient upgrades in buildings.

Energy conservation makes sense from a business point of view. The responsibility for decisions about its cost-effectiveness and practicality rests with individual building owners, energy management consultants and roofing consultants. As discussed, evaporative cooling is application-specific. In some cases, it merits praise as an environmentally-conscious energy savings strategy. In other cases, it may create more problems than it solves, in terms of high maintenance costs and shortened roof life cycles.

Sometimes technology is ignored for no reason other than that it is out of fashion or not well-publicized. For example, green roofs (i.e., rooftops that are used for growing plants) are popular in Europe but unusual in the U.S.<sup>12</sup>.

The upcoming Seventh International Conference on Building Thermal Envelopes (Thermal VII, to be held in Clearwater Beach, FL in December 1998) will pay tribute to the importance of thinking of a building as an energy system, and it will examine some innovative uses of roofs, including green roofs.

Alternative uses for roofs is a topic of growing interest as building owners realize that a large parcel of usable real estate can be put to good use. In Florida, there is a trend toward utilizing the roof for alternative purposes. An example is the St. Petersburg Municipal Pier, which uses the roof as a patio (see *Figure 5*). To obtain the equivalent floor space through the purchase of land or building expansion would be costly.

Evaporative cooling should be considered as part of an integrated design for energy efficiency. As one component of a total HVAC solution, evaporative cooling systems go beyond the issues of roofing, but a roofing consultant can provide information that is essential in the decision making.

In summary, large commercial buildings, plants and warehouses are candidates for evaporative cooling but should be evaluated on a case-by-case basis. There is room for experimentation and innovation with roofs for application-specific purposes. Some energy savings and other benefits can be expected but these must be balanced with the life-cycle cost analysis of installing and maintaining the evaporative cooling systems as well as its effect on the life cycle of the roofing system.

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