Radiant Night-Sky Heat Rejection and Radiant Cooling Distribution for a Small Commercial Building

David Houghton, Resource Engineering Group, Inc.

ABSTRACT

A design for a new 8,000-ft^2 office building in Santa Fe, New Mexico, is using two unconventional cooling systems: a closed-loop night-sky heat rejection system and in-floor radiant cooling. The heat rejection system takes advantage of the low radiant temperature of the night sky, using off-the-shelf solar swimming pool heating panels placed on a flat roof. An insulated water tank is cooled through the night, and then used during the day to cool the building. The closed loop design eliminates evaporative water loss. Cooling delivery is primarily through radiant heat transfer using in-floor tubing in a concrete slab. The building has a dedicated heat-recovery ventilation system that operates independently of the cooling system. The design process included load reduction and the addition of elements such as exposed concrete floors and ceiling fans to assist the mechanical system.

The design for the cooling system uses recently documented values for radiant heat transfer. A study sponsored by the State of New Mexico has produced heat transfer equations and coefficients for night-sky cooling that relate heat rejection rates to the “white plate” temperature (effectively, the radiant temperature of the night sky) and the temperature of the water entering the panel. On the distribution side, ASHRAE research has quantified the amount of cooling that can be delivered through radiant floor or ceiling panels, including the effects of variables such as water temperature, tubing spacing, and finish floor material.

Introduction

The climate of Northern New Mexico offers interesting opportunities for low-energy cooling via rooftop radiant exchange with the night sky. The idea is to run water through rooftop radiant panel assemblies at night to create and store chilled water, then to run that water thru the building’s in-floor tubing during the day to absorb the building’s cooling load. This strategy has limitations on how much heat can be rejected to the night sky, and how much heat can be absorbed by the floor system. However, if a commercial or residential building is designed with passive solar principles and operated with reasonable internal loads, this radiant cooling approach can take care of most or all of the building’s cooling needs. This approach can potentially be used in many climates.

The subject building is a new 8,000 ft^2 owner-occupied office building in Santa Fe, New Mexico. The owner and architect were interested in exploring alternative and low-energy methods for heating, cooling and ventilation, and early design meetings identified radiant night-sky cooling as a possibility, as well as other options such as ground-source heat pumps. The site is urban, relatively open, and sloping toward the north with about 20 feet of elevation difference. The building has a two-story trapezoidal shape oriented east-west, with much of the lower floor bermed into the slope. About one third of the roof is flat, with the remainder gently sloped to allow rainwater harvesting (see Figure 1).

Figure 1. South and West Elevation Views of the Building

(The design for this building, including the features described in this paper, was completed to a "construction documents" level and bid by contractors. At the time of this writing, it is not clear that the building will actually be built, due to changing circumstances with the building owner.)

Cooling Loads

The building has a number of measures to control heating and cooling loads. Windows on the south include solar shades to limit gain, and the west glazing has a low SHGC value (0.32). The skylit atrium uses low-gain translucent material, and the framing of the structure is an R-24 wall assembly with R-40 roof insulation. All slabs and backfilled concrete walls are insulated with R-10 rigid foam. The lighting system uses direct and indirect fluorescent fixtures at 1.1 W/ft^2 connected load, and plug loads were sized at 1.0 W/ft^2 connected load. (We arrived at the latter value by measuring computer workstation wattages in the owner's existing building.) Substantial daylighting with photocell control allowed a reduced lighting operating load. The atrium is also equipped with a thermostat-controlled exhaust fan that operates when the outdoor temperature is cooler than the atrium temperature and the zone calls for cooling.

We modeled the building using the DOE-2/E-Quest simulation software, and based the mechanical system design on zone load calculations using conventional ASHRAE-method software. Total design cooling load was 136,199 btu/hr for 8,573 ft^2 of gross area, or 716 ft^2 per ton of cooling, or 15.9 btu/ ft^2-hr. The interior is divided into 13 zones with a mixture of walled offices and open areas. The relatively low cooling load is important to using the radiant approach, as will be shown below. The DOE-2 modeling was useful in that it provided an hourly load value in addition to the peak design load. A peak design day for this building requires 127 ton-hours of cooling.

Radiant roof cooling

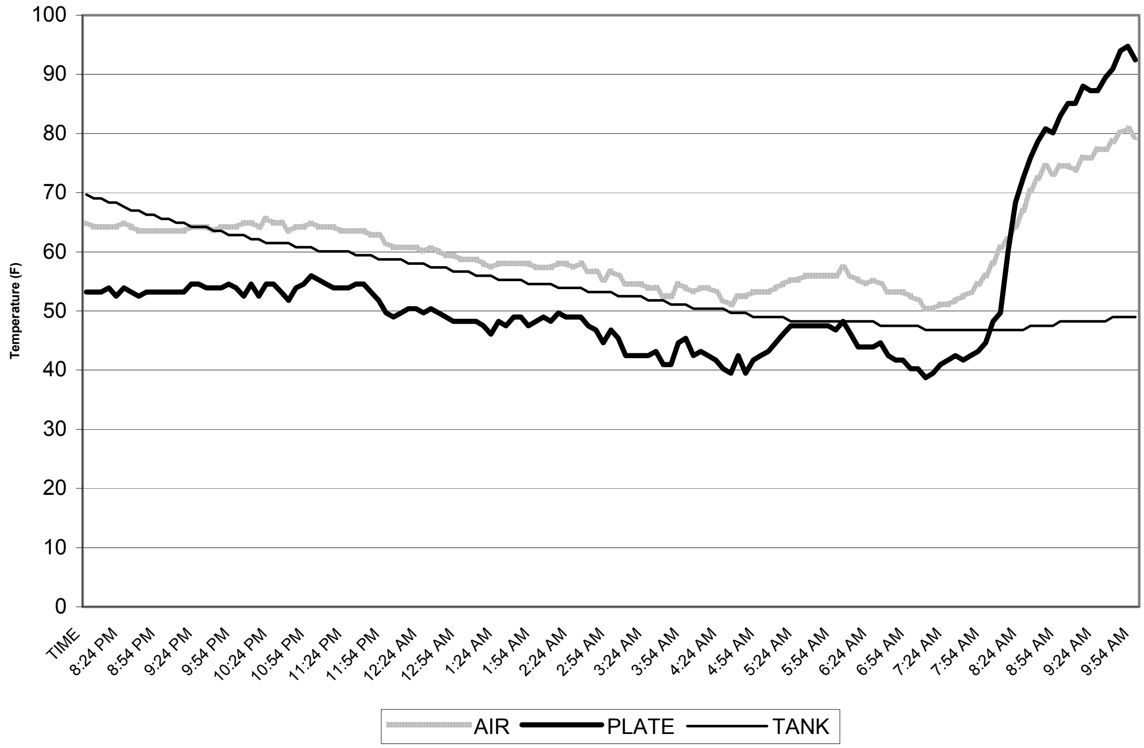
The inspiration for radiant night-sky heat rejection was recent work done by Bristol Stickney and Mark Chalom (Chalom) for the State of New Mexico. (The State is exploring night-sky cooling as an energy- and water-saving alternative to the common evaporative “swamp coolers”.) Stickney and Chalom found that solar swimming pool heating panels placed on a flat roof can provide very effective heat rejection, and that heat transfer can be described by:

$$Q=A(Tw-Tfp)k,$$

Where
A = plate area ($ft^{2)}$
Tw = average water temperature (F)
Tfp = white plate temperature (F)
k = constant that varies with type and brand of solar collector

The white plate temperature is simply the surface temperature of a painted metal plate facing the night sky, and can be easily measured. It is typically 10-15F colder than the ambient air temperature but warmer than the night sky’s radiant temperature. (Stickney measured white-plate temperatures by attaching a thermocouple to a New Mexico license plate mounted on the end of a stick. Plates from other states would presumably work just as well.) Figure 2 gives a comparison of ambient and white-plate temperatures through the course of a September evening in Tesuque, New Mexico. Note the difference in the air temperature (light line) and plate temperature (dark line). The thin line shows the water temperature in a storage tank circulating to a radiant panel on that same evening.

Figure 2. Ambient Air, White Plate, and Cooling Fluid Temperatures



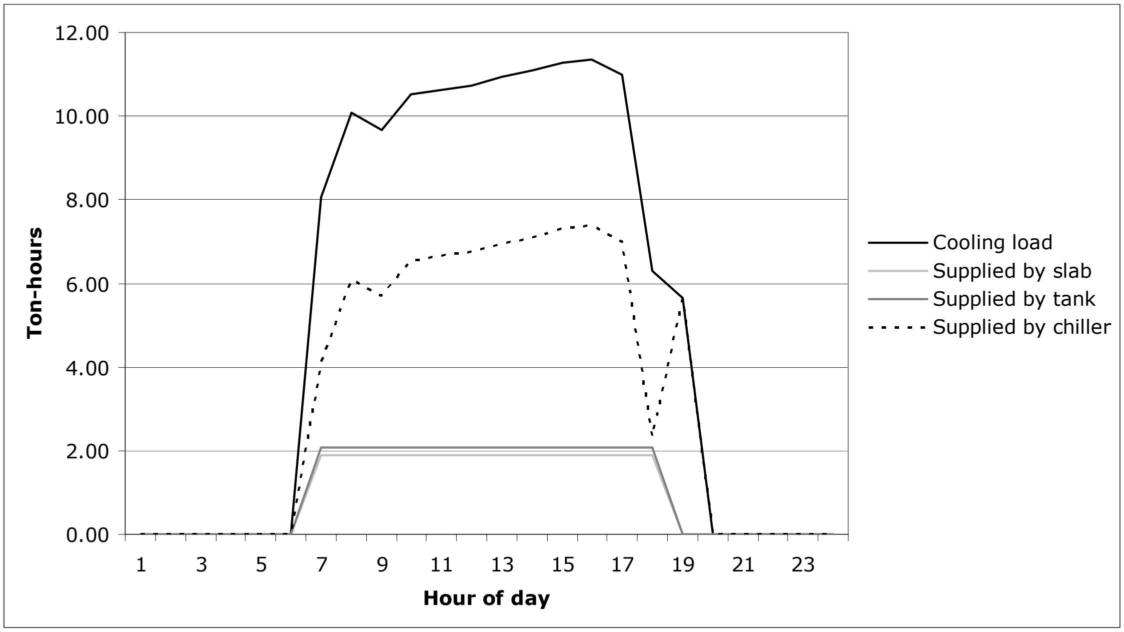
Source: Chalom & Stickney

With this empirically derived equation and seasonal data on white plate temperatures, it is straightforward to calculate the cooling potential of a given roof in the Santa Fe area. For the subject commercial building, the available roof area is 1250 ft^2, and the collector constant for the chosen panel type is 2.26[1]. The water and plate temperatures vary through the night, so we built an hourly spreadsheet model to account for these dynamics.

The calculations showed that we could achieve about 48 ton-hours of cooling on a typical summer Santa Fe night, or about 38 percent of the peak design day. See Figure 3. Although this may seem like a small fraction, the system will work much more effectively in the shoulder cooling seasons as the daily cooling load declines and the lower night temperatures allow more radiant cooling effect. The effective efficiency of the system (EER) is the average cooling provided divided by the average pump wattage. In this system, that value works out to an impressive 122 EER, or a COP of 35.8.

[1] Aquatherm Ecosun panel, a plastic rooftop solar collector. The panel is a simple array of long thin plastic tubes connected by headers.

Figure 3. Cooling Load and Cooling Supply Sources

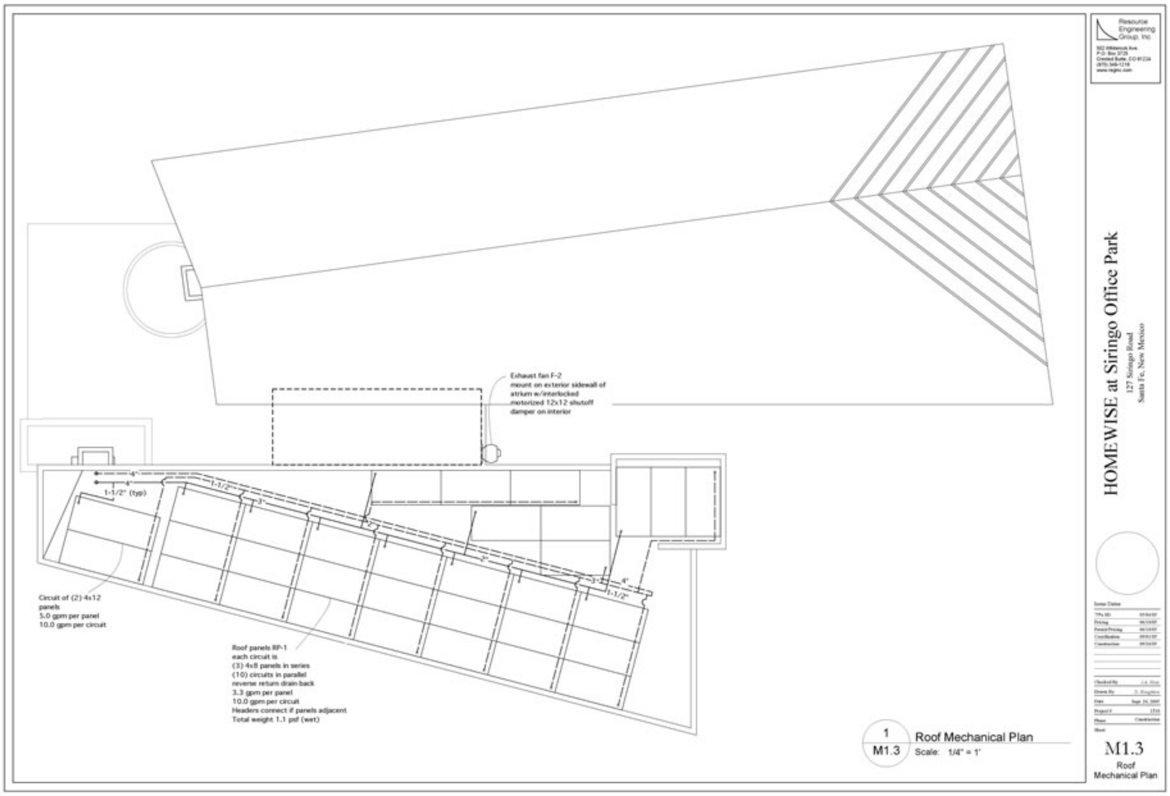


Radiant Roof System Design

This system uses rooftop collector area equal to about 15% of the conditioned floor area to provide nearly over one-third the required ton-hours for a peak design day. Greater collector area, coupled with increased storage, would allow a greater percentage of the load to be met with this strategy. Scaling the values from this building indicates that it would take collector area equal to 40% of the conditioned floor area to achieve complete radiant night heat rejection and eliminate the need for a backup chiller. Thus a two-story building in this climate could be cooled by covering its roof with radiant panels. Buildings with better load control could use less panel area, while buildings with greater cooling loads would require more panel area.

The rooftop cooling system is arranged in much the same way as a solar heating array. Three off-the shelf 4'x8' panels connect in series to form a group, and these are connected to form 11 groups in parallel (see Figure 4). The 5,500 gallon storage tank sits about 20' below; the fluid drains back when the pump shuts off. This drain-back system requires a slight slope to the "flat" roof (1" per foot preferred, 1/4" per foot actual in this case.) No glycol is used in the system. The panels can tolerate freezing without bursting the pipes, but they have longer service life if this does not happen. A priming pump is required to lift the water to the roof at startup, but after 2 minutes the priming pump turns off and a 390W running pump handles the circulation with relatively low head loss.

Figure 4. Roof Plan Showing Placement of Radiant Cooling Panels



The cooling created by the radiant roof system must be stored and distributed through the zones. In this building, we stored about half the ton-hours in an 8'x14'x6' deep concrete water tank that was built into the foundation. The tank design is poured in place with 2" rigid insulation on all sides. On a typical summer cooling day, the tank temperature would start at 62F and increase to 68F, then be brought back down to 62F by circulating the water through the radiant roof panels. (The tank temperature could be brought down lower to provide more cooling.) We arrived at the tank size (about 4.4 gallons of water per square foot of rooftop panel) through a combination of trial calculations and practical considerations of the foundation shape.

The other cooling sink is the pair of 5" concrete slabs that form the floors.[2] The slab temperature would vary between 67.5F at the start of a summer day and 72F at the end of the day, then be brought back down overnight. Many combinations of water tank and slab temperature excursions could be used to store the night cooling.

Radiant Cooling Delivery

The final step is cooling distribution, and we designed a radiant floor cooling system to work with the radiant roof heat rejection system. This in turn allowed us to design a dedicated

[2] Davis Energy Group, Davis California, has done substantial work in coupling "natural cooling" with concrete slabs, and has patented certain processes (U.S. Patent #5,542,260). This work includes the "Cool Roof" concept, with roof sprayers that provide both radiant and evaporative night cooling effects that can be used to cool or precool a slab. See also "Applying Natural Cooling to Slab Floors," ACEEE 2000, Volume 3, p.33.

ventilation system using 100% outdoor air and heat-recovery ventilators. Even though the ventilation system provides more than twice as much fresh air as the code minimums, it is still a fraction of the size of a conventional office air-moving system (1800 cfm total, or about 0.2 cfm/ft2). The building has no forced-air cooling other than two conference room zones with particularly high loads.

There is an increasing body of experience in using radiant cooling to remove heat from commercial buildings. Our approach was to use the same type of in-floor tubing that is commonly used for radiant heating, with the same zone valves, controls, and so on. The entire exposed floor surface becomes the radiant collector that absorbs the building's heat. The in-floor tubing also serves as the heating distribution system in the winter. We considered ceiling panels, which provide higher heat absorption than the floor, but it did not appear necessary and we did not wish to install duplicate systems.

We relied on work by (Oleson), which showed that radiant floor heat absorption of 13–16 btu/ft2-hr is achievable. Oleson's paper provides factors for variables including water temperature, floor covering R-value, tube spacing, tube diameter, and slab thickness. Floors that receive direct solar gain can absorb two to three times the heat per unit area, or up to 50 btu/ft2-hr. The building was designed to use stained and polished concrete as the structural and finish floor, which provided the highest possible radiant heat transfer to and from the space. Carpeting would be limited to runners in high-traffic interior areas where the cooling loads were relatively low.

Another important design feature was individual high-efficiency ceiling fans in each office and in the common areas. These devices had at least two functions: to provide air circulation that increases comfort—especially in the relatively hot and dry Santa Fe cooling season—and to boost heat transfer into the floor by forced convection. We did not find direct research to indicate the effect on heat transfer, but felt comfortable that it would be an increase of at least 50%, to the levels commonly cited for ceiling heat absorption (about 20 btu/ft2-hr). This put our heat absorption above the calculated zone loads for all but two zones, and was important to our confidence in the concept.

Any radiant cooling delivery system must consider the potential for condensation on the radiant surface. The floor temperature must stay above the ambient air's dewpoint temperature to avoid condensation, so the chilled water supply temperature must also stay relatively high. In the Santa Fe climate, this means water temperatures of 65F or higher, and certainly no colder than 62F depending on the relative humidity of the air. This high temperature—and low delta T compared to the space temperature—is the main limiting factor in radiant cooling design. Our system design uses injection control to control the water temperature fed to the in-floor tubing.

Backup Systems

Two zones—conference rooms with high internal loads and relatively large glass areas—exceeded the allowable cooling capacity of the radiant floor system. We elected to install fan-coil units to make up the extra cooling capacity. The fan coil units are supplied with chilled water from the same source, except that the temperature is allowed to go as low as 45F since there is no condensation concern. Even with water temperatures in the low 60's, the supplemental cooling from the fan coils is enough to fill the gap between the design load and the radiant floor capacity.

The radiant rooftop system does not have enough capacity to meet peak cooling loads. The backup cooling system is a pair of 5-ton water-to-air chillers that can feed chilled water into the system through a 120-gallon buffer tank. Another concession to conventional cooling is found in the computer server room, which is conditioned by a dedicated split a/c system. We proposed a small ground-loop heat pump system to serve as the backup cooling source, which would have been a nearly ideal match, but complications with parking lot areas and construction sequencing—and concerns about initial cost—led to the decision to use air-cooled chillers.

Control Considerations

One of the more interesting (difficult) aspects of this system is how to control it. It is relatively easy to make the tank of chilled water overnight; simply run the pumps to the rooftop array when there is sufficient delta T between a permanently mounted white plate on the roof and the tank water. Daytime radiant cooling is also straightforward: if a zone calls for cooling, pump chilled water to the slab. However, half of the cooling capacity is achieved by running cool night water through the slab to precool it. Thus some degree of predictive control is necessary: will the building need cooling tomorrow?

Our control sequence opens the zone valves for night slab cooling when all of the following conditions are present: one or more valid cooling calls in the zone over the past 24 hours, roof cooling pumps running, slab temperature above low-temp cutoff (62F), and space temperature above low-temp cutoff (65F). The latter two conditions are to prevent surface condensation and overcooling of the space respectively. A more accurate, but more complicated, control strategy might be to predict the *level* of cooling for the next day and precool the slab zone to meet this demand. Thus the control system would look at the cooling ton-hours or zone-hours called for in a given day and assign a level (such as 1-4) for the following day's requirements. This would in turn affect the temperature and low-limit setpoints called for in the overnight cooling session. Our system was designed with digital controls and in-slab temperature sensors to allow flexible control approaches such as the one described above. We expect that some experimentation would be required to optimize the system's operation.

The building's radiant heating and cooling system is effectively a two-pipe changeover system. A call for heating with no calls for cooling puts the system in heating mode and allows boiler-fed (we would have preferred heat-pump-fed) hot water to be delivered to the zones for radiant heating. A call for cooling with no calls for heating puts the system in cooling mode, and allows chilled water to be delivered to the zones for radiant cooling. In the event of simultaneous calls for heating and cooling, cooling takes precedence between 10a.m. and 8p.m., and heating at all other times.

Lessons Learned

For Radiant Rooftop Heat Rejection, the Primary Considerations Are:

- Prior to design, log ambient temperature and white-plate temperature using 15-minute (or shorter) data sampling to determine the night radiant potential.
- Reduce cooling loads as much as possible through solar control and internal load reduction.
- Plan on using as much as 50% of the conditioned floor area as the radiant roof surface.

- Design a cooling delivery system that works well with relatively warm chilled water (high 50's to high 60's). Radiant floor cooling is a good match.
- Design for at least 4-5 gallons of water storage per square foot of rooftop panel. (Others have done systems using smaller ratios.)
- The optimal roof geometry is a 1:12 slope (in any direction) for panel drainage, with full exposure to the night sky. Parapets, trees, and other obstructions will reduce the cooling potential.

For Radiant Floor Cooling, the Primary Considerations Are:

- Reduce cooling loads to 15 btu/ft2-hr or less.
- Plan on exposed concrete, tile, or other high-conductivity surfaces as the finished floor.
- Maximize the exposed area of the radiant floor—furniture or floor coverings reduce the cooling effect and may create cold spots that condense moisture.
- Consider passive or active means to encourage air circulation for improved cooling effect, and to mitigate the spot condensation mentioned above.
- In humid climates, dehumidify the outdoor air to reduce condensation potential. (This was not a factor for this project.)
- If necessary, use conventional equipment to handle areas with high spot cooling loads.

Radiant cooling systems such as this one have potential applications to many building types, including residential. The State of New Mexico sponsored the roof cooling research cited above in the interest of saving energy and water compared to conventional air conditioning and even swamp coolers. This approach also lends itself well to buildings that would already have slab floors with radiant heating.

References

Bjarne W. Oleson, Ph.D., "Possibilities and Limitations of Radiant Floor Cooling," ASHRAE Trans., 1997, vol.103, part 1, paper number 4014, 42-48, 3 figs, 8 tabs, refs.

Mark Chalom and Bristol Stickney, "Night Sky Radiant Cooling Potentials for the State of New Mexico," white paper. Contact Mark Chalom, 505-983-1885.