SUMMARY REPORT MAY 2008

SIMULATION OF RADIANT COOLING PERFORMANCE WITH EVAPORATIVE COOLING SOURCES

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EXECUTIVE SUMMARY

This project addresses three closely related and similarly complex questions: First, using currently available simulation software, what methods might be appropriate for comparing slab-integrated radiant cooling to more conventional alternatives, such that the results are sufficiently fair and comprehensive to support system selection and design? Second, what is the relative performance of representative system configurations across a set of climates that test presumed strengths and limitations? Third, what useful conclusions can be drawn from such comparisons to inform the selection, application, design, and control of hydronic radiant cooling?

The particular approach taken to answering these questions is rooted in the contention that useful results must effectively capture five essential aspects of slab-integrated hydronic radiant cooling: a) radiant heat transfer between surfaces; b) the effects of thermal capacity, lag, and decrement in the chilled slab; c) the limitations of evaporative cooling water sources; d) the potential of various control strategies for maintaining thermal comfort while minimizing energy consumption and peak loads; and e) the challenges and benefits of integrating the operation and control of hydronic and airside space conditioning systems.

This report describes whole-building simulations of slab-integrated hydronic radiant cooling with mechanical ventilation, plus a more conventional all-air cooling system as a point of reference. Simulations are performed using Virtual Environment (VE)—an interconnected set of building performance-modeling tools from Integrated Environmental Solutions (IES). Methods are described for the modeling of hydronic radiant cooling slabs. Among these, THERM, a simple two-dimensional finite-element heat transfer tool from Lawrence Berkeley National Laboratory, is used for determining properties of the heat transfer path between the hydronic circuits and cooling surfaces. Attention is also given to modeling limitations of evaporative cooling as a supply water source for the radiant system and waterside economizer for the all-air baseline system. In preparing the models, emphasis was placed on achieving similar degrees of equipment and controls optimization for both systems using methods that could be replicated in the context of practical design processes.

Cooling-season performance is evaluated in terms of system dynamics, thermal comfort, peak loads, and energy consumption for a prototypical office building in Denver, Sacramento, Los Angeles, and San Francisco. The Denver climate was used to optimize system dynamics and performance for minimum energy consumption and peak power. Sacramento—the hottest of the four—was the focus for optimizing and evaluating thermal performance with aggressive hydronic slab nighttime precooling. For the San Francisco climate, added emphasis was placed on optimizing the economizer controls and performance for the all-air baseline system. In all cases, equipment, airflow, and other key parameters were evaluated and re-sized accordingly.

The slab-integrated hydronic radiant cooling is augmented by a dedicated outside air system (DOAS) for conditioning of ventilation air. The hydronic cooling and DOAS utilize only indirect evaporative cooling sources. The supply water source for the hydronic slabs and cooling coils is a closed-circuit cooling tower. The DOAS also incorporates a heat exchanger for sensible energy recovery and indirect-evaporative cooling of ventilation air via a spray chamber in the exhaust air stream. The reference baseline is a modern variable-air-volume system with an efficient water-cooled chiller and fully integrated control resets for supply air temperature and airside economizer operation. A waterside economizer or waterside "free cooling" (WSFC)—essentially the same cooling water source as is used for the hydronic radiant system—and nighttime precooling cycle were modeled as an additional scenario for the baseline system. The DOAS and VAV system use identical high-efficiency fans and motors (differing only in size).

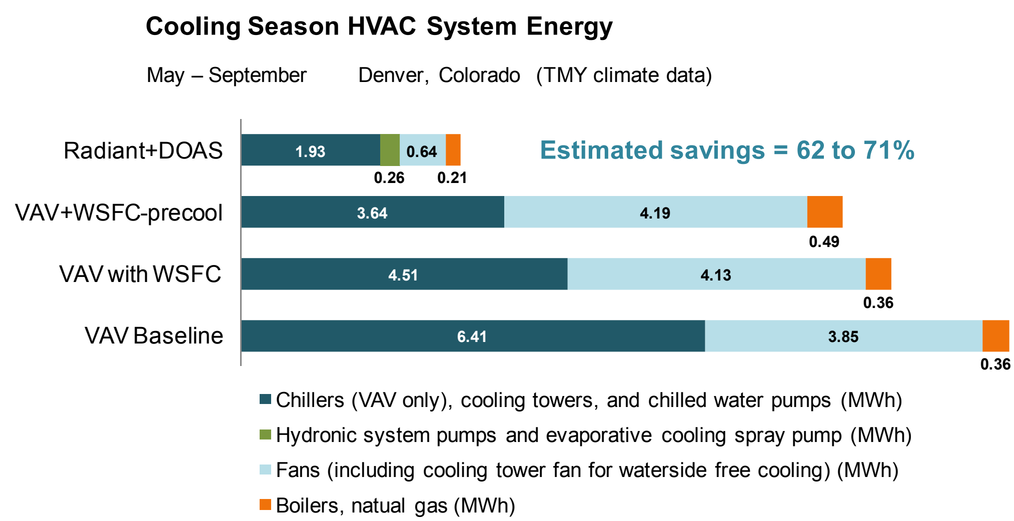

Figure 1: Simulated cooling-season HVAC system energy consumption for Denver, Colorado. The range of estimated saving is relative to the VAV baseline system with and without a waterside economizer.

Simulation results (Figures 1–4) suggest strong energy-saving potential for radiant cooling systems in both Colorado and California climates. In Denver (Figure 1), the simulated radiant cooling plus dedicated outside air system (Radiant+DOAS) with precooling uses an estimated 71% less energy than the standard VAV baseline system and 62% less than the same VAV system using waterside free cooling and a nighttime precooling control strategy. This comparison includes heating for cool mornings, which must be coordinated with the nighttime slab precooling strategy. In Sacramento (Figure 2), the Radiant+DOAS uses an estimated 59% less energy relative to the baseline VAV system and 56% less than the VAV with waterside free cooling, regardless of the inclusion of precooling controls. For this hot but relatively dry climate, the added fan energy for precooling with the all-air VAV system, given its capacity for WSFC is sized for chiller heat rejection, offsets the savings from reduced daytime chiller operation. In Los Angeles (Figure 3), where daytime temperature are more moderate and nighttime temperatures tend not to dip quite as low, precooling—in this case used only for the Radiant+DOAS—confers a lesser net benefit. For San Francisco (Figure 4), where cooling loads are reduced and *airside* “free cooling” is readily available through economizer operation (which still requires the use of fans), total energy for both systems is considerably lower. However, the effectiveness of *waterside* free cooling in this climate contributes to even greater reduction of energy consumption for the otherwise already very efficient hydronic radiant system.

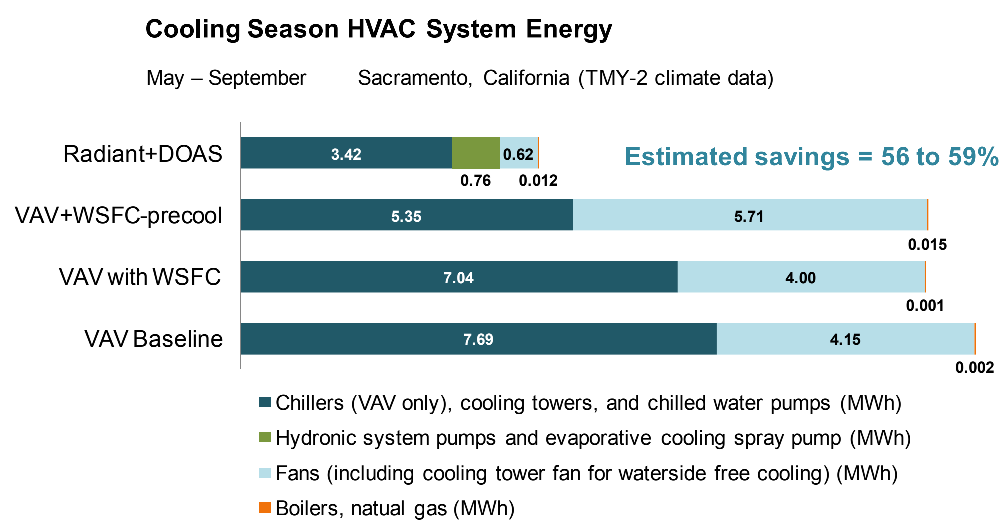

Figure 2: Simulated cooling-season HVAC system energy consumption for Sacramento, CA.

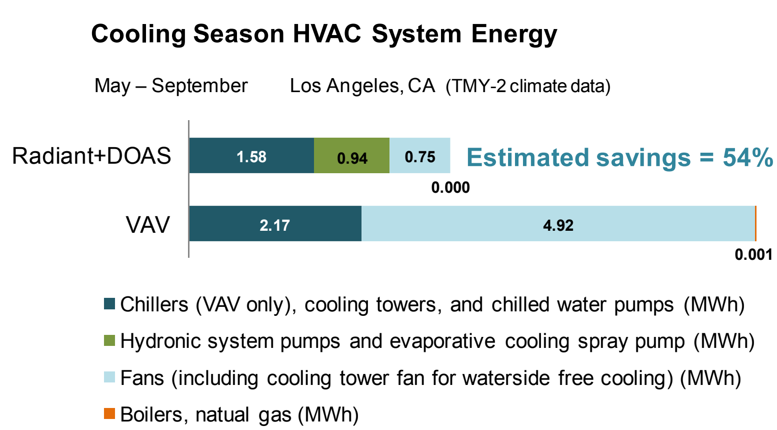

Figure 3: Simulated cooling-season HVAC system energy consumption for Los Angeles, CA.

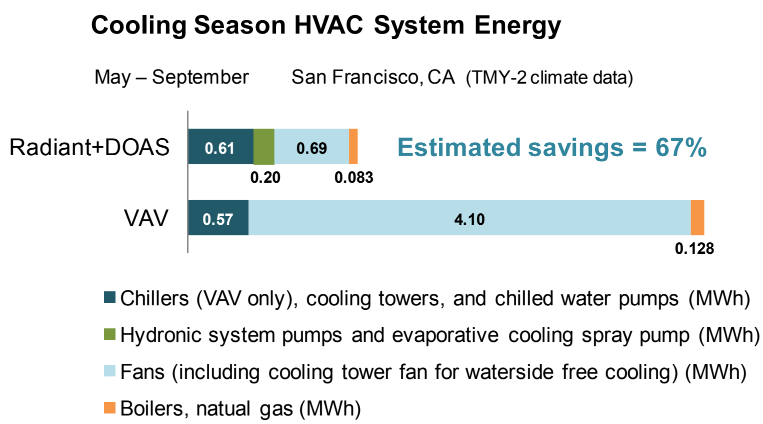

Figure 4: Simulated cooling-season HVAC system energy consumption for San Francisco, CA.

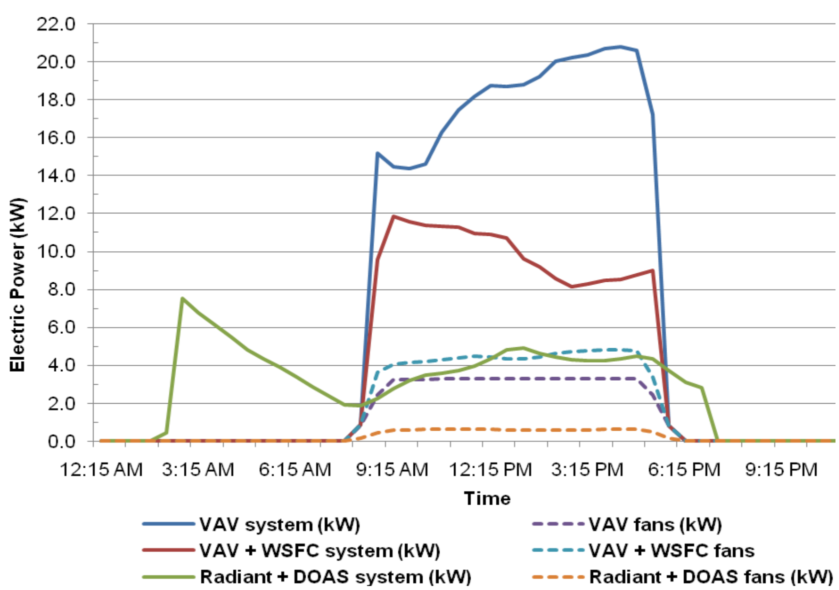

Figure 5: Cooling-system, fan, and nighttime precooling operation in terms of power and energy (the area under the curves) for the Radiant+DOAS, VAV+WSFC, and standard VAV-baseline with water-cooled chiller. The plot is for the day of peak cooling loads in Sacramento, CA (TMY-2 climate data).

Peak power demand for the Radiant+DOAS is both significantly reduced and shifted to off-peak hours (Figure 5): In Sacramento, the VAV baseline system peaks at 20.9 kW on July 19th; on that day, the Radiant+DOAS system peaks at just 9.8 kW—a 50% reduction—and does so at 2:45 AM when utility power demand is very low. During the afternoon hours of July 19th, the radiant-DOAS system peaks at just 2 kW—a 90% reduction. The peak cooling-season demand for the radiant system is 10.4 kW and occurs at 4:15 AM. Evaluating only afternoon hours (noon to 5:00 PM) when electric demands tend to peak, the radiant system has just 34.5 hours of demand over 5 kW, while the VAV system has 504 hours of operation over this same threshold.

Even with aggressive precooling for the hydronic slabs, thermal performance for the two systems in the hot Sacramento climate remains comparable. The greatest difference occurs on the hottest few days in July and August with late-afternoon peak solar gain in the west perimeter zones. At this time, the concrete slabs are relatively warm and the peaking outdoor wet-bulb temperature limits the evaporative cooling of supply water. Under these conditions, operative temperatures for west perimeter zones with Radiant+DOAS cooling exceed 1K (1.8°F) above that of the baseline system only within the very last occupied hour of the day, if at all. For the vast majority of the cooling season, however, the Radiant+DOAS system provides a *lower* operative temperature.

From a gross, whole-building perspective, thermal performance for the low-energy Radiant+ DOAS differs only subtly from that of the baseline VAV system. Even for the afternoon of the *peak* cooling day in Sacramento, with 40°C (104°F) dry-bulb and 23°C (73.4°F) coincident wet-bulb temperatures, the combined average operative temperature for all regularly occupied spaces differs less than 0.5 K (0.9°F) between the radiant-cooling and baseline-VAV cases. This is additionally significant given that the peak cooling provided by the hydronic radiant slabs occurs three hours *after* the hydronic circulation pumps have been shut off to avoid *adding* heat to the slabs. Just 16% of total cooling at that time is provided by the DOAS. However, achieving this with constrained supply water temperatures and at the same time avoiding excessive precooling required careful attention to numerous control parameters. Thus slab precooling with water from a cooling tower and augmentation by indirect evaporative cooling of ventilation air would appear to be an effective strategy for exceptionally low-energy cooling, even in hot climates such as Sacramento, *if* appropriate attention is paid to the design and control of the system.

There were three essential control strategies employed to utilized the slab thermal mass and the extended nighttime cooling-tower capacity: 1) cut off cooling water to any given slab when the water temperature from the cooling tower exceeds the slab core temperature; 2) avoid cooling the slabs in the late afternoon and evening hours, even when the outdoor WBT is low—*i.e.,* begin the nighttime precooling only after the outdoor WBT has dropped significantly *and* the slab core temperature is approaching equilibrium with the occupied space; 3) constrain precooling to avoid overcooling occupied spaces in early morning hours. Together with the location of hydronic cooling at the core of the massive concrete slabs, these strategies maintained thermal comfort while shifting a large fraction of the cooling load to off-peak hours suited to evaporative cooling.