

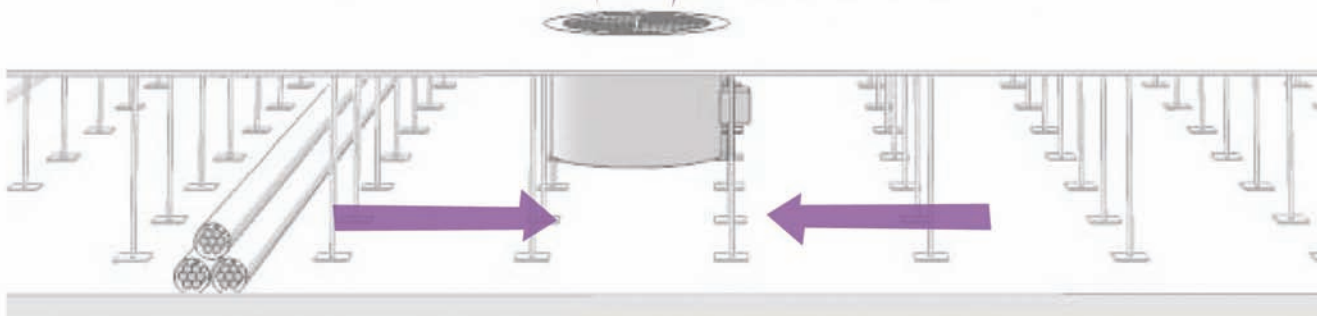
# Cooling With Less Air

## Using Underfloor Air Distribution and Chilled Beams

By **Steve Weidner, P.E.**, Member ASHRAE; **Jerome Doerger, P.E.**, Member ASHRAE; and **Michael Walsh, P.E.**

**F**or a new call center in Kentucky, the design team determined that the optimal HVAC solution was an underfloor air-distribution (UFAD) system combined with some form of passive cooling. After considering several options, the team decided on UFAD with passive chilled beams, which helped to reduce electrical energy consumption by 41%, reduced natural gas consumption by 24%, and addressed all the initial project objectives in an innovative manner.

The master plan for the Kentucky project called for the construction of a 376,000 ft<sup>2</sup> (34 932 m<sup>2</sup>) building designed to house 2,200 employees on an existing campus. The design parameters included LEED certification and optimal flexibility for personnel and functional space. The new facility also needed raised access flooring and UFAD in all office spaces to ensure the flexibility to accommodate future workstation arrangements.



The design team performed cooling and heating load calculations for the proposed facility. All of the relevant building and occupant characteristics were collected, and a standard computer modeling program was used to determine loads. When this design was executed in early 2006, there was no proven computer model for UFAD system load calculations, and certainly none that would have accommodated chilled beams. Using sound engineering judgment, the team used a methodology that attributed heat gains to occupied zones (occupants, computers, and exterior wall/window transmission/solar gain from the floor to a height of 6 ft [2 m] above the floor) and unoccupied zones (lights and exterior wall/window transmission/solar gain above 6 ft [2 m] to the typical ceiling height of 11 ft [3 m]). This data was then used to size central plant chillers and boilers. The plant design included N+1 redundancy chilled water and heating hot water capacity.

### Increasing Efficiency, Maximizing Space

After building loads and central utility plant loads were determined, the design team addressed the selection and sizing of air-handling equipment. Space requirements and overall facility design dictated that the air-handling units would be located in penthouses on the roof, requiring vertical utility chases for supply and return ductwork and service piping. As the team brainstormed potential systems solutions, they considered ways to minimize floor requirements necessary for vertical air chases, maximizing usable floor area.

The solution was to use a UFAD system combined with some form of passive cooling within the occupied space (cooling that would not require central system airflow). To determine the best form of passive cooling, the team investigated a number of technologies, with particular attention given to innovative and energy-efficient applications. The search produced a list including UFAD in conjunction with radiant cooled ceilings (also known as chilled ceilings) and UFAD in conjunction with chilled beams.

For the chilled beams option, active and passive chilled beams were a consideration. However, active chilled beams were quickly rejected because they would require air-handling systems and ductwork that the supplemental cooling system was intended to eliminate. Further, active chilled beam systems have mixing characteristics that eliminate the benefits of supplying fresh air directly to the occupied zone.

### Radiant Cooled Ceilings Versus Passive Chilled Beams

Radiant cooled ceiling systems use cooling panels mounted within the ceiling to provide sensible cooling of the occupied space. The panels typically have a face panel compatible with the installed ceiling, which is combined with chilled water tubing circuited throughout the back surface of the face.<sup>1</sup> The chilled water piping is situated above the ceiling, and the exposed face of each radiant panel is maintained at approximately 60°F to

65°F (15.6°C to 18.3°C). As in the case of any chilled surface in an occupied space, the design must ensure that the surface temperature exposed to occupied conditions not be allowed to drop below the space dew-point temperature to avoid condensation.

This appears simple when studying the design point on a psychrometric chart. The design point for occupied spaces at the facilities is 72°F db [22°C db] and 50% RH, which corresponds to a dew-point temperature of 52.4°F (11.3°C). However, the actual dew-point temperature in an occupied space with an appreciable ventilation (or infiltration) air load may drift well above the design value unless active measures are used to maintain relative humidity within a tolerance value of the design point.

	UFAD Alone	UFAD With Radiant Cooled Ceilings	UFAD With Passive Chilled Beams
Supply Air Quantity (cfm)	560,000	240,000	240,000
Supply Fan Power (hp)	600	280	280
Return Fan Power (hp)	280	120	120
Total Swirl Diffusers* Required	5,600	2,400	2,400
Weighted Airflow (cfm/ft <sup>2</sup> )	1.6	0.7	0.7
Qualitative Flexibility	Good	Fair	Good
First Cost (\$)	Reference	+4,250,000	+100,000
Operating Cost Payback	N/A	>50 years	<2 years

\*Swirl diffusers are floor-mounted air devices for supply air delivery into the occupied space.

**Table 1: Comparison of UFAD with and without supplemental cooling systems.**

Among the factors in favor of radiant cooled ceilings were the noninvasive supplemental cooling (meaning the cooling was accomplished without any ductwork, devices, or duct chases protruding into the occupied space) and the effectiveness of the system. The low cooling capacity, typically around 30 Btu/h-ft<sup>2</sup> (95 W/m<sup>2</sup>), would have required most of the ceiling to be radiant. Initial cost and aesthetic considerations were the primary factors against radiant cooled ceilings.

Passive chilled beams use chilled water piping circuited through coil-like structures at or above the space's suspended ceiling or, in spaces without a suspended ceiling, near the underside of the deck. The units function similarly to finned-tube convectors, except that the chilled beams operate based on the greater density of cooled air relative to the air within the space, as opposed to the finned-tube convectors' reliance on the lesser density of the heated air relative to the air within the space. Ambient air is cooled by the chilled beams and "falls" due to its greater density, displacing warmer room air and creating convective currents.<sup>2</sup>

The condensation concerns governing the installation of radiant cooled ceilings, and the associated chilled water temperatures, apply to chilled beams as well. But the comparative simplicity of components, greater cooling output (beams for this project were selected to provide 180 Btu/h per lineal foot [173 W per lineal me-

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ter]) and the lower cost relative to radiant cooled ceilings favored the passive chilled beam option over radiant cooled ceilings.

### Ideal HVAC Solution

The system evaluation compared air quantity delivered to the space, total motor horsepower, quantity of floor diffusers, future flexibility, and first cost for all three options. The three solutions considered were:

1. UFAD alone, as a baseline for comparison;
2. UFAD in conjunction with radiant cooled ceilings; and
3. UFAD in conjunction with passive chilled beams.

The results of the comparison are summarized in *Table 1* (p. 35). The supply air quantity indicated for UFAD with radiant cooled ceilings was determined based on cooling capacity if the entire ceiling was composed of radiant panels. The decision to provide a radiant ceiling throughout was based on providing a uniform ceiling pattern throughout the space.

The supply air quantity indicated for UFAD with chilled beams was determined through an optimization exercise using a spreadsheet that calculated the amount of cooling provided by UFAD supply air at various outside air percentages. The difference between that cooling capacity and the cooling load would be provided by chilled beam cooling. Ultimately, this process determined that 40% outside air was most appropriate for the application, considering size of air-handling units, fan horsepower, size of ductwork, quantity of swirl diffusers, and quantity of chilled beams.

The usable quantity of chilled beams dictated that they be installed perpendicular to outside walls (as opposed to a more typical along-the-perimeter layout) and above occupant workstations. This was deemed acceptable because of the facility's high ceilings.

The supplemental cooling systems served to reduce supply and return fan horsepower requirements, as well as the number of swirl diffusers required. This represented a significant cost reduction, especially since the decision had been made to use automatic or motorized damper swirl diffusers as a means of maximizing occupant comfort.

The team continued their iterative design investigation, both to satisfy aesthetic and functional aspects of the finished installation and to maximize the energy efficiency of the air-handling system. The mechanical design team worked closely with the design architect to coordinate the placement of chilled beams with the layout of columns and light fixtures throughout the space. *Figure 1* provides a cross-sectional representation of the combined UFAD and chilled beam system.

### Maximizing Energy Conservation

To maximize energy conservation, the team considered heat wheel energy recov-

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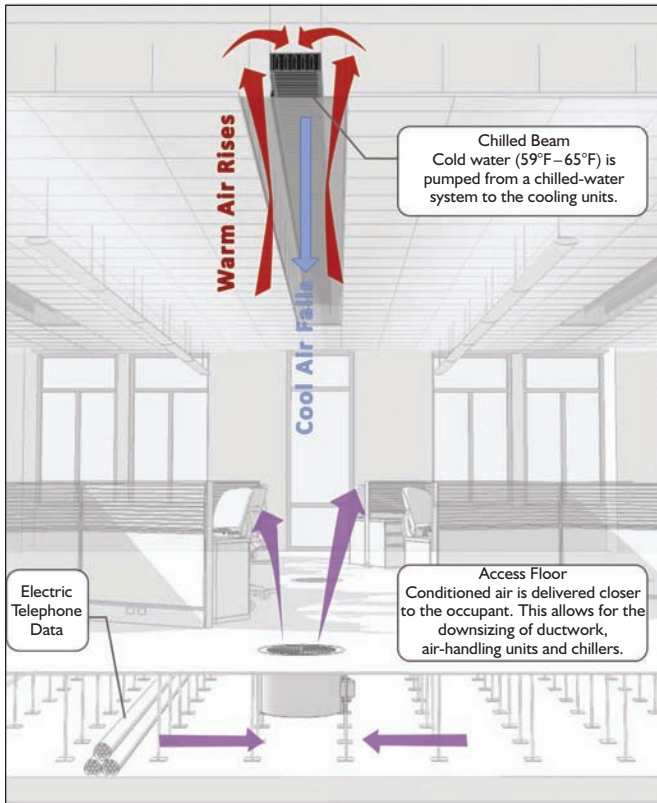


Figure 1: Hybrid UFAD/chilled beam HVAC delivery system.

ery as a means of further improving system efficiency, but the combination of installed cost and equipment space requirements disqualified this option. The concentration of personnel in the occupied space required a substantial percentage of outside air for ventilation, and the equipment required to condition this ventilation air would have been significant. The supply air dry-bulb temperature in UFAD is higher than in a conventional ducted system—roughly 62°F (16.7°C) with UFAD versus roughly 55°F (12.8°C) with conventional. In addition, the space dehumidification requirements in this project dictated a supply air relative humidity approximately 0.0007 lb<sub>w</sub>/lb<sub>a</sub> (0.0003 kg<sub>w</sub>/kg<sub>a</sub>) lower than room conditions. Consequently, some form of supply air reheat was required.

The solution was to intentionally bypass a portion of the return airflow around the cooling coil and mix it with the cooling coil leaving airstream prior to entering the draw-through supply fan. Outside air for ventilation mixes with a portion of return air and passes through the chilled water cooling coil. The cooling coil reduces entering air from 87°F db/77°F wb (30.6°C db/25.0°C wb) to a leaving condition of 50°F db/49°F wb (10°C db/9.4°C wb). This coil-leaving air then mixes with 81°F db/63°F wb (27.2°C db/17.2°C wb) return air (based on estimated 79°F db [26.1°C db] return plenum temperature plus 2°F db [1.1°C db] fan heat), at a ratio of approximately 66% coil air to 34% bypassed return air, to yield a supply air temperature of 61°F db/54°F wb (16.1°C db/12.2°C wb), after supply fan heat and supply duct pickup. This process is depicted psychrometrically in *Figure 2*.

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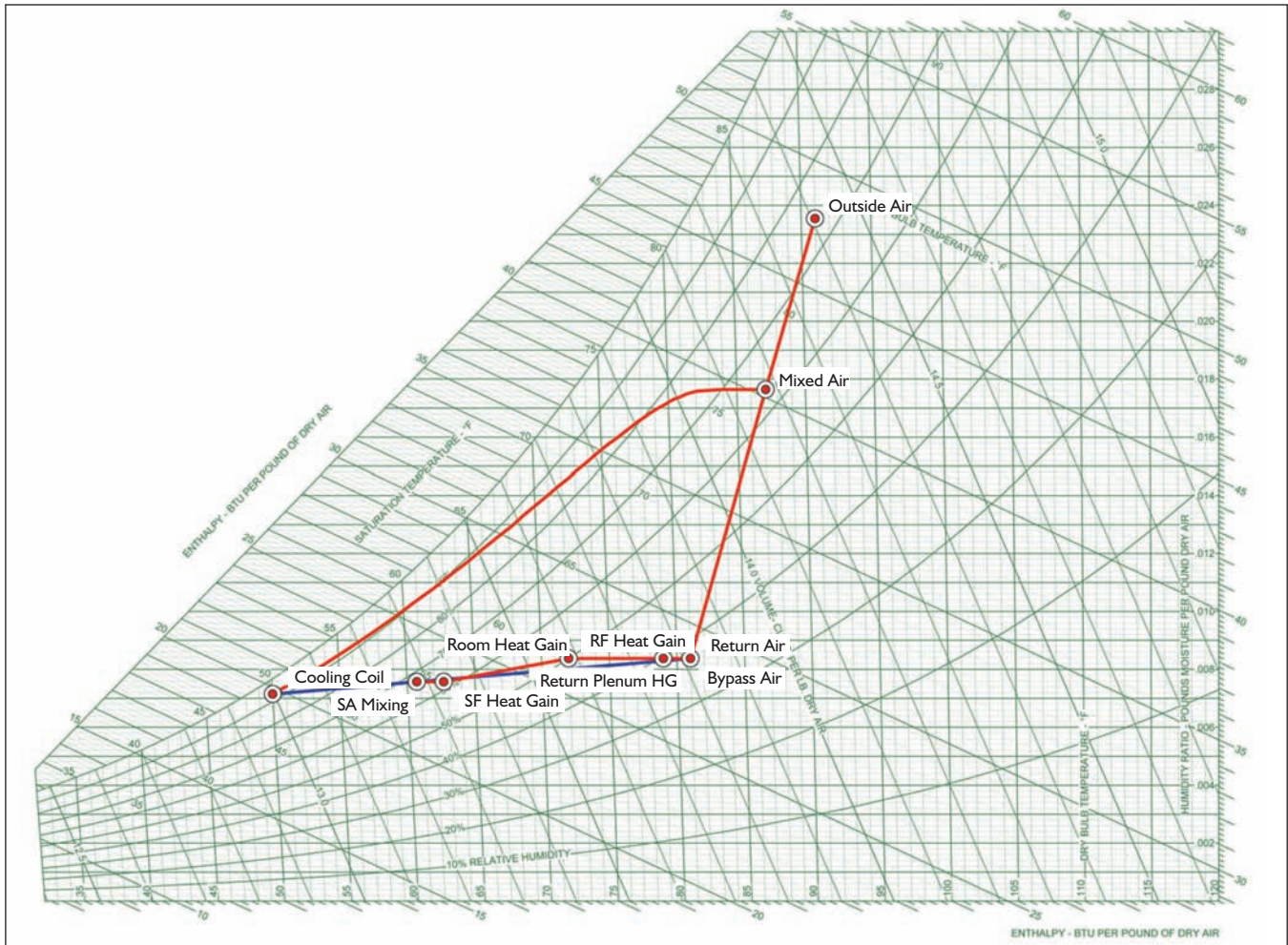


Figure 2: UFAD cooling cycle.

The central station air-handling units provide all ventilation for this building, all latent-load offset and approximately 52% of the sensible-load offset capacity to the conditioned space. The remaining 48% of sensible-load cooling is provided by the chilled beam system. The system also incorporates carbon dioxide monitors within the occupied spaces to control outside air introduction, which minimizes energy use while ensuring that ventilation air requirements are satisfied.

The chilled beams are positioned throughout the ceiling area in a linear arrangement perpendicular to outside walls and are sized to provide approximately 180 Btu/ft (173 W) cooling capacity. The system is designed to use return chilled water after passing through the air-handling unit coils in the penthouses as shown in Figure 3. This return water, at approximately 57°F (13.9°C), is drawn from the chilled water return risers at each floor and pumped to the chilled beams throughout the space. Water leaving the chilled beams, at approximately 64°F (17.8°C), is combined with system return water in a secondary loop arrangement to maintain chilled beam surface temperatures above space dew-point temperatures.

The automatic temperature control system monitors space dry-bulb and wet-bulb temperatures, computes space dew-point

temperature, and then modulates the chilled beam secondary loop two-way control valves to maintain entering water temperature at not less than 3°F (1.7°C) above space dew-point temperature. This chilled beam leaving water, at 64°F (17.8°C), is then routed back to the building mechanical rooms in the basement and mixed with AHU-coil return water, at 57°F (13.9°C), to yield a net system return water temperature of approximately 58°F (14.4°C). The wider temperature difference across the chiller evaporator barrel (13°F [7.2°C] rather than 12°F [6.7°C]) allows the chillers to operate at a minimally higher efficiency. However, the reduced peak chilled water flow rate associated with series flow through cooling coils and chilled beams reduces peak pumping horsepower demand by almost 11%.

### Ventilation Analysis

Following initial layout and system sizing, the team performed a computational fluid dynamics (CFD) analysis of the proposed system. The full CFD analysis was done to evaluate the proposed design for thoroughness of occupied zone air mixing and circulation within the occupied space and the approximate mean age of ventilation air at respiration. Both factor into the overall ventilation effectiveness of the system

and predict occupant satisfaction. The analysis revealed that the proposed system would satisfy design requirements. The only recommended modifications to the system were a slight increase in return air path area and the addition of a few swirl diffusers for indicated hot spots. These changes were implemented and the system design was complete.

### Bidding and Construction for a New Process

One additional hurdle to be overcome in the design process was the bidding and construction phase. Because chilled beams are not yet widely used in the United States, many HVAC installation contractors are unfamiliar with the requirements for installing the systems. To prevent unnecessary difficulties during bidding and construction, the design team erected a mock-up of a chilled beam system and brought in prospective HVAC contractors to observe an actual system and learn about how it is fabricated and installed. The HVAC bids, which could have been inordinately high due to contractor skepticism or lack of familiarity, came in more commensurate with expectations. Ultimately, the selected HVAC contractor was able to install the system on time and within budget.

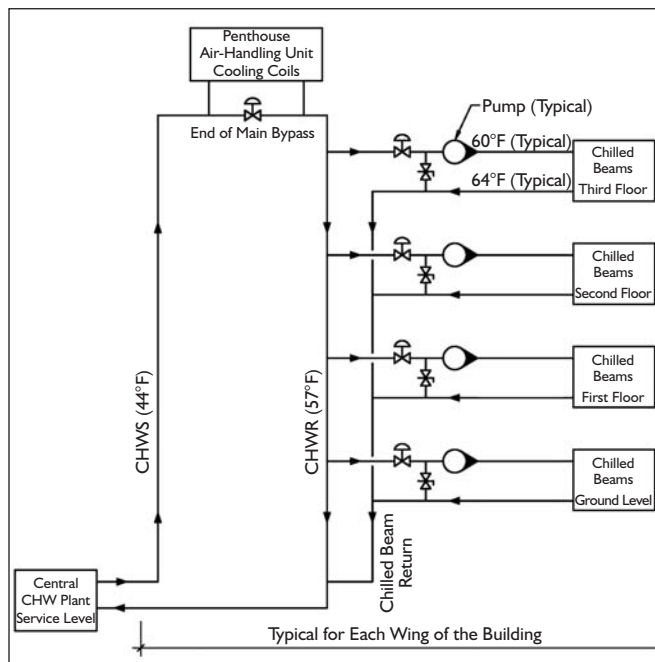


Figure 3: Chilled beam piping diagram.

### Cost Results

Operating cost data has been gathered since occupancy of this building in December 2007. Over 2008, the average electrical energy consumption was 1.89 kWh/ft<sup>2</sup>. Over that same period of time, the average electrical energy consumption of a building of similar construction and occupancy, on the same campus as the subject building, but with a traditional overhead VAV system, averaged 3.22 kWh/ft<sup>2</sup>. This equates to 41% less, as noted in Table 2. Similarly, natural gas consumption for the 2008 calendar year was measured at 24% less. The building is meeting the expectation of considerably less energy consumption.

### Key Lessons

Much was learned on this project during design, system commissioning, and occupied operation. During design, it was believed that temperature stratification would be minimally impacted by columns of cool air dropping from chilled beams into the occupied space. The team also projected that cool air dropping out of the chilled beams would not adversely impact floor diffuser supply airflow patterns. Both beliefs were reinforced by results obtained from the CFD. But in practice, the anticipated stratification did not materialize, and

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	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	
<b>Subject Building (375,909 ft<sup>2</sup>)</b>													<b>Avg.</b>
Total kWh	603,191	620,557	710,214	792,539	670,842	682,702	757,313	718,749	735,248	721,284	723,278	782,832	709,896
Total kWh/ft <sup>2</sup>	1.60	1.65	1.89	2.11	1.78	1.82	2.01	1.91	1.96	1.92	1.92	2.08	1.89
<b>Comparable Building (188,321 ft<sup>2</sup>)</b>													<b>Avg.</b>
Total kWh	752,548	629,850	573,740	589,647	576,489	599,758	635,405	566,343	596,489	580,019	561,847	606,702	605,736
Total kWh/ft <sup>2</sup>	4.00	3.34	3.05	3.13	3.06	3.18	3.37	3.01	3.17	3.08	2.98	3.22	3.22

**Table 2: Monthly electrical energy consumption comparison to a traditional VAV system.**

return air temperature to the facility’s air-handling units is lower than expected. This poses a challenge under dehumidification/reheat conditions. Pursuing this issue further, chilled beams in the immediate vicinity of above-ceiling return air openings are experiencing reverse airflow, contributing to lower-than-anticipated return air temperatures. These beams were unobtrusively blanked off. The conclusion is that, despite taking the precaution of a detailed CFD, airflow is not always entirely predictable, especially when using an innovative approach that has not been tried and tested. Fortunately, cool airflow from correctly functioning chilled beams does not appear to have an adverse impact on floor diffuser performance. In fact, occupant comfort has exceeded expectations. Comfort-related complaints averaged only 28 per month for the 1,700 employees who occupied the building during 2008.

**Conclusions**

It was essential the design team understood the objectives and critical considerations of the project to ensure each was incorporated into the finished design. The innovative air-side system developed in this project combined the existing technologies of UFAD, passive chilled beams, series use of chilled water, and AHU return-air bypass, to yield an efficient system that provides a significant reduction in energy consumption and good occupant comfort.

**References**

1. Dieckmann, J., K. Roth, J. Brodrick. 2004. “Radiant ceiling cooling,” *ASHRAE Journal* 46(6):42–43.
2. Roth, K., et al. 2007. “Chilled beam cooling.” *ASHRAE Journal* 49(9):84–86.●

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