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# Design Guidelines for Underfloor Plenums

## Interim guidance for controlling air leakage, reducing temperature variations, estimating heat gain, using air highways, and more

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*Editor's note: This is the second of two articles based largely on work being conducted under a research grant from the California Energy Commission, with additional funding from the Center for the Built Environment, to develop software for calculating the energy performance of underfloor-air-distribution systems (*www.energy.ca.gov/pier/buildings/projects/500-01-035-1.html*). The companion article—"Design Guidelines for Stratification in UFAD Systems" by Tom Webster, PE, and Fred S. Bauman, PE—was published in the June issue of* HPAC Engineering.

The use of an underfloor plenum to deliver conditioned air directly into an occupied zone of a building is a key feature distinguishing underfloor-air-distribution (UFAD) systems from conventional ducted overhead systems. Current research (*www.cbe.berkeley.edu/underfloorair*) and design practice are focusing on two plenum-related topics that can have significant impacts on the successful operation of UFAD systems:

- Air leakage from pressurized plenums.
- Underfloor-plenum-supply-air heat gain (thermal decay).

This article will present updated design and operating guidelines addressing both of these topics.

### PLENUM AIR LEAKAGE

The following discussion assumes a pressurized underfloor plenum, which is the focus of current industry practice. Evidence from completed projects using pressurized plenums indicates that uncontrolled air leakage from a plenum can impair system performance.[1,2] There are two primary types of plenum leakage—Category 1, or construction-quality, leakage (Figure 1) and Category 2, or floor, leakage (Figure 2)—each impacting system performance to a different degree.

**Category 1, or construction-quality, leakage.** Most detrimental to system performance is air leakage from plenum walls and joints through wall cavities, columns, and other short-circuiting pathways to the return plenum above, directly to the outside of the building, or back to the return of the floor below via fire stops and other floor penetrations. This air loss increases fan power and may increase

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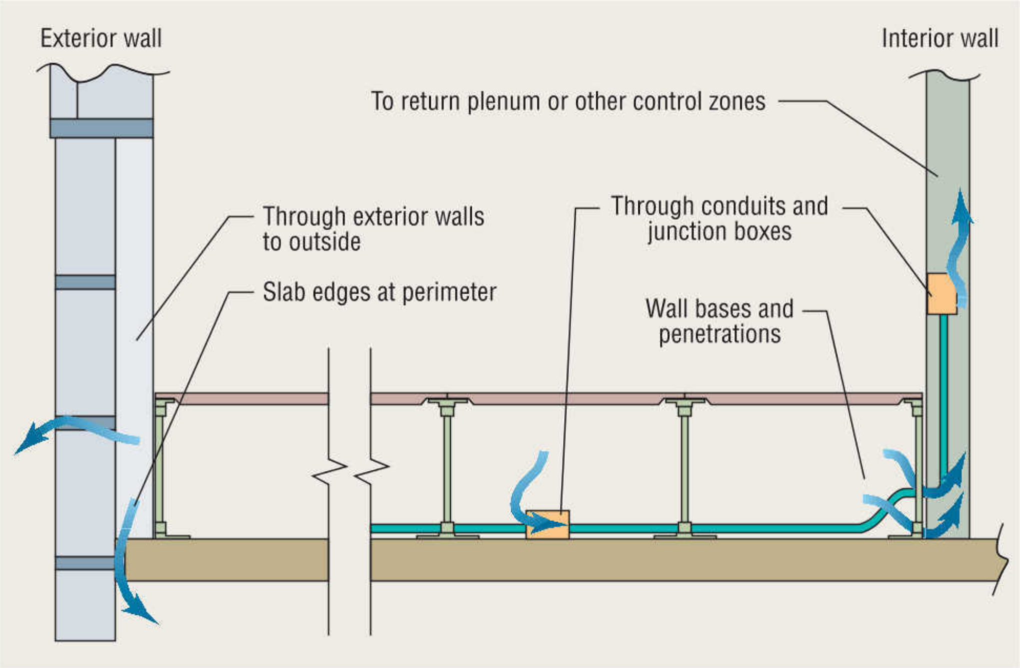

**FIGURE 1. Category 1, or construction-quality, leakage.**

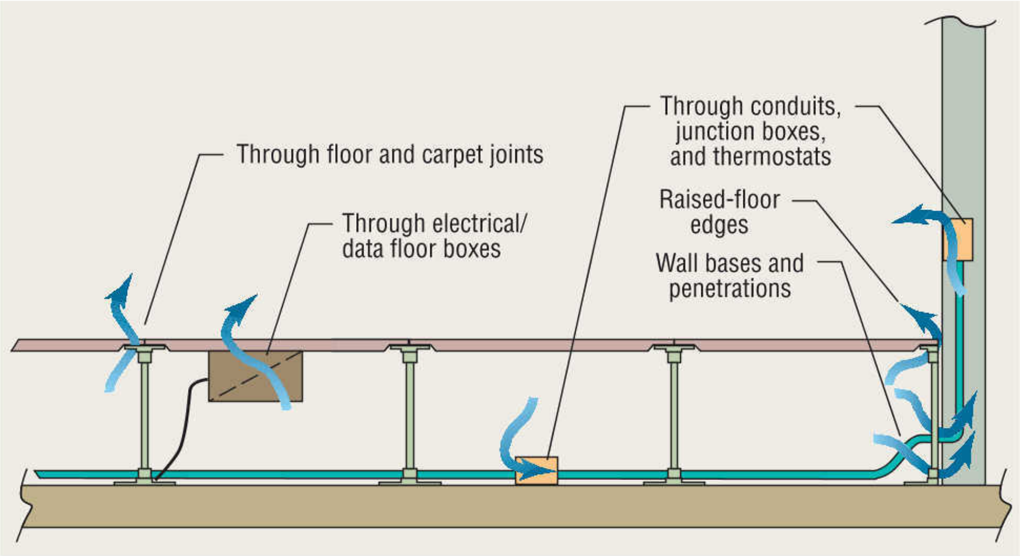

**FIGURE 2. Category 2, or floor, leakage.**

cooling load.

Minimization of construction-quality leaks demands engineered solutions with supporting design drawings and specifications for:

- Interface joints between the access floor and exterior walls, interior walls, and columns.
- Interface joints between the floor slab and exterior walls, interior walls, and columns.
- Interface joints at doorways and floor transitions.
- Slab fire stops.
- Fire-wall base plates.
- Penetrations for piping, cabling, and the like through floor panels, floor slabs, and partitions.

**Category 2, or floor, leakage.** Generally, leakage from a plenum through a raised floor and into an occupied space is not necessarily detrimental to the operation of a system; under certain circumstances, it actually may aid performance. However, if the rate of leakage is high or leakage occurs at the wrong place (i.e., near an occupant), comfort problems may result.

Floor leakage occurs through floor-panel gaps, electrical outlets and other floor openings, and joints at the edges of floors and around columns, providing an alternate path for air into a conditioned space, thus, performing useful cooling—albeit at low velocity and reduced mixing. Research indicates that such leakage tends to increase stratification because air enters in a displacement-ventilation fashion (i.e., relatively unmixed). This increased stratification can be accommodated by accounting for the air attributed to leakage in the total system design-airflow quantity. In practical terms, this can be done by either reducing the number of diffusers (before or after design) or increasing the thermostat set point to mitigate any adverse cooling effects in the occupied zone.

One aspect of floor leakage that can be detrimental to system operation concerns control. In a variable-air-volume system employing passive swirl diffusers (i.e., flow is controlled by varying plenum pressure), a reduction in plenum pressure as load falls will decrease leakage in direct proportion to the decrease in diffuser flow. The ratio of leakage to diffuser flow will remain constant, and the impact on system operation will be minimal. In a system employing constant plenum pressure (i.e., damper-controlled diffusers), however, leakage will remain constant as load and diffuser airflow decrease. The ratio of leakage to diffuser airflow, then, will increase at low load. If the leakage is too high, the system will lose its ability to control temperature because all flow will be supplied by the (uncontrolled) leakage.

**Leak testing.** For leakage to be dealt with effectively, it must be anticipated and measured. In addition to design and construction-detail scrutiny and rigorous and repeated inspections during construction, a full-scale mock-up demonstrating all design details, including examples of all typical penetrations and edge treatments, is recommended. Such a mock-up can be used to conduct an ideal leak test:

- *Total leakage*. A standard (blower-

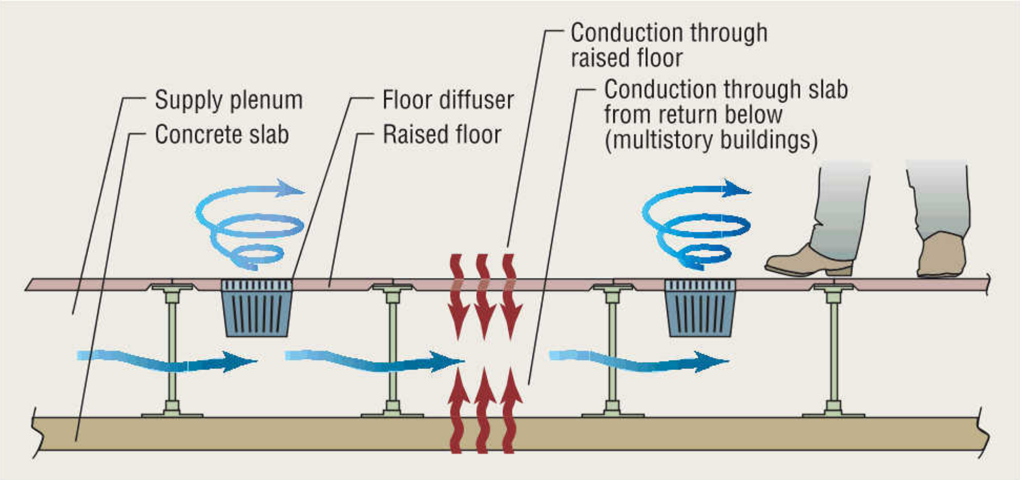

***FIGURE 3. Underfloor-supply-plenum heat gain.***

panel) pressure test at 0.05 in. wc, with floor panels, electrical outlets (power-voice-data [PVD] devices), and other openings in typical densities; carpet; and joints at edges installed according to typical design specifications. To eliminate the effect of diffuser flow, all diffuser openings are sealed shut.

- *Category 1, or construction-quality, leakage*. A second pressure (blower-panel) test in which all raised-floor-surface openings are sealed. This can be accomplished by taping all gaps between floor panels and at edge joints and sealing diffusers, electrical outlets, and other floor openings. Substituting solid panels for panels with openings is recommended. Carpet tiles do not need to be in place. To identify leaks, a smoke test may be helpful.
- *Category 2, or floor, leakage*. The subtraction of construction-quality leakage from total leakage.

While this is the most accurate way to determine the two leakage components, it may not be practical for testing actual installed floor plates—large ones in particular. Efforts to develop alternatives are under way.

**Acceptable leakage rates.** The Center for the Built Environment (CBE) has accumulated leakage-test data for a variety of floor-panel types, carpet types, and carpet configurations. This data indicates that, for new installations, leakage from floor-panel gaps virtually can be eliminated by using close-fitting/die-cut floor panels and offset (non-aligned) carpet tiles installed with resealable adhesive. Over time, as the floor panels and carpet tiles are removed to gain access to the plenum, this seal is likely to degrade. Additionally, there will be leakage at PVDs and other openings, at diffuser mounting rings, and at wall edge joints. Although further research is needed, CBE data and experience suggest the following cooling-airflow targets for the two types of leakage:

- *Category 1, or construction-quality, leakage*: Not to exceed 0.05 cfm per square foot at 0.05 in. wc (e.g., 1,000 cfm for a 20,000-sq-ft floor plate).
- *Category 2, or floor, leakage*: Not to exceed 0.10 cfm per square foot at 0.05 in. wc (e.g., 17-percent leakage for an interior zone with 0.6-cfm-per-square-foot design airflow).

## THERMAL PERFORMANCE OF UNDERFLOOR PLENUMS

Laboratory research and field measurements demonstrate that temperature gain (thermal decay) in open underfloor plenums can be significant, especially in multistory buildings. Figure 3 shows how heat is transferred into underfloor plenums. Figure 4 shows plenum temperatures (temperature gain exceeds 5 F in some locations) measured at 4 p.m. in an office building in Sacramento, Calif.

**Plenum height.** Typical UFAD-plenum heights are 12 to 18 in. The lower limit primarily is determined by the availability of underfloor fan terminal units, which often are used in perimeter-zone solutions. The upper limit is an industry response to seismic building codes

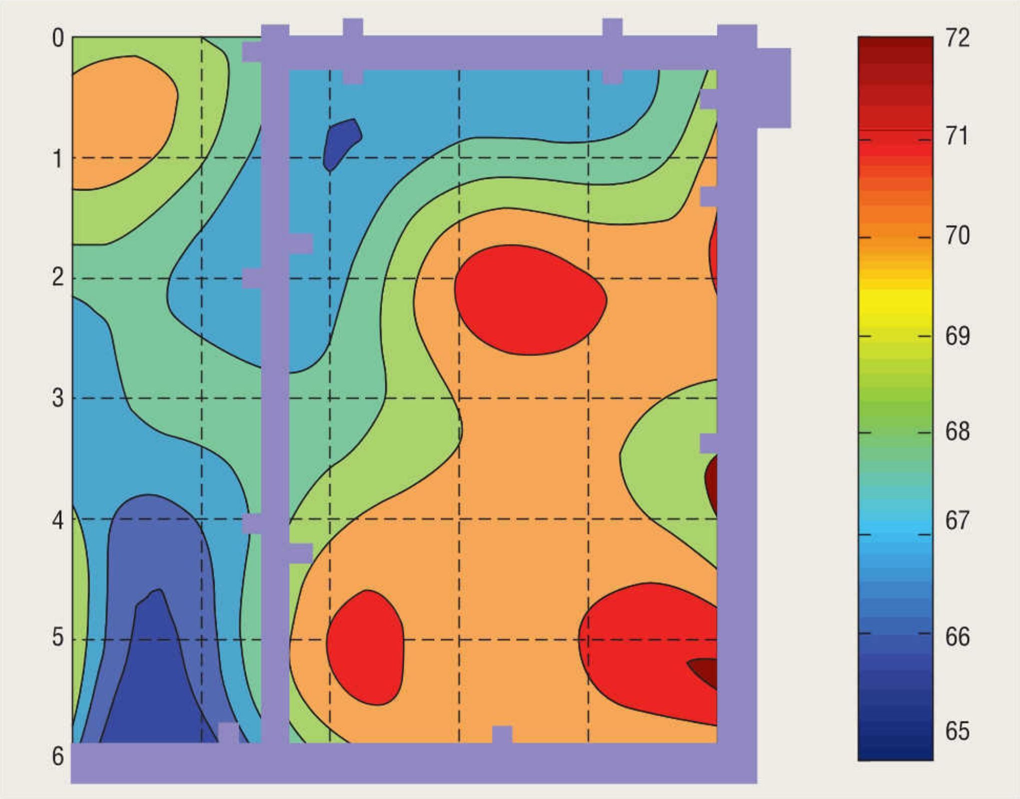

***FIGURE 4. Underfloor-supply-plenum temperatures measured in a Sacramento, Calif., office building at 4 p.m. on Nov. 21. The maximum temperature difference is 5.2 F.***

requiring additional diagonal bracing for raised-floor installations exceeding 18 in. Over this range of plenum heights, air velocities are exceptionally low, except near inlets.

**Room-cooling-load distribution.** In a recent study, CBE investigated the primary pathways through which heat is removed from a room with UFAD.[3] Room-air stratification produces higher ceiling-level temperatures, which change the dynamics of heat transfer within a room and between floors. Under the typical operating conditions of a stratified UFAD system, heat is removed from a room through two primary pathways:

- Return-air extraction via warm return air exiting at ceiling level.
- Heat entering the underfloor supply plenum by conduction through the slab from the floor below and by radiation and conduction through the raised-floor panels from the room above.

Regarding multistory buildings, the major conclusions from the CBE study are:

- With an uninsulated slab (current practice), approximately 30 to 40 percent of total room cooling load will be transferred into a supply plenum, while only 60 to 70 percent will be accounted for by return-air extraction. The greater the stratification, the higher the percentage of plenum heat gain.
- With an insulated (a layer of R-10 on the bottom surface) slab, approximately 20 to 30 percent of total room cooling load will be transferred into a supply plenum, with 70 to 80 percent accounted for by room extraction, depending on the amount of stratification in the room.

After room cooling load is calculated, it is recommended that the above guidance be used to apportion the load between the underfloor plenum and the room. These quantities will have a direct impact on the amount of air-temperature gain within the underfloor supply plenum, as well as the room design airflow requirements.

As described above, heat transfer into an underfloor plenum can be substantial in a multistory building. While the delivery of air through an open plenum can be both reliable and uniform (i.e., plenum static pressure essentially is uniform throughout a zone), limiting supply-air-temperature variability across a plenum zone is an important design consideration. In addition to room cooling load, this can be impacted by supply-airflow volume and plenum inlet conditions.

**Plenum heat gain and plenum-inlet-temperature set point.** For (interim) design purposes, the temperature of air supplied to a room is assumed to be 65 F. This allows the computation of the temperature of supply air required from an air-handling unit. First, plenum heat gain should be estimated by calculating an applicable room cooling load as a weighted average of interior and perimeter loads impacting the plenum zone. For example, a 50-ft-long plenum zone with the outer 15 ft representing the perimeter zone would apply 70 percent and 30 percent of the interior and perimeter load levels, respectively. Application of the total diversified peak airflow affecting that plenum zone is recommended. If a zone covers both interior and perimeter areas, a weighted average of both of those airflows should be applied. The percent load to the plenum is taken from the load fractions described above. With this information, average plenum-temperature gain can be calculated:

$$\Delta T_{\text{plenum}} = \frac{(\text{room cooling load} \div 0.0929) \times \text{fraction of load to plenum}}{(\text{airflow} \times 3.4)}$$

where:

$\Delta T_{plenum}$ is in degrees Fahrenheit

room cooling load is in watts per square foot

airflow is in cubic feet per minute per square foot

From this result, the plenum inlet temperature (degrees Fahrenheit) required to maintain (on average) a diffuser supply-air temperature of 65 F can be calculated as follows:

$$T_{\text{plenum inlet}} = 65 - \Delta T_{\text{plenum}}$$

Note that while $\Delta T_{plenum}$ represents temperature gain averaged across the entire area of the plenum, maximum air temperature inside the plenum could be well above 65 F.

**Plenum-temperature variations.** Extensive research by CBE demonstrates that plenum air temperatures may vary both widely and in non-intuitive patterns across building floor plates, depending on many factors.[4,5] The combined effect of these factors on plenum temperature distribution is difficult to predict. The following guidance is provided to help minimize variations in temperature:

- Avoid excessive (greater than 1,500 fpm) plenum inlet velocities, which can create high-speed jets and large recirculating airflow patterns within a plenum. Higher average velocities increase the rate of heat transfer between plenum air and a slab and floor panels.
- Although research continues, evidence suggests temperature variations can be limited by reducing plenum inlet velocities and spreading airflow across plenums through the use of inlet vanes, multiple inlet locations, etc. Other strategies employ plenum inlets with relatively strong, focused jets interspersed with plenum inlets with greater diffusing delivery characteristics (Figure 5).[4]
- If the building layout allows it, locating supply-air shafts in perimeter zones enables the coolest supply air to be delivered directly to where it is needed most. The increased interior-zone plenum air temperatures that result have a less detrimental effect on system performance.
- Because of the complexity of plenum airflow and heat transfer, the use of computational-fluid-dynamics (CFD) simulations (Figure 5) in plenum design may be advisable.
- More-conventional methods of controlling temperature variations include adding ductwork to deliver supply air farther

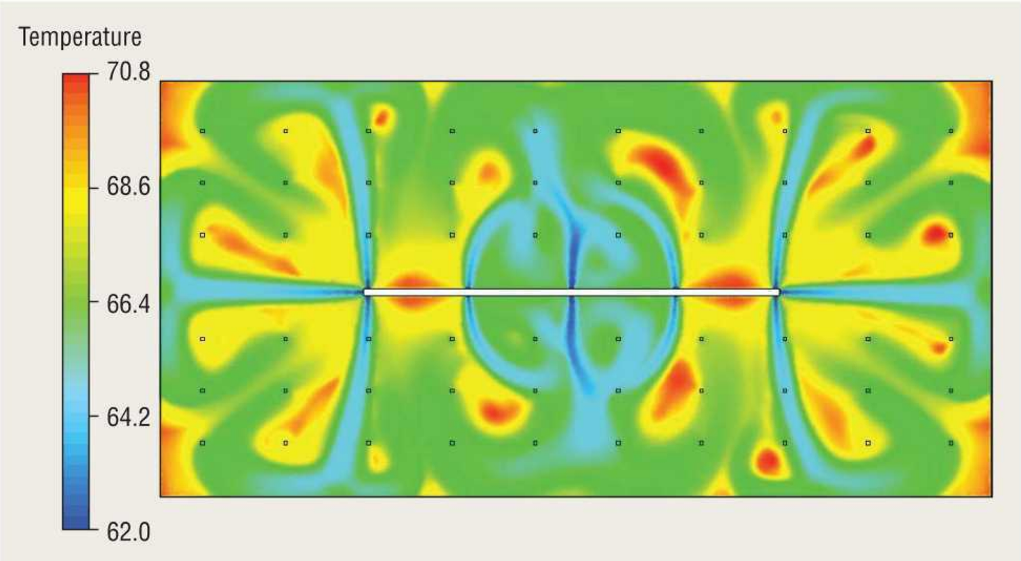

***FIGURE 5. Air temperatures in an underfloor plenum. Multiple plenum inlets (some stronger than others) are positioned at interior (core) locations of the 100-ft-by-200-ft floor plate. The small squares represent floor diffusers.***

into plenum zones. A more-conservative approach is to limit the size of plenum zones by installing partitions; however, this tends to limit the ability of a plenum to serve as an open, flexible, and accessible service distribution plenum.

- If the cost can be justified, installing a layer of insulation (up to R-10) on the underside of structural slabs in multistory buildings is worth considering. To reduce costs, the insulation could be installed only where heat-transfer rates are expected to be highest.

**Slab on grade.** Underfloor plenums on the ground floor of buildings typically experience less heat transfer than underfloor plenums on other floors, which are subject to heat gain from both above and below. Recent CFD simulations of a slab-on-grade configuration (assumptions: ground temperature below slab, 61 F; plenum inlet temperature, 60 F; airflow rate, 1.5 cfm per square foot; room temperature, 75 F; return temperature, 80 F) indicate that ground-floor underfloor plenums experience at least 50-percent less overall heat gain on average. In the CFD investigation, the cool, stable ground temperature, which was quite close to the average plenum air temperature, essentially eliminated any significant heat transfer through the slab into the ground-floor plenum.

**Air highways.** The use of air highways—fabricated rectangular ducts—to distribute supply air through parts of an underfloor plenum is another method of controlling temperature variations. Air highways are unlike underfloor ductwork, which largely is isolated from plenum heat gain, in that their top is the underside of floor panels, their bottom concrete slabs, and their sides sealed sheet-metal partitioning. To accommodate larger volumes of air, air highways often are designed to be at least two floor panels (4 ft) wide. Long runs of air highways have the potential for thermal decay because of heat gain through slabs and floor panels.

A simplified two-dimensional heat-balance model was used to investigate temperature rise in a 120-ft air highway. The following was assumed: temperature at the bottom of the slab, 82 F; plenum inlet temperature, 60 F; room temperature, 75 F; return temperature, 80 F. Table 1 summarizes four cases of predicted temperature rise at the end of the air highway.

| Case | Average velocity, feet per minute | R-10 slab insulation | Temperature rise, Fahrenheit |
|---|---|---|---|
| 1 | 1,500 | No | 0.64 |
| 2 | 1,500 | Yes | 0.32 |
| 3 | 750 | No | 1.17 |
| 4 | 750 | Yes | 0.62 |

***TABLE 1. Predicted temperature rise at end of 120-ft air highway.***

Temperature rise for the assumed boundary conditions likely was underpredicted because heat transfer through the sheet-metal sides of the air highway was neglected, and air velocity was assumed constant. In reality, air would decrease in velocity the farther it travelled through the air highway, as air would be introduced into the plenum at various supply points along the way. A recommended approach to applying Table 1 is to estimate average velocity over the entire length of an air highway. The results would indicate that the amount of heat transfer into the air highway was tied closely to the length of time air was in the air highway. In cases 3 and 4, when velocity was cut in half, temperature rise nearly doubled. Applying a layer of R-10 insulation to the underside of the slab (cases 2 and 4) was seen to reduce temperature rise by 50 percent. Overall, while not insignificant, temperature gain in an air highway is predicted to be less than the average levels of thermal decay observed in open underfloor plenums.

## SUMMARY

Key underfloor-plenum design issues addressed in this article included:

- Uncontrolled air leakage from pressurized underfloor plenums can impair system performance. Guidance for improving the quality of plenum construction, testing plenum air leakage during commissioning, and assessing the acceptability of measured plenum leakage rates was provided.
- Heat transfer into underfloor plenums amid stratified room-air conditions can be significant, amounting to

about one-third of total room cooling load. This finding has important implications for the design and operation of UFAD systems, including estimation of design cooling-airflow quantities and plenum inlet temperatures.

Guidance for reducing plenum-temperature variations through a variety of techniques, including well-designed plenum inlet conditions, the location of plenum inlets, and the use of ductwork, plenum partitions, and slab insulation, was given, as was guidance for the estimation of plenum heat gain for slab-on-grade, ground-floor plenums and the use of air highways in underfloor plenums.

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