

# TECHNICAL FEATURE

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*Part One*

## Thermally Active Floors

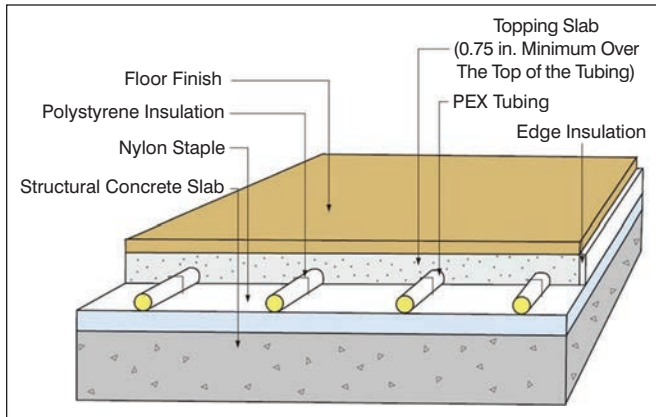
By **Daniel H. Nall, P.E., FAIA**, Member ASHRAE

**R**adiant conditioning has a long history going back to ancient China, thousands of years before the Roman Baths.<sup>1</sup> It takes advantage of the fact that for low ambient air velocities, radiant heat transfer between the clothed body and surrounding surfaces is equal to or greater than convective heat transfer of the clothed body.<sup>2</sup> For most buildings, the interior surfaces of the exterior partitions, exposed on their outer surfaces to the weather, will have the most extreme temperatures in the enclosure. Radiant conditioning balances the radiant interaction between occupants and enclosure, both by offsetting the radiant effects of the exterior partitions, and by interacting radiantly with these surfaces to bring them closer to the desired temperature.<sup>3</sup>

Radiant delivery of space conditioning is attractive because of its inherent transport efficiency and because of its space efficiency. Because of the greater specific heat and density of water, heat can be transported to or from a space using water with between 10% and 20% of the amount of transport energy required when using air as the medium for moving heat. Similarly, the space requirements for hydronic transport of heat within the building are significantly less than those for transport by heated or cooled air. Avoided ductwork, air-handling capacity and architectural ac-

### About the Author

**Daniel H. Nall, P.E., FAIA**, is senior vice president at WSP Flack + Kurtz in New York. He is an ASHRAE certified Building Energy Modeling Professional and High-Performance Building Design Professional.



**Figure 1:** Construction configuration for standard heating/cooling floor with polyethylene tubing embedded in concrete slab.

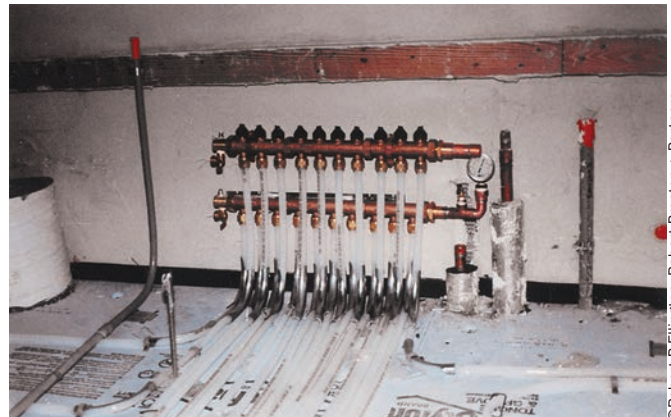
commodation for these systems often can offset much of the cost of the radiant delivery system.

For hydronic transport to be successful, the coupling between the transport medium, and the space must be maximized. To maximize this coupling, radiant conditioning systems often use the most extensive surfaces in the building, the floor and the ceiling. These surfaces have the advantage of convective coupling to the room air and radiant coupling to the room surfaces and occupants. Because of the radiant coupling between the surfaces and occupants, the cold interior surface temperature of extensive glazed areas or other lightly insulated partitions can be offset by warm ceilings or floors.

Radiant heating with floor slabs with extensive, low temperature surfaces has the additional advantage, when heating a high space, of minimizing thermal stratification. The maximum temperature of stratified air is limited by the maximum surface temperature within the space. Small surface area, high temperature convectors, while nominally of adequate capacity for a given heat loss, will generate significant buoyant plumes of high temperature air, resulting in high temperatures aloft, and unacceptably lower temperatures in the lower occupied regions. Stratification of high spaces during heating is inefficient, because the excessive temperature of the upper unoccupied regions of the space created as a by-product of maintaining comfort conditions in the lower occupied region, resulting in excessive heat loss.

Radiant cooling floors, on the other hand, tend to drive stratification. To some extent, this stratification can be beneficial, because only the occupied lower space of a high space need be conditioned to comfort conditions. However, the capacity of a cooling floor is limited because it does not tend to generate convective circulation of the cooled air around the space. Lowering the temperature excessively (below 68°F [20°C]) to increase cooling capacity can result in discomfort due to thermal asymmetry (feet much colder than head) or to condensation.

Thermally active slabs are most effective in the cooling mode when the circulating water removes absorbed solar



**Photo 1:** Radiant floor distribution manifold showing individual polyethylene tubing loop connections.

heat gain directly from the slab. With a lower limit on the temperature of the floor surface of 68°F (20°C), and a room temperature of 76°F (24°C), the maximum cooling capacity of a floor can be less than 10 Btu/ft<sup>2</sup>·h (31 W/m<sup>2</sup>·h). European comfort standards allow a maximum air temperature of 79°F (26°C), giving a minimum floor capacity of 13.5 Btu/ft<sup>2</sup>·h (42 W/m<sup>2</sup>·h).<sup>4</sup> On the other hand, with 40 Btu/ft<sup>2</sup>·h (126 W/m<sup>2</sup>·h) of absorbed solar flux, the cooling floor can remove more than 95% of absorbed solar flux, and maintain the floor less than 2°F (1°C) above ambient air, compared with a more than 23°F (13°C) rise for the inactive floor.

A final advantage of thermally active floor slabs is the possible direct manipulation of the building interior mass. Typical passive thermal mass applications in buildings, because of the limited thermal coupling between the air and the mass, require significant interior air temperature variations to “drive” the interior mass. Thermally active slabs, on the other hand, can be “driven” directly, to pre-cool the space before occupancy and to minimize space condition excursions due to limited conditioning capacity. Radiant floors may access a minimal amount of mass if insulation separates the topping slab/floor finish assembly from the building structure, or a much larger fraction if no thermal barrier separates the two. While radiant slab systems are often accused of slow response to applied loads, the mass of the system, and its close thermal coupling to the space, results in mitigation of peak loads, alleviating the need for quick conditioning response.

### Thermally Active Slab System

The typical installation for a thermally active slab consists of high density polyethylene tubes embedded in a concrete floor slab. Cool or warm fluid, depending upon conditioning mode, flows through the tubing to provide the conditioning. The tubing is often covered by a topping slab, which, in turn, is covered by the floor finish material (Figure 1). If heat transfer through the slab below the tubing is not desired, then a layer of board insulation is inserted between the structural slab and the tubing/topping slab layer. For slab on grade, the insulation may be inserted below the structural slab. Water

is circulated to each loop of tubing through a manifold that serves multiple floor loops (*Photo 1*, Page 34). For capacity control, the system may be configured as a constant flow variable temperature system or a variable flow (multizone pulsed constant flow) with constant fluid inlet temperature setpoints for heating and cooling modes. The author almost always uses the variable flow system because it allows inexpensive individual zone control with only the addition of two-way control valves. A constant flow system with variable inlet temperature requires a pump and a mixing valve or a variable temperature fluid source for each temperature control zone. Zones in these systems tend to be much larger and cannot so easily track solar patterns across the floor of a large sunspace.

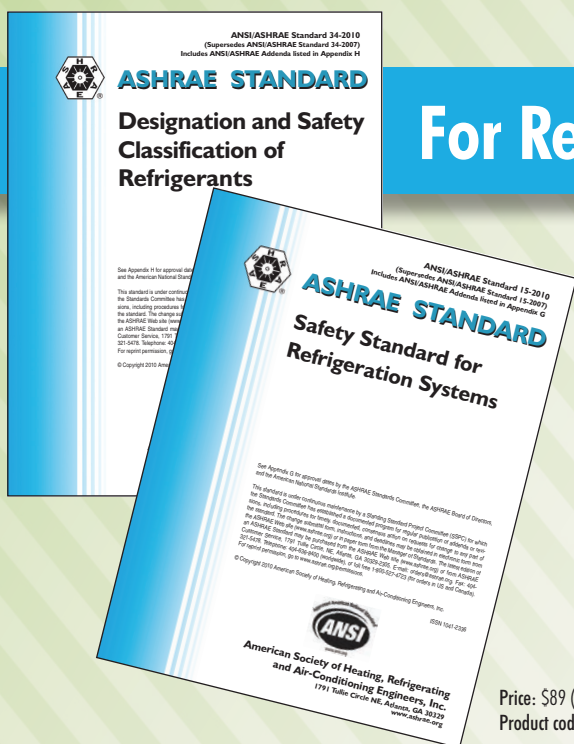
The distribution manifold for a constant temperature variable flow system will generally contain, for each loop, a manual air vent, and either a manual balancing valve, or an automatic control valve to modulate fluid flow through each loop. When individual floor loop control is not required, the manifold itself will have a control valve to modulate flow through all loops on that manifold. The author's standard design varies flow either at the loop or the manifold, based upon maintenance of a setpoint at a temperature sensor embedded

in a representative location in the slab. A digital controller determines the setpoint at any time and determines whether the system is in heating or cooling mode. Algorithms for setpoint determination and heating/cooling changeover will be discussed later. Supply water in each mode of operation (heating or cooling) is typically fixed at 60°F (15.6°C) for cooling in humid climates and at 100°F (37.8°C) for heating.

Because the slab system provides no ventilation or dehumidification, it is almost always accompanied by a dedicated outdoor air system (DOAS). These systems often have been described in the literature.<sup>5</sup> For applications in humid climates, the DOAS should be controlled to maintain a supply air dew-point temperature no greater than 54°F (12.2°C), during all hours of operation. This dew-point temperature setpoint may be lower for certain high density occupancy types. In humid climates, the DOAS may require a low flow recirculation dehumidification mode for control of the maximum interior dew-point temperature during unoccupied periods.

The DOAS and the floor system will require heating and cooling sources for the conditioning water. The temperature requirements for the floor system are typically much less extreme than those for the DOAS, particularly in humid or continental climates. Improved energy efficiency can accrue from supply

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ing the floor system and the DOAS from separate heating and cooling sources, reflecting the different temperature requirements for the two systems. In arid or continental climates, the required chilled water temperature for the radiant floor system can often be met through evaporative cooling, even with cooling tower economizer cycle, resulting in significant energy savings through avoidance of refrigeration energy.<sup>6</sup>

### Principles of Design

A number of design principles have been identified over many projects and 15 years of experience with this system. When these principles are implemented, the system is very reliable and adaptable to different operating regimes. Most importantly, because the system relies upon floor temperature variation within a very narrow range adjacent to the comfort zone, precise modulation of floor temperature is not required for comfort maintenance.<sup>7</sup> Second, the system has a high thermal capacitance, so control sequences should avoid any requirements for rapid modulation. Third, the DOAS and the floor system operate independently, so their control sequences must be coordinated to avoid “fighting.” Finally, in humid climates, the system must be designed to avoid condensation on the floor surface under any circumstance. The previous design principles are implemented through a combination of system physical layout and control sequences.

### Bâtiment Isotherme

Bâtiment isotherme refers to a design strategy developed in Europe that uses a super-insulated envelope in concert with controlled interior thermal mass to create constant comfort conditions with a minimum expenditure of energy.<sup>8</sup> Three dormitory buildings at Dartmouth College in New Hampshire illustrate the successful implementation of this strategy. These buildings use concrete block bearing wall internal partitions perpendicular to the exterior façade of the building with pre-cast plank horizontal structure and concrete topping slab with embedded radiant tubing. The floor sandwich does not incorporate an insulation layer, so that water flow in the tubing affects the surface temperature of the floor above and of the ceiling below. The wall construction incorporates a continuous air barrier, R25 (4.4 m<sup>2</sup>·K/W) insulation underneath brick veneer. Windows are single-hung wood-framed with triple-glazed low-e argon-filled fixed upper lights and double-glazed low-e argon filled lower operable lights. Attic insulation is R40 (7.0 m<sup>2</sup>·K/W).

The conditioning system consists of dedicated outdoor air systems with enthalpy wheels, heating and cooling coils and the thermally active structure. Each student room is ventilated at approximately 30 cfm (14.2 L/s). Demand controlled ventilation is provided to living and study rooms, complying with ASHRAE Standard 62.1-1999 by maintaining 480 ppm concentration differential between the room air and the outside air. Ventilation supply air is chilled to 54°F (12.2°C) when outdoor air dew point temperature exceeds that level. At other times, the ventilation supply air is tempered to 68°F



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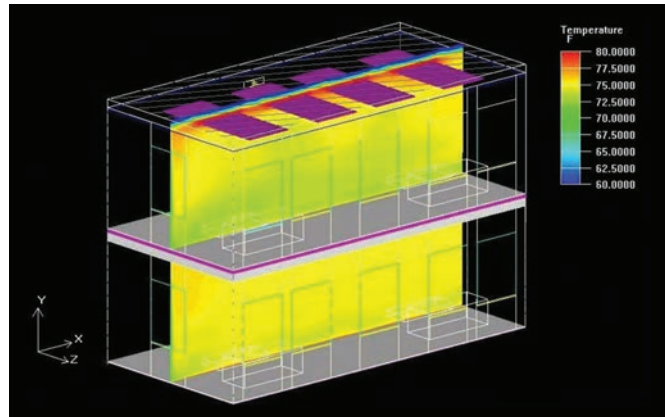
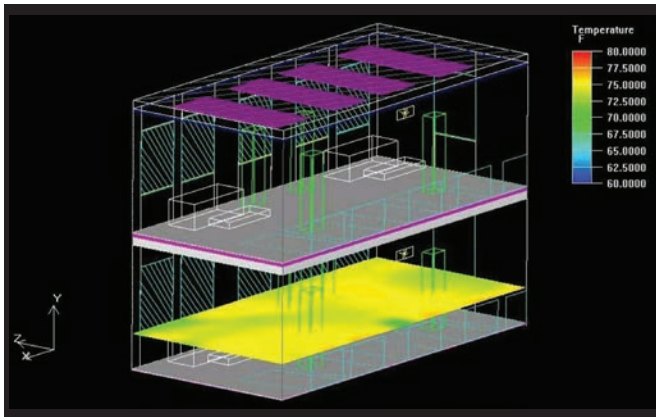
**Photo 2:** Interior of study room at Fahey-McLane Hall at Dartmouth College. Example of Bâtiment Isotherme construction.

(20°C). Comfort is maintained by keeping the floor/ceiling slab at the setpoint, with no air thermostats in the spaces. The slab setpoint is determined as a function of the temperature on the exterior surface of the interior drywall finish of the exterior building wall for that building exposure.

The floor finish is a dense indoor-outdoor carpet with an effective thermal resistance of 0.75 ft<sup>2</sup>·h·°F/Btu (0.13 m<sup>2</sup>·K/W). While this thermal resistance is minimally acceptable for the system, the active ceiling below enhances thermal coupling to the rooms. The acoustic benefit of the carpet more than outweighs the slight thermal disadvantage. A typical study room on the top floor in one of the dormitories is shown in *Photo 2*. The image shows the dense carpet floor finish and ceiling-mounted radiant panels that were added to the ceiling to provide the capacity that would have been furnished by the floor slab above a middle floor.

The buildings have operable windows and because the overheated period is so short in Hanover, N.H., heating/cooling changeover is manual. The building is in nominal heating mode between mid-September and mid-June, depending upon actual weather forecasts. Typically, cooling requirements during those periods can be met by opening the windows. The buildings have minimal occupancy for several days between the normal academic term and the summer session, and manual changeover is accomplished during that period. The client expressed concern that windows left open during the cooling season might cause condensation because of excessive infiltration of humid air. Examination of this potential danger reveals that the danger for wet carpets is far greater from rain penetration through open windows than from condensation.

Multiple studies and CFD analyses examined whether keeping the slab and ceiling temperatures at a specific setpoint would keep the space at a comfortable temperature. The CFD studies incorporated all of the interior contents of the space including furniture, appliances and even occupants. All of these have a significant impact on the air cir-



**Figure 2:** Computational fluid dynamics studies for study rooms in McLaughlin Hall, Dartmouth College.

ulation and long wave radiant thermal interchange in the space. These studies revealed that space conditions were very stable and exhibited little variation of external conditions. An image of the CFD study for a study room at the dormitory is shown in *Figure 2*.

Reset control ramps between the measured temperature within the exterior wall and the floor temperature setpoints were tweaked at occupancy. The result has been an environment that has received uniform praise for comfort by its oc-

cupants. This success is likely due to maintenance of uniform mean radiant temperature in the space. Minimal temperature excursions on the inside surface of the well-insulated exterior wall and the minimal variation of the floor and ceiling surface temperatures create comfort conditions within the space even adjacent to the exterior walls and windows. The effectiveness of this system was demonstrated when one of the valves on the primary side of the radiant heat exchanger in the building failed during very cold weather. The circu-

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lation system continued to operate, with all valves opening more often as the system attempted to maintain floor set-points in the slowly cooling slabs. Conditions remained uniform throughout the building as it slowly cooled. As the air temperature dropped into the mid 60s (16°C to 18°C) more than a week after the estimated time of failure, an investigation revealed the inoperative valve.

### Ground Coupled Heat Exchange With Thermally Active Slabs

Thermally active structures are particularly synergistic with ground coupled heat exchange systems. The cool chilled water and warm water required by thermally active structures can be supplied very efficiently with heat pumps using ground coupled heat exchange. The SAP Americas Expansion building in New Town Square, Pa., (Photo 3) and the National Rural Utilities Cooperative Finance Corporation Headquarters in Herndon, Va., use this technology to condition large atrium spaces. Both buildings use a closed loop well field connected to a water-to-water heat pump system to provide cool and warm water for the thermally active floor in the atrium. A dedicated outdoor air system provides ventilation, dehumidification and supplemental cooling to the atrium space. The air system has a

return air connection to the space for morning or overnight dehumidification. The floor system is controlled as a slave to the air system, operating only when the air system is at more than 40% heating or more than 40% cooling. A diagram of the system for the SAP Headquarters is shown in Figure 3 showing the dedicated outdoor air system and the thermally active floor that is connected to a ground coupled water-to-water heat pump.

Heating/cooling changeover is accomplished at the heat pump itself. In some climates, anti-freeze may be required for the ground loop. Propylene glycol is often used for antifreeze in closed loop ground coupled systems, because it does not present the environmental hazards of ethylene glycol. It does have the disadvantages of increasing the viscosity of the circulating fluid at low temperatures and decreasing the specific heat of the fluid, resulting in higher pumping energy. For these reasons, propylene glycol is undesirable in the slab loop. Using denatured ethanol as an antifreeze agent avoids the viscosity and specific heat issues. The major disadvantage of this product is that in its pure form it is highly flammable, requiring special storage provisions. Storage of the material as a 50% water solution overcomes this problem, rendering the fluid no more hazardous than other commonly stored materials.

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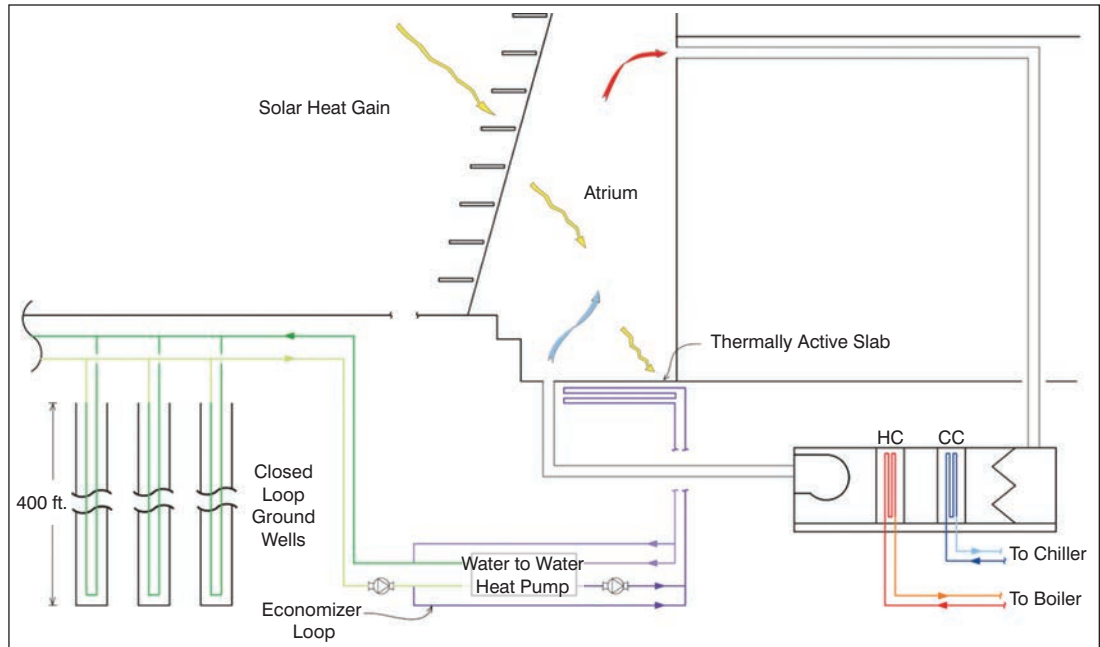
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**Figure 3:** Diagram of ground-coupled heat pump system with thermally active slab at SAP Americas Expansion building.



Several additional energy efficiency options are available when combining the active slab with the ground coupled heat pump. In many climates, the temperature of the water returning from the borehole, early in the cooling season, will be adequate for supply to the active slab. A bypass line around the heat pump allows cooling to be supplied directly from the borehole without requiring energy consumption by the heat pump or temperature drop across a heat exchanger. The very low temperature lift for this system can be more fully exploited through the use of variable speed compressor heat pumps, whose energy efficiency greatly increases at low compressor lift. Variable speed compressor heat pumps that might normally operate with a COP of 4.5 at conventional AHRI operating conditions can operate with COPs as high as 10 with the water conditions often experienced with the ground coupled/thermally active slab system.

One consideration with these combined systems is that the floor system will often operate at a very low part load, lower than the minimum part load capacity of the heat pump. Many small water-to-water heat pumps are furnished with relatively unsophisticated controls that cannot respond to overcooling or overheating of the supply water when the unit is at its minimum unloading point. If the compressor remains on-line at its lowest unloading point even though the leaving water temperature becomes either extremely hot in heating mode or extremely cold in cooling mode, then an additional control sequence is required. A simple aftermarket control sequence to overcome this problem exploits the thermal capacitance of the entire system to accommodate small part loads. When the temperature of the return water, as measured by the aftermarket thermostat falls outside the maximum heating return water temperature or the minimum cooling return water temperature, the heat pump



**Photo 3:** Atrium with thermally active slab at SAP Americas Expansion Building.

compressor is disabled, but the pumping system continues to operate. When the temperature of the return water falls back within those boundaries by a defined margin (typically 5°F [2.8°C]), and after the compressor has been disabled for a

minimum period of time (based on manufacturer's minimum cycling criteria), the heat pump compressor is reenergized. This simple control sequence increases efficiency, avoids excessive strain on the compressor and avoids over-pressure safety trips by the heat pump control system.

### Summary

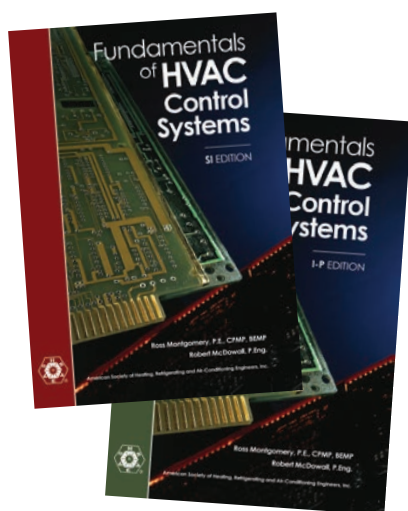
Radiant heating and cooling slab systems are a powerful strategy for energy efficiency and comfort improvement when used appropriately. The aspiring designer must understand the advantages and limitations of the technology to achieve good results. The two most effective applications of the technology are the sunspace, using the effectiveness of the radiant floor for removing absorbed solar heat gain and the *bâtiment isothermale*, which exploits the active manipulation of the building thermal mass to maintain constant conditions inside a super-insulated building envelope. Thermally active slabs are especially effective when used with ground source heat pumps, exploiting the efficiency gains from increased thermal coupling and lower temperature differential to the conditioned space. Successful projects require instructive design tools and effective

construction techniques. These will be discussed in Parts 2 and 3 of this series.

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