Radiant-Floor Heating



## Radiant-Floor Heating: When It Does—and Doesn't—Make Sense

During judging of the Northeast Green Building Design Competition last spring, I was struck by the number of residential entries with really stellar passive solar design and super-high-performance building envelopes. Clearly, I thought as I began reviewing the features, we've come a long way in high-performance residential green building since my first experience with passive solar in the mid-1970s. But something also seemed odd. A majority of these entries had sophisticated radiant-floor heating systems. After going to all the effort and expense to superinsulate the envelopes of these houses and provide passive solar design, did they still need $10,000 heating systems? And did those systems really make sense from a performance standpoint? I wasn't sure, and decided to dig into these questions.

I've long been a fan of the comfort delivered by radiant-floor heat, and strong arguments are often made about energy savings and indoor air quality advantages. But is this really the best match for high-performance green homes? In the most energy-efficient buildings, the answer seems to be "no," though radiant-floor heating can offer both comfort and IAQ benefits. This article provides a quick overview of radiant-floor heating, reviews the benefits of this heat-delivery approach, and reviews when these systems do—and do not—make sense in homes and small commercial buildings.

## Radiant-Floor Heating Overview

Radiant-floor heating has its origin in ancient Rome, where fires were built beneath the floors of villas. Early Korean buildings were similarly heated by channeling flue gases beneath floors before venting those gases up through chimneys. Frank Lloyd Wright piped hot water, rather than air, through the floors of many of his buildings in the 1930s—a practice that has become common in custom homes today.

Radiant-floor heating turns a floor into a large-area, low-temperature radiator. In most modern radiant-floor heating systems, warm water circulates through plastic tubing either embedded in a floor slab or attached to the underside of subflooring. With slab systems, one can use either a standard concrete slab-on-grade, or a thinner, lightweight gypsum-concrete slab poured on a subfloor or over an existing finished floor. In either case, the thermal mass of the slab holds heat and radiates it slowly to the living space above.

In addition to hot water as the heat source, radiant floors can also use electricity or hot air. Due to the high cost of electricity in most areas, radiant-electric floor heating usually makes the most sense when off-peak electricity is available for charging a slab at night and during other off-peak hours. Production of electromagnetic fields (EMFs) is also a potential concern with radiant electric heating (see EBN Vol. 3, No. 2). Radiant-air floors are occasionally used in commercial buildings but are generally impractical and too expensive for residential applications.

For hydronic radiant-floor systems, copper piping has been used in the past, but most systems today use either rubber or cross-linked polyethylene (PEX) tubing—the latter being by far the most common. Design of radiant-floor heating systems is quite complex and should be done by someone with adequate training or experience. Various design manuals, manufacturer-specific installation guides, and software tools are available for use in designing and sizing radiant-floor heating systems. The length of tubing required per square foot of floor depends on such variables as tubing diameter, type of radiant-floor system (thick slab, thin slab, no slab), climate, heat load of the building, and type of boiler and controls used. Manufacturers have done a great job in recent years in packaging the various components to simplify the design of radiant-floor systems.

A key requirement for most radiant-floor heating systems is adequate insulation beneath the heated slab or beneath the tubing (when tubing is attached to the underside of a subfloor). Most manufacturers recommend a minimum of 1" (25 mm) of extruded polystyrene (XPS) for concrete slab-on-grade radiant heating systems, but significantly higher levels are justified in cold climates.

Zoning of radiant floors is usually done with advanced manifold modules that allow the water temperature to be varied in different zones. This provides flexibility for maintaining different temperatures in different rooms and for allowing differential heat delivery to spaces with and without solar gain.

Finally, sophisticated controls are often installed to ensure optimal comfort and to maximize energy performance. Some radiant-floor systems rely on separate temperature sensors outdoors, within the floor slab, and in the living space—with microprocessor control to regulate just when and where hot water should be delivered. Because of the long lag-time with concrete-slab radiant-floor heating systems, standard set-back thermostats usually are not effective, though set-back thermostats that have a built-in anticipation feature may work well for this application, says building consultant Andy Shapiro, of Montpelier, Vermont.

**Benefits of Radiant-Floor Heating**

Radiant-floor heating offers a number of significant benefits:

**Comfort.** By far, the biggest selling point for radiant-floor heating is comfort. The large radiant surface means that most of the heat will be delivered by radiation—heating occupants directly—rather than by convection (the primary mechanism of heat delivery from conventional hydronic baseboard "radiators"). Warmer surfaces in a living space result in a higher mean radiant temperature, a measure of surface temperatures in a space that influences the rate of radiant heat loss from occupants). With higher mean radiant temperatures, most people are comfortable even at lower air temperatures. Delivery of the heat at floor level with a warm floor surface also allows occupants to walk around barefoot even in winter—a very popular feature. Enhanced comfort should be a big selling point in any green home, so a strong case can be made for this heating approach.

"Until you're lived with this form of heat," says Radiant Panel Association executive director Larry Drake (who got involved with radiant heating after years of working with solar houses), "it's hard to understand how comfortable it is." He argues that with green homes in particular, after going to all the effort and expense to incorporate healthy and sustainable materials, ensuring high levels of comfort with radiant heat should be a top priority.

**Energy savings.** There is potential for saving energy with radiant-floor heating through several mechanisms, including lower thermostat settings, lower-temperature boiler settings, and reduced infiltration. Homeowners with radiant-floor heating are likely to be comfortable at lower air temperatures because of the elevated mean radiant temperature in such homes, the lack of significant airflow (as occurs with convective hydronic heating and forced-air heating systems), and the delivery of heat at floor level. Proponents of radiant-floor heating argue that someone normally comfortable at 72°F (22°C) will be comfortable in a building with radiant-floor heating kept at 68°F (20°C). If this is true, one would expect people with radiant-floor heating to keep their thermostats lower and thus realize significant energy savings. (See page 13 for further discussion.)

The second opportunity for energy savings with radiant-floor heating is through keeping the boiler temperature lower than is necessary with conventional baseboard hot water distribution. The typical European approach with radiant-floor heating is to circulate fairly low-temperature water on an almost-continuous basis, varying the water temperature as needed to satisfy the load. This practice might reduce heat loss into unconditioned space if boiler and piping are located in an unheated basement, but experts EBN spoke with suggest that the savings would be very small at best—especially because of the additional electricity consumption to operate pumps for long hours. Green building consultant Marc Rosenbaum, P.E., of Meriden, New Hampshire, suggests using a low-mass boiler that is fired on-demand, rather than a high-mass boiler operated almost continuously.

The third opportunity for energy savings (over forced-air heat) is that radiant-floor systems do not increase the rate of air infiltration. Standard forced-air heating systems can significantly increase or decrease air pressure in different parts of a building, which in turn can increase air infiltration/exfiltration rates—at least in a conventional, leaky building. With radiant-floor heating, as with baseboard hydronic heating, this will not happen. (A well-designed, properly balanced forced-air system should not increase infiltration.)

Potential for use of solar energy. The relatively low temperature required for circulation water in a radiant-floor heating system provides an opportunity to utilize solar hot water. This approach works best with concrete-slab systems; higher-temperature water is generally required when the tubing is attached to the underside of wooden floors. While such systems are fairly complex and expensive, radiant slabs offer one of the best ways to make use of solar energy for heating portions of a building without direct access to sunlight. Most practical are systems in which solar energy heats water in a storage tank that can then be circulated through the slab. According to an EREN Consumer Energy Information Brief (www.eren.doe.gov) titled “Solar Radiant Floor Heating,” such systems typically cost at least $14,000. Backup heat is still required and can be provided with a wood stove, through-the-wall-vented gas heater, electric resistance heat, or backup heating element in the solar storage tank.

**Increased boiler life.** By operating a boiler at a lower temperature, its life can be extended. Radiant-floor heating systems typically use water temperatures of 85–140°F (30–60°C), compared with baseboard hydronic systems that typically operate at 130–160°F (55–70°C). At these operating temperatures, boiler life can exceed 45 years, according to information from DOE. (Shapiro is skeptical of this claim, however, pointing out that newer boilers are made for cold-start operation and should hold up well with this temperature cycling.)

**Quiet operation.** Radiant hydronic floor heating is extremely quiet. Unlike forced-air heat, there is no noise from a fan or airflow through ducts; and unlike hydronic baseboard heat, there is usually no gurgle of water through baseboard radiators or creaking from expansion and contraction. The primary noise will be the sound of circulating pumps and the fan used in power-venting the boiler. With radiant-floor systems that have tubing attached to the underside of wood flooring, there may also be some creaking from expansion and contraction.

**Flexible room layout.** Because there are no baseboard radiators or air registers with radiant-floor heating, there is much greater freedom as to where furniture can be placed. Radiant-floor heating systems are "invisible."

**Improved indoor air quality.** An argument can be made for improved indoor air quality in houses with radiant-floor heat. Compared with a conventional forced-air distribution system, there is likely to be less dust circulated around the house. And unlike electric baseboard or forced-air heat, there will be no surfaces hot enough to burn dust particles—which could introduce volatile chemicals or toxic particulates into house air (even passing through filters). This concern would be greatest for people with acute chemical sensitivities. In fact, veteran builder Max Strickland, of Burkholder Construction in Travers City, Michigan, first became interested in radiant-floor heating several years ago after his wife became chemically sensitive. He's worried about "frying the air" with conventional heating systems and feels that conventional filters on forced-air systems are not effective. Strickland went on to build an American Lung Association (ALA) Health House in Travers City three years ago, and he now incorporates radiant-floor heating into all of his homes (typically 4 to 6 high-end custom houses per year).

## So What's Wrong with Radiant-Floor Heating?

In the right application, radiant-floor heating is a superb heat-delivery system—in fact, perhaps the very best. You usually pay more for it, but the enhanced comfort, potential energy savings, and other benefits can easily justify the extra cost. That said, however, super-energy-efficient green buildings may not be as well-suited to radiant-floor heating. Here's why:

## Economics

It can be reasonably argued that a green home in a moderate-to-cold climate should have very high levels of insulation (at least R-25 walls and R-40 ceiling/roof), extremely low infiltration rates, high-performance glazings (unit U-factors below 0.3), and at least some passive solar gain or suntempering.

We're not talking about conventional houses, mind you, but high-performance green homes. Such a house will use very little heating energy—probably less than 2.0 Btu/ft2 · degree-day (41 kJ/m2 · °C), which would translate into very low heating costs. To achieve that level of energy performance requires a significant investment in the building envelope (for example, double 2x4 walls). In such a house, putting in an expensive heating system doesn't make good economic sense. As Rosenbaum notes, "It just doesn't make sense to put in a $10,000 heating system to provide $100 worth of heat per year."

Investing so much money in the building envelope and still putting in an expensive radiant-floor heating system eliminates the potential for offsetting much of the extra cost in building envelope improvements through savings in the mechanical equipment—one of the key principles of integrated, whole-systems building design. In most highly energy-efficient houses, the same high level of comfort provided by a radiant-floor heating should be achievable simply by installing one or two small, quiet, high-efficiency through-the-wall gas heaters (such as those produced by Rinnai) or a few short sections of electric baseboard heat. At $1,000 to $2,000 apiece for Rinnai heaters (installed) or a few hundred dollars for electric baseboard vs. $10,000 for a typical radiant-floor heating system, savings of $6,000 to over $9,000 would be possible—and that savings could pay for most of the envelope improvements required to bring the heating load so far down that space heating (instead of distributed heat) becomes a viable option.

Even Larry Drake, a strong proponent of radiant-floor heating systems as executive director of the Radiant Panel Association in Loveland, Colorado, admits that radiant heat is more difficult to justify in high-performance buildings. “The tighter the envelope, the less the amount of savings of a radiant system,” he told EBN.

**Heating performance with micro-loads**

Along with the economic questions about the wisdom of radiant-floor heating systems for high-performance green homes, there are building science reasons why this may not be a great fit. Heat is transferred from an exposed slab to the space at a rate of about 2 Btu/ft2 · hr · °F (11 w/m2 · °C), according to Rosenbaum. In a well-insulated house, this rate of heatflow means that even when it is very cold outside, the slab can only be a few degrees warmer than the rest of the room or the room will keep heating up. For a concrete slab to feel warm, however, it needs to be about 80°F (27°C). Thus, for most of the heating season, the greatest feature of radiant-floor heat—a warm floor—won’t occur. With moderate solar gain, heat delivery from a floor slab will be even less. Because the floor is insulated underneath, it will be more comfortable to walk on than most slab floors, but the benefit will be from the insulation, not the radiant heat.

The time lag of heat movement through concrete can also be a problem. In a very well-insulated house, that lag time can result in overheating, particularly if there are other sources of heat being delivered to the space, such as passive solar. If a concrete slab is “charged” with heat during the early morning hours and the surface is warmed to the point where it cannot readily absorb solar radiation striking it, that solar heat will more directly heat the air, increasing the risk of overheating. The same thing happens to a much greater extent in high-performance passive solar homes with masonry heaters because the surface of an operating masonry heater is at a higher temperature. In such houses, occupants usually need to check weather forecasts—if they load up the masonry heater firebox in the morning and it turns out to be a bright, sunny day, the space will very likely overheat. A radiant floor maintains a much lower surface temperature than a masonry heater, so the floor will effectively “turn off” as the room warms up with solar gain. “If the floor temperature is 76°F,” says Rosenbaum, “then the radiant system can’t heat the place to hotter than that.” Therefore, this isn’t a huge problem with radiant-floor heating systems, but it may mean that homeowners will have to open windows periodically in the winter and their overall energy savings from solar energy will not be as great. Shapiro counsels against the use of radiant slabs in areas of houses with passive solar heat. “It’s a waste of energy,” he says, though just how much waste occurs is unclear.

The risk of overheating with concrete-slab radiant-floor heating systems in very energy-efficient buildings leads some designers to incorporate sophisticated control systems. Rather than a simple room thermostat, many radiant-floor designers install control systems that also adjust the circulating water temperature based on outside air temperature and the temperature of the slab. It can also be important to have different zones in a concrete-slab radiant-floor heating system—so that less heat can be delivered, for example, to portions of the slab that are warmed by solar gain. However, according to Rosenbaum, a radiant-floor slab is somewhat self-regulating when it comes to solar gain. If the floor slab begins absorbing solar heat and warms up, it will extract less heat from the circulating water; that heat will return to the boiler and can be circulated to nonsolar zones.

**Heat loss into the ground**

With slab-on-grade radiant-floor heating systems, there is potential for significant heat loss into the ground. According to Paul Torcellini, Ph.D., P.E., of the National Renewable Energy Laboratory, even with insulation under the slab, 20% of the heat entering the slab can be lost into the ground. This reduces the overall efficiency of the radiant-slab system, offsetting the potential savings described above. Typical manufacturer recommendations for 1” (25 mm) of XPS insulation beneath a radiant slab are clearly inadequate; even 2” (50 mm) may not be enough. Shapiro recommends up to 4” (100 mm) in cold climates. In place of ozone-depleting XPS, one can use high-density expanded polystyrene (minimum 1.5 pcf, 24 kg/m3 foam recommended).

It is ironic that most people want radiant floor heat because they don’t like a cold floor, yet there has long been resistance to insulating beneath concrete floor slabs—which would dramatically reduce the cold-floor problem. They solve the problem with an expensive radiant-floor heating system (including rigid insulation under the slab) when the rigid insulation alone would solve most of the problem. (To be fair to radiant-floor heating proponents, the only way to make a slab floor actually warm to the touch is to provide radiant-floor heating—because the high conductivity of concrete makes a slab feel cool even when it is at or slightly above room temperature.)

**Challenges with cooling**

Most radiant-floor heating systems cannot provide cooling, and most homes and small commercial buildings are being built today to provide cooling—even in relatively cool climates. This is why forced-air systems are far more popular than hydronic heating systems nationwide—the ducts used for forced-air heating can also be used to deliver chilled air (see further discussion under “Radiant-Floor Heating vs. Forced-Air Heating” below). One of the problems in turning a floor into a heat sink is the risk of condensation on the cool surface. (Condensation occurs when a surface temperature drops below the dew point—which can be quite high in more humid parts of the country.)

Radiant cooling (generally with ceiling panels) is used quite commonly in Europe, where humidity levels are generally not as high as in eastern North America and where the comfort envelope of building occupants (the temperature range at which they are comfortable) is wider than here. That said, there is some interesting research underway in the U.S. on radiant cooling. This concept is being tried out, for example, at an architecture school studio at Penn State University. Chilled water is circulated through ceiling panels to provide radiant cooling, with 100% fresh air used for ventilation. The key is that the ventilation air is dehumidified before delivery to the conditioned space, thus eliminating the potential for condensation on the radiant ceiling panels. This system is saving energy in two ways: because pumping water requires less energy than moving air, and because the chilled water has to remove only the sensible heat loads—not the latent loads. With the 100% outside-air supply, the total amount of circulated air is reduced by about 80%, compared with conventional recirculating systems.

**Predicted vs. actual savings**

The final concern with radiant-floor heating systems is that much of the assumed energy savings may not be occurring. There is very little hard data to back up the common claim that radiant-floor heating systems save a lot of energy because people with this form of heat are comfortable at lower temperatures and thus keep their thermostats lower. In fact, the only study we could find shows this not to be the case.

Last winter, the Canada Mortgage and Housing Corporation (CMHC) carried out a study of 75 houses in Nova Scotia: 50 with radiant-floor heating and 25 with other heat distribution systems—research that was first reported in the December 2001 issue of the Journal of Light Construction. These houses were visited during daylight hours on weekends, and thermostat settings were recorded. Thermostat settings in the houses with radiant-floor heating averaged 68.7°F (20.4°C), while settings in the control houses averaged only 67.6°F (19.8°C). Although the sample size was small, this study shows no evidence that homeowners with radiant-floor heating keep their thermostat settings lower; in fact, it shows the opposite. Don Fugler of CMHC, who managed the research project, told EBN that they launched the study after a radiant-floor heating product manufacturer contacted CMHC asking for more detail on standard information the agency had been giving out about the energy savings from radiant-floor heat. He cautions that this was a very superficial study, but that it points out the need for additional research into the common claim about energy savings.

Larry Drake of the Radiant Panel Association says that the CMHC study was very interesting and the conclusions being drawn from it are misleading. "To assume that people don't feel comfortable at lower temperature is conjecture," he said. He argues that the relationship between comfort and mean radiant temperature has been well established by ASHRAE for decades. He speculates that if homeowners with radiant heat have opted to keep their thermostats about where they keep them without radiant heat, they have opted to increase their level of comfort rather than going for the energy savings. He also suggests that homeowners may tend to set their thermostats numerically, irrespective of comfort—so that if they used to keep their thermostats at 70°F and then put in radiant-floor heating, they may well still keep their thermostats at 70° (and end up being more comfortable).

Andy Shapiro prefers not to make claims about energy savings with radiant-floor heat. "Radiant heat can be a wonderful amenity in a house," he says, "but to sell it as an energy saver stretches the point."

**Radiant-Floor Heating vs. Forced-Air Heating**

Many people who opt for radiant-floor heating do so because they don't like forced-air heat. There is a common perception that forced-air heating systems dry out air and generate dust. "Nothing could be farther from the truth with a properly installed forced-air system," says Betsy Pettit, AIA, of Building Science Corporation in Westford, Massachusetts.

Forced-air systems, she argues, offer the benefit of being "all things to all systems." A forced-air system can provide heat, air conditioning, ventilation, and filtration—all through a single system of ducts and with shared fans. A radiant-floor heating system, on the other hand, only does one thing, according to Pettit, and it does it at a cost that is typically higher than that of a forced-air system serving those multiple functions. "For me it's just a hard sell," she told EBN. "If you insulate the slab and if you build your building envelope correctly—that is to say, leak-free—you can be more comfortable for less money with a ducted distribution system," she says.

Pettit could think of no tract-home builders in the U.S. who install radiant-floor heating, though there are many custom and spec builders who are very happy with radiant-floor heat. Max Strickland confirms that cost is indeed higher for radiant-floor heat—typically 50% higher than for forced-air—but he notes that if you provide the same level of zoning with forced-air, the costs would be much closer. He deals with air conditioning in houses that have radiant-floor heat by putting in ductless mini-split air conditioners made by Sanyo or Mitsubishi, which he says are very efficient. Larry Drake adds that in addition to using ductless mini-split systems, some builders of houses with radiant-floor heat also often put in high-velocity duct systems for air conditioning, in which very small, 3" (75 mm) round ducts can be run through wall cavities. Drake was unaware of any large tract-home builders who have adopted radiant-floor heating over forced-air systems.

## When and Where Radiant-Floor Heating Makes Sense

It has been pointed out that radiant-floor heating systems may not be the best choice for extremely well-insulated, passive solar homes. So when do they make sense?

• In houses and small commercial buildings with conventional levels of insulation and standard insulated-glass windows—especially those in climates with minimal cooling loads—where the extra comfort of radiant heat is desired and the budget allows.

• In buildings with large open spaces and tall ceilings.

• In buildings where air-flushing is common, such as garages, fire stations, airplane hangars, and industrial spaces (because the large-area radiant floor allows quick recovery).

• When cost is not an issue and satisfying most or all of the heating load with solar energy is a high priority.

• When building occupants have acute chemical sensitivity or allergies—in which case there may be concern that dust could be distributed through a forced-air system or that high surface temperatures from a gas burner or electric heating element will burn dust particles and cause health problems.

## Final Thoughts

It's hard to express doubts about something that's really popular. Like ground-source heat pumps, radiant-floor heating has a loyal and zealous following of builders, designers, and homeowners who consider it to be the best heating option around—and appropriate in almost any situation.

One of the reasons radiant-floor heating is so popular is that it is so much more comfortable than what most of us have experience with: older, drafty houses where there is significant floor-to-ceiling temperature stratification. If more people realized that the same—or at least a similar—level of comfort could be achieved simply by creating a really well-insulated, tight building envelope, we could be keeping a lot of people extremely comfortable while also saving a huge amount of energy, without needing radiant-floor heat. "A house with a good enough envelope to be called green—well-insulated and tight—will have a very high level of comfort no matter what type of heating system is used," says Shapiro, "as long as that heating system is well designed."

In homes with conventional levels of insulation and typical glazings, radiant-floor heating is an extremely comfortable heat-distribution option. It does not contribute to IAQ problems, and it might well even save a little energy if homeowners can be convinced to turn down their thermostats to a level that will provide the same level of comfort as a house without radiant heat. But in an extremely well-insulated, green home, radiant-floor heating usually is not the best option. If you've gone to all the effort and spent all the money to achieve a truly stand-out energy-conserving envelope with passive solar gain, why not offset that cost by dramatically reducing the cost of the heating system?

– Alex Wilson

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