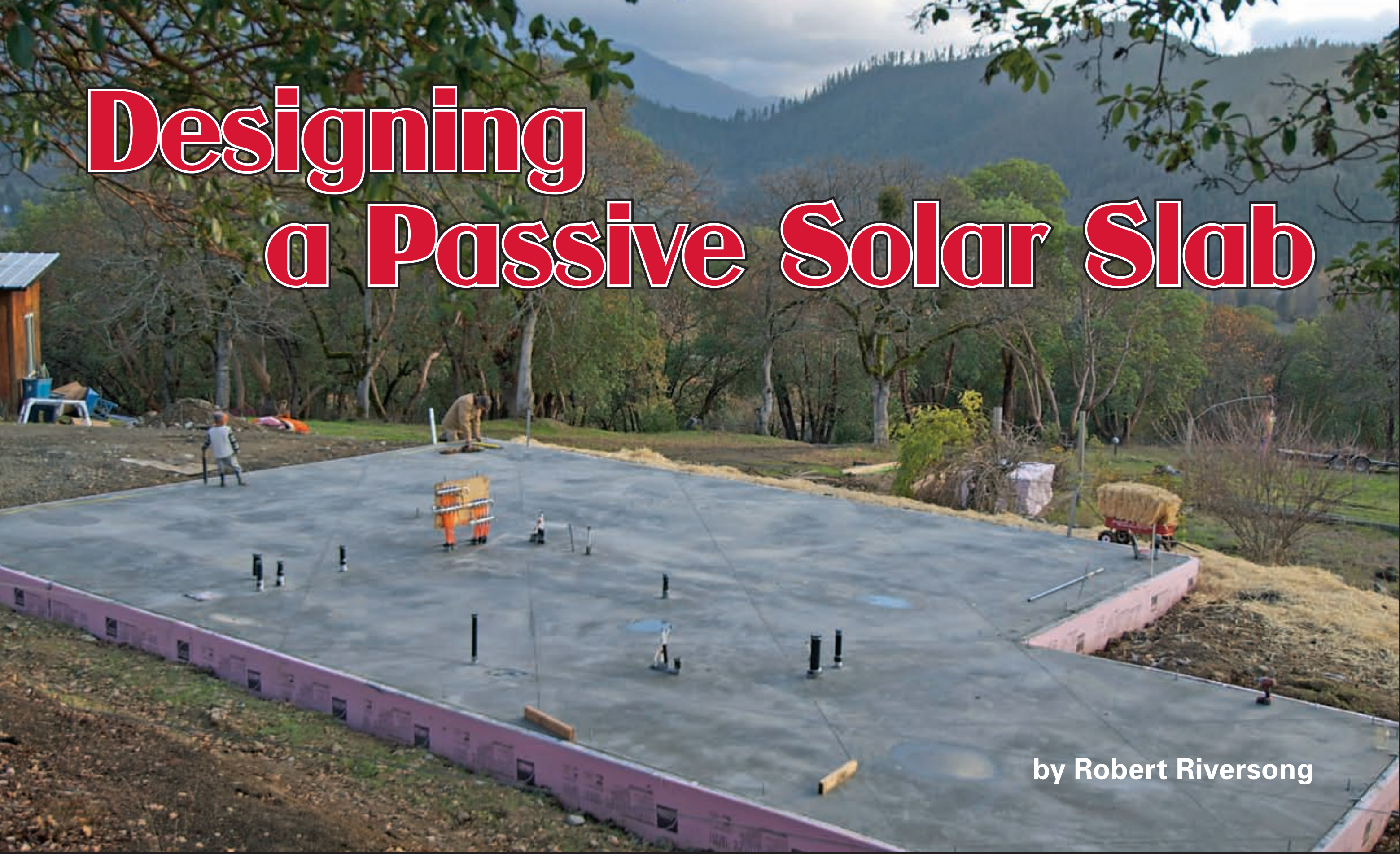


# Designing a Passive Solar Slab

by Robert Riversong

All photos courtesy Robert Riversong, except above: Claire Anderson.

A passive solar home requires five elements to take full advantage of the sun's free heat: apertures to let in the sun's warming rays; a means of preventing too much solar gain in the summer; an absorber surface that minimizes reflection; thermal mass to store the heat until it's needed; and a distribution system to move the heat to where it's required.

For a truly passive house, each of these elements should operate without mechanical power or occupant intervention. As examples, summer solar gain is handled by properly designed overhangs. The distribution system would be natural convection within an open floor plan, with storage and release handled by concrete—a massive and dense material with high specific heat (heat storage capacity per unit volume) and moderate thermal diffusivity (the propensity of heat to dissipate to all areas of the mass).

## Focus on the Slab

Perhaps the least-understood elements of passive solar design, and the ones that plagued the early passive solar pioneers in the 1970s, are the ratios of south glass area to floor area and of south glass area to thermal mass. Without proper balance—and an appropriate absorber and mass storage—an otherwise well-designed house can be unlivable.

Too much glass can mean:

- overheating even in the dead of winter
- overchilling at night
- too little privacy
- too little usable wall space
- too much glare and shadow
- too little sense of enclosure and security

**This house has an 8.25% glazing-to-floor-area ratio on the first floor (with thermal mass).**

But without sufficient thermal mass, even the proper glass-to-floor ratio can lead to daily or even hourly temperature swings and heat stratification that can make a home uncomfortable. The south-facing glazing design standard for today's passive solar homes is a window area between 7% and 12% of floor area. (For example, a 1,000-square-foot space would have between 70 and 120 square feet of south glazing.) That ratio can apply to the entire house if all stories are to be passive solar designed, or just to the primary living floor. It's often more appropriate to design a bedroom floor to be sun-tempered, with south glazing of 5% to 7% of the floor area, which doesn't require any additional thermal mass beyond normal building materials and has the benefit of providing more privacy. Beyond 12%, we enter the active solar range in which direct-gain thermal mass is not sufficient to maintain a uniform and comfortable indoor temperature without fans or pumps to move the heat to remote storage and retrieve it on demand.

## Thermal Mass & Foundation Fundamentals

The goal in designing a passive solar home's thermal mass is to be able to store midday solar heat until the early evening, when it will passively return to the living space. Thermal mass operates like a flywheel that dampens any sudden changes in acceleration or, in this case, changes in insolation—the amount of solar energy entering through the apertures—which would otherwise raise indoor air temperature.

Thermal mass is best as direct-gain, meaning in the direct path of the sun, and uniformly distributed throughout the living space. A thermal mass floor fits this need quite well, and the simplest and most cost-effective thermal mass floor is concrete slab-on-grade (meaning formed by pouring concrete within forms, either directly on the ground or with insulation between).

It's possible to pour a lightweight concrete slab on top of a wood-framed floor—if the structure has been designed to handle the extra weight—or use a tile or masonry floor finish. But to achieve the height of design elegance—using one element to serve multiple essential functions—combine the structural floor with the thermal mass, design it to be earth-coupled (taking advantage of geothermal heat) by placing the floor on a thermally protected mass of dry earth, and perhaps integrate a radiant floor heating system.

Doing this well requires designing the home literally from the ground up, integrating multiple systems, and understanding the engineering requirements of each step in the process. Every material choice and methodology decision must build toward an integrated system.

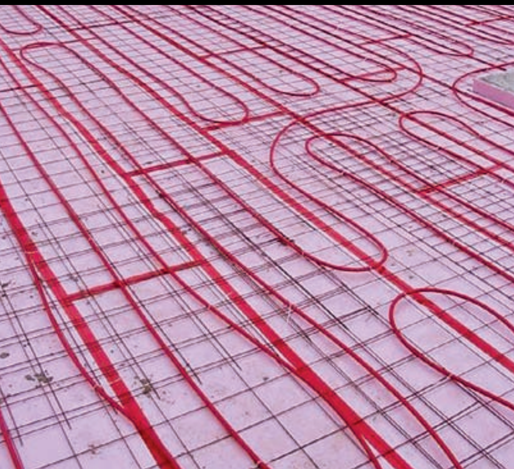
If the slab is also part of the foundation, then gravity loads and soil-bearing capacity, as well as foundation insulation, must be considered. While a monolithic slab—a floor slab with deeper-poured edges that act as footings—is popular in some areas, thermally decoupling the floor slab from the foundation is preferable because most heat loss from a slab is at the edges.

**Step 1: Frost-protected shallow (FPS) foundation with exterior and slab-edge insulation pre-installed.**

**Step 2: Adding the below-slab mechanicals.**

**Step 3: Leveling and compacting the subslab fill.**

**Step 4: With the vapor barrier installed, a layer of rigid foam insulation over it provides a thermal break from the earth.**



**Step 5: Remesh or rebar placed over the rigid foam provides attachment points for PEX tubing.**

**Step 6: Pouring and distributing the concrete.**

**Step 7: The medium-brown integral color used to tint the concrete will help absorb solar radiation efficiently.**

**Step 8: Smoothing the slab's surface to its final texture.**

## Other Important Elements

Solar builders have a wide array of "aperture" (window) options, and with sufficient demand, perhaps manufacturers will begin to offer the kind of highly insulating windows that also have high solar heat gain coefficients (SHGC, as listed on the National Fenestration Rating Council label on new units). Only some Canadian manufacturers and a few high-end custom window makers in the United States are selling windows that are appropriate for passive solar applications. (Unfortunately, the current federal tax credit program, in which consumers can subtract up to $1,500 from their federal tax liability for installing high-efficiency windows, excludes high solar heat gain windows from eligibility, since it calls for an SHGC of $\leq$ 0.30.)

Good building designers are beginning to understand the importance of overhangs, both for rain protection and for preventing summertime overheating in passive solar homes.

Many also appreciate the value of a south-side open floor plan, with private rooms, entries, and utility/storage spaces clustered along the north. An elongated east-west axis enhances a southern exposure that's oriented within 15° of true south to optimize solar availability.

A frost-protected shallow foundation (FPSF) often works well, at least in well-drained soils, and the reinforced concrete grade-beam becomes the building's foundation. In wetter areas, a rubble-trench foundation can be used. With this system, drainage is provided via a perimeter trench, dug below the frost line and drained to daylight at a lower elevation. The trench is then filled with clean mixed stone to grade. Then, a grade beam is poured at the surface, on top of the stone. A more conventional alternative would be a frost wall, though that requires three pours: footings, walls, and slab.

### Slab Details

The building foundation, whether grade-beam or frost wall on footings, needs to be sized to carry the design or code-specified live and dead loads, including snow loads, into the ground, and the ground has to be of sufficient load-bearing quality to receive them. Typical soils, with the exception of loose sand, soft clay, and sandy loam, will carry at least 2 tons per square foot. Though codes may mandate wide footings as a general practice, most two-story homes don't need more than an 8- to 10-inch-wide perimeter footing reinforced with 1/2-inch-diameter steel rebar. Don't forget to place additional steel-reinforced interior linear footings or pads under center bearing walls and point loads, like chimneys and posts.

Clean, granular gravel or sand fill is often required to bring the interior up to the level of the subslab insulation (as shown in the Step 3 photo on page 61), and that fill must be mechanically compacted in 6- to 8-inch lifts. But first, all subslab mechanicals must be carefully placed, since there is no way to move things once they are cast in concrete. This would include any first-floor fixture and floor drains, water lines, and underground electrical and other utilities. It's also wise practice to install a subslab radon vent in any new construction, since radon soil gas is found in all geographic areas of the United States and is carcinogenic. Then, a radon/vapor barrier must be placed on the compacted fill (I use tear-resistant 4-mil cross-laminated Tu-Tuf), and subslab insulation, leaving 4 inches for steel reinforcement (either 6-inch welded wire mesh or steel rebar) and concrete.

The amount of subslab insulation to use depends on the climate zone, the amount of exterior foundation insulation, and whether the slab will be part of a radiant heating system. 2009 International Energy Conservation Code (IECC) insulation standards for foundations are R-10 for zones 4 and 5, and R-15 for zones 6 and 7 (see map).

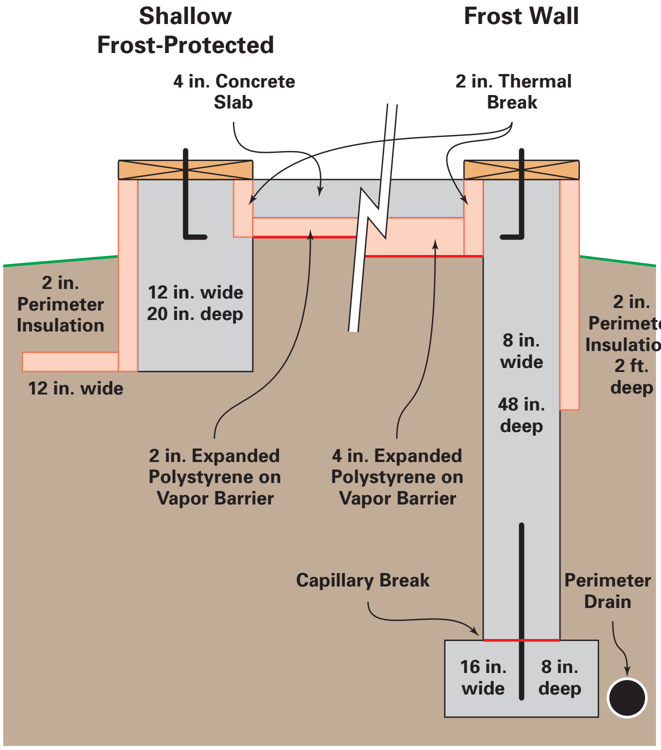
Extruded polystyrene (XPS, Styrofoam) is the industry standard for subgrade insulation because of its durability, compressive strength, low moisture absorption, dimensional stability, and high R-value (R-5 per inch). It is also highly resistant to acids and alkalis. For a heated slab, I recommend an additional R-5 beyond code minimums, except with a frost-protected shallow foundation, which relies on heat loss downward to maintain the earth temperature above freezing and which has an additional R-5 to R-10 exterior foundation and wing insulation. As important as subslab insulation is for a radiant or solar-heated slab, the greatest heat loss from a slab-on-grade occurs at the vertical edges—this is why I prefer to pour a slab separate from the foundation and isolate it with R-10 edge insulation.

Any foundation type, particularly a slab-on-grade, must also be hydraulically isolated from the ground with capillary breaks—a material that prevents the migration of moisture between the earth and the foundation, between the foundation and slab, and between the foundation and wood framing. The subslab vapor barrier and edge insulation serve this purpose, as does the sill seal and metal termite flashing installed on the grade beam before wooden sills. But few builders bother to include a capillary break between footings and foundation wall to prevent the wicking of water up the concrete, which has a theoretical capillary height of 6 miles! I prefer a brush-on latex masonry waterproofing such as UGL DryLock.

## Slabs with the Larsen Truss System

In climates with high heating loads, exterior wood-framed walls can be built 12 inches thick with a modified Larsen truss system to achieve highly insulated walls (R-40 or better). This system readily accommodates a 12-inch-wide grade beam, which includes 2 inches of exterior XPS foam and 2 inches of slab-edge insulation, which all gets covered by the wall.

## Foundation Options




Codes require that concrete used in residential construction have a minimum rated strength of 2,500 psi, which is the compressive strength it achieves after 28 days of curing. But since the mix tends to get extra water during pouring and because stronger concrete is also more waterproof, I order 3,500 psi mix for foundations and 4,000 psi mix for slabs. In addition to 6-inch welded wire-mesh reinforcement (which has a grid pattern that simplifies laying out and securing radiant tubing), I also specify short polyester fiber reinforcement in the slab mix. Steel reinforcement, whether a grid of rebar or welded wire mesh, offers tensile strength to resist cracking from settling or ground movement. The short fibers, invisible once the slab is power-troweled, help prevent the small shrinkage cracks that can occur if mix water is allowed to evaporate too quickly (or excess water is added on site). All concrete work should be covered by plastic or kept wet for three days to allow initial curing to occur, unless the concrete is colored. Covering or wetting can mottle the color, so it's better to apply a curing sealer which should meet the ASTM C1315 standard and be type 1 (clear), class A (non-yellowing), all-acrylic.

Dense materials, like concrete, which have a specific heat of 28 Btu per cubic foot per degree Fahrenheit (about half that of water), tend to allow heat diffusion at a rate of about 1 inch per hour. So the heat of the noontime sun will penetrate to the bottom of a 4-inch-thick slab by about 4 p.m. and all that heat will have returned to the interior by about 8 p.m.—making a

Step 9: Power-troweling the slab provides a smooth finish.

Step 10: Applying a curing sealer over the finished concrete will help protect the surface from stains.

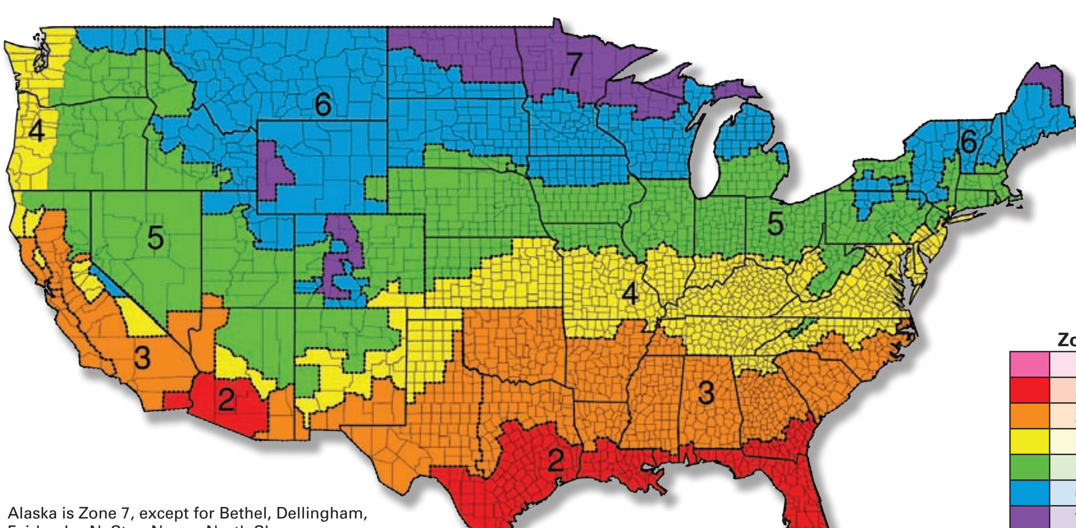
4-inch-thick slab ideal for solar thermal mass. This is called the "diurnal heat constant" and it shows a diminishing return with a slab thicker than 4 or 5 inches. (If the heat is moving in one direction only, such as in a Trombe wall, then 8 inches is ideal.)

## After the Pour

If the slab surface is to be the finished floor, then any of several dozen standard colors can be premixed at the batch plant for a small extra fee, and this saves the cost of additional finish materials and labor. Any solar absorber surface should have low specularity (somewhat matte-textured, not glossy) and a medium hue such as brick red or terra-cotta brown, which have solar absorptivity factors of 70% to 80%. Even untinted concrete has an absorptivity of 65%, which is within the acceptable range. A finished concrete floor also needs to be sealed to prevent water absorption and staining. The choices are surface coatings, which tend to create a sheen until worn in, and penetrating sealers made of siloxanes, silanes, or silicates. Siloxanes are the least volatile, penetrate well, can last for 10 years, and can be applied on a slightly damp substrate. Silicates, unlike the other two, have poor water repellency, poor water vapor permeability, and a shorter working life. A surface film or paint can be applied, but that has to wait until complete cure, which can take up to three months.

If a solar slab is to be fully or partially covered by other floor finishes, those coverings must have good solar absorptivity and a total R-value no greater than R-0.5. Tile or masonry works well, and a 3/8-inch, laminated, prefinished hardwood strip flooring can be installed without too much loss of the floor's thermal mass function. The wood alternative makes a concrete floor "softer" on the feet and offers a warmer feel to the house, but use material with a matte finish for low specular reflection and enough color for good solar absorption. The thin, laminated hardwood will be more stable than solid sawn lumber, which is important on a

## IECC Climate Zones




Alaska is Zone 7, except for Bethel, Dellingham, Fairbanks, N. Star, Nome, North Slope, Northwest Arctic, Southeast Fairbanks, Wade Hampton, and Yukon-Koyukuk, which are Zone 8.

Hawaii, Guam, Puerto Rico, and the Virgin Islands are Zone 1.

Courtesy U.S. DOE

| Zone | Thermal Criteria: CDD 50* | HDD 65** |
|---|---|---|
| 1 | > 9000 | – |
| 2 | 6,300–9,000 | – |
| 3 | 4,500–6,300 | – |
| 4 | < 4,500 | < 5,400 |
| 5 | – | 5,400–7,200 |
| 6 | – | 7,200–9,000 |
| 7 | – | 9,000–12,600 |
| 8 | – | > 12,600 |

* Cooling Degree Days over 50°F
** Heating Degree Days under 65°F

floor that will be changing temperature. Throw rugs are OK if the total area is limited to 20% of the floor's area.

Because a house does not require additional thermal mass until the south glazing area exceeds 7% of floor area, a rule is to allow for 6 square feet of direct-gain, 4-inch-thick mass for each square foot of south glass beyond 7%. For example, a 1,000-square-foot house with 120 square feet of south glazing (12%—the maximum for passive solar) would require 300 square feet of slab floor available to the sun. That would be 60% of the south half of the house, or no more than 40% of the floor blocked by furniture and coverings.

If that small house was super-insulated as well, even in the cloudy Northeast it could get close to 50% of its annual heat requirement from the sun. For the small incremental cost of additional south windows and careful design, coupled with a highly efficient thermal envelope, the heating costs can be decreased by at least half, compared to a conventionally constructed home. Upgrading from energy-code standards to a super-insulated, passive solar home might add 5% to the construction costs of the home. But the energy savings more than offset the additional mortgage payment, so the payback occurs in the first month.

## Mixing Heating Strategies

If the passive solar design is complemented by a radiant heating system, then—sunshine or clouds—the floor will be warmer than room temperature. Human thermal comfort requires warm feet and cool heads. Most heating systems—particularly forced hot air—cause air-temperature stratification, with the ceiling warmer than the floor. This detracts from occupant comfort. A radiant floor increases the mean radiant temperature of the living space. What makes radiant floor heat more efficient is that the thermostat can be lowered a few degrees without any sacrifice in comfort. The average temperature-dependent infrared radiance of room surfaces has

## Solar Slab Fundamentals

Elements of a high-performance passive solar thermal mass slab:

**Must support structural loads and be supported by the ground**

- Perimeter frost wall, grade beam, or thickened edge for footings
- Interior linear or pad footings for load-bearing partitions or concentrated loads
- Well-compacted, mixed aggregate fill under slab

**Must contain all first-floor fixture and floor drains**

- Carefully planned and placed drain-waste-vent pipes
- Inside perimeter radon vent
- Other underground utilities, including wood heater combustion air supply

**Proper concrete mix, reinforcement, admixtures, colorants & sealants**

- Higher-strength concrete reduces the likelihood of surface or settling cracks
- Steel reinforcement (either rebar grid or welded wire mesh), placed 1 inch from bottom of pour
- Short-fiber polyester added to boost tensile strength and improve surface integrity
- Premixed colors for an easy finished floor
- Curing sealer applied after power-troweling to prevent dry-out and preserve color

**Good solar access**

- Sun sweeps across slab in fall, winter, and spring
- Windows are shaded with overhangs in summer
- Maximum slab area in direct sun during peak heating season
- Minimal insulating floor coverings or obstructions in areas of direct gain

**Proper balance of glass to mass**

- No additional mass required with 7% floor area in south glazing
- 6 feet$^2$ of direct-gain slab or 9 feet$^2$ of direct gain, thermal mass wall for every foot$^2$ of glass beyond 7%

**Good surface solar absorptivity**

- Medium-to-dark earth tones
- Matte or textured surface—not glossy, unless thermal mass is in wall

**Ample thermal storage material**

- Dense: concrete, tamped earth, or masonry
- High specific heat (heat capacity per unit volume)
- Moderate diffusivity (distributes heat internally, but not too quickly)
- Good infrared emissivity (ability to radiate heat)
- About 4 inches thick for floor, or 8 inches thick for free-standing wall
- Good diurnal heat capacity (ability to store and release heat in 24-hour cycle)

**Good environmental isolation**

- Insulated from ground below (but not too much for good earth-coupling)
- Well-insulated at slab edges (where most heat loss occurs)
- Protected from water & water vapor with air/vapor barrier
- Subslab radon venting to evacuate carcinogenic soil gas

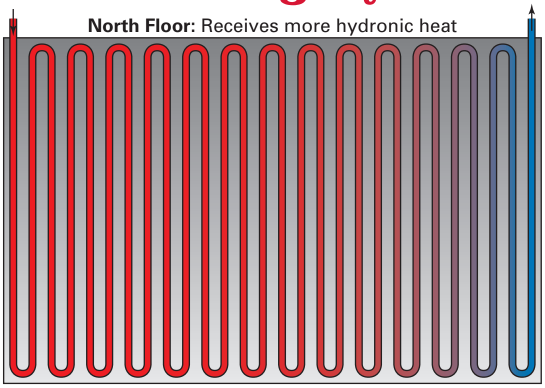
**Natural convection distribution**

- House designed with open floor plan
- If house has more than one story, central open stairway to move heat upstairs
- Perimeter floor grills for return flow (balanced with noise & privacy concerns)

**Appropriate maintenance**

- Re-seal (with siloxane) when floor begins to absorb water or stains

## Self-Regulating Hydronic Radiant Heating System




**The heat exchange rate between the tubing and slab is dependent on temperature difference (ΔT). In the shaded north section of the slab, more ΔT equals more heat exchange. In the sun-warmed section of the slab, less ΔT equals less heat exchange. The result: When the sun shines, more of the hydronic heat is delivered to where it's needed.**

at least as much effect on comfort as air temperature. In other words, warm floors and walls are more important to occupant comfort than warm air. One thing to avoid with a high mass radiant floor, though, is a setback thermostat. There is too much thermal inertia, or lag time, to make changing the floor temperature a strategy for saving energy.

Some building experts discourage mixing passive solar with radiant floor technology since the lag time can make it more challenging to maintain uniform indoor temperatures—especially when the floor is warming from below and then the sun comes out. Even if the thermostat shuts off the radiant circulation, the heat already in the floor will continue to emerge, while the sun is also heating the space. However, this can be an asset. Since the sun is raising the slab temperature, there will be less heat exchange from the radiant tubing in the south half of the slab and more heat available to the north half, which doesn't have the benefit of receiving solar gain. This selective heat redistribution function would be most efficient if the radiant tubing was looped in a north-south orientation.

Throw in a wood heater with outside air for combustion, and the balancing act becomes more delicate. But the learning curve for occupants who have chosen this mix of heat inputs would be short, and the benefits should outweigh the liabilities. With or without supplemental radiant floor heat, a passive solar slab can be a cost-effective multiple-function element of a well-designed and energy-efficient home.

## Access

**Robert Riversong** (housewright@ponds-edge.net) is a master housewright with 30 years' experience designing and building passive solar, super-insulated homes. He teaches and consults on building technology, building science, and engineering.

Larsen truss system details • www.builditsolar.com/Projects/SolarHomes/LarsenTruss/LarsenTruss.htm