Solar Heat

for My Maine Workshop

Guy Marsden

The author with the solar thermal panels that heat his workshop's floor.

Tubing within the concrete slab floor efficiently distributes solar heat, making a comfortable room.

My wife Rebekah and I decided to move from California to rural Maine for many reasons—mostly to live an affordable rural lifestyle in a beautiful environment. Having survived the California "energy crisis," we became even more energy conscious. Rebekah even started to refer to me as an energy nazi!

Using solar energy is something I have always wanted to do, ever since reading the *Whole Earth Catalog* in the late '60s. We were fortunate enough to make a significant profit on the sale of our suburban house in California, and used some of the proceeds for solar energy equipment and energy reduction in our new home in Maine.

We replaced all the incandescent lamps in the house with low wattage fluorescent lights, and purchased a Staber clothes washer. We plan to install a grid-intertied, solar-electric system for the house this year. Rebekah drives a 2001 Honda Insight and loves it! She gets an average of 61.2 mpg on most trips.

We both work at home, and wanted to be sure to have warm, comfortable, and well-lit work spaces. Rebekah's basement knitting studio is heated by a woodstove that heats most of the house. A propane backup heater fills in at night so we don't have to get up and stoke the stove. Our property includes a recently constructed barn that is perfect for my needs.

I make furniture and design electronics for a living. So I need two distinct work spaces. The barn has a full second floor for my electronics lab. That dish antenna you can see above the solar collectors is for a StarBand satellite modem. For my engineering work, I absolutely require high bandwidth. Due to our rural location, a satellite modem is the only viable high-bandwidth option. As soon as cable internet service is available, I will switch, since I find the slow speeds and long delays of the satellite to be much worse than advertised. Bad weather can knock it out entirely!

I suffer from migraine headaches that are triggered by cold temperatures, so heating in the Maine winters is crucial for my well-being. I decided to use a radiant heated floor, which is known for comfort. A particularly nice feature is that the heat rises up from the floor to warm my large, floor-mounted power tools. I had no intention of freezing my hands off in the Maine winters! The radiant floor is heated primarily by two, 4 by 8 foot (1.2 x 2.4 m) SunEarth Empire series solar collectors, augmented by an AquaStar (AQ125-BLP-S) propane on-demand water heater.

Sometimes the Maine winter is relentless—an AquaStar tankless water heater fills in when the sun doesn't shine.

The heating system begins with the two SunEarth solar collectors that are connected in parallel. A PV powered pump circulates the heated glycol mixture through a heat exchanger. A second PV powered pump circulates heated water into the 80 gallon (300 l) storage tank. A thermostat controls the AC pump that feeds the two, 300 foot (90 m) loops of tubing in the concrete floor.

System Design

My first step was to have a heat load analysis done by Peter Talmage of Solar Market in Arundel, Maine. This helped to define my heating system design goals and insulation requirements. The barn was bare stud walls on a concrete foundation and rough concrete floor when we acquired it. It had been built to store the previous owner's lobster boat.

The floor plan is 24 by 28 feet (7 x 8.5 m), with a 10 foot (3 m) high ceiling on the ground floor and a full second floor. The ground floor is framed with 2 by 6 lumber, and the 45 degree roof (unfortunately facing east and west) is framed with 2 by 8 rafters. The barn had seven original windows, and I installed two, standard, well-insulated exterior doors.

Guy's barn was oriented the wrong way to put his solar panels on the roof. The shed Guy built on the south end has a 45 degree roof pitch—perfect for the two, 4 by 8 foot solar hot water panels.

Corbond spray-on foam insulation has an R-value of about 7.3 per inch.

Insulating

The first task of any solar heating design is to get the best possible insulation for the walls, ceiling, and floors, and thoroughly seal any openings that would allow unwanted cold air into the building. I insulated the windows with removable Windo-Therm interior plastic double glazing that will be used only in the cold season (five months in Maine).

I insulated behind the original sliding barn doors by adding two in-swinging doors, which fit within the doorway when closed. Resembling hinged wall sections, the auxiliary doors are framed with 2 by 6s, filled with fiberglass, and finished with 3/8 inch (10 mm) exterior plywood. They are thoroughly weather-stripped. These are huge (4 x 9 foot; 1.2 x 2.7 m) and imposing to open—I call them the "Doors of Doom!"

I contracted the installation of Corbond—a sprayed-in polyurethane foam insulation—throughout the structure. Corbond has an approximate R-value of 7.3 per inch. I had 3 inches (7.6 cm) installed in the walls on the ground floor, and 4 inches (10 cm) in the walls upstairs. A significant advantage of the foam is that it forms an airtight seal throughout the building. I left the building to air out all the urethane fumes for over four weeks before completing the interior work.

The exterior walls of my barn were 1 by 10 inch shiplap barn boards installed vertically over 1 by 2 inch horizontal battens. A layer of Tyvek housewrap is in between the battens and shiplap. As such, it was far from airtight. I added fiberglass inside (over the Corbond) to increase the R-value to about R-30 downstairs and about R-40 upstairs, and installed drywall over that. I estimate that I have approximately R-37 in the roof.

Radiant Floor

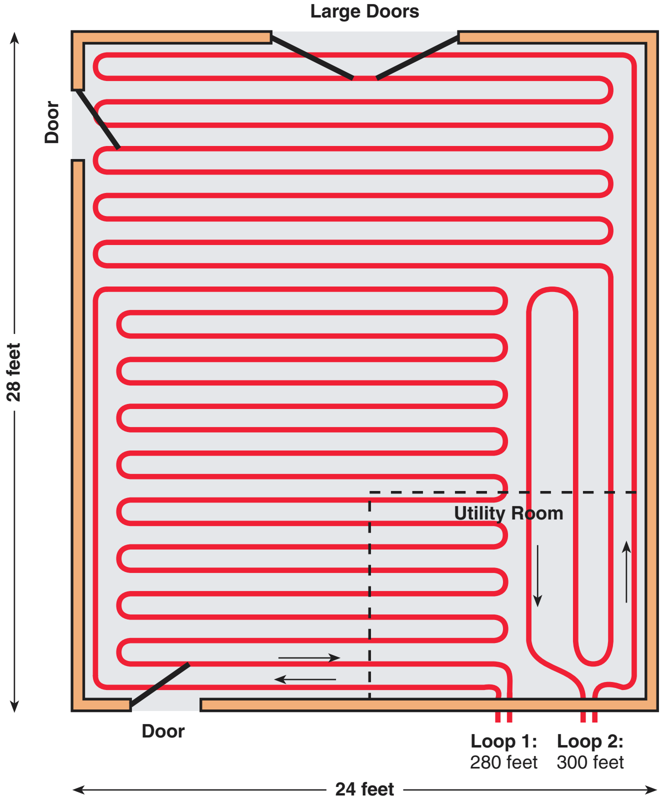
For the radiant floor, my first job was to install 1 inch (2.5 cm) polystyrene high density construction insulation over the existing concrete floor. I then laid 6 inch (15 cm) steel grid (commonly referred to as road wire) over that for securing the radiant tubing, using nylon cable ties. I laid out two loops of 300 feet (90 m) each of the tubing, which I connected to a manifold in the utility room.

A local contractor did a great job of pouring 3 inches (7.6 cm) of concrete over the tubing. I asked him to use a 4,000 psi fiberglass mix to give me a strong workshop floor. Naoto Inoue at Solar Market sourced the materials for this job and specified the details. He originally suggested 2 inches (5 cm) of concrete to create a very responsive system.

Laying 1 inch polystyrene insulation board over the old floor insulates the heated slab from the earth.

The 600 feet of hydronic tubing is held in place by road wire. Three inches of concrete will make the final layer.

Hydronic Loop Layout



Loops are 6 inches from outer walls and roughly 12 inches apart.

I felt that 2 inches would be too thin, and the concrete contractor refused to pour less than 3 inches due to the risk of damaging or exposing the tubing. The 3 inches still allows me to use a single household thermostat to control the heating, though it is less responsive. I'm still testing, but I believe that the system can raise the building temperature by about 3°F (1.6°C) per hour.

Building a Solar Roof

I needed a structure on the south side of the barn to put the solar collectors on, so I built a small shed with a steeply sloped roof. At this latitude, a 45 degree slope is recommended and is easy to build.

My neighbor John Rogers, who is a building contractor, helped me design the shed and gave me a hand for an hour or so to get the collectors mounted on the roof. I was lucky that the weather was still warm enough to sweat the exposed 3/4 inch copper pipe fittings in early October! Maine can be quite chilly at that time of year!

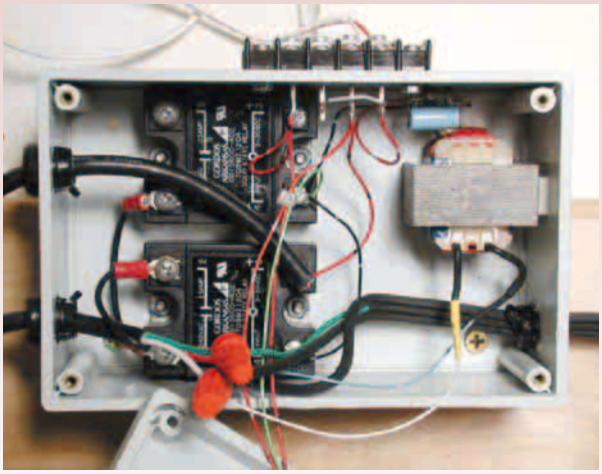
The collectors came with small L-brackets that did not seem to be big enough to raise the collectors more than 1/2 inch (13 mm) off the asphalt roof. Ken Olson suggested that an inch or so would be better, so I made up my own brackets from extruded, 3 inch (7.6 cm) angle aluminum with a 1/8 inch (3 mm) wall.

Thermostat Relay Box

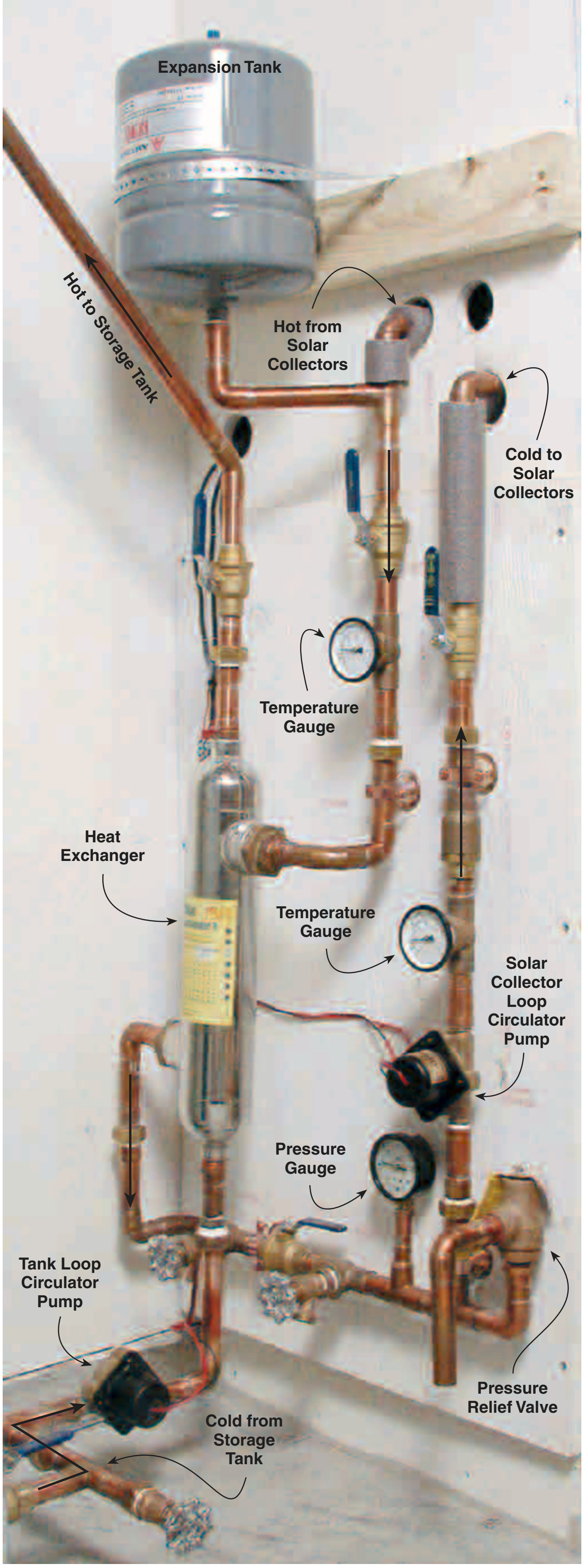
I built a relay box that allows my standard, centralized heating, digital thermostats to control the AC circulation pumps. To power the relays, I used a 12 VDC, "wall wart" plug (wall cube, or AC-to-DC converter), and wired it to solid state relays in a nice plastic box with two LEDs to indicate when each pump was running. I used solid state relays rather than mechanical ones, since they consume a fraction of the energy when activated.

The relay box is quite simple. All it contains is a 12 VDC power supply, pillaged from an old phone answering machine. I actually broke open the plastic housing of the wall wart, and extracted the transformer and electronic parts so I could silicone them into the box nicely. The dissected and reassembled wall wart sends power to the thermostat, which switches the solid state relays and turns an LED indicator on. The digital thermostat that I used runs on its own two AA batteries.

The control box LED requires a 1 K-ohm resistor in series with it for current limiting. I used relays that are rated at 10 amps at 240 volts. These can be found surplus for around US$7. When switching a motor with a relay, it is best to rate the relay at double the current and voltage of the load to allow for protection from the inductive surges that occur during switching.



A homebuilt, solid-state relay box allows standard thermostats to control the system's AC circulation pumps.



I used three, stainless steel, sheetmetal screws to attach each 3 inch long bracket to the collectors, and used a $^{5}/_{16}$ inch by 2 inch (8 x 50 mm) stainless lag screw with galvanized washers per bracket to secure them to the roof. I also put a bit of silicone around the lag screw heads to prevent ice from working down into the roof.

Lots of Plumbing

One thing that is rarely mentioned in articles about homebrew solar installations is the emotional ride. For me, it has ranged from excitement to total freak out at the daunting complexity and overwhelming amount of detail. Fortunately, I already had considerable experience in all the skills needed to accomplish my installation, so I was able to trust in my knowledge that I could complete the project almost single-handedly.

I am an experienced home and light industrial plumber from a previous life in photo processing. Nonetheless, it took many visits to the hardware store over a period of a couple of weeks to locate all the copper fittings for the system components. The plumbing assembly took more than a week to build. I sweated together each section of the various assemblies of valves, gauges, and pumps, which I then assembled into a complete system.

It was very helpful and timely that *HP85* came out as I began the plumbing phase. That issue contains Ken Olson's excellent article on closed loop antifreeze systems. I downloaded a copy and used it as a working reference on the job.

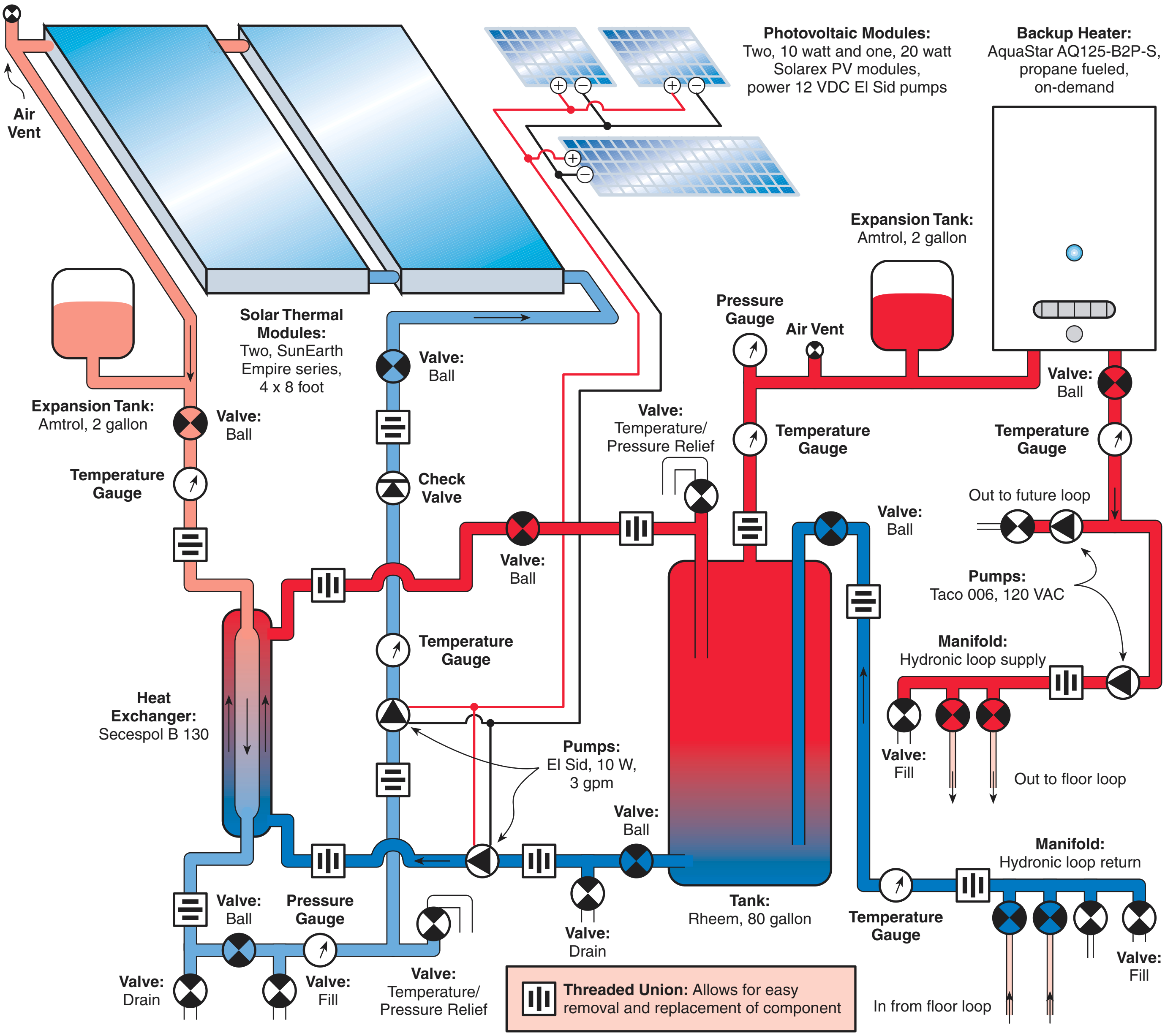
Some Plumbing Tricks

One neat plumbing solution that I found was a good way to mount thermometers into $^{3}/_{4}$ inch copper pipe. The thermometers that I used come standard with a $^{1}/_{2}$ inch pipe thread, and if you sweat a $^{1}/_{2}$ inch thread adapter onto a $^{3}/_{4}$ inch tee with a short length of $^{3}/_{4}$ inch pipe, the thermometer sensor stays out of the fluid flow. This can give inaccurate readings, especially if the tee is mounted so that air stays trapped in the stub tube.

A brass seat tee with reducer (right) keeps the thermo-meter sensor in the fluid's flow. Copper fittings (left) don't work as well.

The solar loop portion of the system's plumbing, showing the Amtrol 2 gallon expansion tank, Secespol heat exchanger, and 2 El Sid circulating pumps.

Guy Marsden's Solar Heating System



I used a brass sweat tee with 1 inch female threads instead. Then by putting in a $^{1}/_{2}$ inch reducer bushing, I found that the thermometer's $^{1}/_{2}$ inch thread would fit in snugly, allowing the thermometer sensor to protrude fully into the water flowing through the tee. I believe that this setup will guarantee accurate readings.

When plumbing the indoor section of the collector loop, I placed unions around the heat exchanger and pump sections. The sections can be removed easily for service or replacement, or to tighten the couplings. It turned out that I needed to make use of this feature, so it definitely paid off.

Another trick that I devised involves weatherizing the foam insulation on the exterior plumbing. I took some 2 inch PVC pipe and ripped it in half on my table saw and clamped it back around the insulated pipe using nylon cable ties.

The air vent needs to be located at the highest point in the system, which means at the top corner of the collectors for me. I ended up with a vent that is about 6 inches (15 cm) above the collectors. To insulate and protect it from the elements, I wrapped the pipe in foam, and put a length of PVC pipe with an end cap over it.

That's not Gatorade! Filling and pressurizing the solar collector loop with the propylene glycol solution.

Filling the System

My workshop has no running water, so I had to pull a garden hose over 70 feet (21 m) from the house to fill the system. I came up with a neat way to monitor the fluid and air bubbles entering and exiting the system. I made up two, 3 foot (0.9 m) lengths of 5/8 inch (16 mm) ID clear plastic hose and added garden hose fittings. One hose was connected to the fill pump outfeed, and the other to the system drain. This made it possible to monitor the fill process, and to clearly see when the air was purged from the system.

I let the fill pump continue to recirculate until the returning fluid stopped showing air bubbles. Air bubbles in a closed system can impede flow and limit the efficiency of the system, and should be carefully and thoroughly eliminated. When filling the water tank, I attached the clear plastic infeed hose directly to a garden hose, and let the overflow drain out the window!

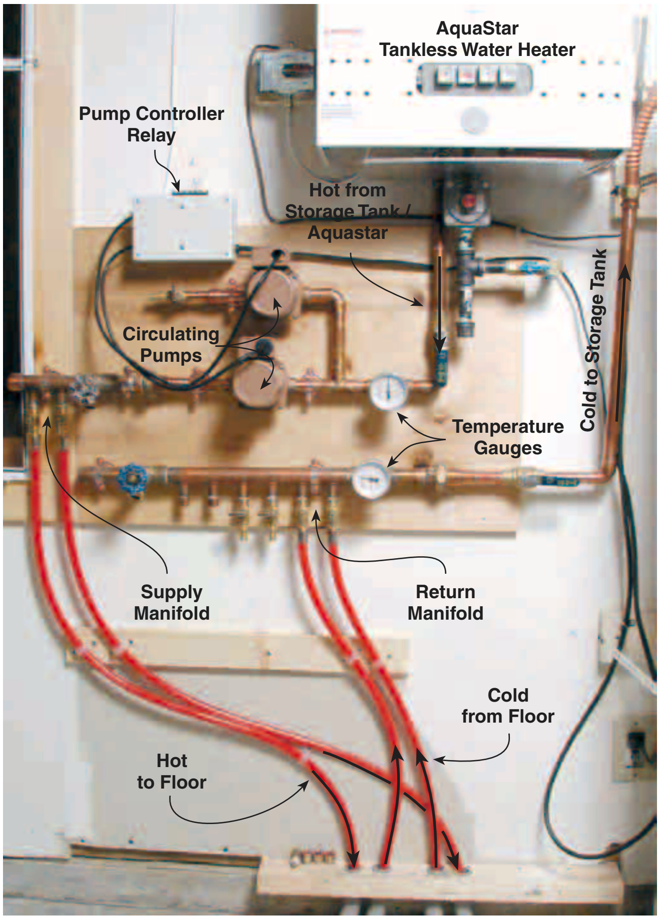
My solar collector loop holds approximately 3 gallons (11 l), so it was relatively easy to prepare a 50:50 glycol solution by mixing it in a 5 gallon (19 l) bucket. Use propylene, *not* ethylene, glycol. Ethylene glycol, as used in automobile radiators, is highly toxic. The propylene glycol that I used is formulated for the high temperatures that the collectors can generate.

The SunEarth collectors can reach a stagnant temperature of 240°F (116°C). A collector will achieve its hottest temperatures under what is called stagnation conditions. When no fluid is flowing through the collectors, heat is not being removed, and the temperature rises to a maximum. Stagnation temperatures will eventually break down most types of glycol. Stagnation should be avoided in closed loop systems unless high temperature (350°F; 177°C) propylene glycol is used.

The Break-In Period

After a late night of filling and checking the system, I was up with the sun the next morning to watch the solar powered El Sid circulating pump kick in and begin warming my system. I was disappointed at how long it seemed to take with the sun shining brightly, until I realized that I had installed the pump in the wrong direction. The pump was trying to suck against the check valve to no avail. Being quite dyslexic, this is something I have grown used to—getting things backwards!

The supply and return manifolds of the two hydronic floor loops. Notice the extra Taco 006 pump for a future heating loop in the barn's second floor.



The liberal use of threaded unions allows for easy removal of components for repair or replacement.

Fortunately, I had installed unions around the pump with serviceability in mind, so I simply closed some valves and removed the section. I unscrewed the fittings on each side of the pump, reversed it, and reinstalled it. The moment the pump began to run, I watched the incoming temperature gauge rise to over 220°F (104°C) from the stagnant hot water in the collectors. In a few minutes, it settled down to a nominal 155°F (68°C), which seemed to be the system's normal capacity (more on that later).

I wholeheartedly recommend that all systems have a liberal sprinkling of unions to allow for service disassembly. I also found some leaks around my heat exchanger, and rectified that by removing the whole assembly and tightening the fittings.

PV & Collector Problems

In the first few days of full sun, I noticed that the pump didn't kick in until after 10:30 AM. I first thought that the solar-electric panel that runs the circulation pump was underpowered. On the third sunny morning, I went out and looked at the PV panel. I saw that I had mounted it up slope from the air vent I had installed on a 6 inch (15 cm) extension above the collectors, and the air vent was shadowing the PV! So I moved it over by a foot and fixed that silly mistake!

When I mentioned to Naoto that my operating temperature was a nominal 155°F (68°C), he was surprised, since the design spec is closer to 180°F (82°C). He had been having trouble with other SunEarth Empire series units underperforming, and contacted the factory.

The SunEarth engineers were very responsive and soon learned that there was a manufacturing defect in the units. They arranged with Solar Market to replace those units that were already installed. The first set of replacements I received was not packed properly and the panels were badly damaged in shipping. Almost four months later, I finally have the new units, and must now wait for a warm, dry day! Right now it's inches of mud and raining hard, with snow in the forecast! Check my Web site for details on the new panels and their performance.

The air vent shaded the PV panels in the early morning, causing a delay in pump operation—Oops!

Underpowered Floor Circulating Pumps

The next setback came when the propane supplier came to hook up the AquaStar heater. We couldn't get the heater to kick in, even though the circulating pump was running. I realized that mine is a closed system, and the AquaStar relies on a pressure difference of 10 psi to turn on.

This is fine in an open system. When you turn on a faucet, the outfeed pressure drops, turning the heater burner on to the degree needed to bring the water flowing through it to temperature. It looked like the pump (Taco 003 series) was underpowered. This was very distressing!

I called Naoto at Solar Market and he immediately drove over (a trip of more than an hour!) in his biodiesel

Marsden Heating System Costs

Item	*Cost (US$)*
2 SunEarth Empire series 4 x 8 foot collectors	952
AquaStar 125BS propane water heater	690
1,000 ft. Rehau radiant floor tube, 1/2 inch (600 ft. used)	616
Lumber for shed	580
Copper pipe, fittings, valves, etc., 3/4 inch	500
2 El Sid PV-driven circulating pumps, 3 GPM 10 W	420
Rheem storage tank, 80 gallons	369
2 Taco circulating pumps, model 006, 120 VAC	332
Secespol B 130 heat exchanger	256
2 Solarex SX-10M PV modules, 12 V, 10 W	212
Solarex SX-20M PV module, 12 V, 20 W	180
2 Manifolds, 6 outputs & 6 valves for floor tubes	138
Wayne PC2 utility pump, 60 gph at 40 feet of head	85
5 Temperature gauges	80
2 Amtrol 2 gal. expansion tanks, high temperature	76
Check valve, light-action spring	24
Amtrol air vent	9
Total	$5,519

powered Mercedes. He brought a larger pump. Naoto has been unfailingly supportive and helpful throughout the entire project. I simply couldn't have done it all without his help and advice. We were lucky that the larger pump (Taco 007 series) that he brought was the same brand and used the same size motor body as the underpowered unit.

The quick fix was to remove the motor from its housing and replace it with the larger motor and impeller. This saved a lot of work replumbing all the copper! The modified pump created enough draw to pull a pressure drop across the AquaStar and trigger it to fire up its burners.

After running this modified pump for several days, I noticed that it ran hot—too hot to touch comfortably. I decided to call the manufacturer, Taco, Inc. The application engineers there were very helpful and reviewed my design thoroughly. They asked me to take amp readings while the pump was running, and also ran a lab simulation of my system configuration.

Their conclusion was that I would be better served by a 006 series pump. It comes with 3/4 inch sweat fittings rather than the 1/2 inch sweat fittings that I had used with the original 003 series unit. This model is also more efficient electrically. The 007 model is rated at 0.7 amps, while the 006 model is rated at 0.52 amps. Both pumps operate at 120 VAC. I found that the rated amps are a rough value, and the actual draw varies with the operating temperature of the pump—cooler equals lower current. My pumps seem to run a bit lower than their rated specs even after running for hours.

The Taco engineers were kind enough to send me replacement pumps to solve my design issue. It required resweating a chunk of my manifold, and refilling my system, but it was worth it if only to reduce my electrical load!

When Naoto came by with the replacement pump, he reviewed the details of my system with me. He agreed with my assessment that the system efficiency could be improved by pumping heated water through the heat exchanger. In the original design, heat flowing up through the secondary side of the heat exchanger would create a thermosiphon effect to heat the water stored in the tank. My feeling is that this flow is insufficient to maximize the potential heat transfer capability of the heat exchanger. Heat rising through the heat exchanger does not flow as rapidly as it would if pumped.

We decided to add another PV panel with its own separate DC pump installed on the cold side of the heat exchanger. The neat thing about circulation pumps that are direct wired to PV panels is that they only operate when there is sufficient sun to heat the solar collectors. We also decided to add a temperature gauge before the AquaStar heater, at the storage tank exit. Previously, I had no way of monitoring the temperature of the solar heated water emerging from the storage tank.

Underpowered PV Circulating Pumps

Another issue arose when I noticed that the PV-driven circulation pumps didn't kick in until well after sunrise on sunny days. I e-mailed Dan Fieldman at Ivan Labs and asked what might be wrong. He explained that he recommends 20 watts of PV per pump when they are installed north of Jacksonville, Florida. He also corrected me on the orientation of my pump—the motor should be horizontal, not vertical.

Since the pumps are rated at 10 watts, Solar Market had sold me one 10 watt Solarex PV panel per pump. I have added another 20 watt Solarex unit for a total of 40 watts wired in parallel to run both my El Sid circulation pumps. This has dramatically increased my system efficiency.

Guy Marsden installed the whole solar hydronic heating system himself.

Learning How to Best Use Solar Heat

I bought a standard electronic thermostat for space heating systems that has four settings per day. It included a mode for radiant floor heating that makes it shut off as soon as the temperature is 1°F (0.56°C) above the setpoint. Originally, I set it to 60°F (16°C) at night, and 68°F (20°C) at 7 AM. I learned that this is the wrong thinking for a radiant floor, solar heating system.

My system has a very slow response time. So setting the temperature low at night appears to be a false economy, since it takes several hours to get back up to 68°F (20°C) in the morning. I experimented and learned to set the thermostat to 70°F (21°C) from 5 to 9 AM, and to 67°F (19°C) for the rest of the day.

The heat coasts up by several degrees during the two to four hours after the circulation pumps shut off. The building is so well insulated that when the heat shuts off between 9 and 11 AM (on days well below freezing outside), it does not come on again for over twelve hours. On days where the outside temps stay below 10°F (-12°C), the heat stays on all night, and cuts off midmorning when 67°F (19°C) has been reached. There is enough direct solar gain from windows that sunlight plays a big factor in daytime heating.

Many radiant floor solar heating systems suffer from an overproduction of heat in the summer, since there is little or no space heating load. My understanding is that the antifreeze formulation in the Dow Frost propylene glycol mixture that I used is rated to 350°F (177°C), as opposed to other mixtures that are only rated to 280°F (138°C).

In the summer months, I'm going to disconnect the PV modules from the circulation pumps and let the collector loop fluid stagnate. This will shorten the life of the glycol in the system, but I still expect to get five years or so out of it before it needs to be changed. I plan on checking the pH of the glycol before the heating season begins to make sure it hasn't degraded and is up to snuff.

You can see a detailed journal with many images of the whole process of building this system on my Web site. I am now enjoying building furniture in a warm work space. It is a very efficient system, and best of all—it's heated by the sun! Radiant heat makes a very comfortable work environment, and I have found that I am setting the thermostat lower than I had expected.

Access

Guy Marsden, Art Tec, 61 Delano Road, Woolwich, ME 04579 • 207-443-8942 • Fax: 207-443-8677
guy@arttec.net • www.arttec.net/Solar/BarnHeat.html

Solar Market/Talmage Solar Engineering, Inc., 25 Limerick Rd., Arundel, ME • 877-785-0088 or 207-985-0088 • Fax: 207-985-5577
naoto@solarmarket.com • www.solarmarket.com

Windo-Therm, 2746 NY 7, Valley Falls, NY 12185
800-819-9463 • Fax: 518-663-7678
windo@albany.net • www.windotherm.com

Corbond Corporation, 32404 Frontage Rd., Bozeman, MT 59715 • 888-949-9089 or 406-586-4585
corbond@corbond.com • www.corbond.com • Corbond insulation

Radiant Floor Company, PO Box 666, Barton, VT 05822 • 866-927-6863 or 802-525-1132
Fax: 802-525-3940 • info@radiantcompany.com
www.radiantcompany.com

Controlled Energy Corp., 340 Mad River Park, Waitsfield, VT 05673 • 800-642-3199 or 802-496-4357
Fax: 802-496-6924 • sales@controlledenergy.com
www.controlledenergy.com • AquaStar tankless water heater

Taco, Inc., 1160 Cranston St., Cranston, RI 02920
401-942-8000 • Fax: 401-942-2360
marcha@taco-hvac.com • www.taco-hvac.com

Ivan Labs, Inc., Dan I. Fieldman, 305 Circle West, Jupiter, FL 33458 • 561-747-5354 • Fax: 561-746-9760
ivandelsol@juno.com