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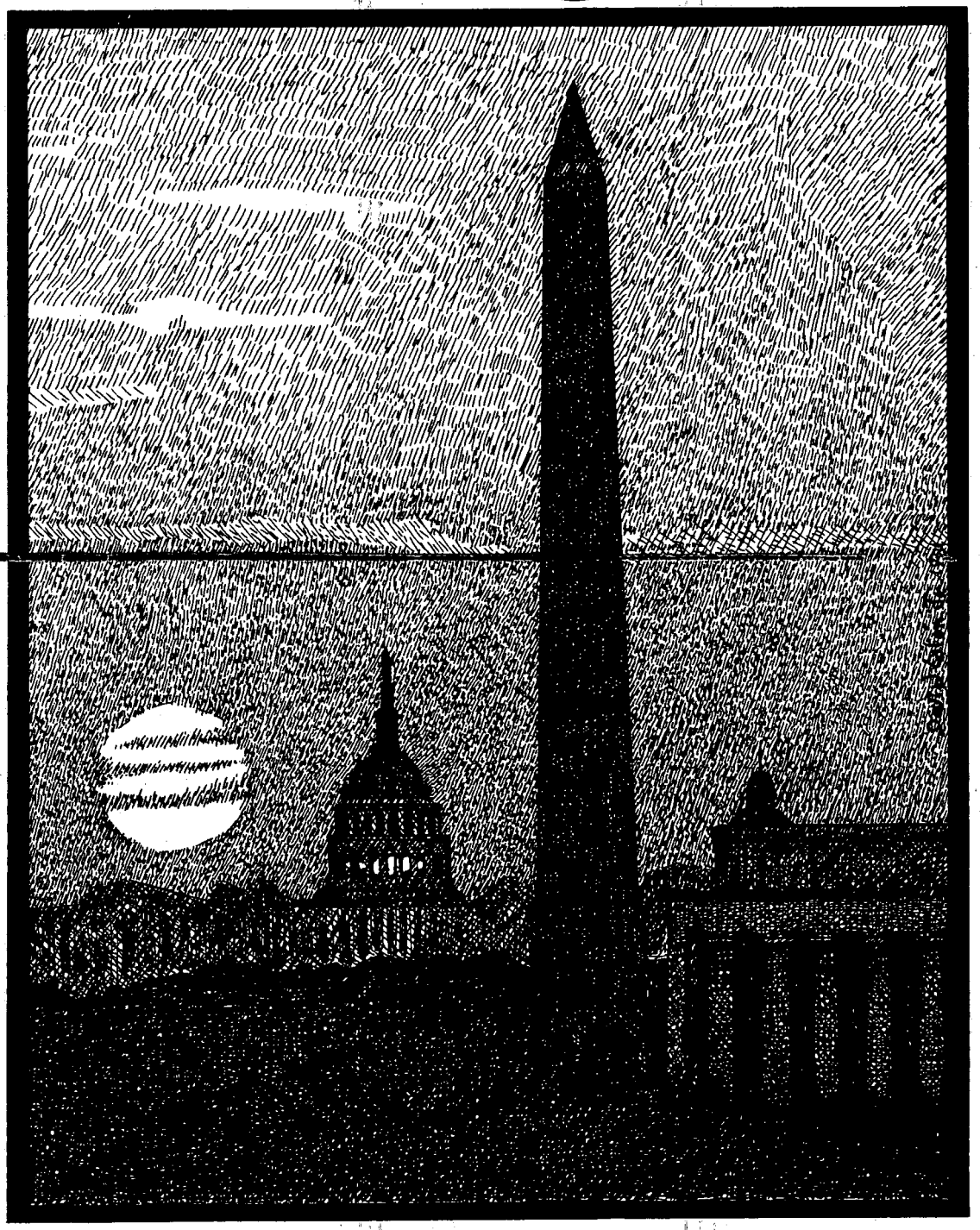
U.S. Department of Energy

May 1981

Solar Energy Education



MASTER

Solar Solutions

READER Part III

Release for Announcement i
Energy Research Abstracts

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The Solar Energy Education Curriculum

The booklet in your hands is just one part of a series. The Solar Energy Education materials include

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For more information on the Solar Energy Education curriculum, contact

Solar Energy Project
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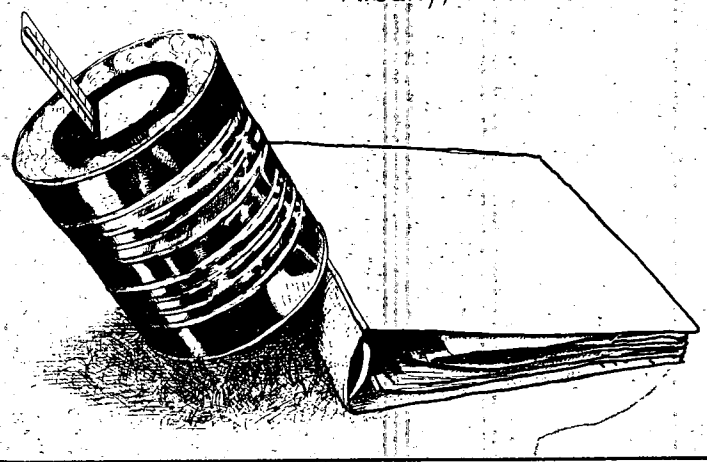

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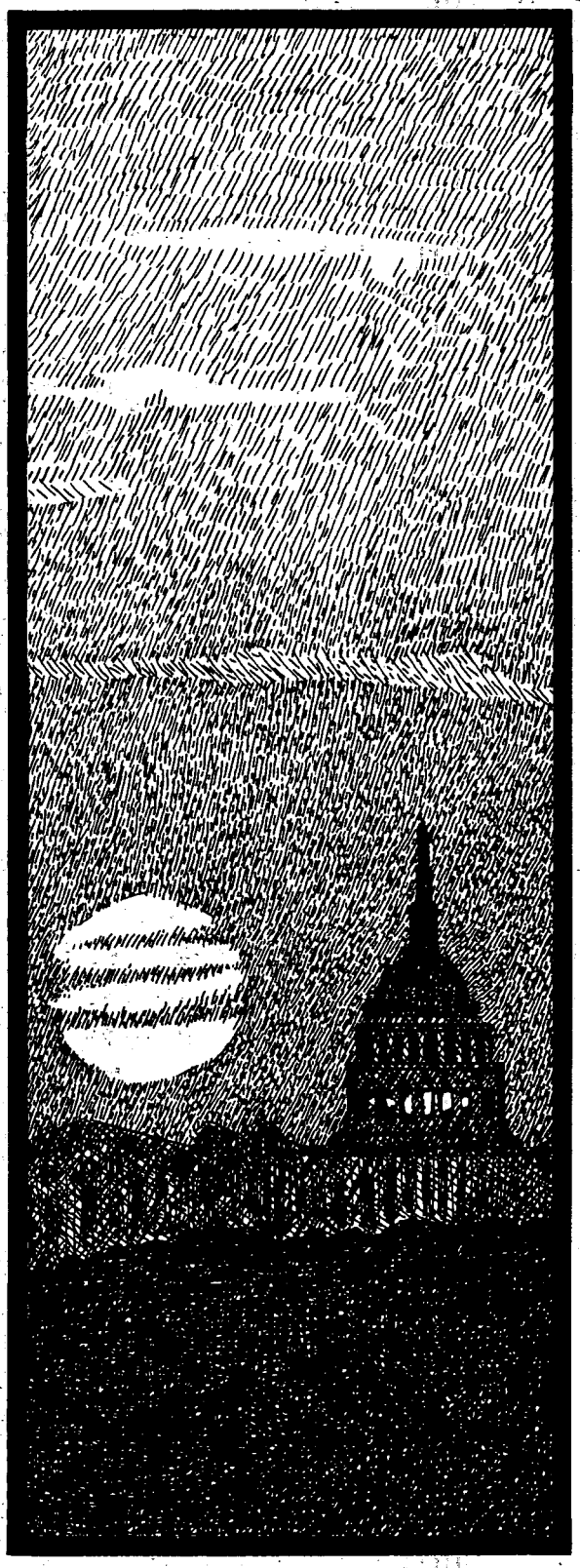
Solar Energy Education



READER
Part III
Solar Solutions

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Introduction

The energy picture is changing too fast to be captured in books. Before the ink is dry new experiments, technologies, and legislation make some of a new book's information obsolete. Magazines and newspapers are better able to keep pace with rapid change, and it is on these media that the well-informed energy consumer depends.

In your hands is a collection of magazine articles selected to help you focus on an important part of the changing energy picture: solar energy. This booklet is Part III of the Solar Energy Reader, a series of four booklets:

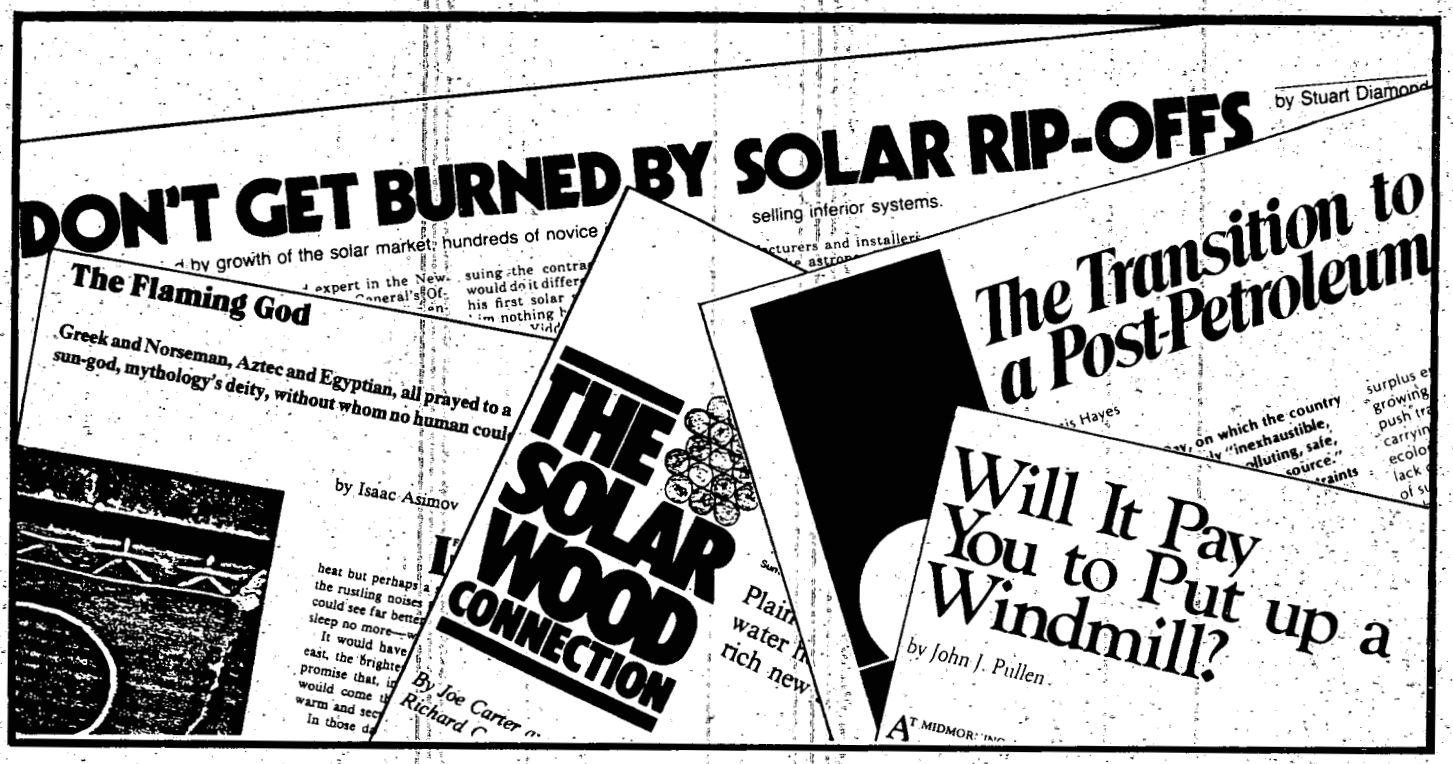
I. Energy, Society, and the Sun
(General readings on philosophical, political, and legal topics)

II. Sun Story
(Solar history, mythology, and poetry)

III. Solar Solutions
(Articles on the many applications of solar energy: heat, photovoltaics, wind, hydro, biomass, etc.)

IV. Sun Schooling
(Easy readings on energy and articles about teaching solar)

The bibliography at the end of this booklet will guide you to articles that time and space would not allow us to include here. But the magazines represented in the bibliography and the reader are continually publishing new reports on recent developments. The person who wants to be well-informed about the changing energy picture will follow these publications regularly.



The Readings

PS Energy House

We can't all build the home of our dreams. But most of us can benefit from some of the energy ideas incorporated into Ralph Merrill's dream house, and at the same time catch a glimpse of how future houses could be built.

PS energy house

packed with energy-saving ideas, materials, and devices you can use in your home

A PS reader/architect builds his low-energy solar home

By RICHARD STEPLER
DRAWINGS BY ROBERT RITTER

BOUNTIFUL, UTAH

Suppose you reviewed every issue of POPULAR SCIENCE published in the past seven years for energy-saving ideas. Then suppose you designed a house that incorporated nearly every one of them. That's what Ralph Merrill, Salt Lake City-based architect and loyal PS reader, did.

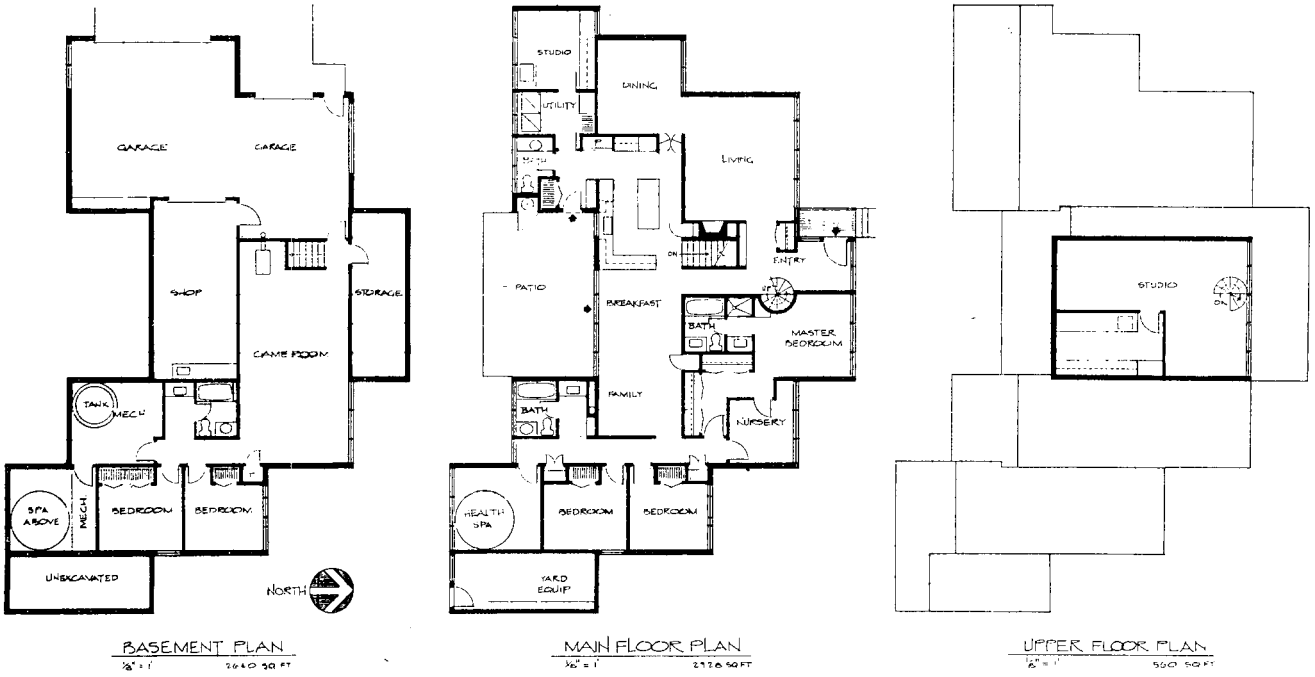
And Merrill's house is no pipe dream. His cedar-clad "Idea House '80" nestles into a scrub-oak-covered mountainside near here, with a spectacular view of the Great Salt Lake. To the north, snow-covered mountains soar to 10,000 feet.

I had flown into Salt Lake City for a look at Merrill's state-of-the-art home. What first struck me was that the house didn't look its size. Merrill has designed it in 12-foot modules (see photo) to minimize the bulk of a structure that includes, among other amenities, a three-car garage, workshop, five bedrooms and nursery, indoor spa, and a home office and darkroom for the resident architect. It adds up to more than 6000 square feet of living space for an active family of six.

On the way to the home site, Merrill filled me in on some of the home's state-of-the-art features he gleaned from the pages of POPULAR SCIENCE:

- The house is carefully sited so that it's shielded from winter winds, yet open to the south. The basement level is partially earth-bermed, and windows are concentrated on the south facade. (These design techniques were outlined in "Solar Architecture," PS, July '76.)
- It's built on a wood foundation of treated lumber and plywood, assembled with Senco stainless-steel fasteners, saving both energy and labor. (PS first covered this innovation in the Sept. '72 issue.)
- Exterior walls are framed with 2×6's, placed 24 inches on center.

Idea House '80: three levels of living space for a large family



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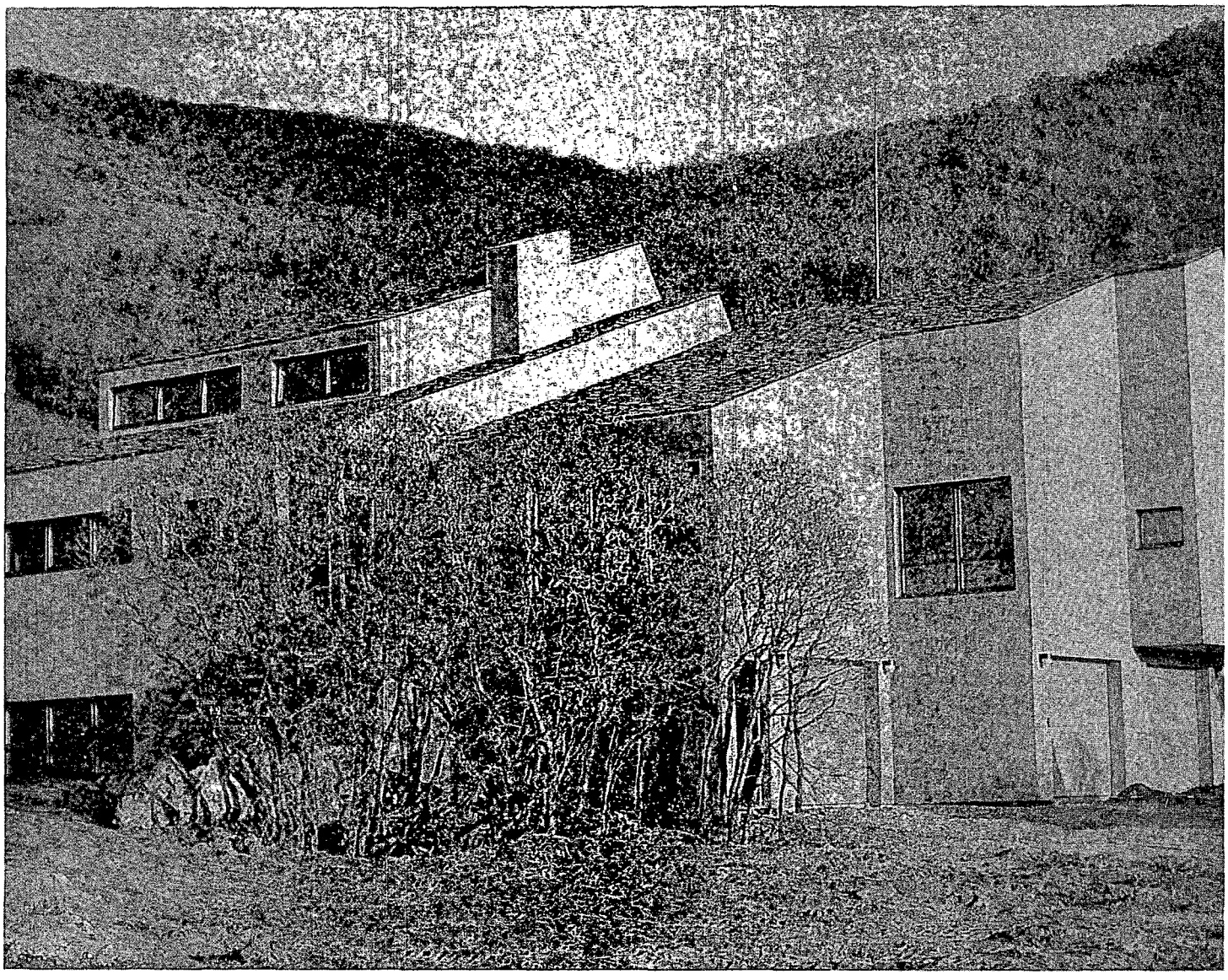

Cedar siding is dramatically lighted by setting sun as house neared completion in spring. Note that no windows are placed on western exposure, and windows on north, with spectacular view of Great Salt Lake, are triple-glazed, small in size.

They're filled with fiberglass batts and sheathed with one-inch-thick Styrofoam under the cedar siding, as detailed in our Sept. '76 issue.

- Cathedral ceilings get the same treatment, except that fiberglass batts are thicker for a total insulating value of R-43.
- The home's solar heating system is a first: Israeli-made "free-flow" collectors that use a light oil as a heat-transfer medium are the first to be installed in the United States. Architect Merrill read about these high-efficiency, low-cost collectors in the April '79 issue. (See the end of this article for a complete PS bibliography.)

The careful planning Merrill put into the project is evident everywhere. Take windows, for example:

- They're triple-glazed in sedentary areas (bedrooms, living room) and double-glazed in utility and activity areas (kitchen, laundry, halls).
- They're located at eye level—not near the ceiling where the air is warmer.
- Most window area is on the south side for passive solar gain. Roof overhangs shade them from high summer sun angles.
- Windows on the north, where there is a view, are small.
- No windows are placed on the east or west, to reduce solar heat gain in summer.
- Total window area is 12 percent of floor area to minimize heat loss.

Merrill's heating system has multiple backup capabilities. Solar heat from the collectors is stored in an 1100-gallon water tank via a heat exchanger. Another heat exchanger preheats drinking water on its way to a Rheem Energy Miser water heater. When solar heat is exhausted (Merrill is figuring on a 70 percent solar contribution), a heat pump takes over down to 32 degrees F. Below that, two high-efficiency Carrier furnaces with pilotless ignition carry the load. One furnace handles the basement level; a larger one heats the upper levels. The mechanical room is insulated from the rest of the house and is vented to provide outside combustion air. Additionally, there's a separate furnace (from Williams Furnace Co.) that keeps the garage at 55 degrees. It's more efficient than "stealing" heat from the house to keep the garage warm, and complies with local codes that prohibit return air from garages.

A Hydroheat wood-burning stove in the family room adds heat to the solar storage tank by means of a heat-exchange loop. "The solar tank is a central battery for two sources of heat," explains Merrill. And a Temco prefabricated fireplace in the living room contributes heat, as well. It's equipped with air-circulating ducts, outside combustion air, and glass doors.

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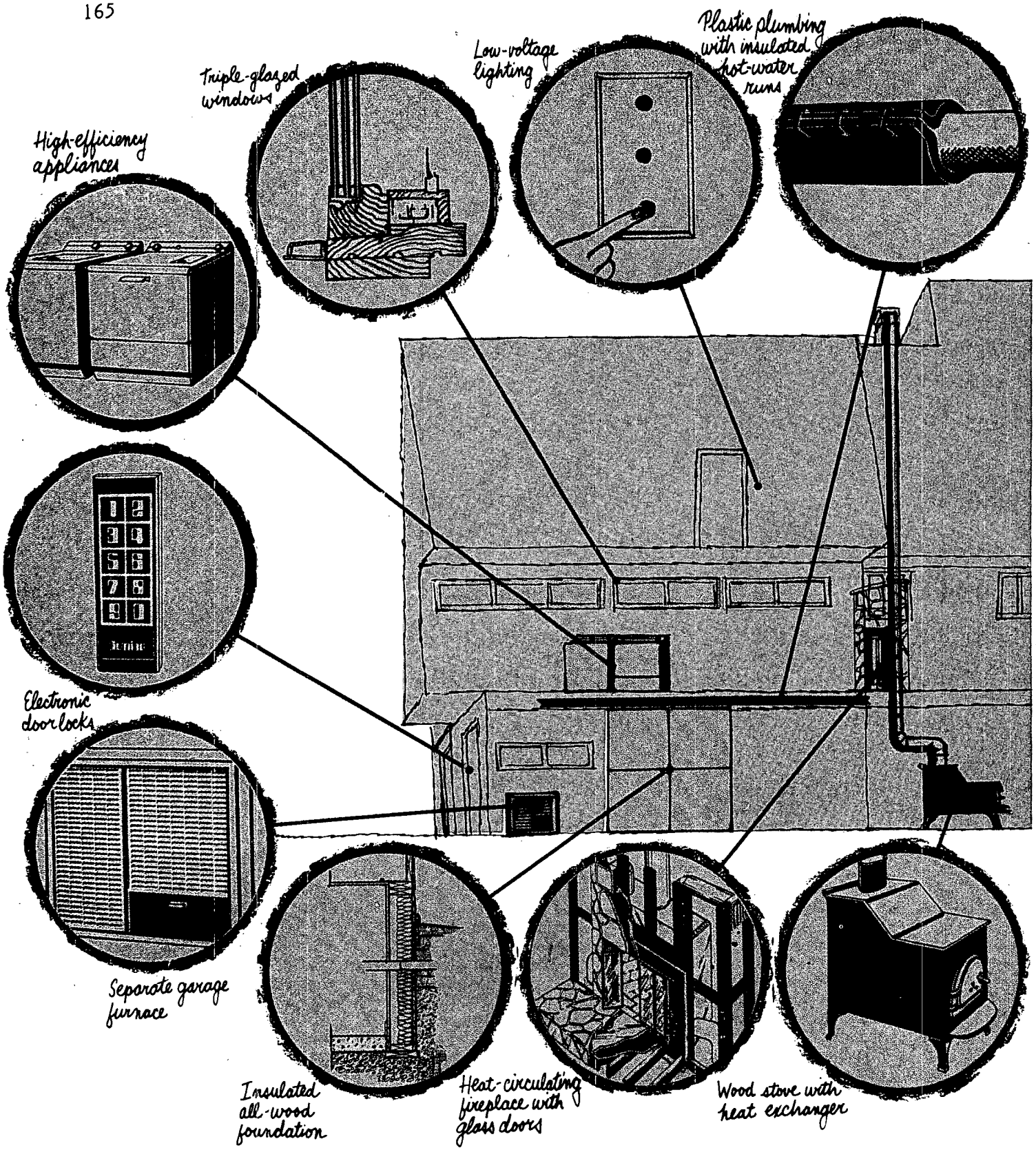
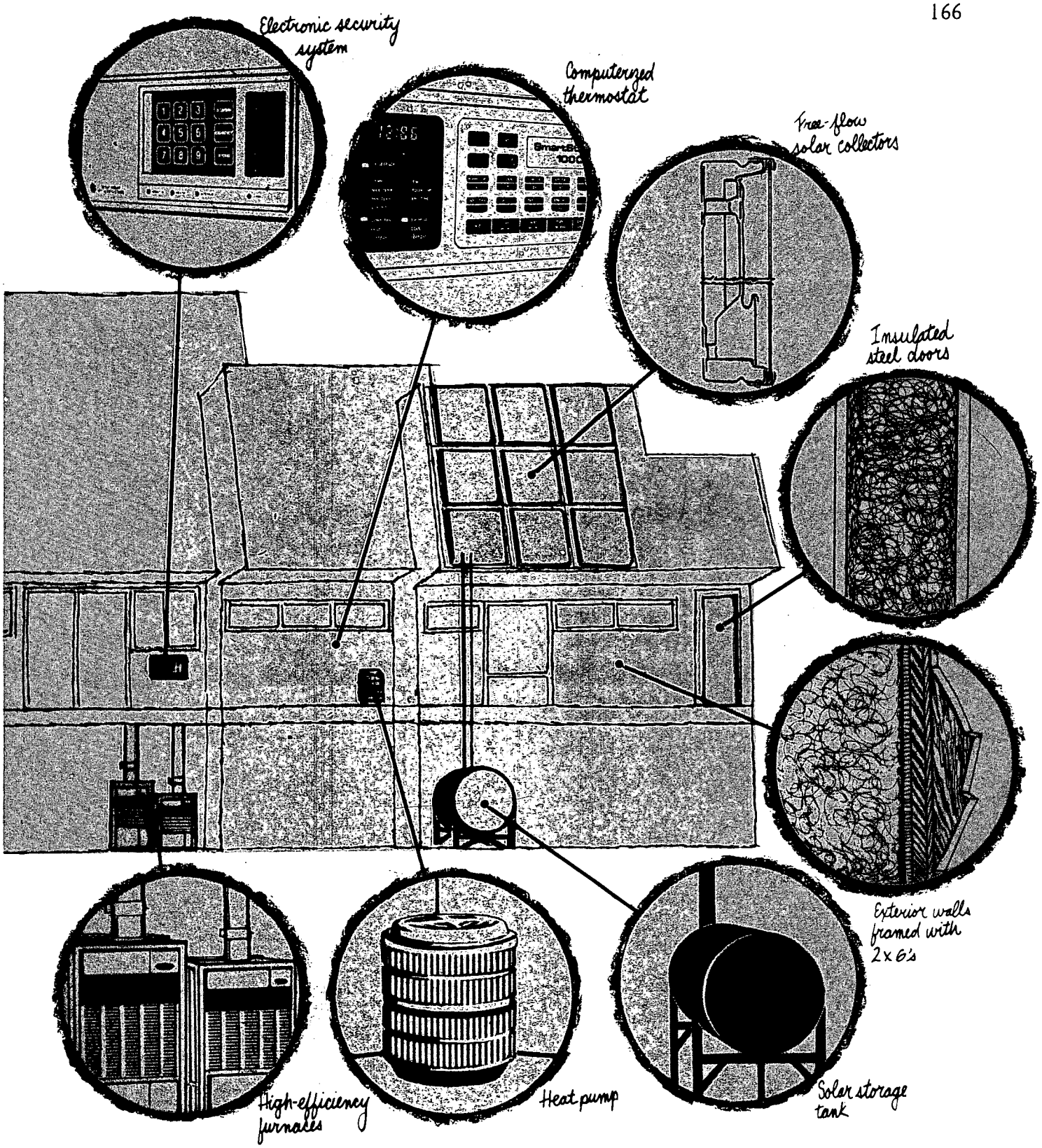


The home is carefully sealed against infiltration. Dow's Styrofoam t&g insulating sheathing is applied to exterior walls, cathedral ceilings, and the all-wood foundation. Exterior doors (steel with insulated core from Lee Haven) have magnetic weatherstripping. Windows from Weathershield are double weatherstripped. Insulating foam (Polycell II) was injected into shim spaces around doors and windows, and into holes in the top and sill plates of exterior walls.

Humidifiers make the home more comfortable at lower temperature settings, and electronic air cleaners ensure that indoor air stays pollution-free. (Watch for a major article on indoor-air quality in an upcoming PS—Merrill anticipated *us* on that one.)

In summer, excess solar heat is "dumped" into the home's indoor Great Western Spa whirlpool. (Solar heats all domestic water in summer months.) And the heat pump provides air conditioning.

Merrill chose the other components in the house for energy efficiency, security, or for their convenience: energy-efficient appliances from Whirl-



pool; keyless electronic locks (Domino and Essex) for garage and exterior doors; an energy monitoring computer; solid-state alarm system (Silent Knight) for fire and burglary; computerized thermostat (SmartStat) for temperature setback/setups during the heating and cooling seasons; attic fans (Pryne) to cut cooling load; a solid-state, low-voltage lighting system (Electro Controls) that permits programming, grouping, timing, and dimming of fixtures in different combinations; plastic plumbing with insulated hot-water runs; and more. (For a complete list of products and sources, see the end of this article.)

According to Merrill, there are only three energy-saving features he *didn't* incorporate in Idea House '80.

- He didn't use optimum exterior-skin-to-volume ratio—the sphere being the perfect shape with maximum volume to minimum skin. He chose the modular design for siting reasons and to minimize the bulk of the house. "The amount of insulation we used compensates for this," adds Merrill.
- There are no air-lock vestibules

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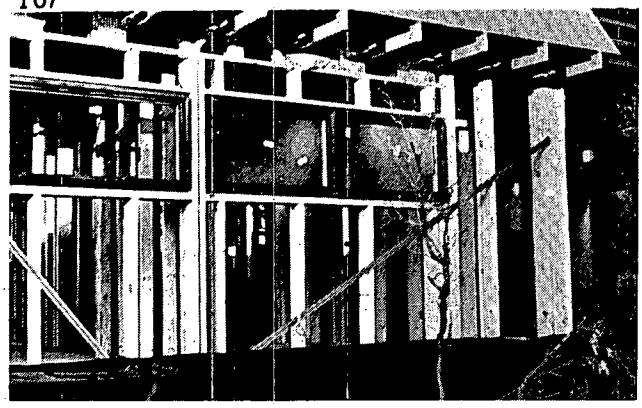

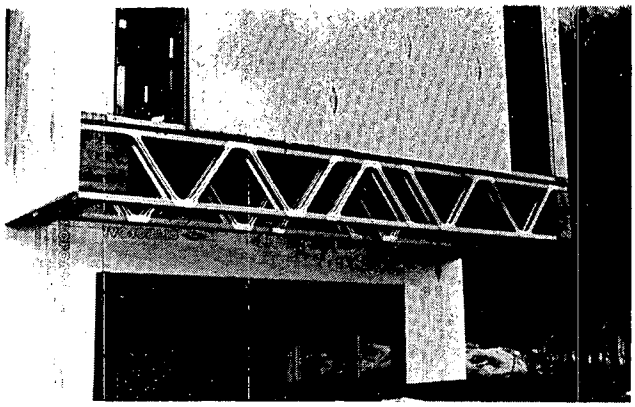

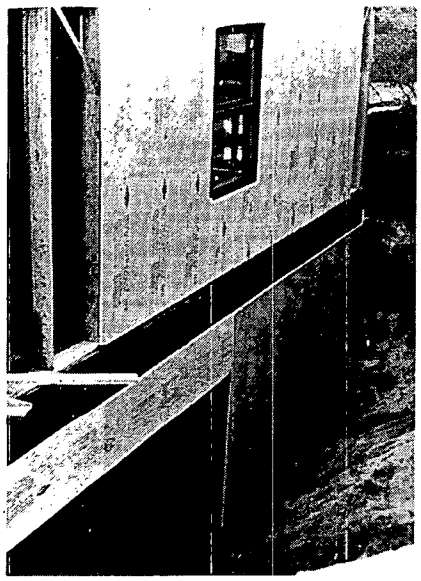

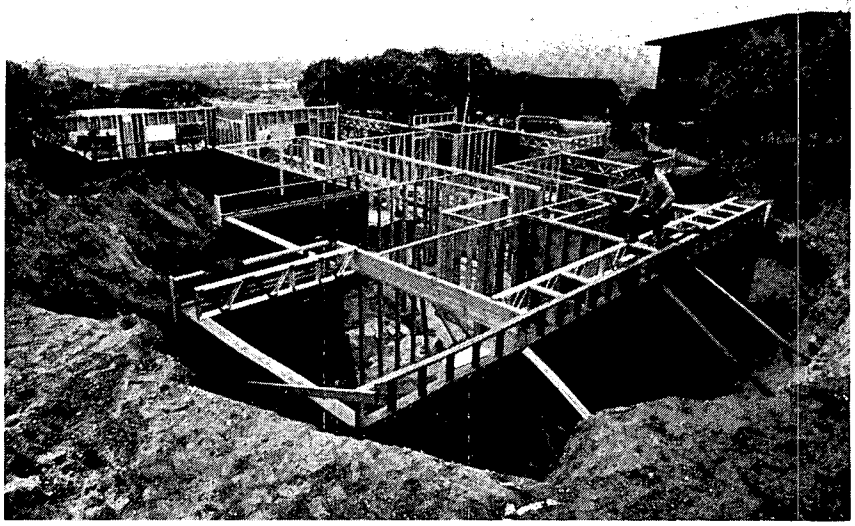

Construction details: Exterior walls are framed with 2×6's, 24 in. on center (top left). Windbracing (diagonal metal straps) is needed because insulating sheathing is not structural. Triple-glazed windows are placed at eye level. Top right photo shows prefabricated trusses used throughout structure. All-Weather wood foundation is nearly complete in lower right photo. Styrofoam t&g sheathing was applied to skin of house, down to basement footings (lower left).

[PS, Sept. '75]. "Most traffic will go through the garage," says Merrill.

- There's no "warm room"—an activity core that's insulated from the rest of the house [PS, Nov. '77]. Merrill feels the home's passive features make this feature unnecessary.

Aside from energy conservation, Idea House '80's theme is wood. Merrill has used it throughout, from the all-wood foundation to the cedar shakes used on the roof. Tongue-and-groove cedar siding covers the exterior, and it's used as feature or accent wall covering in most rooms.

Want more information on Idea House '80? A set of drawings plus specifications is $75 from Ralph Merrill, architect, 3617 South 400 East, Bountiful, Utah 84010. PS

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Sources of products in Idea House '80

American Standard Inc., Box 2003, New Brunswick NJ 08903; **American Wood Council**, 1619 Massachusetts Ave., N.W., Washington DC 20036 (All-Weather wood foundation); **Autotronics**, 1399 Executive Dr. West, Richardson TX 75081 (thermostat); **Carrier Corp.**, Carrier Pkwy., Syracuse NY 13221 (gas furnaces, heat pump, solar package, humidifier, air cleaners); **City Investing Co.**, Rheem-Ruud Div., 76005 Kedzie Ave., Chicago IL 60652 (water heater); **Columns, Inc.**, Pearland TX 77581 (spiral stairway); **Congoleum**, 195 Belgrove Dr., Kearny NJ 07032 (sheet-vinyl flooring); **Craftsman/St. Charles Kitchens**, 2200 South Main, Salt Lake City UT 84115 (kitchen cabinets); **Domino Engineering Corp.**, Box 376, Taylorville IL 62568 (electronic garage-door lock); **Dow Chemical Co.**, Midland MI 48640 (Styrofoam insulating sheathing); **Dupont Energy Management Corp.**, 10730 Composite Dr., Dallas TX 75220 (energy monitor); **Electro Controls, Inc.**, 2975 S. 300 West, Salt Lake City UT 84115 (low-voltage lighting system); **Emerson Electric Co.**, Payne and Rittenhouse Div., Honeyoye Falls NY 14472 (intercom, burglar alarm, door chimes, smoke detectors, and exhaust fans for kitchen and attic); **Essex Transducers**, 1130 Mark Ave., Carpinteria CA 93013 (solid-state door locks); **Forms and Surfaces**, Box 5215, Santa Barbara CA 93108 (carved panels, hardware); **Halo Lighting**, 400 Busse Rd., Elk Grove Village IL 60007 (lighting fixtures); **Hydroheat Div.**, Ridgeway Steel Fabricators, Box 382, Ridgeway PA 15853 (wood stove); **Iron-A-Way, Inc.**, 220 W. Jackson, Morton IL 61550 (built-in ironing board); **Koor Metals Ltd.**, Box 300, 58100 Holon, Israel (solar collectors); **Laminating Services, Inc.**, 4700 Robards La., Louisville KY 40218 (wood veneers); **Microtimer Controls**, 1050 E. Duane, Sunnyvale CA 94068 (Vigilite lighting control); **E.C. Miller Cedar Lumber Co.**, Box 750, Aberdeen WA 98520 (cedar siding); **Monarch Marshall**, Box 2041, San Angelo TX 76901 (ceramic tile); **Nordic Controls**, 155 N. Van Nortwick Ave., Batavia IL 60510 (Nola controller); **Nuclear Systems, Inc.**, 2255 Ted Dunham Ave., Baton Rouge LA 70821 (SmartStat solid-state thermostat); **Owens-Corning**, Fiberglass Tower, Toledo OH 43659 (fiberglass insulation); **Robert H. Peterson Co.**, 2835 Sierra Grande St., Pasadena CA 91107 (gas log); **Prest-On Clip Co.**, Box 156, Libertyville IL 60048 (drywall fasteners); **Reynolds Metals**, Arch. & Bldg. Products Div., Richmond VA 23261 (aluminum gutters); **Rubatex Corp.**, Bedford VA 24523 (foam-rubber pipe insulation); **Schulte Corp.**, 11450 Grooms Rd., Cincinnati OH 45242 (ventilated shelving for closets); **Senco Products, Inc.**, Cincinnati OH 45244 (fasteners for wood foundation); **Silent Knight**, 1700 Freeway Blvd., Minneapolis MN 55430 (security system); **Temtex Products, Inc.**, Box 1184, Nashville TN 37202 (Temco prefabricated fireplace); **Thermasol**, Thermasol Plaza, Leonia NJ 07605 (steam-generating unit); **Truswal System West, Inc.**, 3850 East Miraloma Ave., Anaheim CA 92806 (wood/metal trusses); **Jim Walter Doors**, Box 22703, Tampa FL 33622 (garage doors); **Weather Shield Mfg., Inc.**, 4604 Medford Dr., Loveland CO (windows and doors); **Western Products Co.**, Box 803, Union City CA 94587 (polybutylene pipe and fittings); **Whirlpool Corp.**, Benton Harbor MI 49022 (high-efficiency appliances: cooktop, microwave/conventional oven, trash compactor, dishwasher, refrigerator, washer and dryer); **Wilhold Glues**, 8707 Millergrove Dr., Santa Fe Springs CA 90670 (construction adhesive and butyl sealer for wood foundation); **Williams Furnace Co.**, 14960 Firestone Blvd., La Mirada CA 90638 (garage furnace).

A Home-Built Solar Heater

If the "gas-guzzler" in your life is a house instead of a car, here is help in the form of a simple, affordable add-on. If you are thinking of building this solar heater, be sure to use a glazing that won't deteriorate with long exposure to heat and sunlight.

A Home-Built Solar Heater

It works, it's simple and it can actually cut your winter heating bills by 25%

by Roger N. Perry Jr.

Prof. Bruce McQuarrie got into his car one cold winter noon and sat for a moment enjoying the warmth created by the sun's shining through the glass all morning. "Why not capture some of this heat at home," he mused, heading to his job as mathematics professor at Worcester Polytechnic Institute at Worcester, Mass.

Not long after that, the sun was helping heat his home, working on the same simple principle. Prof. McQuarrie's device was a simple lean-to heater, which reduced his heating bill by about 25% and which he calculated would pay for itself in two or three years. That was three years ago when heating oil cost less than half what it does today.

The heater he built consisted of an insulated triangular plywood box placed against the wall of his house. The sloping face, at an angle to take full advantage of the winter sun, consisted of two layers of translucent plastic sheets. The box covered one window, which he opened during the day to let the heat into the house. An open cellar window allowed cool air to enter the box. In the normal flow of air through the house, the air was recirculated.

The following year, three students conducted a project based on his original design. They determined that about 25% of the homes in several areas surveyed could take advantage of this type of solar heater. The main requirement was a south-facing wall without winter shade from nearby buildings or evergreen trees.

They evaluated the heating characteristics of McQuarrie's device. They investigated alternate materials. Eventually, they drew up plans that could be used by the average home handyman to build his own solar device.

Last fall the idea was picked up by the Worcester Labor Co-op, which provides free labor to qualifying homeowners in such areas as plumbing, wiring and carpentry. Over the winter the co-op built five of the passive solar heaters for individuals who met the agency's age, disability or income level requirements. The homeowners paid for the materials; the co-op provided the labor with CETA funding. All five units showed they can help reduce heating costs.

Douglas Counts, the co-op designer, head carpenter and construction boss, finds each new installation a challenge. "There's room for experimentation with each one. While I'm building one, I think of variations I'm going to try on the next one.

"Finding a cellar window right under a proper first floor window doesn't usually happen. On some of the heaters, we solved that by running a duct around the corner of the house to a cellar window. On the last one, we built on a concrete slab with no cellar window within reasonable distance. In that case, we tried running it by opening both the top and the bottom of the first floor window. In all cases, the heaters worked just about the same," he reports.

"The temperature measurements on the last one we built are typical. At 10 a.m., the temperature inside the heater was 110° F., while the outside temperature at the time was 20°. In the living room, which was at the far end of the house from the heater, the temperature was 72° F., although the thermostat was set at 64° F. A small fan helped circulate the air through the house."

The heaters built so far have been permanently attached to the house. Counts is now building a portable one, which can be disassembled for moving or summer storage. This would be ideal for the tenant who rents. It will also allow normal use of the window in summer.

Since the cost of the plastic panels is about half the cost of the whole structure, he's looking at ways to use old storm windows, which are often available at little or no cost.

Another advantage of the portable heater is that if the house doesn't face south, the heater could be set to catch the sun squarely with an insulated duct carrying the heat around a small bend. Also in some areas, building codes require footing below frost line when installing a permanent addition; with a portable heater, this requirement could often be waived.

"The basic design works," says Counts. "However, I'd encourage anyone who plans to build one to be willing to experiment. Adding a layer of bricks on the bottom should store up enough heat to give an extra hour's heat in the evening. Adding black painted metal objects inside would help, too. On the last heater we built, we used corrugated aluminum sheets painted black and installed against the house to help absorb heat.

"By making the heater larger, or building it with a hip roof, there'd be room to walk inside it. If you were going to use it as a greenhouse, you'd need some roof vents to prevent cooking the plants at mid-day. However, by the time you were ready to start plants, the winter heating season would be about over. You'd also need some supplementary heat in case the night temperature fell below freezing, something like a small electric heater."

How It's Built

The solar heater consists of a floor and two triangular end walls of plywood nailed to both sides of 2x4 studding on 16" centers. The space between contains insulation. The collector surface, through which the sun shines, consists of two layers of special plastic sheeting separated by an air space.

An access door on one end wall permits entry for maintenance, such as repainting, caulking, etc. A plywood lid folds over the face of the heater in warm weather. When open, this lid helps reflect the winter sun into the heater.

A professional carpenter or an experienced handyman should have no trouble adapting the concept into an actual design for a specific location.

Step 1. Determine the latitude of your home to the nearest even degree. Most highway maps indicate latitude. As a general rule, the slope of the collector face with the horizontal will be an angle equal to the latitude plus 15°.

Step 2. Determine where the heater will be placed on the south-facing wall. The type of installation shown in Fig. I does not interfere with normal use of the first floor window. (It does require cutting an opening through the wall under the window to admit the heated air.) The installation in Fig. II simplifies

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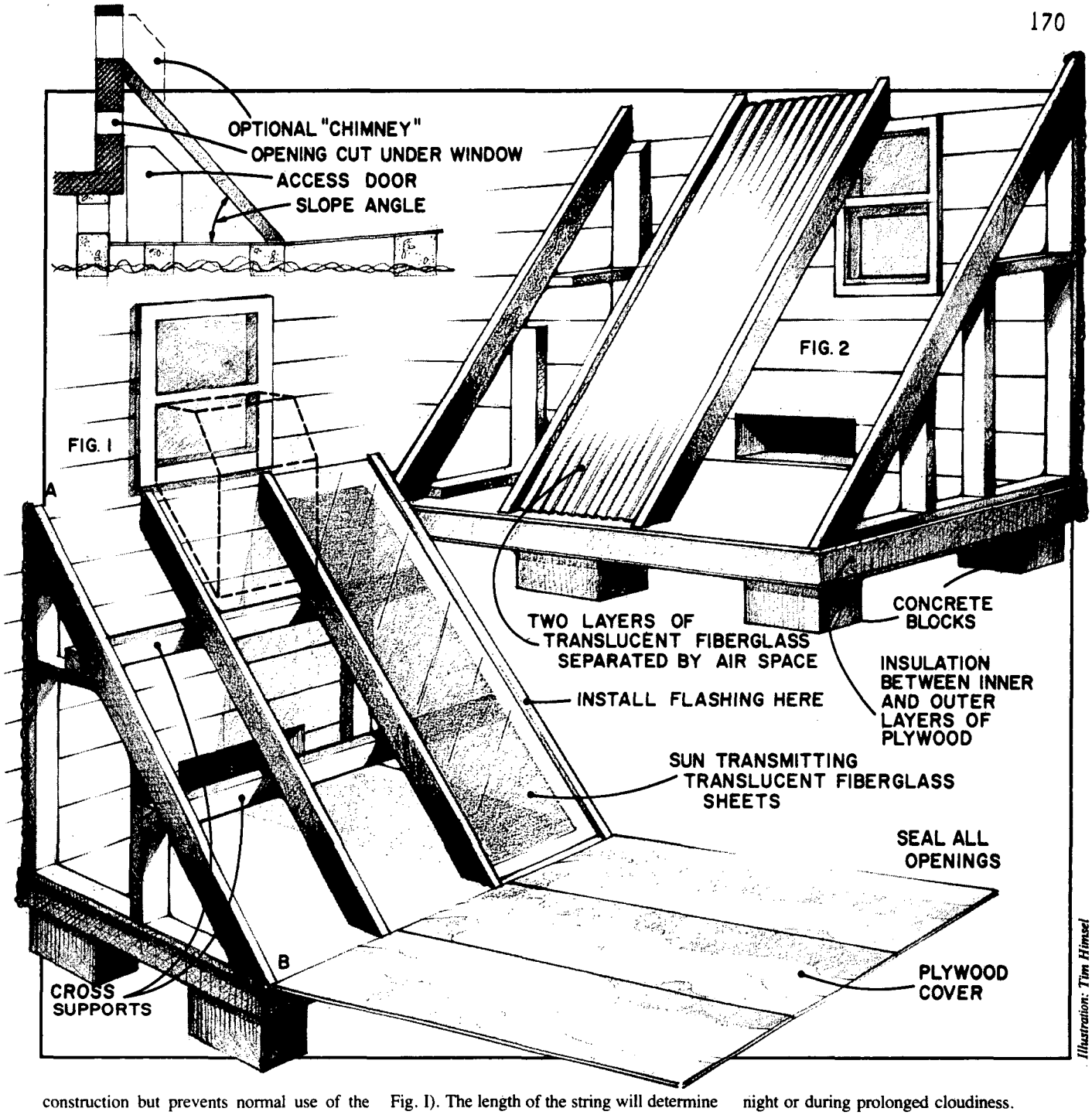


Illustration: Tim Himsel

construction but prevents normal use of the window with the heater installed.

If you prefer not to cut through the wall, a detachable plywood "chimney" (which can be removed after the heating season) can be used to convey the heated air into the house through the lower half of the window. This "chimney" should be insulated and sealed around all edges to minimize heat loss.

Step 3. Determine the exact position and size of the sloping studs, which will support the translucent fiberglass sheets, before ordering the sheets. On two concrete blocks, set a 2x4 on edge to simulate the position of the level floor. From the height on the outside wall of the house — which will mark the upper edge of the heater — stretch a piece of string to form the desired slope angle with the base. (Point A to point B in Fig. I). The length of the string will determine the length of the sloping studs and of the translucent sheets you'll need. The horizontal distance of the string from the cellar will determine one of the base dimensions. The fiberglass sheets are available in pre-packaged rolls, 4′ wide by 8, 10, 25 and 50′ lengths. One 50′ roll should be enough to make a heater 12′ long with a sloping face of 8′, such as shown in Fig. I. To avoid waste, consider using standard dimensions in determining actual construction details.

Step 4. If you decide to cut an opening under the window rather than use a "chimney," do this next. The opening should have about the same area as the basement window. Finish off the opening neatly, inside and out. Provide a cover on the inside to prevent cold air leakage at night or during prolonged cloudiness.

Step 5. Construct a base of ⅜″ plywood or particle board made for outdoor use. Select inexpensive grades. Nail the plywood to 2x4's on 16″ centers and then turn the base over and level it on concrete blocks, shimming until it's level and evenly supported. Install roll insulation and nail on plywood flooring. Nail vertical studs to the side of the house to support a back wall of plywood. Insulate, particularly along basement wall to prevent heat loss. Nail on the plywood back wall.

Step 6. Install sloping 2x4 supports. Space them to the exact width of the fiberglass sheets to eliminate cutting the sheets. Thus, the length of the base will be 12′ plus the thickness of four 2x4s. Nail in the end wall studding, providing for an access door at one end. Nail the outside

plywood panel to the studding. Install roll insulation between studs. Nail on the inside plywood panels.

Step 7. Install flashing under the shingles or clapboards on the house wall at the top of the heater to prevent water leaks.

Step 8. Nail 1x1" strips to the lower edges of the sloping studs to support inner fiberglass panels. Install the panels and caulk the edges with silicone sealant. If you use the "chimney" method, build and install it before installing the fiberglass sheets. Sides may be made similar to sidewalls (with insulation between layers of plywood). The top surface may be made of fiberglass sheets separated by an air space.

Step 9. Nail a second set of strips to sloping 2x4s to support outer fiberglass panel so that panel is flush with upper surface. Caulk edges.

Step 10. Caulk flashing at upper edge of panels to prevent leakage. Nail 1x3" strips along edges of sloping 2x4s to finish off the sloping face.

Step 11. Make a plywood cover to fit between 1x3" strips when it's closed over the heater in summer. Install hinges so it can be opened for the winter heating season.

Step 12. Make and install the access door. This should be constructed like the end walls, with insulation between both faces.

Step 13. Paint inside plywood surfaces with flat black paint to aid in absorbing heat. Do not paint the house wall. Paint the inner surface white to reflect sunlight. Paint the outside to match the house.

Building Tips

This heater works best when the basement window and the first floor opening are diagonally opposite, since air must travel farther and stay in the heater longer before entering the house.

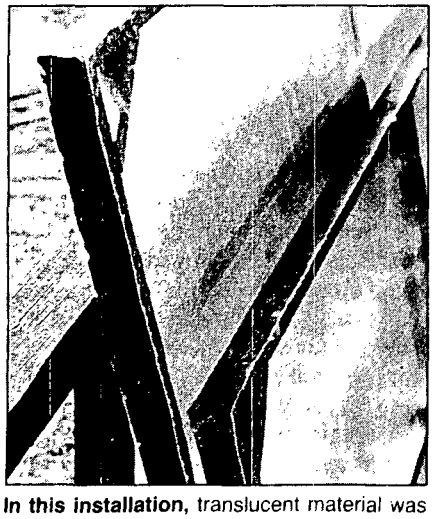
Here are other tips to consider:

- To eliminate moisture produced by condensation between the fiberglass sheets, drill small holes at the bottom of each section for drainage.
- Roll insulation should be R-11 foil-faced fiberglass insulation. Install it with the foil toward the inside of the heater.
- Since fiberglass sheets are flexible, install some type of cross supports between the 2x4s. You can use wooden dowels or cross strips of wood. Place them at the one-third and two-thirds points on the sloping 2x4s.
- Clearance above ground is important to prevent the wood from rotting. Concrete blocks provide about the right spacing.
- Clean the surface of the fiberglass sheets as needed. Dirt and snow obstruct the light and cut down heater efficiency. □

Wood frame for heater floor is built first, filled with insulation, finished with plywood flooring top and bottom.

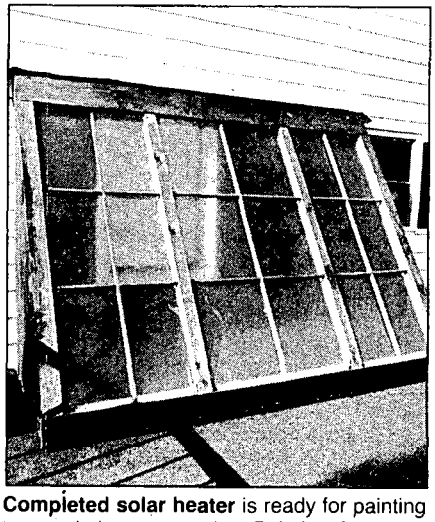
Angle of studs to horizontal plane should equal the home's latitude plus 15°. Studs are spaced to exact width of fiberglass sheets.

Strips are nailed to bottom edges of 2x4s to support fiberglass panels. Here, felt weather stripping is applied to insure close fit.



In this installation, translucent material was nailed directly to frames that were then attached to sloping studs.

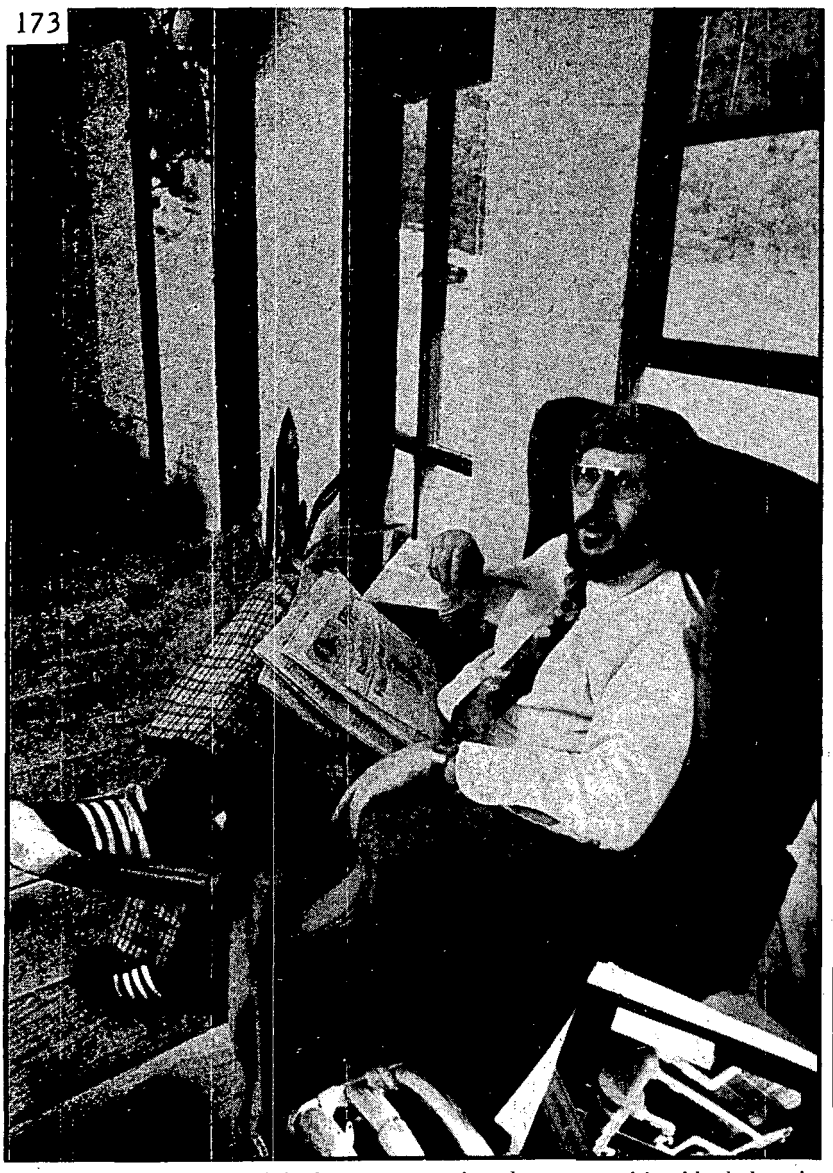
The 1x3 strips nailed along edges of 2x4s cover panel joints, protect against leakage of water and wind, as does flashing.



Completed solar heater is ready for painting to match house exterior. Painting floor and inside wall black will help capture more heat.

Virginia Is for Louvers

Here is the genius of simplicity and the simplicity of genius. This owner-builder has taken the traditional solar mass wall, turned it on its ear, broken it into sections, and angled the sections. Read on and see how it works.



Above: *The west sides of the louvers are painted a sun-catching black, but the angle of the masonry columns prevents the dark color from being seen easily from the home's living spaces. Unlike drum walls or ordinary mass walls, there are few aesthetic drawbacks to masonry louvers.*

This owner-built home has something new under the sun

Virginia Is For Louvers

by Frederic S. Langa

Ferrum, Virginia, doesn't look like a hotbed of solar inventiveness. To a hurried traveler, it's just a quiet college community located in the eastern foothills of the Blue Ridge Mountains about an hour's drive from Roanoke. But if you turn off the main street that bisects the town and follow the winding road that runs past the college, you'll enter the Whetstone Branch River Valley, and there on your left will be Jim Bier's handmade house; the first in the world heated by huge masonry louvers.

These vertical louvers are an ingenious takeoff on ordinary solar heated mass walls. With just one basic alteration, Jim found a way to avoid almost every major drawback of conventional solar walls, while retaining all the advantages. "When energy and building costs get high enough," he told me, "you get really inventive."

One basic design alteration eliminates almost all the drawbacks to standard mass walls, while retaining all the advantages.

Like other solar wall designs, Jim's giant louvers sit in the sun behind south-facing glass and get warm during the day to heat the house at night. (In a way, *all* solar heating is simply "mass under glass.") Construction is fairly standard, using 8 × 12 × 16-inch cinder blocks packed with sand. And as you might expect, the sunward sides of the louvers are painted black for maximum heat absorption. The similarities end there.

Most solar walls heat in two steps: The sun shines through glass to warm thousands of pounds of mass, usually poured concrete or drums of water. Once the mass is warm, heat begins flowing into the home's living areas. The interval between the time when solar heat is first collected and the time when it's finally delivered is called *thermal lag*. Thermal lag is terrific because it means your solar

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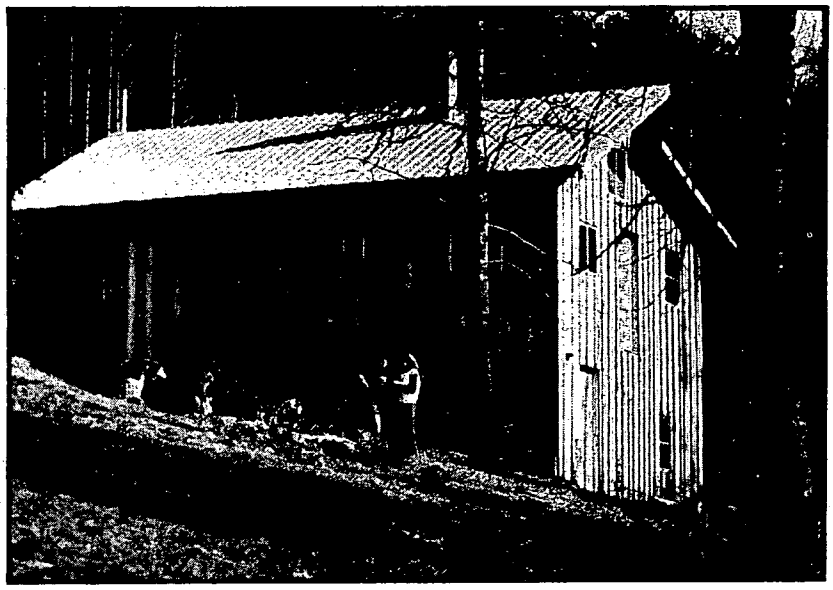
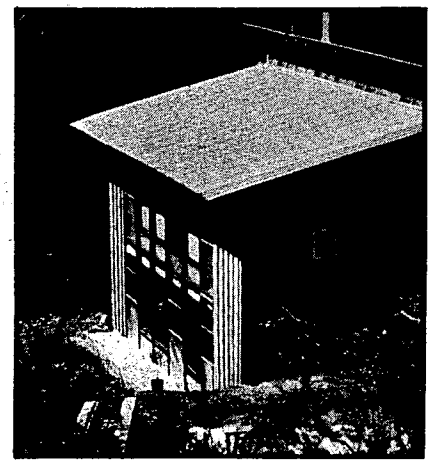


Above: *Like all sensible solar architecture, the north side of Jim's house presents no doors and few heat-leaking windows to cold winter winds. The home's west side (to the right in this picture) has more windows, to allow the afternoon sun to warm to the interior. (Note the window at the roof's peak. This and a twin vent on the east side are opened in summer to provide ample natural ventilation.)*

Below: *The combination of rough-sawn native poplar siding and expanse of south-facing glass on Jim Bier's home create an attractive marriage of traditional and modern, blending well with its Blue Ridge Mountain setting. Behind the glass are the solar louvers. Above, a clerestory roof admits extra light into the house and minimizes the need for artificial lighting.*



wall pours out its heat at night, when you need it most. But next morning the wall is busy re-charging. You don't get any early morning solar warmth; the wall gets it all.

Jim's wall eliminates that drawback. Instead of building a solar wall that acts as a barrier between living space and the southern sky, he constructed five separate side-by-side cinder block pillars. Each 32-inch-wide pillar is angled 45 degrees from due south on a southeast-to-northwest line. Because the sun rises in the southeast, and the louvers are edge-on to solar energy coming from this direction, very little incoming sunlight is blocked. Instead, the morning sun shines deeply into the house, quickly warming the floors and living spaces. "All morning, my whole house acts as a solar energy collector," Jim explained. "I don't have to wait for the louvers' mass to warm up before I start getting heat. Instead, the sun shines *between* the louvers, so temperatures begin going up inside the house as soon as the sun rises, with no thermal lag."

Later in the day, the sun moves to the southwestern sky. Now, incoming sunlight hits the louvers broadside, warming the masonry and storing heat for the night. "My louvers work two ways," Jim said. "They provide direct gain and quick heat in the morning when the house is cold, and mass heat storage in the afternoon when the house is warm and there's solar heat to spare.

"I guess it was just a bit of insight that made me think of breaking up a standard mass wall this way, and angling the segments. But it works so well, frankly, I'm surprised no one thought of it before."

The louvered wall design also solves other problems that often plague mass walls. Aesthetics, for example. "If I was going to pay for all that south glazing, I wanted to be able to see out of it. Conventional mass walls such as Trombe walls and drum walls block the view, which is silly. You could build windows in a standard mass wall, but costs skyrocket when you have to include framing for lots of little holes. My way is simpler and cheaper."

Jim's careful design also insures that the living and dining areas have an almost unobstructed view between the louvers. As a result, his house feels bright, spacious, and open. "In fact, it's a lot more open than I imagined it would be," he said. "Especially compared to a house in which the south glass is hidden behind a solid masonry wall. This one doesn't feel closed in at all. And the louvers take up only 40 square feet of floor space," or three per cent of the home's 1300-square-foot floor plan.

The beauty of passive systems is that they're automatic, self-regulating, and an integral part of the building.

"No one had ever built a house with these louvers before," Jim said, "so it was hard to imagine just what the place would look like. But I think it turned out pretty well." Jerryanne, Jim's wife, agrees. "I really like it," she told me. "The columns add interest and appeal to the house, and no one's ever had a negative comment about them."

Aesthetics aside, the open construction of the wall also makes for easy and inexpensive maintenance. "With my louvers," Jim said, "you can walk right up to the south glazing. Cleaning is a snap, and you don't need any long-handled tools to reach the glass, as you sometimes do with Trombe walls and drum walls. I also have access to the sunward side of the mass itself for cleaning or for eventual repainting. This means I can keep my whole solar collection system operating at peak efficiency all the time. Maintenance is no bother at all."

Access to the glass makes nighttime insulation easier, too. Come sundown, Jim rolls down an inexpensive bamboo curtain that's been fitted with colorful quilted bedding. Deploying the home-made insulating curtain takes about three minutes.

Highs And Lows

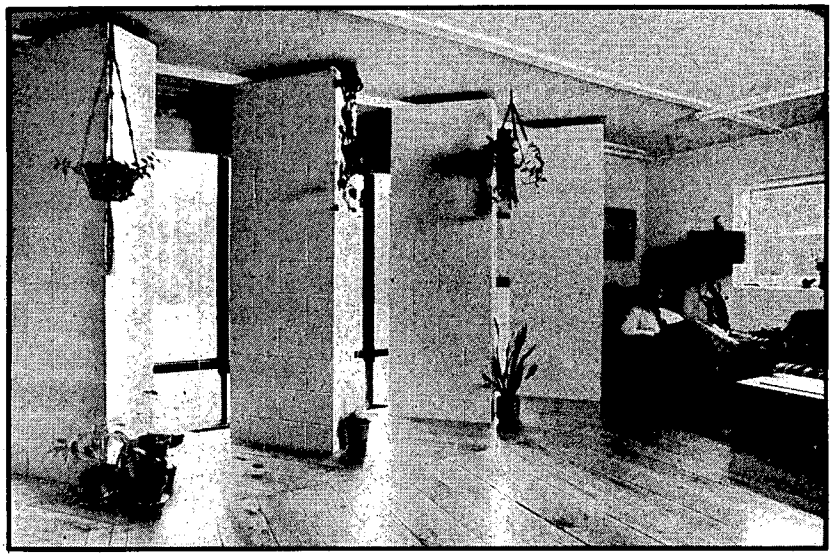
The most important thing about Jim's wall is that it works. I visited the

Biers on a sunny February day when the outside temperature was about 40°F. It was a tropic 78°F. inside the house, and Jim was wearing a short-sleeved shirt. As I peeled off my overcoat, I could actually see billows of warm air rising from the louvers. The rising heat cast rippling shadows on the floor.

"I monitor temperatures at three locations with high/low thermometers," Jim said. "And I've kept careful records virtually every day since we moved in last fall. On very cold days, indoor temperatures might fall to around 60°F. before rebounding when the sun finally clears the hills to the east of the house.

"High temperatures are another matter. I actually used too much glazing on the south side—about 325 square feet in all—because there weren't many reliable solar building guides available when I designed the house. Sometimes we even have to open windows in the evening to dump the excess heat we've collected during the day." Although this is an inconvenience, it's not really a waste because Jim's passive solar heat is free and inexhaustable.

Another factor in the home's sometimes too-high temperatures is the lightweight cinder block Jim used in constructing his louvers. "My reasoning was that a light block would warm rapidly from front to back, with just a small temperature gradient from the sunward to the roomward side. But it turns out that the lightweight 28-pound blocks are made from thermally resistive materials, so they're actually harder to heat than the standard 40-pound blocks. If I were starting over, I'd use the heavier blocks in the columns: They'd cost a little more, but they would store more heat and reduce the day-to-night temperature swings."



Above: *The backs of the louvers are painted a reflective white to allow light—and heat—to bounce deep into the Bier home. An added benefit of Jim's design is the bright, spacious interior that makes the house both attractive and efficient.*

Tightness Counts

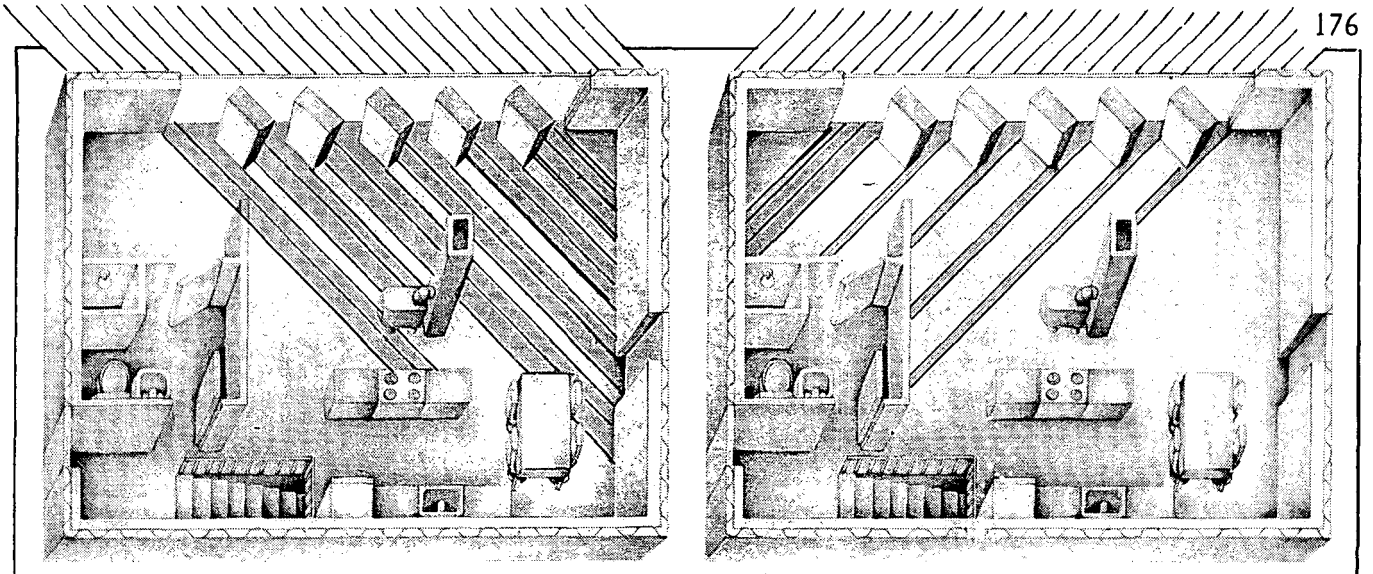
The home's cinder block walls are externally sheathed in four inches of foam insulation so the walls are enclosed within the home's thermal environment, adding thousands of pounds of total heat storage capacity to the building. Native poplar siding covers the foam for weather protection and aesthetics. The ceiling is insulated and the entire living space is enclosed in a vapor barrier of heavy plastic sandwiched between the cinder block and the foam insulation.

This tight, heavily insulated construction limits Jim's auxiliary fuel use to a trifle. In fact, the only source of back-up heat in the house is a $35 sheet metal wood stove mounted in the middle of the second floor. "It's not worth having a more elaborate stove," Jim said. "As it is, I burn only about a cord a winter."

I asked if the abundance of hard masonry surfaces led to problems with noise. (It has in some other masonry homes.) "Not for us," Jim said. "The louvers are at an angle to the rest of the masonry surfaces, and that seems to eliminate any echoing effect."

Jim built his louvered wall freehand, using nothing more complex than a bubble level and a string (stretched across the floor at a 45 degree angle) as guides. Jim did most of the work on the

ILLUSTRATIONS BY MARY WEST



A.M. **Left:** *On winter mornings, the sun rises in the southeast, and shines* between *the louvers, deep into the house. Temperatures rise very quickly, and the entire house acts as a solar energy collector.* **Right:** *Later in the day, the sun moves to the southwest sky and hits the louvers broadside, warming the masonry and storing large amounts of heat for the night. This solar design is so passive, the sun is the only moving part.* **P.M.**

house himself over a period of three summers, and the final cost for the finished building and its louvers, including what little subcontracting was needed, was just $14,000. That's less than $11 per square foot—a rock-bottom price by any standards.

"I think owner-built passive systems are the trend," Jim said. "Especially as fuel and interest rates continue to climb. It is the only way most middle-class people are able to afford a new home, and then afford to run it. Passive designs, especially low-cost passive designs like mine, are the only way to go."

Jim is also looking into ways of making the louver concept even more flexible: Oval water tanks to simplify construction and improve heat storage capacity, or pillars of lightweight phase-changing materials for existing homes.

If you have specific questions for Jim, you can write to him, c/o The Whetstone Branch Living School, Route 2, Box 35, Ferrum, VA 24088. Jim asks that you enclose $1 to help cover his copying and mailing costs. ■

The Insolarium: One Way to Solarize a Mobile

A mobile home can be an oversized energy eater, but it does have advantages. For one thing, it's a manageable size and shape for insulation and solar retrofitting. Here is one mobile home dweller's creative solution to his energy problem.

The Insolarium:

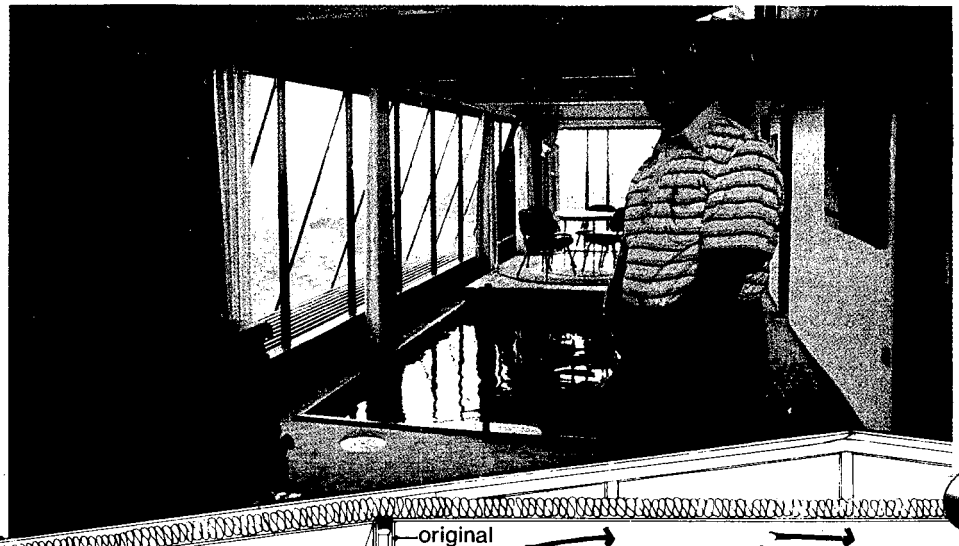
One Way To Solarize A Mobile

by Frederic S. Langa

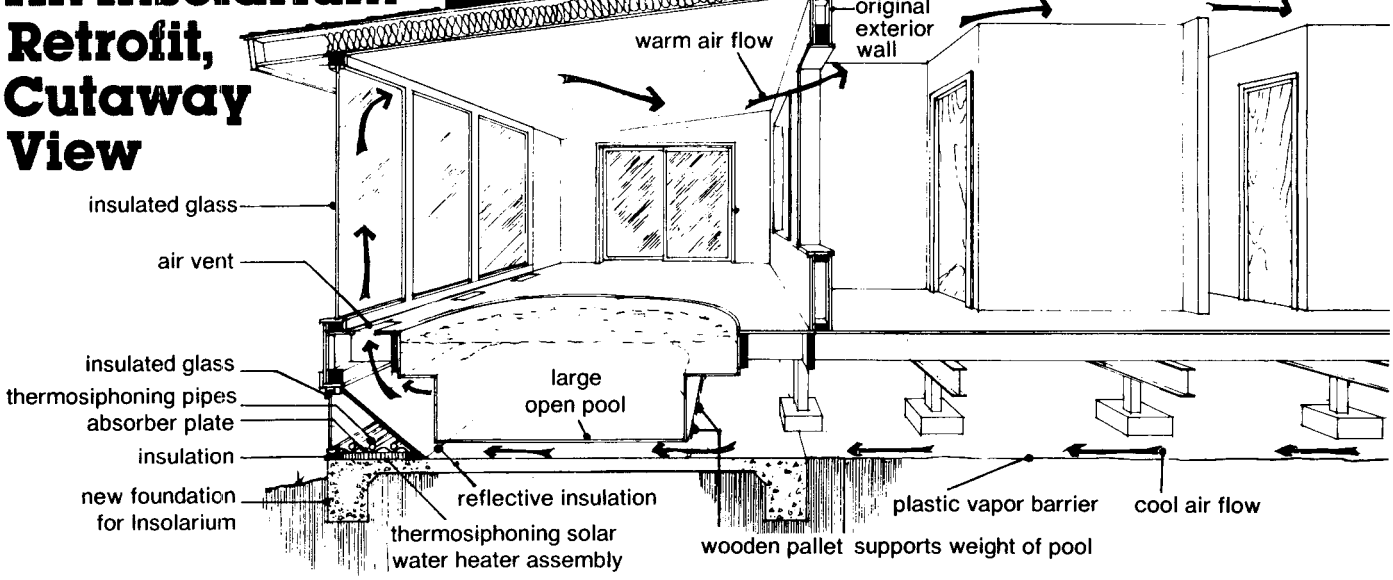
Siting a brand-new mobile home for permanence and beauty is one thing, but what about the millions of mobiles already in place? Ken Kessel, a building designer in Sonora, California, thinks many of them could be converted into state-of-the-art passive solar buildings, and he's showing how it can be done.

Over the last seven years, Ken has developed a three-part retrofit that allows virtually any mobile home to make use of some widely differing elements of energy-efficient design: free solar warmth, constant earth temperature, and thermal mass. By blending these concepts together in an unusual way (and in a way unheard of in mobiles) Ken's system can trim 30 to 40 per cent of an average home's fuel bills. And if the mobile has been weatherized and tightened (as it should before a solar retrofit), the savings can top 85 per cent.

The first part of Ken's system is simple: *Let in the sun.* Ken's preferred method is to build a large solar-heated addition on the mobile's sunniest wall. He calls his sunspace an "Insolarium," and it simultaneously gathers the solar



An Insolarium Retrofit, Cutaway View



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warmth and provides extra living space.

The second part is more sophisticated: *Use the earth.* Ken has developed a way to isolate the ground beneath the mobile, transforming it into an insulating device, and quite possibly a source of low-grade heat, as well.

The third part of the system: *Use multiple-functioning thermal mass.* Any thermal mass would work, but Ken chooses to temper the indoor climate of a mobile with a shallow open pool of water which stores and releases heat, humidifies the air, and provides visual appeal, all at the same time.

The system works because it mimics nature. "Think of a summer night," Ken says. "There's no energy coming in from the sun, but it's warm outside because of the daytime heat stored in the earth and in lakes and oceans. On a much smaller scale, that's how my system works. The day's solar warmth is stored in the earth beneath the mobile and in the indoor 'ocean' of the pool, where it can be released as needed."

In all, it's a simple system that Ken says, "was specifically designed with do-it-yourselfers in mind." But it's also an unusual system, especially in its use of unfamiliar, and untested, concepts such as earth heating.

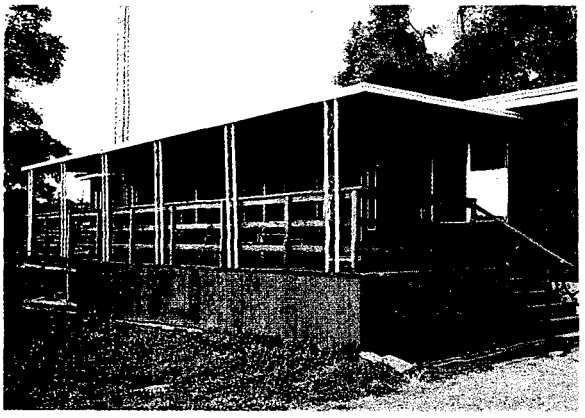
Heat From The Earth?

The deeper you go in the earth the steadier the temperatures become. While the top few inches of soil closely follow the air temperatures, rising and falling throughout the day, the earth 10 to 20 feet below the surface changes only a few degrees from summer to winter. "Deep earth temperatures here in Sonora average about 65° F. year-round," Ken explains. (He bases that figure on the average temperature of well water in his area.) "Most buildings never get to use this heat, because moisture in the soil carries it away like a wick. But if you sheathe a building's foundation to the frost line with an air- and watertight layer of insulation, you create a 'bubble' of dry, protected earth beneath the building." Dry earth is a pretty good insulator, running as high as R-4 per inch. And because the "bubble" of dry earth beneath Ken's foundation is itself underlaid with 65° F. earth, winter heat losses through the building's floor are virtually nil.

In addition to the insulative effect, Ken claims the earth could actually heat the house. "The earth under my foundation doesn't dip below 60 degrees," he says. Should the temperature of the living space drop significantly below 60° F., the "bubble" would begin "heating" the house because warmth always moves to cold until the two reach equilibrium. By the same token, when the house is kept warmer than the earth, the house loses a little heat to the earth. In the summer, the 60–65° F. temperature of the earth helps cool the mobile. In sum, Ken says he tempers the living space by *coupling* it with the ground.

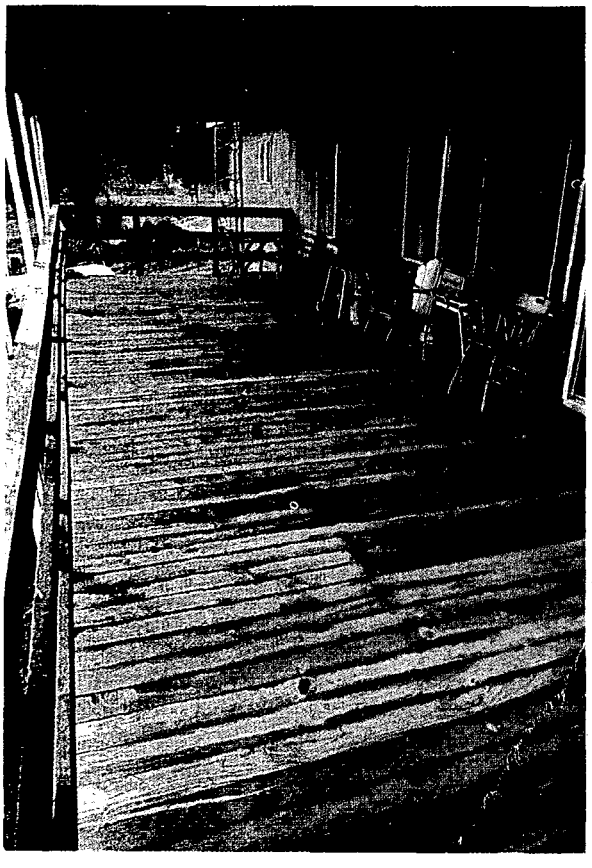
Not every spot on earth has the same benevolent 65° F. deep earth temperature, however. In colder climates the earth's low temperature probably doesn't produce any heating effect although the insulating value of the "bubble" remains the same.

Mobiles and modulars are especially easy to retrofit for earth coupling because they usually have a crawl space protected with skirting. By extending the skirting down to the frost line, insulating it and making it airtight, the crawl space becomes an insulated plenum for collecting the earth's moderate temperature. Also, because a mobile or modular home's heating system most often uses air ducts beneath the floor,

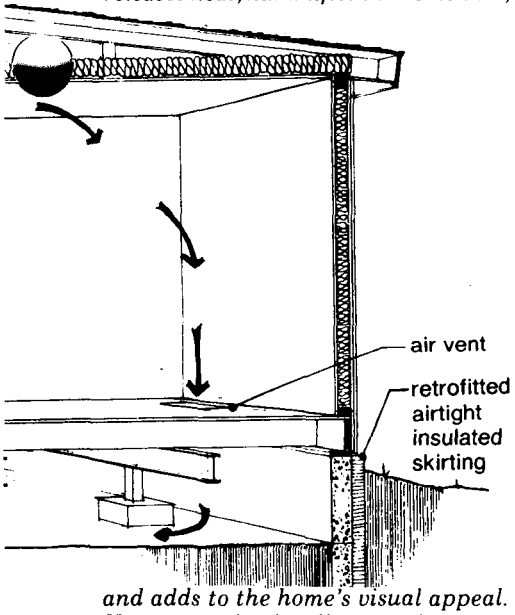


Above: *John Stewart's 10-year-old mobile home, prior to retrofitting. The home's skirting will be made airtight with insulation extending to the frost line, and the existing porch will be enclosed to create a sunspace. John expects to do all the work himself, figuring on three to four months of part-time labor.*

Below: *Believe it or not, an ordinary porch deck like this can become the heart of an "Insolar" system looking much like the one shown in the photo at left. The porch will become the sunspace, with the pool recessed into the floor. The existing home's doors and windows will be removed, opening the mobile to the warm air collected and tempered inside the sunspace.*



Left: *The pool is the first thing you notice about Ken's "Insolarium" sunspace. It simultaneously stores and releases heat, humidifies the home's air,*



and adds to the home's visual appeal. Ken uses a plastic roll-out pool cover to control the amount of humidity in the home, and adds a movable wooden platform (seen at the pool's far end) to turn the pool's surface into useful floor space. Also shown: the south-facing window wall, with thermal drapes for night insulation; the black-painted thermosiphon water heater on the window sill; floor vents below the windows to allow air circulation through the insulated plenum beneath the building; and the back-up wood-burning heater. This building (Ken's first design for modular homes) is about 85 per cent solar heated.

ILLUSTRATION BY TOM EVERETT

it's easy to arrange for the home's air to circulate through the crawl space/plenum, picking up and releasing heat as needed.

Multiple-Functioning Mass

Ken's "multiple-functioning thermal mass" is an open pool of water that absorbs heat when the house is warm and gives it back as the house cools. "Multiple" refers to the pool's other uses as a humidifying source and a pleasant focal point for the home. Ken used ordinary swimming pools in his early designs, but now opts for the least expensive and simplest pools he can find. "Right now, I use heavy-duty plastic bins which are normally used by farmers for crop transport. They're one-piece, totally waterproof and corrosion-resistant, and the largest ones can hold up to 4000 gallons of water. Also, because I legitimately can call these 'heat storage bins' instead of 'swimming pools,' they qualify for the federal energy tax credit." Ken recesses the pool into the home's floor so the weight of the water rests on the ground in the crawl space/plenum, and so the plenum's air can flow around the sides of the pool for improved heat transfer.

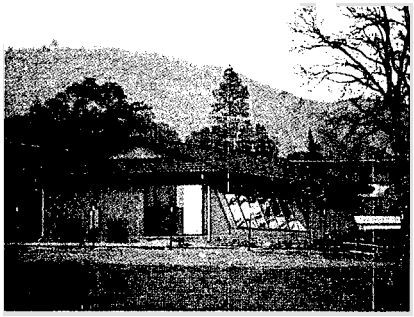
The "Insolarium"

Ken's "Insolarium" uses a simple tried-and-true sunspace design, coupled with a built-in thermosiphon solar water heater to help keep the pool warm. (Sunspace design has been thoroughly covered elsewhere. If you're unsure of the principles, check the references at the end of this article.)

Almost any manufactured home can be retrofitted with Ken's system. About the only ones automatically excluded are those lacking at least one sunny wall (for the sunspace), and those where the water table is too close to the ground surface to allow the creation of a "bubble" of dry earth. (If in doubt, talk to a local well driller, or dig a test hole. If you can strike water or very damp soil within a few feet of ground level, don't try for deep earth heating.) If a home meets the basic requirements, it's ready for the actual retrofit.

The Retrofit

First, remove the existing skirting, and pull off all the insulation beneath the floor of the home. Then scrape away all debris from the ground in the crawl space, and lay down a layer of heavy plastic sheeting. (This plastic vapor barrier prevents residual moisture from finding its way into the home.) Work carefully around posts or jacks, and



Above: *Modular and mobile homes can be both efficient and beautiful, as this shot of a recently finished double-wide "Insolar" home clearly shows.*

overlap any seams to be sure that the soil beneath the house is completely sealed. Then, to prevent damage to the plastic, spread about two inches of clean, dry sand on top.

Next, dig a trench around three sides of the mobile. On the fourth side (the sunniest side), dig the trench where you want the foundation of the sunspace to be. The trench should be wide enough to accept the insulation method you plan to use, and should reach down to the deepest frost penetration in your area. (The frost line in Ken's area is two feet down, but Ken dug his foundation to a three-foot depth.) When digging around an existing home, locate the trench directly beneath the home's outer walls, and provide extra temporary supports to the undercarriage so the home's footings are not disturbed by the digging.

When the trenches are ready, install an airtight, insulated skirting in the trench around the three sides of the existing home and construct a similar foundation for the new sunspace. The skirting can be fabricated easily from large sheets of blue polystyrene (Dow Styrofoam) tongue-and-groove insulation boards. Glue or tape all the seams for airtightness, and use a simple 2 × 4 framework for support. Or attach a metal mesh such as chicken wire to the home's undercarriage, letting one end hang down into the trench, and spray the hanging mesh with a heavy layer of foam insulation.

The foundation for the sunspace can be anything you want, as long as it includes insulation down to the frost line. Ken's favorite method is to stake two parallel walls of polystyrene insulation a short distance apart. (Leave an open space equal to the width of your sill board between the walls.) He then fills the space with poured concrete, eliminating the need for separate wooden forms, and produces a durable, insulated wall in one quick step. (The polystyrene must be well supported by wooden stakes and by the trench walls in order to withstand the considerable weight of the wet concrete. Talk to a local concrete dealer for advice about your own particular installation.)

When the airtight, insulated skirting and sunspace foundation is complete, refill the trenches with dirt. Then, if possible, contour a low embankment or berm to the bottom of the home's original walls to insure that the newly-formed plenum area stays warm, stable, and draft-free. If berming isn't possible, either the original or a new skirting can be installed to cover the insulation.

Next, build the sunspace of your choice. It doesn't have to be elaborate, as long as it contains a large, sunny window wall with either double glazing or a system of movable window insulation, and space for the thermal mass.

With the sunspace complete and weathertight, install your thermal mass. As Ken found, the best results come from an open pool, but if space or money preclude this, any thermal mass will do—water-filled glass or metal containers; rocks, bricks, etc. Once the mass is in place, remove the doors and windows in the wall between the home and the sunspace to let the sun-warmed air circulate freely.

The next step is to open up the crawl space so that the home's air can flow through. Work on opposite sides of the home: Cut vents in the sunspace's floor beneath the window wall, and in the floor along the wall farthest away from the sunspace. Install standard grills over the holes. Now, warm air should rise in the sunspace, circulate through the home to the distant vents, and return to the sunspace for reheating via the earth-tempered plenum. The existing furnace is now the back-up heater, or you can install a more appropriate auxiliary heat source, such as a wood stove.

Costs

Like any addition to a home, Ken's retrofit package can be no-frills or gold-plated. If every effort is made to cut costs, a home could be equipped with the basic insulated plenum, a small plastic-glazed sunspace, water jar or barrel heat storage and floor vents for somewhere in the range of $500 to $900, depending on the size of the home itself and the specific materials used. On the other hand, a top-of-the-line addition with concrete foundation, glass windows, an open heat storage pool, and about 500 extra square feet of floor space for the home could easily cost $10,000.

Is it worth it? We asked John Stewart, the Chief Building Inspector for Tuolumne County, California. He's installing Ken's system in a 10-year-old mobile that may be the ultimate in retrofits: It

was purchased at salvage and rebuilt after it had rolled over twice in a windstorm. "Frankly, it sounded a little crazy to me at first," John said. "Here I was talking about remodeling, and Ken came up and said, 'Why not make it solar?' I just didn't think it could be done to a 10-year-old home that had been this heavily worked on. But now that I've seen that it doesn't involve anything a person handy with a hammer and saw couldn't do, and that it doesn't cost much more than a non-solar addition of the same size and quality, I'd recommend it to anyone. Though there's a lot of work, it's pretty easy."

Ken agrees: "Easy? Why, it's a lead-pipe cinch!" ■

For further information on sunspace design and construction, see our February 1980 issue or read the following:

The Passive Solar Energy Book (Rodale Press)

The Complete Greenhouse Book (Garden Way)

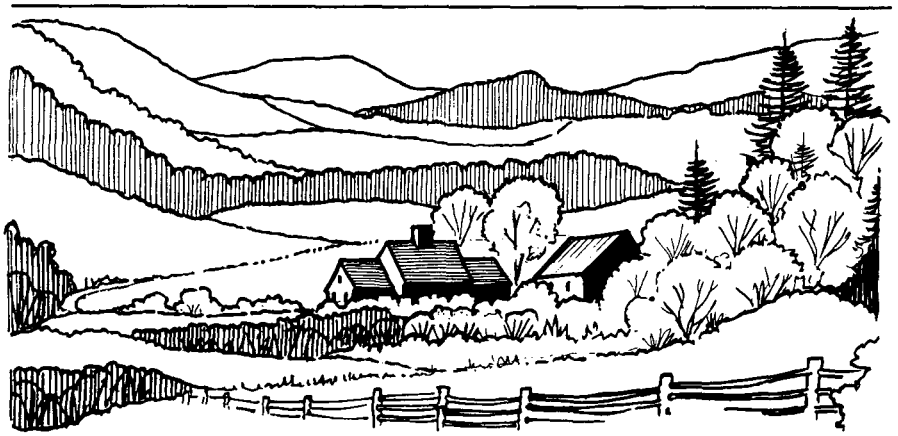
The Solar Greenhouse Book (Rodale Press)

How to Site a House

Windbreaks, proper siting and orientation, and added-on outbuildings were all included in the house plans of colonial builders. When we learn to take advantage of our natural environment, we'll have gained the knowledge that they already had long ago.

HOW TO SITE A HOUSE

When setting their houses on the land, early New England builders used certain techniques to help them cope with our climate. These guidelines are as valid today as they were 300 years ago.



text and illustrations by Terry Hallock

□ BEFORE THE EARLY YANKEE BUILDER located his house on a plot of land, he studied the conditions of the site and carefully placed his house and outbuildings to take advantage of any natural features that would help him to stay reasonably comfortable through the cold New England winter. With today's need for energy conservation, we can learn from the earlier builders some ways that will help us site our new houses, or improve the site on which we presently live.

Housewrights and homeowners had good reasons for their approach to siting a house. In fact, anyone who studies early architecture soon finds that many of their techniques have been incorporated into the guidelines used for siting a passive solar home today. Contemporary residential design should embrace all of these basic rules. Whenever possible, a house should face the sun and turn its back to the cold winter winds. Location should take into account topography, existing vegetation, exposure to the sun, wind, early frost, and as many other conditions as the builder or designer can identify.

What is referred to as passive solar technology is essentially an integrated approach to the design and construction of a house that can gather the sun's warmth without power-driven mechanical devices. A simple example is the way a south-facing window will warm a room

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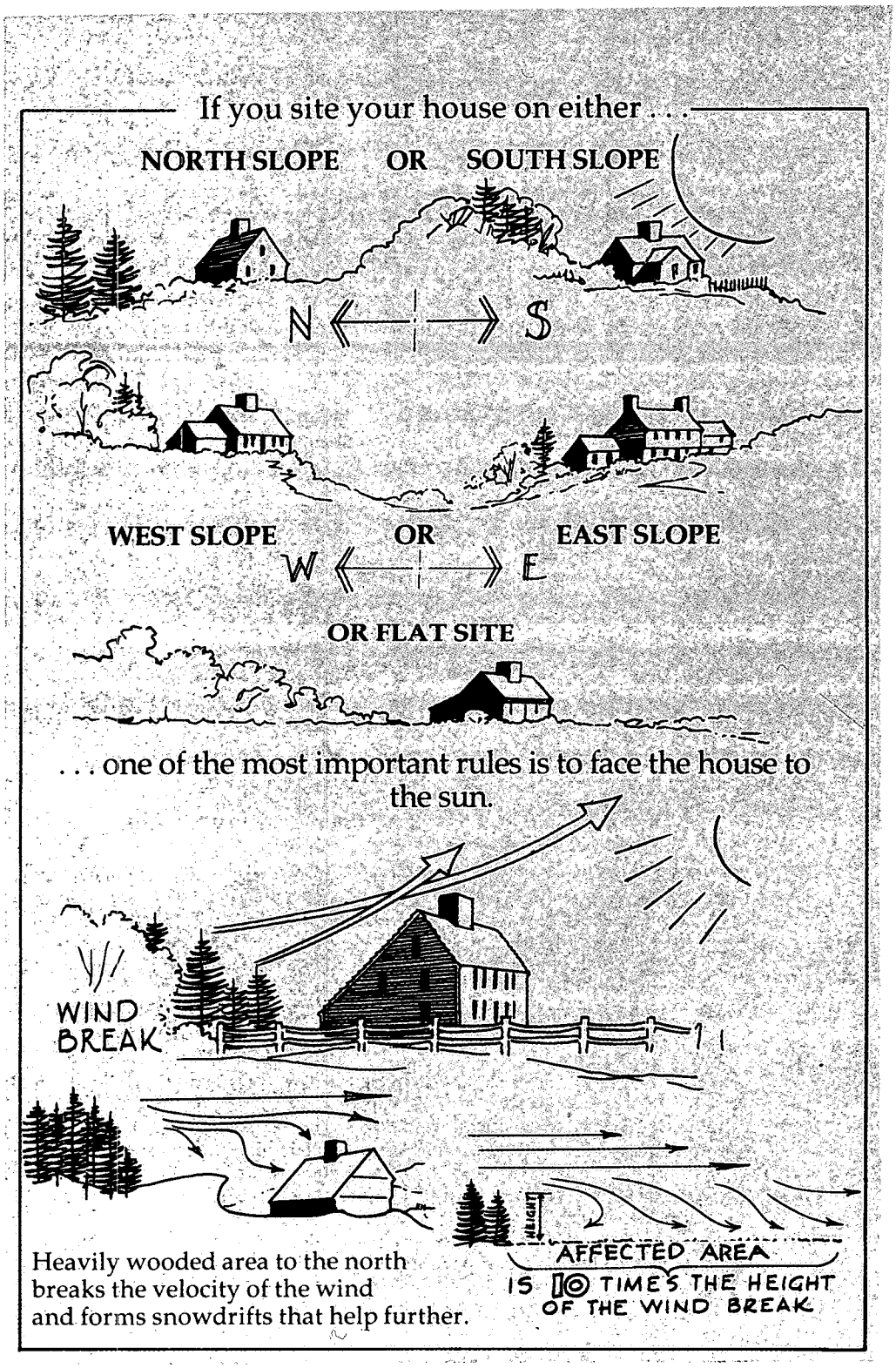
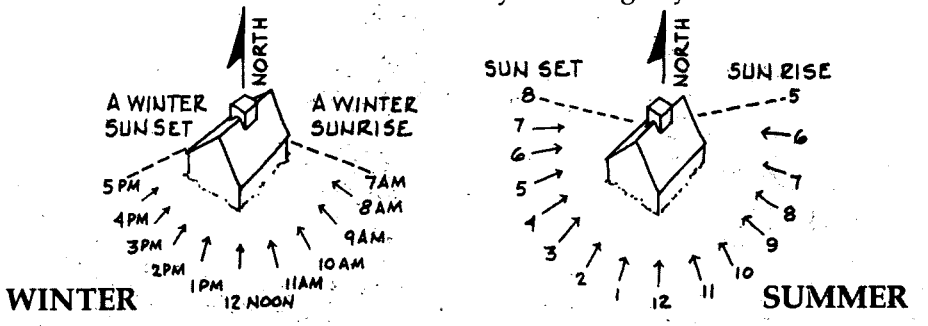

If you site your house on either . . .
NORTH SLOPE
OR
SOUTH SLOPE
N
S
WEST SLOPE
OR
EAST SLOPE
W
E
OR FLAT SITE
. . . one of the most important rules is to face the house to the sun.
WIND BREAK
HEIGHT
AFFECTED AREA
IS 10 TIMES THE HEIGHT OF THE WIND BREAK
Heavily wooded area to the north breaks the velocity of the wind and forms snowdrifts that help further.

during daylight hours even on a cold winter day. This integrated approach involves reinforcing the original design with heavy insulation, and, just as important, correct orientation and siting of the structure.

The New England saltbox house (named for its similar appearance to the kitchen saltbox) is a shape that can be very energy-efficient when properly oriented. Placed in the correct location it is ideally shaped to deflect the New England winter's northwest wind up and over the low-pitched north-facing roof. This means that only one story faces north with few windows, while two stories face south to catch the warmth of the sun.

Evergreen trees are beautiful year-round, but when planted in the correct

It is possible to orient the house so that all four sides of the house will receive some sun for almost the entire winter — and in the summer the house will catch the early morning rays of the sun.



Properly placed deciduous trees will shade the house from the hot noon and afternoon sun.

What were called the bride and groom trees . . . in summer provided cooling shade . . .

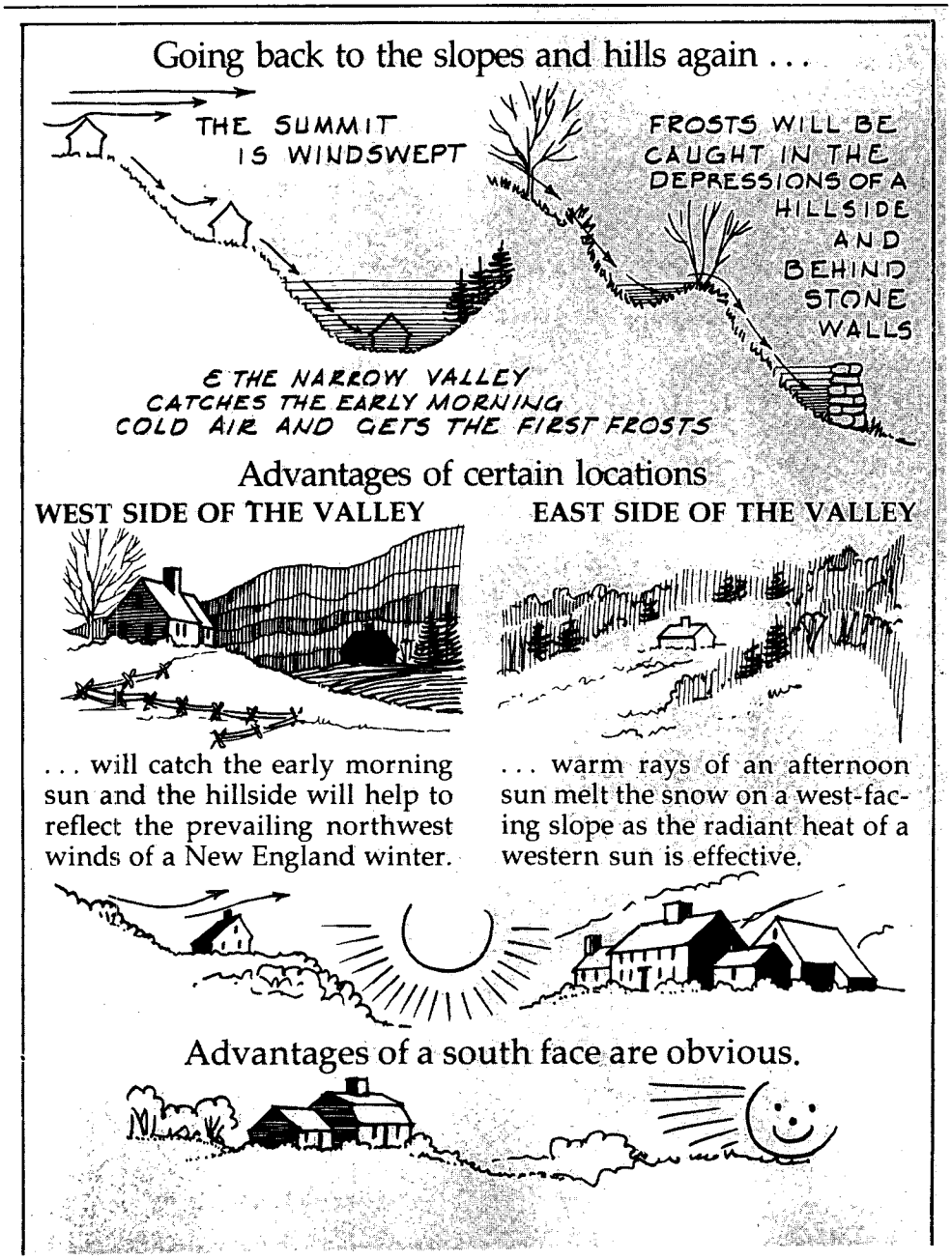
. . . but in winter

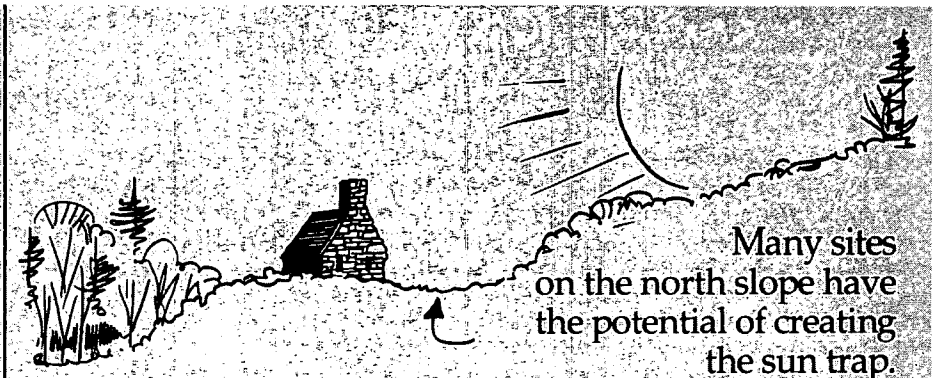
the sun shines through the leafless branches.

However, it's always good to disturb the site's natural contour and growth as little as possible. The house fits better and site preparation and landscaping costs can be reduced.

configuration they can also form a dense windbreak in winter, or deaden sounds of traffic at any time of year. If you've ever examined the drifts on the lee side of a snow fence, you'll see the compound effect of a hedgerow planted near a house on the side from which prevailing weather patterns approach. A hedgerow interrupts a prevailing wind for a distance of 10 times the height of the protective vegetation.

If you have the opportunity to site a house on a plot of land that contains trees, those that are growing to the north and northwest of the house location should be left standing as a buffer to the cold winter winds. The land to the south of the house site can be cleared, allowing the sun to warm the house and earth immediately in front of it. If possible, a

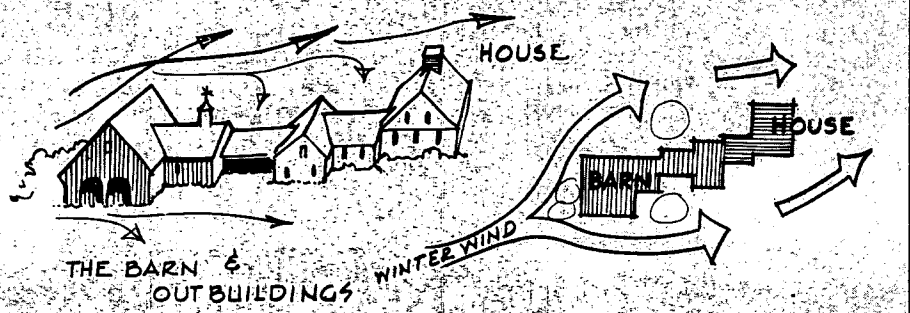




Many sites on the north slope have the potential of creating the sun trap.

And on the flats, there are all kinds of possibilities with proper orientation.

The windbreak of connected buildings is an effective energy-saving design.



A barrier to the prevailing cold winds can be achieved by . . .

. . . stacking the cord wood along the north side.

. . . banking the house with leaves or hay.

deciduous tree or two should be left standing close to the house on the south and southwest side to shade the house from the hot summer sun; after they lose their leaves, these trees allow the sun to shine through in winter. If no trees are growing on your site at the time of construction, then consider planting a dense hedgerow on the winter wind side.

If you carefully examine the various orientations possible for a rectangular structure, you will note that it is possible to place a New England house so that all sides of the basic rectangle will receive some sun during the day. This is true of both the southeast- and southwest-facing houses. Even in winter the oblique rays of the sun will dry and warm the northeast and northwest sides. The south faces will receive the greatest benefits of the sun, but of most importance is the fact that the properly oriented house will receive the sun on all four sides.

In traveling through New England, one can often still see evidence of the "bride and groom" trees planted in front of many early houses. Now they may be only giant stumps or just twin mounds of earth covering the ancient root systems. Or perhaps the old trees still exist, casting their canopy of shade over the house to protect it from the hot summer sun. The term "bride and groom trees" is a logical one, as it is likely that they were planted by the first inhabitants of the house.

If your house is on a rise facing east, likely you will never be able to boast the lowest temperature in town on a bitter cold day. Because temperatures are at their lowest just before sunrise, if you face east, you'll receive relief almost immediately, while those on the west-facing slope will not get sun until later (very much later if the mountains are steep).

Although the western-facing slope is late to receive the early morning sun, this slope has attraction as a homesite. The warm rays of the afternoon sun melt the snow on a western slope.

Living through harsh winters, early builders learned certain basic facts about placing houses in weather-wise locations. They avoided barren windswept summits for the obvious reason that these locations are constantly bothered by the cold north and west winds. They also avoided the low, narrow valley areas that would collect the cold air descending from the slopes, the damp fog on fall mornings, and early, killing frosts.

A clean sweep of a gentle slope, without swales or depression that catch the cold, is the ideal site. The cold night air travels down the slope to settle in the basin of low land below. During the daytime the reverse happens. Currents of air nearest the ground go up the hill as the sun penetrates the low lands, warming the earth and sending the currents of air rising up the hill.

Another way of supplementing the protection of the hedgerow or wooded area to the north is to build interconnected outbuildings off to the weather side, offering further protection from the blast of the cold winter winds. Properly placed, these interconnected structures adjoining the main living unit give a lot of protection to the family living area. The mass of the farthest barn, adjoining perhaps a milk house, wood shed, buttery, summer kitchen, and workshop, placed in logical progression depending on protection desired, was a refined plan often found in houses of New England.

In addition to considering the foregoing, there are other important factors to study in choosing a site. They include the condition of the soil and the ground beneath. The ground should be investigated to see if it will provide good bearing for the footings to support the weight of the house. The porosity of the soil should be checked to see if the site will have good drainage and leaching capabilities. The presence of ledge and large boulders should be determined, as this will affect the amount of excavation possible. The presence of water in the ground will have to be considered to avoid the possibility of a wet basement, interference with leaching, and the reduction of the bearing capacity of the soil. Wetlands and potentially flooded lands should always be avoided.

The topography of the land has many effects on the success of the site, in addition to the factors already pointed out. Does the contour help the site's natural surface drainage? Is the slope gentle enough to easily accommodate the structure, or is it too steep to build on economically?

Existing plant life and vegetation are also important, as they can provide cooling shade and protection from storms and cold winds. Check to see if there are trees or buildings on adjacent land that will block the sun.

Other practical considerations are ease of access from the highway and the proximity of utilities. Zoning regulations should be investigated and thought should be given to potential construction on adjacent sites, and how it will affect your immediate environment. Is there potential pollution from noise or atmosphere?

In choosing your home site, look at the characteristics that will assist in growing food for your family and animals, and provide space for outdoor living, recreation, and privacy.

If you already have a site on which you intend to build, or if you have a home presently located on a plot of land, many of the good features discussed here can be created on your existing site. Even the orientation of the house can possibly be changed to face south by constructing a greenhouse on that side, and by closing up selected north windows; or an unheated storage addition can be built on the north side. Evergreens can be added to deflect the cold winter winds, and shade trees can be planted.

No homesite is perfect, but by carefully analyzing a potential building site with these thoughts in mind you are better equipped to make a decision that you will be happy with over a period of years.

Shelterbelts

Here is all you need to know to plan an attractive and energy-saving windbreak.

Shelterbelts

Keeping the wind out and the fuel bills down

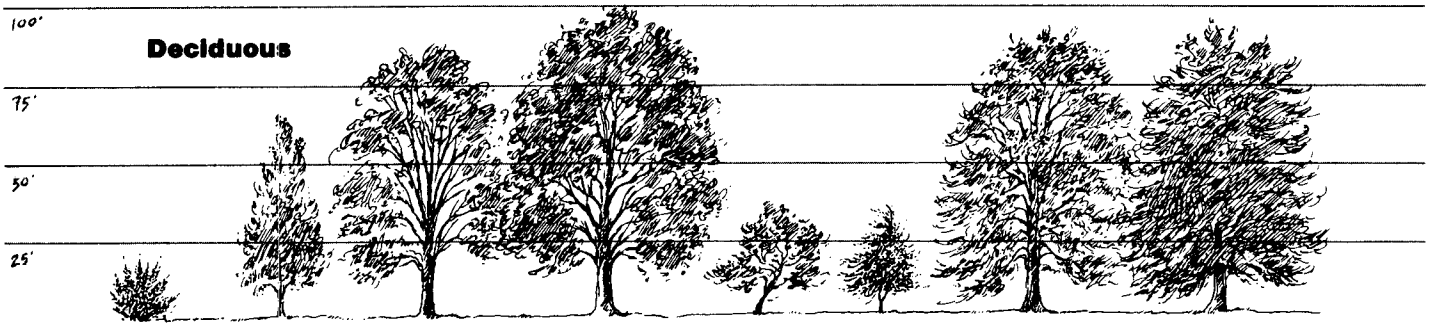
by Fred J. Nisbet

TREES FOR WINDBREAKS

Evergreens

Name	*Juniperus chinensis*	*Juniperus virginiana*	*Picea abies*	*Picea glauca*	*Picea omorika*	*Picea pungens*	*Pinus nigra*	*Pinus resinosa*
Common Name	Chinese Juniper	Red Cedar	Norway Spruce	White Spruce	Serbian Spruce	Colorado Spruce	Austrian Pine	Red or Norway Pine
Hardiness	−20°F	−50°F	−50°F	−45°F	−20°F	−50°F	−20°F	−45°F
Comments	Not as dense as red cedar. All junipers have separate sexes.	Will tolerate dry, rocky, poor soils. Don't plant near apples because of rust.	All spruces need fertile soil and good drainage. This one retains its lower branches better than most.	The weakest wood of the spruces.	Hard to find. Beautiful, but not too hardy.	Varies widely in color, with the more blue in the foliage the greater the beauty. Slower growing.	Fairly rapid in growth. Stiff needles.	Rapid in growth for a pine.

Deciduous



Name	*Acer ginnala*	*Acer platanoides*	*Acer rubrum*	*Acer saccharinum*	*Carpinus caroliniana*	*Crataegus phaenopyrum*	*Fagus grandifolia*	*Fagus sylvatica*
Common Name	Siberian Maple	Norway Maple	Red Maple	Sugar Maple	American Hornbeam	Washington Hawthorn	American Beech	European Beech
Hardiness	−50°F	−35°F	−35°F	−35°F	−45°F	−20°F	−35°F	−20°F
Comments	Multi-stemmed, shrublike, very adaptable.	Very deep shade, heavy surface roots. Difficult to grow other plants nearby.	Will stand moist soils, rapid growing for a maple, fairly strong wood. *Don't* use silver maple, very rapid growing but intensely brittle.	Only for long-term use. Slow growing but tough. Needs space.	Hard to transplant when large.	Dense in habit, fine flowers and fruits but subject to several diseases.	Dense and rapid growing, holds lower branches well and leaves until late.	All beeches stand shearing well.

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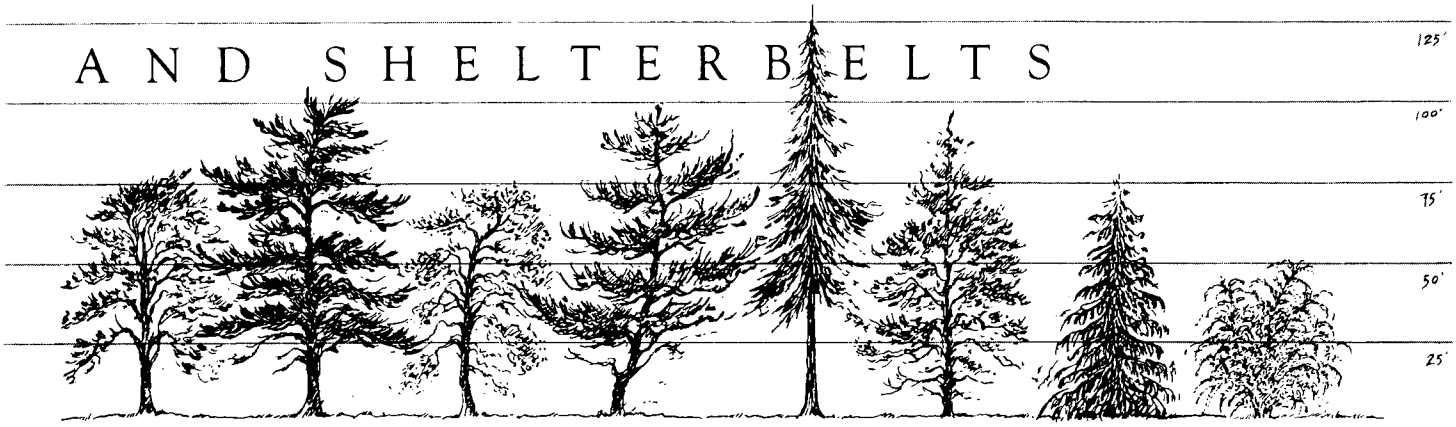
TOO FEW HOMEOWNERS, in the Northeast especially, have given much thought to shelterbelts and windbreaks. As the nation's energy problems worsen it is time to change our way of thinking; it is surprising what screens of plants can do to save fuel and still keep us comfortable.

We know of their value and abundant use in the Great Plains, where, for the survival of man and beast, it has been necessary to temper the frigid winter winds. In addition, plant screens trap enough snow to supplement the scant rainfall (12 to 14 inches per year) and make a few crops, especially winter wheat, feasible.

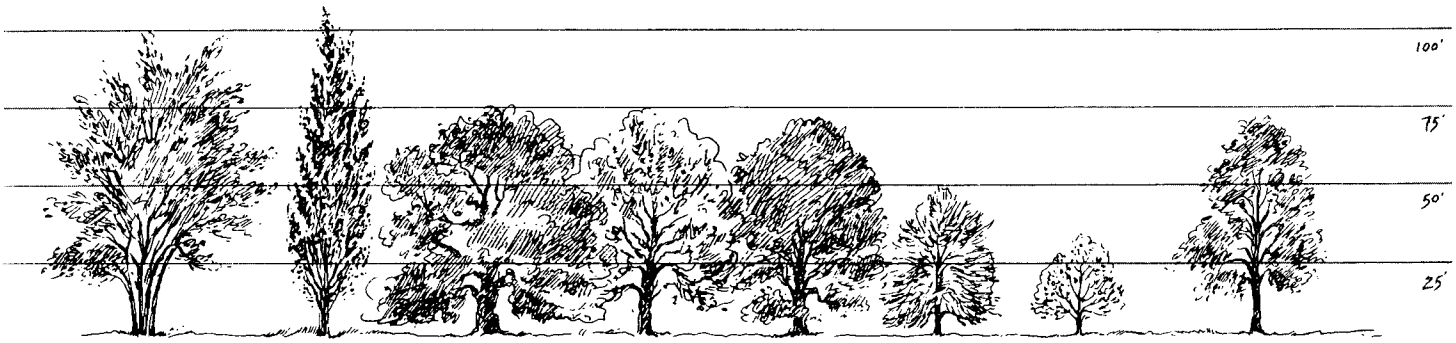
Up to the present, most research on the subject of shelterbelts has been conducted on the Great Plains and on the Russian steppes, under conditions quite dissimilar from those that prevail in the East. Despite all the unknowns, however, one fact shines through: wind barriers can have a significant fuel-saving effect in our region of the country.

One favorable factor in the Northeast is plentiful rainfall: we can usually count on 35 to 45 inches a year. This not only speeds the growth of the plants but also allows the use

AND SHELTERBELTS



Pinus rigida	*Pinus strobus*	*Pinus sylvestris*	*Pinus thunbergi*	*Pseudotsuga taxifolia*	*Tsuga canadensis*	*Tsuga caroliniana*	*Tsuga diversifolia*	**Name**
Pitch Pine	White Pine	Scotch Pine	Japanese Black Pine	Douglas Fir	Common Hemlock	Carolina Hemlock	Japanese Hemlock	**Common Name**
−20°F	−30°F	−45°F	−20°F	−20°F	−35°F	−20°F	−10°F	**Hardiness**
Fairly open; use only on soils too poor for other plants.	Fairly fast in growth and one of the best. Stands shearing well.	Rather open, but will grow almost anywhere. Much used in Europe.	A real beauty, if you can find it. Does well near the coast.	One of the most beautiful of evergreens, but only hardy when from seeds of high-altitude trees.	All hemlocks need moist, fertile soils, cool locations.	Denser, more expensive, and less hardy. For the ornamental garden.	Less hardy, slower in growth, but thick and lovely	**Comments**



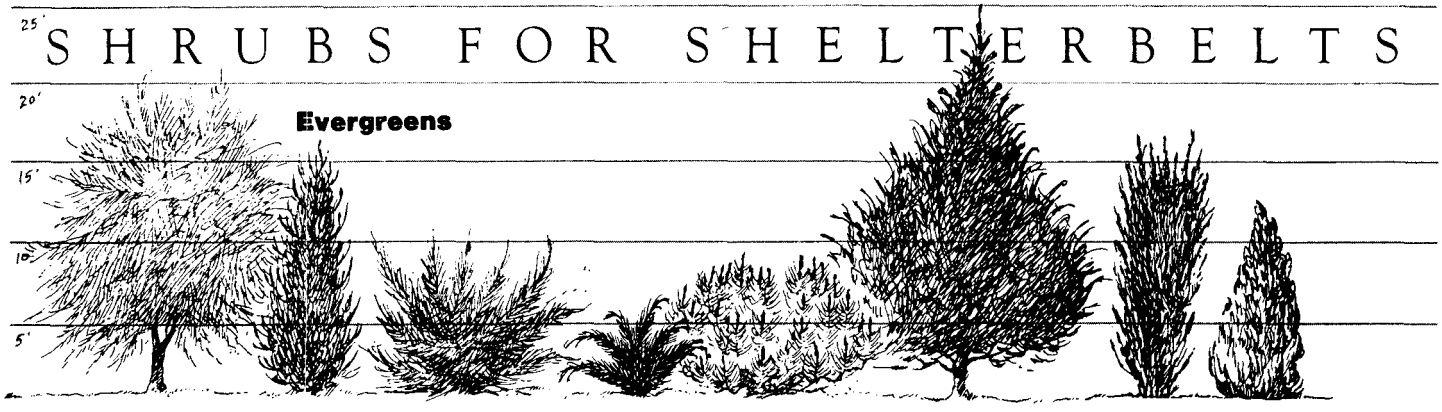
Populus alba	*Populus nigra italica*	*Quercus borealis*	*Quercus imbricaria*	*Quercus palustris*	*Quercus phellos*	*Rhamnus davurica*	*Ulmus pumila*	**Name**
White Poplar	Lombardy Poplar	Red Oak	Shingle Oak	Pin Oak	Willow Oak	Buckthorn	Siberian Elm	**Common Name**
−35°F	−45°F	−20°F	−10°F	−20°F	−5°F	−45°F	−20°F	**Hardiness**
Poplars withstand drought and poor soil. Rapid growing but wood is brittle, life is short.	The better of the two, but use as a last resort in poor areas.	Most rapid growing of oaks, strong.	Leaves hang on all winter, stands shearing well.	Needs acid soil and added iron.	Not too hardy, but a fine tree.	Grows in almost any soil. Fine bird shelter and food.	Grows quickly, even in dry soil, but short lived. Best in the West.	**Comments**

Drawings by Margot Apple

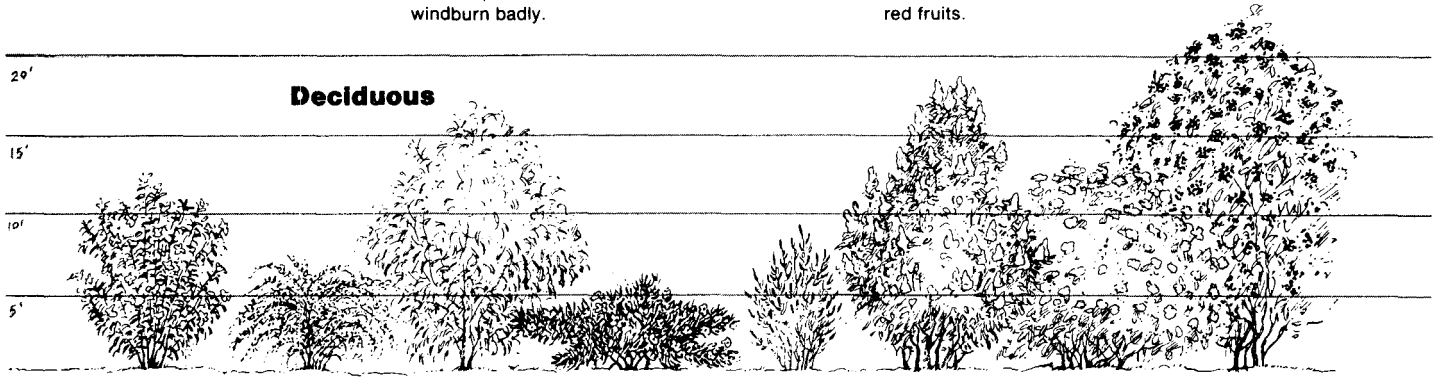
of many plants that are more effective, more attractive, and longer-lived than those that are tough enough to withstand the harsher conditions farther west. Another factor is terrain. Although we do have areas where the winds are concentrated and sweep down with considerable fury, we do not have, for the most part, the wide-open, flat country where no natural protection is afforded.

How much fuel can be saved by planting wind barriers depends on many factors, and research on the subject is so new and complex that no one answer can be given. But in general terms, if a good wind shelter is raised between your house and the prevailing winter winds, you can expect an *overall* reduction of fuel needs of about 12 to 15 per cent. If, on the other hand, you have shelters on two sides (pick the worst two in your locality), the savings can soar to 25 to 30 per cent. Interestingly, shelters on the northeast side of the house seldom increase the savings much further, unless the house is on or near the coast. (For special problems of wind protection, get in touch

SHRUBS FOR SHELTERBELTS



Name	*Elaeagnus angustifolia*	**Juniperus chinensis*	*Juniperus communis*	*Juniperus sabina*	*Pinus mugo mugo*	**Taxus cuspidata*	*Taxus media*	**Thuja occidentalis*
Common Name	Russian Olive	Juniper varieties	Common Juniper	Savin Juniper	Mugo Pine	Japanese Yew	Anglo-Japanese Yew	Shrubby American Arborvitaes
Hardiness	−45°F	−15° to −20°F	−50°F	−20°F	−45°F	−20°F	−20°F	−20°F
Comments	One of the best, stands shearing well.		Varies widely in height but will grow in dry, infertile soils. Avoid Irish and Swedish varieties, which windburn badly.	Also varies widely in height and will grow in poor soils.	Varies widely in height. Large plantings attract scale insects.	All are handsome, stand shearing well. Not fast growing. Pick mainly female kinds for their red fruits.	Varieties used more than the hybrid. As lovely as the above.	Many fine smaller varieties are available, but the naming is chaotic.



Name	*Philadelphus* species	*Physocarpus opulifolius*	*Rhamnus frangula*	*Rosa rugosa*	*Salix purpurea*	**Syringa* species and varieties	*Viburnum dentatum*	*Viburnum lentago*
Common Name	Mock Oranges	Eastern Ninebark	Alder Buckthorn	Rugosa Rose	Purple Osier	Lilac	Arrowwood	Nannyberry
Hardiness	−10° to −35°F	−50°F	−50°F	−50°F	−35°F	−10° to −50°F	−50°F	−50°F
Comments	There are many mock oranges. They tolerate many soils, are dense, and need little care.	A coarse, not very attractive shrub, but extremely hardy, has no pests and will grow in almost any soil.	Will grow rapidly in most soils, has yellow autumn color.	Grow species or variety "alba" for best results under poorest conditions. Will stand very sandy soils, drought, and even salt spray along the coast.	Dense in habit and with purple bark in winter. Will stand very moist soils.	It is an impossible task to choose just a few lilacs (avoid the Japanese tree lilac, which is too tall and coarse). Any of the Preston or Skinner hybrids are very hardy.	Grows rapidly in almost any situation, preferred to *V. cassinoides*, which has yellow fruits that stink. *V. lantana* is better for dry soils.	Only for large areas, as the branches arch over and root, making big masses. Good for bird food and fall color.

*Many fine varieties with a range of color and shape are available. Ask nurseries in your area for recommendations.

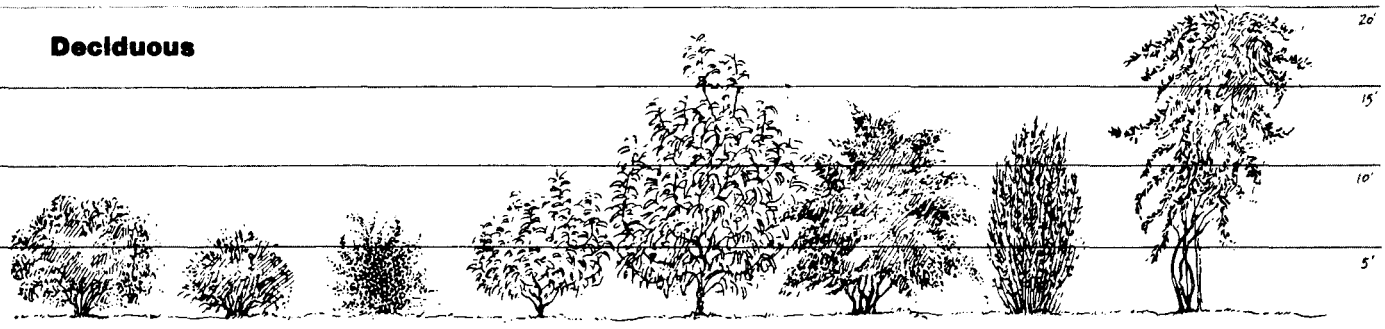
with your local Soil Conservation Agent, the county foreman of your highway department, or the U. S. Army Cold Regions Research and Engineering Laboratory, Hanover, N.H.)

Let us take an example. If you raise a shelter directly against the prevailing winter wind, the modifying effect will be greatest on the shelter's lee side up to three to five times the height of the barrier (obviously, the protected distance increases as the plants grow). The effect will be moderate from ten to thirteen times the height of the shelter and will be detectable up to twenty times the height of the barrier.

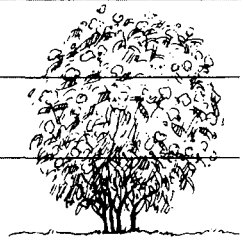
The desired density in your shelter is 50 per cent, which will reduce a 15-mph wind to about 5 mph for a distance of approximately three times the height of the barrier. At 30°F this will amount to a fuel saving of about 20 per cent; at 0° the saving would be about 25 per cent. By estimating the wind reduction and checking your thermometer, you can check the savings quickly from the Wind Chill Chart.

OR GAPS IN WINDBREAKS

Deciduous



Acanthopanax sieboldianus	*Aronia arbutifolia*	*Berberis thunbergii*	*Cornus alba "Siberica"*	*Cornus mas*	*Kolkwitzia amabilis*	**Ligustrum* species	**Lonicera* species	**Name**
Five-leaved Aralia	Black Chokeberry	Japanese Barberry	Siberian Dogwood	Cornelian Cherry	Beauty Bush	Privets	Honeysuckles	**Common Name**
−20°F	−20°F	−20°F	−50°F	−20°F	−20°F	−20° to −35°F	−20° to −45°F	**Hardiness**
Needs shearing to be dense, stands heavy shade, full sun, poor soil.	Not choice, good bird food.	Will grow almost anywhere except in densest shade. Thorns make it a good barrier.	Beautiful red bark in winter.	Dense, early flowers. Fruits good for birds and humans.	Very dense growth, fine bird shelter.	Select only the hardiest.	There are a great number of bushy honeysuckles, easy to grow and tolerant of many soils.	**Comments**



Viburnum prunifolium

Black Haw

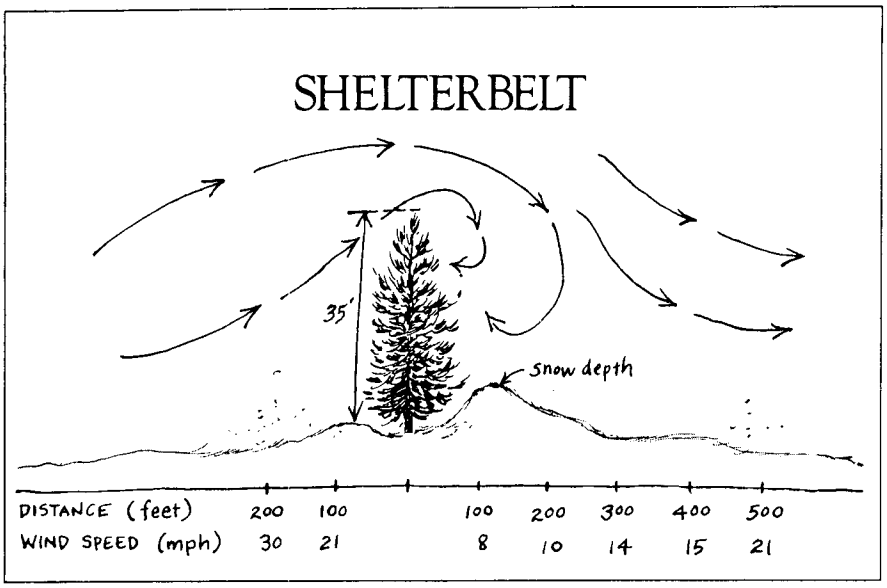
−35°F

Will grow almost anywhere. Red fruits.

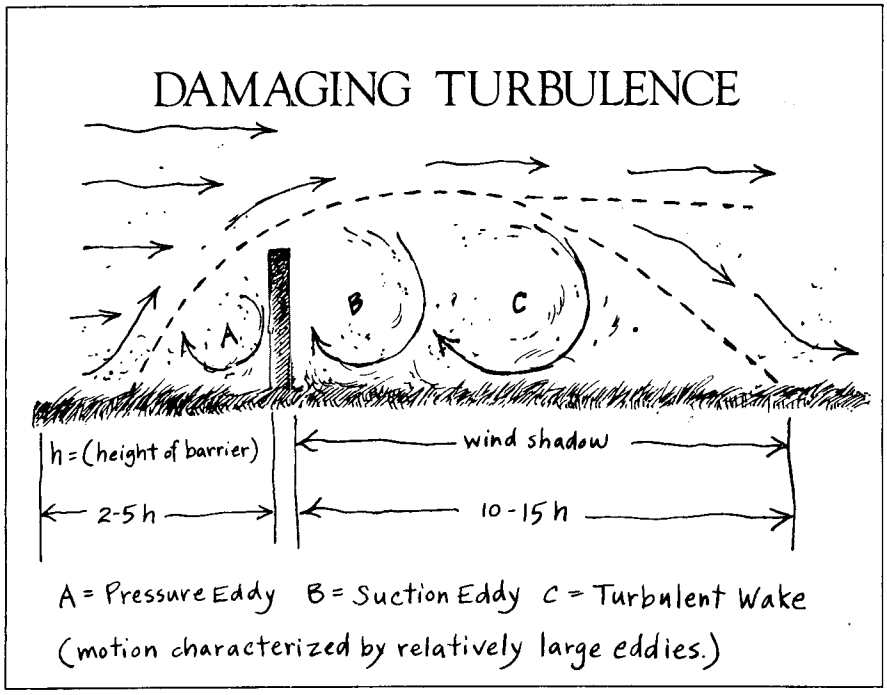
WIND CHILL CHART

When the wind blows at the listed speeds, your body—and heating plant—will react as if the temperature were:

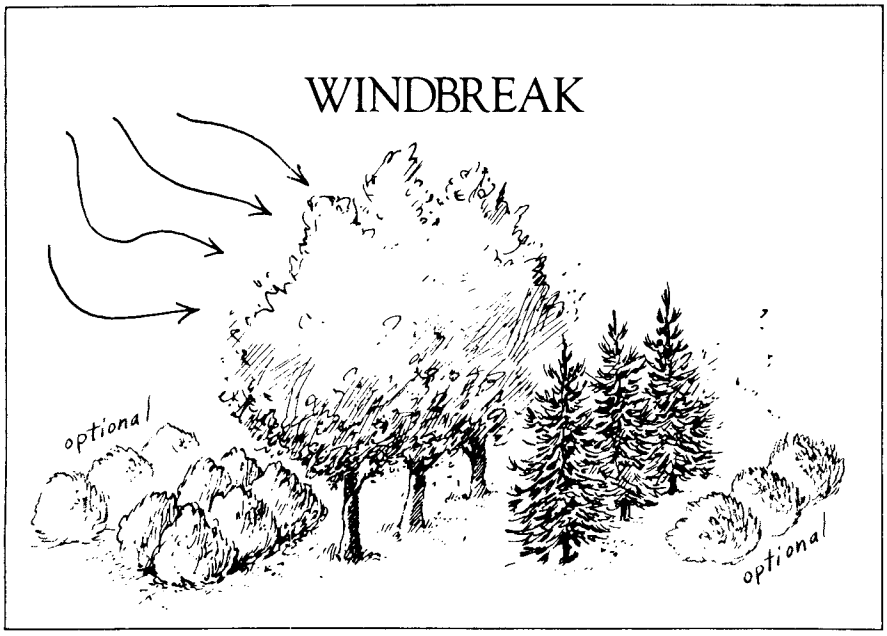
Temperature, degrees F	calm	5 mph	10 mph	15 mph	20 mph	25 mph	30 mph	35 mph	40 mph
50	50	48	40	36	32	30	28	27	26
40	40	37	28	22	18	16	13	11	10
35	35	33	21	16	12	7	5	3	1
30	30	27	16	11	3	0	−2	−4	−4
25	25	21	9	1	−4	−7	−11	−13	−15
20	20	16	2	−6	−9	−15	−18	−20	−22
15	15	12	−2	−11	−17	−22	−26	−27	−29
10	10	7	−9	−18	−24	−29	−33	−35	−36
5	5	1	−15	−25	−32	−37	−41	−43	−45
0	0	−6	−22	−33	−40	−45	−49	−52	−54
−5	−5	−11	−27	−40	−46	−52	−56	−60	−62
−10	−10	−15	−31	−45	−52	−58	−63	−67	−69
−15	−15	−20	−38	−51	−60	−67	−70	−72	−76
−20	−20	−26	−45	−60	−68	−75	−78	−83	−87
−25	−25	−31	−52	−65	−76	−83	−87	−90	−94



The sheltering effect of a windbreak is evident from this simplified drawing. Wind speed drops considerably more on the leeward side of the shelter than on the windward side.



The turbulence that develops on both sides of a solid barrier may well create wind problems instead of solving them.



A typical windbreak using trees and shrubs of varying heights

The density of the screen requires a bit of explanation. Wind shelters are effective not because they stop winds, but because they slow them down. A screen with a density of less than 50 per cent does not give maximum benefit. On the other hand, greater densities, which block rather than filter the wind, create turbulence on the lee side of the barrier. In fact, a solid board fence will create much higher velocities in the range of one to five times the height of the barrier than will exist over an open field and can often cause enough "swirl" to be destructive.

A point often overlooked is that a good windbreak decreases the wind velocity appreciably for two to three times the height of the barrier on the *windward* side of the barrier as well. Because of this effect, snow drifts on the windward side will be fewer than on the lee. This can be a fine way of diverting heavy snow accumulation from well-traveled areas. But if your shelter is on your property line, it most certainly could cause strained relations with your windward-side neighbor, especially if the drift zone includes his driveway! Fuel-cost reductions from this effect are apt to be on the slim side, in any event.

A typical shelterbelt consists of two (sometimes three) rows of trees, usually with the taller ones on the windward side. Two or even three rows of fairly large, dense shrubs are then placed on the windward side of the trees. If sufficient space is available, a row of tall shrubs is placed on the lee side as well. Staggering the plants in adjoining rows increases the efficiency of the planting.

If there is not enough space for such a wide planting, you can use a windbreak that consists of only two rows of trees. This is less efficient but far better than nothing. The rows are planted close together, trees staggered in the rows.

Evergreens are most efficient in slowing winds, especially during the winter when they are needed most. Unfortunately, they are much slower growing than many deciduous trees, which are most effective—and least needed—when in full leaf. Because of this, many windbreaks are planted with evergreens on the lee side and faster-growing deciduous varieties on the other. As the evergreens gain sufficient size, the deciduous row is cut out. The two-row protection can be salvaged to some extent by replacing the cut trees with dense shrubs that grow fairly high, or other evergreen trees. These plants must be strong-growing varieties as they will have to compete with the established trees. They will need extra attention in watering, fertilizing, and weed control for two or three years until they are well enough established to make it on their own. A mulch is a big help here.

Russian olive is one of my favorites if shrubs are indicated, but if trees are to be used it is hard to beat the better pines. If space is available, grow the replacement evergreens somewhere nearby while the main windbreak is becoming established. When the fast-growing trees are cut, the replacements will be quite large. An experienced backhoe operator can dig the holes and move the balled replacements very quickly—burlapping is not necessary for such a short, quick move.

Choosing the deciduous trees must be a compromise. The faster-growing varieties, to a great extent, have more brittle wood, increasing the danger of damage by wind, ice, or snow. This is especially true of poplars and willows. Red maple, though, is relatively fast growing and very strong, while sugar maples and oaks are too slow growing to consider.

IN FIRST PLANTING a windbreak, the rows must be properly spaced so that the evergreens can attain an effective size without crowding from the deciduous trees; otherwise the lower branches will die. If this happens, the actual wind velocity under the remaining branches will be greater than that in open fields, and the desired effect will be lost. Spruces are especially bad in this respect, as they often lose their lower branches as they grow older. Pines and red cedar are much better choices. When loss of lower branches is first seen it can be minimized by heavy pruning of the deciduous trees on the side facing the evergreens. Columnar trees reduce this problem; even Lombardy poplars may be used, in spite of their other faults.

Spacings between trees or shrubs in a wind barrier are much closer than for ornamental plantings, but those who suggest planting trees four to six feet apart in rows only three to four feet apart are overdoing it. The rows in a shelterbelt should be at least five to seven feet apart.

Even under the best of circumstances, plant screens take a back seat to fiber glass or rock wool insulation in the walls of your house: they take time to become effective. But there are ways of reducing this time lag. First, start with the largest plants you can afford. State forestry nurseries have plenty of very cheap plants, but they are generally quite small. Larger plants from commercial nurseries cost more but can cut years from your program. If you are now living in your home year round, your budget will be the limiting factor. If you have a summer home to which you expect to retire in a few years, you can make substantial savings by starting with smaller (and cheaper) plants. Either way, give your plant screens plenty of attention so that they will attain maximum growth. Plant trees or shrubs in large holes with some superphosphate dug into the bottom. Then fill around the roots with a combination of equal parts of good topsoil, compost or peat moss, and sharp sand. Firm this with your fingers until there are no air holes left, then water well and add some soluble fertilizer. A good, fluffy mulch is always a help in getting the plants growing rapidly and keeping them in good shape later. Prune heavily the first few years to make the plants bushy at the base.

If rainfall doesn't average an inch a week, water thoroughly once a week. After the plants have made some root growth—in about six weeks or so—fertilize lightly with a chemical fertilizer, such as 8–8–8 or 10–10–10. Fertilize again about six weeks later, but not after the middle of June. Foliar fertilizers can be used until the first of September, especially if they are not too high in nitrogen.

One final word on pruning. Deciduous plants and scaly-leaved evergreens are normally pruned in late winter or just as growth starts. Needle-leaved evergreens, which have a single terminal leader, should not be pruned until the new "candles" are half to two-thirds grown, depending on how close you wish the whorls of growth to be.

If you make good selections for your area from the accompanying tables, get strong, healthy plants, and give them the best of care, your savings in fuel will eventually pay off and you will be more comfortable in the meantime. ◇

FRED NISBET has had a long association with gardening and landscaping. He is the author of more than a hundred articles on the subject, and co-author of *The Golden Guide To Flowers*.

Life in the Greenhouse

Despite growing interest in solar greenhouses and sunspaces, many potential owners discover apparent conflicts between what's best for energy savings and what's best for plants. The author suggests a total plan to enhance both heat gain and horticulture.

NESEC photo

Life in the Greenhouse

What Plants Want in Solar Designs

By Miriam Klein

A great deal of information on the construction and design of solar greenhouses is now available, but, to date, little of it has been directed towards horticultural management and even less towards this topic on a regional basis. This article focuses on the relationship between the performance and the design of the greenhouse.

A solar greenhouse requires consistent attention and care. Time and time again, greenhouse crops suffer because no one is there to open the vents, night curtains are not lowered, plants are over-watered, or pests are permitted to reproduce unchecked. The commitment of time is not a large one but must be consistent, sun up and sun down. Most growers spend from one to two hours a day on general maintenance, recording temperatures, opening and closing vents and night curtains, watering, pest control, and fertilizing. Planting and harvesting can require a total of two to three days per month, depending on the size of the greenhouse, the experience of the grower, the crops being raised, etc. Most people choose to spend more time in the greenhouse because it is a pleasant place to be and growing is such an appealing activity.

There is always a trade-off between optimization of thermal performance and horticultural performance. Until recently, the scales have been tipped towards thermal performance, because most designers have been solar engineers rather than growers. Now that our experience in this

Miriam Klein is with The Memphremagog Group, Newport, Vt. She has accumulated six years of experience with community groups working on small-scale food production and is a specialist on the ecological management of solar greenhouses with emphasis on applications for low-income communities. Photos by Miriam Klein and Andy Shapiro. Drawings for this article were reproduced for Solar Age by Malcolm Katz.

Above, the solar greenhouse atop the Northeast Solar Energy Center's Cambridge, Mass., building was used one year. NESEC moved its offices, dismantled the greenhouse, and gave it to the Urban Solar Energy Association in Boston, which recycled the materials.

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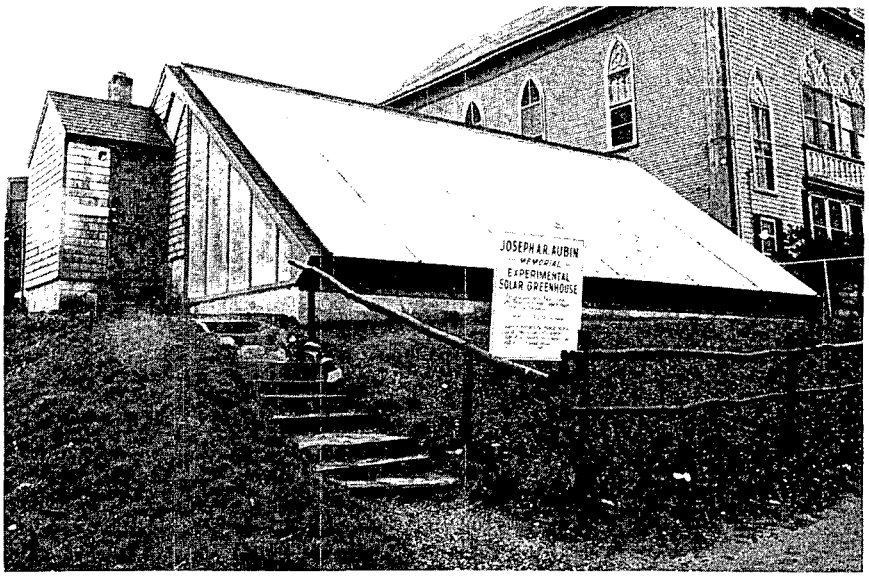
area has increased, growers are beginning to influence design and to suggest modifications that make the structure a greenhouse rather than a sunspace. Consider the plant's needs before you build a solar greenhouse. The design of the building must recognize certain basic horticultural requirements: light, humidity, carbon dioxide, and temperature.

The following discussion deals with each requirement separately because it is convenient to do so, but there are no easy divisions among them.

Similarly, vents, fans, storage, back-up heat, insulating curtains, the angle of glazing, and other design factors do not affect only one of these basic horticultural needs. It is beyond the scope of this discussion to detail all the inter-relationships. Simply keep in mind that no one factor operates independently.



This greenhouse has good light levels. The south side comes up high to meet the solid north roof so light is evenly distributed. East and west walls are partially glazed. Community Greenhouse, Fall River, Mass.

Light

The major difference between a solar greenhouse and a conventional greenhouse lies in the attempt to capture and retain heat. North walls and usually at least part of east and west walls are insulated. Since heat is rapidly lost from a transparent surface (glazing), designers tend to try to minimize the square feet of glazing and maximize the square feet of insulated surfaces. But a greenhouse is for growing plants, and plants require light to live and grow. The lesson has been learned by many greenhouse managers. *Don't sacrifice light to minimize heat loss.*

Morning light seems to be most beneficial for vigorous plant growth. If you have to choose between east and west glazing, choose the east. The west side is often subject to westerly winds that contribute greatly to heat loss, while the east side provides early heat and morning light.

Shading in the prime growing area is affected by the number and size of glazing bars on the south side. The prime growing area is right up against the glazing. Try to avoid using very wide rafters if the glazing material is not too heavy. If the glazing requires large rafters, be sure to paint the rafters white for better reflection of sunlight into the greenhouse.

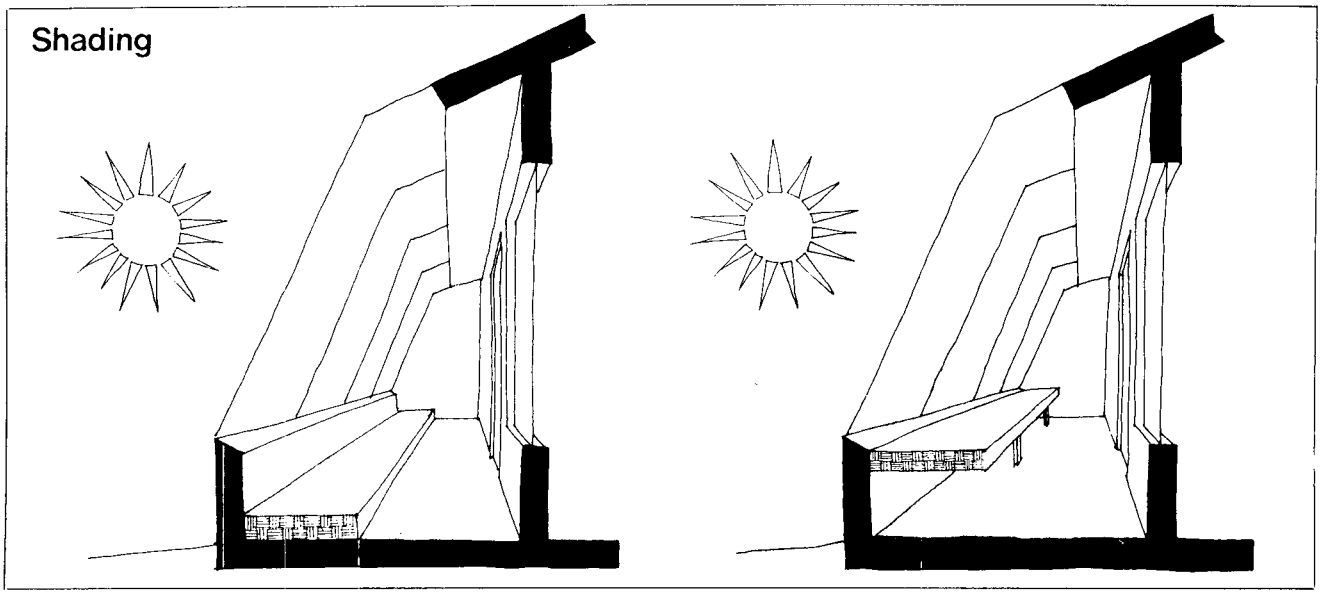
All interior surfaces in the greenhouse should be painted white to reflect diffuse light back onto the plants.

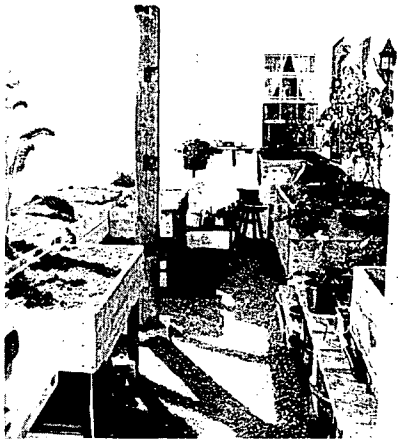
(A technical note from S.A. editors—blue and red offer the reflected range of light the plants need, so white, painted surfaces are not essential.)

If your greenhouse is built with a solid kneewall, be sure to bring your bed or bench up to the level of the glazing. If the bed is below the glazing level the front portion of the growing area will be in shade.

Studies done at Brace Research Institute in Quebec, Canada, have shown that the use of reflective materials in the greenhouse can contribute to larger yields and higher nutrient content in greenhouse

Recycled storm windows pose some problems if placed on an angle. The many cross pieces collect dirt, snow, and moisture and also contribute to shading on the front bed. Sonia Wallman, Northwood, N.H.





In May the back of this greenhouse is in total shade. The solid roof keeps the greenhouse cool in summer but limits the growing space because of low light levels in the back of the greenhouse. Len and Nancy Meserve, Westmoreland, N.H.

vegetable crops. There are two types of reflective materials used to increase the amount of available light to the plants.

A **diffuse reflector,** such as flat white paint, scatters light uniformly throughout the greenhouse. All interior surfaces are usually painted white to provide this diffuse light that plants prefer. Snow on the ground outside also acts as a diffuse reflector.

A **specular reflector,** such as aluminum foil, provides direct beam reflection. This is less beneficial than diffuse light and can also cause "hot spots" of concentrated sunlight that can burn plant leaves. Reflective foils can be used in the greenhouse but take care that the foil is not too close to the plants. Reflective paint serves the same purpose and will not burn the plants.

This greenhouse has a very narrow solid roof section against the north wall. The glazed roof vent allows light to penetrate to all parts of the greenhouse. Action Inc., Gloucester, Mass.

If you want to use the greenhouse to grow plants in the summer, be sure that your design permits light to penetrate to the back of the greenhouse. Often this means having a partly glazed roof. Even in the winter, when the sun is low in the sky, if there is a large solid roof section, some shading may occur in the back of the greenhouse, particularly higher up on the north wall.

Humidity

The ideal relative humidity (the actual amount of water in the air compared with the total possible amount) in the greenhouse should be about 60 percent. Humidity is closely related to temperature. The colder the air, the less water it can contain. Since high relative humidity (75 percent plus) leads to pest and disease problems, a cool greenhouse should be kept quite dry. When the relative humidity is too low, plants dry out. This problem can be controlled by watering down the walkways and misting the plants. High relative humidity is generally more difficult to control but can be handled with good ventilation.

Condensation is a result of hot humid air being cooled so the air can no longer hold the moisture. Usually, the glazing is the coldest thing in the greenhouse. Thus, water condenses first on this cold surface. This presents three problems: water droplets on the glazing reduce the amount of light that enters the greenhouse; water may drip onto plants, creating humid conditions that lead to pest and disease problems; and water drips onto sills. This leads to rot.

Be sure the seal between inner glazing and frame is tight so condensation doesn't form between the double glazings.

Bevel the sills on both the outside and inside of the greenhouse. Water should be shed off the sills rather than forming puddles that will eventually rot them.

Carbon Dioxide

Without enough carbon dioxide (CO_2), as without enough light, plant growth will be stunted. Fresh air must be introduced and circulated around the plants. When air conditions are stagnant, a boundary layer of air forms around plants' leaves. This boundary layer can be deficient in CO_2 even though there is plenty of CO_2 in the surrounding air. Plants take in carbon dioxide and give off oxygen. Composting in the greenhouse provides extra CO_2. You can also talk to your plants, or do your exercises in the greenhouse. It can't hurt, and the greenhouse is by far the most pleasant place to be on a sunny winter day.

It is a critical design mistake to skimp on venting area in order to cut down on heat loss through air infiltration. Adequate **ventilation** is vital for reducing temperature and humidity and increasing CO_2 availability. Air infiltration can be corrected by caulking or weatherstripping vents during the winter months. Don't sacrifice ventilation. If no fans are used, the rule of thumb is that the total square feet of openings to the outside should equal from 1/5 to 1/6 of the total floor area of the greenhouse. For example, in a 150-square-foot greenhouse, the vent area should equal from 25 to 30 square feet.

Cross venting is an effective way to provide good air circulation. This can be achieved by placing vents on both east and west walls. The windward vent (the side most exposed to wind) should be lower and approximately half the area of the leeward vent (the side most protected from the wind) to create a good cross-draft. One vent should be lower than the other so they do not pull against each other.

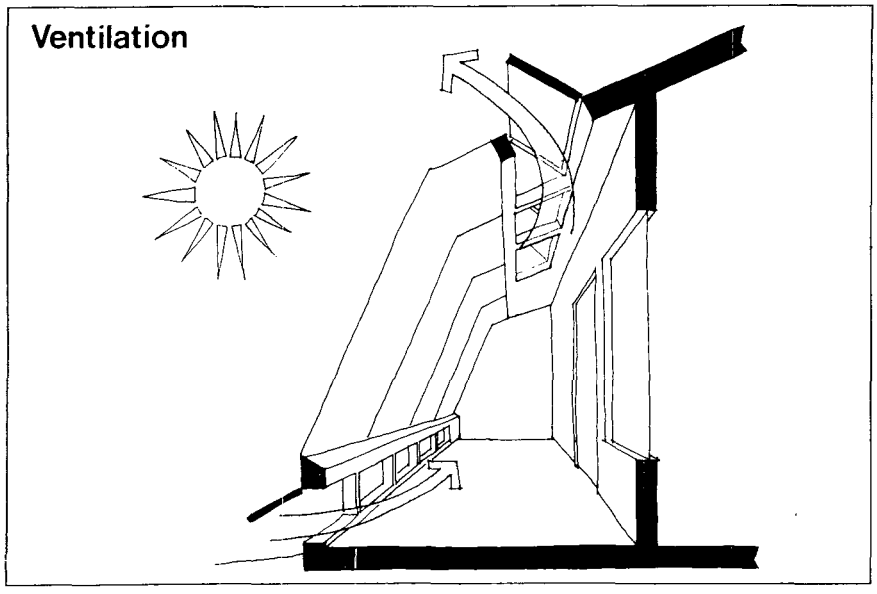
In many cases vents are situated at the ridge and kneewall of the greenhouse. The rising hot air at the ridge pulls the cooler air from below, providing good air circulation. The size ratio of the top and bottom vents should be 55 percent and 45 percent, respectively.

Unless the vents are automatically operated, the greenhouse grower controls ventilation. In the Northeast, in an attached greenhouse, vents are only operated during the warmer months—May to October. From November to April, excess heat from the greenhouse is vented into the attached house rather than to the outdoors. In a free-standing greenhouse, however, the vents must be operational 12 months a year. Without ventilation the greenhouse will overheat even on a cold sunny day in January. One Vermont free-standing greenhouse overheated to 140°F on Christmas Day, when no one remembered to open the vents. The outside temperature was 20°F.

Be sure to vent adequately. In the summer this will mean leaving all the vents open most of the time. In the fall, spring, and winter, someone must open and close vents in the early morning and evenings. Sometimes it may be necessary to operate the vents during the day. You learn to be very attuned to changes in the weather. Many greenhouse operators noticed that they had much greater sensitivity to their environment, seasonal changes, sunny periods, cloudy periods, etc. Gardeners share this sensitivity; the greenhouse enhances it.

If your situation does not allow you to be present to operate vents, fans may be the answer. They can be used in three ways: assisting air exchange from the greenhouse to the outside; assisting air exchange between the greenhouse and the house; and mixing air within the greenhouse.

A thermostatically controlled fan can be a greenhouse-saver for people who work



far away from home, or in community greenhouses where weekend duties are difficult to coordinate. The fan automatically turns on when the maximum temperature setting is reached and turns off at any point below that setting.

A small fan placed at the ridge of the greenhouse will help to move air into the house and to mix air within the greenhouse. Without a fan, you will need two openings into the attached house; one at the top of the greenhouse and one at the bottom. If this is impossible, a door will work to some extent. Windows used to vent excess heat into the house should be opened from the top to bring the warmer air into the house. Do not use an unheated cellar as the cold air opening if the temperature in the greenhouse is permitted to fall below freezing. One such case resulted in frozen cellar pipes.

Temperature

Most plants prefer no more than a 10° to 15°F change from day to night. Since the temperature in a solar greenhouse can fluctuate by as much as 30° to 40°F between sunny days and clear nights, something must be done to reduce this fluctuation.

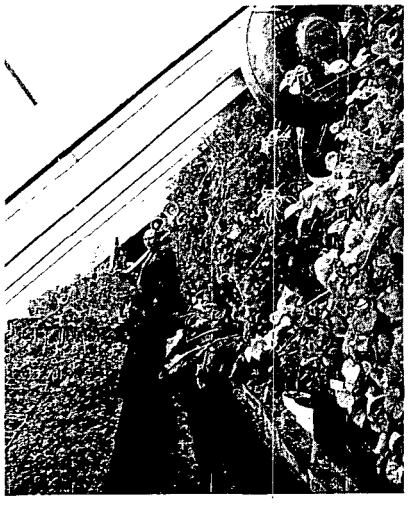
In a solar greenhouse, most of the heat is lost at night and on cloudy days through the glazed south side. To reduce this heat loss, insulating curtains or shutters are placed against the glazing at night and are removed during the day to admit light. Styrofoam brand sheets that fit against the glazing at night are a simple solution as long as you have somewhere to store them during the day. Curtains may be a major expense. The most effective curtains cost between $3 and $5 per square foot. A blanket/curtain rigged over the plants on very cold nights may be more sensible than insulating the entire south side of the greenhouse. Of course, this will not keep the air temperature of the greenhouse from falling, and if there is a succession of cloudy days the plants will suffer from the low temperature.

More experience is needed to come up with a low-cost night insulating curtain to solve the problem of low nighttime temperatures.

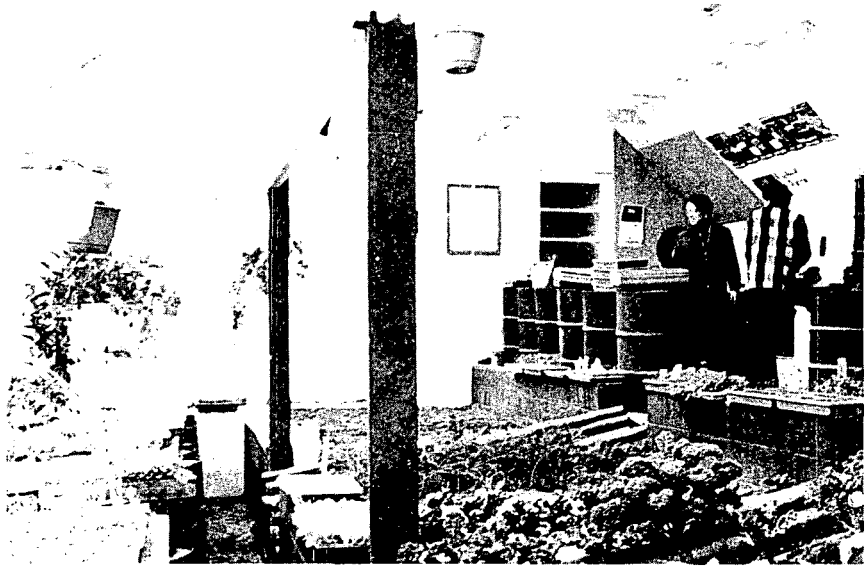
In an attached greenhouse in the winter, vents and doors to the outside should be insulated and sealed to cut down on air infiltration. Greenhouse operators in Fall River, Mass., just stuff the vent with fiberglass insulation. The insulation doesn't get wet since the vent is louvered on the outside. Styrofoam or other insulating material can be cut to fit the vent and sealed around the edges to prevent infiltration of cold air. The idea is to stop heat from escaping during the cold winter months and still have enough vent area to keep the greenhouse from overheating when outdoor temperatures are high.

Some form of supplementary heat can be used in the greenhouse to prevent temperatures from falling too low. If your greenhouse is attached to your house, you can vent excess heat into the house during the daytime (using the house as part of your storage) and put some heat back into the greenhouse at night and on cloudy days.

Gail and Joe White let the snow build up against the south slope of their pit greenhouse in Brentwood, N.M., during cloudy spells. The snow acts as an insulating blanket, and the plants are fine without light for those few cloudy days. When sun is forecast, they shovel the snow away early to make sure that the plants get the



Joe White uses two circulating fans 24 hours a day in his pit greenhouse. He runs an herb business nine months out of the year and finds that the fans reduce his pest disease problems, particularly in the case of white fly. Yearly cost for operating the fans is estimated at $10.00. Joe White, Brentwood, N.H.



This greenhouse is designed for food and seedling production. Ample storage is provided by 55-gallon drums stacked two high along the north wall and deep soil beds running through the middle of the greenhouse. Drums along the south side are less effective at picking up heat since they do not receive any direct sunlight. Community Greenhouse, Fall River, Mass.

benefit of the morning sun and heat.

Attached greenhouses are often built at a lower level than the adjoining house. Unless you have a circulating fan, cold air settles and stays near the ground. This means that some plants will always be sitting in the coldest air in the greenhouse. For this reason, plant benches and beds should be as high or higher than the floor of the adjoining building. The plants have enough to put up with in the winter without being in the coldest spot in the greenhouse.

Thermal Storage

Thermal storage in solar greenhouses keeps temperatures from fluctuating too much.

Water storage systems are simple and require no parts beyond the containers themselves. Here are some examples. Consider how long they'll last and how much room they'll take up.

55-gallon drums are usually used because they are inexpensive (free to $5 second-hand) and easy to locate. Check the yellow pages under drums. Problems: they take up a lot of space; they rust after a few years and start to leak; and once filled, they are very hard to move.

Honey tins are small (five-gallon), square metal containers. They can be stacked very efficiently to any height. They take up less room than the round drums. Problems: they are expensive; they are difficult to find in quantitiy unless you are associated with a coop or some place that consumes a lot of honey; and they rust at least as quickly as the drums.

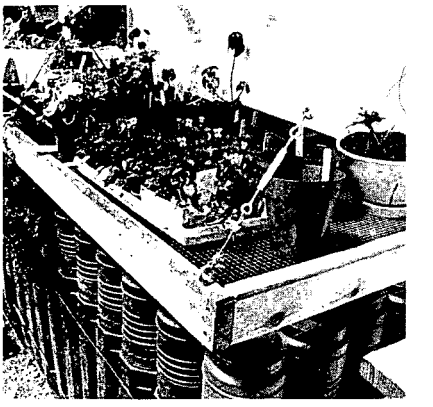
Dark colors absorb heat best. Paint containers any dark color, dark green, dark blue, dark red. You can paint pictures if you like, as long as they are dark.

Cider jugs are small (one-gallon) plastic containers. Problems: they're not strong enough to stack and are fairly expensive. They can be very useful as extra storage that can be popped in wherever there is some spare space.

Sonar buoys are five-gallon containers used by the U.S. Navy. They are easy to stack and take up less room than drums. Problems: unless you have connections with the Navy, they are expensive ($1 to $5 each).

Anything that holds water can be used as extra storage on sunny days. Look around for other containers.

Rock is also a good storage medium but you need to use a fan to push warm air through the rock. This is more expensive and complex than water storage. It requires more parts, and there are more break-down problems than with a water system.

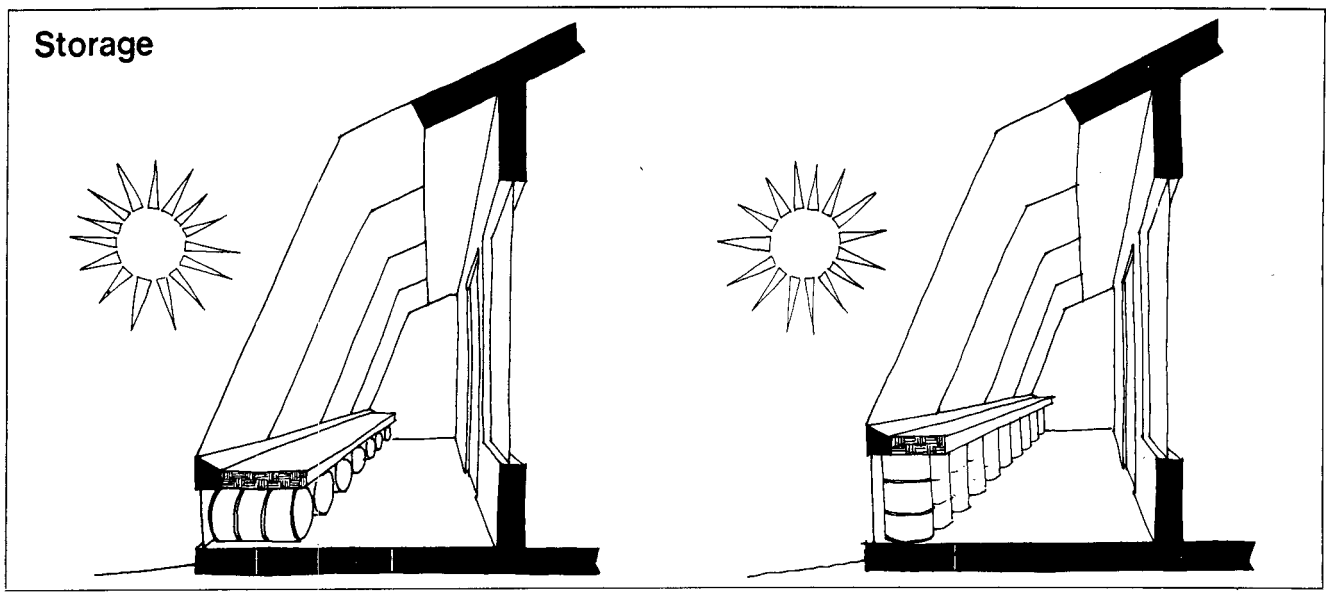


Sonar buoys arranged three deep along the north wall. Screen suspended from above allows heat to rise, warming the plants. Action Inc., Gloucester, Mass.

Soil is an excellent storage medium. Most people use it without realizing that it is acting as storage. Wet soil, in particular, has the capacity to hold a lot of heat and to release it very slowly.

If you have a masonry wall on the back of your greenhouse, or would like to build one, paint it a dark color and use it as storage instead of or in addition to water.

How much storage? In the coldest parts of the Northeast, 3 to 5 gallons of water per square foot works very well. In a 150-square-foot greenhouse, (10 by 15), eight or nine 55-gallon water drums would be about right. This is only a general formula. You will need less storage if: the greenhouse is tight and well insulated; the



plant varieties you choose can withstand temperature fluctuations and fairly low nighttime temperatures; you are willing to put some heat back into the greenhouse from the attached house at night and on cloudy days; or nighttime insulation is used to cut down on heat loss at night.

There is always a trade-off between placing the storage where it will pick up the most heat and having the most space for growing plants.

Since every greenhouse is different, there is no set formula for where to place the storage containers. Here are some general rules.

Try not to shade storage with tall plants growing in front of the containers during the winter months. The more direct sun the storage is exposed to, the better it is at storing heat.

Nothing should block the flow of air from the greenhouse into the attached house. Don't place the storage where it will block a door or window used to vent heat into the house.

Try to balance the storage throughout the greenhouse. Don't place all the containers on one side (east or west) of the greenhouse.

Storage is often placed along the north wall. The angle of the south side is usually designed to allow direct sun to hit the north wall in mid-winter. A shelf for starting seedlings can be run along the top of 55-gallon drums stacked two high. Since warm air rises, this takes advantage of the warmer air at the top of the greenhouse.

Storage can be placed under beds or shelves on the south side. The advantage to this is that the storage will pick up a lot of heat when placed against a glazed south side. The disadvantage is that you must then work with raised containers instead of ground beds, which are preferable for growing.

Place storage so that the largest surface area is exposed to the sun. The efficiency of the storage at picking up heat will make a big difference to the temperature's stability, and in turn, how well your plants will grow.

When filled with water, each 55-gallon drum weighs 450 pounds. Make sure the drums are securely placed, one on top of the other. Placing 2 by 2's between the two drums or staggering the drums allows air to move more freely between them.

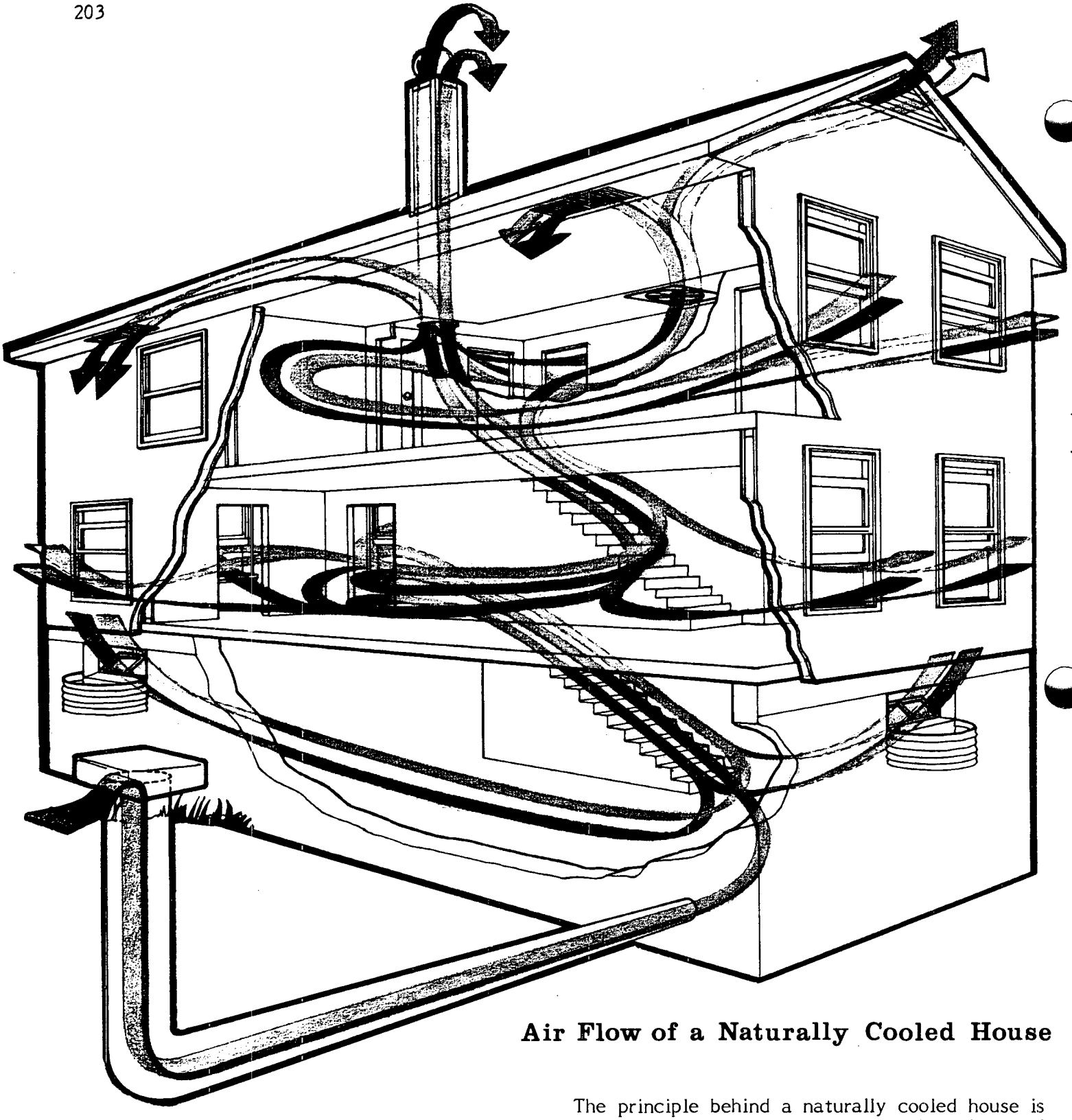
The way you lay-out your greenhouse will depend on what you want to grow. Potted plants can be grown on benches, shelves, or suspended from the ceiling. Most vegetable crops will grow best in deep soil beds that can be at ground level or elevated and adequately drained.

(Ed. note—For a discussion of the pros and cons of using thermal storage in solar greenhouses and for more information about actual experiences with attached greenhouses, see "Riding the Learning Curve" by Jeremy Coleman, Solar Age, June 1979.)

This article has been excerpted, condensed, and edited from a manual entitled, "Horticultural Management of Solar Greenhouses in the Northeast." The manual was written in order to share the successes and failures that solar greenhouse growers have been encountering and to provide basic information on how best to use these structures to produce food. The manual was produced and published by The Memphremagog Group, P.O. Box 456, Newport, Vt. 05855. Newport is located on Memphremagog, which means "Lake of the Beautiful Waters." The group is a non-profit corporation formed to provide services and conduct research on the way communities can become more self-reliant in meeting basic human needs of food, shelter, education, and meaningful work. The manual can be obtained from The Memphremagog Group or from the Center for Ecological Technology, 74 North Street, Room 610, Pittsfield, Mass. 01201. Price: $4.00 for one copy; $3.50 for two to five copies; $3 for six to 19 copies; and $2.50 for 20 copies or more.

The "Other" Energy Crisis

The natural thermosiphoning effect of heated air can, paradoxically, be used to bring about passive cooling for hot summer days. This article tells how.



Air Flow of a Naturally Cooled House

The principle behind a naturally cooled house is upward air flow. By day, cool air enters through a cool tube into the basement or, by night, through basement and upper level windows. This air is then drawn up through and out of the house by the pulling action of the whole house fan or a thermal chimney. The components are interchangeable, but the results are the same: cool summer comfort.

The "Other" Energy Crisis

Energy is usually portrayed as the stuff that keeps our teeth from chattering on a winter's night. And when we think of alternate energy, it seems as if the heating season has a monopoly on exciting solutions: A hundred beautiful contraptions for burning wood . . . a thousand homes of striking design, made almost entirely of glass and green plants . . . people calling for a new harmony with the sun.

How are those things going to help you come summer, when you're looking for shade? The cooling season presents an energy crisis of its own. Those Northerners who move to the Sunbelt, thinking to escape energy's high price, find it comes back to haunt them with the first electric bill after the air conditioner is turned on.

Just as winter is fended off with passive solar heating, summer can be subdued by something called "passive cooling." Passive cooling is a lot like passive heating, in that it works its magic by using the laws of nature and a minimum of moving parts. In a way, it's the mirror image of passive heating: Whereas the first commandment of passive solar is to do everything possible to prevent heat loss, passive cooling's mandate is first to reduce heat gain. Then passive solar collects heat from the sun, whereas passive cooling gets rid of it.

There's one more parallel to draw. Like passive solar heating, passive cooling is "ninety per cent common sense and good design," according to Dr. Donald Elmer, chairman of the Passive Cooling Standing Committee of the International Solar Energy Society (American Section).

Elmer notes that there are four factors affecting human coolness: (1) air temperature (2) the temperature of surrounding objects (3) air movement, and (4) humidity. Accordingly, Dr. Elmer's definition of passive cooling is use of the structure (home, office, whatever) to reduce heat gain to the interior, or increase air flow, or reduce humidity. There is more than one way to get cool, and you choose your weapons according to your site and climate.

As you might guess, our ancestors knew more about passive cooling than we do. For instance, the adobe houses of the Southwest had such thick and slow-to-heat walls that the human body would radiate its warmth to them throughout much of the day (that's cooling factor #2). At night, of course, the process would reverse and walls would heat bodies. In the Southeast, where high humidity makes air movement crucial to evaporation of perspiration, "dog run" houses took advantage of a central hallway to funnel prevailing breezes through the hall and into adjoining rooms. In coastal Georgia and South Carolina, the oldest houses are positioned to catch onshore/offshore breezes. Tall ceilings—10 to 12 feet above the floor—allow the warmest air to rise above the inhabitants. Double-hung windows, nearly as tall as the rooms, can be opened at top and bottom so breezes strip heat off the ceiling and dump it outside.

If you ever visit Thomas Jefferson's home, Monticello, in southern Virginia, take note of his design: thick masonry walls, plenty of tall windows and breezeways to capture hilltop breezes, a two-story-high central hallway, and cellar-level passageways leading to outbuildings. These passageways may have acted as rough cool tubes, drawing the earth's coolness into the main building.

So we have much to re-learn, and much to borrow from other, less energy-intensive cultures. For the last 30 years or so, we have been able to make our homes into giant summertime refrigerators. But as the cost of electricity rises, we'll use our air conditioners less. Other solutions will fill the gap. We can draw from the past; we can also use modern technology to be naturally cool as never before.

The solutions, both old and new, fall into these categories:

Preventing heat gain This is simply the hiding of your home's interior from sun and heat. If you're designing a new home, it means positioning it so your shortest walls face east and west, and keeping west-facing windows to a minimum. It means overhangs so your windows are shaded. If you already have a home, preventing heat gain means all manner of shading devices, from trees and trellises to bamboo screens. If you can, use those screens to shade your windows from the outside, not from inside. Inexpensive little solutions like that are remarkably effective. Insulation and weather stripping are also passive cooling devices, believe it or not. They slow down the invasion of heat and hot air into your home. A well-insulated house with windows closed and shades drawn should keep you cool for the first half of a hot summer day.

Earth cooling Eight feet down, the earth is cooler than summer air. If household air is brought in contact with the earth, it will give up some of its heat. This idea is put to use in cooling tubes, underground homes, and systems that pump well water through coils in the house, whereupon a fan blows air over the coils to achieve cooling.

Sky cooling In the clear, cool nights of the Southwest, massive materials radiate their heat to the nighttime sky. The most well-known design to take advantage of this effect is Harold Hay's patented roof pond system. By day during the summer, a pond of water on a flat roof is covered by insulation while it absorbs household heat. By night the pond is uncovered, the heat is released to the sky, and by next morning the pond is ready to cool the house again. During the winter the process is reversed: The pond is covered by night and uncovered by day.

Ventilative cooling This includes all the old ways to capture prevailing breezes and let them move through the house by means of hallways, transoms, windows and louvered shutters. It also includes new ways to induce a breeze when there isn't any. These ways take advantage of the "stack effect"; that is, as air warms it rises, seeking a way out and drawing cooler air from below to replace it. A thermal chimney is a prime example of naturally induced ventilation.

Desiccant cooling In the Southeast, high humidity can be a bigger demon than temperature. The body's natural cooling mechanism, perspiration, can't work effectively because the moisture-laden air has a hard time evaporating it. In such a condition, any air movement is welcome, even if it comes from a sluggish ceiling fan. Even more welcome, however, is something that dries the air. Air conditioners and dehumidifiers do this wonderfully, but at great expense, so researchers are exploring new techniques. Fuller Moore, an architect and educator at Miami University in Oxford, Ohio, has designed a two-chamber box that looks like a solar collector attached to a house. On one side, humid air flows over trays of activated charcoal before entering the house. In the other chamber, saturated trays sit under glass to dry out.

Evaporative cooling Air's temperature is actually lowered when it absorbs water because the evaporative process uses up heat—1,000 BTUs, in fact, for every pound of water added to the air. This is used most effectively in hot, dry

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climates. Incoming breezes are cooled in passing over jars of water, through fountains, across pools and around trees (which transpire water pulled up from their roots). Though its effect in humid climates is much reduced, it may be of some comfort.

Flywheel cooling This is the cooling effect achieved by the massive adobe houses of the Southwest. The sheer mass acts like a thermal flywheel, taking a long time to "get rolling" (heat up) but also taking a long time to "slow down" (cool off). The long delay in heating the mass causes interior air and inhabitants to be cooled by mass walls on hot afternoons. In houses with insulation on the exterior side of mass walls, this effect is heightened. The walls soak up only interior heat and can be "discharged" at night by drawing cool nighttime air through the house.

Some of the applications of these cooling methods are still very much in the experimental stage. Some may turn out to be impractical. But the overall concept of passive cooling will, in the end, probably prove much more practical than the air conditioned summers we live in now. ■ **L.R.S.**

Cool Tubes

Making use of all the mild weather down under

by Julie Lalo

It's so hot, it's stifling. You seriously consider setting up camp in the basement. Why is the basement so cool? The answer lies in the earth. Just a few feet below the surface, the earth maintains a fairly constant temperature which, in the summer, is cooler than the air.

In order to take advantage of the vast uncharted cooling resource beneath our feet, a few innovative home builders are now developing ways to channel air underground and then circulate it through the house. These naturally cool channels are called cool tubes.

The bad news about cool tubes is, nobody yet knows exactly how well they work. Because so few examples have been built, tested, and lived with, there are no rules of thumb for constructing them. *New Shelter* contacted more than a dozen builders of the tubes; each had a different way of doing things, and all wanted to hear about everyone else's method. How long should the tubes be? What width? Of what material? These are the kinds of questions that need to be answered.

The good news is, builders and designers are getting a handle on these problems, and work being done across the nation should lead cool tubes beyond the experimental stage in the next couple of years. So we took a look at some pioneering installations to see what's happening now and what the future may hold.

In a suburb of Atlanta, Georgia, Terry and Andrea Schneider are spending their first summer in a solar home they built themselves. Their cooling system consists of four cool tubes, each 100 feet long, and a thermal chimney.

The cool tubes are made of eight-inch diameter galvanized duct material, the same ducting commonly used to distribute hot and cold air through houses with conventional HVAC systems. A price of 23 cents per linear foot certainly makes this material "low-cost." The four tubes stretch out under the earth on the eastern side of the house. The east wall of the house is bermed, so the tubes are buried under 12 feet of cooling earth before dipping under the house's concrete slab and up through it to exit at floor registers. The floor registers are standard 3 × 14-inch louvered vents that would fool you into thinking the Schneider house has a conventional central air conditioning system. The registers open and close, so the house can be shut off from the tubes when the cooling isn't desired.

The tubes themselves are only half the total cooling operation. Air doesn't move through them by itself; it needs something to pull it through. The driving force to do this is a thermal chimney on the west side of the house. Atlanta architect Richard Sibly, who designed

Right: *Terry Schneider and the house he's built in suburban Atlanta. The thermal chimney, which provides the driving force for the cool tubes, is an integral portion of the sloped glazing you see at rear.*

the Schneider house and its cooling system, says the cool tubes and thermal chimney are "the natural equivalent of a one-ton air conditioner. We tested it earlier this year and we've gotten a good draft through the system." Sibly has confidence in his system because he based it on measured performance of other thermal chimneys, and consulted the ASHRAE (American Society of Heating, Refrigeration and Air Conditioning Engineers) Handbook to figure out how much friction the cool air would encounter when dragged through 100 feet of eight-inch metal tube. "It wasn't a guestimate," says Sibly. "We had some sanity in our design."

Just how well the system will function, especially during the hot sticky month of August in Atlanta when the earth's temperature gets its warmest, is something that Sibly hopes to find out this summer.

The four cool tubes at the Schneider residence were wrapped in polyethylene before being buried in the earth, and all four tubes slope upward from their inlets to the house. The polyethylene seals the tubes from disease spores and insects that can inhabit the soils of the local region, and the slope insures that any moisture in the tubes drains away from the house, rather than toward it. The Schneiders want to keep their tubes as dry as possible because a number of cases of Legionnaires' Disease have been traced back to cool, wet environments such as the central air conditioning systems of office buildings. (Andrea Schneider works at the Center for Disease Control in Atlanta.)

Moisture within the cool tube is something that *should* be happening if the tube is working well in a humid climate. As you know, hot air can hold more moisture than cold air. As hot, humid air is cooled on its way through the tube, some of its moisture condenses on the sides of the tube, just as if the tube were the outside of a glass of iced tea. So cool tubes should dehumidify air as well as cool it.

That's the effect Ohio builder Ray Baker is really counting on. He has installed two cool tubes as part of a natural cooling system at a new house in suburban Cincinnati. "If we can just dehumidify the air, we don't have to cool it that much," he says.."Here in the summer, it's the humidity that kills you."

The two cool tubes at the suburban Cincinnati residence are each 40 feet long. They are 12-inch galvanized corrugated metal buried seven feet deep. Like the Schneider residence in Atlanta, the driving force pulling air through the tubes is a thermal chimney. A test run late last year, when cool tube inlet temperatures were in the 50s and thermal chimney stack temperatures were in the 90s, produced a 200 cfm (cubic feet per minute) air flow in each tube.

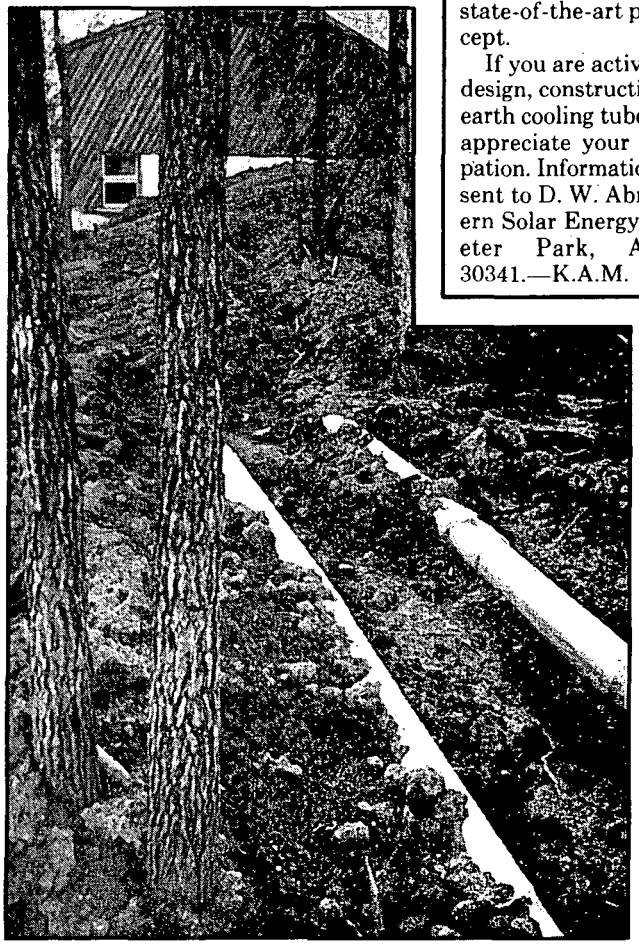
But how well will they work through a Cincinnati summer? "I don't know what's going to happen to these things; nobody knows," says Baker. "We'll

Cooling Tube Clearinghouse

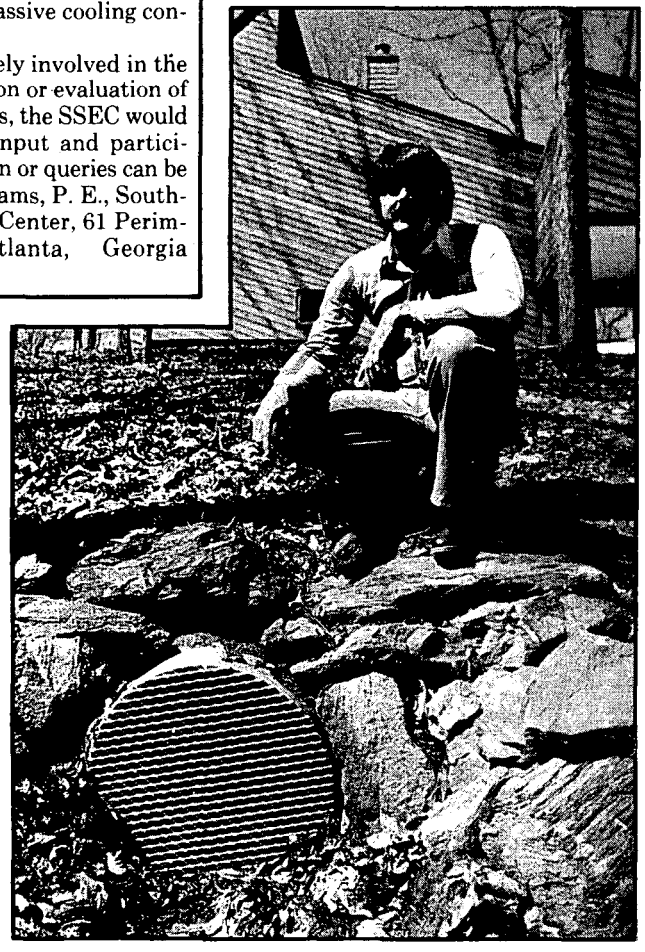
The Southern Solar Energy Center currently is establishing an Information Exchange Group to aid the advance and development of this state-of-the-art passive cooling concept.

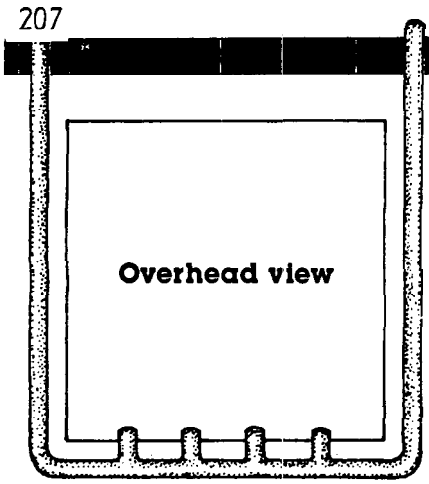
If you are actively involved in the design, construction or evaluation of earth cooling tubes, the SSEC would appreciate your input and participation. Information or queries can be sent to D. W. Abrams, P. E., Southern Solar Energy Center, 61 Perimeter Park, Atlanta, Georgia 30341.—K.A.M.

Below: *Here are two of the Schneiders' four cool tubes. The photo shows them as they were this spring, before landscaping was complete. They are now completely buried. Their inlets, 100 feet away from the house, draw cool shaded air from a wooded spot.*



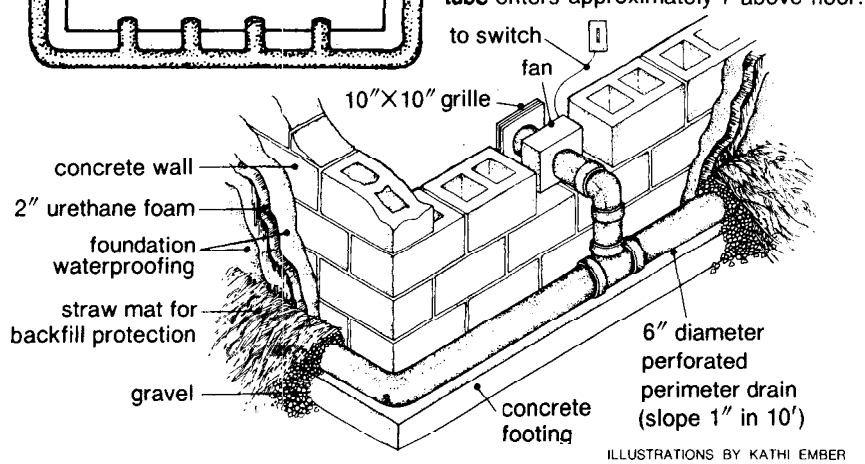
Below: *Skeet Stokes kneels next to the inlet for one of two tubes that cool his Canton, Georgia, home. The 20-inch diameter aluminum cool tube is covered by an aluminum screen to keep frogs, mice, and other little creatures from paying a visit.*





Mike Ondra's Cool Tube Design

Mike Ondra is an architect and partner of Shelter Design Group, Stony Run, Pa.



ILLUSTRATIONS BY KATHI EMBER

know for sure this summer, but frankly, I'm not that concerned. If common sense is anything at all, they're going to work. If the earth down there is 60°F. in August, which is what it will be, and you bring in heavily moisture-laden air, you're going to wring out moisture. You'll just have to."

One source of inspiration for Baker's cool tube work has been Richard Strayer, an architect and energy consultant in Dublin, Ohio. Strayer recently built a home in Ottawa, Ohio, that has a series of cool tubes and the *effect* of a thermal chimney. That is, all ceilings in the home are vaulted toward a high point, where an operable vent allows rising hot air to escape. This draws air through the cool tubes, which vary in length from 20 to 30 feet. All are made of concrete. They enter the home through the basement wall, and feed (through metal duct work) directly into the home's forced air heating system. So the cool summer air enters through ordinary-looking registers, as in the Schneider home. But *unlike* the Schneider home, Strayer designed his cool tubes to run downward into the basement, rather than uphill. Water accumulation in the tubes so far has been "almost nothing," Strayer claims.

The cost of the cool tube system in Strayer's Ottawa home came to $1,000. "Of course, that's much cheaper than an air conditioning package," he says. "And here is a method of cooling in which you won't be paying for the energy ever afterward."

Mike Ondra, a Pennsylvania designer of energy-efficient homes, has a little different approach. He takes advantage of the perimeter drain he installs around his houses to do double duty as a cool tube. (See Illustration) The plastic tubing, six inches wide, runs around the perimeter of the foundation. Picture a "U" with the house at the elbow and you have a birds-eye view of Ondra's design. The tubing ($1 per linear foot) is perforated for drainage as it circles the house. Ondra packs it in gravel with a layer of straw on top and earth covering that. Then, as the tube stretches out beyond the house, it is not perforated and it's packed only in earth.

A small, low-wattage blower at the cool tube's basement outlet pushes the cool air up, into and through the house. Ondra says he places the fan at the cool tube outlet rather than where the hot air is vented out the top of the house for a very good reason. "One disadvantage of having the fan at the hot air outlet is that you're drawing air through all the leaks in the house (in addition to the cool tubes), creating a negative pressure."

Winter use, Ondra says, depends on the home owner's wishes. Duct work can be added to connect the cool tube to a wood stove, so combustion does not burn up already-heated house air. Or a damper at the inlet can be closed to discontinue its use during the cold months.

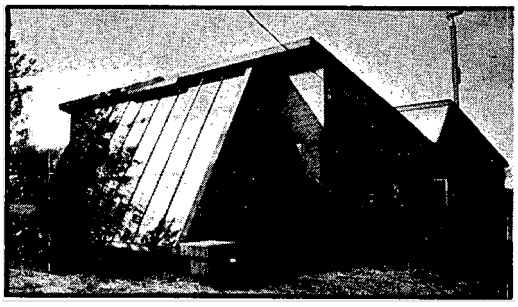
Like Baker, Ondra sees cool tubes partly as a dehumidifying device. He likes to compare their effect to that of squeezing a wet sponge. "As you squeeze the sponge, water drips out. When you release it, the sponge returns to normal size and air has taken the place of the water." Similarly, as warm air cools on its way through the tube, the temperature differential acts as the hand squeezing the sponge. The cooler the cool tube, the more water is squeezed out, which condenses on the side of the tube. As long as some provision is made for the water to drain out, the system can work effectively, he says. And he hopes for good things to happen with the cool tubes in the homes he built this spring. "I am expecting a 15 to 20 degree temperature drop in the tubes as well as a 30 per cent relative humidity drop," he says.

So much for builders and designers. Do the owners of tube-cooled homes enjoy their low cost method of cooling? Sistie Howie of Raleigh, North Carolina, says of her cool tubes: "Last summer, even though our house wasn't finished completely, our house was definitely cool. I am confident that we will have an enjoyable temperature in here this summer." Mr. and Mrs. Roger Brahler of Milford, New Jersey, are also happy with their system. They had a cool tube installed last May and they say, "We didn't specifically monitor the cool tube, but from a comfort standpoint, the tube performed very well."

What Mike Ondra had to say about moisture drainage rings true with Bob Mastin, the owner of an Ekose'a designed Rhode Island home. Mastin says his cool tube, completed in March of 1979, took 92°F. outside air last summer and effectively cooled it to 68°F. But his tube, 50 feet of 24-inch diameter corrugated aluminum culvert pipe, was installed without perforations. "It was constantly soaked, so I literally had to crawl through the pipe and drill holes in the corrugations."

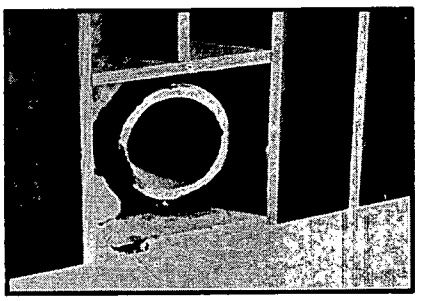
Another home owner is Paul Hansel of Dalton, Minnesota. In April 1979 Hansel installed four 125-foot-long pipes underneath his yard, spending

PHOTO BY LONGLEY STUDIOS

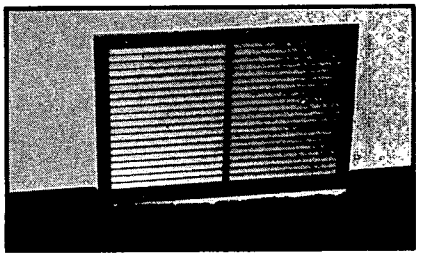


Above: *The low T-shaped wooden bench in the foreground is Ray Baker's attractive way of camouflaging his cool tube inlet in the yard. The uppermost portion of the slanted glazed wall serves as the thermal chimney.*

PHOTOS BY LONGLEY STUDIOS



Above: *The outlet: Now you see it, now you don't. The photo above shows the tube's floor-level hookup in a suburban Cincinnati house built by Ray Baker.* **Below** *you see the tube disguised as a mild-mannered forced air vent.*



$608 in doing so. The pipes are plastic drainage pipes, "the cheapest you can buy," he says. "If they make pipe so water can be carried away by it, well, the same thing will happen if condensation's in there." Hansel says his pipes don't fill up with condensating water because they are perforated for drainage, and the only place such perforations would be a problem is in places with a high water table. In that case, "the pipes would be full of water and wouldn't do anything."

Hansel is happy with the performance of his cool tubes. "Our house temperature now is always more than 10 degrees below the outside temperature, and usually 15 degrees below." The humidity is also lower inside, he says. Hansel's inspiration for installing the tubes came not from architects or solar homes he'd seen, but "from Encyclopedia Britannica. They did this stuff in Persia in 6 B.C." He took on the project without benefit of formal engineering background or calculations. "The only thing I set out to do was stay cool," he says.

Doug Nordham, a researcher at the Solar Energy Research Institute in Colorado, says about Hansel and his cool tubes: "I asked him how he decided what depth to put it at, how long to make it, and all that, and he just said, 'Well, I dug down far enough until the earth felt cool, and I stretched it out far enough to make sure it would work.' And, you know, he probably got pretty close to what the optimal specifications of a cooling tube should be. It's like solar collectors. You can spend lots of money on fancy arrays that are highly efficient, but basically, if you put a black hose on your roof and run water through it, you're going to get heat. And basically, if you put something in the ground and run air through it, you're going to get cool air."

That was good enough for experimenters like Hansel, but many builders, designers and home owners want to know the very *best* way of doing something. Thus, more site experiments and computer simulations have to be done. Soil characteristics, tube material, drainage and cost vary greatly from site to site. These and a multitude of other variables have to be shaped into finite "rules of thumb." Harold Hill, a professor of architecture at Virginia Polytechnic Institute, says a definitive system for calculating variations is possible, and he is working to develop such a system. Others, such as the Princeton Energy Group, an architectural firm in New Jersey, are conducting experiments this summer to determine optimal cool tube specifications. And still others are doing research into the cool tube's potential as a pre-conditioning tube for warm air intake in winter.

When the answers emerge, we'll let you know.■

Further reading:

Paul Hansel has written a five-page report containing plans and details of his cool tube system. He is selling copies for $8.50 each. His address is: Paul Hansel, Dalton, MN 56324.

Ekose'a Homes, Ekose'a, 573 Mission St., San Francisco, CA 94105 $24.95

The Thermal Chimney

A new device cools an old house on 100-degree California afternoons

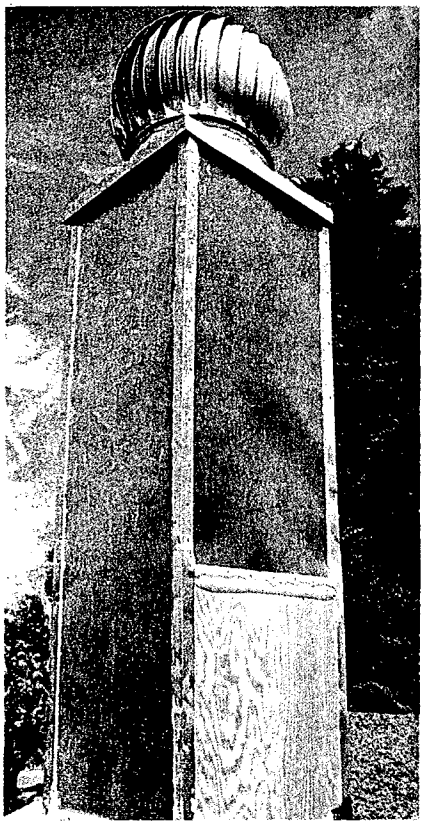
by John Burton and Jeff Reiss

On a summer afternoon, Sacramento is a baked-out sack of tomatoes. Temperatures sometimes exceed 110°F. On days like that, people in Sacramento and throughout California's Central Valley start reaching for their air conditioners in unison.

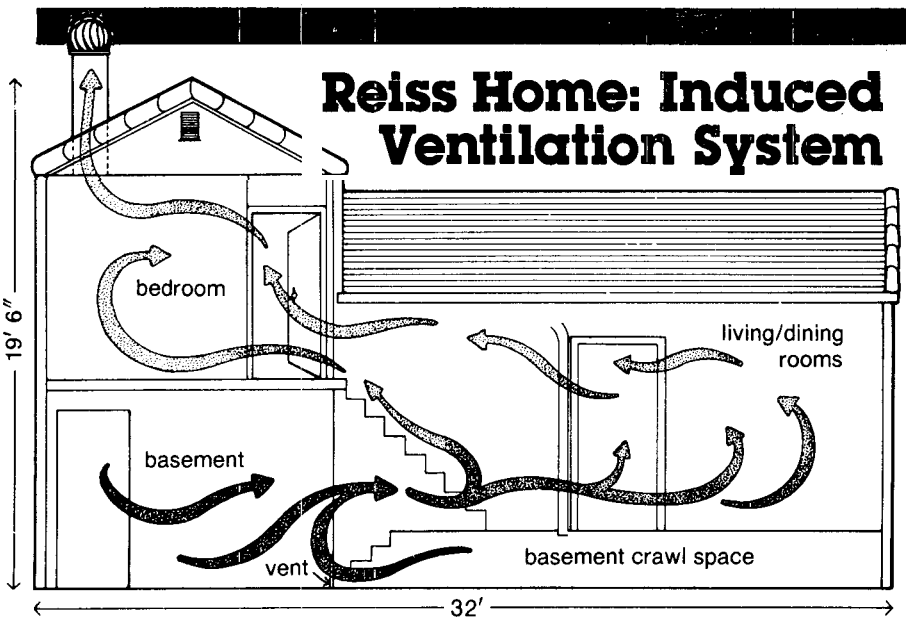
But when the sun goes down, the land cools off. Sea breezes from the San Francisco Bay begin to pour through the Carquinez Straights, and by early morning it's not uncommon for our outdoor thermometer to have dipped below 50°F. These cool and breezy nights offer a near perfect opportunity for natural cooling. Ventilation, rather than air conditioning, could purge overheated air from our house.

So early last summer we built a thermal chimney to achieve cooling with 100 per cent natural ventilation.

A thermal chimney uses the sun's heat to take away the sun's heat. It is placed at the highest point of the house, where hot air collects, and it lets the air escape to the outdoors. To give the air a little "push," the chimney has glazing over a dark surface—like all solar collectors—to further heat the air on its way out. This makes the air rise faster, and the faster you get hot air to leave, the



Right: *The finished chimney, glazed and flashed, awaits its first coat of paint.* PHOTO BY JEFF REISS



west ← **Diagram A** → east

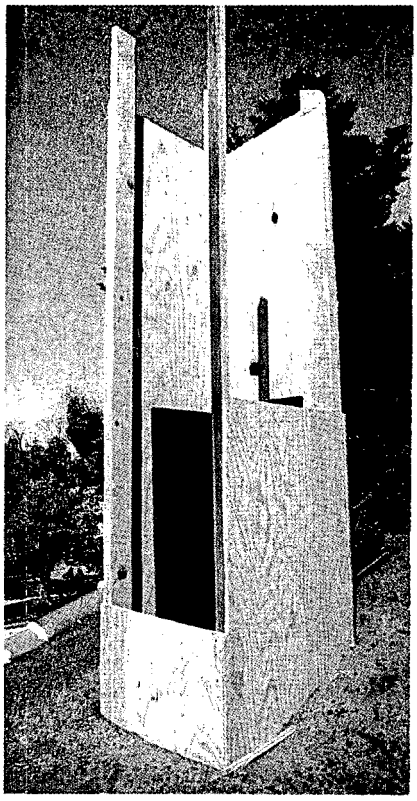


PHOTO BY JEFF REISS

Right: *The wood skeleton of the Reiss thermal chimney. Pieces of plywood form the sides; four vertical 2 × 4s serve as corner posts. The left front side with barely a stub of plywood faces west; the right front side faces south.*

quicker you get cool air coming into the house to replace it. [It serves the same function as a whole-house fan, but without moving parts-Ed.]

The thermal chimney, a very old idea, is being rediscovered by architects and builders of new passive solar homes. But as far as we know, we're the only ones to have retrofitted one onto an existing home.

Ours is a modest one and one-half story 1300-square-foot Spanish style house built in 1932. The house is in a typical older tree-lined residential neighborhood in downtown Sacramento. An attached solar greenhouse and passive solar water heater facing onto the backyard were installed on the south wall of the house in 1978.

The thermal chimney looms above the roof at the northwest end of the house. The chimney glazing faces 30 degrees west of south and west. This location is fully exposed to the sun during the afternoon and until just before sunset in the summer. The chimney is exposed to light winds and occasional gusts because it is above all neighboring housing and vegetation.

The layout of our house has many features that contribute to the practicality of a thermal chimney retrofit. A compact, stepped, three-level floor plan including a large crawl space under the house provides a good volume of air inside a relatively small exterior shell. The crawl space (connected and open to the lower basement level) provides a good thermal contact with the ground. The middle (living, dining) level of the house is on the east side and well insulated from the hot afternoon sun. The outside of the house has thick, white stucco walls that help to keep summer heat out. A large deciduous Catalpa tree and a large pine tree provide shade. Other additions to the house that contribute to keeping the house cool during the summer include the installation of ceiling insulation to an R-25 value and shade screens on all solar exposed windows throughout the summer.

Chimney Placement

The chimney should be placed where the overall air flow does the most good. Our chimney was placed above the northwest corner of the upstairs north bedroom. As shown in Diagram A, this placement allows cool air from below the house to be drawn up the stairwell, and into and across the north bedroom as the heated air is vented out the chimney. In this way, the thermal chimney is designed to work in conjunction with the architecture of the house. The entire house becomes part of the ventilation cooling system.

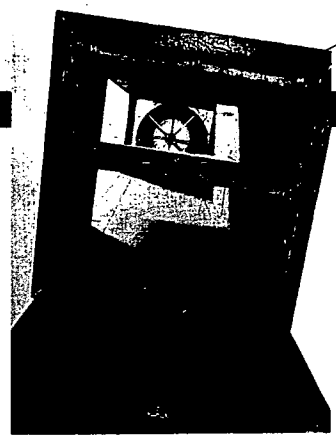
Starting in the basement, the cool air intake from the 1,590-cubic-foot crawl space was placed in the center of the house below the staircase. This position insures that the air most isolated from the warm outside air at the perimeter of the house, is used first. As this cool air is being drawn up into the house it spreads throughout each floor. During the day the cool air in the crawl space is the primary source on which we can draw to replace air in the upper stories of the house on summer afternoons.

To a large extent, the resulting size and shape of the chimney was based simply on very practical considerations and constraints. In order to keep down the cost of materials, standard dimensions were used. This gave us 2 × 2 × 8-foot dimensions. (This also made effective use of standard 4 × 8-foot plywood sheets.) We knew that a taller chimney would have a stronger drawing effect but we needed to consider the overall height from different perspectives: structure, wind load, how it would be visually suited to the house's exterior and how easily it could be built. The resulting chimney, which extends about seven feet above the roof, seemed to be the structural and visual limit. The square chimney fit well with the conventional visual expectations and allowed construction with standard materials.

Chimney Glazing

Glazing on the south side of the chimney was limited to the top four feet to prevent sunlight from shining directly below into the bedroom and thereby causing an unwanted heating effect. (The sun is virtually straight overhead in the summer.) We first discovered this while we were constructing the chimney and figured that the easiest way to maintain maximum south glazing yet prevent sunlight from entering the house was to install a "baffle shade" in the center of the chimney. This "baffle shade" allowed south and low western sun to strike all the glazed surfaces (the

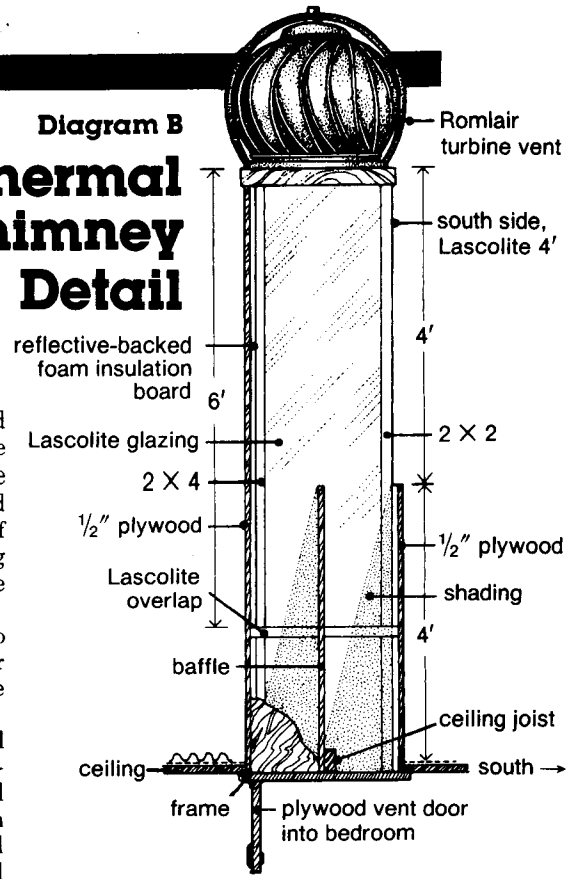
ILLUSTRATIONS BY KATHI EMBER



Right: *This view looks up from the bedroom through the half-finished chimney. The dark horizontal bar across the opening is the silhouette of a ceiling joist. A baffle shade was later nailed to the joist to prevent noontime sun from shining directly into the bedroom. During cooler seasons the inside shutter is closed and sealed to prevent heat loss.*

Diagram B

Thermal Chimney Detail



western side of the chimney was completely glazed) but shaded the inner base of the chimney when the midday sun rose to almost directly overhead. (See Diagram B) Finally, an 18-inch diameter wind turbine vent with a custom-made cap was installed on the top of the chimney to keep moisture (and birds) out of the house and to catch wind which enhances the induced ventilation effect.

Building The Chimney

Construction of the thermal chimney itself was fairly simple. We had to find an appropriate location in the ceiling to cut a hole for the chimney. So, the ceiling joists and roof rafters in the attic were measured (with a tape measure and some tapping on the ceiling) and we found a location that would tie in to the vertical chimney (2 × 4) members and have minimal disruption to the roof structure. After clearing away the ceiling insulation, the hole was cut through the ceiling and then through the roof.

Blocking then was installed to tie into joists and rafters and frame the hole for the chimney. Care was taken so that the ceiling and roof blocking were plumb.

The plywood (2 × 8-foot for north and east sides, 4-foot for south side and 2-foot for west side) was cut and secured into place against the blocking. Then four 8-foot vertical 2 × 4s were nailed into the corners of the hole and blocked at the top and bottom. This formed the basic structure of the chimney. The 2 × 4-foot baffle shade was secured to an east-west ceiling joist which ran through the center of the chimney opening.

Reflective-backed foam insulation board was cut, painted flat black and fit snugly inside all the plywood. (Reflective-backed was used to retard disintegration from exposure.) All other exposed areas on the inside of the chimney were painted flat black. Flashing was carefully installed around the chimney at the roof interface to provide weatherproofing. Lascolite glazing was cut, caulked with silicone and nailed on the south and west chimney faces. White paint (to match the house walls), vertical flashing and careful sealing around the roof flashing completed the outside construction. The final step was setting the turbine vent on top of the thermal chimney.

The chimney opening was accessed from the house by a tight-fitting, plywood door which was framed and flush-fitted into the bedroom ceiling. In winter and cool days this would be closed to keep in the house's warm air. All cracks were filled either with caulking (for inside the chimney) or plaster (for the ceiling around the chimney hatch). In the attic, the insulation was replaced around the chimney.

To allow our chimney to draw cool air from the crawl space, we built a 2 × 3-foot vent in the basement wall. We also built a plywood cover to keep out cold winter air.

Below: *Once completed, John and Jeff place the turbine vent atop the completed chimney. The turbine spins in a breeze to help pull hot air out of the house, while keeping rain from getting in.*

How It Works

At night, the thermal chimney and the basement vent are left open to draw in cool air and release the heat accumulated from the day. In the morning, all the vents and other external windows or openings are closed to hold the cool air inside. Around midday, when external heat passing into the house begins to

heat the upper floor, just the solar chimney vent is opened. All other external doors and windows are kept closed to allow the chimney to induce ventilation of cool air up from under the house.

One to two hours after sunset, when the inside temperatures have reached equilibrium with the outside, all operable external windows are opened. Doors inside the house are also left open (if possible) to allow better circulation of the cool night air. The next morning the house is closed up to keep the cool air inside and this begins the process over again.

Based on the limited monitoring of the system, operation of the induced ventilation cooling system keeps the temperatures within the house noticeably cooler than outside temperatures, and holds the average indoor temperature just a few degrees below the average outdoor temperature. We estimate the solar chimney addition keeps the upstairs about 5–10 degrees cooler on summer afternoons than before.

The 18-inch wind turbine gives a net increase in the drawing power of the chimney when winds are available. Unfortunately, the hottest temperatures and thus the need for cooling often occur when there is very little air movement. The sea breezes usually pick up just after sunset. These breezes help the turbine vent exhaust hot air out of the upstairs rooms.

Cool Savings

It is difficult to determine the exact dollar cost on this or any of our projects because we always have leftover materials and lots of odds and ends in the wood pile that lower the actual cost. The total cost for someone (exclusive of labor) could be calculated to be about $180.00.

The California state tax credit at 55 per cent equals $99. That leaves an actual cost of $81.00 for the entire induced ventilation cooling system. The installation took both of us a full weekend and another day or so to finish it up. (Finishing up always seems to take the longest.) So labor, including the vents and finishing details amounted to about six person days.

Since we had no existing cooling system, there were no dollar savings realized. However, there was a considerable increase in our comfort level. And if you compare what we spent to what we *could* have spent buying and operating an air conditioner, the savings from our "natural" cooling system are substantial.

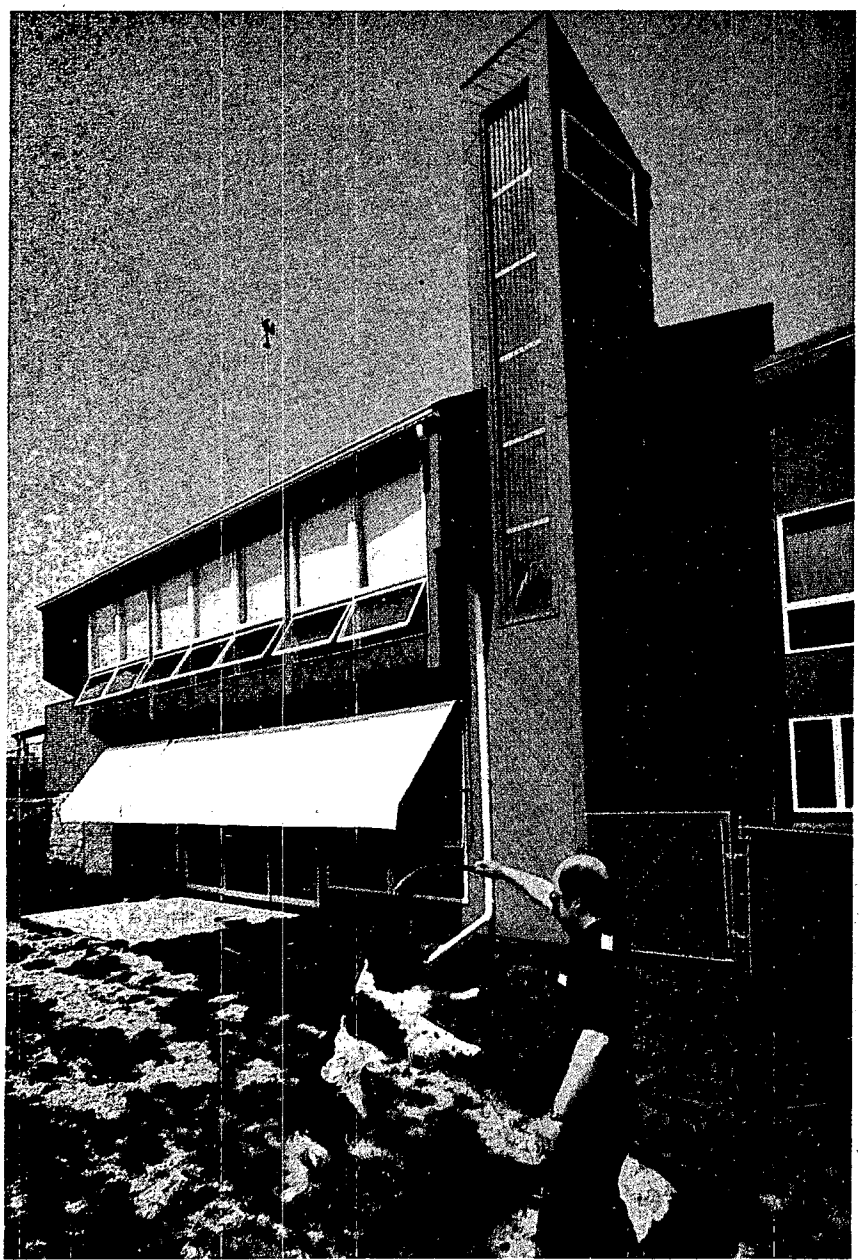
The peak electric load in the California Central Valley occurs during the hot summer afternoons when the demand for cooling is the highest. This creates a tremendous draw on the electrical generation capability, forcing people often to lower or turn off their air conditioners completely. Our thermal chimney competes against this expensive peak electrical energy and gives us "free cooling."

The system works as well as we expected. We feel that the increased comfort was certainly worth the effort. Obviously, an air conditioner could provide cooler temperatures but the costs—economic, environmental, and social—make this passive cooling option our preference.

In Retrospect

An improvement on the existing solar chimney would be to install a light metal grate material in the chimney behind the glazing. The grate, painted flat black, would increase the efficiency of solar heat transfer to the air within the chimney. Another possibility would be to install bricks or another form of thermal mass inside the chimney to help the draw later in the evening after the sun has set and there is still a need for cooling.

This winter we experienced some storms with over fifty-mile-an-hour winds. The thermal chimney is still standing, having weathered the storm well. However, we did have some minor leaking (apparently water being blown in through the chimney). This fall we'll take the turbine vent off and cap the



Left: *You'll find most thermal chimneys incorporated into the design of new homes, rather than added onto old ones. This is a new house in Iowa City, Iowa, with a towerlike thermal chimney at its side. The house was designed by Iowa architect James Schoenfelder. Shown frolicking with his trusty dog is the house's owner, Gregory Iverson.*

chimney until it's time to put the turbine vent on again for another season of operation.

Deciding On A Thermal Chimney

Now, what about *your* house? If you have a cool air resource (intake) such as a crawl space or basement area, the addition of a solar ventilation cooling chimney should be effective—especially if you have a multi-story floor plan. The appropriate size and number of solar chimney vents will be related to the extent of the cool air resource. Can the cool air resource be replenished by the available temperatures overnight?

Chimney location relative to the cool air intakes will affect the extent of cool air circulation within the house. Things to consider include: Which parts of the house need cooling? Where can the chimney be placed to get good sun and wind exposure? Where will cool air intake vents provide the most efficient use and distribution of the resource? What measures are needed to provide good circulation of air within the rooms and corridors of the house? Finally, what combination of answers to the above questions provides for the simplest and most effective system?

The actual design and construction details of the solar chimney itself can vary greatly. Other possible chimney designs include the use of a standard vent pipe painted flat black. The same vent pipe surrounded by a Kalwall tube should be even more effective. Wind turbine caps seem to provide the best combination of weather protection and utilization of local winds to increase draw. The juncture of the chimney and the roof must be waterproofed well. This should be carefully considered with a planned construction method before cutting any holes.

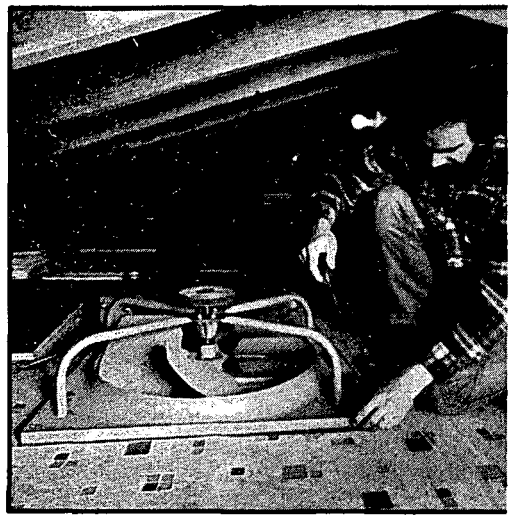
Building codes normally do not address this type of ventilation cooling system and may present some problems if you get into a discussion with the building officials. Be sure you have a structurally sound design and that no undue hazards exist (such as fires from drafts) before approaching building officials. It is your responsibility to do your homework as most building officials think only in terms of conventional construction.

The chimney design described in this chapter is simple, low in cost and effective for the conditions and environment in which it was placed. Variations on our chimney design and ventilation cooling retrofit strategy hold promise of providing effective cooling in diverse structures and environments. There is more than one way to beat the heat. ■

Back To The Fan

Bringing in those summer breezes

by Tony Birch



Above: *A whole-house fan, in position and ready to cool.*

My mother picked me up in her arms so I could reach the switch. At the top of the stairs a distant rumble came from behind a frame of louvers set in the ceiling. In a few seconds a fan got up to speed, popping open those louvers. Cool air was suddenly coming from nowhere. Growing up in surburban New Haven in the early 1950s, this was part of my bedtime ritual.

Thirty years later, whole-house fans have gone the way of soda shops and bobby socks. Although magazine articles of the late 40s and early 50s extolled their virtues, by the middle of the prosperity-crazed 50s the newly developed residential air conditioners had caught the fancy of the public. Now it seems we are never more than 10 feet from artificially chilled air. The American Ventilation Association estimates that almost half of the nation's 50 million residences have some form of electricity-eating, refrigerant-type air conditioning.

But the energy crisis has brought renewed interest in what used to be called the attic fan, now re-christened with the more exact term "whole-house fan" because it cools the house, not the attic. The term "attic fan" is reserved for fans of smaller capacity (1000–1500 CFM) that ventilate the attic only.

That distinction can save you money. Some manufacturers of attic fans claim their products help cool the entire house and reduce the running time of an air conditioner because the fans prevent heat buildup in the attic. But research to the contrary was presented at a workshop held in July 1978 at the National Bureau of Standards (NBS). First, attic heat buildup is not a major problem. A Florida Power Corporation study of attic temperatures in 30 Florida homes on 90°F.-plus summer afternoons showed that the hottest attic was 108°F., and the average was 96°F.; a far cry from the 130°F. to 150°F. temperatures sometimes quoted by attic fan vendors.

Second, if your attic is properly insulated, the heat that does build up in the attic has a tough time migrating downward through the insulation. So forced venting of the attic space doesn't do much to cool you. Tests conducted by the Center for Building Technology (part of the NBS) showed that in houses with three or more inches of attic insulation, the slight reduction in air conditioner use due to an attic fan was offset by the cost of the electricity to run the fan. So an attic fan is a risky cooling investment.

A whole-house fan, on the other hand, was lauded by the researchers as a cooling device with "substantial" energy-saving potential. It costs about $400 to $600 installed (half of that if you do the work yourself) and it runs on one-tenth the energy of an air conditioner. The reason for its success is disarmingly simple: At night the outdoor temperature usually falls 10–20°; the fan draws in the outside air, producing an artificial breeze to cool occupants and house to within a few degrees of the outside air temperature.

A Midsummer's Eve

During the day a well-insulated, unoccupied house with the windows and drapes closed gains heat at the rate of about one degree per hour, when outside temperatures are 85–90°F. The inside temperature is a few degrees lower than outside. Then comes a crossover point, usually about 6 p.m., and the situation is reversed. The ceiling, floor, walls, and furnishings of the house radiate the day's heat. Even if all the windows are opened, the thermal mass of the house causes it to cool about half as fast as the outside air. To make matters worse, cooking dinner adds more heat to the

house. So inside temperatures reach a high point hours after temperatures outside have begun to cool. Many of us are familiar with insufferable tossing and turning as we wait until midnight or later for the house to cool down.

Here is where the whole-house fan comes to the rescue. It is turned on in the early evening, and by inducing rapid air changes throughout the house (usually 40–60 per hour) the house temperature follows close behind the natural fall of the outside air temperature. Thus, comfortable inside temperatures are reached many hours earlier. When the whole-house fan runs until the outside low is reached, about 4–6 a.m., the house can be cooled to about 70°F. by 6 a.m. The fan is then turned off either manually or by a timer. In the morning, the windows and drapes should be closed as soon as you get up to keep out the hot sun. The house then heats up during the day (at one degree per hour) and by 6 p.m. it is about 82°F. inside. At this point, if the outside air is 82°F. or lower, the fan is turned on again and the cycle repeated.

It is important to understand that it's not just air *temperature* that affects your comfort; it is air *movement* as well. The breeze produced by the fan makes the air feel 4 to 10 degrees cooler than it actually is, depending on relative humidity and air velocity. This is the same effect we call "wind chill" in winter. Experience has shown that a whole-house fan can produce comfort conditions when the outside air is from 82–85°F. due to this "wind chill" effect. If

Whole-house Fan Installation

1 *Locate the joists in the attic and frame the opening by cutting out the joists. Be sure the inside dimension of the framed opening matches that of the opening dimension of the shutter. (The frame of the shutter exceeds the opening size by 2 inches.)*

2 *Frame the opening with a platform of 1 × 6s or 1 × 8s (depending upon the size of your fan) on which the fan will be mounted.*

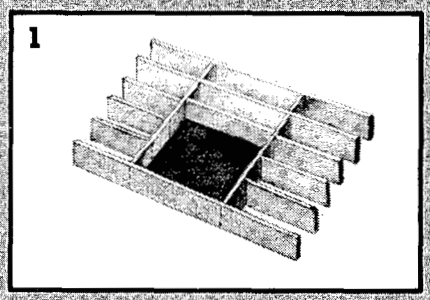
3 *Set the fan over the opening.*

4 *Secure the fan to the frame by toenailing (nailing on an oblique angle) along the edges of the fan through to the wooden frame.*

5 *Install the ceiling shutter on the underside of the fan opening, using screws included in the manufacturer's package.*

6 *Hook up the electrical current, switch and timer (optional). (Be sure to disconnect the main power before wiring.)*

1



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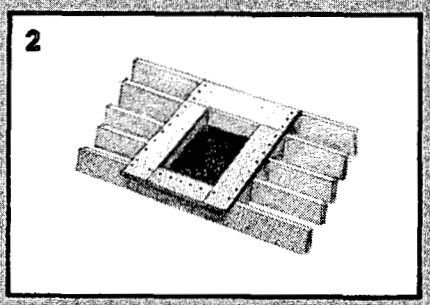

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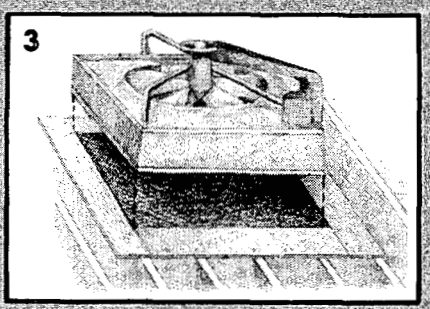
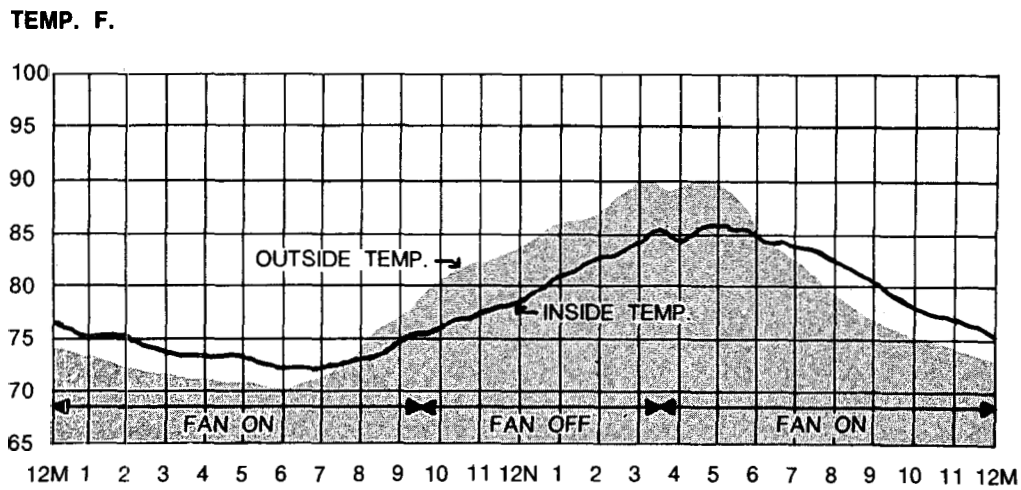


ILLUSTRATIONS BY JAMES DEPIETRO

Figure One *This graph shows indoor and outdoor temperature fluctuations registered during a typical 1942 summer day in Atlanta, Georgia. A whole-house fan brings cool nighttime air into the house.*



Inside and outside temperatures for A.S.H.R.A.E. test printed house. Air change rate: 45 per hour.

Source: *Heating, Piping & Air Conditioning*, May, 1944, p. 300

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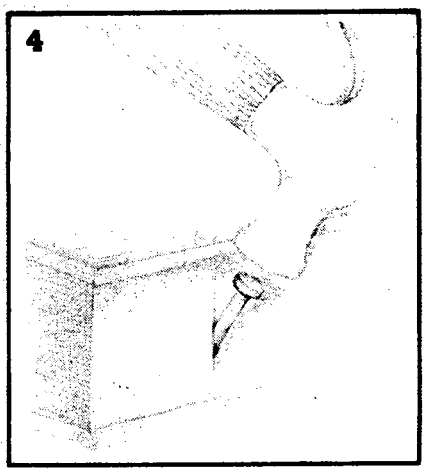

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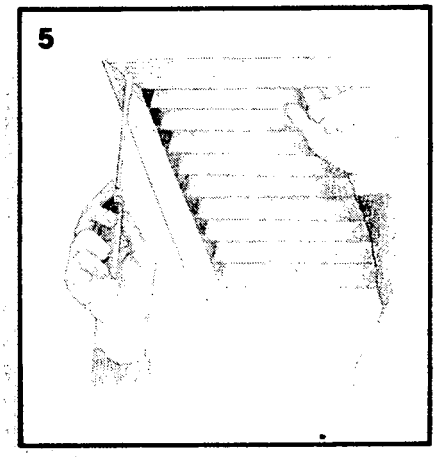

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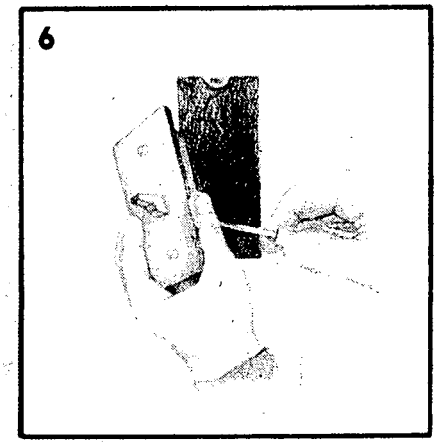


the house is occupied during the day, the heat gain rate will be slightly higher and it may be necessary to operate an air conditioner during part of the afternoon, but the whole-house fan can be used exclusively any time the temperature falls below the 82–85°F. range.

Figure One shows the actual inside and outside temperatures for an Atlanta, Georgia house in an experiment performed by the American Society of Heating and Ventilation Engineers during a typical summer day in 1942. Notice that the fan should have been shut off at 6 a.m. when the outside temperature began to rise, but was left running till 9:30 a.m. The earlier shut-off time would have kept the house a few degrees cooler all day. Also, the fan was turned on again at 3:30 p.m., just when the outside temperature was hitting its peak. Why that was done, I don't know, but it's interesting to note that the 85°F. house temperature did not rise when the fan began to draw in 89°F. outside air. At any rate, you can see that the whole-house fan pulled house temperatures into the 70s by 9 p.m.

There are very few areas of the United States that do not have comfortable nighttime temperatures, which frequently is when the home owner needs cooling most. Climates such as those in Virginia, southern Ohio, Iowa, Colorado, and coastal California are ideal for whole-house fans. But even in Texas, Florida, and Louisiana, where the cooling season lasts five to six months, you can save money. A home owner in Houston told me she saves two full months of air conditioning bills by using a whole-house fan exclusively at the beginning and end of the season. The more you substitute whole-house fanning for air conditioning, the more you'll save.

Sizing The Fan

Fans are rated by the number of cubic feet of air they deliver per minute (CFM). The size you need is based on the volume of your house and an air change rate. In areas where temperatures are moderate, use 40 air changes per hour. In the South, you'll need 60 air changes per hour.

Calculate the floor space of your house (exclude basement, closets, etc.), multiply by the ceiling height to get the volume, then multiply by the number of air changes per hour and divide that by 60 to get the CFM.

$$\frac{\text{HOUSE VOLUME} \times \text{AIR CHANGES}}{60} = \text{CFM}$$

Example 1:
A house in Ohio:
1200 sq. ft. floor area; 7′ 6″ ceiling
1200 × 7.5 = 9000 cu. ft.

$$\frac{9000 \times 40}{60} = 6000 \text{ CFM}$$

Example 2:
A house in Arkansas:
1800 sq. ft. floor area; 8′ 0″ ceiling;
1800 × 8 = 14,400 cu. ft.

$$\frac{14{,}400 \times 60}{60} = 14{,}400 \text{ CFM}$$

Most manufacturers list their fan capacities in terms of their "free air delivery." This is *not* the actual CFM the fan will deliver when it is installed. Knock off about 25 per cent of the free air figure to obtain the correct value. In the Ohio house example above, the fan would have to be rated at about 8000 CFM free air delivery. Also, don't sell yourself short on the physical size of the fan. A larger fan is more efficient and quieter because it can deliver more air at a slower speed. I recommend 36″ as the minimum blade diameter size, 42″ preferred for most applications.

Sizing The Discharge

In most cases, you have to increase the size of the attic ventilation openings in order to insure proper operation of the fan. Multiple openings totaling the correct area are preferable and work effectively regardless of the prevailing wind direction. If a single opening is used, it should be placed on the leeward side. Openings may take the form of wood or metal louvers installed in the gable ends of the attic, or holes backed with ½-inch wire mesh in the soffit. If you make these modifications yourself, calculate the required square feet of free area by dividing the actual CFM by 750. Wood louvers are about 50 per cent free area, metal louvers about 63 per cent free area, depending on how they are constructed, and ½-inch wire mesh is 80 per cent free area. (See Figure Two for minimum sizes.) The wire mesh bird screen should always be placed on the

Figure Two

MINIMUM SIZES FOR DISCHARGE OPENINGS
(in sq. ft.)

Actual (not free air) CFM of the fan	Wood Louvers with ½″ wire mesh	Metal Louvers with ½″ wire mesh	Plain Openings with ½″ wire mesh
6000	19.2	15.2	9.6
8000	25.6	20.3	12.8
10,000	32.0	25.4	16.0
12,000	38.4	30.5	19.2
14,000	44.8	35.6	22.4
16,000	51.2	40.6	25.6

back of louvers, but insect screening should be avoided since it requires that opening sizes be again doubled and may easily become clogged.

Installation

The fan should be placed in a central location—in a hall or stairwell ceiling. Alternatively, the fan can be mounted vertically on an attic wall. This arrangement, however, allows outside air to be drawn in through cracks in the roof and attic side walls, so it is apt to require a fan of increased capacity.

Installation of the fan is not difficult, and you can do it yourself by following common sense and the manufacturer's instructions. But if you lack tools and experience you are probably better off having a qualified professional do the job.

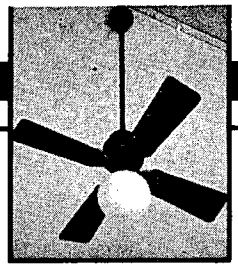
Insulation should be placed over the fan opening in winter. (See how in "The Tighter House," this issue.) Some manufacturers provide an insulative winter seal which attaches directly to the exterior of the shutters.

Operation

The fan should be turned on between late afternoon and sunset and turned off early in the morning before the air temperature begins to increase. An inside/outside thermometer is useful for determining the best times. A timer switch is a good idea. A low cutoff thermostat could also be used in case it gets too chilly in the early morning. It would be a dangerous idea, however, to have the fan come on automatically by a thermostat. In the event of a fire, the thermostat would be triggered and your fan would start fanning the flames. The fan should never be operated without a door or window open, unless you want to draw soot out of the chimney and blow out your pilot lights.

The motor should have a thermal overload protector. A fusible link that shuts off the motor and/or closes the louvers in the event of fire should also be provided with the unit.

If your house has a basement, the basement windows and basement door should be left open. This way the fan draws in air where it is the coolest—at ground level—and the air comes into contact with the cool basement walls before it enters the house. If your summer heat isn't accompanied by high humidity, you might even try hosing the lawn outside your basement windows at night for an additional cooling boost through evaporative cooling of the air as it passes over the lawn. When the fan is running, doors to unused rooms should be shut to increase air velocity in the room you're using.



Ceiling Fans: Fact and Fantasy

Those slow-turning bladed objects that hit their public peak in *Casablanca,* and sent hundreds of home owners scurrying to give their living rooms the sleepy romance of tropical hangouts are still popular. Now, however, their merits are promoted by both romantics and energy-conservers alike.

In winter, the old-time fan recycled rising warm air back down into the room. In summer, unfortunately, it did the same thing. The room just *felt* more comfortable because the air movement caused evaporative cooling against the skin.

Some modern-day manufacturers have improved upon the Casablanca-era fan by designing models with adapters to alter the angle of the blades: downward to return rising heat in winter, upward to pull up cool air in summer.

Ceiling fans can't replace the cooling efficiency of a whole-house fan but a large, well-designed one can considerably increase comfort in an otherwise hot, stale room. And you never know what it can do for your piano playing.

Like most energy-saving devices, the whole-house fan involves a change of habits. The first thing most people do when they feel a "scorcher" coming on early in the morning is open everything they can get their hands on. You could get away with this if you were simply to flip on an air conditioner come afternoon, but not if you have a whole-house fan. The morning coolness should be "conserved" in the house as long as possible and sunlight should be kept out. Insulation, by the way, holds in your cool summer morning air the same way it holds in your warm winter air. Whole-house fans should work even better in today's well-insulated homes than they did thirty years ago.

A whole-house fan also asks you to become reacquainted with greater temperature fluctuations. Some people may not be bothered by a range between 70–80°F.; just as they wouldn't be bothered by swings from 65–75°F. that are wintertime norms in passive solar houses. But others can't seem to live without the year-round 72°F. provided by air conditioning and fuel-intensive heating.

"You can have a much lower cooling bill with a whole-house fan, but it takes more participation on your part," says Dr. Gautam Dutt, a researcher for the Center for Energy and Environmental Studies at Princeton University. A whole-house fan asks you to be sensitive to when and how heat builds up inside your house, whereas air conditioning can be turned on anytime—and is most likely left on, often even when it's cooler outside than inside. Dr. Dutt cools his Princeton, New Jersey, home with a whole-house fan. "Except for two or three days a year, we are quite comfortable," he says. "What do I do about those two or three days? Well, I find somewhere else to be."

Let it not be implied that a whole-house fan is great only because it uses less electricity than an air conditioner. To me, there's something sterile, stuffy and metallic about being in an air-conditioned room too long. By contrast, I remember with fondness my childhood nights back in New Haven. The cool breeze throughout the house felt healthful and good. It brought into the house the natural fragrances of nearby trees and other smells of a summer night.

So if you're looking for a more down-to-earth way to get cool, consider going back to the fan. ■

Manufacturers

Whole-house fans are available at many of the big chain stores, including Sears, J. C. Penney, Ward's, and K-Mart. Some other suppliers of fans and equipment are:

Aspen Aire
Triangle Engineering Co.
P.O. Drawer 38271
Houston, TX 77088

Cool Attic Corp.
P.O. Box 11558
Fort Worth, TX 76110

Fasco Industries, Inc.
P.O. Box 150
Fayetteville, NC 28302

Hunter Division
Robbins and Myers
2500 Frisco Avenue
Memphis, TN 38114

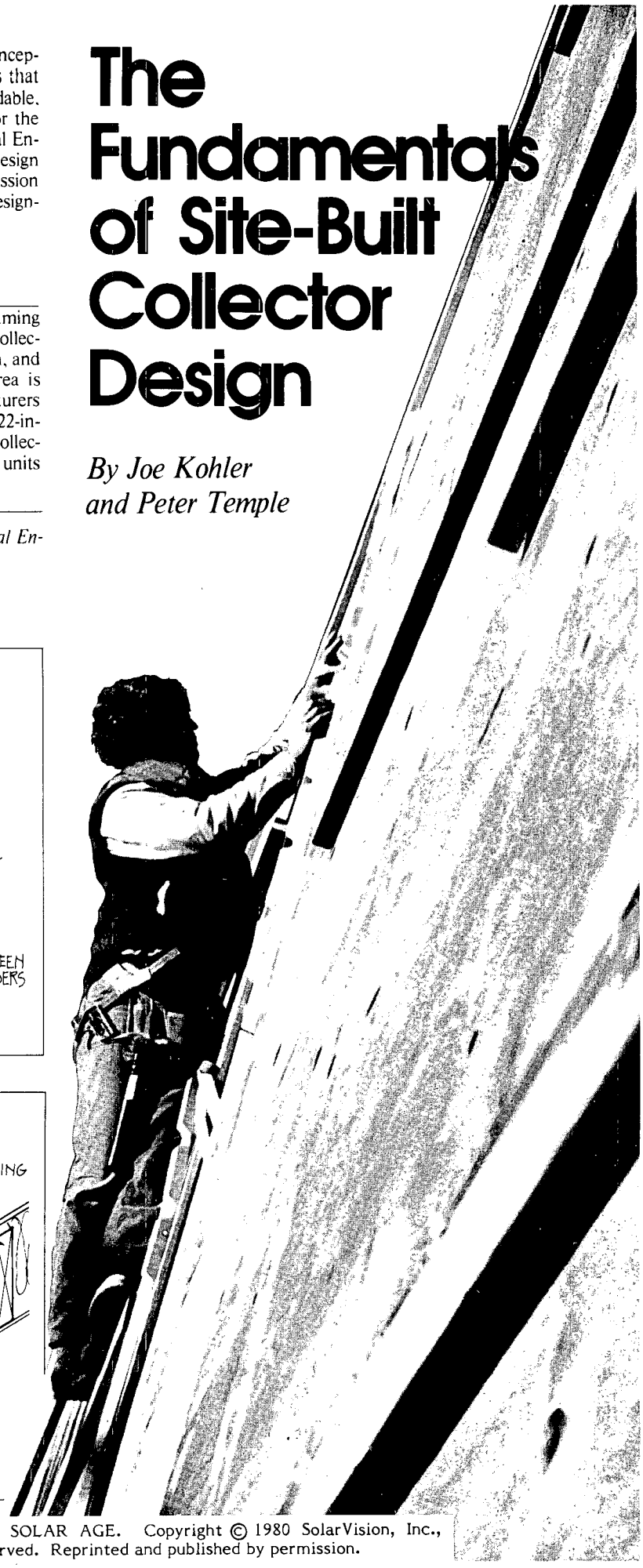
Lau Industries
Div. of Philips Industries
2027 Home Avenue
Dayton, OH 45401

The Fundamentals of Site-Built Collector Design

Here's a comprehensive survey of the choices involved in designing and building a hot air solar system. The authors base their recommendations on their first-hand experience.

The Fundamentals of Site-Built Collector Design

By Joe Kohler and Peter Temple

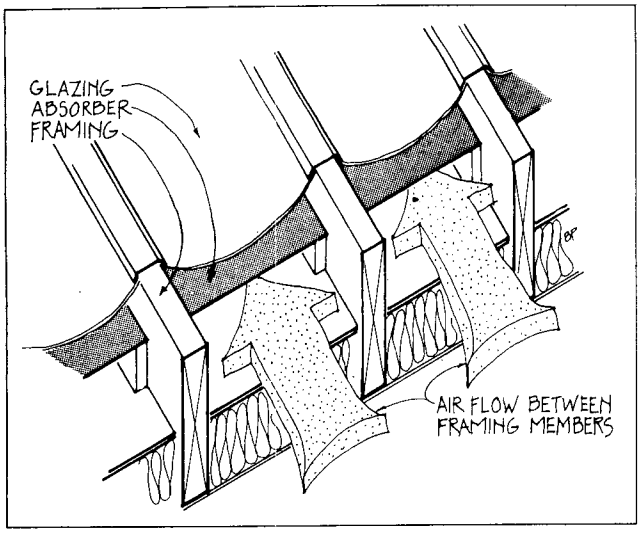


Although the design of a hot air solar system is conceptually quite simple, there are, in fact, many factors that must be considered if the final system is to be buildable, durable, reliable, efficient, attractive, and cost-effective. For the past two and a half years the authors and other staff at Total Environmental Action, Inc. (TEA) have been involved in the design and development of a site-built system. The following discussion presents many of the alternatives that were considered in designing this system.

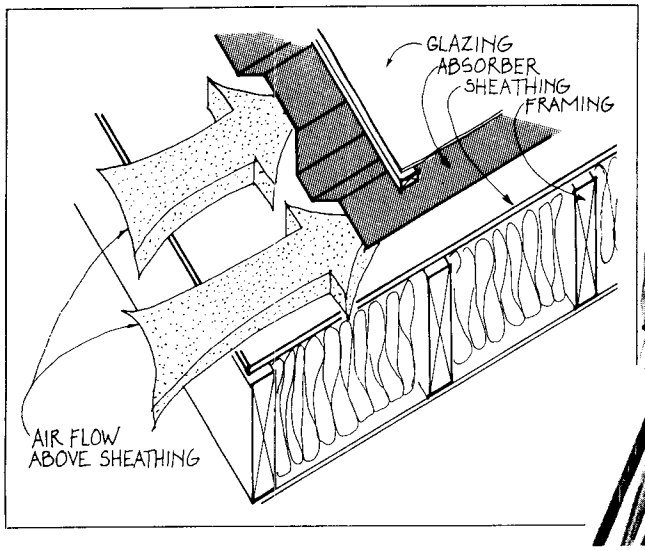
Flow Over Framing Vs Flow Between Framing

Site-built collectors can either be mounted on top of the framing members or between the framing members. Mounting the collectors between the framing provides a low profile installation, and may be aesthetically advantageous when the collector area is small in comparison with the roof area. Several manufacturers offer factory-built components, or modules, approximately 22-inches wide, designed to be site-built between the framing. Collectors mounted between the framing are always vertical flow units

Joe Kohler and Peter Temple are research engineers at Total Environmental Action, Inc. in Harrisville, N.H.



Flow Over Framing Vs Flow Between Framing



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in conventional construction. It is important to ensure that there is sufficient blocking, bracing, or structural integrity of the collector to provide racking resistance usually provided by the sheathing, and also to protect the glazing from damage due to twisting rafters.

Mounting collectors over the framing provides more flexibility in design. The collector can be either horizontal or a vertical flow design, and is not constrained to a 22-inch wide module. Since the sheathing is left in place, no special provisions for bracing are necessary. Retrofit is somewhat simplified because it is not necessary to remove the sheathing. Mounting collectors over framing is probably essential if the roof is finished on the inside (cathedral ceiling) in order to have sufficient space in the rafters for insulation.

Horizontal Vs Vertical Flow

As previously mentioned, collectors with flow between the framing are always vertical flow collectors. The primary advantage of vertical flow collectors is that they are adaptable to convective venting in the summer to protect them from stagnation. The major disadvantage is that it is necessary to connect every vertical collector bay to manifolds running horizontally along the top and bottom of the collector. This increases the potential for leaks and adds to labor costs. If the collector is located on a roof or wall adjacent to the living space, the manifolds protrude into the living space and must be boxed in or otherwise incorporated into the design of the interior space.

Horizontal flow collectors must be mounted over the framing. They have the advantage that the manifolds can be located vertically between the framing at each end of the collector. The manifold can be formed by inserting a metal pan into the space between the framing, thus creating an integral manifold. The connection between the collector and manifold is achieved by overlapping the absorber plate over the manifold. A disadvantage of horizontal flow collectors is that they are difficult to vent by natural convection.

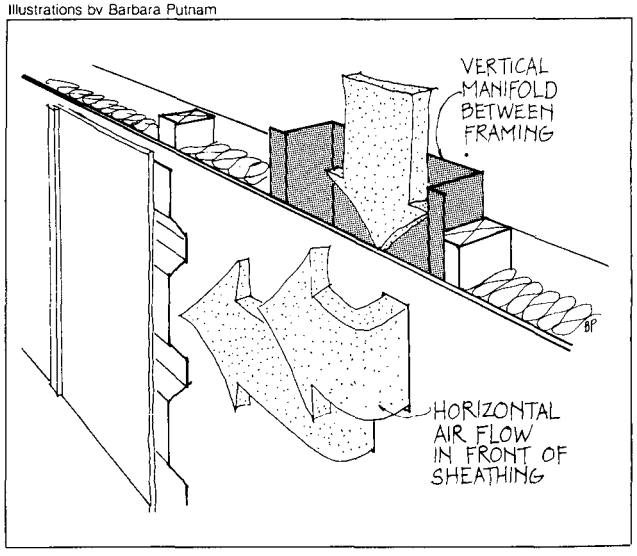
Flow Over Absorber Vs Flow Behind Absorber

Most air collectors are designed such that the flow is behind the absorber plate, in channels formed by the absorber plate and the collector back plate or sheathing. It is possible to design collectors such that the flow is between the absorber plate and the glazing. This allows for the elimination of the conventional absorber plate, with absorption of solar radiation occurring directly on the collector back plate. In essence, it would be possible to add glazing directly over sheathing painted black, considerably reducing both materials and labor costs. However, this requires that the glazing assembly be air-tight and that it withstand the air pressure forces. It would be prudent to test carefully such designs for leakage and durability on a small scale before planning large scale installations. In TEA's experience, it is very difficult to obtain such an air-tight seal over a long period of time.

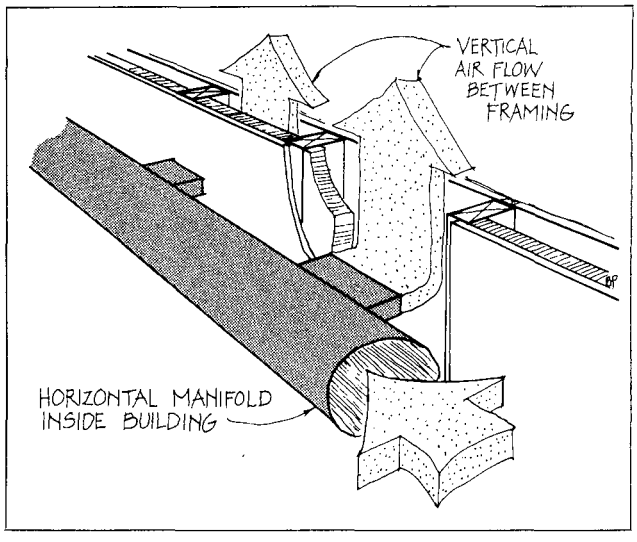
Matrix Collector Vs Flat Plate Collector

In a matrix collector, solar radiation is absorbed on several layers of wire mesh, perforated metal lath, or other material with a high surface area that is in intimate contact with the air stream. "Beer can" collectors, and designs incorporating fins or perforated plates to maximize surface area could loosely be considered a type of matrix collector. The collector is designed so that the air passes through the matrix absorber material. The advantage of the design is that the heat exchange is very good because of the high surface area of the matrix in contact with the air. This advantage is somewhat offset by the fact that air flow rates in matrix collectors must generally be lower than in flat plate collectors to prevent excessive pressure drop. Lower flow rates lead to higher average collector temperatures and greater losses to ambient, par-

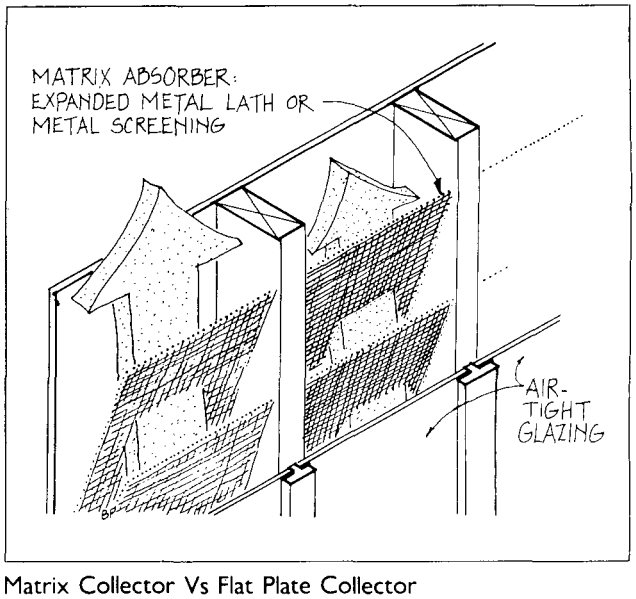
Illustrations by Barbara Putnam



Horizontal Vs Vertical Flow



Flow Over Absorber Vs Flow Behind Absorber



Matrix Collector Vs Flat Plate Collector

ticularly in long collector runs.

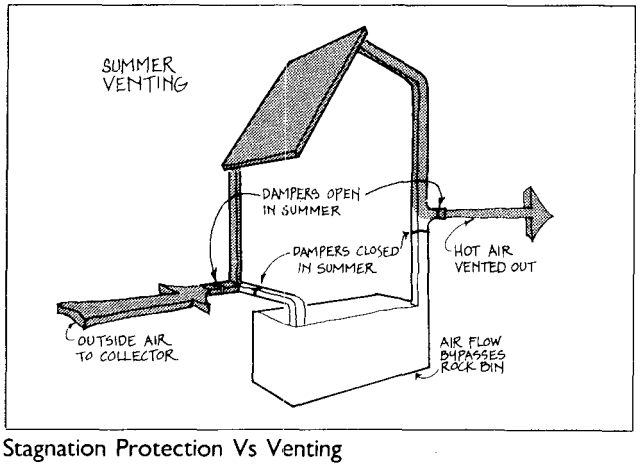
Matrix collectors are probably more difficult and expensive to build than other flat plate collectors. Several layers of mesh must be carefully installed in a framework that prevents the air from by-passing the matrix. Most matrix collectors would be flow through framing, flow over absorber designs and share the problems previously ascribed to those design approaches, including structural considerations, manifolding, and providing air-tight glazing.

Flat plate collectors can be designed in a wide variety of ways. Actually, most site-built flat plate collectors are not flat, but use a corrugated metal roofing or industrial siding. The ribs are desirable because they add structural strength to the plate and provide room for expansion. A true flat plate will buckle when subject to the pressure and temperature in a solar collector. In some designs, the ribs also form channels for the air flow.

Stagnation Protection Vs Venting

During the summer, when there is no heating load, the energy absorbed by the collector must be dissipated. If the blower is stopped, and the collector is allowed to "stagnate," its temperature will increase until the convective and radiative losses equal the solar gain. For a typical single-glazed roof collector, stagnation temperatures may exceed 350°F. Temperatures of this magnitude can have deleterious effects on collector materials. There are basically three approaches to the stagnation problem: (1) cover the collector, (2) build the collector with materials that withstand stagnation, or (3) vent the collector during the summer. Covering the collector is an effective approach for a lean-to collector on the ground, but is probably impossible for most roof-mounted collectors. Building a collector to withstand stagnation temperatures requires careful selection of materials. Wood and plastic should not be used, and caulking materials and rubber seals must have high temperature ratings. Even with these precautions, problems could occur due to the large thermal cycling that the collector undergoes (expansion-contraction due to temperature extremes). It is also apparent that no matter what caulks and sealants are used, their lifetime will be shorter than if the collector were not subject to stagnation.

Venting the collector in the summer is the surest and most general approach to assure long-term durability of the collector. Air from outdoors is drawn through the collector to cool it and then the hot air is exhausted (after passing through a coil to provide domestic hot water, if desired). Flow may be by natural convection or it may be fan-powered. The principal advantage of natural convection is that it requires no power consumption or sophisticated controls. To cool a collector, it is necessary that an intake be provided in the ductwork near the bottom of the collector and an exhaust be provided in the ductwork at the top of the collector. Two potential problems exist. First, the ductwork must be engineered to have a low resistance to flow or the convective flow rate will be insufficient to cool the collector. Second, the exhaust vent must be located somewhere near the top of the collector (which presents access problems) and must seal very tightly to prevent unwanted leakage during winter. Natural convection cooling is impractical on horizontal flow collectors.



Stagnation Protection Vs Venting

Fan-forced ventilation is easier to design, but requires electrical power and additional control logic and dampers. A sensor, located on the collector plate, turns on the blower when the temperature exceeds a set limit (typically 160°F). Electrical consumption would run $50 per year, and the controls and logic would cost several hundred dollars for a typical system. It is easier to accept the idea of running a fan in the summer if the system is designed to provide hot water as well as stagnation protection.

Wall collectors do not experience nearly as high stagnation temperature as roof collectors due to reduced incident and transmitted radiation on the vertical surface in summer. As long as high temperature caulks and sealants are used and plastic glazing avoided, wall collectors should not need to be vented.

Single Glazing Vs Double Glazing

TEA's experience indicates that double glazing increases the efficiency of a typical site-built air collector by approximately 20 percent in most areas of the country. It also increases the cost by a similar amount. Thus, a single-glazed design 20 percent larger than a double-glazed design will provide the same amount of energy at the same cost. Since more roof is typically available than is necessary for collector area, and since it is much easier to install single glazing than double, it makes sense to use a single-glazed system on roofs. On the other hand, since wall area is usually limited, and double glazing can easily be handled on the ground, it makes sense to use double glazing on the wall.

Since this decision depends on costs and performance of double- and single-glazed collectors, it is difficult to generalize for all collector designs. It is also important to note that single-glazed collectors are more cost effective than double-glazed collectors in many southern cities.

Glass Vs Plastic Glazing

A wide variety of plastic glazings is available. The advantage of plastic glazings is that they are usually less expensive than glass, and they may be easier to install. However, most plastic glazings do not have as good a resistance to thermal or ultraviolet degradation as glass. In addition, most have a relatively high coefficient of expansion which must be accommodated in the design.

Glass is an ideal material for solar collectors. It is not affected by ultraviolet or thermal degradation and has a low coefficient of expansion. However, it does require that the collector be carefully designed to allow for expansion. (The April 1979 issue of *Solar Age* provides a detailed discussion of plastic and glass glazing systems.)

Silicone Vs Urethane Caulks

Silicone caulks possess ideal physical properties for solar applications: long life, excellent ultraviolet and thermal resistance, and excellent adhesion and elongation. They are ideal for caulking glazing assemblies. However, they tend to set or "skin-over" rapidly. This presents a problem in site-built applications where layered construction is used because the bead of caulk sets up on the first layer (e.g., the sheathing), before the second layer (e.g., the absorber) can be tightly screwed down. This, of course, results in leakage.

Urethane caulks have physical properties that are nearly as good as those of silicone caulks. Because they do not "skin-over" as rapidly, they are recommended for use in layered joints.

Other caulks, such as acrylics, latexes, butyls, and oil-based caulks will have limited service life in site-built collector applications, and it is strongly recommended that they not be used.

photo by Jennifer A. Adams

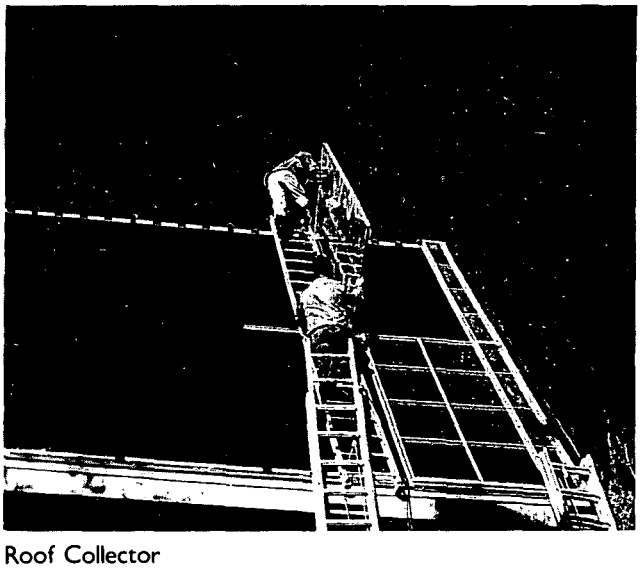
Wall Collector

Wall Collector Vs Roof Collector

The decision of whether to use a wall-mounted collector or a roof-mounted collector depends primarily on the architectural characteristics of the building.

A wall collector requires an uninterrupted section of wall at least 12-feet long. Wall collectors are generally simple to construct because work is done from the ground. A wall collector system is also generally less expensive because there is no need to vent the wall system. If the wall collector is small, storage can be omitted, further reducing costs. Wall collectors are also ideal for retrofit applications. The major disadvantage of wall systems is that it is frequently difficult to incorporate more than a couple of hundred square feet of collector on the south side of a building without compromising the architecture or eliminating desirable passive features. In order to achieve high solar fractions using wall systems, buildings generally have to be designed around the collector.

Roof collectors offer more flexibility to the designer. Most roofs have sufficient area to accommodate a reasonably sized site-built collector (generally 300 to 600 square feet on a typical tight, well-insulated house). Although the optimum slope for space heating is approximately "latitude +15°," roof slope can be as low as 35 to 40 degrees without sacrificing much performance. Roof collectors are more difficult to build than wall collectors simply because of their location. The system is more expensive because there is the need to provide summer venting. However, roof collectors are more suitable for the production of domestic hot water than wall collectors because their sun angle is more favorable in summer.



Roof Collector

Storage Vs No Storage

Storage is usually required with collector areas greater than 100 to 500 square feet to collect excess energy during the day and return it to the house at night. Typically, from 0.75 to 1.0 cubic feet of rock storage should be provided per square foot of collector area. More than 1.0 cubic feet of storage does not significantly improve the system efficiency. Washed stones or crushed rock ¾-inch to 1½-inch in diameter should be used. The type of stone does not affect performance as long as the density is similar to granite and proper void fraction is obtained.

If a small wall collector is installed, as might be the case in a retrofit, such that the total south-facing aperture (including windows) does not exceed roughly 150 square feet, storage is not necessary. Heat provided by the collector will be stored directly by the normal mass in the building and used to supply the daytime heating load.

Thermosiphon Vs Fan-Forced Systems

Thermosiphon collectors do not require the fans and controls required in an active air, or fan-forced system. However, without fans it is somewhat difficult to design a system with storage because the storage must be located above the collector. In addition, the efficiency of thermosiphon collectors is usually lower than that of active collectors because the heat transfer and heat removed is poorer at lower velocities and lower flow rates. If storage is required, fans and controls are required in most instances. If storage is not required, the cost of a small fan and a simple thermostat is more than justified by the resulting increase in collector efficiency.

Air Handler Vs Components

There is a choice as to whether to use a commercially available air handler or to build one on site using components. The decision is somewhat akin to buying a packaged home entertainment center or assembling one from components.

A packaged air handler is generally simpler to install. All blowers and fans are installed in a sheet metal cabinet, and in some products prewired controls are also included.

Building a system with components requires familiarity with available equipment and the knowledge and ability to put it all together correctly. In this way, a more efficient and flexible layout can be accommodated, and possibly, better components can be selected. However, experience is required and the resulting system is not likely to be less expensive if labor costs are included.

Acknowledgements

The authors wish to acknowledge Jennifer Adams, Dan Lewis, Paul Sullivan, and Charles Michal of Total Environmental Action, Inc., who helped identify and resolve many of the considerations discussed in this article, and Jeremy Coleman, Ray Bliss, Al Converse, Vic Reno, and others outside of TEA who made many valuable contributions. The two-year project on which much of this discussion is based was supported by the Solar Heating and Cooling Research and Development Branch of the U.S. Department of Energy. Prior TEA experience with air collector design and system design, has provided direct field experience.

A comprehensive 250-page construction manual on the MODEL-TEA Solar Heating System can be purchased from TEA. The manual presents step-by-step instructions, detailed construction drawings, and all the necessary background information for site-building the MODEL-TEA collector, storage, controls, and air-handling equipment.

Our Down-to-Earth Series on Solar Hot Water

The first of a series of articles published in Rodale's New Shelter on solar hot water systems, this article explains the major types of systems, and the advantages and drawbacks of each.

Part 1

SUN on TAP

Introduction

Our down-to-earth series on solar hot water

by Frederic S. Langa

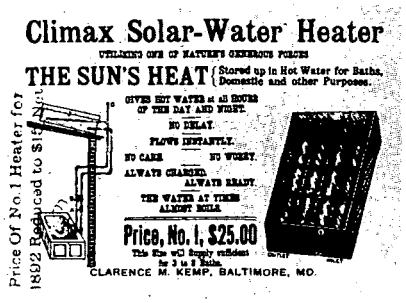
"Free hot water," the ads said. "We put 'em up, and old Sol does the rest!" The year was 1897, and in Pasadena, California, "Climax" solar water heaters were the answer to a local shortage of low-priced fuels. Climax heaters were offered in a range of prices and sizes from the basic $25 32-gallon model, up to a $380 700-gallon version designed to heat swimming pools. "Reduce your fuel bills by forty per cent—the sun's rays utilized!" read the brochures. "You simply open a cock, and instantly comes the hot water!"

By the turn of the century, almost one out of every three homes in southern California was equipped with a solar water heater, and similar solar booms were taking place in Arizona and Florida. By 1918, the "Day and Night" Company alone claimed more than 4,000 installations of their bargain-priced $100 40-gallon units. (Today, that $100 Day and Night unit would cost just $650—still a bargain.) "Sunshine, like salvation, is free!" proclaimed the ads. "No expense for fuel, and it can't explode or start a fire!" Solar water heating was a common and reliable answer to high fuel bills.

Almost a century has passed since the granting of the first solar water heating patent. A hundred years of progress, technological advancement, and refinement of solar know-how has led to this; taken from a Department of Commerce report: "The growth of the solar industry . . . has been accompanied by . . . poorly designed systems, installation mistakes, and fraudulent business activities. Warrantees presently offered by the solar industry give consumers little protection against these problems."

What happened? How could a proven technology devolve into unworkable designs, installation errors, and downright fraud? If solar water heating was reliable and economical before the years of wartime metal shortages and the era of cheap fossil fuel, it should once again be reliable and inexpensive now that those price constraints are history. But it's not. To quote again from another federal report, "Solar energy systems are generally viewed as uneconomical and risky investments with little practical use."

To find what's keeping many modern solar heating systems expensive and impractical, we have to look at an issue that runs deeper than the economics of an old war. It's something that almost every industry has to contend with at one time or another, and when it strikes, it has been known to send otherwise rational designers and engineers rushing down the blindest of alleys. It's our national mania for complex gadgetry.



Above *Advertisement for Climax solar water heater, 1892. The price of this, the smallest unit, had just dropped from $25 to $15.* Courtesy of *A Golden Thread*, Cheshire Books/Van Nostrand Reinhold Co.

Back in the fifties, for example, cars began sprouting wings and fins and mock-rocket tubes, power windows, power seats, and power ashtrays. These chromium geegaws and power gizmos seemed compelling at the time, but now they look rather silly.

Something similar appears to be happening in the solar industry. Instead of refining proven, reliable, low-cost designs, more and more manufacturers are competing in terms of high-tech plumbing, computer-assisted tracking devices, and "black box" control panels encrusted with flashing lights and digital readouts. When you've finished installing some of these systems, your cellar looks like the control room of Three Mile Island.

It wouldn't be so bad if this complexity produced results, but so far that's not the way it has worked. An experimental study in New England looked at 100 professionally installed solar water heating systems that had an average price of just over $2,000. For this substantial investment, home owners were led to expect about a 50 per cent reduction in their water heating bills. Instead, the first-year average savings of all the tested systems were just 21 per cent—less than half the design value—and 15 of the systems delivered *less* than a five per cent savings! (The payback on a $2,000+ system delivering a five per cent savings is about 170 years. All you have to do is keep your solar heater working for seven generations to break even.) Admittedly, these were the 15 worst systems, but even the 15 *best* systems averaged only 39% savings, still less than the design value.

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If you want to buy a commercial system, use the references listed at the end of this article to find some reputable ones. If you want a system that's even more reliable and a lot less expensive, you can build your own. According to a report published by the Department of Energy, owner-built systems fail 13 per cent *less* often than professionally-constructed systems. The report doesn't say why, but it's a safe bet that the owner-built systems are (1) simpler, hence more reliable; and (2) owner-builders are often motivated to work more carefully than a solar contractor's crew. (This isn't a blanket condemnation of solar installers. Good ones exist, but they can be hard to find.) If you carefully build your own system using designs known to work, and using materials known to be reliable and cost-effective, you can eliminate almost all the risk of solar water heating. You'll be dealing only in degrees of success.

And that's where "Sun On Tap" comes in. *New Shelter*'s research staff has built, installed, and monitored all of the most popular types of solar water heaters, choosing designs that can be used anywhere in the country (including freezing climates), and designs that can be built easily by home owners. Rather than test isolated components, we looked at entire working systems. And instead of testing these systems in laboratories, our units have been installed on homes where they experience real weather conditions and the varying patterns of water usage by real families. In as many ways as possible, our solar water heaters are meant to represent systems as they would be installed in a home like yours.

In fact, about the only way our solar heaters might differ from one you would construct yourself is in the extensive monitoring we've incorporated. We're keeping track of more than 30 variables which can affect the performance of the systems, so we can see not only how each heater works by itself, but how it compares to the others.

That's really what "Sun On Tap" is all about: detailed comparisons of how these systems work so you can see how much they cost, how they're assembled and installed, and how they rate in terms of relative efficiency and reliability. We'll be talking about these do-it-yourself systems in the next eight issues. By the end of the series, you'll be able to select the one system that best fits your budget, your skills, and your hot water needs. And you'll be able to build that system with confidence that it will work.

Here's what we'll be covering:

Conservation

There's a rule of thumb that says nothing will save you more money in less time than conservation. Everyone who wants to solarize a home should write that rule a hundred times, or repeat it until it's unforgettable, because putting a solar water heater on inefficient plumbing is like gold-plating a rusty tin can.

Fortunately, it's easy to tune up your existing water heating system, and you'll see how to turn about $80 and one weekend into a permanent 25 per cent savings on your annual water heating bills. Flow restrictors and pressure reducers, pipe and tank insulation, point-of-use (tankless) water heaters, automatic timers, tempering tanks, and voluntary reductions in water temperature and volume are just a few of the options we'll discuss. (For a head start, see "Easy Ways To Save Water," in this issue.)

Solar Basics

Next, we'll look at the underlying concepts that make our solar water heaters work. We'll talk about the differences between active and passive systems, open and closed loops, and all the other specialized terminology that is used to describe just what makes things "tick." We'll cover everything from where to mount your collectors to how to deal with local building codes.

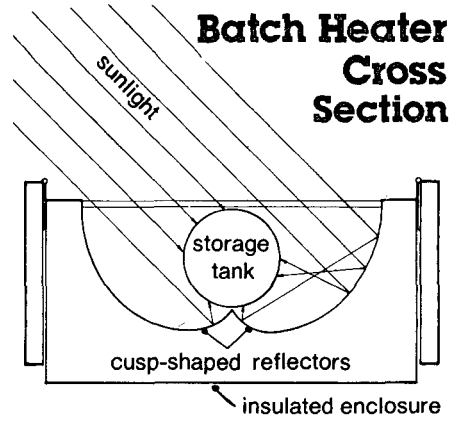
Batch Heaters

Once we've pinned down the basics, we'll move on to actual systems, starting with the simplest: *batch heaters.*

Batch heaters are really nothing more than insulated, weather tight boxes that contain one or more black-painted water tanks. The south wall of the enclosure is clear glass or plastic, so the sun can shine directly on the tank, warming the "batch" of water within. This sun-warmed water is then fed either directly to the home's taps, or to the existing water heater.

It's hard to imagine a simpler design. Batch heaters need no pumps, blowers, differential thermostats, or other externally-powered devices. Instead, batch heaters are powered solely by the sun and by the existing water pressure in the home's plumbing. As sun-warmed water is drawn off the top of the tank (having risen there by natural convection), cold water automatically enters the tank through the bottom. This extreme simplicity makes batch heaters very reliable and inexpensive.

We'll discuss three designs. One costs just $180 and is meant to fit inside an unused south-facing window. You can build it in two weekends and it will trim about 15 per cent off your water heating bills. The second model is designed for use in a greenhouse or sunspace and is larger than the window-mounted version. It still costs just $180, but the extra size means it can provide as much as 35 per cent of your hot water. Finally, our top-of-the-line model is a superinsulated freestanding unit that can be mounted almost anywhere in your yard (see Illustration A). It uses a sophisticated "cusp" reflector to focus all the incoming sunlight on the water tanks, giving the advantages of a sun-tracking collector without the added cost and complexity. (For all its sophistication, our cusp reflector is made with a string and a pencil.) For about $400 and three or four weekends, you can build what may be the most advanced, efficient, and foolproof batch heater currently available to do-it-yourselfers.



Above: *A cusp is a point where two curves intersect. A cusp-shaped reflector accurately focuses sunlight onto the batch heater's tanks regardless of the direction from which the sunlight is coming. This type of reflector operates almost as efficiently as a sun-tracking device but at a fraction of the cost.*

Thermosiphons

There's another kind of solar water heater that uses no pumps, controls, or other external power sources: It's the *thermosiphon,* which relies on warm water's natural tendency to rise (see Illustration B). Unlike batch heaters, in which a tank simultaneously collects and stores solar heat, thermosiphons have a collector which absorbs solar warmth, and a separate, heavily insulated water tank mounted above the collector that stores the sun-warmed water. You'll see plans for a $600 unit you can build in about four weekends that should perform as well as $1,200 commercial models.

Right: *Our top-of-the-line batch heater is a freestanding, highly-insulated box containing two black-painted water tanks. It's mounted in a sunny spot in the yard, facing south, with insulated pipes carrying water to and from the unit. A "cusp" reflector (see inset) focuses incoming sunlight onto the tanks, heating the "batch" of water within. The sun-warmed water is then fed to the home's existing water heater. The pictured unit, with 32 square feet of collection area, costs about $400, and should trim about 35 per cent off our test home's water heating bills.*

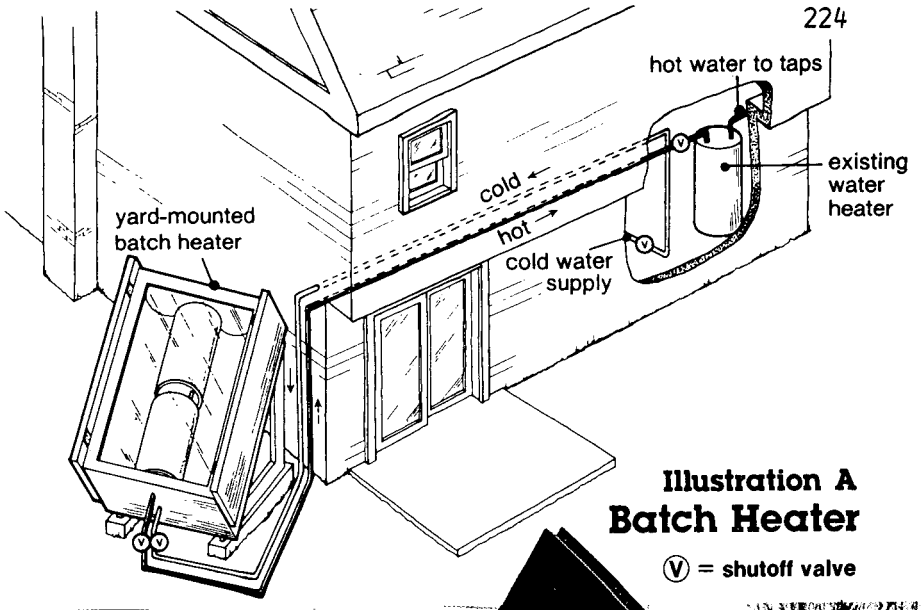
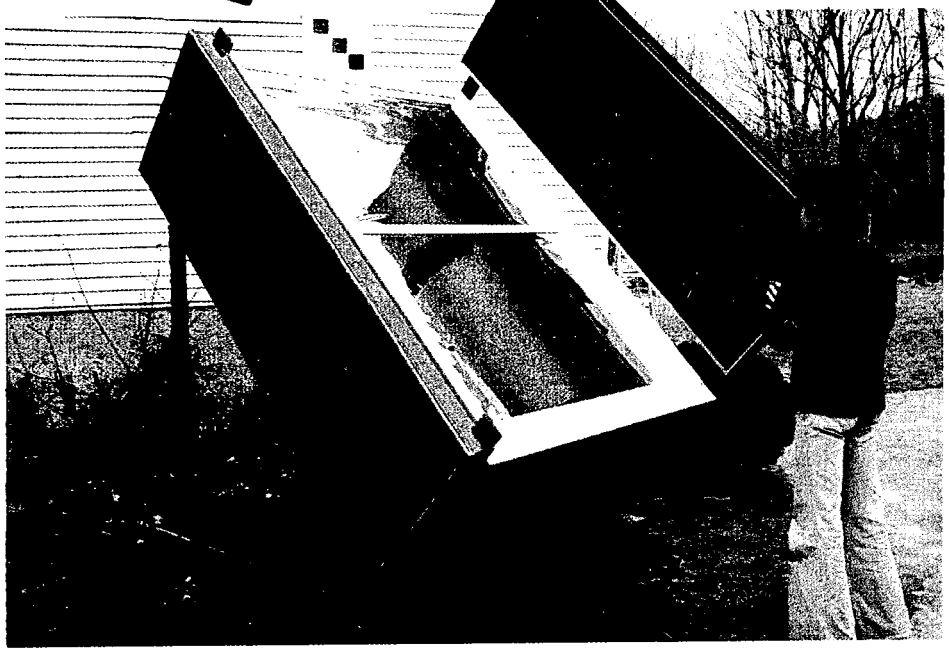


Illustration A
Batch Heater
Ⓥ = shutoff valve



Above: *Our batch heater features large, insulated doors to help hold in the heat at night or during cloudy weather. Opening and closing the doors takes less than a minute, and helps the heater to operate at peak efficiency.*

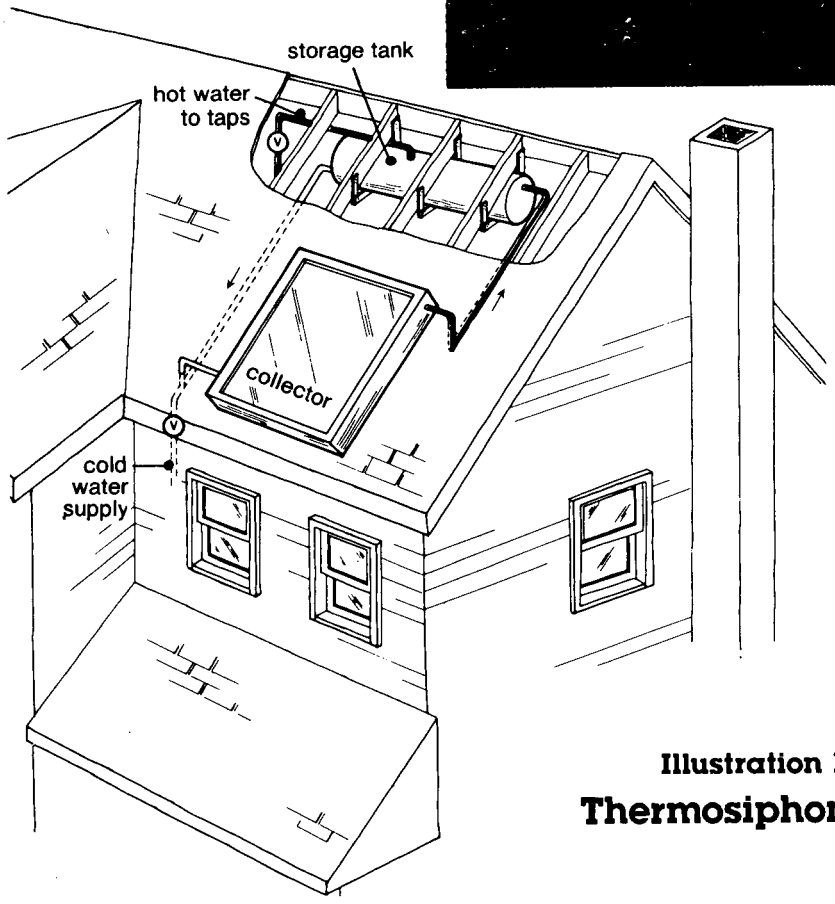
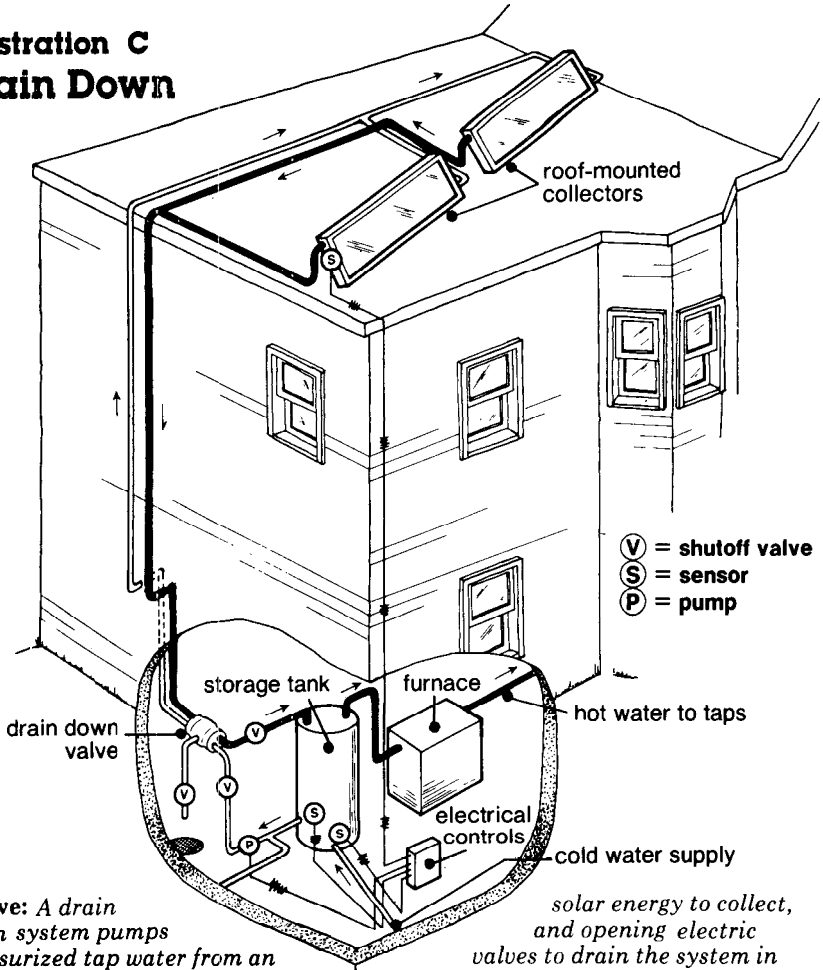


Illustration B
Thermosiphon

Left: *In a thermosiphon, water heated in the collector rises by natural convection to a heavily insulated storage tank, mounted above the collector. As warm water leaves the collector, cold water is automatically drawn from the storage tank into the base of the collector, where it heats, rises, and continues the convective cycle. Because thermosiphons have no moving parts, they are highly reliable. The pictured 27-square-foot unit can be built from scratch for about $600, or purchased as a commercial kit for about $1200.*

ILLUSTRATIONS BY FRANK ROHRBACH

Illustration C
Drain Down

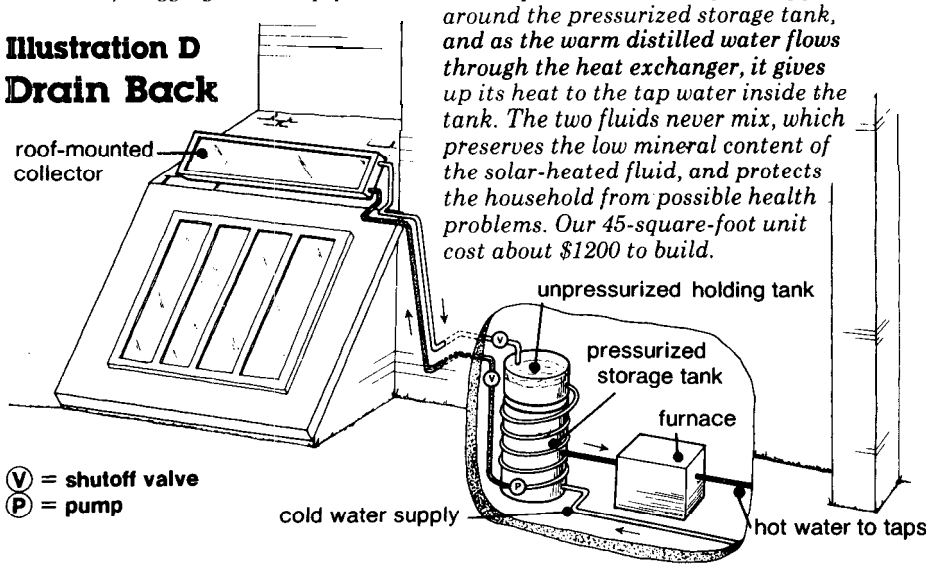


Above: *A drain down system pumps pressurized tap water from an insulated storage tank through collectors for heating. An electronic control panel monitors the system, turning on the pump when there's solar energy to collect, and opening electric valves to drain the system in the event of freezing weather or mechanical failure. The illustrated 32-square-foot system can be built for about $950.*

Above: *Thermosiphons are well suited to homes in which a tank can conveniently be mounted higher than the collectors. Some models use built-in tanks; others, like the one shown here, mount the collectors low on a roof and place the tank in the attic.*

Below: *A drain back system uses two separate fluids: One is ordinary tap water, the other is purified or distilled water (chosen because its very low mineral content reduces the chances of clogging the thin pipes in our collector). The cold distilled water (green) is pumped to the collectors for heating (yellow), and then flows back to a holding tank by gravity. The holding tank empties into a spiral heat exchanger wrapped around the pressurized storage tank, and as the warm distilled water flows through the heat exchanger, it gives up its heat to the tap water inside the tank. The two fluids never mix, which preserves the low mineral content of the solar-heated fluid, and protects the household from possible health problems. Our 45-square-foot unit cost about $1200 to build.*

Illustration D
Drain Back



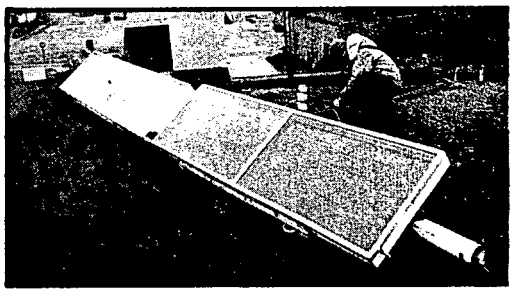
Active Drain Down

Moving into the "active" systems—systems that rely on electrical power to operate—we'll examine a *drain down* system, which pumps pressurized tap water through collectors for heating. Valves open automatically at a preset low temperature to drain the system in the event of freezing weather (see Illustration C). Because the system has electric controls, sensors, valves, and a pump, it costs more to build and operate than batch heaters or thermosiphons. Even so, a drain down system can be the best choice in freezing climates where the collectors and storage tank must be widely separated. We'll show you a design you can build in three to four weekends for about $950.

Active Drain Back

Next, we'll look at a *drain back* system, whose primary difference from a drain down system is that the water flowing through the collectors never reaches your taps. Unpressurized water is pumped from a small holding tank through the collectors—where it is warmed—and then through a heat exchanger where the solar warmth is transferred to a large storage tank filled with pressurized tap water (see Illustration D). A drain back system doesn't need electric valves, because gravity automatically drains the collection loop back into the holding tank whenever the pump stops. Our drain back system uses a variety of easy-to-work-with plastic components, and should take about four weekends to assemble, at a cost per square foot comparable to the drain down unit.

Above: *Drain back systems use collectors which can be mounted out of sight on a roof. Externally, they look almost identical to drain down systems, but there are significant internal differences in cost, complexity, and building ease.*



Above: *Drain down systems show little to the passerby. Often, the rooftop collectors are all that are visible, which can be an important consideration in areas regulated by strict building codes.*

Phase Change

Finally, you'll see some state-of-the-art *phase change* systems; the most technologically advanced solar water heaters in our tests.

A "phase change" is an alteration in physical form, such as from liquid to gas or solid to liquid. A material undergoing a phase change absorbs and releases far more heat than a substance that merely heats up or cools down without physically changing. The systems we'll be testing use a phase change material called Freon, which as a liquid has a boiling point in the 70° to 90° F. range (see Illustration E). Liquid Freon boils in the solar collectors, absorbing large amounts of heat as it changes phase from a liquid to a gas. The hot Freon gas then enters a heat exchanger, where it is condensed back to a liquid, releasing the solar heat into the home's water supply. Phase change systems should be more efficient collectors of solar energy than standard systems, but they're also five to ten per cent more expensive, and require a higher level of assembly skill. Whether they're worth this extra expense and bother is one of the more important questions we'll answer.

Comparisons

Once we've looked at the five aforementioned system types, we'll compile our year-long test results in one article for easy side-by-side comparison. Here you'll see exactly what each system cost; how much conventional fuel was saved; what the payback time was; how easy or difficult each was to construct; how each rated in terms of efficiency and reliability; what the strengths and weaknesses of each design were (best for large families or small? warm or cold climates? etc.); and finally, as the bottom line, what was the "Btus per dollar" rating of each system. Like "miles per gallon," Btus per dollar lets you compare different systems in similar terms, and is invaluable in helping select the system that's best for you.

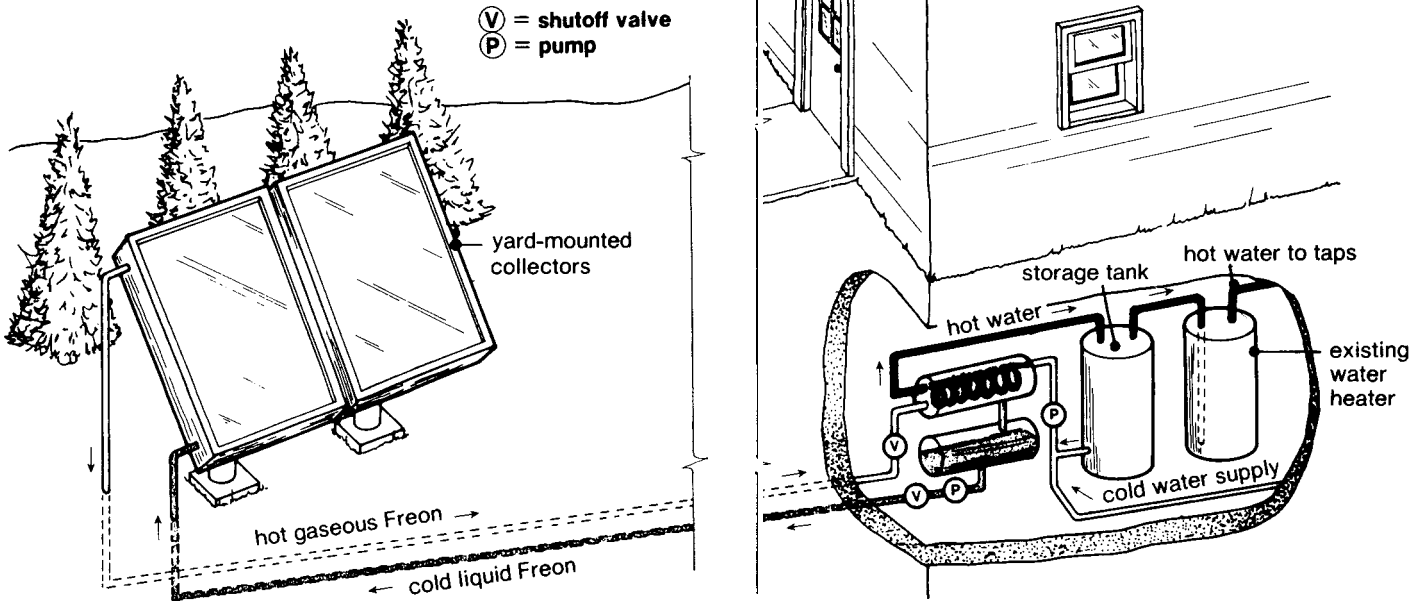
Grand Finale

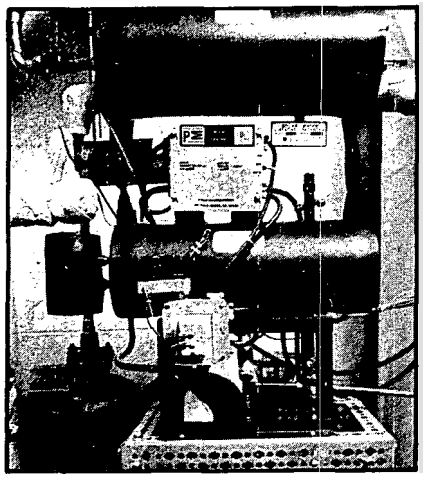
We won't leave you guessing. Along with each system, we'll include lists of parts and suppliers, information on basic assembly, and sources for additional information. With ordinary handyman skills, you should be able to read our coverage, then head for the workshop. But we're going one step further for those of you who may be unfamiliar with construction techniques, or who are hesitant to launch a major project on the basis of one magazine article. When all the test results are in, we'll select the one system we feel has the most going for it, and present highly

Below: *In this phase change system, liquid Freon (green) is pumped to the collectors, where it boils into a hot gas (yellow). The hot gas passes through a heat exchanger which contains a coil of the home's tap water piping. The hot gas condenses, turning back into a liquid and giving up its heat to the home's water supply. Phase change systems should be highly efficient, but they require unusual materials and a higher level of construction skill than other systems. The illustrated system, with about 80 square feet of collector, costs about $2500 in kit form.*

Illustration E

Phase Change





Above: *Our phase change system uses yard-mounted collectors, with buried insulated pipes carrying Freon to and from the home's basement. Keeping long runs of outdoor piping warm is difficult, and can severely limit the performance of any system.*

Left: *The heart of a phase change system is the two-tank heat exchanger. The top tank receives hot, gaseous Freon, and condenses it to liquid. A coil of ordinary copper pipe inside the top tank carries tap water, which is warmed by the condensing Freon. Liquified Freon collects in the lower tank, until it's pumped out to the collectors to be reheated.*

detailed step-by-step plans for that system. You'll see the right way to do everything from buying the components to trouble-shooting the finished product. Clear photos and diagrams will help make things simple to follow.

Whether you build the system in our Grand Finale, or one of the other four we'll cover—or even if you only follow the no-cost/low-cost conservation suggestions in our next issue—you'll be on your way to a more economical, more independent future.

It was done eighty years ago in California and Florida. It's about time we did it better. ■

For more information on selecting an efficient, economical solar water heater from commercial sources, here are some suggested books:

Solar Age Catalog (Solar Vision, 1977)

How To Buy Solar Heating Without Getting Burnt (Rodale Press, 1978)

Solar Energy Utilization (Van Nostrand Reinhold, 1980)

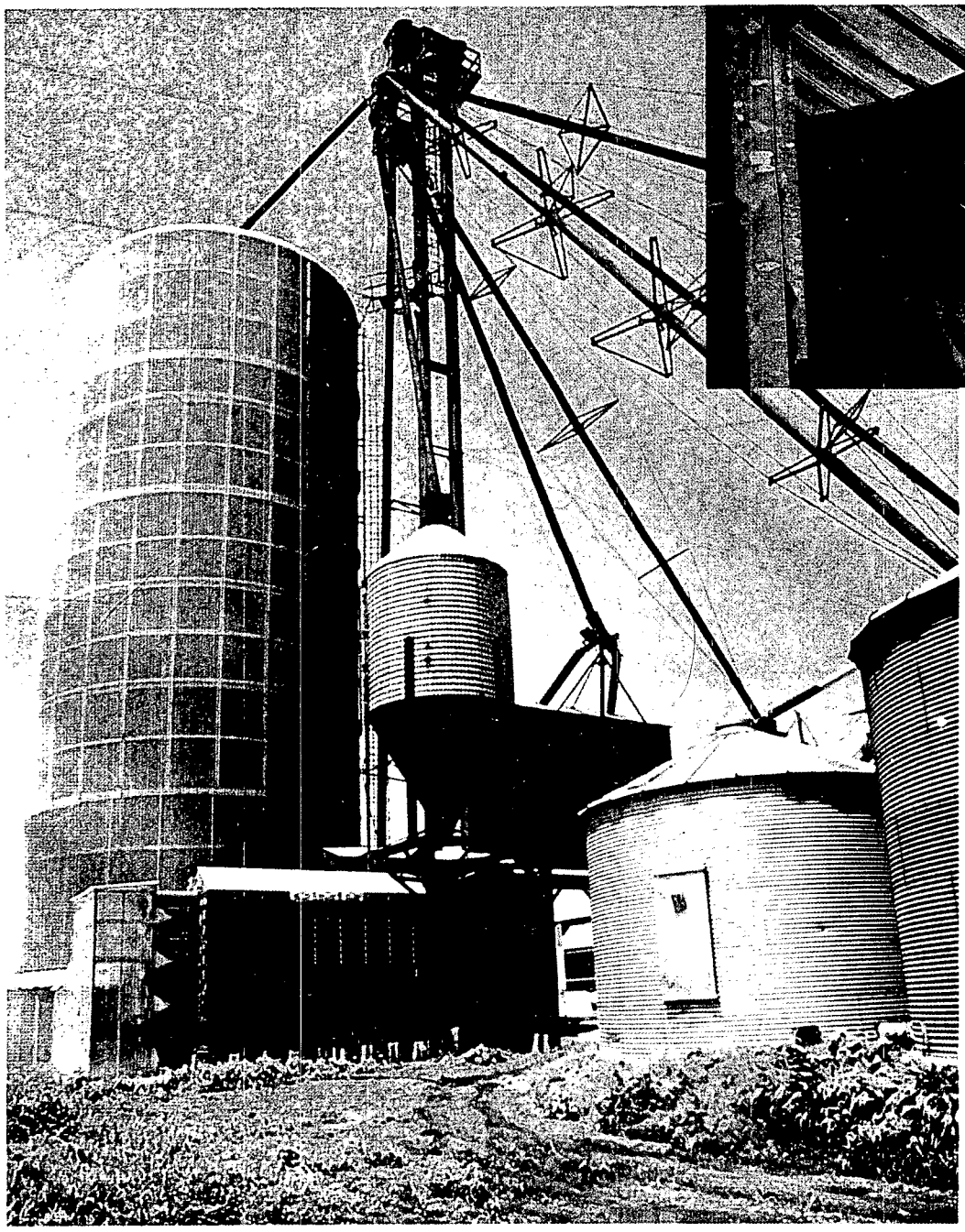
The Sun Catalog (Solar Usage Now, 1979)

Low Cost Sources Of Energy For The Home (Garden Way, 1975)

or call the National Solar Heating And Cooling Information Center at 1-800-523-2929 (in Pennsylvania, call 1-800-462-4983; Alaska and Hawaii call 1-800-523-4700).

New Heat Collectors Harness More Energy from the Sun

Many of the processes that consume energy in this country don't require high temperature heat. Grain drying is one such process, and farmers who use the sun to do the job are reaping dividends in both costs and quality.



Photos: Paul M. Panoc

Curved solar collector 80′ tall on the side of a Harvestore warms air 12° to 15° for Carl Behme, Macoupin County, Ill. He directs it to a dryer (above) to cut fuel costs, or diverts it into underground ducts that go to two 20,000-bu. bins where he dries late corn with solar heat only.

New heat collectors HARNESS MORE ENERGY FROM THE SUN

■ A heat collector on a glass-coated steel silo cuts corn-drying costs to the bone for Carl Behme (photos).

"We burned 500 gal. of fuel to help dry the first 15,000 bu. last fall," says Behme. "Solar did the rest."

He figures his solar collector almost paid for itself the first year.

Aluminum strips and brackets attach a wood-furring-strip frame to the silo to hold the fiberglass out about 6″ from the wall.

A plenum chamber at the base of the silo encloses the same volume of air as the collector surface and delivers air either to the dryer or directly to underground ducts leading to two 20,000-bu. bins.

Small fans on the bins pull warm air from the plenum.

Behme designed his grain handling and drying system himself, with help from Marvin Hall, area Extension adviser at Macomb, Ill. He installed it, including the grain leg and underground ducts, with help from four men who work regularly in his corn-hog-beef farm operation.

He starts combining corn at 22% to 26% moisture and runs the earliest corn through a multi-stage dryer.

Last fall, after moisture

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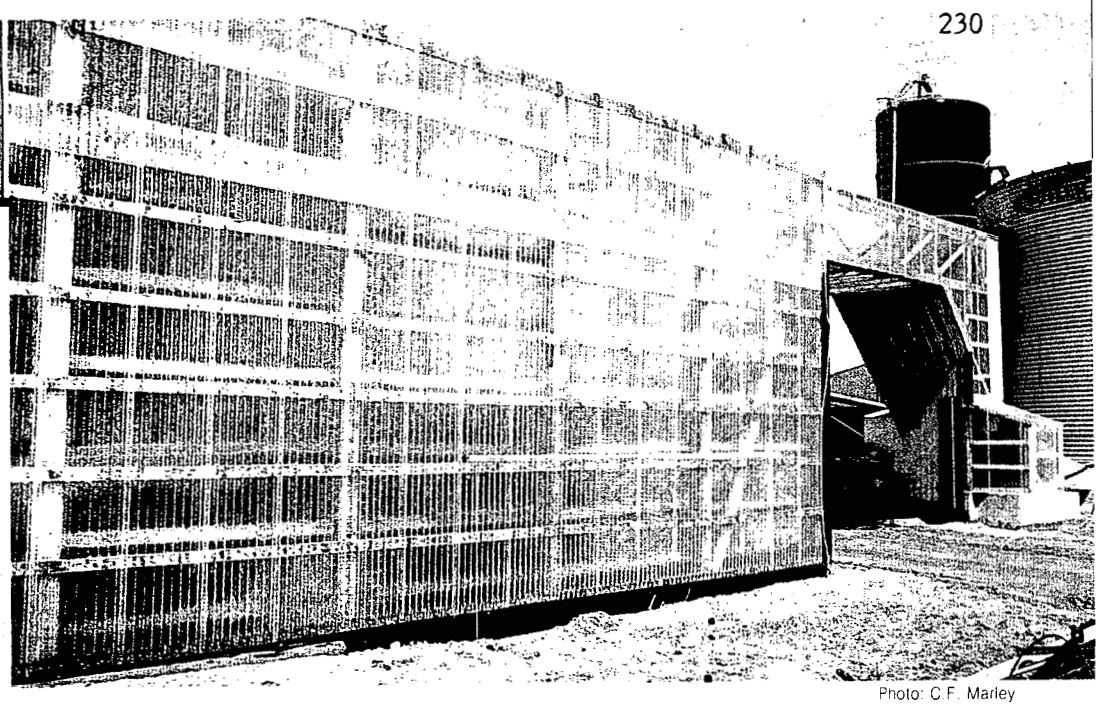


Photo: C.F. Marley

An overhead duct delivers warm air from a solar collector on the machine shed to a grain bin on the other side of a driveway for Hubert Stoll, Logan County, Ill. Clear fiberglass covers a 16′ x 120′ wall on the machine shed and the 34′ x120′ south half of the roof to boost air temperature by 10°. A rock bed under the machine shed floor will store solar heat for the farm shop.

dropped to 21% in the field, Behme put corn directly into the bin and dried it to 16% using only solar-heated air.

A big solar collector built by dairy farmer Hubert Stoll (photo, right) delivers warm air through an overhead duct and a fan house that also capture the sun's rays.

"The top of the duct has the same pitch as the machine shed roof," explains Stoll. "This made the joint easy to seal and makes the duct 6′ high on the north, 4′ high on the south. It's 6½′ wide."

Twin 15-hp. fans, housed beside a 16,000-bu. bin in clear fiberglass, pull air from the duct and off the 120′ machine shed roof and wall.

Stoll plans to start harvest at 28% moisture and expects to dry the first binful in about seven days, then sell it and refill the bin.

"Solar heat dries faster early in the fall," he observes. "Air is warmer then, and so is the sunlight."

In Macoupin County, Ill., Don Colburn (below) built a solar collector roof over his farm scales and grain dump. Black-painted plywood under clear plastic traps the heat from the sun's rays.

Like Behme and Stoll, Colburn got help on fan and duct size from Marvin Hall.

Hall recommended a 10-hp. fan and a 4′x4′ air duct. The duct, 20′ long, has clear plastic sides and roof, and a painted plywood floor to trap more heat.

Low-cost dryers built by Robert Metz and Chuck Harley (lower right) are made from lumber, metal and salvage materials.

Metz mounted his 12′x24′ collector on an old wagon frame. He put steel railroad car wheels underneath and can switch to rubber-tired wheels from a pickup truck to tow it over the road.

Most farmers drying corn with solar heat say they're impressed with the high quality of the grain.

"Corn I took out of the drying bin at 16% moisture last fall was beautiful," says Metz. "None of it stuck to the bin walls, and there was no dust. And I cut fuel bills in half." ◁

Double-duty solar collector. Don Colburn, Macoupin County, Ill., will warm air to dry grain with a sloping, clear plastic roof over his scalehouse (below). In the spring, Mrs. Colburn plans to use it as a greenhouse.

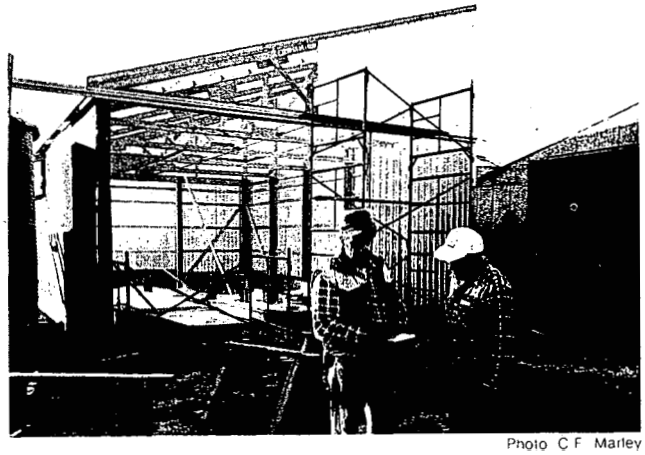
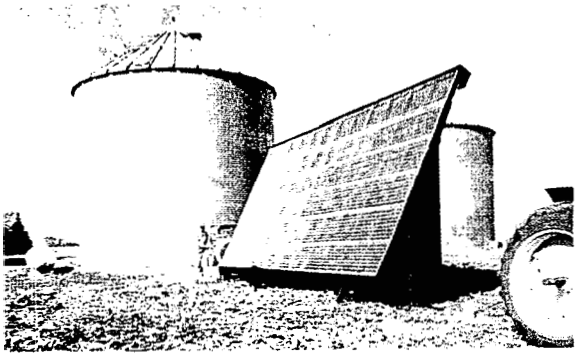


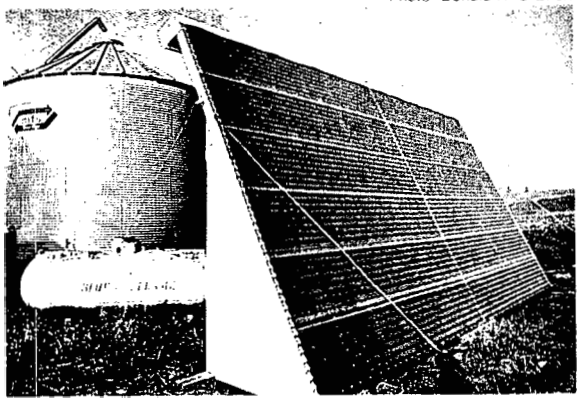
Photo C.F. Marley

Photo C.F. Marley



Solar collectors that cost $600 dry corn for Robert Metz (above), Logan County, Ill., and for Chuck Harley, Jackson County, Ohio (below). "I got the plans for $1 from the University of Illinois," says Metz. Harley financed his with a farm facility loan from the USDA's ASCS. Both collectors are portable. Harley's moves on skids, while Metz's rolls on old rail-car wheels.

Photo Donald K. O'Brien



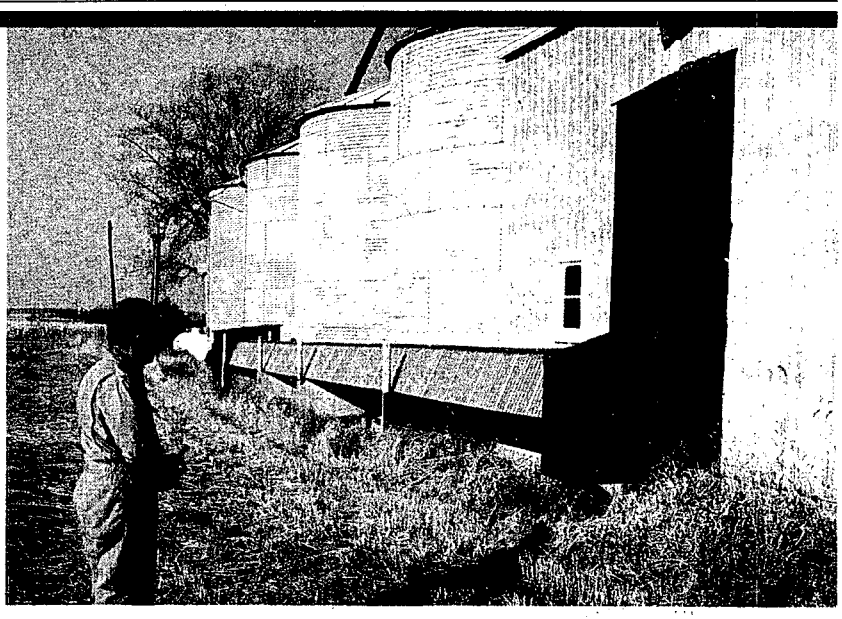
SOLAR DRYING IDEAS from FARMERS

When the sun stays bright, John and Hank Brandt heat air 30° to dry corn from 25% moisture down to 15.5% in eight days inside an 18,000 bu. bin they hooked up to a big solar collector on a machine shed (above).

A portable 36′x12′ solar panel captures the sun's rays for Gene McMillan (top photo, opposite page), after a tornado left only the floor and running gears of his mobile home. He dries corn to between 20% and 22% moisture with a gas dryer, then finishes the job with solar-heated air.

And Steve Funk (center, far right), added a sloping solar jacket to a "retired" storage building where he's putting in a fuel alcohol still. "It dries corn in the fall and will help heat the still after that," he says.

In Michigan, Lavern Bivens (photos, lower right), designed a "solar-assist" system to warm air going into electric dryers on his 20,000-bu. bins. ◁

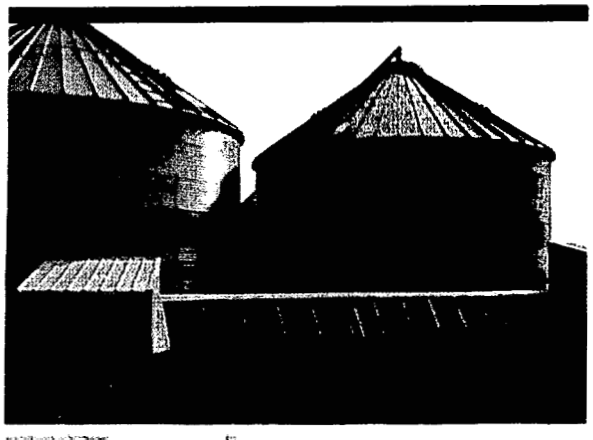


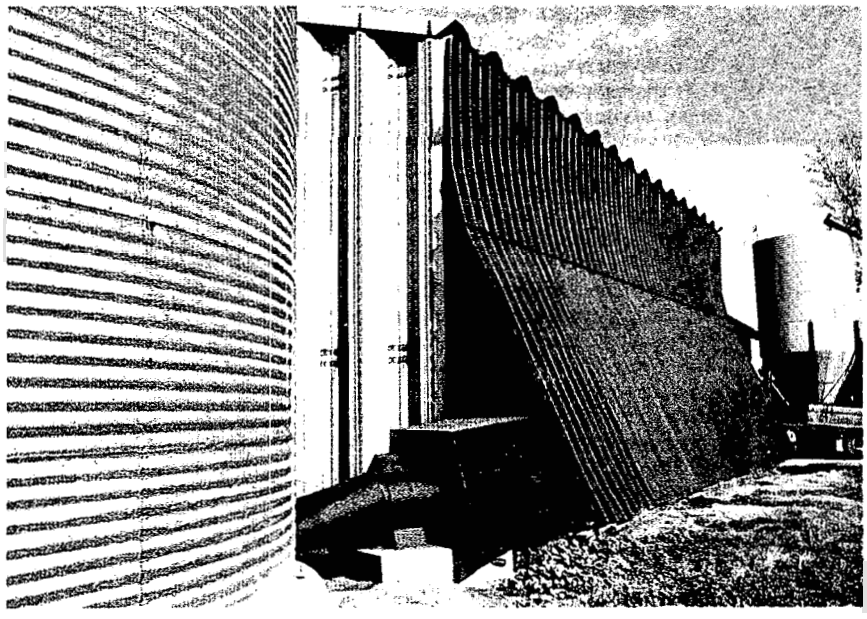
A duct 108′ long (top photo) delivers warm air to a drying bin from a big solar collector that covers half the roof and all the south wall on a 60′x135′ machine shed. John and Hank Brandt, Logan County, Ill., used no dryer fuel in 1978, filled the tank only twice in 1979. White building near bin houses a 25-hp. fan.

Low-cost solar collector on a 42′x 60′ machine shed pre-heats air ahead of a gas bin dryer for Wayne McBride, McHenry County, Ill. (above). He nailed Celotex to the rafters under a corrugated metal roof, built a duct and draws the sun-warmed air through with a 10-hp. fan. Total cost: $1,208.

Photos C.F. Marley

Heat collectors on wheels, on roofs and on walls speed up drying, cut costs





Solar collector on a mobile home chassis warms air 10° to 15° to finish drying 50,000 bu. of corn in the fall for Gene McMillan, Sangamon County, Ill. (top photo). He dries corn at two bin sites, then uses the collector to warm his farm shop in winter.
Photo: C.F. Marley

A corrugated metal wall angled 60° (above) raises air temperatures 16° inside. Steve Funk, McLean County, Ill., nailed plywood on a vertical frame inside and added a duct, so the dryer fan on an adjoining bin can pull air from the A-shaped space.
Photo: C.F. Marley

A machine shed roof (left) warms air going into two bins (inset) for Lavern Bivens, Barry County, Mich. A 20'x120' roof area of 3/8" black plywood covered with Lascolite, a corrugated fiberglass, warms air 12°. Solar panels on the duct also collect heat.
Photos: Norm Reeder

What's In Store for Phase Change?

PCM's (phase change materials) store large amounts of thermal energy in the process of changing from solid to liquid or liquid to gas. Experiments in phase change materials offer hope for practical, compact heat storage in solar systems.

Dow Chemical Company's thermal energy storage compound, calcium chloride hexahydrate, crystallizes from the liquid phase.

What's in Store for Phase Change?

Thermal Storage Materials for Active and Passive Solar Applications

By David Eissenberg and Charles Wyman

Thermal energy storage plays an important role in both active and passive solar heating systems, absorbing surplus thermal energy during sunny periods and releasing it when there is insufficient solar gain to meet the load requirements. In active solar heating systems, lower-cost energy can be provided with storage than without it. Storage is vital in passive systems to prevent the building from overheating during the daytime or cooling off excessively at night.

Most active solar heating systems store thermal energy as sensible heat by raising the temperature of water or rocks. In passive applications, sensible heat is frequently stored in concrete structural materials or drums of water. Water, rocks, and concrete are usually chosen for storage because they are inexpensive and reliable. However, the large space required for these storage media may not be readily available in many applications, particularly for retrofits. In addition, if the temperature swings allowable for energy storage and recovery are limited, as in passive building heating, the quantities of storage materials and the space needed to store them become very great.

For some time, storage materials which undergo a change in phase, called phase change materials (PCM's), have been viewed as an attractive alternative to sensible heat storage media. These materials absorb a large quantity of heat during the phase change and then release it at a constant temperature as the process is reversed. The phase transitions generally occur over a narrow temperature range which, in principle, can be matched to end-use requirements. Any reversible change of phase can be used for thermal energy storage, but because of volume considerations liquid/gas transitions are not generally considered practical, while solid/solid transitions tend to have smaller heats of transition. Solid/liquid transitions (melting/freezing) have been the focus of all practical investigations and will be the only phase change storage mode discussed here.

Storage material selection

Considerable effort has been spent in identifying and testing candidate solid/liquid PCM's for both passive and active solar applications beginning with the early work of Maria Telkes, now director of solar thermal storage development at the American Technological University, Killeen, Texas. Candidate materials should have these characteristics:

- appropriate melting points
- little or no subcooling
- high heat of transition
- chemical stability (no loss of storage capacity over time)

David Eissenberg, a chemical engineer, was formerly manager for the Thermal Energy Storage Program at Oak Ridge National Laboratory (ORNL), Oak Ridge, Tenn., and is currently group leader of a coal conversion group at ORNL. Charles Wyman is group manager for the Thermochemical Sciences Section, Solar Thermal Research Branch, Solar Energy Research Institute, Golden, Colo.

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- low cost
- non-flammable and non-toxic properties.

Other desirable characteristics include a small volume change on transition, a high thermal conductivity, a low vapor pressure, and a rapid rate of crystallization.

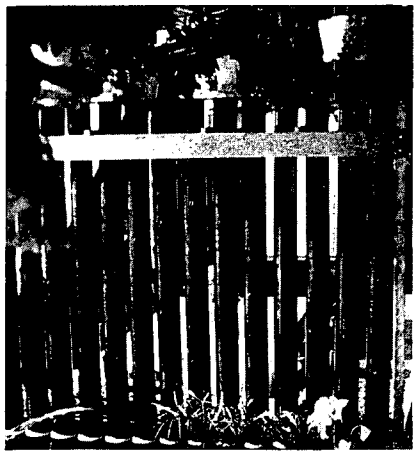
Two general classes of storage materials are considered most attractive for both passive and active solar use: organic compounds and salt hydrates. Many organic compounds are potential PCM's, based on their melting points and heats of transition. However, the list of compounds is rapidly reduced when those that are either unstable or too costly are excluded. Paraffins (saturated hydrocarbons), some crystalline polymers (plastics), and some naturally occurring organic acids are the most practical compounds for thermal storage systems, because they are relatively inexpensive. The organic PCM's do not have to be pure chemicals if the mixture properties are within the desired range and do not change over time. Mixtures of organic compounds tend to have broader melting ranges, however, spreading the heat of transition over a large temperature range.

In general, organic PCM's have three limitations—low thermal conductivity, flammability, and high volume changes during melting. Appropriate engineering of the complete storage system can resolve these difficulties, although it may increase system cost compared to salt-hydrate based systems.

The phase change behavior of salt hydrate PCM's is more complex than that of organic compounds because hydration/dehydration occurs, rather than simple melting/freezing. Salt hydrates exhibit three general types of phase-change behavior: congruent, incongruent, and semi-congruent melting. The desirable behavior is congruent melting, which occurs when the solid phase composition (ratio of salt to bound water) is the same as the liquid phase composition. In that case, the hydration/dehydration process appears identical to the melting/freezing process.

Semi-congruent melting occurs when a material has two or more hydrate forms with differing solid compositions and melting points. The material can be transformed into other hydrate form(s) before either complete melting or freezing occurs, resulting in a broadened melting point range similar to that obtained with organic mixtures. In addition, there is a temporary loss in thermal storage capacity.

Incongruently melting materials yield two distinct phases upon melting: a saturated solution and a precipitate of insoluble anhydrous salt. If the precipitate settles to the bottom of the container, the anhydrous salt will not hydrate completely upon cooling and some thermal storage capacity will be lost with each freezing/melting cycle.



Martin P. Burks

Ken Eigsti's house, 9,000 feet above sea level in the Colorado Rockies, uses Thermalrod-27 phase change storage tubes in an attached greenhouse.

Unfortunately, the congruently melting hydrated salts that have suitable melting points are either too expensive or have other undesirable characteristics for solar storage applications. On the other hand, semi-congruent salt hydrates such as calcium chloride hexahydrate and incongruent salt hydrates such as Glauber's salt (sodium sulphate decahydrate) are inexpensive (Table I). Because of their low cost, these materials have been the most thoroughly studied in spite of their complex melting behavior, and many approaches to resolving semi-congruent and incongruent melting problems have been developed.

Salt hydrates cool below their normal freezing point without solidifying and the heat of fusion will not be available from storage. Methods have been devised, however, for reducing or preventing this subcooling in the commonly used hydrated salts. Heat must also be removed through the frozen PCM, which impedes transfer, and various approaches are available to improve the heat transfer.

Active solar storage system components

PCM's must be incorporated into suitably designed containers and heat exchangers for active solar thermal energy storage. Usually the cost of these components far exceeds the cost of the storage materials themselves; so the key to successful PCM application lies with the economical design of the entire storage system. The functional requirements for active storage systems include containment, heat transfer, and mechanical devices to reduce loss of storage capacity.

Containment

The phase-change materials must be housed in suitable containers so that the melt remains in place. Materials may be contained directly in tanks, or in many small containers that are enclosed in a large insulated tank. The primary container must not react with the storage material, and expansion during phase change must be allowed. The size, shape, and material selection for the PCM container is dictated by heat transfer efficiency, corrosion resistance, and cost. Metals and plastics have both been used.

Heat transfer

Heat transported from the solar collector by either liquid or air is transferred to the PCM by either indirect (heat exchanger) or direct (immiscible fluid) heat transfer mechanisms. Sufficient surface area keeps the temperature difference between the working fluid and the PCM to a minimum, to take advantage of the constant storage temperature. The rate of heat transfer is determined by the design of the solar system, but should generally be large enough to fully charge the storage medium during one day.

To maintain the overall heat transfer rate to and from organic-based PCM's at the desired level, the PCM must be contained in relatively thin layers between heat transfer surfaces. The heat transfer problem is less severe for the water-based salt hydrates because their thermal conductivity is greater. To minimize cost, the same fluid and heat transfer mechanism is often used for both heat removal and addition, although the rate of heat removal will usually be less than that of heat addition.

Design of salt hydrate systems

The design of active solar storage systems using salt hydrates includes techniques for preventing performance loss from melting and subcooling problems. To minimize subcooling, two approaches to nucleation have been tried—the addition of small quantities of a chemical nucleating agent to the PCM and the use of a cold finger.

Nucleating agents are substances upon which the PCM crystal will deposit with little or no subcooling. Crystals with shapes and spacings similar to the PCM, but with a higher melting point, are used to nucleate the hydration reaction. Borax, for example, is an excellent nucleator for sodium sulfate

Table I: Salt Hydrate Phase Change Materials

Name	Phase Change Temperature	Latent Heat	Type
Sodium Sulphate Decahydrate (Glauber's salt)	89°F	120 Btu/lb	Incongruent
Calcium Chloride Hexahydrate	81°F	75 Btu/lb	Semi-congruent
Sodium Thiosulfate	116°F	90 Btu/lb	Semi-congruent

decahydrate. Other chemical nucleators may also work, but it is difficult to predict their capabilities since all of the mechanisms for nucleation are not well defined. For example, claims have been made that the impurities present in technical grade sodium thiosulfate pentahydrate may act as a nucleator for that hydrate.

When the PCM is stored in bulk form, a simpler nucleation method is the use of a cold finger. A surface within the storage container is maintained at a cooler temperature than the maximum subcooling temperature needed to promote nucleation, so that some PCM crystals are always present to initiate the solidification of the remaining PCM.

With semi-congruent salt hydrates, the concentration of the solution must be controlled to prevent crystallization of the lower hydrates that have a higher melting point. In the event that such hydrates form, the solar system must be capable of producing sufficiently high temperatures to melt them.

Incongruent melting (precipitation in the melt phase), as observed with sodium sulfate decahydrate, is a more serious problem because it can result in a continual loss of latent heat storage capacity. Three methods have been tried for preventing this loss of storage capacity: forced circulation mixing of the precipitate, addition of thickeners, and the use of thin containers. All three methods have been investigated, and success has been achieved at least in bench-scale and prototypes.

Forced circulation of the precipitate has been accomplished by stirring with an immiscible fluid and by rotating a horizontal cylindrical drum, containing the PCM, on its axis. (Figure I) With the immiscible fluid stirring method, the working fluid (generally a natural or synthetic oil) is bubbled through the PCM, stirring it and providing direct heat transfer. (Figure 2)

Thickeners help prevent settling of the precipitated anhydrous salt in the melt, so that during subsequent freezing the salt more completely recrystallizes as the hydrate. Both clays and silica gel derivatives have been used as thickeners for this application.

The third approach to prevent storage loss from incongruent melting is to package the PCM in very thin horizontal trays. If the settling distance is sufficiently short, then the redissolving/recrystallization processes can proceed to near-completion.

Status of PCM systems for active solar

At present, PCM storage technology has been developed to the point where systems can be built for residential active solar heating applications; their reliability will be demonstrated over time. Such systems may not be cost-effective, however, compared to water or rock sensible heat storage, so at present PCM storage applications may be limited to situations where space is at a premium. This situation will change as more attention is paid to the engineering of those systems that can be mass-produced at low cost or constructed with low-cost materials.

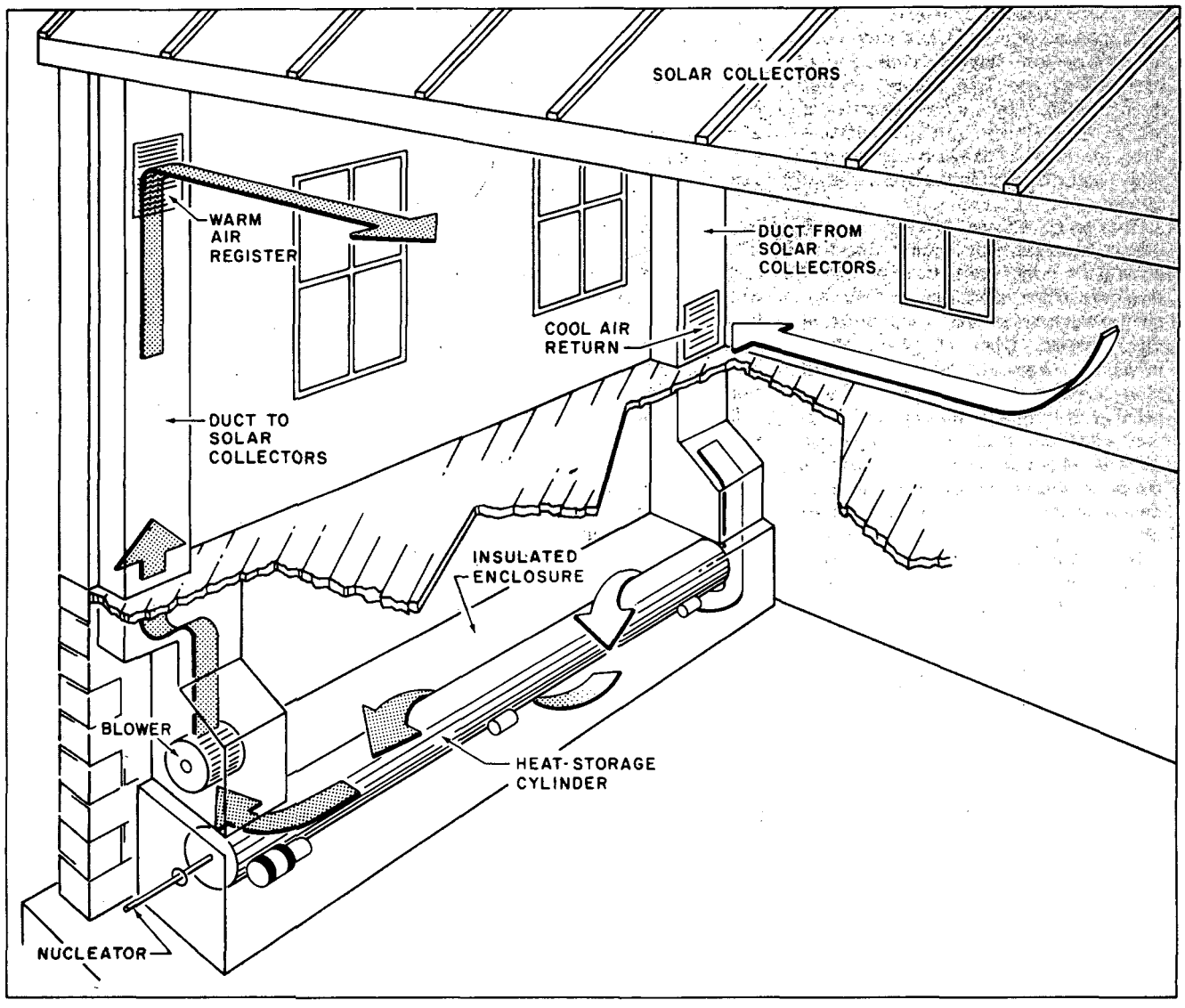


Figure I. Forced circulation mixing of the precipitate is accomplished by rotating the storage cylinder on its axis.

Passive solar storage systems

A significant challenge for passive solar heating is the storage and control of the heat to maintain suitable comfort standards within the building. One approach to reconciling storage with the building comfort requirements is to use such a large mass of building material that its temperature does not vary widely. A second approach is to locate the storage so that it is directly heated by the sun (e.g., a Trombe wall) rather than indirectly heated by sunlight that has already been absorbed within the building space. In either case, however, more storage mass is required for a passive solar heating system than for an active one.

Smaller building temperature excursions are possible with phase change than with sensible heat storage, provided the melting point is suitably matched to the application. Containers of PCM's can be located in the heated space for indirect heat storage. Directly heated PCM's are expected to provide greater comfort since the interior temperature does not have to cycle above and then below the melting temperature for heat to be stored and released. When directly exposed to solar radiation, the storage container must not degrade significantly.

Maria Telkes is developing a Trombe wall system that incorporates a phase change material, to which thickeners and nucleating agents are added. The wall is located approximately one-half inch behind a cellular foam, exterior plastic window-wall that transmits at least 60 percent of the incident solar radiation while lowering thermal losses to that of one inch of conventional insulation.

At the Solar Components Division of the Kalwall Corporation, Manchester, N.H., a phase change thermal storage system has been developed for installation behind south-facing solar windows and roofs. With a special coating on the packaging and a translucent phase change material, this system is unique in its ability to transmit and control natural daylight levels within the buildings. The modular and compact units can be used in almost any new or existing building. Real time and accelerated testing indicate a system life in excess of 20 years. Patents have been applied for.

Incorporation of PCM's into structural materials has the advantage of forming an integral part of the building. The thermal performance of concrete impregnated with paraffin wax was analyzed by R. Godfrey and S. Mumma at Ohio State University in 1976, and the composites were predicted to absorb as much as 75 percent more heat than in a wall constructed of either component alone. Because of its melting, the paraffin wax improved the thermal storage capacity of the wall, compared to one of pure concrete. The higher heat conductivity of the concrete ensures that more heat penetrates the material than if the wall contained only wax. Impregnating the concrete with 30 to 40 percent paraffin was predicted to provide the highest heat absorption.

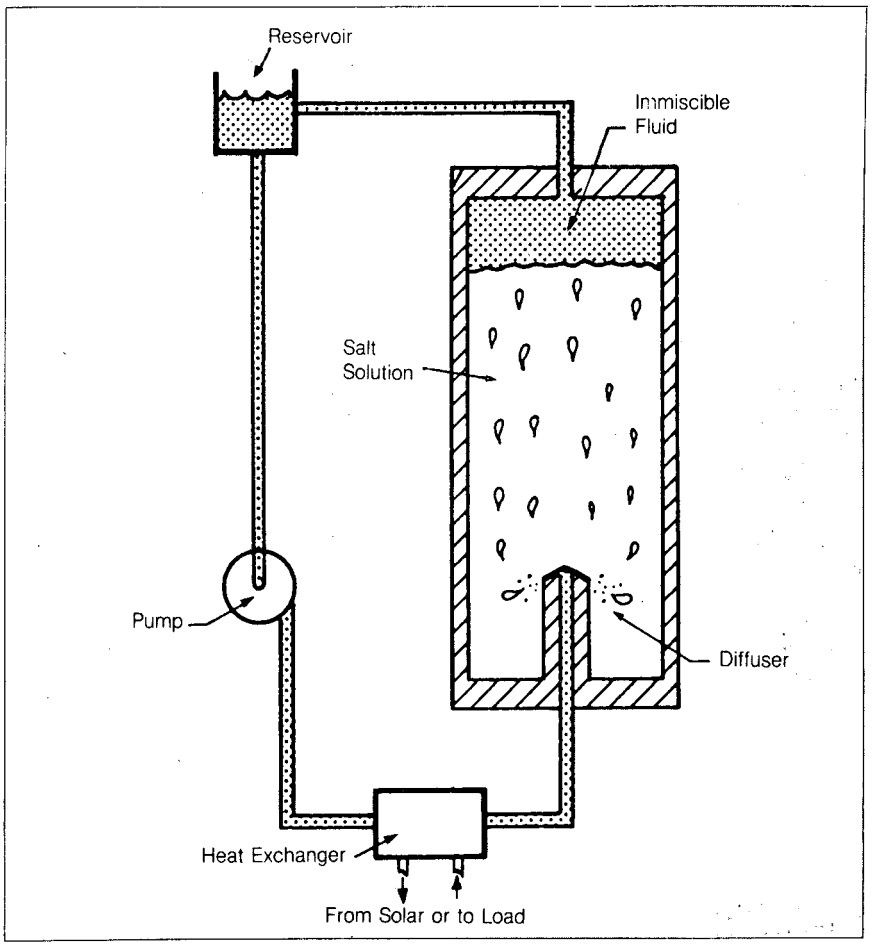


Figure 2. With the immiscible fluid method, the working fluid is bubbled through the PCM, stirring it and providing a direct contact heat transfer.

More recently, researchers under the direction of Professor Mumma at Arizona State University have made concrete with paraffin wax dispersed in it. Paraffin wax is formed into an aggregate-like material mixed and with cement, sand, aggregate, and water. The specific heat of small one- and two-inch cubes has shown large apparent increases due to the wax. Concrete with about 40 percent paraffin wax by volume has been made, but above this level the wax tends to run out. Although the experiments have been performed only on a small scale, the researchers believe the process can be commercialized. Experiments are still required to test the material's structural properties, transient thermal behavior, and flammability. If the material proves acceptable, it could be used in rock beds as well.

When salt hydrates are used in building materials, higher fractions of the phase change material should be desirable than for paraffin wax, since the heat conductance of the hydrates is much closer to that of concrete. Suntek Research Associates, Corte Madera, Calif., has developed Thermocrete™ blocks, made of porous concrete impregnated with a salt hydrate and sealed with epoxy or some other surface coating. The Thermocrete test samples contained about 50 percent calcium chloride hexahydrate by weight, and provided latent heat storage at 80°F. Initially, the blocks looked promising, but after aging the concrete would swell and rupture. This breakdown was apparently caused by the reaction of the salt hydrate with the lime in the concrete. Use of a lime-free cement has been proposed to overcome the degradation problem, and some new blocks have lasted for over one year. However, no tests have been performed with these blocks to determine whether they can withstand the continued thermal cycling expected in actual use.

Phase change materials were first incorporated into a ceiling in the Solar Building 5 at the Massachusetts Institute of Technology (MIT). Solar insolation is reflected to the dark-colored ceiling by louvers placed in southern windows. Within the ceiling tiles there are thin pouches of the phase change material—sodium sulfate decahydrate with a Borax nucleating agent, sodium chloride melting point depressant, and Cab-O-Sil® fumed silica thickener. This mixture provides about 35 percent of the ideal heat storage capacity of sodium sulfate decahydrate, but the performance

Commercial Suppliers of Phase Change Materials

Manufacturer	Product Name	Phase Change Material	Container	Total Weight	Phase Change Temperature	Heat Storage Capacity (at phase change temperature)	Warranty
Addison Products Co. Addison, MI 49220 (517) 547-6131	Solar Therm	paraffin	steel, round, 1 gallon	7.25 lbs.	115°F	80 Btu	1 year
Architectural Research Corp. 40 Water St. New York, NY 10004 (212) 943-3160	Sol-Ar-Tile™	Glauber's salt	polymer resinous concrete tile, 2 feet by 2 feet	44 lbs.	73°F	1,000 Btu	2 year
Blue Lakes Engineering Pace Corp. P.O. Box 1033 Appleton, WI 54912 (414) 733-0941 (a distributor for PSI Energy Systems, Inc.)	Thermol-81	calcium chloride hexahydrate with additives	black polyethylene tube, 6-feet long, 3½-inch diameter	35 lbs.	81°F	2,460 Btu	10 year
Boardman Energy Systems, Inc. 5720 Kennett Pike P.O. Box 4198 Wilmington, DE 19807 (215) 388-7454	product available July 1980	sodium sulphate	plated steel tubes, 30-inch long and 4-inch diameter; built-in spacers, selective coating available	22 lbs.	45°, 64°, 74°, 78°, 81°, 89°	1,444-2,000 Btu, varies with phase change temperature	will be available
Colloidal Materials, Inc. P.O. Box 696 Andover, MA 01810 (617) 475-3276 (a licensee of Cabot Corp.)	Heat Pac™	sodium sulphate	3-ply aluminum foil laminate pouch, ¾ inch by 2 feet by 2 feet	10 lbs.	73°F (may be varied between 65°F and 89°F)	350 Btu	5 year
Energy Materials, Inc. 2622 South Zuni Englewood, CO 80110 (303) 934-2444 (under OEM agreement with Dow Chemical Co.)	Thermalrod-27	calcium chloride hexahydrate	black polyethylene pipe, 5-feet long, 3½-inch diameter	35 lbs.	81°F	2,542 Btu	10 year, limited
PSI Energy Systems, Inc. 1533 Fenpark Drive St. Louis, MO 63026 (314) 343-7666 (under OEM agreement with Dow Chemical Co.)	Thermol-81	calcium chloride hexahydrate, with additives	black polyethylene tube, 6-feet long, 3½-inch diameter	35 lbs.	81°F	2,460 Btu	10 year
Texxor Corporation 9910 North 48th St. Omaha, NE 68152 (402) 453-7558	Texxor Heat Cell	calcium chloride hexahydrate (Bisol II)	steel cylinder, 7-inch long, 4.26-inch diameter	4.56 lbs.	81°F	345 Btu	5 year
Valmont Energy Systems, Inc. Valley, NE 68064 (402) 359-2201		Glauber's salt	polyethylene rectangular cube, 2 feet by 1 foot by 2 inch	16 lbs.	89°F	1,294 Btu	5 year, limited

compiled by Elizabeth Holland

has not degraded with continual cycling. Flexible pouches of this material, which can be placed on top of a fire-rated dry wall ceiling, are commercially available from Colloidal Materials, Inc., Andover, Mass. The pouches store about 200 Btu per square foot and cost approximately $2.00 per square foot. Melting points of 88°F, 73°F, and 66°F are standard. A ceiling tile containing the pouches was first developed at MIT; the tile is now produced at the Architectural Research Corp., Livonia, Mich., but the availability is limited.

Status of PCM Storage for Passive Solar Heating

Several concepts have been developed which promise the enhanced volumetric heat storage capabilities of phase change materials while overcoming their historical reliability problems. For passive solar energy applications, PCM's with suitable thickeners and nucleating agents can be used in commercially available plastic containers to moderate building temperatures and store heat. Incorporation of the PCM s into the building structure is advantageous since the storage capacity of the structure is increased significantly and the storage material is concealed. PCM's have been employed in ceilings with some success. Although integration of PCM's into walls or floors has not been successfully demonstrated, several limited tests are encouraging. The use of PCM's in structural materials has significant potential advantages, and further work is important to develop satisfactory enhanced heat storage structures for passive solar heating.

Rising Oil and Gas Prices Are Making Hydropower Look Better

A hydropower installation is neither cheap nor simple. But as fuel costs rise and energy demand continues, hydropower becomes more cost-competitive. Existing dams and reservoirs especially are receiving new attention, and abandoned hydropower sites are being refurbished. As one utility president says, "The water's there. Let's use it."

ENERGY REPORT

Rising Oil and Gas Prices Are Making Hydropower Look Better Every Day

The economics for expanding hydroelectric potential are looking more attractive, and a record number of requests for operating permits are now pending.

BY WILLIAM J. LANOUETTE

SAFE HARBOR, PA.—After 50 years, the original federal operating license for the hydroelectric dam here is up for renewal this month, and its owners are seeking not only to keep it operating but nearly to double its capacity.

Spring runoff is now raising the Susquehanna River in the lake behind Safe Harbor Dam, forcing operators to "spill" water in dramatic—but unproductive—cascades. To tap that wasted resource, they propose to add five more turbines to the seven that have whirred here for half a century.

"With the price of oil going where it is, the economics favoring additional hydro here are compelling," said Donald B. Chubb, president of the Safe Harbor Water Power Corp., which owns the dam. "At this facility, we can produce electricity for 3.5 mills per kilowatt-hour. The most likely alternative is a gas turbine, which can cost up to 10 cents a kilowatt-hour."

To be sure, the economics for expanding the country's hydroelectric potential are not always as attractive as they are here. Safe Harbor Dam is used chiefly to provide "peak load" power, the extra electricity needed only at certain times of day. When it is used for generating "base load" power for customers' normal demand, the cost comparison with coal and nuclear plants is favorable but less dramatic.

Yet the cost and availability of hydropower are still so appealing that along with Safe Harbor's application, there are now a record number of requests—more than 250—before the Federal Energy Regulatory Commission (FERC) for new, expanded and rehabilitated generating facilities.

These applications range from plants that can generate 12 kilowatts (thousand watts) for individual use to projects of 572 megawatts (million watts) for large utilities. Together they represent generating capacity of more than 17,000 megawatts.

Ronald A. Corso, the director of FERC's division of licensed projects, boasts that this is the equivalent of about 17 nuclear power plants. Hydropower already provides about 15 per cent of U.S. electricity, compared with about 10 per cent for nuclear power.

The relationship between these old and new electricity sources was highlighted just upriver from Safe Harbor a year ago at Three Mile Island. General Public Utilities Corp., the owner of the two infamous nuclear power plants there, chose as the cover picture for its 1978 annual report a photograph of the Three Mile Island units, with the 75-year-old York Haven hydro plant in the foreground. The report appeared a few weeks before the celebrated nuclear accident that began on March 28, 1979. While the 1,700-megawatt nuclear units have been idle ever since, the 19-megawatt hydro plant is still contributing modestly to the company's power grid.

Of course, hydropower does not always compete directly with nuclear energy, since it is often used just for peak load while nuclear plants often contribute to base load. Hydropower plants, to be sure, run only when the water does; on the other hand, they aren't subject to months-long shutdowns for annual refueling or to the vagaries of high technology, as nuclear plants are.

It's true that the five new turbines at Safe Harbor are likely to be used for only about two months a year—the average time during which the operators now spill water over the dam—and add only 187.5 megawatts to the 230 used most of the year. But even with that limited use, the $150 million cost of the turbines is seen as a bargain when compared with other available sources of electric power.

Hydropower is appealing for several reasons beyond its price. In most cases, it poses fewer environmental problems than coal or nuclear power. It can be built more quickly than its alternatives, with some plants operating within 4 years after planning begins, compared with 4 to 8 years for coal plants and 8 to 14 years for nuclear plants.

Because the environmental hurdles are fewer, the licensing time is also shortened. And last fall, FERC began to streamline its review of hydropower applications by cutting the number of required exhibits from 23 to 7 and reducing the number of words in their regulations from 10,700 to 2,300.

Red tape still exists, however, and this is compounded if an applicant takes advantage of the federal grants now available to assist in conducting surveys and preparing license documents. At Safe Harbor, for example, the application for license renewal is four inches thick, and contains among other details a list of more than 750 local plants—among them the downy rattlesnake-plantain, sleepy catchfly, pale touch-me-not and sweet joe-pye weed—that grow in the area.

"By far, the environmental materials were the most difficult to compile," said Louis Brethauer, vice president of the Safe Harbor Water Power Corp. "There are a lot more formalities this time than there were 50 years ago."

Metropolitan Edison Co., the General Public Utilities Corp. subsidiary that operates Three Mile Island, had tried to build a pump storage facility at Stony Creek, north of Harrisburg, but found itself bucking the objections of sportsmen and environmentalists.

The opponents eventually persuaded the Pennsylvania General Assembly to declare the site part of a wild and scenic river system, which further hampered the

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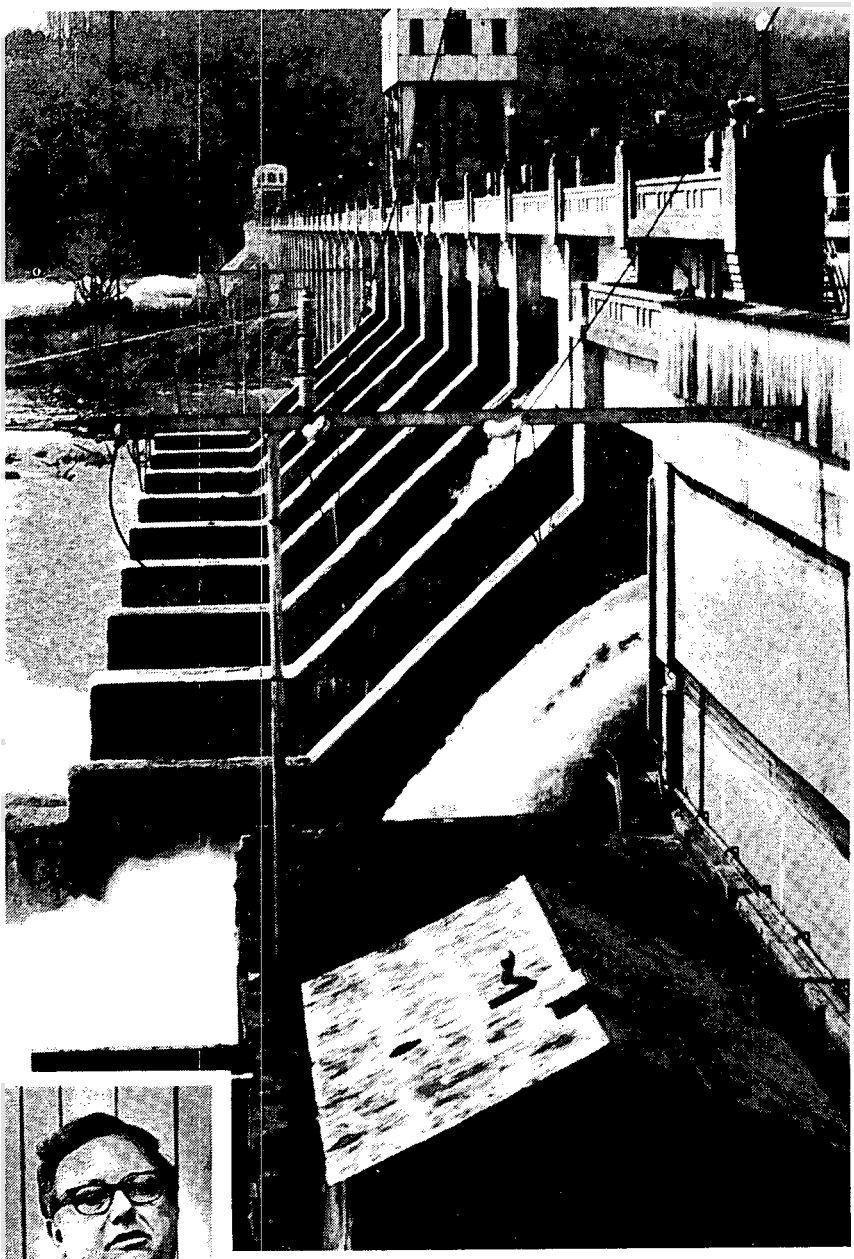


Donald B. Chubb is president of the firm that operates Safe Harbor Dam in Pennsylvania. The dam has a capacity of 230 megawatts.

efforts to obtain a FERC license for the project.

A typical pump storage facility, which raises water to a reservoir and stores it until needed for peak load generating, is much larger than a conventional hydro plant. In fact, the seven applications now before FERC for pump storage projects would provide considerably more generating capacity than the 225 conventional hydropower projects for which licenses are currently being sought.

From 1970 to 1979, FERC reported, 10,200 megawatts of capacity were completed for pump storage facilities, compared with only 1,000 megawatts in previous decades.

But this potential can be misleading. For one thing, the extra capacity is used only intermittently; for another, as Metropolitan Edison and other utilities are learning, the size of the plants and the constantly changing level of water in the dams' reservoirs make them less than popular with the local populace.

Thus their eventual contribution to the nation's energy mix may prove to be less than that of the smaller, conventional hydro projects.

The economics for realizing the country's hydroelectric potential vary from site to site, according to the Energy Department, and few generalizations are possible. George Grimes, engineering development program manager at the Energy Department's small-hydro division, said a survey by his office revealed a range of project costs from less than $500 per kilowatt installed to more than $2,000. The average is about $1,500.

Corso, in a speech at Harrisburg last fall, said that newly installed hydropower will cost between 1.5 and 8 cents per kilowatt hour. By contrast, nuclear power now costs 4 to 5 cents per kilowatt hour and power from coal, 6 to 8 cents. Electricity from solar photovoltaic cells can be produced at about 48 cents per kilowatt hour, he said, and wind-generated electricity at a test site in North Carolina is estimated to cost about 18 cents per kilowatt hour.

HYDRO'S POTENTIAL

The 17,000 megawatts in applications now before FERC represent only a small percentage of the identified hydropower potential, although they mark a significant shift in interest. *(See box, p. 688.)*

These applications reverse a decline in hydropower operations over the past quarter century, a period when the low prices of fossil fuels and the rising expectations for nuclear power made many hydro plants uneconomical.

In 1977, the Army Corps of Engineers reported that there were 57,000 megawatts of generating capacity in operation, with another 8,200 megawatts under construction. It concluded that the potential existed for another 54,600 megawatts from three sources: 5,100 megawatts from rehabilitation of existing hydro dams, 15,900 megawatts from expansion of existing hydro dams and 33,600 megawatts by developing non-hydro dams. *(See NJ, 4/29/78, p. 672.)*

The corps conceded that its survey, ordered by President Carter in his energy policy message that April, was superficial, and that many impediments stood in the way of realizing the full potential it identified.

Since then, the corps has completed a more ambitious "Preliminary Inventory of Hydropower Resources," based on an analysis of its original survey and released last July in six regional volumes. It found 63,702 megawatts of installed capacity at 1,251 facilities, which could be supplemented by 94,636 additional megawatts at 5,424 existing dams, whether or not they are producing electricity today.

At another 4,532 sites where no dams exist, the corps reported, 353,948 more megawatts could be installed. Thus if hydro's full potential were realized, the country could have an installed capacity

of 512,286 megawatts—perhaps by early in the next century.

The inventory's authors, however, issued this sweeping caveat: "The incremental potential and that estimated for undeveloped sites do not include detailed consideration of the engineering, economic, financial and environmental constraints; nor do they include an assessment of the competitive use of water at existing impoundments, or consideration of the complex social, legal and institutional feasibility, all of which could preclude full development of the hydroelectric potential."

The most common way to measure hydropower is in terms of installed capacity, but output must also be considered. New turbines may be economical operating only two months a year at Safe Harbor because they are primarily providing peak load power, although at other sites this intermittent use may prove too costly to justify the investment.

At the Energy Department, Grimes said some of the projects on the Corps of Engineers list appear to hold little economic promise. He noted that the corps has estimated that 338,217 megawatts of the potential 512,286 would come from undeveloped large-scale sites where capacity exceeds 25 megawatts. The corps estimates that these sites would produce only 884 billion kilowatt-hours of energy a year, based on estimates that they would be operating only 2,600 hours a year—or less than 30 per cent of the time.

"I doubt that the investment capital will be there to support that kind of low capacity factor," Grimes said. "At today's prices, that seems mighty costly."

At undeveloped sites, he added, construction costs could far outweigh the expected returns.

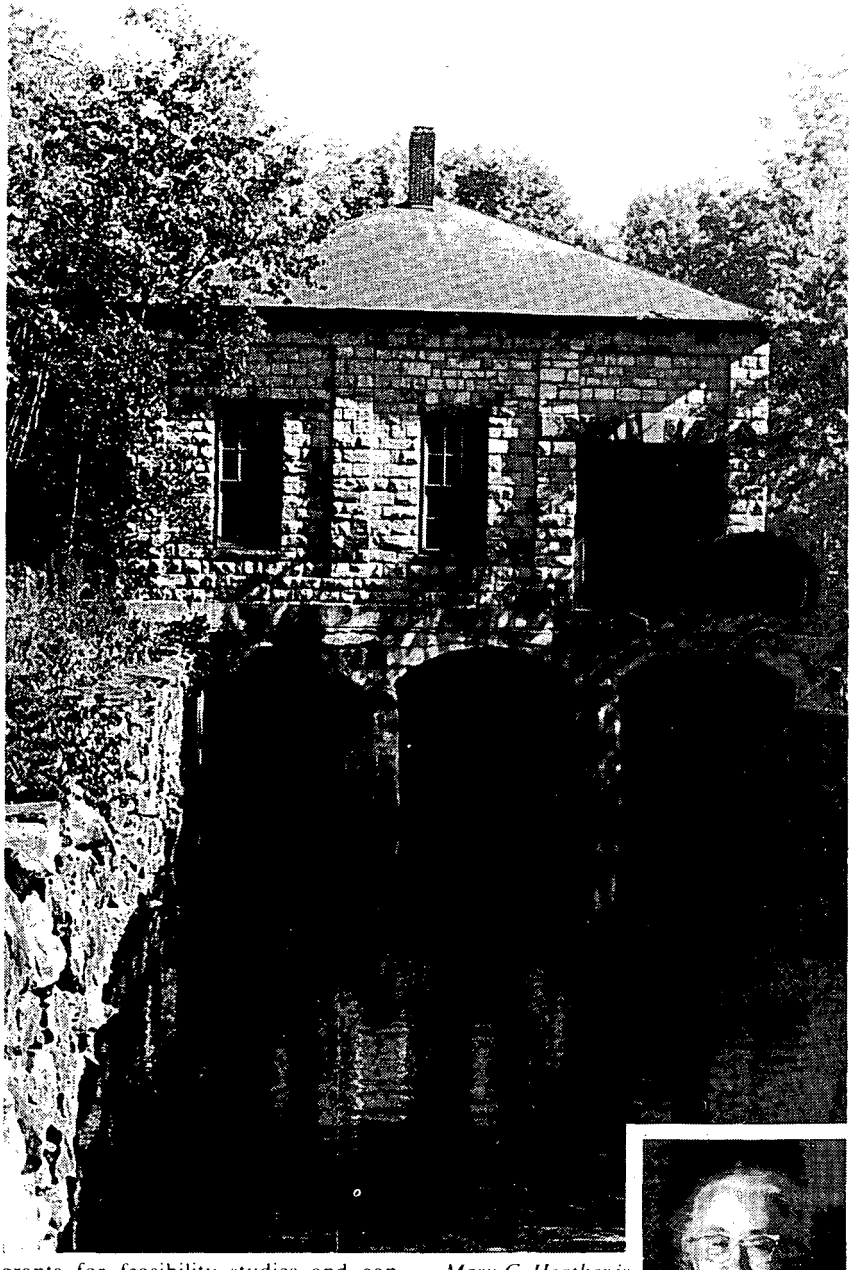
But economic conditions are not static, and if the environmental problems of coal and the safety problems of nuclear power continue to rise, hydropower sites that are now too costly may soon become more attractive.

In fact, new applications for hydropower arrive at FERC almost daily and, said Corso, there's a flurry of new filings every time there's publicity about oil price increases.

"If it is assumed that inflation persists," said Robert C. Richert, a hydraulic engineer at General Public Utilities Corp., "it can be demonstrated that the capital-intensive power costs of the hydroelectric facility will remain relatively stable and should be significantly less than inflation-prone fuel or power costs at some time in the future."

The Energy Department has encouraged hydropower development with grants for feasibility studies and construction that have totaled $30 million since they began in 1978. In addition, the department is mailing checks for $20 million this month in loans for feasibility and licensing studies at more than 500 sites. The loans are forgiven for sites that are not feasible.

Guy W. Nichols, chairman and president of the New England Electric System, praised the Energy Department and FERC for their efforts on behalf of hydro. "They're sincerely trying," he said, "and I usually don't say nice things about those agencies."



Mary C. Heather is restoring this 300 kilowatt hydro plant in Stockbridge, Mass. She hopes to begin operations soon and expand to a capacity of 500 kilowatts.

PROJECTS HERE AND THERE

The New England River Basins Commission, which released a study of the "Potential for Hydropower Development at Existing Dams in New England" last January, concluded that existing dams can make a "significant local contribution" and that "hydropower's regional contribution will obviously rise as conservation measures reduce over-all needs." Nevertheless, the commission cautioned, "from a regional viewpoint, it is evident that the electrical energy contribution

Hydropower Potential in the States

The table shows the potential for hydroelectric power in each of the states. The first four columns show the estimates by the Army Corps of Engineers of existing hydropower capacity, additional power that could be achieved at sites where dams have already been built and power that could be generated by streams without dam developments now. In the last two columns are applications before the Federal Energy Regulatory Commission (FERC) as of March 7 for additional capacity. (All figures are in megawatts.)

	Corps of Engineers				FERC	
	Existing	Additions	Undeveloped	Total	Conventional	Pump storage
Ala.	2,271	4,121	581	6,973	148.0	—
Alaska	129	418	666,775	167,322	84.3	—
Ariz.	1,406	156	13	1,575	—	—
Ark.	1,080	2,886	6,235	10,201	569.0	—
Calif.	7,636	5,447	13,053	26,136	2,213.8	200.0
Colo.	401	1,593	7,072	9,066	289.7	3,840.0
Conn.	103	88	NA	191	13.5	—
Del.	0	0	2	2	—	—
D.C.	0	0	0	0	—	—
Fla.	30	45	30	105	8.8	—
Ga.	2,050	406	2,060	4,516	79.0	—
Hawaii	19	31	30	80	—	—
Idaho	2,448	5,172	40,536	48,156	829.1	—
Ill.	132	730	259	1,121	9.0	—
Ind.	28	96	444	568	—	—
Iowa	135	1,117	257	1,509	72.0	—
Kan.	2	220	480	702	—	—
Ky.	636	9,271	4,036	13,943	373.2	—
La.	81	291	2,353	2,725	425.5	—
Maine	354	369	NA	723	29.9	—
Md.	476	532	252	1,260	—	—
Mass.	237	115	NA	352	42.7	—
Mich.	486	1,133	0	1,619	6.5	—
Minn.	158	989	1,027	2,174	2.2	—
Miss.	0	133	119	252	54.0	—
Mo.	598	1,368	1,249	3,215	—	—
Mont.	2,418	2,332	15,313	20,063	193.0	—
Neb.	136	94	112	342	50.0	1,336.0
Nev.	677	46	74	797	—	—
N.H.	386	261	NA	647	27.9	400.0
N.J.	6	40	647	693	4.3	—
N.M.	24	286	404	714	—	—
N.Y.	3,741	12,458	3,127	19,326	24.2	1,000.0
N.C.	1,937	653	1,553	4,143	20.8	—
N.D.	430	324	10	764	—	—
Ohio	0	314	90	404	122.1	—
Okla.	1,029	1,630	1,019	3,678	—	—
Ore.	6,853	14,190	37,453	58,496	382.0	—
Pa.	403	1,731	3,245	5,379	296.5	—
R.I.	2	40	NA	42	6.4	—
S.C.	1,532	628	1,175	3,335	3.9	—
S.D.	1,500	420	37	1,957	—	—
Tenn.	2,096	3,269	7,264	12,629	—	—
Texas	321	372	1,875	2,568	11.9	—
Utah	190	348	4,014	4,552	—	—
Vt.	197	134	NA	331	112.9	—
Va.	686	497	1,777	2,960	22.9	3,000.0
Wash.	17,374	13,482	22,716	53,572	927.2	—
W.Va.	148	2,969	1,184	4,301	210.0	—
Wis.	429	812	437	1,678	2.2	—
Wyo.	227	487	3,546	4,260	8.7	—
Total	**63,648**	**94,544**	**353,935**	**512,757**	**7,108.1**	**9,776.0**

from hydropower development at existing dams (*not* currently generating power) is limited at best and is somewhat less than originally anticipated."

The commission has identified 363 active dams in New England that the Corps of Engineers estimated to have a capacity of 1,300 megawatts, although the commission's staff questions some of the corps's numbers. Of the 10,670 dams that the commission identified in its study, 1,750 could, it said, produce new hydropower.

But their combined capacity would be only about 1,000 megawatts, equal to that provided by one nuclear plant. Although not dramatic, this potential is significant, the study noted: equivalent to about 7 per cent of the 1978 New England winter peak load demand.

The New England Power Pool has just completed a hydropower survey of its own, but has not released its findings. "This is not an economic analysis or a site-specific study," said James R. Smith, director of the survey. "It was a paper-screening study, in which we looked at 11,044 sites and identified the 105 that seemed most promising and warranted further study."

Smith said in an interview that he had identified some 540 megawatts of feasible capacity that should be explored further. Projects would range in size from 100 kilowatts or less to 48 megawatts. "We analyzed every dam site, and I mean that in more ways than one," he said.

Antonio Ferreira of the utility industry's Electric Power Research Institute, who worked with Smith on the New England study, said that both the 1977 and 1979 studies by the corps were "very theoretical and optimistic" because they did not consider competing uses for dams—recreation, flood control, drinking water sources and the like.

A look at potential new hydro generating sites in Massachusetts and Vermont shows that hydro's promise of inexpensive electricity must stand the tests of economics and engineering.

The New England Electric System, for example, is involved with a 300 kilowatt hydro plant in Stockbridge, Mass., which is being restored by Mary C. Heather, a 75-year-old retired school teacher. With the help of her brother, Joseph A. Guerrieri, a retired electrical engineer, Heather purchased a plant on the Housatonic River that was operated from 1906 to 1947.

The plant is expected to begin operations this summer, and eventually expand to a 500 kilowatt capacity—at which time it will produce enough electricity for about 250 homes. New England Electric last August agreed to buy power at a price that will reflect the

company's costs for oil to generate the same amount of electricity: now about 4.0 cents a kilowatt-hour.

The Green Mountain Power Corp. in Vermont is now involved actively with two hydropower projects: one to renovate an abandoned site, the other to build a new dam and power plant.

A hydroelectric plant operated at Bolton Falls, on the Winooski River near Duxbury, from 1901 until it was abandoned in 1938. The Energy Department, having chosen the site as a demonstration project in 1979, awarded a $1.5 million grant for the redevelopment that is estimated to cost about $10 million and produce 6 megawatts. Operations could commence by 1983.

Green Mountain is also building a new dam and power plant downstream on the same river between Winooski and Burlington at the site of a former water-powered woolen mill. A powerhouse will be built at the end of an 1,800-foot tunnel to produce 9.3 megawatts at an installed cost of about $9 million.

"We found that with federal money involved, things slowed down and administrative procedures became more complex," said Peter McTague, Green Mountain's president. "But at both sites, costs increased and planning schedules slipped for other reasons as well."

McTague said that at Bolton Falls, engineers discovered that more rehabilitation work was needed than they had expected, "a problem characteristic of redevelopment sites." And at the Winooski-Burlington site, he said, "prices escalated just as they do at any new installation, for the same reasons they do at a coal or nuclear plant."

Green Mountain Power now gets about a third of its power from coal and oil, a third from nuclear and a third from hydro, McTague said.

He cited changes in federal and state regulations as a principal cause of delay—and increased cost. It is still uncertain, for example, whether the Environmental Protection Agency will require a fish ladder at the new dam.

"One thing we've discovered," McTague said, "is that it's often more expensive to take apart and rebuild what's there than it is to start from scratch. Building a new opening for [an intake] hole at Bolton Falls will cost us almost as much as building a new dam."

A similar problem occurred here at Safe Harbor, even though the space and support structures for the five new turbines were installed when the dam was built. "They had great foresight in leaving room for eventual expansion," Chubb said, "and that will hold down costs—but not as much as you might think." The question of whether to install a fish ladder, at a cost of perhaps $15 million, has also been raised.

AN UNCERTAIN FUTURE

The only thing certain about how much of hydropower's potential will be realized is its uncertainty: its potential appears to increase as fossil fuel prices soar and nuclear power fortunes waver, however.

Since electricity was first produced at a dam in Appleton, Wis., in 1882, hydro has risen and fallen as a share of the nation's energy supplies, and it can be expected to continue to fluctuate.

The stability of the electric utilities will be important, and Herman G. Roseman, an economist for National Economic Research Associates Inc., concluded in a study released in March that "the key to financial health is a change in the method of regulation to give utilities a better chance to earn the allowed rate of return—a change which becomes imperative in an era of double-digit inflation."

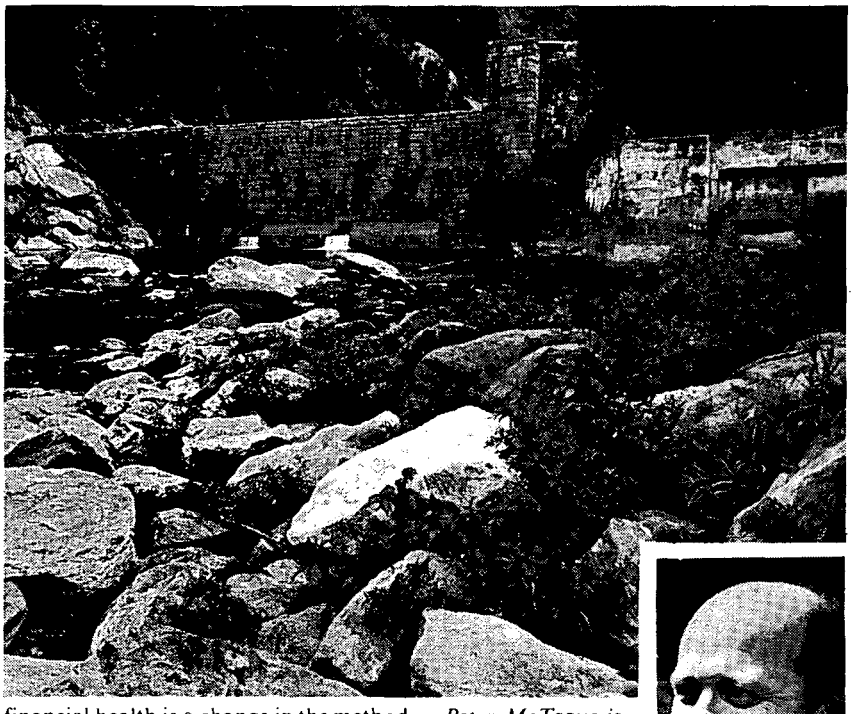
He warned that "even with a stable capital structure, it would be most difficult to raise the required equity capital after a few years. One has to conclude that in a few years, the average utility would be unable to finance current construction."

But beyond the utilities, there is a further promise for hydropower that is just now being tapped: construction of power plants by industries and by cities that need the power for their own purposes.

Among the applications for licenses from FERC are the BSR Co. Inc. in Vermont, the Kimberly-Clark Corp. in Wisconsin, the Madison Paper Co. in Maine, the Fries Textile Co. in Virginia and the Tupperware Division of Dart Industries Inc. in Rhode Island.

More than 40 municipalities have also applied for licenses, including Madison, Maine, Springfield, Vt., Woonsocket, R.I., Saugerties, N.Y., Paterson, N.J., Columbus, Ohio, Martinsville, Va., Vanceburg, Ky., New Roads, La., Gonzales, Texas and Muscatine, Iowa.

"Although the total potential for hydropower is small compared to projected U.S. electric generation needs," the Corps of Engineers said, "in conjunction with other evolving energy production systems such as solar, wind, tidal, biomass conversion, geothermal and other small-scale techniques, [it] could provide a significant amount of relief to our current dependence on foreign fossil fuels."



Peter McTague is president of the firm renovating this hydro dam at Bolton Falls, Vt. The plant could resume operations in 1983 and produce 6 megawatts.

Small-scale turbines that require minimal water flow might contribute to the amount of electricity—and the share of the nation's energy—that hydropower provides in the years to come.

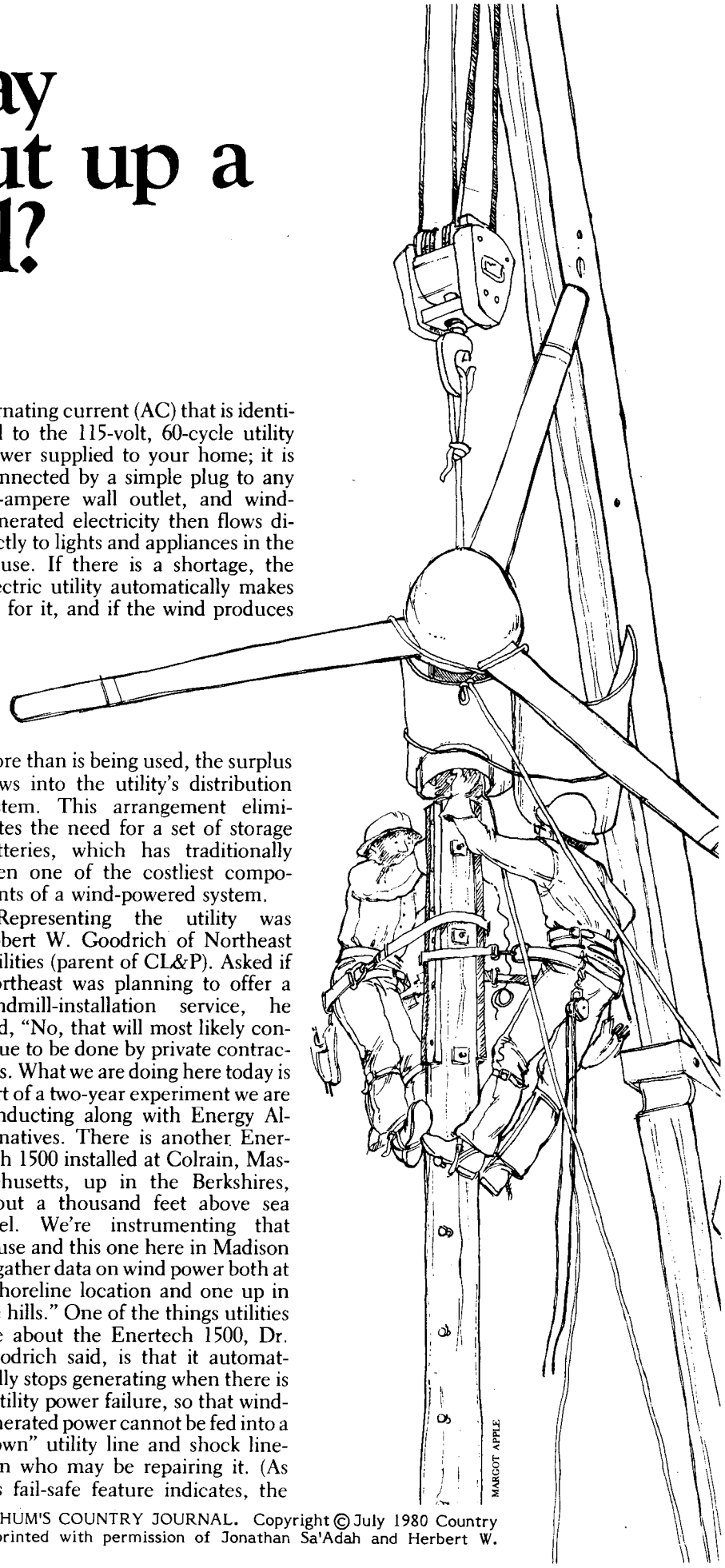
"We're spilling water over the dam today that could be spinning power," Chubb said here recently. "It's there. Let's use it." □

Will It Pay You to Put Up a Windmill?

The wind has the potential for making a growing contribution to our energy budget. But, cautions the author, wind systems are not for everyone. Here are some questions to help a prospective user calculate cost-effectiveness, as well as sources of further information.

Will It Pay You to Put up a Windmill?

by John J. Pullen



AT MIDMORNING OF April 12, 1979, a pleasant day with the still-leafless treetops swaying in a moderate breeze, I joined an unusual group gathered at the home of Rosemary and Alan Hanks in Madison, Connecticut, on a hill overlooking the East River about a mile north of its outlet into Long Island Sound. Conspicuous on the scene, and most curious, was the presence of men in yellow hard hats from the Connecticut Light & Power Company. They were there on private property to help install a windmill, which might have moved a casual observer to ask, "What hath the energy crisis wrought? Are the wind folk now in bed with the electric utilities?"

When I arrived the CL&P fellows were digging a hole in which to plant a 70-foot wood pole, which was lying nearby. Their machines included a 50-ton crane, a backhoe, a line truck with cherry picker, an earth tamper, and an air compressor. "This is overkill," the foreman told me. "You don't need a fifty-ton crane to put up a three-hundred-pound wind generator. But it's what we had available." The generator itself, which was to be mounted on top of the pole, was about 6 feet long and 2 feet across, with a three-bladed propeller 13 feet in diameter. Across its gleaming fiber glass nacelle was lettered the word ENERTECH, the name of the manufacturer (also a distributor of other types of wind plants). Busy supervising the installation of the generator were Eugene Butler and Peter Kaminsky of Energy Alternatives, Inc., a distributor of energy equipment with a home office in Greenfield, Massachusetts. At odd moments they discussed with me a feature of the machine, known as the Enertech 1500, that represents something new in windmill technology. The Enertech 1500 produces alternating current (AC) that is identical to the 115-volt, 60-cycle utility power supplied to your home; it is connected by a simple plug to any 20-ampere wall outlet, and wind-generated electricity then flows directly to lights and appliances in the house. If there is a shortage, the electric utility automatically makes up for it, and if the wind produces more than is being used, the surplus flows into the utility's distribution system. This arrangement eliminates the need for a set of storage batteries, which has traditionally been one of the costliest components of a wind-powered system.

Representing the utility was Robert W. Goodrich of Northeast Utilities (parent of CL&P). Asked if Northeast was planning to offer a windmill-installation service, he said, "No, that will most likely continue to be done by private contractors. What we are doing here today is part of a two-year experiment we are conducting along with Energy Alternatives. There is another Enertech 1500 installed at Colrain, Massachusetts, up in the Berkshires, about a thousand feet above sea level. We're instrumenting that house and this one here in Madison to gather data on wind power both at a shoreline location and one up in the hills." One of the things utilities like about the Enertech 1500, Dr. Goodrich said, is that it automatically stops generating when there is a utility power failure, so that wind-generated power cannot be fed into a "down" utility line and shock linemen who may be repairing it. (As this fail-safe feature indicates, the

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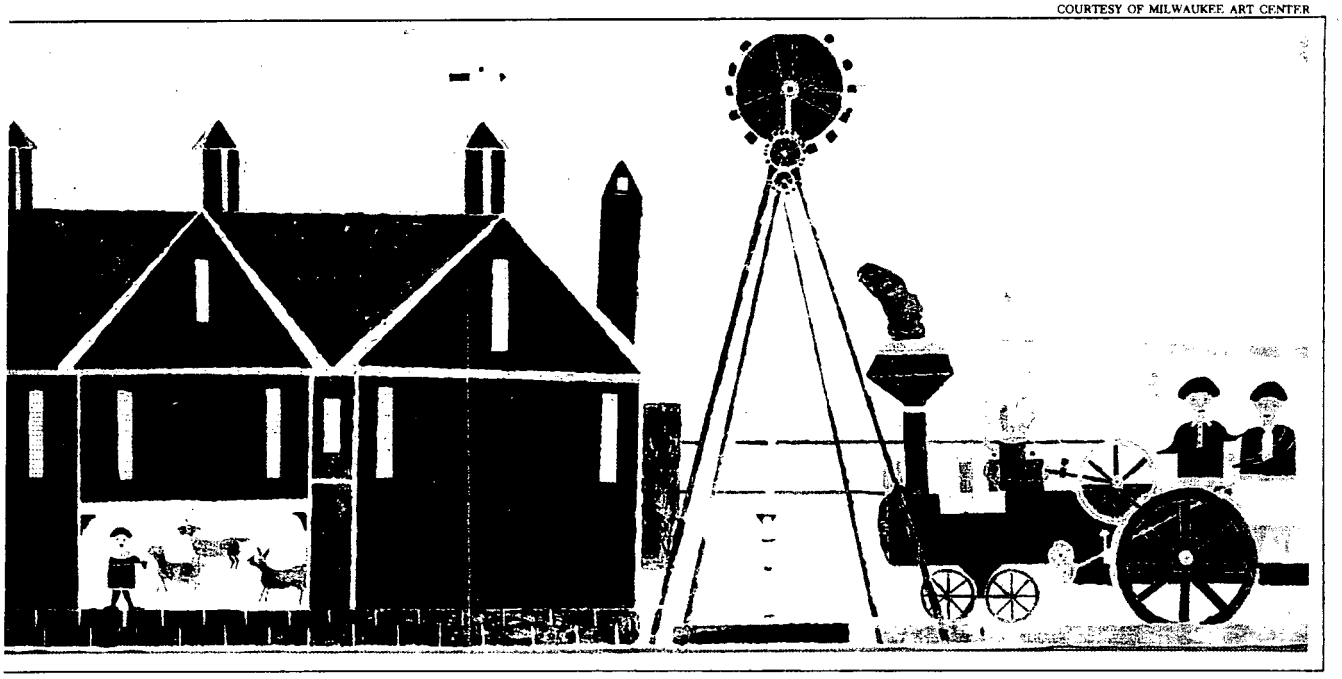

Windmill and Traction Engine, *by J. C. Huntington from the collection of Herbert Hempill*

Enertech 1500 is not at present a stand-alone, or back-up, system. It is designed to slow down your consumption of utility power and reduce your electric bill.)

By early afternoon the pole at the Madison site was in place and securely guyed. The generator was lifted to the top of the pole and attached. The connecting cable and accessory equipment were installed. At 2:40 P.M., whirling with a sound like the distant beating of wings, the propeller started making red, white, and blue circles in the sky. Almost involuntarily, everybody cheered. On a control box inside the house, a meter showed that the Enertech 1500 had begun to deliver.

A fast, simple operation. The cost? In this case, I was told, Northeast Utilities had contributed the pole and the installation out of its research budget, but the normal cost is reasonable. The wind turbine generator and its control system as of the end of 1979 was priced at about $3,475 F.O.B. Norwich, Vermont. The additional cost—the pole or tower, installation, and wiring—may run from around $1,000 to $4,000 depending primarily on the height and the type of pole or tower. (A wood utility pole, if it can be used, is less expensive than one would think.) It was obvious that much planning and technical expertise had gone into this accomplishment, so I was not surprised to learn that Enertech's chief design engineer is Henry Clews, a nationally known pioneer in wind-energy systems. Driving home from Madison, I couldn't help thinking about another trip I had made, to East Holden, Maine, where Henry Clews was running his own business, the Solar Wind Company, almost five years previously. [*See* "Energy from the Wind," January-February 1975.] A lot of wind has gone over the mill since then. In 1974 I could identify only one U.S. manufacturer of wind turbine generators. Now there must be twenty-five; there are generous federal and state incentives for installing windmills; and there is a federal program to encourage and aid the commercial development of wind-power.

Back in 1974, struggling by himself in Maine, Henry Clews was a distributor for a couple of imported wind machines, and he quickly learned a lot about the windmill business as distinct from the windmill art. "We had thousands of inquiries," [he told me, "probably more than fifty thousand, but of those only a small percentage, maybe one in a thousand, turned out to be buyers. If it hadn't been for the little booklet 'Electric Power From the Wind' that I wrote and sold, I probably wouldn't have been able to stay in business. Eventually I sold the franchises for the imported machines and began to work on a design of my own. I actually built several prototypes, but I didn't put any into production. They were direct-current (DC) battery-charging types, and the problem was that none of them could ever be competitive with utility rates. So it didn't seem to me that they'd ever have widespread acceptance. It wasn't until I closed down Solar Wind, spent a summer riding a bicycle across the United States and then went to work for Enertech that I got started on the new idea.

"The new approach came about as a result of a project we did at Enertech for Xerox Corporation, making a bicycle-powered generating system. They wanted a bunch of little units that children could pedal to generate electricity that could be fed directly into a power line to light up the White House Christmas tree—a sort of public relations project. We built twenty of these. In doing so, we learned a lot about using induction generators to feed power directly into an AC line."

THIS IS A KEY POINT. The machines traditionally used in wind systems—the DC-producing generators and the AC-producing alternators—cannot accomplish this direct feed-in, because as wind speed changes they turn out an electric current with varying voltage and frequency, not synchronous with utility power. Therefore their output must be stored in batteries. Since batteries accept and supply only DC, the current from an alternator must

be changed to DC by an appropriate device before storage. When electricity is drawn from the batteries it can go directly to lights and some appliances that will function on DC; but many appliances require AC, and for these there must be an inverter to change DC to AC. The inverter is expensive and uses up a good deal of power just in running itself. All rather complicated.

The induction generator that Henry designed into the Enertech 1500 produces AC that is always synchronous with that of the electric company, therefore it can simply be plugged into a wall outlet, eliminating the need for batteries and inverters. The induction generator is actually (and should be called) a motor-generator. When electric power is fed into this machine it causes a rotor to turn and a mechanical driving force to be produced; it is then acting as a motor. But mechanical force, such as that of the wind, can be applied to turn the rotor and do the opposite—that is, cause electricity to be produced. It is then acting as a generator. Induction motors (generators) are standard, off-the-shelf items, so their cost is quite reasonable, and millions of them have been in use for decades, so their reliability has been proven, and the bugs have been pretty well worked out.

Another noteworthy feature of the Enertech 1500 that would seem to make for simplicity and trouble-free operation is the power train. One problem in windmill design is to get all the power possible at low wind speed, but to prevent high-speed operation that could destroy the machine. Traditionally, many manufacturers have provided this overspeed control by means of a variable-pitch propeller. Instead of adding this mechanism, Enertech uses a fixed-pitch design based on a "rather subtle" (as Henry calls it) aeronautical principle that sends the blades into a progressive stall when wind speed gets too high. At the same time, the propeller is efficient at low wind speed. It is not self-starting, but this potential difficulty is easily overcome. Utility power is used for the first few seconds to bring the machine up to synchronous speed as a motor; then the wind takes over, and the motor becomes a generator. Even after start-up a small amount of electricity from the utility continues to flow through the machine

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Technicians assemble an Enertech 1500 windmill at the company's Norwich, Vermont, plant. The schematic drawing at the right shows suitable and unsuitable locations for a windmill.

to energize the magnetic field necessary for generating electricity. If there is a utility "outage" and this flow stops, wind-generated electricity also stops perforce. This is the ultimate fail-safe feature that protects utility linemen. In addition, the Enertech 1500 has an electromechanical brake. Operation of the motor-generator is controlled by a small logic circuit that receives signals from an anemometer located on the tower near the windplant. When the anemometer indicates that wind speed is at least 11 mph, the brake is released, and the machine is "motored up" to synchronous speed. If wind speed drops below 8 mph (at which point the motor-generator would start drawing instead of generating power) or if utility power fails, the brake is automatically applied, and the wind machine stops.

Will a Windmill Pay Where *You* Live?

The amount of electricity a wind turbine generator produces varies with wind speed. For those who have forgotten their electrical terms, a brief refresher: a *watt* is the basic unit for measuring the electricity a piece of equipment is producing or using. A *kilowatt* (kW) is 1,000 watts. A *kilowatt hour* (kWh) is 1,000 watts produced or used for an hour or the equivalent; for example, 100 watts produced for ten hours. Enertech has designed the Enertech 1500 to reach its rated output of 1.5 kW at a wind speed of 22 mph and to produce roughly 370 kWh a month at a site where winds average 12 mph. The rating and claimed output of any wind generator must similarly be related to specific wind speeds.

Although the discussion that follows uses the Enertech 1500 as an example, it is mostly applicable to all windmills. To begin with, on a general basis, wind systems are not for everyone. They are best suited for windy locations where the cost of commercial power is unusually high. They are better suited for rural or semirural locations than they are for urban or suburban areas where building and zoning regulations, as well as interference with the wind caused by nearby structures, may be encountered. Given a location that seems generally favorable, the most critical remaining factor is average wind speed at that site. As little as 1 mph at ground level can make the difference between a system that will pay for itself and one that will not. And winds can vary considerably between sites that are only a mile or so apart. It is therefore highly important to determine carefully the average wind speed for each individual location.

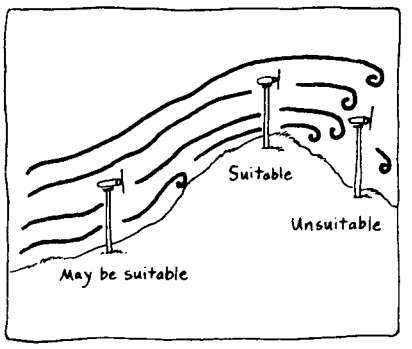
Starting with a visual check, a good site is one where treetops sway or a flag flies fully extended most of the time. Deformed trees may also provide a clue; strong continuous winds tend to reduce foliage on the side toward the wind. Sites may benefit from irregularities in the local terrain, such as narrow valleys that compress, or rounded hill crests that speed up, wind flow. Old residents, Forest Service personnel, and others who may have observed local wind behavior are worth consulting.

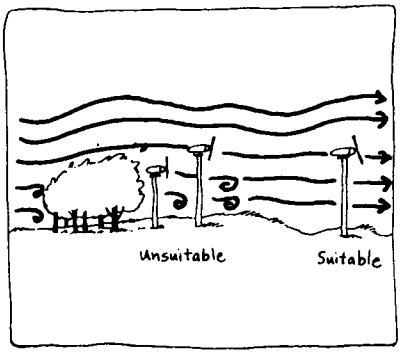
For preliminary estimates, it may be enough to measure and record wind speeds at eye level twice a day for two or three weeks, using a simple hand-held instrument that costs about $10. If the average of these measurements is less than 8 mph and commercial power is available, Enertech advises you to go no further; the site is probably not satisfactory. Other manufacturers may suggest different minimum wind speeds. If the site appears to be promising, the next step is to install an anemometer, a recording device to measure and record wind speed over a period of several months or even a year. The resulting data may be compared with the records of public or private weather stations near you. The U.S. Department of Commerce, National Climatic Center, Federal Building, Asheville, North Carolina 28801, issues two publications: "Local Climatological Data," which is inexpensive and includes monthly average and mean wind speeds for a current year; and "Airport Climatological Summary," which is more detailed and technical and covers a longer period. The first publication is prepared for about 290 stations, the second for about 160. One of these stations might be near enough to your site to provide helpful data. (When looking at these summaries, be sure to note the height of the recording instrument above the ground.) One great value of a comparison with historical records is that you can judge the effect of seasonal variations, which do not change much from year to year. For example, if your measurements are made in summer, you may see that you can predict a higher year-round average by taking into account the windier winter months.

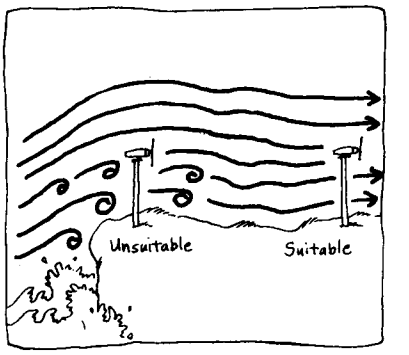
Choosing Tower Height and Type

One purpose of the tower or pole is to raise the wind machine above and away from turbulence, which may damage it, and from "wind shadow," caused by nearby trees or buildings. A site on a hill doesn't necessarily lessen the need for a high tower. [*See* drawing.] Some authorities suggest that both turbulence and wind shadow can be avoided by erecting a tower that is at least 30 feet higher than any obstacle within 100 yards, or 40 feet high, whichever is greater. Others say the tower should be at least 60 feet high.

Another purpose of the tower relates to wind speed. Wind measurements at ground level can be misleading; here winds are slowed by the drag of the earth's surface and by various obstacles. Wind speed generally increases with height, and even though this increase may be only 4 or 5 mph, it is significant,







MARGOT APPLE

because power varies with the cube of the wind speed. Going from 10 to 15 mph will produce not half again as much power but more than three times as much, while going from 10 to 20 mph will produce eight times as much. The average wind speed at your site should be measured at several elevations for a preliminary appraisal. In the following example, based on information from Enertech, 5 feet is given an index of 1.00, and what happens at higher elevations is shown. The increase factors are theoretically derived and apply to moderately flat terrain; on hilly or rough ground the factor differences would be even greater. For this example, a 9 mph wind speed at eye level (about 5 feet) is assumed. The increase factors could be applied to any other eye-level wind speed by simple multiplication (*wind speed* times *increase factor*.) And any other manufacturer should be able to provide monthly outputs in kWh corresponding to average wind speeds.

Table 1

Height Above Ground (Feet)	Wind speed Increase Factor	Average Wind speed in mph	Approx. Output* in kWh Monthly (Enertech 1500)
5	1.00	9.0	180
30	1.29	11.6	345
40	1.35	12.2	385
50	1.39	12.5	405
60	1.43	12.9	425
70	1.46	13.1	445
80	1.49	13.4	460
90	1.51	13.6	475

*Estimates based on standard wind distribution patterns, which may vary from one site to another. Also, at high terrain altitudes, lower air density will diminish the output of any windmill.

The cost of attaining the desired height is an important consideration. The real trade-off is between a low-cost 40- or 50-foot utility pole ($1,000 to $1,500 completely installed and wired) and an 80- or 90-foot tower ($3,000 to $4,000 completely installed and wired).

Generally, since tower increments are not too costly, the least expensive way to get more power is to increase tower height. However, there are at least three considerations that may be limiting.

(a) *The number of kilowatt hours you want*. In the case of the Enertech 1500, you would have to think about the utility tie-in. Experience is limited, but Enertech believes that at sites where the output of the wind system is no more than 50 per cent of your electrical demand, less than 15 per cent of the output is likely to be fed back to the utility. If you are not getting paid for this backfed power, a system yielding about 50 per cent of your monthly usage is about as large as you would want for optimum economic return.

(b) *The point of diminishing return*. Looking at each tower option (type, height, cost) and the electrical output you are likely to get from it, you should be able to identify a point at which an added increment of tower or a different type of tower adds more in percentage of total cost of the system than it adds in percentage of power output.

Or you might perceive a situation in which two wind turbine generators, mounted on wood utility poles at a lower elevation would be more cost-effective than one generator mounted on a higher and more expensive tower.

The cost of the generator is more or less a constant. The cost of putting the generator up in the air—and what you get for this expenditure—is a variable. It will all make an entertaining exercise for you and your pocket calculator.

(c) *Local restrictions*. Local building codes, zoning restrictions, Federal Aviation Administration rules, and other such regulations may limit the height of the tower and dictate its type. These possible restrictions must be checked for each individual site.

(d) *Insurance*. Your wind system may or may not be covered by your existing homeowner's insurance. Ask your insurance agent for specifics.

Looking at True Costs

Having arrived at the type, size, and gross cost of the wind system, the next step is to determine net cost after taking advantage of federal and state benefactions.

Tax Credits. For installing a wind-powered system you are allowed to take as a direct credit against your federal income tax 40 per cent of the first $10,000 of the system's cost. (This is not just a deduction from your gross income; it comes off your tax payment.) This credit is available until January 1, 1986; other criteria are available from the Internal Revenue Service. In addition, many states offer tax credits, deductions and exemptions, low-interest loans, and so forth. Some are quite substantial; for example, California offers a personal income tax credit of 55 per cent of the system's cost up to a maximum of $3,000 (reduced by the amount of any federal income tax credit used). Vermont provides an income tax credit of 25 per cent of the system's cost, or $1,000, whichever is less. One of the most comprehensive programs is Oregon's, with an income tax credit (25 per cent up to $1,000), an anemometer loan service, the *Oregon Wind Book* (an excellent guide), and fairly stiff eligibility criteria which serve to protect the windmill purchaser as well as the state treasury. Your own state tax department and energy office can acquaint you with the incentives and criteria that apply to you.

Cost of Your Utility Electricity. Electric rates vary widely depending on the state you live in, the company that serves you, the amount you use, and other things. The only reliable way to determine the true cost and what is happening in your situation is to gather up your electric bills for as far back as you can and, for each billing period, divide the amount of your bill in cents (excluding such extraneous costs as water-heater rental) by the number of kWh used in that period. I did that for my own ghoulish amusement, by some miracle finding bills from 1970 on, and recorded the results in tabular form. I saw that in recent years the rate seems to have varied by as much as 0.8 cents between certain summer and winter months, reflecting the different quantities used. It was also apparent that our rate has more than doubled since 1970, a trend all across the nation. The pronounced rise in the 1970s was caused mainly by increases in the price of fuel oil burned by the power plants, but utilities also buy other materials, equipment, and services, so inflation in general is also to blame. Conversion to coal by some plants may reduce dependence on OPEC oil, but it will not cut costs much. What will happen in the future is anybody's guess, but an annual increase of 10 per cent or more for electric rates does not seem unrealistic.

Credit for Backfed Power? Your electric company must agree to any tie-in with its system. This probably will not be a problem if safeguards are provided similar to those of the Enertech 1500; utilities seem to be accepting this machine quite readily. However, what, if anything, will the utility pay you for wind-generated power that is fed into the

utility lines? That question should be settled when the tie-in agreement is being discussed. It may be that the utility will choose to "ratchet" your meter—to fix it so that power fed into the grid will not turn the meter backward, meaning you get no credit for it. Or you might pay to have a second meter installed; it would register the power you feed back, and the utility would pay you for it, but not at the retail rate. Or there could be some other arrangement. Your state's utility control board may have ruled on this matter by now. If you are paid something, the calculations that follow would be somewhat altered in your favor.

Putting It All Together

What follows is simply a suggested format for calculation. In your situation, the state credit and your income tax bracket will probably be different, or the two may not be compatible as shown below. Also, your electric utility rate is likely to be different, and perhaps you'll have a different estimate of its future increases. The calculations can be modified for these or other variations.

This example stems from Table 1. We have a 9 mph wind speed at eye level. We have put up a 60-foot pole which brings wind speed up to 12.9 mph. This translates into 425 kWh per month on the Enertech 1500, or 5,100 kWh annually. Reduced by the 15 per cent we expect will be fed back to the utility without compensation, this amounts to 4,335 kWh per year. Other assumed conditions:

Gross cost of system	$5,000
Federal income tax credit	2,000
State tax credit or other incentive	1,000
Net cost of system	2,000
Electric utility rate per kWh	$0.06
Owner's federal income tax bracket	25%
Design life of the machine in years	20

It is further assumed that the electric utility rate will have doubled by Year 11 and tripled in Year 21, as indicated in column B of the following table. Column C is simply 4,335, the annual usable production in kWh, multiplied by the rate in column B. As you'll note, this rate is a key factor, comparable to wind speed in importance. Column D is the figure in column C divided by .75 to convert it to the equivalent value for someone in the 25 per cent federal income tax bracket, since the value received in column C can be considered to represent tax-free income.

Table 2

A	B	C	D
Year	Utility Rate per kWh	Value of 4,335 kWh at Utility Rate	Equivalent Value in 25% Tax Bracket
1	$0.06	$260	$ 347
2	.066	286	381
3	.072	312	416
4	.078	338	451
5	.084	364	485
6	.09	390	520
7	.096	416	555
8	.102	442	589
9	.108	468	624
10	.114	494	659
11	.12	520	693
12	.126	546	728
13	.132	572	763
14	.138	598	797
15	.144	624	832
16	.15	650	867
17	.156	676	901
18	.162	702	936
19	.168	728	971
20	.174	754	1,005

There are all kinds of ways in which different individuals might look at Table 2 and proceed with their calculations. Here are a few.

(1) This purchaser, who has $2,000 in pocket, looks at the windmill as an investment and uses the values in column C. The first year's saving ($260) amounts to a return of more than 13 per cent on the investment, tax-free. At that rate, even if the price of electricity does not increase, the system will pay for itself in less than eight years. If the utility's price does increase as shown in Table 2, the system will pay for itself after the sixth year, and the return on investment in that year will be nearly 20 per cent.

(2) This purchaser, with $2,000 in cash, also looks at the windmill as an investment, but chooses to base his calculations on column D. The value of the first year's saving ($347) represents better than a 17 per cent return, and the system pays for itself in the sixth year assuming no utility rate increase; but if this increase takes place, the system will pay for itself in the fifth year, and the return in that year is more than 24 per cent.

(3) This purchaser goes to the bank and borrows the $2,000 at 14 per cent on a four-year home-improvement loan. His first four years (with reference to column D) look like this.

Table 3

Year	Value Received	Payments to Bank	Net Loss
1	$ 347	$ 656	$ 309
2	381	656	295
3	416	656	240
4	451	656	205
	$1,595	$2,624	$1,029

The $1,029 deficit will be wiped out by the beginning of the seventh year, and the total interest cost of $624 will be a deduction from gross income in figuring the purchaser's income tax. If the "value received" figures of column C are used, the payback will occur during the eighth year.

Another purchaser might want to figure in maintenance and taxes. Manufacturers realize that much of the industry's success will depend on its ability to produce long-lasting and trouble-free machines. For a well-designed and well-built system, maintenance should consist primarily of lubrication and replacement of minor components after long periods of service; it should not be too costly. And, as a bonus, in many states windmills are exempt from property taxes.

Meanwhile, back at the windmill in Madison, Connecticut, what has been the performance? As of April 12, 1980, a year after its installation, that was difficult to determine precisely. Problems with instrumentation resulted in incomplete recording of average wind speed and kilowatt hours produced; the house was new, preventing exact comparisons with previous years' use of electricity; and the winter of 1979–80 had been somewhat mild. Nevertheless, after taking all this into consideration, Rosemary and Alan Hanks estimated that their windmill reduced their electrical bill by at least 50 per cent—a saving of about $600 a year.

A Brief Overview

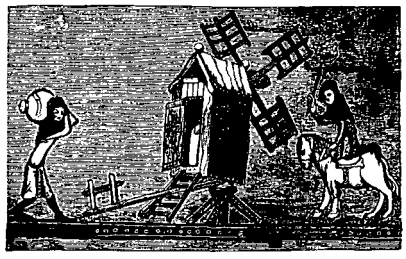
This article has dwelt upon the Enertech 1500 because it exemplifies what now appears to be the most promising trend in wind energy: the utility tie-in. The U.S. Department of Energy (DOE) has recently awarded a $700,000 contract to Enertech for a much larger (15 kW) machine to be based on the Enertech 1500 design and built to serve farms and small businesses. Many other organizations are at work on wind machines, including industrial giants like United Technologies and McDonnell Douglas, as well as a

number of enterprising smaller companies. Much of the impetus is coming from the DOE's Wind Energy Program, which is aimed at the full commercialization of wind power and is funding and evaluating the development of wind systems that range in output from one or two kilowatts all the way to megawatts (1,000 kW). Examples of larger systems include a 200-kilowatt generator installed at Block Island, Rhode Island, and a 2-megawatt machine at Boone, North Carolina.

In addition to equipment that will tie into utilities (through induction generators, synchronous inverters, and other means) battery-storage systems will continue to serve many remote sites where commercial power is not available. Water-pumping windmills represent an efficient use of wind energy. They are inexpensive; they can function in average wind speeds of 7 or 8 mph or less; and they allow the energy storage problem to be solved neatly with ponds or elevated tanks.

Windmills supplied a significant amount of rural America's energy until the federal government, through the Rural Electrification Administration, introduced REA cooperatives and low-cost electricity to the farms in the 1930s. Now, in an interesting turn of events, federal funds and tax subsidies are helping to restore windmills to the landscape. How much of our electricity can the wind contribute? Perhaps only 3 to 4 per cent of the nation's generating capacity by, say 1990. But to put this into perspective, one estimate has it that conventional U.S. hydro-electric plants—the Hoover, Grand Coulee, TVA, and all other dams and waterways—will be accounting for 7 per cent at that time. In other words, 3 or 4 per cent of the nation's production is a tremendous lot of electricity. Ned Coffin, head of Enertech Corporation, estimates that each of his Enertech 1500 machines, in its lifetime of twenty years, could save as much as 8,000 gallons of the fuel oil burned by utilities. Equally compelling is the availability of wind energy. Nuclear fusion, photovoltaic cells, and generators powered by the sun, the tides, and geothermal heat represent exotic methods whose technical and economic feasibility on a large scale may be decades away. In contrast, wind power is here now. It works and has worked for centuries. To adapt it to our modern needs only careful and imaginative engineering is necessary—in these tight economic times—close figuring. ◇

This is the latest of JOHN PULLEN's many articles on sources of energy. In May he boosted "Energy from Muscles."



For more information

DURING THE PAST FEW YEARS wind-energy equipment has become much more widely available. For the person who wonders where to begin a search for information, I suggest writing to Wind Power Digest, 54468 CR 31, Bristol, Indiana 46507, enclosing $2 for the latest Wind Access Catalog, contained in a recent issue. This catalogue lists and describes commercially available wind machines, anemometers, inverters, storage batteries, towers, and accessories, and it also provides names and addresses of manufacturers and distributors. *Wind Power Digest*, published quarterly, is a continuing up-to-date and comprehensive source of information; a subscription is $8 a year.

American Wind Energy Association is a nonprofit organization serving the wind-energy industry, state, local, and federal government agencies, academia, and the general public. Annual dues are $25 for individuals, $500 for educational and nonprofit institutions, $1,250 for small businesses with fewer than one hundred employees, and $2,500 for corporations and associations. Membership includes voting privileges, a monthly Windletter, reduced registration fees for AWEA conferences, opportunities for participation in workshops and other activities, and a subscription to *Wind Technology Journal* (individual members may subscribe at a reduced price). A free brochure and membership application may be obtained from American Wind Energy Association, 1609 Connecticut Avenue, N.W., Washington, D.C. 20009, (202) 667-9137.

Bibliographies and other suggestions for reading are available from the Wind Systems Branch, Department of Energy, 600 E Street, N.W., Washington, D.C. 20545, (202) 376-4878. Many state departments of energy, resources, or conservation can also provide information.

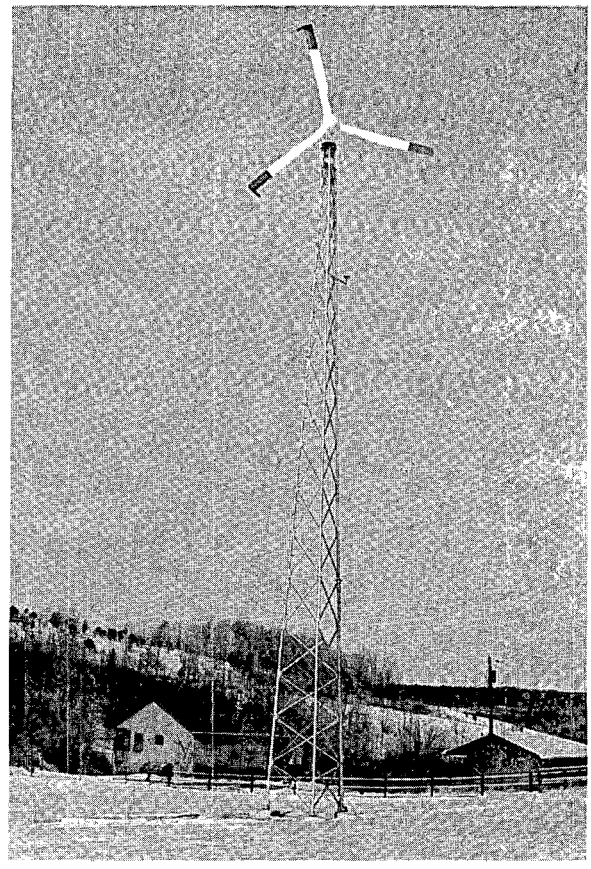
Data on the Enertech 1500 are available from Enertech Corporation, Box 420, Norwich, Vermont 05055. J.P.

Wind Energy: Homeowner Utilization

Where does alternative energy meet the local utility company? Maybe in your own back yard. Thousands of wind power enthusiasts are finding the best of both worlds: free energy from the wind, plus the insurance of a link with the electric company.

Wind Energy: Homeowner Utilization

by Rick Nelson
Adirondack Wind Electric, Inc.



Since the 1973 oil embargo, interest in wind energy has suddenly been revived by conservation-minded citizens living in windy regions. Windmills designed to provide electricity to individual homes and farms have actually been in use since the 1920's. The 1930's and 40's saw a dramatic increase in these small "single family" turbines, especially in rural areas far from urban power sources. This trend was reversed upon the widespread implementation of the Rural Electrification Act. The act brought power to virtually all residences nationwide, and the plentiful supply of cheap oil and gas to fire the nation's power plants brought the days of wind power to a close.

Today, we still have the power lines to almost every residence, of course, but the price of electricity generated from fossil fuels is increasing at a staggering rate. The reawakened wind energy industry is addressing this new situation in a way never considered in previous decades. Today's wind generators, while still owned and operated by individuals, are tied directly into the utility power grid system. This unique marriage between the oftentimes conflicting camps of the utilities and the conservation-minded alternative energy buffs, has led to a more practical and modern utilization scheme for wind energy. For example, gone are the days when costly batteries were needed for energy storage during windless periods. Now, if the wind does not blow, you automatically use utility power. Conversely, when there is a strong wind and your windmill produces more power than your household can use, you actually sell the excess to your local utility. In addition, the new windmills are all AC alternators, eliminating the need for special circuits and appliances required when DC power drawn from batteries is used.

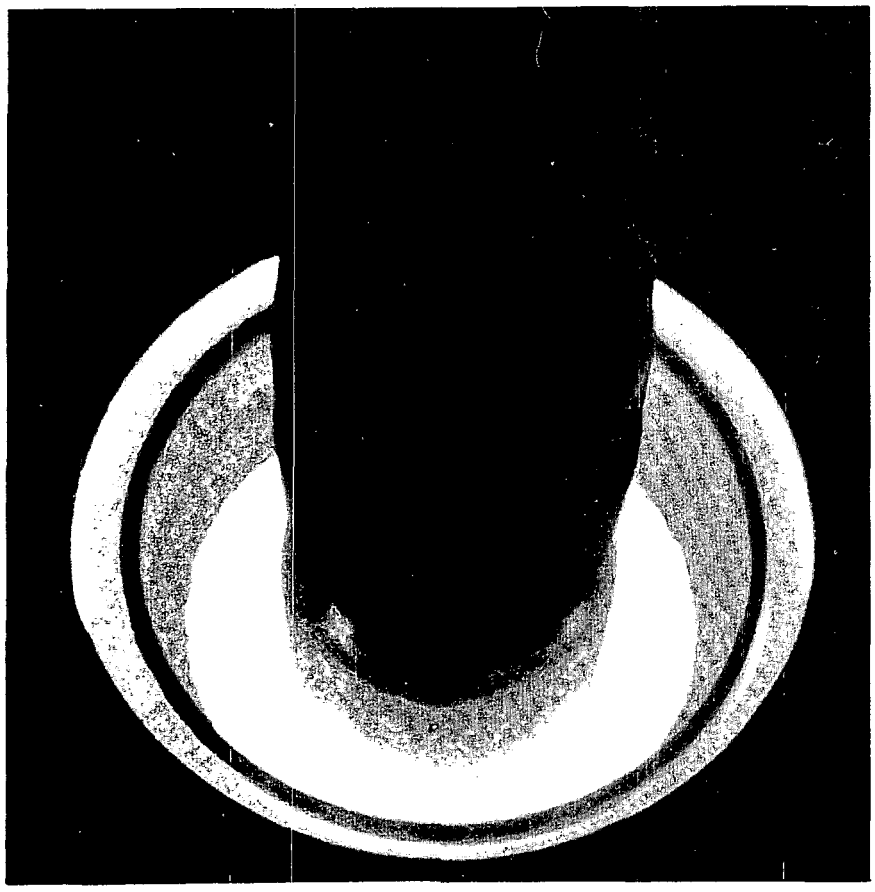
The photograph above shows a 4 kW wind turbine which provides most of the power requirements of the small home shown in the background. On this and other homesteads, we can see a growing awareness of the power of wind.

Reprinted with permission from Adirondack Wind Electric, Inc., Warrensburg, New York.

Photovoltaics: Milestones Passed, Miles Ahead; Sales Chase Wider Markets

The photovoltaic cell works (as any observer of the manned space flight program can testify). The question remains, "At what cost?" Major industrial research efforts are focused on bringing that cost down, and hardly a week passes without news of some new breakthrough.

Photovoltaics: Milestones Passed, Miles Ahead



An ingot is grown from molten silicon at Spectrob, Sylmar, Calif.

By Bill D'Alessandro

"In 1986 a salesman will call you up, offer a photovoltaic system, and quote a price that's equal to or less than your monthly electric bill," asserted Paul Maycock of the U.S. Department of Energy (DOE). "The only considerations will be those that you make for anything else that you buy. 'How will it look? How long will it last? Do I want to spend the money?' "

Maycock's statement is one way of pinning down the federal government's goal to have solar cell systems penetrate select commercial and residential markets within six years. As the man in charge of DOE's photovoltaic development program, Maycock is accustomed to fielding questions about the federal timetable for economical solar cells. What the curious want to know most about photovoltaics is "When" and "How much?"

Led by Wall Street analysts, the business community has been kept abreast of the photovoltaic option for solar energy. Arcane advances in solar cell technology were reported accurately in the press, when Time magazine was confusing the flat-plate solar domestic water heating system at the White House with a "passive" solar water heater, and the Wall Street Journal was expressing its bewilderment over a definition of a direct gain window proposed by the Internal Revenue Service.

The impetus, and perhaps much of the confidence, behind photovoltaic technology grows out of the hugely successful space program of the 1960's. Solar cells powered U.S. satellites and manned space ships, and there can hardly be a doubt that public perceptions of terrestrial applications for solar cells are colored by the record posted by the National Aeronautics and Space Administration.

However, cost was no obstacle in making solar cells for space use. The price of today's systems are competitive only for limited purposes, like consumer items, navigational aids, communications devices, and telemetry, and for inhabited sites far from electrical distribution lines. But the precedent for optimism about photovoltaics is deeply rooted in the history of the semiconductor industry. The cost of transistors has dropped a thousand times below the prices paid in the early days of space exploration. Up to this point, the silicon material used for electronic circuits and the manufacturing techniques of the semiconductor industry have been adopted by makers of photovoltaic cells—and with modifications, they have slashed the price of cell arrays by one-half since the Arab oil embargo of 1973-74. With the introduction of new processing methods and entirely new materials other than silicon, plus the promise of savings through mass production for the residential and commercial market, the future for photovoltaics is bright.

The rosy picture painted by technological breakthroughs and by pure speculation (the stock of Texas Instruments rose $6 in two days, after investors learned the company was embarking on a four-year effort to develop a new silicon cell system) has not been overlooked even by average consumers. Several solar architects report that clients have asked for new houses with roofs that can accept photovoltaic cells later.

The price of photovoltaic installations is slated to get better and better in DOE's plan to foster widespread use of solar power. The all-out assault on technical, institutional, and social barriers now underway aims at a target only six years off commercially competitive solar cell systems for households and medium-sized businesses in the Southwest and the Northeast. By 1990, according to the current DOE plan, solar cells and the batteries and other components needed to generate solar electricity could be ready for homeowners everywhere in the United States and even for the central station power plants of some utility companies.

DOE's multi-year photovoltaic development plan contains a laundry list of precise, time-related technology and cost objectives. Expenditures must be $1.3 billion or more

Bill D'Alessandro is editor of Solar Age Magazine.

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over the 10 years ending in FY 88, if all the goals are to be met seasonably. The federal photovoltaic budget for FY 80 has risen to $139.7 million, making this the best funded solar energy initiative. An extra $10 million is available this fiscal year for federal agencies to buy and install photovoltaic systems under a Congressionally sponsored bill to stimulate commercial markets in preparation for the day when realistically priced systems are ready for private purchase.

But DOE's schedule of activities and milestones over the next 20 years looks like a transcontinental bus map—it would fill two pages of this magazine—and the plan is only a draft, still subject to revision, additions, and government approvals. The number of stops along the way and the difficult route laid ahead make quick commercial success seem less of a fait accompli.

DOE has designated the Jet Propulsion Laboratory (JPL) in Pasadena, Calif., and the Solar Energy Research Institute (SERI) in Golden, Colo., as the lead centers for the photovoltaic program. SERI will sponsor more than 140 research contracts with an FY 80 budget of over $38 million. SERI's photovoltaic laboratory will be fully operative in a year to evaluate the progress of projects that the institute funds.

JPL focuses on technology development and applications, i.e., projects that involve improving photovoltaic cells once SERI has studied their technical feasibility, and the building of photovoltaic components and testing of entire systems. JPL is also responsible for activities at Sandia Laboratories in Albuquerque, where concentrating solar cell systems are examined, at MIT Lincoln Lab, which checks out residential systems, at NASA Lewis Research Center in Cleveland, which experiments with stand-alone solar cell systems like those being designed for remote settlements in developing nations, and at MIT Energy Lab and Aerospace Corp., both of which study the economic and institutional issues inherent in the use of photovoltaics.

Leaving aside questions about solar cell arrangement, energy storage, and integrating complete systems in a power network—all of which are under study—photovoltaic cell research is spanning the whole spectrum of topics from fabrication to assembly in a finished module.

☐The raw material for solar cells is pure silicon, an expensive product used in the semiconductor industry. It costs roughly $65 per kilogram. Battelle Columbus Laboratories and Union Carbide hope to meet DOE's target of $10 per kilogram through cheaper production processes. There are also federally funded projects looking into the production of so-called solar-grade silicon feedstock and to examine the effects of using this impure material in silicon solar cells.

☐Virtually all commercial solar cells are made by pulling an ingot from a silicon melt and slicing the salami-shaped length into paper-thin wafers. More than half of the silicon is wasted in shaping, sawing, and polishing. Several companies are investigating techniques to improve upon existing cell growing and slicing processes.

Mobil Tyco, Waltham, Mass., Motorola Inc., of Phoenix, Westinghouse Electric Corp., and Honeywell Inc., are researching various systems to stretch the silicon into wide ribbons or to coat a ceramic tile with a thin layer of silicon held in a vat (Honeywell). The processes that bypass the ingot slicing system require new materials and fabrication devices.

☐Once manufacturers have a wafer or ribbon, they must form a junction in the cell to separate charge carriers. Electrical contacts are attached, and the cell must be encapsulated to, prevent environmental damage. Contracts have been negotiated with various companies to come up with low-cost methods and materials for the final fabrication steps.

☐All the steps along the solar cell array manufacturing process have to fit together in a plant that can be standardized for production-line assembly. JPL has developed a model called SAMICS (Solar Array Manufacturing Industry Costing Standards) to help companies choose among the processes and equipment, which may provide low-cost modules at a reasonable profit. Contractors such as ARCO Solar, Texas Instruments, Motorola, RCA, and Solarex Corp. are preparing plans for automated photovoltaic factories.

☐There are alternatives to the single-crystal silicon cell. Polycrystalline silicon cells would dramatically lower the cost of materials, so experiments have focused on making these cells as efficient in converting sunlight to electrical energy as thicker silicon cells in use today. Some companies are gearing up to produce polycrystalline cells.

Activity in silicon devices is also centered on amorphous films, which have no crystalline structure and seem to be promising candidates for inexpensive cells. High efficiency amorphous materials for photovoltaic cells still must be demonstrated in the laboratory.

☐There are corporations and research groups, which are banking on combinations of materials, and not on silicon, as the best option for commercial cells of the future. Cadmium sulfide/cuprous sulfide cells promise to be low in cost, and SES Corp., a subsidiary of Shell Oil Co., Photon Power Inc., El Paso, Tex., and the University of Delaware's Institute of Energy Conversion have plans for production plants.

Fabrication methods are being explored for gallium arsenide solar cells, which have the potential for high conversion efficiency and can stand up to higher temperatures than silicon cells can tolerate. Gallium arsenide is being considered for use in concentrator systems, which focus sunlight through lenses onto the cells.

SERI is exploring high risk concepts deemed too expensive and chancy for privately funded research. High risk efforts include metal-insulator-semiconductor cells, multi-junction concentrator cells, luminescence converters, electrochemical

Milestones on the Path to Residential and Small Commercial Photovoltaic Systems

1980

- Technologically, $2.80 peak watt collectors are ready.
- A decision is made on purchase mechanisms to establish systems that can be sold for $6-$13 per peak watt.
- Residential system evaluation experiments are initiated.

1982

- Systems that sell for $6-$13 per peak watt are ready for sale (provisional on 1980 decision).
- Go-no go decision on larger-scale residential and small-load center application experiments in the field.

1983

- Initiate commercialization activities to establish residential and small-load center systems for sale.

1984

- Residential and small-load systems of $1.60 per peak watt are built and successfully operated in an actual user's environment.

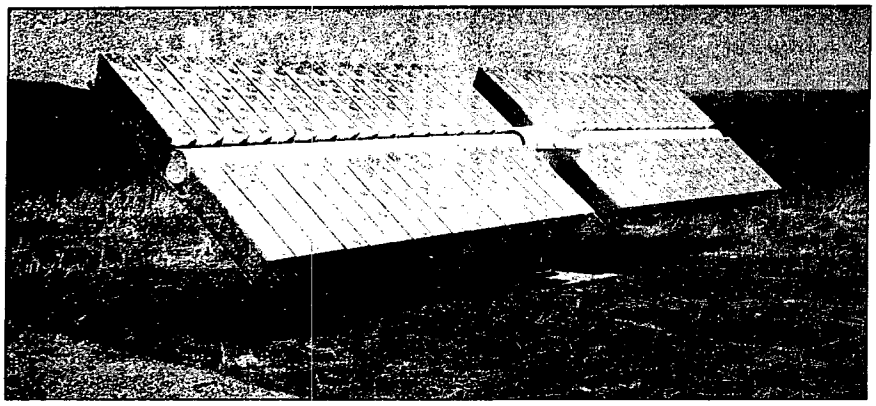
1985

- Go-no go decision for residential and small-load center commercial readiness development projects.

1986

- Residential and small-load center components and systems can be offered for sale at economically competitive prices in the Southwest and Northeast.

Roof shingles using solar cells from Solenergy Corp., Wakefield, Mass.



The 2.5-kilowatt concentrator array designed and built by Martin-Marietta over the past two years will be part of the world's largest photovoltaic power system for two small villages in Saudi Arabia. The array features Fresnel lenses and silicon cells from Applied Solar Energy Corp., City of Industry, Calif.

cells, and amorphous materials other than silicon.

☐On top of the activity in low-cost and advanced solar cell research and development, DOE is funding projects dealing with the equipment needed for photovoltaic arrays, including power-conditioning units and storage batteries. The government has spent $7 million on studies to determine cost reductions possible in balance-of-system equipment. On paper, at least, much can be achieved through improvements in commercially available supplies.

Personnel who administer various parts of the federal photovoltaic program have wondered whether the price goals established for the 1980's are not overly ambitious. Views of analysts within the industry and outside it have ranged from very dark to glowing. It was a little more than a year ago that DOE's hired consultants, Booz-Allen and Hamilton, published a detailed assessment of the industry and concluded that investments in and commitments to photovoltaics were only "marginal," that the markets for solar cells were hazy, and that DOE's strategy for systematically reducing the costs of solar cells actually hampered an accelerated program for commercialization. Manufacturers were described as hesitant to spend enormous sums on production processes that would become obsolete in a few years.

The author of that study, is not as gloomy now as he was then. For one thing, Michael Eckhart said, production methods and cell performances have been improved. For another, some companies have raised their investment in facilities.

But Eckhart isn't sanguine. He said that institutional barriers to the use of photovoltaics are significant and could become of paramount importance by the time competitive solar cell systems are ready for the wider marketplace.

DOE's Paul Maycock echoed Eckhart's concerns by qualifying his comment that photovoltaic systems would penetrate some electricity markets by 1986.

"Those customers in areas with a cooperative utility company will have no difficulty in purchasing a system," Maycock said.

The sellback price of electricity generated on site and favorable financing terms for photovoltaic systems are among areas where friendly agreement is required, if solar cells are to wind up on the roofs of eligible buildings.

Another perspective on photovoltaics is gained by estimates of just how much capacity can be deployed by the year 2000. The main thrust of federally supported work is to nurse the technology along to the point where solar cells can displace a significant portion of primary fuel, like coal, oil, and nuclear energy, now used to generate electricity. The guesses of photovoltaic capacity 20 years into the future range from virtually none to as much as 7 quads. (One quad is 10^{15} Btu, roughly equivalent to three weeks supply of imported oil at the current U.S. rate.) The Solar Energy Domestic Policy Review concluded that photovoltaics could displace from 0.1 to 1 quad of primary energy annually by the turn of the century. The lower 0.1 quad estimate implies the existance of 500,000 houses equipped with photovoltaic systems of 8 to 10 kilowatts each by the end of this century, or more than 33,000 installations every year starting in 1985. But 0.1 quad of photovoltaic generating capacity is dwarfed by comparison with the total energy consumption of the United States, which was recorded at about 76 quads in 1977. The contribution of photovoltaics to the total U.S. energy supply will be infinitesimal before the 21st century, if the prevailing wisdom of forecasters is accurate.

The forecasts have little to do with the day to day marketing efforts of a dozen photovoltaic cell manufacturers with products to sell today. And, as cost targets fall, the big business in grid-connected photovoltaic systems becomes more tantalizing.

Sales Chase Wider Markets

By Allan Frank

Foreign countries remain among the most important markets for photovoltaics, but the time may not be too far off when wealthy American homeowners can have a solar cell-powered house. Prices of the solar generators have been falling rapidly—so much so they have outpaced the optimistic projections of the Department of Energy (DOE), making the devices the only solar equipment to be ahead of all expectations in development.

Still, there are significant problems ahead. The plunge in prices will probably taper off until manufacturing is automated and new materials are introduced in quantity. Also threatening the industry is the prospect of tightened supplies of pure silicon at inflated prices (see Solar Age, November 1979). Because photovoltaics produce a pollution-free and highly versatile form of energy anywhere the sun shines regardless of climate, the technology is getting more attention almost daily. Solar cells are being introduced at both remote outposts and downtown offices, and in consumer products.

Today most of the solar cell sales are for such uses as village power systems, water pumping, and communication networks, often with the help of the federal government. Late last year, DOE erected a 3.5-kilowatt system at the Schuchuli Indian Village in Arizona for home lighting, medicine, food refrigeration, and appliances. Now under construction in two tiny villages in Saudi Arabia is a 350-kilowatt system using Fresnel lense cover, box-state reflectors developed by Martin-Marietta Corp. for

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use with concentrator solar cells.

However, other large projects are not U.S. funded. Solar Power Corp., Woburn, Mass., has sold Australian National Railways a $500,000 network of solar cell modules to power communication lines. And Mexico is actively pursuing water pumping for irrigation with solar cells (as well as solar thermal pumping).

But it is not just the remote sites that are acquiring solar cells. Under construction is a 240-kilowatt, utility-interconnected power plant for the Blytheville, Ark., Mississippi County Community College campus, which will provide 90 percent of the electricity for that facility. It will feature solar concentrators by Acurex Corp., Mountain View, Calif., and cells by Solarex Corp., Rockville, Md.

Other government projects include a Motorola Government Electronics PV system at an airport in Phoenix, one by E-Systems, Inc., Dallas, Tex., and Optical Coating Laboratory, Inc., City of Industry, Calif., at an airport in Dallas-Fort Worth, plus solar cells for a hospital in Hawaii and a corporate headquarters in Albuquerque.

Still, because most areas in the U.S. are served by electric utilities, foreign sales are increasing in importance. According to Pacific Northwest Laboratories, Richland, Wash., the international PV market could grow from the present 500 kilowatts annually to anywhere from 100 to 1,400 megawatts. Some companies are reporting that as much as one-half of their sales are going to foreign users, and many of them are launching joint ventures with European firms to gain entry into lucrative overseas markets.

Dyneer Corp., parent company of Sensor Technology, Chatsworth, Calif., signed an agreement with CIPEL and SAFD, subsidiaries of France's Compagnie General D'Electricite (CGE), an electronics giant. Solarex has sold minority shares to Leroy Somer SA of France, Holec of the Netherlands, and unnamed Italian interests (as well as to Standard Oil Co. of Indiana). Solarex also has a joint venture with France's—Photon SA. Exxon Enterprises, which owns Solar Power Corp., has signed up with Thompson-CSF for a joint venture, and Energy Conversion Devices, Troy, Mich., which has not even begun marketing, has a product development and licensing agreement with ARCO Solar, Inc.

As prices continue to decline from the present level of $7 to $10 per peak watt, there is the growing promise of residential applications. Researchers at MIT say that when cell prices fall to about $1 per peak watt, interconnected systems in the U.S. southwest will be competitive with conventional utility-supplied electricity for homeowners.

But some companies are not waiting for that. ARCO Solar this past June set up a solar cell-powered mobile home on the grounds of the Capitol in Washington, D.C. Although the 3-kilowatt, $20,000 system ARCO displayed was admittedly too expensive and perhaps only half as large as necessary to power a home for a family of four, ARCO Solar's president Robert Chambers said that a reduction to $5,000 would be cheap enough.

ARCO is looking toward applying polycrystalline solar cells or single-crystal silicon, the same as that of its competitors, to batten seam metal sheeting used for roofing material across the country. And Solarex spokesman, Tony Clifford, predicts that the first photovoltaic house will be sold on the open market in 1984 or 1985.

Getting to that market breakthrough will surely require new materials and new production techniques. Energy Conversion Devices believes that its amorphous silicon cells will eventually produce electricity at 5 to 10 cents per peak watt. Solarex is planning a production facility for its polysilicon material that it believes it can "ride right on down to 50 cents per peak watt or lower." ARCO Solar also is building an automated production facility for its single-crystal silicon cells, and Solar Power Corp., and Sensor Technology both are beginning to automate their manufacturing process.

Of particular concern are the price and availability of pure silicon, which has been the most widely used material in the cells. Solar Power's technology development director Richard Ardiss points out that until recently this silicon could be purchased for $45 per kilogram, based on excess production capacity by silicon processors who supply the semiconductor industry.

But as the surplus dries up, the competition for silicon used by manufacturers of transistors and diodes becomes more keen —hundreds of these devices can be made with the same amount of silicon as a single solar cell. Prices have shot up to $65 per kilogram. Solar Power and other PV companies are concerned about a shortage in the 1980's.

With government help and on their own initiative solar cell companies and research laboratories are looking at cells that produce electricity from a broader spectrum of light, have liquid junctions, use high technology laser annealing and ion implantations, and use gallium arsenide, cadmium sulfide, or other materials.

Meanwhile, experimental projects continue to grab attention. Stanford Research Institute in California has announced a one step process that could lead to production of solar grade silicon for only one-twelfth of its current price, or $5 per kilogram. And MIT is developing a way to grow a thin layer of oriented crystal silicon on the surface of an amorphous substrate in a process called graphoepitaxy that could also lead to dramatically lower prices.

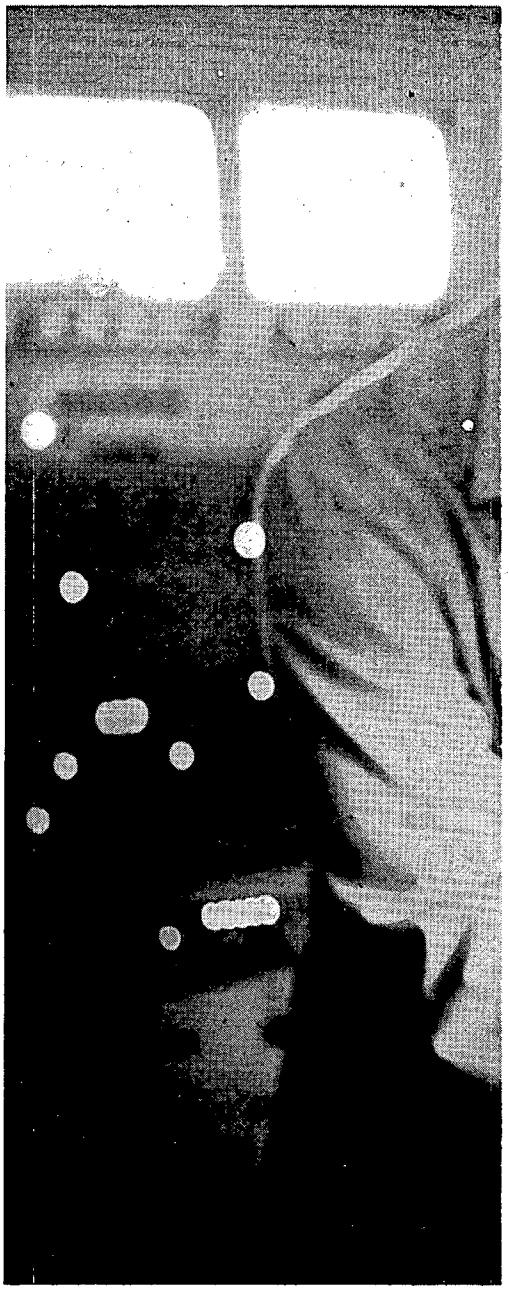
Allan Frank is Washington correspondent for Solar Age and editor of the Solar Energy Intelligence Report, Silver Springs, Md.

Sunshine into Electricity

As big business gets into the photovoltaics field, the question about cost-competitive solar electricity changes from "if" to "when" and "who" and "how". Giants of research and development are competing to bring in the cheapest, most efficient solar cell. Here the author discusses several of the newer technologies that show promise.

Sunshine into electricity

New research brings solar-cell power closer to your roof



A Motorola researcher uses a pair of focused

A flood of new devices and technology points the way to sun-powered rooftop systems during the 1980's

By JOHN FREE

LARGE, PA.

Growing crystalline solar-cell ribbons that convert sunlight directly into electricity is an unexciting, slow-motion process. At Westinghouse's advanced energy systems division here, I peeked into a small furnace containing white-hot silicon. A grayish, one-inch-wide ribbon was emerging from it and a row of other furnaces at a barely perceptible four inches per minute.

Westinghouse's ribbon-pulling process, called dendritic-web growth, was a laboratory curiosity several years ago. But the snail-pace ribbon growth at this pre-pilot production line near Pittsburgh belies the excitement among photovoltaic (solar-cell) researchers about recent advances in dendritic growth. Westinghouse believes these new developments can eventually cut solar-cell costs—currently a major stumbling block to large-scale cell use—enough for practical power generation.

But Westinghouse can expect intense competition from other photovoltaic technologies. As a result of the 1978 solar photovoltaics act, the Department of Energy has undertaken a 10-year, $1.5-billion effort to develop various solar-cell systems. Contracts to dozens of institutions and firms have produced an explosive growth in research: Announcements of significant advances and "breakthroughs" occur almost every week.

Automation of production, for example, is trimming the costs of traditional circular cells sliced from ingots of silicon, such as the Arco device shown on the cover. Another very promising technology I observed recently at RCA Laboratories in Princeton, N.J. is concerned with thin films: cells with layers so skimpy you can see through them.

Still another approach uses concentrators (instead of flat panels of cells): optics to focus solar energy and boost cell efficiency. And other technologies rely on exotic, costly cell materials or construction methods that capture portions of the solar spectrum that are usually wasted.

How significant are these developments? Can solar cells be counted on by the turn of the century—as experts hope—to supply a substantial portion of the energy this nation will need? I've just visited solar-cell research centers around the country to learn about recent advances and the future outlook. And it is becoming clear that those in the field are bristling with new optimism. They are confident that they will soon reach the old, elusive goal of producing solar cells that can turn solar energy into electricity at a cost that makes it practical.

Ribbons vs. wafers

Today, the high cost of solar cells makes them practical only for applications such as powering isolated communications stations or producing electricity in countries with limited conventional utility power. That's because almost all such cells are made by slicing thin wafers cut from so-called Czochralski silicon ingots. This produces reliable, high-efficiency solar cells of the type used by space satellites and in a few specialized land-based applications. But a lot of expensive single-crystal silicon is wasted as wafers are cut from ingots, polished, and cleaned. So the cells produced are expensive—perhaps 10 times too expensive to compete with conventional forms of electrical generation.

The Westinghouse dendritic-growth approach promises to bring down the production cost of solar cells drastically.

The present, essentially hand-operated line is really a learning tool. This year it's expected to turn out cells capable of providing 27 kilowatts (kW) of power—about half its full capacity.

Raw material for the ribbons is a nearly (99.999 percent) pure polysilicon that costs about $100 per kilo-

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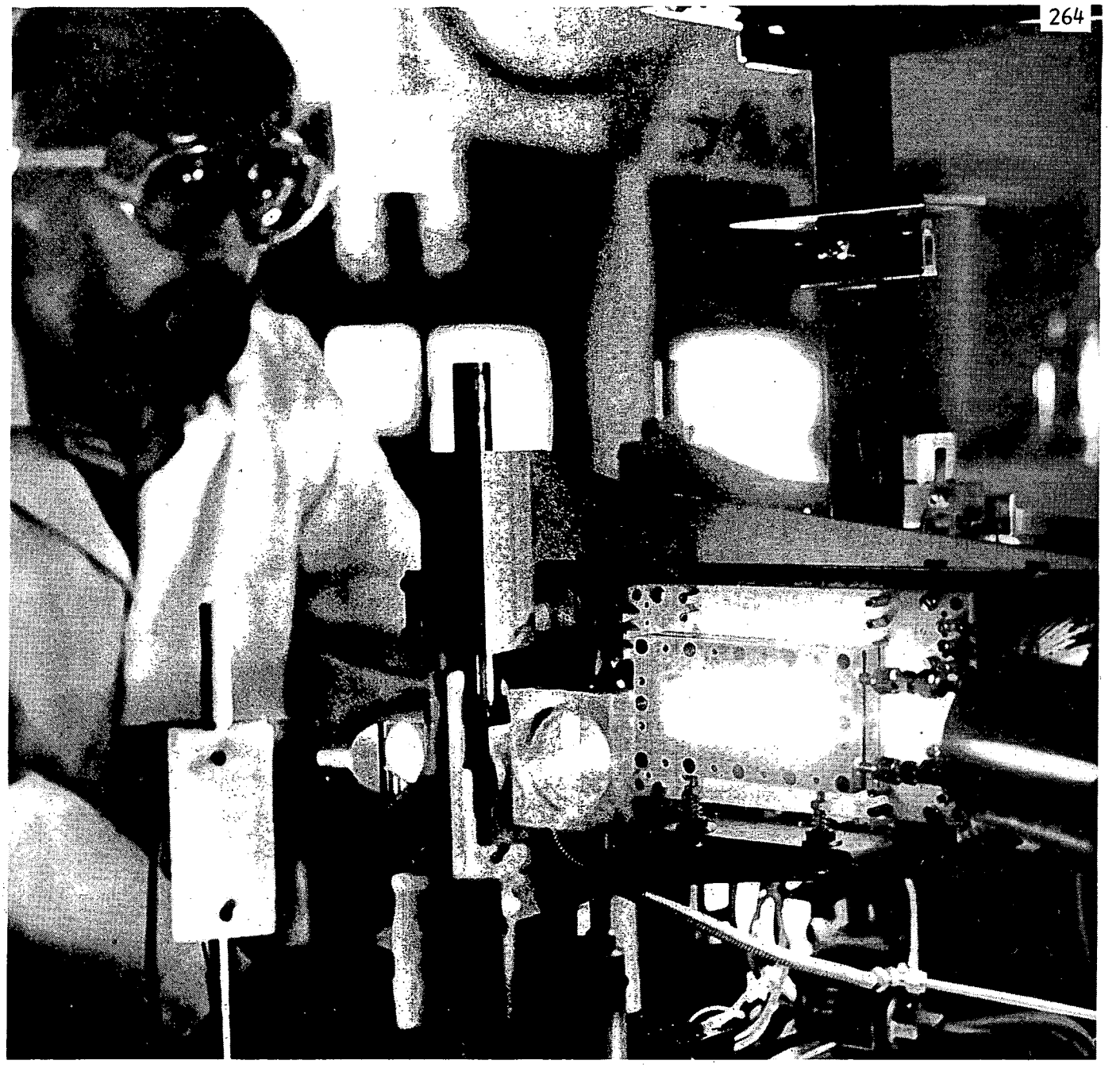

carbon dioxide laser beams to melt polysilicon. A large-grain ribbon of silicon (upper right) is pulled for use with solar cells.

gram. The gray, metallic polysilicon ingots are sliced into tiny pellets and fed continuously into furnaces. A seed filament crystal fixed to a belt on a large spool is lowered into the vat of molten silicon. Then, with controlled movements and temperature changes, the crystal magic starts.

The filament crystal widens as it "grows," and narrow filaments or dendrites at its edges poke into the hot silicon. As the seed pellet is pulled up, the dendrites continue to grow. A smooth web of single-crystal silicon six thousandths of an inch thick also forms between the dendrites—like soap film between a pair of wires. From 1977 to 1980, Westinghouse researchers accelerated by 10 times the maximum rate at which this crystal ribbon can be grown—to 10 inches per minute.

Was there a key development or technique responsible for this major gain in ribbon growth rate? "It was the computer," Dr. Dan Muss, head of Westinghouse's silicon-cell research, had told me earlier in New York. "It was our ability to model the growth process by computer and optimize the temperature shields." These metal shields just above the molten silicon regulate ribbon cooling. Using ordinary cut-and-try design methods, Muss said, would have taken significantly longer.

Once a long silicon ribbon is pulled from a furnace onto a spool, several additional steps are required to make a solar cell. I watched a technician use a laser to cut off the dendrites from ribbon sections. Next, the mirror-like pieces of crystal silicon undergo a chemical diffusion and baking process.

This diffusion step creates two different semiconductor layers—silicon "doped" with phosphorus on the front, silicon with boron on the back of the ribbon. Light striking the front frees electrons near the junction of these two layers.

Instead of the diffusion step I saw, which involves baking the cells in an oven, semiconductor impurities can be added to the silicon much faster with a high-energy ion beam. Slamming boron or phosphorous ions into the silicon is more efficient, but it

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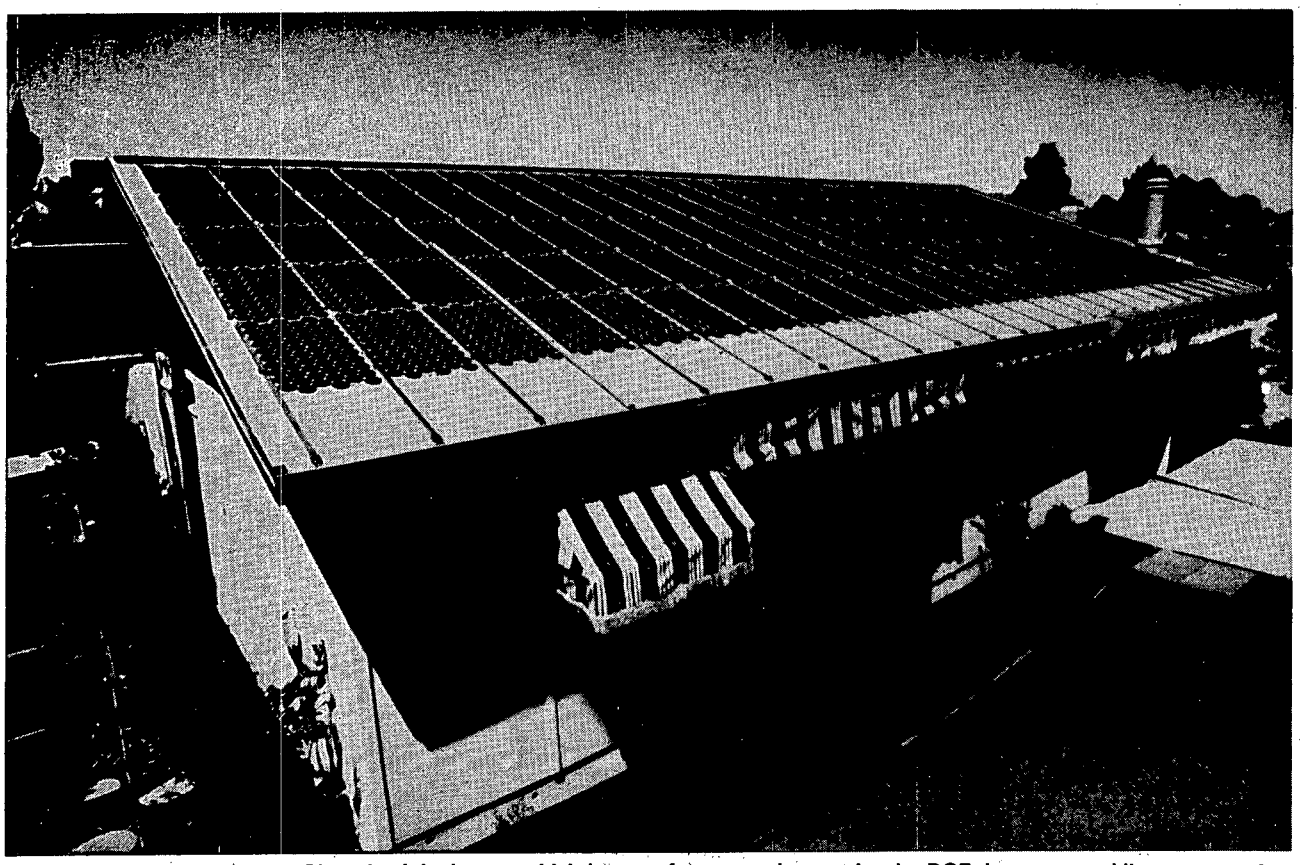


Rooftop solar-cell system on Phoenix, Ariz. home, which is one of many under test by the DOE, has a seven-kilowatt capacity.

damages the cell surface. This requires a baking stage for repair.

But for later mass production, Westinghouse could adopt a new technique discovered by the Dutch that doesn't involve delays for baking. The Institute for Atomic and Molecular Physics near Amsterdam revealed that a low-cost laser can quickly repair the surface of silicon crystals after bombardment with ions. This bombardment/laser-healing process could take place in one vacuum chamber, providing the required semiconductor layers for development of electron charges.

Add cell electrical contacts, and these electrons can flow through a load and perform work—just like a chemical cell battery lighting a bulb or running a DC motor. Westinghouse coats the rear of its cells with a metal contact and etches a computer-designed, fan-shaped metal grid on the front. The cells are also coated with an anti-reflection layer to capture more sunlight and boost sunlight-to-electrical conversion efficiency by 50 percent.

Cell efficiency is critical. The cost of cells is only 15 to 20 percent of the cost of a complete system. So low-efficiency cells (under 10 percent) require more cell area and costly panel materials; this makes them uneconomical. Westinghouse has achieved spectacular efficiency results: 16 percent, with 18 percent conversion efficiency expected shortly.

"In production, with cell efficiencies up to 18 percent, overall solar-panel efficiency should be about 16 percent," said George Hardigg, vice president of the firm's advanced power-systems division. "That exceeds the DOE goal of 12.9 percent by a significant margin." A square foot of panel could deliver about 16 watts (peak) of electric power on a clear day at noon.

When I visited Westinghouse's small pre-pilot line, technicians were preparing to build their first large panel. It contains 196 cells, is 16 by 48 inches, and produces 60 watts at 30 volts DC. The small cells are matched for electrical properties and hand-wired into place.

But by 1984 Westinghouse is committed to building a new semi-automatic line for annual production of panels that can deliver one megawatt (1,000 kW) of electricity. In 1984 the firm will also start designing a fully automated production line with a 25-MW capacity. By then, the company hopes to be using a low-cost grade of polysilicon (about $10 per kilogram).

"Considering the high efficiency achieved and lower production cost for dendritic web, the DOE 70-cent-per-watt goal (in 1980 dollars) may be achieved or improved upon by 1986," said Hardigg. "By the late 1980's dendritic growth is not going to be a technological curiosity, but a real source of electricity," says Bob Maxwell, director of division solar programs.

That 70-cent-per-watt figure quoted by Hardigg refers to cell-module cost. The DOE 1986 goal for a complete solar-panel system is $1.60 to $2.70 per watt—figures experts believe are practical for some residential uses. In the 1990's, DOE's goal is for a 15- to 50-cent-per-watt module and $1.10- to $1.30-per-watt completed-system cost. While estimates vary, at these reduced costs solar cells might supply six to 12 percent of residential electrical power by the year 2000 and up to four percent of the nation's total demand for electricity.

What would it cost you to build a complete home solar-cell system today with commercial components? Dr. Muss, using a $12-per-watt figure for modules (big-volume purchases would be less), estimates $120,000 just for cells. A complete, wired, 10-kW system (including a solid-state power conditioner to convert the DC output of cells into AC for appliances) would cost $150,000 to $200,000, he estimates.

Workers at the production facility here have a frequent reminder of a

similar but competing cell technology: wafers cut from Czochralski silicon ingots. To monitor the quality of polysilicon shipments, an ingot is "grown" from each order. Then silicon wafers are prepared with the same methods used by the semiconductor industry and 95 percent of solar-cell firms. An inescapable disadvantage of this cell-preparation method is the waste of precious single-crystal silicon as wafers are cut from ingots, polished, and cleaned.

Thin-film cells

At RCA's Princeton, N.J. research laboratories I saw cells being made that require far less silicon—which is, incidentally, the second-most abundant element on earth (after oxygen). RCA and researchers elsewhere are devising ways of depositing incredibly thin layers of silicon—under one micron (millionth of a meter)—on metal and glass substrates.

Walk into several equipment-packed RCA labs and you'll detect the acidic, darkroom odor of development chemicals. You'll also hear the periodic click of relays, followed by whooshes of compressed gas. The gas comes from tanks labeled silane, phosphine, and diborane. As it's needed, the gas is precisely metered into chambers and subjected to either a strong radio-frequency (RF) field or a high DC voltage.

The ionized plasma created forms ultrathin layers of so-called amorphous silicon ["Semiconductors Made from Glass," PS, April '78] on a substrate. This silicon has a chaotic atomic structure like that of glass instead of the orderly arrangement of atoms in single-crystal silicon. The most important gas is silane (SiH_4), a combination of silicon and hydrogen. By varying how the silicon is "doped" with the other gases and how it's deposited, a tremendous variety of solar cells can be made.

So far, both RCA and Energy Conversion Devices (in Troy, Mich.) have made cells with conversion efficiencies just over six percent. Dave Carlson, who has pioneered amorphous-silicon work at RCA, seemed confident that efficiencies can be pushed steadily higher. One advantage to making amorphous-silicon cells, Carlson told me, is that less energy is required: Gases need be heated only to between 200 and 350 degrees C versus the 1,410 degrees C needed to melt polysilicon. Also, of course, far less silicon goes into thin-film cells.

"Research in the field of amorphous semiconductors is presently in a dynamic phase involving a succession of new discoveries and concepts," Carlson notes. He said the Japanese are moving quickly to produce this new type of cell. To dramatize the point, he handed me a new, light-powered Sanyo calculator with an amorphous-silicon cell.

Later, in Dr. Joseph Hanak's RCA lab, I discovered other advantages to thin-film technology. I was curious how large the cells could be made. "We intend eventually to go to this size," Hanak said, gesturing to the surface of a medium-size table before us. Moreover, mammoth cells like this could be formed in an automated operation requiring only six minutes.

Hanak passed me a pocketbook-size version of these huge silicon cells of the future. Formed on a glass substrate, its thin translucent layers appeared orange when held up to a window. Instead of a metal grid on its front surface, this cell had a translucent metal oxide layer. Hanak then connected a portable radio to the cell and operated it with sunlight.

Conventional single solar cells can't produce the voltage necessary for such a demonstration. But the amorphous silicon can be deposited as a series of parallel, connected strips, created with photolithographic techniques such as those used to make complex integrated circuits. This produces a solar-cell panel in one fabrication sequence.

> "One 12-cell module uses Fresnel lenses to focus the equivalent of 400 suns on cells"

Another potential advantage to thin films is that several types of layers can be "stacked" one atop the other, Hanak said. "The idea behind stacked cells is one of matching different ranges of the solar spectrum to band gaps of the cell." But so far, anticipated gains with this technique have not materialized. RCA is also looking at a technique of capturing sunlight that passes through thin-film cells with parabolic reflectors, then using it to heat fluids.

Many other organizations are investigating thin films. Last summer, the University of Delaware's Institute of Energy Conversion announced that it has produced a thin film with 10 percent efficiency using different materials: cadmium-zinc sulfide and copper sulfide. The institute, with financial help from Chevron Research Co., is developing the technology needed to mass-produce these thin-film cells.

Yet while many researchers are struggling to achieve 10 percent conversion efficiency, several contractors for DOE are working on advanced cell designs for a spectacular 30 percent efficiency. Varian Associates (in Palo Alto, Calif.), for example, devised a lab setup that uses a selective filter to break sunlight into red (long wavelength) and blue (short wavelength) components. Selected silicon and gallium arsenide cells then achieved 28 percent conversion efficiency.

Under a Sandia National Laboratories contract, Varian Associates also built a 12-cell solar module that uses Fresnel lenses to focus the equivalent of 400 suns on cells. The gallium arsenide cells achieved a 16.4 percent conversion efficiency and delivered an impressive 100 watts of DC power. A side benefit is the thermal energy from water used to cool the cells in the 67-pound module, which is designed to track the sun.

Meanwhile, Bell Telephone Laboratories in Murray Hill, N.J., which invented the first practical silicon solar cell in 1954, has made significant improvements in liquid-junction cells. These devices, which combine liquids and solids, promise easier construction, less-expensive materials, and potentially longer cell life. But most liquid-junction cells tend to be destroyed by surface corrosion caused by intense light. With the Bell Labs device, sunlight actually *enhances* its longevity.

"Our cell uses indium phosphide as a photocathode, and with future materials specifically designed for liquid-junction cells, these devices could cost much less than single-crystal silicon cells," says Klaus Bachmann, a member of the research team.

"We are very excited about this new cell," says Adam Heller, head of Bell Labs' electronic materials research applications. But he adds a cautionary note voiced by other researchers: "It should be emphasized that even major research breakthroughs today could not be expected to make a significant contribution to the nation's energy needs for some time." PS

FOR FURTHER READING

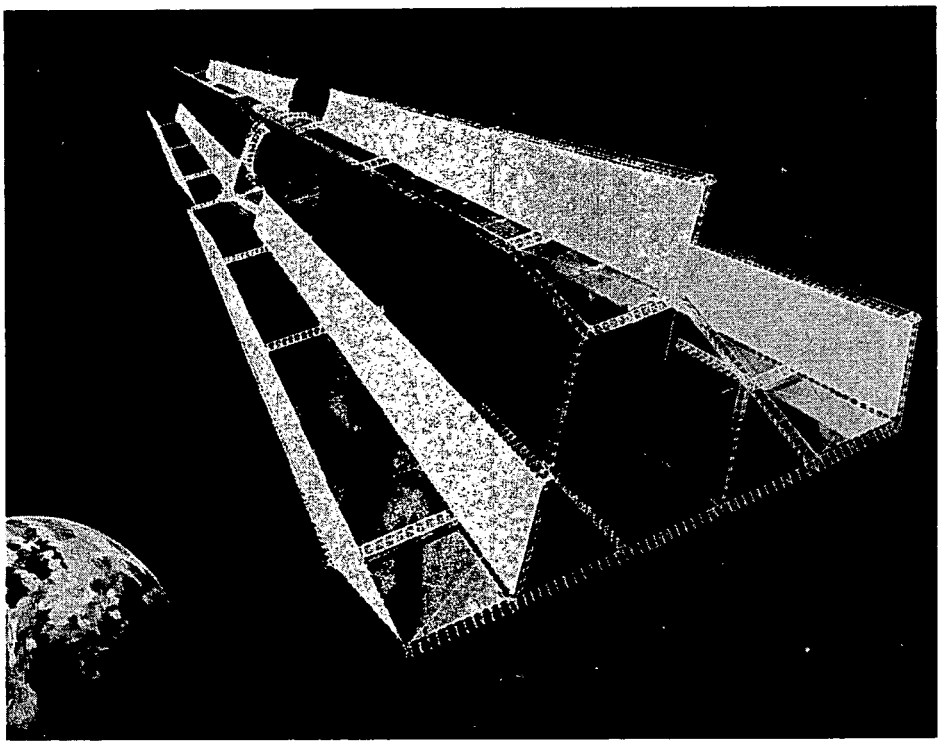
Solar Energy in Review, issued by the Solar Energy Research Institute, Golden CO (has a good photovoltaics overview chapter by David Redfield of RCA Labs).

Solar Energy Technology Handbook, William Dickinson and Paul Cheremisinoff, eds., 1980, Marcel Dekker, Inc., 270 Madison Ave, New York NY 10016 (has three chapters on solar cells in Part A). Price: $85.

Edmund Scientific, 101 E. Gloucester Pike, Barrington NJ 08007 (offers basic books on solar cells, hardware).

Energy from Space

Often dismissed as a grandiose and impractical vision, the solar power satellite may well continue to haunt the dreams of this generation and those to come.



SPACE AND THE CIVIL ENGINEER

Energy from space

By 2030, some 30% of U.S. electricity could come from the sun via a solar power satellite. Although this concept may seem more science fiction than fact to some, both the government and private industry are currently researching various aspects of building such a satellite in deep space. Not the least of the questions to be answered are costs, environmental effects and, ultimately, whether or not a satellite is a viable energy source.

ANN SELTZ-PETRASH
CIVIL ENGINEERING

IT'S A BIRD . . . IT'S A PLANE . . . it's a supersatellite—beaming electricity from space to your house. As recently as 10 years ago, this idea was farfetched. Now, however, the Department of Energy (DOE) and the National Aeronautics and Space Administration (NASA) along with 50 contractors, are involved in a complex program to evaluate the potential of the solar power satellite system (SPS).

The SPS is a satellite—a solar array orbiting above earth with a microwave transmitter. The array is composed of photovoltaic solar cells which convert sunlight to electricity. The electricity is then converted to microwave energy and beamed to earth. The earth receiver—called a rectenna—reconverts the energy to electricity (with an efficiency rate of 83%) and feeds it into a conventional power grid.

The projected cost to produce this electricity is 4-7¢/Kw hr which, according to estimates from the Edison Electric Institute, would be competitive with projected costs of nuclear-produced electricity (6-9¢/Kw hr). The technology more or less exists to plan, build and operate the satellites, each of which would probably produce 5 times the power of a big new powerplant (fossil fuel or nuclear).

The key questions are first the cost: as much as $74 billion for technology verification, research and development, creation of a prototype and heavy launch vehicles, and building the first satellite and rectenna. Second, the environmental concerns are serious, far reaching, and as yet little understood.

Why collect sunlight in space rather than earth? First sunlight in space is almost continuous, providing baseload power with minimal storage required. Second, four times more solar energy is available in space than at most earth locations. Third, 60 orbiting satellites could produce 300 GW of electricity with minimal environmental disruption, minimum maintenance requirements and require no energy to operate. (A gigawatt is a billion watts.) The SPS in combination with ground collection could provide as much as 60 to 70% of our electricity needs in the next century and could help avoid U.S. dependency on nuclear power.

The SPS concept was developed by Dr. Peter Glaser (a Vice-President of Engineering Science at Arthur D. Little) in 1968 and patented in 1973. Since that time it has been studied by both the DOE and NASA, and, under contract to those agencies, a host of aerospace and solar energy concerns.

The SPS conceptual design now in use to evaluate technical, environmental, economic and societal problems is a solar array 6.5 mi x 3.3 mi x 550 yd with a .6 mi transmitting antenna. The array is composed of 128 bays (780 x 780 yd ea.) of solar cells—more than 400 million solar cells (see diagram). The array (satellite) should orbit 22,300 mi above earth

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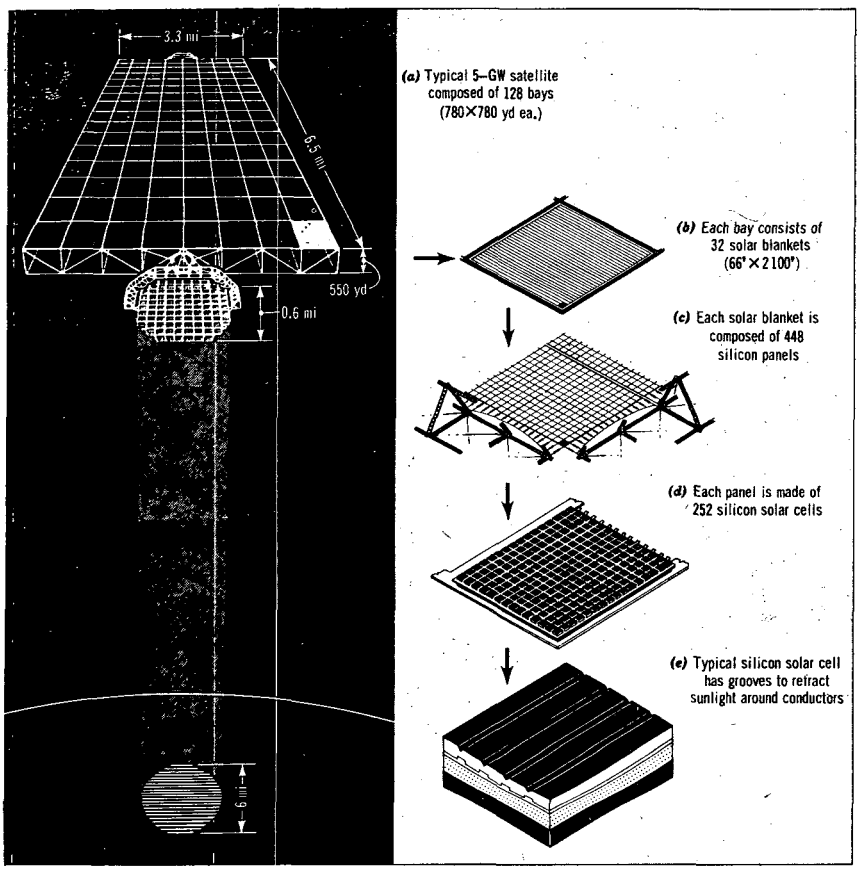


Fig. 1. Solar power satellite; one NASA proposal for the design of the solar power satellite. This design uses silicon solar cells (e); another possibility is gallium cells which require a different satellite design. Solar cells produce electricity from sunlight. Electricity is then converted to microwave energy and beamed to the rectenna on earth (lower left), reconverted to electricity and fed into a conventional power grid. The satellite would probably orbit in geosynchronous orbit (22,300 mi above earth). At right are components of the orbiting solar array.

The satellite configuration is slightly different from the first concept proposed by Dr. Peter Glaser. In his design, the microwave transmitter is in the center of the solar array. Satellite design above has transmitting antennas on each end. Antennas may be directed at ground stations a half a continent apart. Twin transmitters may be convenient to balance the satellite and reduce orbit-keeping propellant requirements. This arrangement may also be advantageous to the earth power grid operation.

The rectenna is a series of panels with a structural support system, wire mesh screen ground plane which is opaque to microwave energy but has 80% optical transparency and many half-wave dipole antenna elements which collect microwave energy and feed it to Schottky barrier diodes for conversion to d.c. power. Test conducted at NASA's Jet Propulsion Laboratory demonstrate reception efficiency of prototype rectenna elements at 83%.

If a total failure occurs at either the rectenna or microwave transmitter, the total beam would be defocused. Thus the power level would be reduced to 0.003 mW/cm² (natural solar flux at ground level is about 100 mW/cm²; microwave oven door seals are permitted leakage as great as 5 mW/cm²).

in geosynchronous (GEO: always above the same point on earth) equatorial orbit. The panels would always face the sun; the microwave transmitter would always face the earth rectenna. Sunlight in GEO is almost continuous, but some storage facilities would be necessary because there are two 72-min eclipses a year.

Technologically, design of much of the hardware required is understood, although the scale is much larger than anything attempted previously (21.5 square miles for the array). The satellite structure would be too large to build on earth and launch. The first satellite would be assembled in space of lightweight materials, probably stored at work stations in low earth orbit (LEO). Materials would then be towed to GEO by the as yet to be developed space tug, and satellites built. Building in space has its advantages: there is very little stress for which to compensate; the structure does not have to be particularly strong to support the panels because everything is weightless. Finally, there is no active environment (snow, ice, wind, rain) to affect the structure, although there is active radiation.

Before addressing building problems, the problem of launching that much material into space must be solved. It will require a reusable vehicle with a payload of approximately 465 tons (compared to the 32.5-ton payload of the Space Shuttle). To put the material and workers for the first satellite into LEO would require 3 launches per day for one year. Much construction would be by remote control from the Space Shuttle (or related vehicle), but some 400 space construction workers may also be necessary. One important advance that makes constructing in space conceivable is the beam builder (see article on space structures). This machine (for which three prototypes now exist) creates beams from cassettes of rolled metal or graphite/resin composite material.

Once operational, a solar satellite could have, according to Glaser, a working life of several hundred years. Electricity production for each satellite in the design now in use is 5 gigawatts per satellite. (The largest nuclear plant produces 1 GW). The capital investment costs per kilowatt hour for electricity produced by solar power satellites (assuming that costs of materials transportation and production are reduced) is estimated to be $1500-3000/Kw hr (with the first satellite on-line in 2000). This compares to $1400/Kw hr for a nuclear (fission) plant ordered today and on-line in 1985. These costs are all estimates, but the order of magnitude is thought to be accurate.

Major problems: cost and environment

A recent DOE/NASA report ("SPS Concept, Development and Evaluation Program Plan," DOE/ET-0034) states "Preliminary economic analysis suggests that, if cost targets are achieved for the SPS, then both on an investment and time-and-energy cost basis, the SPS would be competitive in the post-2000 time frame. However, the program would require a heavy front-end investment in order to achieve first demonstration plant—and this will be expended whether or not the SPS . . ." is ever built.

What amounts of money are involved? The scale of expenditure is almost beyond imagination. Glaser estimates as much as $74 billion investment (over the next 20 years) before the first 5-GW satellite would begin beaming energy down. Some of that $74 billion would break down as follows: $5 billion for technology verification; $43 billion for research and development; $12 billion for the first satellite and ground receiver—plus development of a heavy load launcher, space tug and other mechanical and nonmechanical requirements.

By way of comparison, the capital investment of privately owned utilities (according to the Edison Electric Institute) in 1978 was $30 billion to increase electricity production by 22.8 GW. The $74 billion expenditure to develop and launch the first SPS (and rectenna) would be spent over a 20-year period and would yield 5 GW. Each additional 5 GW satellite and rectenna would cost about $12 billion. Advantages of the solar power satellite are a very long working life, no earth pollution, and no fuel needs. And, of course, SPS figures assume inflation because the first satellite would be built

in 2000; the Edison Electric figures reflect only 1978 dollars.

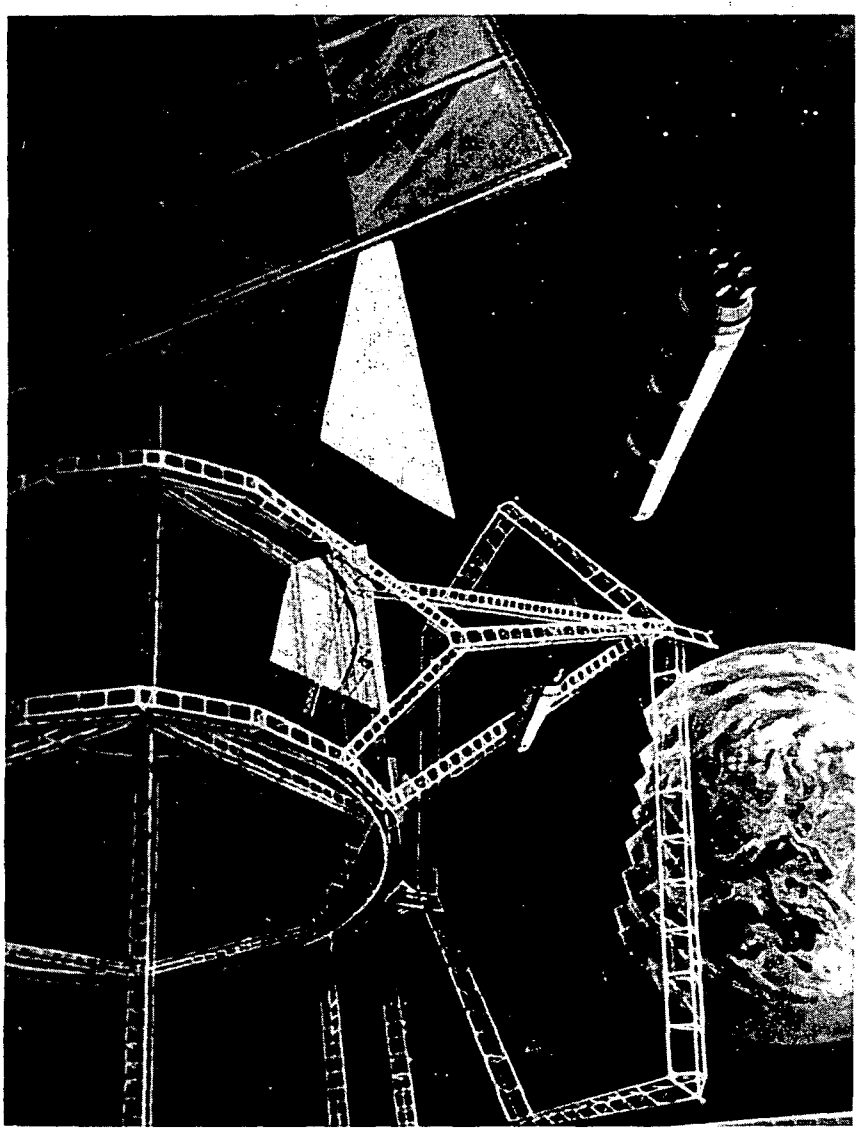
The second set of questions about solar power satellite systems is environmental and societal. Briefly, the environmental concerns under study are

- microwave health and safety: will low-level microwave radiation affect people, plants or animals? What radiation levels are acceptable?
- nonmicrowave health and safety: effect of prolonged weightlessness on space workers, effects of repeated launch accelerations on humans.
- atmosphere: effect of regular launches on ionosphere, stratosphere and troposphere. Effect of microwave beam on atmosphere.
- communications: will communications be affected by microwave beams? Will on-board computers of orbiting satelites be altered by microwaves?

Societal concerns are:

- land requirements: cost and amount of land needed for rectennas (6 to 8 mi) and how to integrate this power system with existing power grids.
- resources: material requirements, such as gallium, and tungsten, must be estimated along with cost to extract, energy to extract and which minerals, if any, might be depleted by a mammoth SPS building program.
- international aspects: first order of business is to establish worldwide microwave exposure standards; second is to agree to the frequency of the microwave transmission. Third, the problem of ownership in space must be settled. Some nations maintain "property rights" extend above their country into space. Fourth, the governing structure must be agreed to. Many people think that any system this large and centralized must be internationally owned. A likely model would be Intelsat, a consortium of 102 nations formed to buy satellite services.

Finally, although not least, is the issue of public acceptability. While there is opposition, there are no strident foes of solar power satellites. There are, however, many people who are wary of centralized power generation, of the cost, of the environmental dangers (see Box). DOE hopes to hold discussions to provide information and (when possible) answers.



A close-up view of mid-point of a solar power satellite. SPS would be built from a space shuttle.

What's in it for civils?

Most of the technological problems facing the SPS are engineering-related. One is the structural dynamics of erecting a huge (21.5 mi^2) structure with a light mass in a weightless environment. In addition, once built and in place, the SPS must be kept facing the sun, so a system of attitude control must be included.

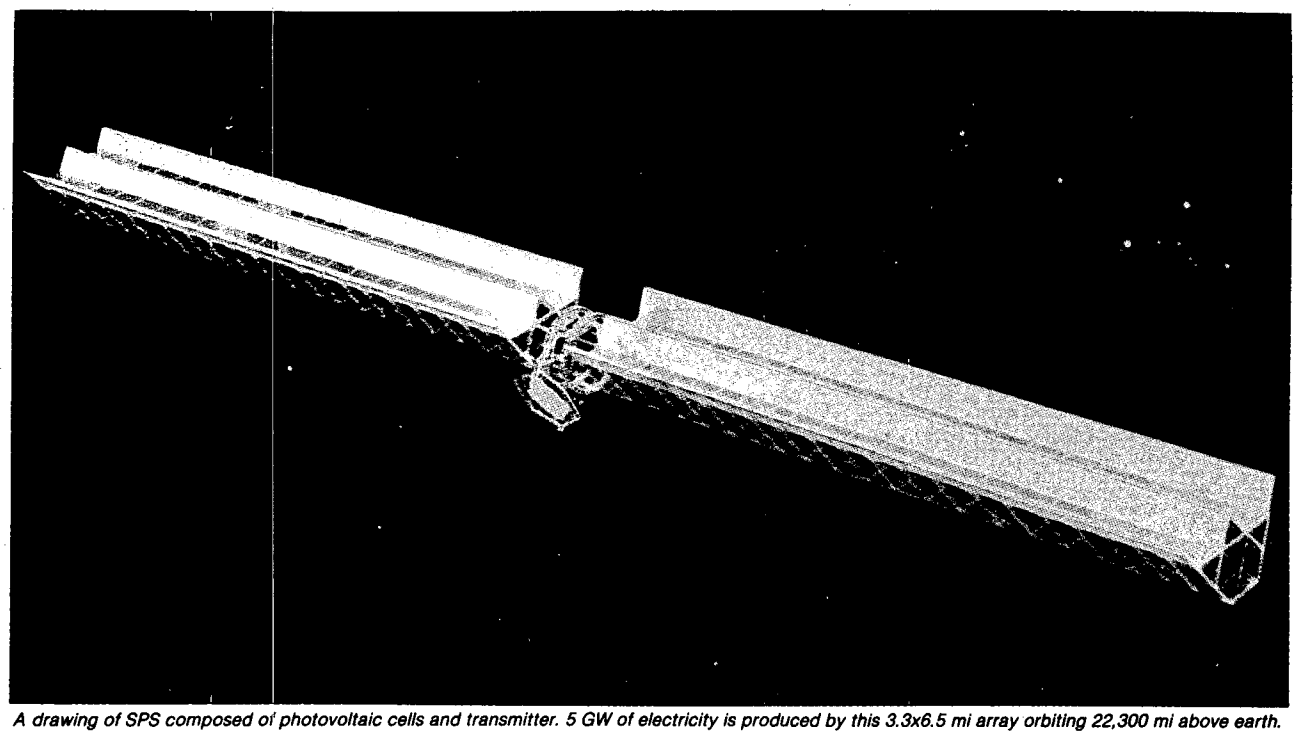
A second challenge is mass-producing the necessary solar cells, microwave generator and structures. According to Carl Schwenk (SPS Systems Definition Division, NASA), the technologies are understood, but the scale of the satellites and the number that would be built (60 5-GW satellites) is very large and the structures must be light and comparatively low cost.

According to Glaser, however, the biggest challenge for civils is on the ground. The rectennas will be very large, much larger than any existing antennas. These structures, Glazer says, cannot rely too heavily on steel and concrete. And they must be built in such a way that underlying land is usable for solar collectors, storage facilities, agriculture, etc. The design will prevent any microwave radiation under the rectenna. In urban, coastal areas, rectennas may be floated in the ocean, involving another set of engineering problems. In short, these rectennas must be cost effective, have minimal environmental impact and be of a design that allows multiple use of the land.

Also, if the SPS program continues until the first satellite begins sending electricity, the next step would be a massive construction project. This would involve building two satellites and rectennas per year (cost: $24 billion, perhaps less as mass production economics takes over). The total output estimated is 300 GW. Very many ground facilities would be needed to support such a construction program, including airports (from which to launch materials and to which launch vehicles would return), landing fields, storage facilities, rectenna factories. In a sense, a new space freight line would be created to move materials and people back and forth from low earth orbit, (LEO) and eventually, back and forth from LEO to geosynchronous orbit (GEO).

Next step: more decisions

By the summer of 1980, the Department of Energy will issue a summary on the feasibility studies to date. If there are no cost, environmental or societal reasons not to procede says Fred Koomanoff



A drawing of SPS composed of photovoltaic cells and transmitter. 5 GW of electricity is produced by this 3.3x6.5 mi array orbiting 22,300 mi above earth.

(project manager for the SPS program) then DOE will request additional research funds. Next step, in the 1980s, would be a ground-based exploratory program including concept studies and technical evaluations designed to answer questions such as will the microwave beam behave, will the structure work, what should the composition of the photovoltaics be?

In 1985, another major review would take place. If the program continues, flight experiments would begin. A prototype would be developed in the early 1990s; first launches of material could begin in 1990 with expected operations to begin in 2000.

SPS research is good investment

Funding for the SPS at this point is on the order of $8 million per year. Funds are allocated from DOE and NASA's operational budget. Currently, there is a bill to allocate an additional $25 million/year expressly for solar power station research and experimentation. The bill, sponsored by Representative Flippo (D., Alabama) has passed the House of Representatives and is now before the Senate. If that money is allocated, exploration process would move more quickly.

What if the satellite is never built? Millions of dollars may have been spent only to learn the system is not feasible. Right now, says Koomanoff, "I would have no problem justifying the expenditure for research and evaluation of the SPS. The microwave research alone is worth the money. We are gathering information that is needed for other projects . . . one of which is the effect of microwave energy (produced by appliances and high voltage transmission lines, among other sources) on plants, animals, people and machines. At this point, the U.S. has no microwave standards, nor does the scientific community know if the standards set by the Eastern Europeans are adaptable."

Another benefit will be the information compiled on health and safety requirements of space travelers and workers. With the launch of the Space Shuttle expected in early 1980 (see "NASA's reusable link with space," p. 58) space travel for more than a few people is no longer a dream. There may be health effects not yet known.

The methodology that DOE is developing to compare large-scale systems by incorporating all factors, not just dollar costs, will be, says Koomanoff, an important contribution. In the future, he says, most large-scale programs will be evaluated in a comprehensive manner. This methodology (more complex than a computer model) will allow comparison of many factors without putting dollar values on environmental/societal effects.

The information gathered on materials availability, necessary in order to compute actual cost of the solar power system, will be as applicable to any new system or product using those materials. And once in place, the information-gathering mechanism can be applied to any materials.

Finally, there are the advances being made in photovoltaic research. This research, according to Koomanoff, will push the state of the art. Whether or not the SPS is ever built, photovoltaics are an already proven means of collecting energy from the sun. Up to now, one of the major drawbacks of solar energy has been the high cost of the solar collectors. Research may show how to cut costs.

In summary

It is difficult to talk with those working on SPS research and read their reports and keep any perspective on the solar power satellite system. The idea is fantastic, the costs phenomenal the societal and environmental assessments required complex and far reaching.

Still, slightly more than 20 years ago, the idea of space travel was more fantastic—required a greater stretch of the imagination. Also the total costs of electricity produced by conventional means (oil, coal, nuclear) are fast growing.

Asked if this project was comparable to the 1961 mandate given to NASA to land a man on the moon, Carl Schwenk said, "The difference is that our mission in the 1960s was to land a man on the moon—any safe way we could. Now, our mission is to solve the energy problem in the most safe, efficient and economical way. The problems we overcome in the former did not require so great a technological stretch as do the energy problems we now face." ▽

Metric conversions

Following is a list of factors for converting measurements to the International System of Measurement: 1 ft = 0.305m; 1 mi = 1.6 km; 1 mi^2 = 2.5 km^2; 1 yd^2 = 0.836 m^2; 1 ton = 907.2 Kg.

Solar power satellite—does it have a future?

The solar power satellite (SPS) concept made its public debut in 1968 when Dr. Peter Glaser presented a paper at an energy meeting in Boulder, Colorado. Most of his colleagues, says Glaser, found the idea "imaginative."

Eleven years later, the concept is still mindboggling to most people: collect sunlight in space, beam it to earth as microwave energy, convert it to electricity and feed it into a conventional power grid. The collectors would cover about 21.5 square miles of space; the ground receiver would be about 6 x 8 miles.

How did Glaser come to conceive of the SPS? When he joined Arthur D. Little in 1955, he worked on a variety of solar projects. In the early '60s, Glaser's work was mostly space-related. The space program, says Glaser, made him aware of what space offered and the energy-producing possibilities of constant sunshine.

Finally, he says, "I put two and two together and decided the only way to produce baseload power—that is to say continuous power—was to go where there was continuous sun: space." (Ground collectors are not a continuous source of power and involve some fairly complex storage problems, according to Glaser.)

In 1972, Glaser began work with three companies with a commercial, interest in space development. He patented the design concept for the solar power satellite system in 1973 and in 1974 the team delivered its first feasibility report.

Federal role in SPS research

There now is a $8 million/year Department of Energy (DOE) program to evaluate the feasibility of the SPS. Fred Koomanoff, head of the Solar Power System Project Office at DOE has overall managerial responsibility for the project. NASA is evaluating the hardware/systems aspects for DOE and there are 50 additional contractors. Says Koomanoff, "We consider ourselves to be similar to a high-risk venture capital group working within a large corporation. It is our job to evaluate as completely as possible the costs, effects (economical, environmental, societal) and, of course, feasibility, of the solar power satellite."

NASA developed a reference system on which to base further studies. The system is not a prototype or an engineering design but a conceptual design. It is very similar to Peter Glaser's design concept, but Koomanoff stresses that it is by no means final.

Carl Schwenk heads up the Systems Definition Division for NASA, under DOE. NASA must evaluate the engineering needs of the SPS: structures, power conversion, power transmission, transportation and operations. Says Schwenk, "I don't know of any large-scale technological project that was examined this closely, this early in its development.

Why such careful scrutiny? "Because," continues Schwenk, "The SPS is very important to this nation and to the world, and because it is a complex concept, it is expensive and it is not the only possibility. It must be competitive: technologically, socially and environmentally." He adds, "I am pro-evaluation and pro-exploration in a careful, detailed way. And I think other energy sources should be examined in the same manner. For example, how much does energy from coal really cost: training miners, laying and maintaining railroad tracks to transport coal, coping with the environmental effects of mining and burning, mining costs, etc. We've never objectively looked at those costs either."

Who's for and against the SPS?

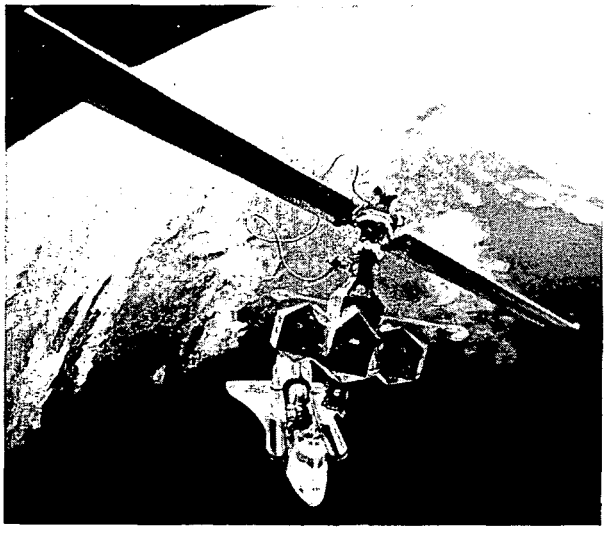
Schwenk, Koomanoff and Glaser are quick to point out that they are not advocates of building solar power satellites. There are very serious environmental questions to be answered even before a prototype is built. In fact, most of the people connected with this project are very careful to say "if we proceed" not when.

There are nonsupporters of this system, although the SPS does not seem to arouse anger as does nuclear power. Jerome Williams, Public Information Officer for the Solar Energy Research Institute (the national laboratory of solar research funded by DOE) thinks the SPS is pretty much pie-in-the-sky. "To be economically feasible," says Williams, "the satellites would have to supply most of the U.S.'s energy needs. This would make the country very vulnerable as it is not hard to knock a satellite out of commission."

Another powerful nonsupporter is Barry Commoner who in a recent article in *The New Yorker* described the satellite as "an enormously expensive, totally untried device . . . which might cost upward of a hundred billion dollars." Commoner goes on to say that because "solar energy is diffusely spread over the entire surface of the planet . . . there is no economy of scale. This means that any solar device that is large and centralized—such as a solar power station or satellite—is inherently uneconomical."

Commoner's statements hint at but don't state outright a fear expressed by Karmin Amed of the National Resources Defense Council. "One of the consistent arguments against large utilities of the 1970s is that no one controls them. They are centralized and very powerful. Ground-collected solar power would be decentralized, which is attractive to many people. The SPS is centralized on a far bigger scale than any existing utility and that may be the most serious political problem it faces."

It will be decades before a satellite circles the earth collecting sunlight, if one ever does. Meanwhile, there is thorough, cautious research in process and careful, quiet discussions among energy professionals taking place.



This is an artist's concept of a free flying power station. It would provide power to a space shuttle for up to 120 days. It is similar to a small solar power station: converting sunlight to electricity.

Power with Heliostats

Designing, building, and operating a successful "solar power tower" to generate electricity cost-effectively is no mean technical challenge. But, argue the authors, if you consider the drawbacks of other forms of electrical generation, it's a challenge worth accepting.

Power with Heliostats

A central receiver illuminated by a field of heliostats can absorb 10 to 100 megawatts of sunlight at 600° to 1000°K.

Alvin F. Hildebrandt and Lorin L. Vant-Hull

Many solar collectors presently on the market are suitable for providing domestic hot water and for heating homes. The higher quality energy required to effectively drive an air-conditioning cycle is proving somewhat more difficult to obtain with flat-plate collectors, but promising solutions are on the horizon. There is a general consensus that further increases in energy costs or collector performance coupled with the cost reductions resulting from mass production will result in a sizable domestic market for solar collectors, and substantial reductions in fossil fuel requirements for residential heating and cooling over the next 10 to 20 years.

We would like to consider here a much larger potential market, the electric and gas utilities. Consideration of turbine cycle efficiency leads to the obvious conclusion that to generate electricity effectively high-quality heat is required, for example, 300°C and higher. Similar temperatures are required to drive most useful thermochemical reactions. Such temperatures are beyond the range of flat-plate collectors and are marginal for linear-focus, concentrating collectors. A further requirement of an electric utility is that individual units produce on the order of 100 megawatts of electricity. Smaller units tend to be less efficient and more costly to purchase and to operate. To power such a unit requires the use of most of the solar energy incident on 3 to 5 square kilometers. The use of 20,000 to 40,000 tracking parabolic dishes, each concentrating energy on an individual heat engine, is one relatively complex alternative. A second alternative is to collect the thermal energy from such a distributed array of linear- or point-focus concentrators by means of a fluid and use it to operate a turbine. The combination of costs and heat losses associated with such a heat transport system can easily become prohibitive. A third alternative is to collect energy optically from a large area with the use of heliostats.

Heliostats—large, nominally flat, two-axis tracking mirrors—can be used to hold the image of the sun (helio) stationary (stat) on an elevated absorbing receiver continuously. This procedure permits the absorption in a working fluid of about 2/3 of the flux incident (taken as the product of about 1 kilowatt per square meter penetrating the atmosphere multiplied by the total mirror area). Because of the central focusing of energy from thousands of heliostats, the absorbed energy can be extracted from the receiver and delivered to the ground at a temperature and pressure suitable for driving a conventional utility-type steam turbine for electrical generation. Three large design studies (discussed below), currently nearing completion, have shown no substantive technical problems with this approach. Cost estimates show that no dramatic technical breakthroughs should be required to bring the cost of this system, once it is in mass production, into the range where it can compete with other environmentally benign power plants.

In the balance of this article, we shall discuss (i) the plan of our solar thermal power system or "solar power tower" based on optical transmission, (ii) the history of the solar tower, (iii) the receiver subsystem, (iv) the design of the heliostats and their placement in a field, (v) thermal storage, (vi) environmental concerns, and (vii) economics.

The Plan of the Solar Tower System

A tower supporting a solar receiver-boiler is located near the center of a field of mirrors or heliostats (Fig. 1). Radiant energy reflected from the sun is intercepted by the receiver and absorbed as heat on its surface. High-pressure water circulating through tubes forming this surface is converted to steam and returned to the ground. Here it may be used to power a 100-megawatt (electric) turbine generator set and simultaneously to charge a thermal storage unit for deferred operation.

Although differing in detail, a variety of systems consisting of an external receiver (as shown in Fig. 1) or a cavity receiver can be designed to have an overall efficiency of 2/3 for the conversion of the energy incident on the optical aperture of the system into thermal energy (available as high-pressure steam), where the reference is the mirror area multiplied by a representative direct beam insolation of 950 watts per square meter. Typically, 20,000 heliostats each 40 square meters in area are arrayed over an area of 3.5 square kilometers surrounding a receiver elevated 260 meters above the ground to provide 100 megawatts (electric). Such a system can deliver an annual average of 5.5 kilowatt-hours of steam energy per square meter of mirror area on clear days in the deserts of the U.S. Southwest.

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History of the Solar Tower Concept

The concentration of the direct beam component of sunlight with heliostats was first attributed to Archimedes, who instructed soldiers to reflect the sun onto the sail of an enemy vessel by carefully orienting their burnished shields (heliostats). Their efforts were successful, for the vessel was set afire. It was not until several thousand years later that Trombe and his co-workers added hydraulically controlled servomechanisms to an array of large heliostats to produce an automatically controlled 1-megawatt (thermal) solar collector (*1*). Interested in producing high temperatures to melt materials, Trombe added a large, fixed concentrator consisting of a parabolic dish and achieved a temperature of 4100°K. Baum *et al.* (*2*) investigated a tracking array consisting of heliostats on moving railroad cars, aimed at an elevated cavity receiver-boiler. The cavity was to be rotated to face the heliostats throughout the day to achieve improved performance. They found that a prohibitive power requirement would arise because, at the very slow speeds involved, the wheels on the dusty railroad track would experience starting friction continuously.

Francia developed an intricate clock-driven field of 271 heliostats and was able to produce steam at a rate equivalent to 150 kilowatts (*3*). Using flat mirrors, he obtained an intensity somewhat less than 271 times the local beam component of direct sunlight, and with dished mirrors somewhat more. This concept is not suited for large-scale utilization of solar energy on a megawatt (electric) basis because it is impractical to connect many thousands of heliostats into a single clockwork device with sufficient precision. Moreover, the mechanism is not well suited to the larger mirrors required for an economical system design.

A reinvention involving a large number of heliostats took place in 1970–1971 at the University of Houston (*4*). [This work was supported by the RANN program of the National Science Foundation (NSF) beginning in 1973, and in 1975 it was transferred to ERDA (Energy Research and Development Administration) along with related investigations (*5*).] During our study of long-term problems in science and engineering, it became apparent that the outlook for energy sources beyond fossil fuels was hopeful but uncertain. Clearly, solar energy could be utilized. Since some investigation of the possibilities had already been carried out, we considered only the most promising options. Photovoltaic cells were considered first but, because of their large cost and low efficiency at that time, were rejected in favor of potentially efficient thermal conversion cycles compatible with the utility grids. Steam-electric conversion cycles producing 100 to 300 megawatts (electric) are well developed by the utilities, which also have a large-scale distribution system. It seemed advisable to utilize available transmission methods.

The laws of physics tell us that the highest quality solar energy is obtained with a point-focusing device and that the radiative equilibrium temperature is limited to that of the source, in this case the sun at about 5720°K. To approach this temperature would require an ideal lens or a perfect-focusing mirror. Because large lenses require excessive bulk material, mirrors are preferable. Although many small focusing parabolas can be used, it is expensive to produce accurately curved mirror surfaces, and the required heat transport system entails substantial loss. Less loss would result if, using essentially flat mirror segments, we could have a single parabola with an aperture of about a square mile (2.6 square kilometers). In the 1950's Pilkington Brothers, Ltd., developed an economic process for casting precision flat glass by slowly cooling a continuous sheet of molten glass while floating it on a bed of molten tin (*6*). The resulting strips of float glass, 3 to 4 meters wide, can be used to construct large, two-axis steered mirrors or heliostats as depicted in Fig. 1. An array of these heliostats constitutes what might be described as a tracking Fresnel reflector.

In discussions of the solar tower concept, the question of the "best" size system always arises. The correct answer to this question depends upon the assumptions made or requirements imposed at the onset. For example, one may assume focusing optics with the total of aberrations and other optical errors fixed at some design value. Typically, a standard deviation of 0.166° or 3 milliradians can be achieved at moderate cost (the solar disk subtends about 10 milliradians). For such a system the concentration is fixed by the rim angle of the collector and the geometry of the receiver and will not be affected by scale. Thus, one is then free to choose the "best" system based on thermodynamic cycle efficiency and the economics of producing the selected collector, receiver, and energy transport system.

A capacity of 30 to 100 megawatts (electric) at a single site is probably as small as the utilities would like to consider integrating into the grid because of synchronization, switching, and dispatching problems. One can generate this electricity with a single turbine, using energy from a field with an area of 1 square mile collected either optically (so-

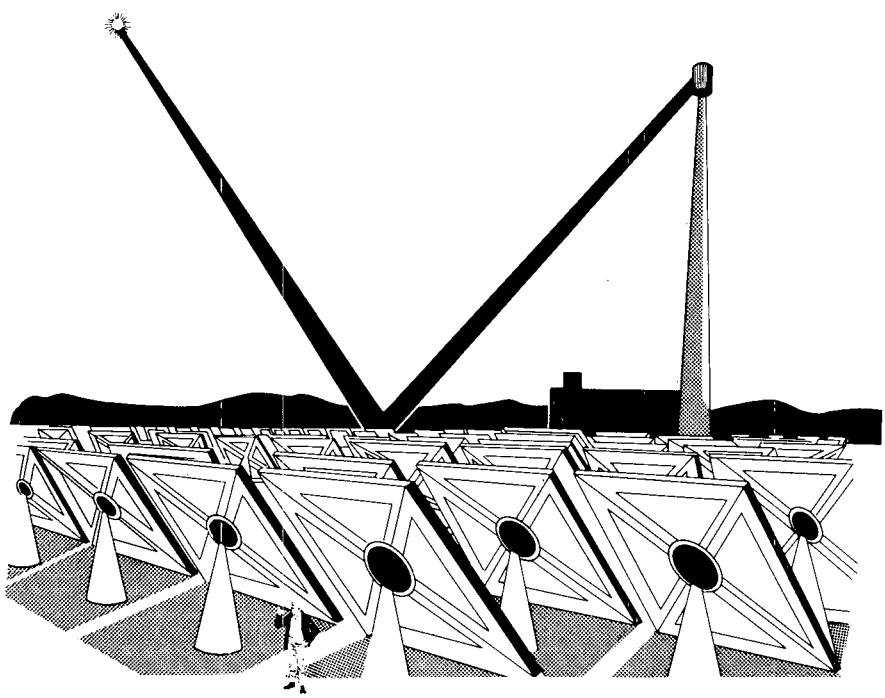

Fig. 1. The 100-megawatt (electric) heliostat power plant concept. The tower (260 meters high) near the center of the field has a boiler on top. About 20,000 heliostats (6.4 by 6.4 meters) would be required, spread over an area of about 3.5 square kilometers. A 10-megawatt (electric) pilot plant is under development by ERDA. Water is pumped up to the receiver and the steam is brought down to the conventional steam-electric generator usually employed by utilities.

lar tower) or by means of a heat transport system to gather to a common point the energy absorbed by a distributed system of collectors. The distributed system of collectors may consist of either numerous minitowers or a multitude of individual collectors. As an alternative to this heat transport system, one can use either small turbines with each small distributed field or minitower or very small engines at the focus of parabolic dishes. We believe that these alternate approaches will be less efficient and less economical than the single tower approach. Heat losses in the smaller scale systems are much harder to deal with, and smaller heat engines currently available are appreciably less efficient than the large utility turbines. In addition, the parts associated with each reflector unit are markedly increased in number and complexity if one adds a small heat engine to each one, such as a Stirling, or Ericsson, cycle isothermal expansion and compression engine. The shorter focal length of the smaller systems also makes it necessary to use a larger number of more highly curved reflector segments to achieve the required 3-milliradian beam error including aberrations.

The choice between one or a few solar towers is less sharp. The cost of towers up to about 350 meters in height tends to scale with the corresponding collector area, becoming appreciably more expensive in the 400-meter range. Below 200 megawatts (electric) the tower cost does not significantly affect the argument. In the range from 10 to 200 megawatts (electric), suitable steam turbine generator costs and thermal-to-electric conversion efficiencies favor the larger sizes. A 10-megawatt (electric) generator would cost approximately $300 per kilowatt (electric) and have an efficiency of 35 percent, whereas the corresponding values at 100 megawatts (electric) are $250 and 40 percent. Consequently, under the stated assumptions we would conclude that central receivers in the range from 50 to 200 megawatts (electric) are the most economical way to supply solar energy to an electrical grid.

This conclusion is reinforced by the fact that mirrors with a radius of curvature greater than a few hundred meters can be either stress-curved from flat sections or simulated adequately by a small number of facets, each canted at the appropriate angle. Either of these approaches is sure to be cheaper than casting self-supporting curved mirror segments of adequate optical quality to guarantee a high fraction of undistorted, specular reflection. For larger scale systems in the 50- to 200-megawatt (electric) range, the allowed segment size becomes equal to the 6-meter diameter of an economical heliostat, and nominally flat mirrors can be used. Removing the requirement for focus or canting segments relaxes a constraint on the heliostat design that will inevitably lead to lower cost heliostats and, consequently, a lower cost system.

For applications where a smaller amount of power is required at a local site, for example, a process heat or pumping requirement, other considerations come into play as well, such as the availability of a grid tie-in and the availability or requirement for reliable backup. Smaller units with a lower optical concentration will usually require lower operating temperatures to reduce convection and reradiation losses. In general, we believe that a single solar tower will be the most efficient, lowest cost, and most reliable means of supplying any solar requirement in the range from 1 to 1000 megawatts (thermal). Below 1 megawatt (thermal) a few parabolic dishes or troughs may be competitive. The only systems currently under development which may compete with the solar tower are the fixed reflector–moving receiver concepts. Although these are linear systems and so tend to provide lower concentration than is available with the "point focus" solar tower concept, these systems have the advantage of an emplaced reflector which does not require support or steering. After this advantage has been weighed against the disadvantage of a tracking receiver and relatively poor aperture utilization, a definitive comparison can, perhaps, be made. Because the reflector contour must be carved in the ground, individual collectors larger than a few megawatts are not practical. Thus for larger power requirements, the earlier arguments against distributed systems apply.

Aspects of the solar tower system—external or cavity receiver, flat or focusing heliostats, and methods of storage—are under study by a four-team ERDA effort to result in a preliminary design for a 10-megawatt (electric) pilot plant by June 1977 (*7*). Barstow, California, has been selected as the site for the pilot plant. It is anticipated that the first step in bringing costs for commercial solar plants into the range experienced for the construction and fueling of nuclear plants will be to increase plant size to at least 100 megawatts (electric) at a single site to achieve better collector and turbine efficiency. Figure 1 depicts the concept for a 100-megawatt (electric) demonstration plant (*7a*).

Other solar tower developments include pilot plants planned by the Electric Power Research Institute as well as the French and Japanese governments. An ERDA-funded Solar Thermal Test Facility (STTF) is under construction at Sandia Laboratory, Albuquerque, New Mexico, and is scheduled for completion in early 1978. The STTF is a small 5-megawatt (thermal) solar tower collector for testing the 10-megawatt (electric) pilot plant prototype components and performing related solar energy research.

The Design of the Heliostat Field

Because the heliostat field comprises about 50 percent of the total cost of a commercial solar tower system, design is crucial. For the 10-megawatt (electric) pilot plant there would be approximately 2000 heliostats, and for a 100-megawatt (electric) demonstration plant about 20,000 heliostats. The four design teams have all concluded that the most economical heliostats have an area of about 40 square meters and are composed of up to nine segments. For the pilot plant, the segments must be either curved or canted to provide an added degree of focusing. Important design factors are wind and gravity loading. The elevation and azimuth sensors and actuators must have a long life and will require only a fraction of a percent of the energy collected. The design should be suitable for mass production and easy installation.

The heliostats must be spaced in such a way as to avoid excessive shading of one another or blocking of the reflected radiation in the daily and yearly operation. Detailed computer analysis has shown that this can be accomplished for a nonuniform mirror distribution resulting in a ratio of reflector area to land area, ϕ, varying from 0.4 to 0.1 and averaging about 0.25. Far from the tower the heliostats must be sparsely distributed to prevent blocking of the reflected sunlight by adjacent heliostats. The heliostats are individually servo-controlled by a closed-loop sensor feedback system or by an open-loop computer control to reflect the solar beam onto the receiver all day.

A computer override initiates operation each morning and stow (shutdown) each night, sustains a uniform track in the event of a brief cloud interruption, initiates a rapid scram (shutdown) mode in case of coolant or boiler failure, or directs the heliostats to a safe orientation in case of adverse, inclement weather conditions. A vertical stow (orientation of the heliostat in a vertical position) can minimize hail damage or counter ice

loading and, if the heliostats are facing downwind, can alleviate damage from blowing sand. A horizontal stow reduces structural specifications for surviving high winds, whereas a partially or totally inverted stow reduces the accumulation of dust. The heliostats are designed to withstand wind gusts to 170 kilometers per hour in horizontal stow. The possible requirement of an inverted stow is still under study and could add approximately 10 to 15 percent to the energy costs because of structural requirements in the heliostat mount and frame. A typical heliostat with sensor is shown in the far left of Fig. 2.

A map of the estimated direct annual beam radiation over the United States (Fig. 3) suggests why solar tower plants, as outlined, would be primarily situated in the desert Southwest. The heliostat system approximates a point-focus parabola and requires direct-beam radiation for imaging. The clear, dry, usually dust-free desert air ideally meets this requirement. As the solar elevation decreases, absorption due to the atmosphere increases; a useful number for the solar intensity when the sun is high overhead in clear days is 950 watts per square meter on a surface perpendicular to the rays. This is to be compared to about 1.35 kilowatts per square meter above the atmosphere.

Using a clear-air insolation model for an optimized heliostat layout, we obtain daily power curves as shown in Fig. 4 for flat ground at 35°N. However, favorable south slopes should be utilized where available. These calculations account for optical and thermal losses for a 100-megawatt (electric) generating plant with 6 hours of storage. While shading of heliostats and blocking of the reflected radiation is accounted for, losses can be kept negligible for solar elevations greater than about 25° by careful field layout. The mirror reflectivity is assumed to be 0.91 and the receiver absorptivity 0.95. Dust losses (5 percent) and radiation and convection losses (7 percent of the peak value) are also accounted for. The amount of energy transmitted into the working fluid varies with solar elevation from 2/3 to about 1/2 of the product of the solar intensity and the total area of the mirrors.

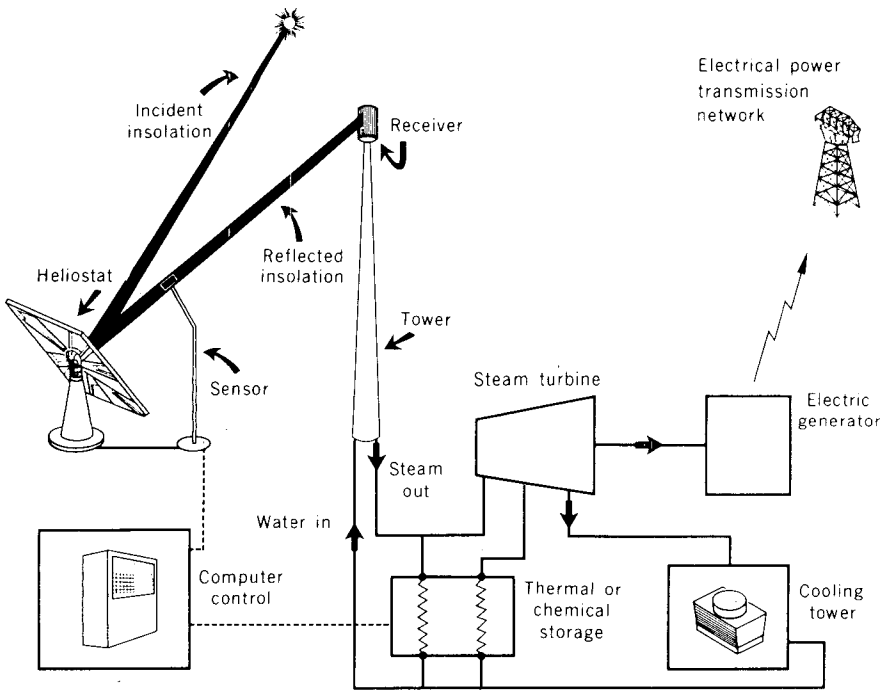

Fig. 2. Solar tower steam-electric power plant schematic. About 2000 heliostats would be required for the 10-megawatt (electric) pilot plant.

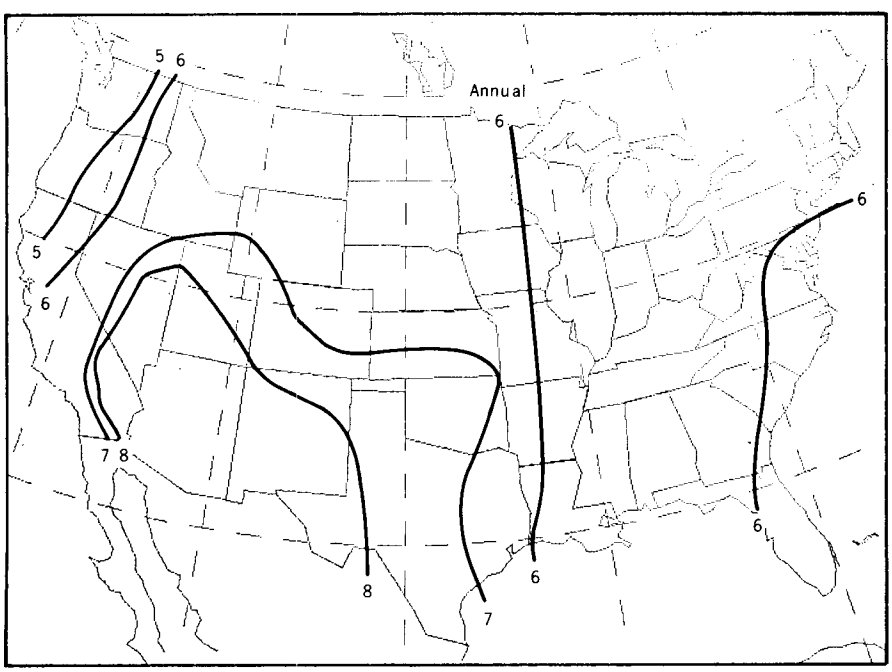

Fig. 3. Annual average direct-normal insolation (in kilowatt-hours per square meter) estimated from total hemispheric insolation (*17*).

The Receiver

The receiver subsystem must be able to effectively intercept the sunlight reflected from the heliostat field and absorb it as heat. The heat must be transferred to the receiver coolant at the desired temperature with minimal loss due to reradiation and convection. For a 100-megawatt (electric) commercial receiver we have determined that these requirements can be met effectively by a cylindrical receiver 17 meters in diameter and 25.5 meters tall, supported 230 to 300 meters above the heliostat field. The outside cylindrical wall forms the absorbing surface, which is made of 24 identical panels each 2.2 meters wide. For a water-steam receiver each panel will be composed of 170 Incoloy-800 tubes 13 millimeters in outside diameter connected to headers or manifolds at the top and bottom. The water will be transformed to superheated steam in a single pass through the receiver. The flow of preheated coolant through each panel will be independently controlled to compensate for variations in incident flux. Consequently, the output from all panels can be combined into a single downcomer. With normal design and in-

sulation, the heat loss of this energy transport subsystem is insignificant. For the external receiver using water-steam as a working fluid, the outlet temperature is between 500° and 550°C. At this peak temperature a perfect blackbody can radiate only about 25 kilowatts per square meter, and convection losses, even in a strong wind, are only about half as great, for a maximum loss of less than 40 kilowatts per square meter. For the steam system the receiver flux will be reduced by a multipoint aim strategy in the pilot plant to about 300 kilowatts per square meter (600 in the commercial design). In each case the average flux (and mean loss) is about 2/3 the quoted value, so that the respective receiver losses are about 12 and 6 percent, respectively. The higher receiver temperatures tolerated in a receiver cooled with liquid sodium we have considered might double the thermal loss per square meter, but, since fluxes of up to 2 megawatts per square meter can be tolerated, a smaller receiver can be used so that the percentage loss would, in fact, be less.

A variety of cavity designs are under study as alternatives to the external receiver we describe here. These include tube type, multiple-pass, water-steam boilers; open-cycle air or closed-cycle helium ceramic tube or honeycomb surfaces; and cavities incorporating direct absorption in a molten salt flowing over the inner wall of the cavity. Although the cavities are likely to provide lower thermal losses, we prefer the external design for five basic reasons. (i) It has a very wide acceptance angle and so has less influence on the design of the heliostat field, the largest cost item in the entire system. The area of the cavity aperture, which radiates as a blackbody, must be kept small to retain any advantage. The acceptance cone half angle, θ, is therefore restricted to about 60° because the required radius of the aperture is ($R/\cos\theta$), where R is the radius of the extreme beam. (ii) The cavity must be supported and insulated on its exterior surface. This exterior structure is substantially more massive than the interior support structure of the external receiver. (iii) Any one of the 24 modular panels of the external receiver can be replaced overnight, whereas the cavity would have to be serviced and repaired in situ. (iv) It is easy to design minimal constraint supports and structures for the exterior receiver panels, whereas the added complexity of the cavity boiler designs for the steam system tends to constrain the tubing, leading to excessive thermal stresses. (v) The lightweight components of the external receiver can more readily follow the variations in insolation due to clouds and other adverse weather conditions.

The Tower

For a 100-megawatt (electric) system our analysis of the most cost-effective collector field geometry shows that the receiver must be elevated 260 meters above a field of heliostats with an area of 3.5 square kilometers. To support the considerable weight of the receiver and its steel support structure as well as the thermal transport system, we have chosen a tapered cylindrical-shell, slip-cast concrete structure. Inasmuch as this structure is designed to survive probable seismic disturbances in the West, it is sufficiently rigid to restrain sway of the receiver to less than 0.3 meter in winds occurring while the heliostats are operating. Sites near major seismic faults should be avoided because of the accompanying increase in the costs of the tower and heliostat supports. For most of the southwestern United States we have used a tower cost of $8 million.

Storage

Opponents of solar power insist that the solar tower concept should provide reliable power on cloudy days and also meet the nighttime baseload requirements. We believe that both of these requirements are unreasonable, at least in the early stages of development. Because thermal storage for cloudy days would be used only occasionally, the cost per cycle would be prohibitive. Although the storage system to provide for overnight operation would be used every day, the baseload application is the least competitive first use of solar energy. The market value of baseload electrical power is about half that of load-following power, that is, power that is generated to meet intermittent high demands, usually during the hours of 10 a.m. to 8 p.m. The electrical load parallels the solar supply (with a 2- to 4-hour delay); therefore, the most attractive first application is a plant designed for load-following with storage for 4 to 6 hours of operation to provide stable operation and to better match the observed utility load. A gas turbine plant with a low capital cost and a relatively high fuel cost can be added to the grid to supply the intermediate load power on the rare cloudy days when electrical demand is high.

The amount of thermal storage incorporated in the current design effort is sufficient to operate the turbogenerator for about 6 hours. This will permit penetration of the intermediate-to-peak-load utility market which usually occurs in the evening. Capacity credit will accrue to such a plant, and the storage will provide a cost-effective way of handling solar insolation differences in summer and winter. In the winter, a plant may be in the on-line, standby mode in the mornings so that the storage can be fully charged for evening operation, whereas

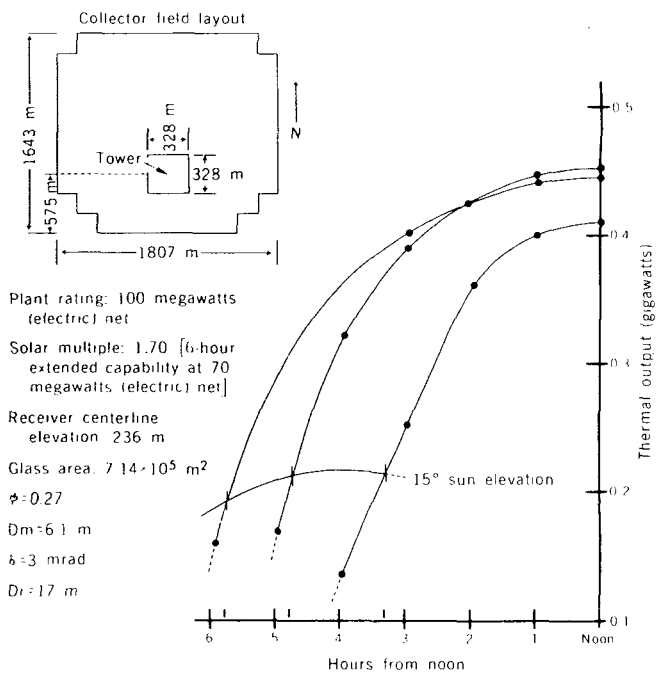

Fig. 4. Diurnal power curves for the field shown in the inset at 35°N. This field, coupled with 6 hours of thermal storage, would supply a 100-megawatt (electric) steam-electric generator. The thermal output, in 10^9 watts, is that deposited in the working fluid and includes loss estimates of 9 percent for reflectance, 5 percent for absorptivity, 5 percent average for dust, and 32 megawatts for combined convection and reradiation at the operating temperature of 515°C; Dm = effective mirror diameter; δ = angular standard deviation of the reflected light due to heliostat imperfections; Dr = receiver diameter.

in the summer there is sufficient daily energy to run at capacity all day and still charge the storage unit so that the evening market can also be supplied.

In an alternate mode of operation fossil fuels would be used when solar energy is not available, especially on cloudy days. Fossil fuels could also be used in the evening market, but some form of thermal storage is still required to ensure plant stability. Such a solar plant with fossil backup is classified as a fuel displacement plant and may be given little capacity credit. However, further depletion of our petroleum reserves may make such a facility acceptable. We have yet to develop an adequate methodology for estimating capacity credit for the solar component when fossil fuel is used in reserve.

A second form of storage is the use of suitable deep geological formations into which high-temperature fluids can be pumped. The requirement is a porous formation where leakage to the outside would be minimal, such as abandoned oil wells. Porous rock is a relatively good thermal insulator. If we consider a sufficiently large unit, the fractional loss per day is small because the surface-to-volume ratio becomes small. Calculation shows that geothermal storage for a 100-megawatt (electric) tower would require about 2 months to charge and then could be used cyclically each day to provide load-following capacity (*8*). Because the extraction is regenerative, injection and withdrawal temperatures could be very nearly equal and quite high. If, however, we should encounter difficulty in injecting or producing fluids at sufficiently high temperatures for power production, large quantities of process heat at 150°C and above are in demand and such geothermally stored heat can be harnessed to service those process needs.

Another approach to storage, which we believe deserves further emphasis, is chemical bond storage, with molecules having bond strengths of several electron volts per molecule. An obvious example is the electrolysis of water into hydrogen and oxygen. This method is under investigation for photovoltaic cells and wind energy systems but it is not the leading candidate if a thermal cycle is involved, because about 2/3 of the energy will be wasted in the thermodynamic cycle unless, perhaps, viable fuel cells are developed. The storage battery constitutes another form of chemical bond storage which is currently under intense study as electric storage for photovoltaic cells. Batteries provide more compact storage than hydrogen gas and are well suited for individual use, such as in an electric car.

Table 1. The 1977 cost estimates for a mass-produced 100-megawatt (electric) solar tower plant.

Subsystem	Relative cost (%)
Generator plant	30
Energy storage (6 hours)	11
Installed heliostat costs ($80 per square meter)	43
Receiver, tower, and piping	14
Spares, land, and yard	2
Total system: $1700 ± 15 percent	100

The Germans have under development a closed-cycle, decomposition-recombination chemical reaction in which methane and water react to form hydrogen and carbon monoxide [the process bears the acronym EVA-ADAM (*9*); the hydrogen-generating reactor is called EVA (Einzelsphaltrorvernsuchsanlage), and the back reactor is called ADAM as the mate to EVA]. This reaction is to be coupled to high-temperature, nuclear gas reactors to deliver heat at a substantial distance. Calculations indicate that more heat can be delivered by this system than through a thermodynamic-to-electric cycle, and transmission costs are less than for electricity. This cycle can possibly be developed for use with the solar tower, but techniques for banking the catalysts (removing the reactants while maintaining the catalyst bed at operating temperature) during sunless hours must be studied. Moreover, the gases involved require large-volume storage.

A most attractive form of chemical storage is the simulation of fossil fuels. One would like to use solar heat to decompose a liquid compound into several other liquids that can be stored or transported and recombined at will with the liberation of heat, Q. The liquid-liquid reaction would offer ease of handling and would allow storage of more energy in a given volume than either a chemical cycle involving gas reactants or a sensible heat storage system. The heat generated in the reaction can be used in home heating and cooling and, if it is of sufficient quality, in the production of electricity. If we consider the reaction between ammonia (NH_3), water, and sulfur trioxide (SO_3),

$$NH_3 + H_2O + SO_3 \rightarrow NH_4HSO_4 + Q \quad (1)$$

considerable heat is generated as the reaction processes exothermically to the right without a catalyst at temperatures up to 500°C (*10*). The chemicals are liquid at near room temperature and pressure (NH_3 requires some overpressure and SO_3 requires some heating to avoid solidification). The chemicals are cheap and abundant, and the density of energy storage is about 800 kilocalories per liter: about 1/7 that of gasoline or 10 to 20 times that of sensible heat stores.

Recycling of the chemicals would require the thermally activated decomposition of the ammonium hydrogen sulfate (NH_4HSO_4) into the compounds on the left in Eq. 1 and then separation. This back-reaction and separation have been carried out and at temperatures attainable with the solar tower (*10*). Basically, there is a temperature for each chemical system above which dissociation and absorption of energy occurs and below which the chemicals recombine with the release of energy. Such synthetic fuels can be readily integrated into our technological structure, displacing fossil fuels and bypassing the inefficient electrical generation cycle in many cases.

The development of methods for storage of sufficient energy to operate through several sunless days, or of a viable backup will probably be slow in coming, but, once such storage systems have been developed, solar plants in the Southwest can supply a significant amount of our national energy requirements by electrical transmission. The high-voltage direct-current net from the Northwest to the Southwest (1600 kilometers) is adequate demonstration that power can be economically transmitted over long distances. Therefore, it is possible to transmit power from Lubbock, Texas, in the sun-rich Southwest, to Detroit (1600 kilometers).

Environmental Concerns

For economic reasons, utilities have recommended the use of wet cooling systems in the pilot and demonstration plants. The dry cooling tower (Fig. 2) is somewhat more expensive and operates at a loss of a few points in plant efficiency, but dry cooling may be required to minimize environmental impact in the desert, a first-choice site for emplacement of the solar tower plants. With dry cooling towers, solar plants are expected to have a minimal environmental effect. In contrast to fossil-fired plants, the increase in global heat from a solar plant is a second-order effect since the system is simply converting incoming radiation to useful mechanical energy before it is ultimately deposited as heat by the electric utility. This figure compares favorably with conventional fossil-fired systems that deposit 3 to 4 units of thermal ener-

gy (waste heat) into the biosphere for each useful unit of energy utilized. In fact, continued dependence on nonsolar energy might eventually require the reflectance of sunlight back out into space to preserve the heat balance of the earth.

Economics

There are no technical barriers to the development of power with heliostats. The technology is available and plans are for a contract to be written with an engineering firm this year to initiate final design and construction of a first system, although it will be expensive. Cost estimates for the first-of-a-kind 10-megawatt (electric) pilot plant, scheduled to be completed in 1980, are in the range of $7,500 to $10,000 per kilowatt of installed electrical capacity, including provisions for thermal storage for 6 hours of operation beyond sunset (*11*). No dramatic technical discoveries are necessary to reduce this prototype cost by a factor of 5 to bring it into a range comparable to the $1000 per kilowatt (electric) currently required for the construction and fueling of nuclear plants.

A significant cost reduction will result from the better collector and turbine efficiency associated with an increase in plant size to 100 or 300 megawatts (electric). In addition, specific mass-production approaches have been identified which are likely to lead to the required cost reduction for an integrated large-scale, dedicated heliostat production facility. One such production facility would produce heliostats for ten 100-megawatt (electric) plants each year. If a facility sized to produce only one plant per year were built in 1985, a second in 1988, and an additional full-size production facility were built each year from 1990 to 2000, about 40 gigawatts (electric) of installed capacity could be online by the year 2000. This capacity is enough to meet the anticipated requirement for new intermediate electrical load for the entire Southwest and would require a land area of about 1400 square kilometers (550 square miles). Development of economic storage could expand this market manyfold.

Assuming at least 785 megawatts of capacity is constructed each year in an integrated and dedicated plant with a 30-year life, the midpoint cost of installed heliostats in 1975 dollars is $66 per square meter. Under the same assumptions, the total capital cost of a plant is given, in 1977 dollars, in Table 1. The $1700 per kilowatt (electric) includes 6 hours of thermal storage (*12*).

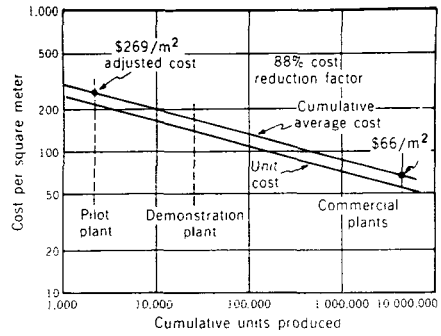

Fig. 5. Projected heliostat costs (1975 dollars). Mass-production learning would lower the average cost of $269 per square meter expected for the pilot plant heliostat to below $70 per square meter for commercial application after about 1 million units had been produced. This figure reflects projected cost reductions for a single facility resulting from integration of steel fabrication facilities, mirror and glass fabrication facilities, and experience-dictated improvements in plant operation, heliostat operation, and other factors. On the log-log scale, the upper line refers to the average value for all production to date, whereas the lower curve gives the cost projected for a single unit, which approaches $50 per square meter by the end of the production run of 25 to 30 years. (To convert to 1977 dollars multiply by 1.20.)

Once production of 100-megawatt (electric) units begins, costs would begin to drop as a result of learning curve effects. As an example, production of the first 10,000 Model T Fords resulted in an average cost, in constant 1958 dollars, of about $4000 for the cars produced in 1909. Continued cost improvement occurred in the manufacture of essentially the same car until 1927, at which time 14 million units had been produced. The cost for the last units of the production run was about $850 per unit (*13*). On the basis of this type of cost-reduction program, a reduction of 10 to 15 percent in the unit cost should be possible each time the total number of units produced is doubled until the bulk material costs predominate, and even then design refinements and new materials can further reduce costs. In Fig. 5 we show the anticipated learning curve for heliostats, where the upper curve represents the average cumulative cost for the entire production run and the lower curve is the unit production cost. Here $269 per square meter is the cost of the pilot plant and $66 per square meter is the average cost of heliostats produced by the plant after construction of approximately 20 gigawatts of capacity (1975 dollars).

Such a cost improvement permits us to put capital costs into perspective. A 10-megawatt (electric) pilot plant is estimated at $10,000 per kilowatt (electric) or less, whereas a first demonstration plant may cost $2500 per kilowatt (electric). To produce units selling in the range of $1700 per kilowatt (electric) requires that average heliostat costs, in 1977 dollars, be reduced to about $80 per square meter, which may require production of 5 million heliostats. In such a production run, the second million heliostats would already meet the cost requirements, having an average production cost of about $78 per square meter, whereas the first million would have an average cost of about $100 per square meter. Thus, the excess cost of the first million heliostats, each about 40 square meters in area and having an excess cost of $20 per square meter, is about $800 million. Compared to the expected cost of oil imports for 1977 of $40 billion, this is truly a small differential, which incidentally, will be paid back by even lower heliostat costs for the last 3 million heliostats produced in our hypothetical run of 5 million.

Since the cost of the heliostats is approximately half of the total cost of the commercial plant, less than $2 billion investment (subsidy) is required to stimulate a new technology that will integrate into the present utility structure. This amount should be compared to nuclear energy investments, recent space ventures, annual deficit of payments, 1976 oil import costs of $35 billion, and future escalation of oil costs.

There is sufficient unused desert land available in the United States to meet all of our energy needs by means of solar tower plants, an option not likely to be exercised. Energy production by solar towers would have an efficiency factor for land usage which would compare favorably with that of any renewable system presently under consideration. At a cost of $2000 per acre ($4900 per hectare), the land cost for a 100-megawatt (electric) plant is only $17 per kilowatt (electric).

Another indirect economic criterion is the energy amplification factor (EAF), defined as the useful energy produced over the useful life of a device divided by the capital energy required to create the device. Table 2 records an estimate of the energy required to produce materials, including transportation energy in manufacture and delivery, for the thermal component of a solar tower concentrator. Because this energy may have to be processed through a thermodynamic cycle with an efficiency of about 1/3, the collection time translates to less than 1 year. With the addition of the energy costs for fabrication, construction, and miscellaneous expenses, we expect the final required energy figure to be equivalent to less than 1.5 years, giving an EAF

Table 2. Material and transportation energy requirements for a 100-megawatt (electric) commercial solar tower system (fabrication and construction energy not included).

Part	Material (*12, 15*)	Weight (metric tons) (*12, 15*)	Energy required [megawatt-hours (thermal)]	Days to collect total energy	
				Thermal	Electric
28,605 heliostats (each 30.4 square meters)	Steel	23,084	144,055 (*18*)		
	Glass	13,959	45,196 (*16*)		
	Concrete	69,224	22,312 (*18*)		
	Sand	100,003	4,291		
	Polyurethane	257	715		
	Motors (copper)	372	8,152		
Receiver	Incoloy-800 and structural steel	1,127	7,655		
Riser and downcomer	Steel	182	1,135		
Tower	Concrete	41,757	13,517		
	Steel	1,266	7,899		
				70	210
Estimated transportation costs (*15*)			55,053	15	45
Total			309,980	85	255

of approximately 20 for a useful life of 30 years. This estimate can be compared to estimates for nuclear plants described in ERDA 76-1, where the EAF of a nuclear plant is estimated as 4 (*14*). Incidentally, the duty factor of the nuclear plant is taken realistically as 0.61, only 50 percent above the 0.41 expected for the solar plant with 6 hours of storage discussed here.

There still remains the energy cost of disposing of radioactive wastes and of shutting down a reactor after its useful life and safely disposing of the radioactive debris, whereas the steel used in heliostats can be reprocessed. The EAF factor clearly indicates a constraint which must be considered when deciding to build either nuclear or solar plants if the total fossil fuel requirements of the country are to be reduced over the next 25 years rather than expanded. The question of long-term economics requires the consideration not only of present dollars and capital development but also of long-term commitments to ensure both the availability of reliable sources of energy and the preservation of the environment.

The quantity of materials required in the solar tower design helps us to understand the economics of solar energy (Table 2). The heliostat cost of $66 per square meter appears reasonable if the cost of construction approximates $1 per pound or $2.25 per kilogram (for metal and glass). This represents an achievable goal, particularly if we realize that one can buy domestic pickup trucks in this country that sell for a little less than $1 per pound, and that a truck is a far more complex unit than a heliostat.

The cost of intermediate (load-following) power produced with the tower concept is estimated in the range of 80 mils per kilowatt-hour, based on a capital cost of $1700 per kilowatt (electric) and operating costs. We believe this cost is competitive. A charge of 30 percent was used for development of capital (the construction period is assumed to be 3 years), and the construction costs were amortized by means of a linearized fixed fee of 16 percent per year. Learning curve experience will lead to still lower capital costs for later production. The escalation of fuel costs will have no first-order effect upon constructed solar plants.

Conclusions

The estimated capital cost per kilowatt-hour of $1700 for solar tower plants is competitive with other means of energy production, such as hot-water nuclear reactors, including the complete fuel cycle. With 6 hours of thermal storage, the capacity factor is better than 0.41 compared to realistic capacity factors of 0.61 for nuclear reactors. Production costs seem reasonable, and there are no critical shortages of materials. Although there will obviously be improvements in design and management which will scale down costs, no radical technical discoveries are needed to construct and operate a solar energy plant. Once heliostats are in mass production, solar plant construction periods of only a few years are anticipated. The period for the construction of the pilot plant including final design is estimated at less than 3 years.

Most countries are in need of a long-range economic and political plan involving private enterprise and the federal government to develop a process for the national use of solar energy during the next hundred years. A national commitment would reduce the investment risk involved in building the first solar tower facilities. The greatest potential exists for adopting new technology in the utilities, but U.S. regulations essentially forbid the utilities to invest in new technology until it is proven over a period of time. Development of solar energy can reduce U.S. oil imports as well as help undeveloped countries that have no exports to offset the need for oil imports. A stable energy future demands that we examine all the energy options available.

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19. This work was supported in part by the University of Houston and NSF/RANN grant SE/GI-39456, ERDA grants AER73-07950 A03 and EG-76-G-05-5178, and ERDA contract E(04-3)-1108 with G. Kaplan as program manager. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of either ERDA or NSF.

Power from the Sea

The oceans, covering three fourths of the globe, are our largest solar energy storage reservoir. But because of their size they store all that energy without much change in temperature. The problem of ocean thermal energy conversion (OTEC) systems is to extract that energy without the aid of the high temperatures that assist heat exchange.

Power From The Sea

BY MARK SWANN

Twenty-four hours a day

ONE OF THE most tantalizing potential energy sources in the world today is relatively unknown to the general public – it is *sea thermal power,* a method of producing energy by using heat engines to harness the small temperature variations between the sun-heated surface of the tropical seas and the cold deep water.

Sea thermal power is by far the ocean's greatest renewable energy source, being replenished daily by solar radiation. One team of researchers has estimated that this power source is capable of providing, on a continuous basis, 200 times the earth's total power needs in the year 2000.[1]

There is one great difference between sea thermal power and other solar energy technologies: Because the surface of the tropical seas never falls below 78 degrees F. at any time, it will be possible to operate sea thermal power plants at full output, or close to it, for 24 hours a day year-round. That is, since the ocean's surface waters act as a vast repository of solar heat, sea thermal plants will not require heat storage capacity in order to produce power during periods of little or no sunlight. Down time (when plants are not in operation) will therefore be limited to periods when major repairs and maintenance must be undertaken.

All other proposed systems for use of the sun's energy (with the exception of arrays of solar cells orbiting in space beyond the earth's shadow and outside its atmosphere) require some means of storing heat or electricity. Such a constraint increases plant costs in two ways: First, the solar collectors themselves must be several times as large in such systems as in a system which requires no storage. Solar collectors in the Arizona desert, for example, receive useful solar heat for about 8 hours a day. If such a system is to provide energy for 24 hours a day, it must have three times as much power capacity as one which operates continuously day and night. Second, if a highly efficient storage and retrieval system is used, it is very expensive. In a small windmill power system, for example, the cost of the battery storage component is usually 50 percent of the total cost. In a large power system, a cheaper, less efficient (about 50 percent) storage system would probably be used. The power capacity of such a system would have to be further increased, in order to supply the additional power lost in

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Since the ocean's surface waters act as a vast repository of solar heat, sea thermal plants will not require heat storage capacity in order to produce power during periods of little or no sunlight.

retrieval. Limits on available amounts of sunlight constitute probably the most important obstacle to widespread solar development. (Of course, if a solar power system is intended for peak power demands only, which usually occur during daylight hours, storage is not necessary.)

How It Works

The heat engines in sea thermal plants transform heat energy into the mechanical work of spinning a turbine. Heat engines in fossil-fueled and nuclear power plants perform the same operation. In both cases, generators are connected to the turbines to produce electricity.

The main consideration here is the step involving transformation of heat energy into mechanical energy to drive the turbine. According to the second law of thermodynamics, heat can be transformed into work only while it flows from a hotter "heat source" to a colder "heat sink." In a steam turbine powered by oil or coal, fuel is burned to provide heat, and the natural outside environment is the heat sink. The burning fuel heats the water in the boiler, producing steam (the working fluid), which expands and is driven by the rush of heat to the heat sink. The turbine, a special kind of wheel, or series of wheels, with vanes or buckets mounted on it, harnesses the rushing steam. Some of the steam condenses into water as it gives up energy in the turbine. Remaining steam is condensed in the heat sink, also called the condenser (see Figure 1).

This entire process is what is meant by harnessing the *variation* between two temperatures. The application of this principle to the ocean's stored heat was first suggested in 1881 by Jacques d'Arsonval. One of his students, Georges Claude, went on to build a small working sea thermal plant on the coast of Cuba in the late 1920s.[2]

While steam is the working fluid in a steam turbine, Claude used warm sea water as the working fluid in his sea thermal plant, a method now referred to as the Claude process, or the open cycle method. The problem with the Claude process, however, is that the air pressure on the warm water must be lowered to a point where vapor will form which can propel a turbine. Water vapor, however, has a low density which requires that the turbine have a proportionately large area of vanes. Such a turbine for a commercial plant would be inordinately large, expensive, and difficult to maintain. An open cycle turbine for a 100-megawatt sea thermal plant, for instance, would have to be more than 40 feet in diameter.

An alternative to warm water would be a type of working fluid which vaporizes (boils) at the upper reaches of the given temperature range, yielding a high-density vapor, and, of course, condenses in the lower end of the range (as in an ordinary refrigerator). Warm

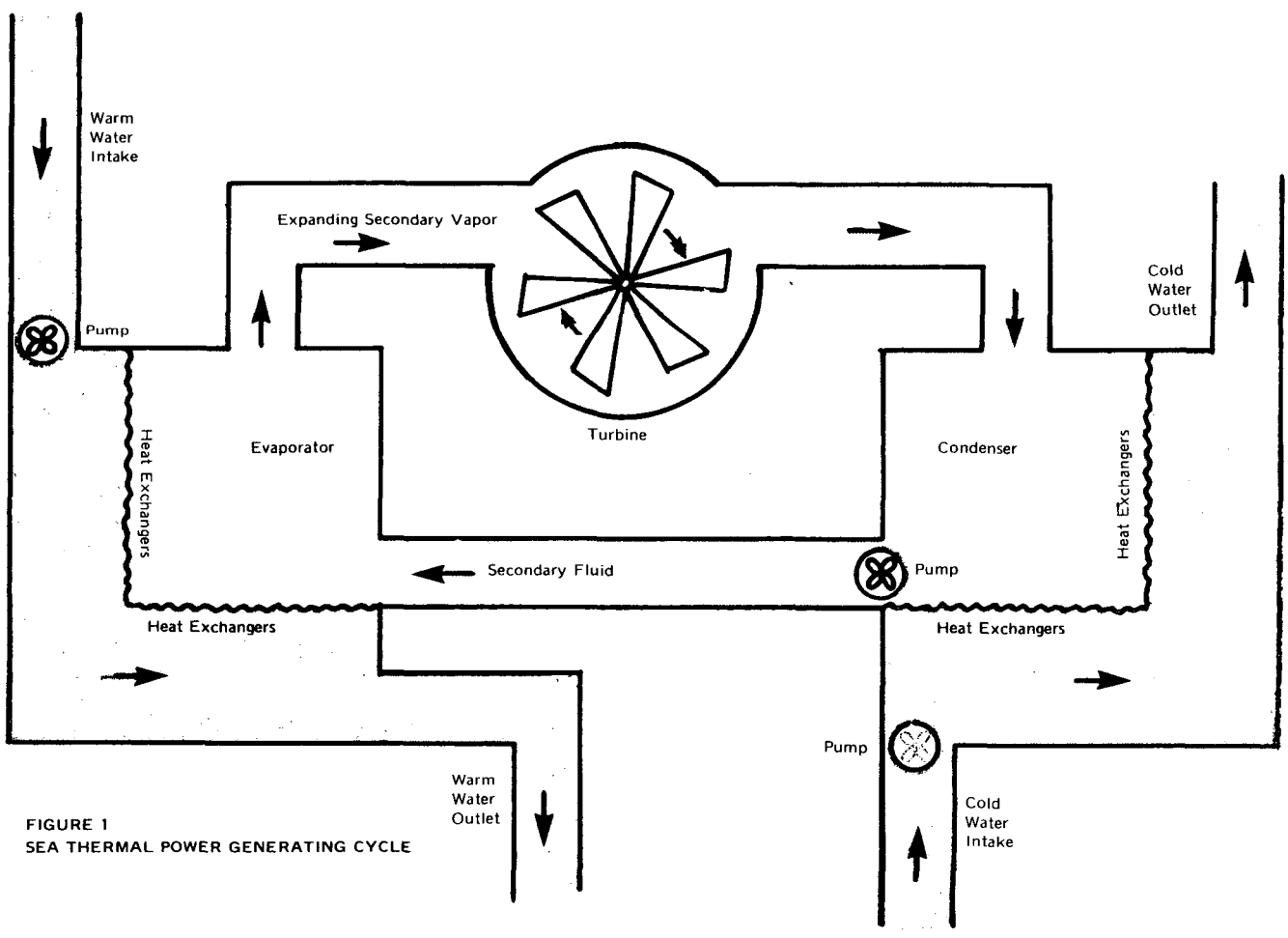


FIGURE 1
SEA THERMAL POWER GENERATING CYCLE

and cold sea water would then be used alternately to vaporize and condense the working fluid. Turbines for the working fluids – of which ammonia and propane are two possibilities – can be approximately one-tenth the size of an open cycle turbine.

The use of a working fluid other than vaporized sea water, however, presents its own problem: Heat exchangers must be built into the plant design. A heat exchanger is simply a surface – usually metal – which separates the working fluid from the heat source and the heat sink, permitting the heat to travel from the source (in this case, warm sea water) through the working fluid (a more volatile fluid) and into the heat sink (cold sea water). There are many technical difficulties associated with the design of efficient heat exchangers for sea thermal plants. These will be discussed later in connection with plant construction costs.

Finding Warmer Waters

The general location of the sea thermal resource is, roughly, the 1,700-mile-wide area around the equator between the Tropic of Capricorn and the Tropic of Cancer. The ocean covers 90 percent of the earth's surface in this equatorial region. Some of the most promising areas for sea thermal development are the South Atlantic Equatorial Current area, the Gulf of Panama, Micronesia, and the northwest coast of Australia south of Java.[3] Other areas with usable temperature variations are the sea around Hawaii, most of the Caribbean, the Gulf Stream off the east coast of Florida, the Gulf of Mexico, the Arabian Sea, the Indian Ocean, the East Indies, and the Atlantic Ocean of the coast of West Africa.

One of water's most important properties in this application is that it forms relatively stable isothermal layers – layers determined by temperature and density – which can be tapped for sea thermal power without significant disturbance. The combination of this property with the global pattern of ocean circulation forms the physical and environmental foundation for sea thermal power. In general, warm water flows away from the equatorial regions while cold water from the polar regions flows under it toward the equator. In the Gulf Stream off the east coast of Florida, for example, warm sea water flows northward in a current more than 100 feet deep at a rate of 27 million tons per second with cold water flowing southward just beneath it. As the cold water reaches equatorial regions, it is heated, its density decreases, and it rises to the surface to begin its flow toward one of the poles. The reverse process takes place with warm water reaching the polar regions. This vast ocean circulation guarantees the renewability and reliability of sea thermal power's heat sink.

Cost Factors

While nuclear and fossil-fueled plants operate with artificially induced temperature variations of hundreds of degrees, sea thermal plants must operate on small, naturally occurring temperature variations (30 to 40 degrees F.). A fundamental law of thermodynamics is that, given a heat source and a heat sink, there is a maximum theoretical amount of useful work output. With a large temperature variation, the maximum theoretical amount is close to 90 percent; with a smaller variation, it is less than 10 percent. However, the *actual* amount of useful output is approximately half of the theoretical amount. Hence, a sea thermal plant will only yield about 2 to 4 percent efficiency in actual operation, while nuclear and fossil-fueled plants yield 30 to 40 percent. For many years, this extremely low efficiency discouraged many investigators of sea thermal prospects. What these investigators perhaps failed to consider is the total economics of the power source; if the fuel is free, the efficiency factor changes significantly.

With the costs of all conventional fuels continuing to escalate since the 1973 Arab embargo of crude oil, alternative energy sources have been more closely examined than ever before. Two years ago, the National Science Foundation (NSF) and the Energy Research and Development Administration (ERDA) awarded large grants for parallel feasibility studies of sea thermal power to two aerospace companies, TRW, Inc., and Lockheed Missiles and Space Company, Inc. These studies resulted in cautious corroboration of the conclusions of earlier pioneering studies: Sea thermal power is technically feasible and commercially promising.

The TRW feasibility report included close examination of the cost estimates of three different sea thermal research groups. One of the report's major conclusions was:[3]

"The TRW team has conservatively estimated capital costs of proponents' concepts, based on present technology in equipment, materials, and fabrication. A range, in 1974 dollars, between $1,400 per kilowatt and $1,700 per kilowatt spans the proponents' concepts. These figures are higher than proponents' estimates, all of which appear to *reflect significant economies resulting from technology development.* If the TRW estimates are regarded as reflecting present technology, the proponents' estimates would seem to give incentive to OTEC [ocean thermal energy conversion] technology development."

By comparison, estimated construction costs of nuclear plants planned for 1985 operation will range between $830 and $1,000 per kilowatt. Coal-fired plants, including devices to reduce emissions of sulfur dioxide and particulates, will cost about $750 per kilowatt to build. Both must buy fuel. Electricity from these nuclear plants will cost at least 37 mills per kilowatt-hour; electricity from the coal-fired plants will cost about 44 mills. Electricity from the sea thermal power plants may be as low as 25 mills per kilowatt-hour.

ERDA's position, based on the TRW and Lockheed studies, is that sea thermal power will be commercially attractive if the predicted capital costs can be cut from the estimated $1,400-to-$1,700 per kilowatt to about $1,000 per kilowatt. Research teams at the Johns Hopkins Applied Physics Laboratory, the University of Massachusetts, and Carnegie-Mellon University all believe the $1,000 figure is achievable.

Clarence Zener, professor of engineering at Carnegie-Mellon University and a leader of the sea thermal team there, believes that the cost of one of the most expensive items in a sea thermal plant, the heat exchangers, might be cut in half if specially designed surfaces to improve heat transfer were used – an improvement which would make possible the use of heat exchangers with a smaller surface area. While some experts estimate the exchangers to constitute 26 percent of the total cost of sea thermal plants, others estimate the cost at more than 50 percent. Thus, a significant cut in the cost of the heat exchangers could greatly reduce the construction cost of the entire plant. Most researchers agree that the development of low-temperature heat exchangers, a relatively new field, presents the greatest challenge in the field of sea thermal power.

Unlike conventional heat ex-

The heat engines in sea thermal plants transform heat energy into the mechanical work of spinning a turbine.

changers, sea thermal exchangers must handle enormous quantities of water – about 13,000,000 gallons per minute in a 100-megawatt plant. The area of the exchangers must be correspondingly large, running into millions of square feet. Since the available temperature variation is small, the efficiency of heat transfer must be high. While the heat exchangers in sea thermal plants are not required to withstand the high temperatures characteristic of nuclear and fossil-fueled plants, they must be able to resist corrosion by sea water. Fouling by marine organisms (slime and barnacles) could also be a very serious problem. Mechanical or chemical cleaning may be too expensive, as well as possibly harmful to marine life in the surrounding water. The choice of materials and design for heat exchangers must take all of these problems into consideration.

Yet another consideration is the differing characteristics of sea water in different locations. According to a privately funded feasibility study, performed for Sea Solar Power, Incorporated:[4] "Site selection is extremely important to the generation of trouble-free power. . . . The ideal site should have a gentle, directional current and an absence of fouling organisms and corrosive elements in the sea water."

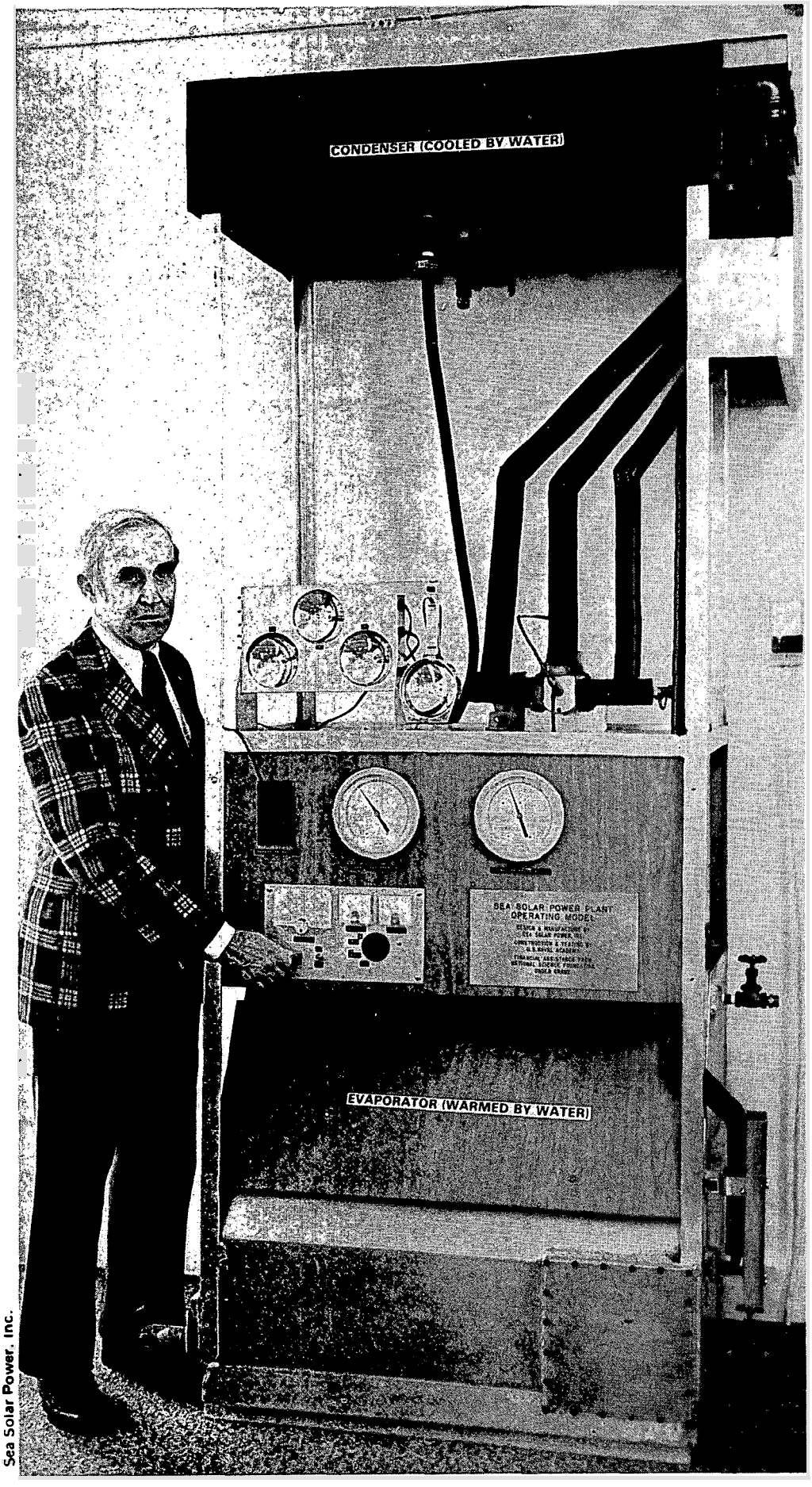
The longevity of the plants and the reliability of power generation are two more aspects of the costs. Other specific economic factors will be discussed later.

Going to Sea

Most of the construction of sea thermal plants will be done in shipyards. Tugboats will move the plants to their sites. Cold-water pipes could be floated to the sites in telescoped form, as has been proposed by Lockheed, to be installed and extended there, or hauled to the site in sections for on-the-spot assembly.

According to a member of the TRW research team:[5]

Electricity from nuclear plants will cost at least 37 mills per kilowatt-hour, from coal-fired plants, about 44 mills, and from sea thermal power plants, possibly as low as 25 mills.



Sea Solar Power, Inc.

"In contrast with land-sited power plants, the opportunities for cost savings through replication are significant. An analogy, in terms of design and construction, is shipbuilding: Identical OTEC plants might be constructed in quantities constrained only by demand and production capacity."

Zener pointed out some years ago that the principles at work in sea thermal power do not involve advanced technology but, rather, "sophisticated plumbing."[6] A large part of the escalation of capital costs of nuclear plants has been laid to increasingly stringent safety and environmental standards. Sea thermal power, because of its intrinsic safety and ecological acceptability, will not be similarly affected.

The job of stationing a sea thermal plant on site involves problems of ocean engineering. The greatest challenge here is probably presented by the cold-water pipe, which must have a very large diameter (at least 40 feet) in order to decrease expensive pumping requirements. The pipe must be from 1,000 feet to 4,000 feet in length, depending on the site, in order to obtain the coldest water possible. With the small temperature range involved, each degree of temperature difference is crucial; questions of economy, such as whether it is worthwhile to lengthen the pipe to obtain water which is one degree colder, will have to be decided on the basis of further research and experience.

Several types of cold-water pipe have been proposed: concrete pipe resting on the ocean floor, telescoped concrete sections with voids for buoyancy, welded reinforced aluminum, steel pipe with inner walls of smaller-diameter pipe, and reinforced synthetic pipes. Research is now being done to determine the static and dynamic loads on these various pipes.

Fiber-reinforced plastic, or nylon coated with neoprene and stiffened with steel rods, appear to be promising materials for the cold-water pipe. It is not clear at this point whether the technology has advanced far enough to enable such pipe to be constructed economically.

The size and construction of the plant's hull are also significant factors in determining cost and siting. TRW's and Lockheed's baseline concepts call for very large cylindrical and spar hulls of reinforced concrete which will house the turbines, the pumps, and the heat exchangers.

J. Hilbert Anderson and his son, James H. Anderson, two pioneers in the field and founders of Sea Solar Power, Incorporated, believe that a much more compact hull is possible if the heat exchangers are placed outside the hull at depths where the ocean's hydrostatic pressure equals the pressure inside the exchangers. If the Andersons' proposal is feasible, not only can the hull be significantly smaller, but the heat exchangers can have thinner walls (because they do not have to withstand internal pressure) and can therefore be less expensive.

Positioning the plants will probably be done with the use of jet streams of used warm water and cold water from the plants, another innovation first proposed by the Andersons. Permanently mooring the plants appears expensive and unnecessary.

The most formidable ocean condition is the "sea-air interface," where waves, winds, and storms can do much damage. The best strategy is simply to submerge a large portion of the plant to depths where the water is free of wave action. The resulting stability will be much greater than, for example, that of off-shore oil rigs. Maintenance, of course, is made more difficult, but most of the plant should be relatively maintenance-free. The periodic use of frogmen, if only for inspection purposes, is probably unavoidable.

Sea Thermal Products

Neither the TRW nor the Lockheed investigators were asked to study the question of energy delivery to shore. Yet energy delivery is obviously of great significance for sea thermal power because the best plant sites, generally speaking, lie far from the biggest users of electricity.

A very important factor which most investigators have come to realize is that forms of energy other than electricity must be produced if the use of sea thermal power is ever to become widespread. One such use, first proposed by William E. Heronemus, professor of civil engineering at the University of Massachusetts and head of the university's sea thermal team, is the production of hydrogen at the plants by electrolysis. Many experts consider hydrogen theoretically the ideal synthetic fuel: It can be mixed with natural gas; it can power fuel cells; it can be burned in power plants; and, unlike electricity, it can be stored cheaply.

Other investigators, especially G. L. Dugger at the Applied Physics Laboratory at Johns Hopkins University, have proposed the production of ammonia, an energy-intensive product usually manufactured from natural gas. Dugger would combine nitrogen removed from the air with hydrogen produced by electrolysis to make ammonia.[7]

The most ambitious proposal so far has been made by the Andersons:[8] Fresh water, marine food, carbon dioxide, oxygen, and nitrogen could be produced with relatively little power consumption. Hydrogen, methanol, and ammonia could be produced using on-site power.

Fresh water is produced by vaporizing some of the used warm sea water and then condensing it with used cold water. Only 1 to 2 percent of the warm water passing through the plant would ordinarily be made into fresh water, according to Anderson. In a 100-megawatt plant, this would run to about 150 million gallons per day. At 20 cents per one thousand gallons, the fresh water could earn $11 million a year. Fresh water can be barged very cheaply. And in areas where fresh water is more valuable than electricity or synthetic fuels, plants could be designed to produce much larger amounts of fresh water.

A portion of the nutrient-rich cold water will be sufficiently warmed in condensing the fresh water for it to remain near the surface of the ocean, where it can be used in food-related projects. An experimental mariculture farm based on nutrient-rich cold water has been in operation on the island of St. Croix for several years.[9] Depending on the required number of tons of water per kilogram of fish, income could range from $7 million to $80 million per year.

The Andersons propose to deaerate the warm sea water before sending it through the heat exchangers, in order to control fouling of the exchangers by aerobic organisms. The components of the removed air – mainly oxygen, carbon dioxide, and nitrogen, which are present in higher concentrations in sea water than in the air above – could then be separated by refrigeration techniques. The yearly income from carbon

Most researchers agree that the development of low-temperature heat exchangers, a relatively new field, presents the greatest challenge in the field of sea thermal power.

dioxide is estimated at $32 million; from nitrogen, $6.5 million; and from oxygen, $5.5 million.

The electricity itself would be worth $17 million at 25 mills per kilowatt-hour. If the electricity is used for electrolysis, the resulting hydrogen, at $1,900 per ton, is worth $33 million. Additional oxygen worth $6.5 million would also be produced.

The synthetic fuel, methanol, can be produced by combining hydrogen from electrolysis with carbon dioxide, but at current prices such production is not profitable. Ammonia, which can be produced by combining hydrogen and nitrogen, would cost $170 per ton to produce and, again, may not be profitable at this time.

If gases such as hydrogen, oxygen, carbon dioxide, and nitrogen – all of which have important industrial uses – are produced on sea thermal plants, it may be a natural step for the plants to act as bases for major refining and manufacturing processes. The possibilities of ammonia and methanol production have been mentioned. Both Anderson and Dugger have proposed locating aluminum reduction factories on board sea thermal plants or nearby on shore. Several countries with large bauxite deposits, such as Jamaica, are in the tropics near the sea thermal resource. Yet, currently, bauxite ore is transported as far away as Canada, where it is then made into aluminum – an energy-wasting proposition. (Primary production of aluminum in the U.S., incidentally, accounted for about 12 percent of the total 1975 industrial electrical sales.) ERDA and the U.S. Maritime Administration have made grants for the study of the potential of sea thermal industrial complexes.

The main product of the first sea thermal plants, however, will probably be electricity. Hawaii, Puerto Rico, and Florida have sites near centers of high demand for electricity. According to a privately funded feasibility study,[4] underwater cable power transmission is feasible, costing $13 million for a twenty-mile cable system, or 5 to 10 percent of the total capital cost of a 100-megawatt plant.

Environmental Effects

Because the use of sea thermal power does not require extraction of fuel from the earth or burning of fuel in its operation, many of the environmental effects, such as air pollution and radioactive contamination, associated with nuclear and fossil-fueled power plants are not present. Nevertheless, one direct consequence which has been suggested by the Andersons is the heating of the ocean. It might seem, at first glance, that just the opposite would occur; that is, that the ocean's temperature would be lowered because of the removal of energy from the water. The Andersons hypothesize, however, that removal of the warmest water from the surface and its subsequent release into the ocean's depths (a necessary step in the sea thermal process) will enable more solar heat to enter the surface water, thereby slightly increasing the total heat in the ocean.

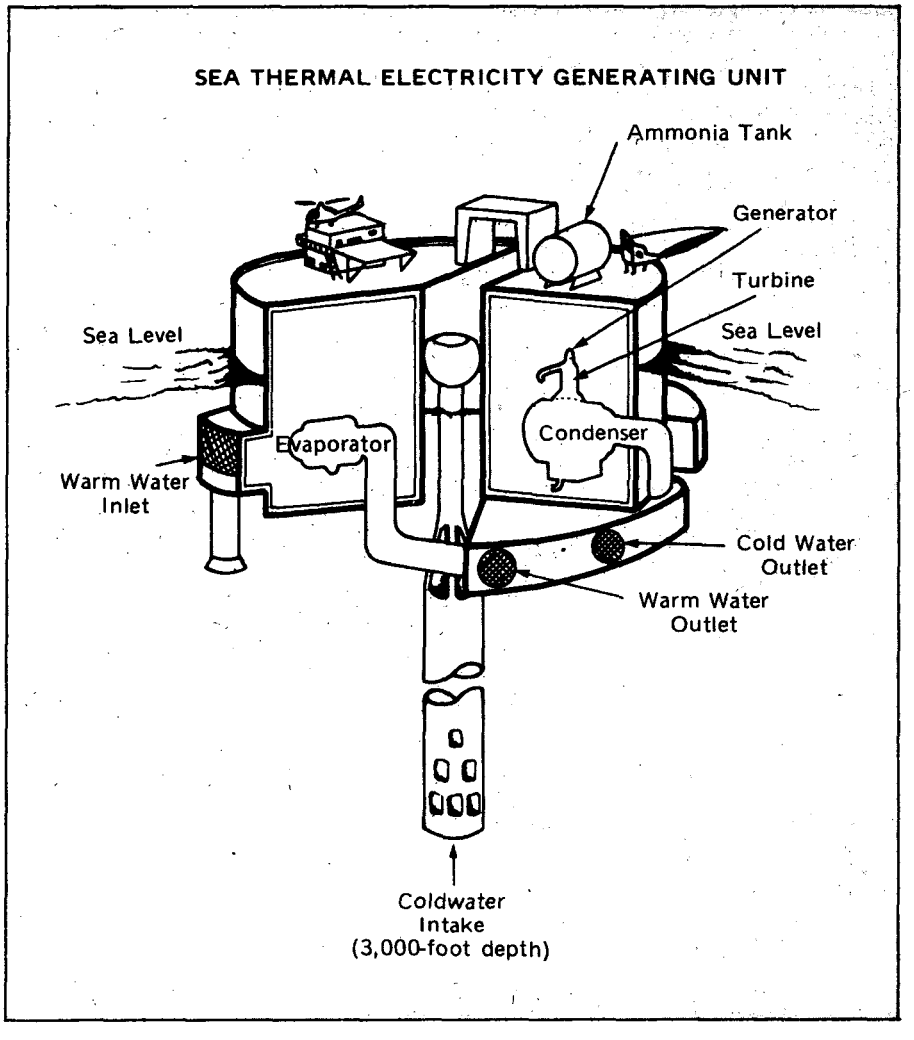
It should be stressed that the predicted temperature increases, even if the sea thermal resource were developed on a large scale, are so small that they can be measured in thousandths of degrees. Most other sea thermal investigators do not believe there will be any change at all in the amount of heat in the ocean. This, again, is an area which needs further study, both in regard to effects on marine life and on weather conditions. (Weather modification can be caused by even small alterations in the heat balance of the ocean.)

Another possible effect on marine life might be caused by a massive spill of the working fluid. Obviously, the effect would depend on the type of working fluid being used. Proposed so far are ammonia, the hydrocarbon propane, and any one of several heavy halocarbons. The possibility of such an accident occurring, and its consequences, must be considered.

As mentioned earlier, local fertilization will occur as the result of warming of cold water through its use as a condensing agent. This is considered commercially beneficial. Still, it is also a major ecological stress the long-range effects of which are not fully understood. ERDA is supporting studies in the entire area of ecological consequences of sea thermal power.

World Impact

The results of developing an entirely new energy source would naturally be significant, as well as varied and unpredictable. Sea thermal power's economic effects on the tropics alone will be profound. Economic growth has historically been harmful to ecological balance, causing depletion of natural resources and fouling of the air, water, and soil. Environmentalists have under-



standably come to the conclusion that the populations of economically advanced nations must begin to learn to "do with less."

In this light, the alternative of sea thermal power offers several advantages: For instance, its widespread use would require, in some measure, clean oceans. The presence of oil slicks could foul the exchanger surfaces, making efficient use of the resource difficult. Corrosive chemicals in the sea water could shorten the life of the heat exchangers.

Another point in favor of sea thermal power is that it taps constantly replenished solar heat instead of releasing the concentrated stored heat accumulated over millions of years. The Lockheed report states:[10]

"The approximate 3 percent of the energy that OTEC extracts from the sea water passing through it at one time is a small amount, to be sure. But the balance of the energy is returned to the ocean reservoir where it is augmented by the sun and can be used again later."

ERDA (and, earlier, the NSF) deserves credit for making sea thermal power acceptable as a possible new energy source. Since the research program began in 1972, the federal support for it has approximately tripled each year; and from 1974 to 1975, it quadrupled to $3,000,000.

J. Hilbert Anderson, the earliest modern innovator in the field, believes the technology exists now for the design and construction of a 100-megawatt sea thermal plant which could be in operation within four or five years. It is his opinion that only the existence of a completed plant producing significant amounts of power will provide sufficient motivation to launch an intensive development program. Once launched, he believes, sea thermal power will prove to be the most important technological advance of the twentieth century. □

The title of this article as originally submitted was "Sea Thermal Power." The publisher and editors of ***Environment*** *are responsible for the published titles and subtitles, selection of photographs and lead-in excerpts, photo captions, and preparation of most graphs and illustrations which appear in* ***Environment*** *articles.*

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Biomass Energy: the Promise and the Problems

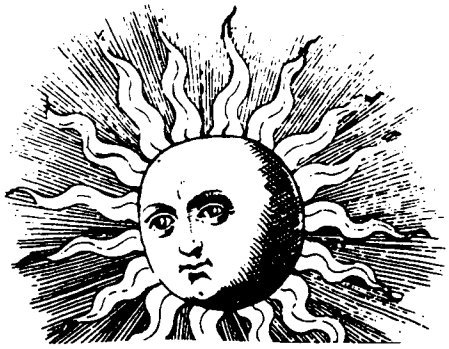
While urging research on and development of biomass-based energy, the author reminds us that the environmental impacts of such development should be carefully assessed as we go along.

Using Solar Power Captured by Plants

Biomass Energy

The Promise and the Problems

WILLIAM LOCKERETZ



SOLAR ENERGY usually brings to mind flat plate collectors, photovoltaic converters or other devices that transform the sun's rays into heat or electricity. Yet long before these conversion devices were invented, the sun supplied virtually all of the world's energy requirements without technological help. It did this through one of nature's most fundamental chemical reactions, the synthesis of carbohydrates from carbon dioxide and water in the presence of light—photosynthesis.

Besides directly producing food crops, photosynthesis has yielded firewood for warmth and for cooking. Animals that convert the energy in their feed have transported us, tilled our fields and turned grinding wheels. From animal fats we've made candles to light our dwellings. But with the advance of technology, these simple conversions of photosynthetic energy have been increasingly supplanted by their modern fossil-fuel-based counterparts: steam and internal-combustion engines, electric light bulbs and furnaces fueled by coal, natural gas or petroleum. Even food production, once the exclusive domain of photosynthesis, now involves considerable use of fossil fuels. Now, of course, the problems resulting from heavy dependence on fossil fuels have become evident. So there is considerable interest in finding ways to reverse this trend, and many methods are being developed for using the energy captured by photosynthesis—or, to use the more recent term, "biomass energy."

Biomass energy systems vary in the material that is the original energy source, in whether this material is produced primarily for energy, and in the process used to extract the energy in usable form.

Almost every type of plant can be a source of useful energy—trees, nonwoody perennials, cultivated annual or biennial crops, and freshwater and marine plants. Either the whole plant may be used, or only the residues after harvesting and subsequent processing steps; usable residues include cotton-gin trash, rice hulls and nut shells. And almost every type of plant can be transformed into a particularly rich and available potential source of energy—livestock wastes or, from humans, sewage sludge. Energy can be extracted, too, from municipal refuse, since much of it is paper, wood and related products.

Some of the materials used as biomass energy sources are produced primarily for that purpose—kelp grown in offshore energy "farms" is one example that has been given considerable attention recently. But many of these materials are processed for some other purpose, with energy a potential byproduct. Some materials, in fact, occur naturally and need only be collected to be usable energy sources. Gathering fallen wood in an unmanaged forest is at one extreme among the many ways of exploiting trees for energy. At the other is the ultimate extractive use of forests—coppicing, or harvesting whole trees at three-to-five-year intervals from special plantations. (With an appropriate choice of species, such a plantation will renew itself—new trees will grow from the stumps left after harvest.) An intermediate system would manage a forest primarily for lumber, in an environmentally responsible manner, while extracting energy from chips and such unusable residues.

Such cultivated crops as corn could be grown specifically as an energy source. But since corn grain is more valuable as food, a more advisable scheme would be to extract energy only from the ordinarily unused residues (cobs, leaves, and stalks) as an adjunct to normal corn production.

Energy can also be produced from naturally occurring aquatic plants. In fact, obtaining energy from a plant that would otherwise be a nuisance, such as the water hyacinth, is a particularly attractive possibility—it offers an economic incentive for clearing the densely growing hyacinth from clogged waterways. How-

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ever, with many aquatic plants, obtaining enough material to justify energy extraction would require intensified cultivation, as in the kelp farms.

Many processes can be used to obtain energy from plant materials or organic wastes. The most obvious is simply to burn them. But except for wood, direct combustion is generally not very suitable, either because the material contains too much moisture, because it is not clean-burning, or because it is too bulky to be readily transported to where it will be burned. However, what is regarded as unsuitable in an affluent society might be a necessity under other conditions. Nineteenth-century pioneers on the treeless Great Plains burned hay and dried animal dung for home heating and cooking, and dung is still important in countries such as India. When the price of corn fell to disastrously low levels during the Great Depression, American farmers sometimes burned corn because it was cheaper to do that than to sell it and buy coal.

Even in affluent and technologically advanced societies, there are some circumstances—generally when the material is a waste that has to be disposed of anyway—in which direct combustion is a practical and economical way of obtaining useful energy. The Hawaiian sugar industry not only provides energy for its own use by burning bagasse (wastes from sugar-cane processing), it even generates a surplus of electricity, which it sells to the state's utility company. The pulp and paper industry also derives appreciable amounts of energy from its own wastes.

But for most materials, some kind of processing is desirable to produce a more concentrated and clean-burning fuel. Some of the many possible methods have been in use for a long time. Fermentation of plants rich in sugar has produced alcohol since antiquity, sometimes (but not usually!) for use as fuel. When livestock wastes, crop residues and other organic wastes are digested by anaerobic bacteria (those that grow in the absence of oxygen), a gas is produced that contains methane, the main component of natural gas. Anaerobic digestion is also a common method of stabilizing sewage sludge, and for several decades European treatment plants have collected the methane thus produced. (In the United States, the methane is often used to supply at least the treatment plant's own energy needs.) Combustion of wood or crop residues in a limited oxygen supply produces a low-energy gas containing carbon monoxide and hydrogen. This process is similar to the old method of producing "town gas" from coal, which became obsolete with the abundance of natural gas. Gas made from wood was used in Europe during World War II because of severe motor-fuel shortages. This gas can also be converted to methanol, or wood alcohol—adding this to gasoline makes a more efficient, cleaner motor fuel.

Energy from biomass can also be obtained with more exotic techniques—some are in use now on a limited scale, and some are still being developed. In a process known as pyrolysis, organic materials are heated in the absence of air to yield a low-energy gas and a charcoal-like solid fuel. Or, to produce a liquid fuel from organic materials, they can be hydrogenated at high pressure. One of the most common forms of organic materials is cellulose, an important component of wood and crop residues, and this resists many of the simpler conversion processes. Now, considerable attention is being given to treating it with enzymes that break it down into sugars which can be fermented. Older techniques exist that use acids instead of enzymes to digest cellulose, but the sugar yield is much lower.

There is a natural tendency among researchers to work on whatever offers the most interesting research . . . while ignoring simpler approaches that could be applied right now.

Of course, not every combination of energy source material, production method and conversion process results in a practical (or even physically possible) system for obtaining biomass energy. Still, there are many systems already in use, or that give considerable promise of becoming practical after further research. Each of these systems has certain benefits and limitations. If biomass energy programs are to evolve in a rational way, the advantages and disadvantages must be taken into account, and priorities must be assigned to the various schemes. There is a natural tendency among some researchers to work on whatever scheme offers the most interesting research—usually the most technically sophisticated one—while ignoring simpler approaches that could be applied right now. Biomass energy development will not be served by the kind of thinking that, in conventional solar research, has led to work on microwave transmission of solar energy from satellites when as yet few homes have even simple solar water heaters.

Whatever disagreements exist among advocates of various biomass energy systems, methane generation from livestock manure by anaerobic digestion is near the top of almost everyone's priority list. Large quantities of livestock manure are constantly produced and must be disposed of in some way. The technology of methane generation is well established and, at least in simple form, is readily available. Thousands of methane generators are in use in India and other parts of Asia, although they leave room for considerable technical refinement.

Methane is produced by letting bacteria digest a slurry of manure and water in a vessel from which air is excluded. Through a complicated chain of biochemical reactions, some of which are not completely understood, the complex organic molecules are broken down first to simpler organic compounds such as acetic acid (the acid of vinegar), and eventually to carbon dioxide and methane. If a gas with a higher energy content is desired, this mixture, frequently called "biogas," can be purified into a form that is essentially the same as natural gas. Besides removing the inert carbon dioxide, purification takes out trace contaminants such as hydrogen sulfide that otherwise would interfere with certain uses of the gas. Livestock manures can be made to yield methane on any scale, from a simple farm operation with a few head of cattle to enormous digesters handling wastes from several thousand head in a commercial feedlot.

Methane production from livestock wastes illustrates an important dilemma concerning biomass energy systems generally: Maximizing energy production is not necessarily compatible with environmental quality. With interest in renewable energy sources increasing, it is sometimes assumed that "renewable" automatically implies "environmentally sound." Certainly the inverse can be true: Although many nonrenewable energy technologies, such as offshore drilling, stripmining and use of supertankers, are not environmentally sound, it would be a serious mistake to assume that the potential environmental

impact of biomass can be ignored just because the source is renewable.

With livestock manures, the conflict between maximum energy production and environmental protection arises because methane production has an efficiency of scale. Larger units are more efficient, especially in temperate climates where some of the methane must be burned to maintain the digester's temperature in the range required by methane-producing bacteria. Heat loss from the digester becomes less of a problem with larger facilities because of the decreasing surface-to-volume ratio. Consequently, net energy production is increased when livestock are concentrated into large feedlots or when the manures are collected from scattered smaller farms. In either case, one then has the problem of disposing of organic residues left in the digester.

On a farm, using the amount of organic material left from methane production is no problem; the material is very good as a soil conditioner and fertilizer, even better than raw manure. But the quantities accumulating at a large centralized facility might greatly exceed the carrying capacity of nearby agricultural land. Besides posing a potentially serious environmental threat, disposing of the residues by applying them to land at excessive rates or by means other than land application would be significant waste of a resource.

The same tradeoff occurs with systems that use plant residues left on the fields after harvest. Using all the available plant material will certainly maximize energy production, but it will also leave the soil unprotected against erosion and unreplenished by the decaying vegetation. Siltation and sedimentation from excessive erosion is a serious environmental problem in many areas and, what is even more significant, it indicates the loss of an irreplaceable resource. It would be ironic if, out of a desire to find substitutes for one nonrenewable resource, fossil fuel, we increased the loss of topsoil, a resource that not only is not readily renewable but, unlike fossil fuels, has no substitutes.

There is also tradeoff between technical efficiency on one hand and, on the other, the ease with which a system can be used (and thus the likelihood that it will be adopted). Because biogas generation is very sensitive to changes in temperature and in the quantity and composition of the manure supply, net energy production can be increased by using more sophisticated monitoring and control equipment and by devoting more attention to the system's operation. This may not pose a problem for a large, specialized facility primarily intended for energy production. On a farm, however, biogas production could only be a subsidiary activity. Presumably, farmers will not be interested in it if it requires too much care—especially during periods when their main concern is planting or harvesting on time. The design of biogas and other biomass energy systems is, unfortunately, sometimes approached only as an engineering problem, with little consideration given to the needs of the ultimate user. The system that works best when run by engineers under the highly controlled conditions of a laboratory or experiment station may not be the one most farmers would prefer. While farmers differ considerably in their attitudes towards risks and their willingness and financial ability to invest in expensive equipment, it seems likely that many would accept a lower net energy output in exchange for dependability, lower capital cost and relatively carefree operation.

Finally, there is the obvious question, how much of our energy budget can be supplied through biomass? If the supply of biomass is the only constraint considered, the answer is that all of our energy budget could be, although such an answer does not mean much. A better way to put the question would be, how much of our energy budget can be supplied through biomass with acceptable environmental impact, without excessive loss of other resources, and using systems that farmers and other users will find attractive? This question is much harder to answer; it is not easy to define "acceptable" and "excessive" and, even after environmental and other constraints have been agreed upon, it is still difficult to come up with a good estimate. But development of biomass energy need not be delayed until we have a precise answer to this question. We already know that biomass can supply enough energy to matter, certainly a lot more than we are getting from it now. Additional research will provide us with improved and more efficient systems. Available and appropriate technology, if put to use with adequate attention to environmental and resource factors and to the needs of eventual users, can make biomass energy a significant component of a sensible energy program. The most important question, therefore, is what are we waiting for? □

William Lockeretz is a research associate at Washington University's Center for the Biology of Natural Systems. He edited Agriculture and Energy *(Academic Press, 1977) and serves on the Alternate Sources Subcommittee of the Club's Energy Committee.*

Thought Snacks

Producing food uses energy, and the energy-intensiveness of some foods should give us pause. Here are the results of some hard thinking about what we eat and where it comes from.

What's your steak?

Thought Snacks

By Thomas Hanna

We'll venture a guess that until very recently most of us, when it came to thinking about food, hardly considered the energy involved. We were not much different from the city dude who thought that milk came from cartons not cows. In fact, 16 percent of the nation's energy is consumed to produce, process, distribute and prepare food for the table.

There is another form of energy involved in what we eat — just as real but usually unnoticed: solar energy converted and stored by plants as food. From the human perspective, this is a crucial process. The diffuse energy of the sun is concentrated into a consumable form at no cost and with no depletion of fossil fuel sources.

We also tend to forget that of the energy thus stored in our crops, a considerable portion will be converted again to generate animal protein, the *sine qua non* of the American diet: beef, chicken, pork, eggs, milk, butter, lamb and turkey.

Every form of energy conversion has waste built in. A familiar example is the automobile engine. About 80 percent of the available energy in gasoline goes out the pipes as waste heat: a disconcerting ratio of five Calories burned to do one Calorie of useful work.

Our use of energy to put meat on the table is even more inefficient than the internal combustion engine. An analysis of protein production by Cornell scholars David and Marcia Pimentel has documented the costs by measuring land use, energy and economic factors. David Pimentel, a professor of entomology and agricultural sciences, has been studying ecological considerations in agricultural practices for several years. Marcia Pimentel is a lecturer in nutritional sciences concerned with the implications of the food system for human nutrition. Their analysis of resources and the environment, prepared for the Ford Foundation, implies that the American diet may have to change in the future because of the energy crisis.

They point out, for example, that 90 percent of all plant protein produced in the U.S. that is suitable for human consumption is fed to livestock. And, on the average, it takes five pounds of edible plant protein, plus forage, to produce one pound of animal protein.

The energy ratios are even more dramatic. By the Pimentels' estimate, 36 Calories of fossil energy are expended in work on the farm for every one Calorie of milk protein produced.

A ratio of 36:1 fossil energy to protein energy is considered very favorable in animal protein production. Feedlot beef require 78 Calories of fossil energy to accomplish a similar protein conversion. Range-fed and pasture-fed beef are more efficient than their feedlot counterparts, converting protein at a ratio of 10:1. But their advantages are greater than the numbers imply. First, they require much less fossil energy than feedlot beef. Second, they eat plants that, for the most part, humans do not use as food. Finally, the best ranges and pasture lands are not well suited to growing vegetable crops for human consumption. The grain diet for feedlot beef, on the other hand, is grown largely on high quality cropland.

The Pimentels analyzed land use and found that one acre can yield about eight times as much protein from plants as it can from animals. Soybeans and potatoes are leaders in protein yield, with corn, rice and dried beans in the second rank (Table 1). Even the most energy expensive grain (rice, at 10:1) is 8 times as energy efficient in protein production as feedlot beef.

Table 1. Two measures of plant protein production efficiency

	Kcal of fossil energy/ kcal of protein	Kg of protein/ hectare
Soybeans	2.06	640
Oats	2.70	276
Dry beans	3.44	325
Wheat	3.44	274
Brussels sprouts	3.51	604
Corn	3.63	457
Potatoes	4.25	524
Rice	10.01	388

What do various sources of protein cost at the supermarket? The Pimentels calculated the retail price of 20 grams of protein (one-third the Recommended Daily Allowance). Bargains include dried beans, peanut butter and eggs. More expensive sources include fish, chicken, beef and pork. (Table 2).

Table 2. Cost of 20 grams of protein

Dry beans	$0.10
Peanut butter	.17
Eggs, large	.18
Bread, white enriched	.18
Hamburger	.21
Chicken, whole, ready-to-cook	.22
Milk, whole fluid	.25
Round beefsteak	.38
Rib roast of beef	.60
Pork chops, center cut	.62
Haddock, fillet, frozen	.65

Source: Agricultural Research Service U.S. Department of Agriculture 1977

From the Pimentels' work it could be said that we are in the habit of devoting our cropland to growing protein-rich plants suitable for our table, and feeding much of the harvest to livestock. In the process, we expend critical stores of fossil energy to support our diet of meat. We even pay for the privilege — willingly — with higher prices for favored sources of protein. And, on the average, we consume twice as much protein as we need for good health.

The Pimentels imply that such national behavior may be changing. In a paper delivered before the Institute of Food Technologists they noted:

"Pressure for energy, food, land, water, and other resources is significant

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even today. With the U.S. and world population projected to increase greatly during the next twenty-five years, shortages will become critical. Hence, it is important that research on various aspects of the food production problem, and particularly protein supply, be initiated."

They outlined five targets for research, each having obvious implications for public policy and agricultural practices.

Cropland Studies. Noting that urban and highway development alone have removed 36 million acres of excellent cropland from production, and that erosion of much of the 460 million acres left has already cost us about a third of our valuable topsoil, they call for careful study of cropland losses. Even more important, they say, is a sound program to protect and conserve our remaining agricultural lands for food production.

Relocating Production. The Pimentels documented our growing reliance on centralized food production. California produces and ships 95 percent of our broccoli, and 80 percent of our lettuce and processing tomatoes. About 96 percent of our rice is produced in Arkansas, California, Louisiana and Texas. Michigan, California, Idaho, Nebraska and Colorado account for 76 percent of our dried beans. Needed is an analysis of the relative energy costs of maintaining this system of production that relies on growing in the ideal location only to send it through an energy expensive transportation and preservation process. Would it make sense to encourage seasonal production in local areas, even if crop variety were limited? Behind the question the Pimentels find a problem with an implicit solution: as energy costs increase, what choice will we have?

Changing the Protein Diet. Imagine a time when you cannot expect to consume twice the protein you need because food shortages everywhere make such a practice more than just an American indulgence. Much less meat, eggs and milk. Less chicken. More beans, corn, potatoes and soybeans. More rice.

Dietary changes are slow to occur in any culture. The Pimentels encourage research that will make major changes in our diet possible, even though they recognize that our meat-oriented diet will be difficult to modify.

Grass-Fed Livestock. The Pimentels estimate that moving to an exclusively forage-based livestock production system would reduce animal protein production from six million metric tons annually to two million metric tons. To accomplish this, we'd need to switch from pork and chicken to range-fed beef, lamb, mutton and goat. They call for appropriate research emphasizing improvement of forage production and reduction of overgrazing.

Packaging and Processing. We called attention at the beginning to how much energy we devote to food production. Only 5 percent of our nation's energy goes to the production of what we eat. Another 5 percent goes into processing that food for the marketplace. The Pimentels note that three times the energy required for corn production is used to process and package it. They advocate more careful assessment of processing and packaging costs (in energy and dollars) in the hope that more energy efficient technologies might be developed.

Their own conclusion is:

"The critical interdependencies of food, population, energy and land use must be understood and more carefully examined if we are to assure that our nation and the world will be properly fed in the year 2000. Research goals in agriculture need to be redefined and constantly appraised. We have the talent to begin to solve food problems. But we must realize that we cannot afford to wait for a new decade to begin the job."

Other factors than energy are involved in food production, but energy may become a critical consideration in food bills and food policy as well. ◘

Gasohol: a Choice That May Buy Grief

In a world that continues to know famine, Lester Brown's question hits home: Will Americans run their cars on corn alcohol while the Third World goes hungry?

Gasohol: A Choice That May Buy Grief

It takes about one-quarter of an acre of cropland to provide food for the average person in the Third World. It would take almost 8 acres to grow enough grain to run an average American automobile entirely on grain-derived ethanol.

Would an American citizen drive his car at direct expense to the nutrition of people elsewhere? That the question can even be raised is the result of the national goal announced by President Carter in January 1980 to produce 500 million gallons of ethanol a year by the end of 1981. Once the distillery capacity for such a production volume is in place, a direct and possibly permanent link will have been created between the world markets for food and for liquid fuels.

The consequences of forging this awesome chain have been explored by Lester Brown of the Worldwatch Institute in Washington, D.C. "The price of oil could eventually set the price of food," is Brown's conclusion. As the United States and other agricultural producers develop the means to convert crops to fuel alcohol, farmers will have the choice of producing food for people or fuel for cars, and in the absence of government controls are likely to do whichever is more profitable. "The stage is set for direct competition between the affluent minority, who own the world's automobiles, and the poorest segments of humanity, for whom getting enough food to stay alive is already a struggle," Brown concludes in a new report.*

Proponents of gasohol, who have built a powerful lobby among farm state senators, contend that alcohol production from corn will not reduce the amount of food available because the protein content of the corn is untouched and can be fed to livestock. Brown observes that starch is also a valuable component of food. In any event, he believes, the worldwide use of crops for energy is "certain to drive food prices upward, thus leading to more severe malnutrition among the poor."

A year ago the Administration's gasohol policy was one designed to avoid any entanglement with the food supply. "Through the mid-1980's there appear to be sufficient surplus and waste raw materials to meet any realistic projected level of alcohol production. . . . There does not now appear to be a need to grow additional crops for alcohol production," concluded a Department of Energy review published in June 1979. Cheese whey, citrus wastes, and distressed crops would supply feedstock to distill 660 million gallons of ethanol a year.

In the wake of the January 1980 embargo on Russian grain sales, however, Administration spokesmen talked explicitly of converting the grain to ethanol, and announced plans to increase distillery capacity. These plans had been in preparation before the Russian invasion of Afghanistan, presumably in response to pressure from the gasohol lobby.

What will the distilleries use for feedstock? The embargoed Russian grain is not sitting in a big heap in Kansas: apart from one Administration purchase, the grain is still in private hands, and may yet be sold on world markets. The DOE calculation that 660 million gallons of ethanol could be obtained from wastes and spoiled crops is regarded as a gross overestimate in the Department of Agriculture. It seems likely that the new distilleries will use corn, and world food supply will be the less.

**Food or Fuel: New Competition for the World's Cropland.* Lester R. Brown. Worldwatch Institute, 1776 Massachusetts Avenue, NW, Washington D.C. 20036. $2.

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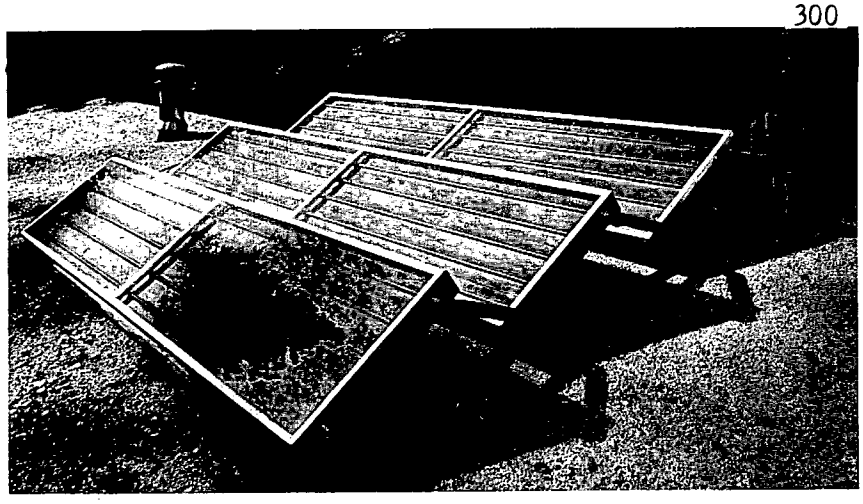
The Solar Wood Connection

Here's a wood stove with a difference: a wood stove domestic water heating system to back up your solar collectors. Details on costs, installation, and safety are included.



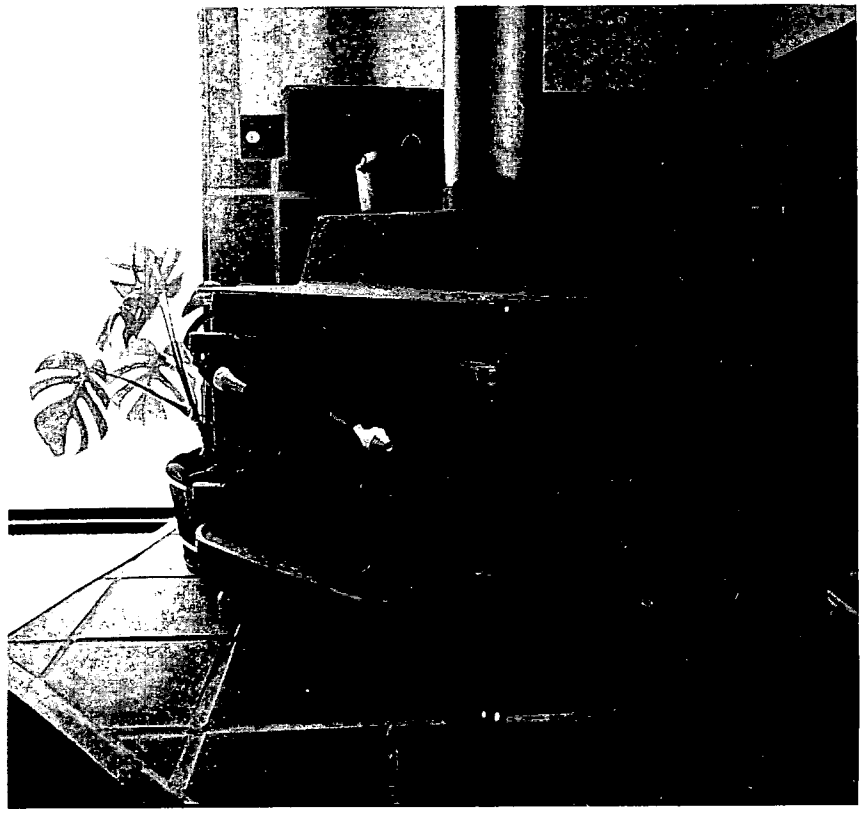
Sunworks/Healdsburg 2 x 10 collectors in a solar-woodstove domestic hot water system.

THE SOLAR WOOD CONNECTION

Plain know-how on solar-woodstove domestic water heating systems is scarce. Here is a rich new supply.

By Joe Carter and Richard Conrat

drawings by Barbara Putnam



Fisher "Grandma Bear" stove fitted with factory coil; thermosiphon system.

It doesn't take too much cogitation to figure out that wood stoves present as high a potential for domestic water heating as they do for space heating—their traditional role. In terms of the heat energy required, a cold-weather domestic water heating load is likely to amount to but a fraction (up to about 10 percent) of a building's space heating load over equal periods. The combined load will not overtax the capability of a stove or require a large increase in wood burning.

In terms of temperature, woodstove fireboxes contain relatively high-grade heat in developing "ambient" levels that are five to ten times hotter than useful hot water temperatures (120°-130°F). In terms of hardware, a little mind's eye plumbing draws a schematic whose simplicity will relieve the installer and whose economy will gladden the consumer (a double bonus for do-it-yourselfers).

Basically, this is old news. Wood burning and water heating have been partners for centuries, and the pressurized, open-loop system that we have experimented with is at least three quarters of a century old (roots: wood cookstoves and black pipe coils). Until lately, however, there was little known about woodstove water heating in the way we like to know about things nowadays—things like component sizing and system performance, and cost-benefit. Also in short supply has been plain operating experience; even a straightforward system has quirks that cannot be identified in advance. In mid-1978 we received funding from the Department of Energy's rivulet of support for small groups studying appropriate technology. The project, Optimized Solar-Wood Stove Domestic Water Heating Sys-

Joe Carter is with Rodale Press, Book Division, where he is writing and editing a book on do-it-yourself solar retrofitting and remodeling, to be published in early 1981. Photos are by project partner Richard Conrat of Healdsburg Sunworks, a California solar manufacturing, installing, and design group. Drawings are by Barbara Putnam, Harrisville, N.H.

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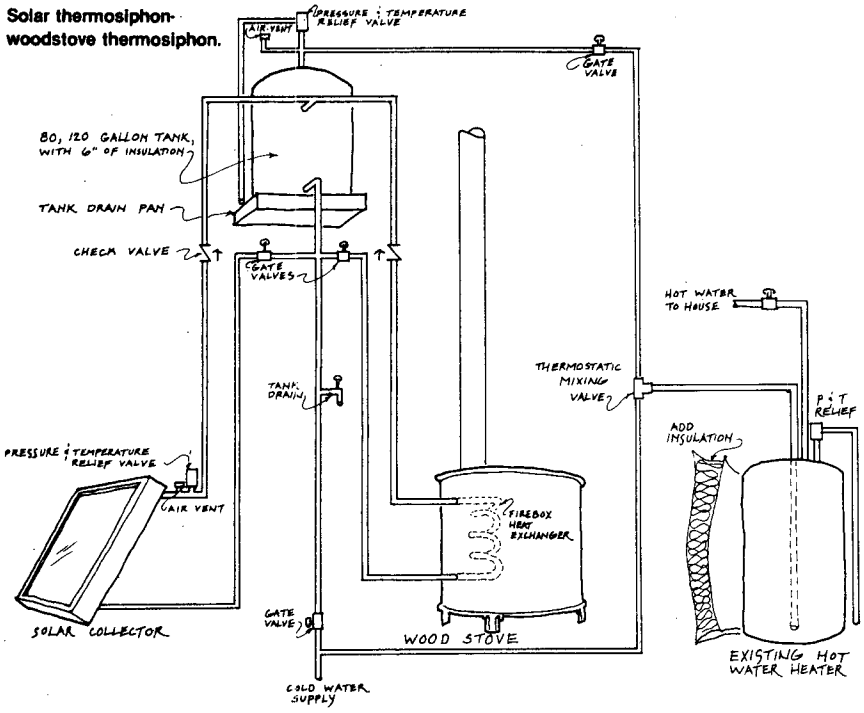
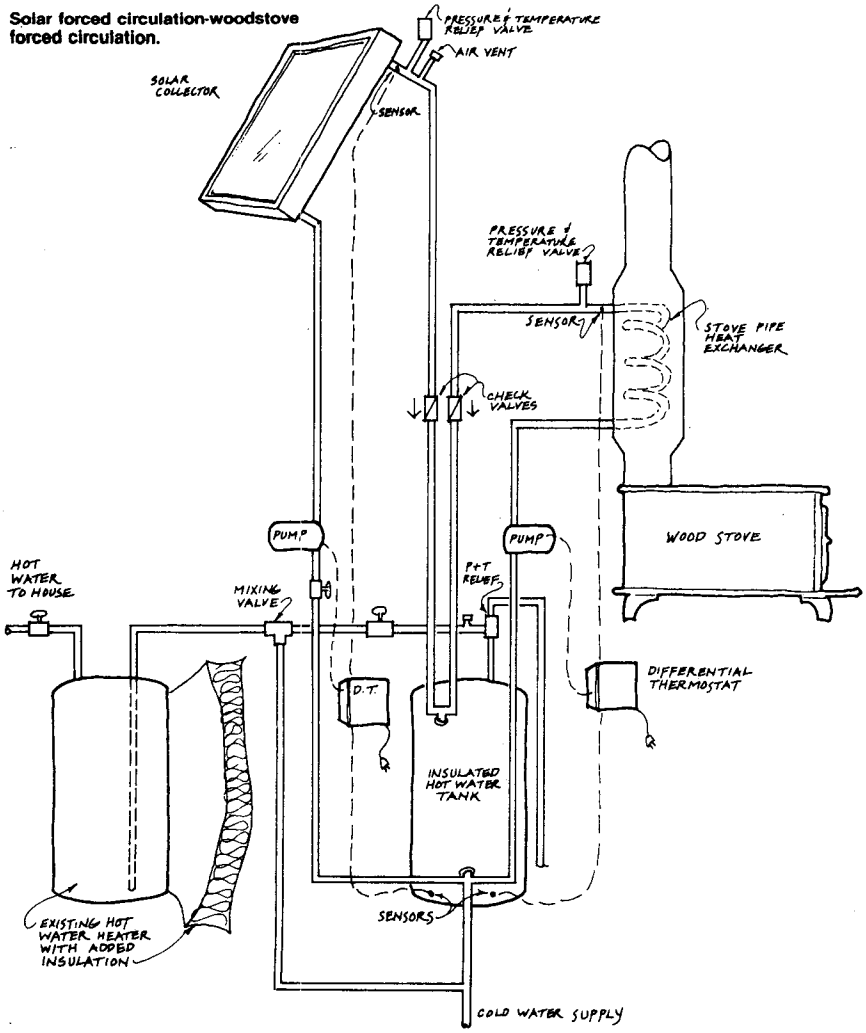
Solar thermosiphon-woodstove thermosiphon.



Solar forced circulation-woodstove forced circulation.



It is possible to tie the solar-wood heat sources directly into an existing water heater of at least 60 gallons, provided there is no more than 40 square feet of collector.

tems (DWHS), investigated the possibilites for systems that were fueled year round by renewable sources of energy. The solar-wood connection is a natural and obvious one to make, and it works very well. Since the solar component is very much a known factor, this article primarily discusses the woodstove DWHS, how it combines with solar, and the cost-benefit of the individual and the combined system.

The primary rationale for the appropriateness of the solar-woodstove application was that rural people, living away from supplies of natural gas, must heat their water with electricity or propane, yet are turning to wood for low-cost space heating.

These days, the woodstove market is strong even in suburban areas, where even at $50 to $100 a cord, wood still offers a lower-cost and more aesthetic alternative to oil and electric space heating (gas too, when it becomes fully deregulated).

The project

As the project was initially planned, four Healdsburg, Calif., area residences were to be retrofitted with variations of wood- or solar-woodstove DWHS. The variations revolved around water flow—whether by architectural circumstances or owner preference the solar or woodstove components were operated by pumped or thermosiphon circulation. (Two flow modes times two heat sources equals four possible systems.) These systems would be monitored with simple instrumentation and by other observations to learn about performance, operating characteristics, and about how much people could save. Local interest in the project resulted in a total of eight installations.

Also, several woodstove manufacturers were queried about their interest in the woodstove DWHS, and they donated twelve stoves to the project for heat exchanger retrofit and performance testing. A test facility (lots of pipe runs, valves, and a tank from a stripped water heater) was put together in the Sunworks workshop for this purpose, and the project became both a field and laboratory study.

The workshop was new and as yet unheated, and start-up of the test facility coincided perfectly with the onset of cold weather.

Researchers who are new to the research business can easily underestimate their need for instrumentation and for a budget. We did—a caution to other AT'ers. When we found ourselves establishing exciting research tasks and goals that were also very expensive, "appropriate" instrumentation became the byword. By begging, borrowing, and renting, as well as buying, we could study just about everything we were interested in: thermosiphon and forced circulation flow rates (float-type flow indicator); firebox and exhaust stack temperatures (pyrometers with chromel-alumel thermocouples); water temperatures at

several stations (12-channel electronic thermometer); pump and electric water heater on-time (elapsed time indicators); and total residential hot water consumption (totalizing water meter).

Flow meters that give a true reading of a thermosiphon flow rate (less than 1 gpm) in a 3/4-inch or 1-inch pipe, and that don't break the AT budget, are hard to locate. But we were pleased to be able to rent a Fischer & Porter series 10A-3500 "Flowrater" ™ from a Bay Area dealer. The float used to measure thermosiphoning (#1-GUSVT-611) was designed for a maximum flow of 1.3 gpm with a pressure drop at maximum flow of only 1.28 inches of water—perfect for our needs. The flow indicator was the heart of the instrument group. Flow rates correlated with temperature rises through the solar and woodstove components gave the essential data on Btu gain.

Installing the systems

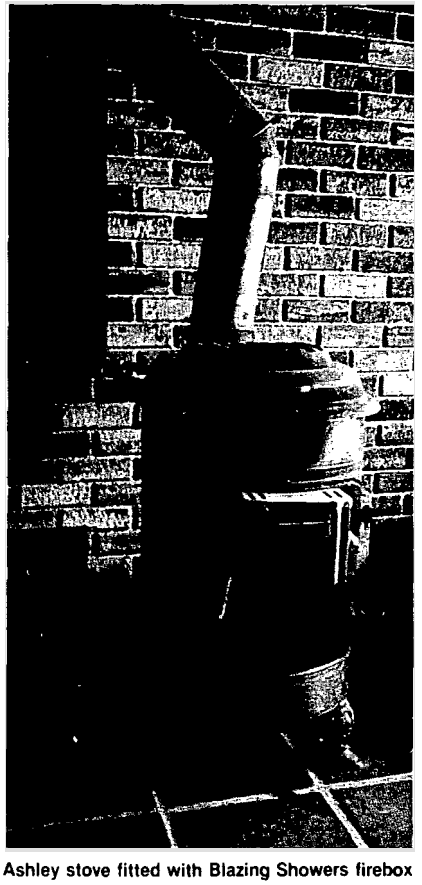
The woodstove DWHS for this study was a pressurized system in which potable water circulates directly from storage through the firebox or stack-mounted heat exchanger. The solar component is also an open loop system that employs circulation or "hot shot" freeze protection when a pumped system is installed. An all-copper absorber in a 2-foot by 10-foot module was used, and sizing was figured at one collector for two people with conservative use (10 to 15 gallons per person per day) and at up to two collectors for two people when there was a heavier water heating load.

Out of the eight installations, four were solar forced circulation—woodstove thermosiphon. This would seem to be one of the most easily applied combinations. Typically, the collectors were roof-mounted. With the stove set on the first floor, it was often most appropriate to place a storage tank in a second floor closet, or in an attic or a rafter crawl space. (A nice synergism: since the wood stove is to be primarily a cold-weather water heater, the collectors can be mounted closer to the horizontal than the standard "equal to your latitude" rule of thumb. This makes for greater efficiency in warm-weather operation when solar altitudes are higher.)

A water tank installed over a living space should be set into a safety drain pan to be ready for the day a leak springs, a fitting fails, or the tank must be drained for system servicing. A hose leads from the pan to the outside or to a drain.

Galvanized pressure tanks were used for the combined solar-woodstove storage, and the size used for smaller systems (no more than 40 square feet of collector) was 80 gallons. When 60 to 80 square feet of collector was installed, a 120-gallon tank was used. These sizes have proved to be quite adequate, even when the solar and woodstove components are in day-long simultaneous operation. With either tank size, a rope, ladder, and muscles, grunting and wriggling are the primary installation tools.

When tank location allowed for a woodstove thermosiphon loop, the main challenge was to conceal the plumbing. Hiding the plumbing as soon as possible after it took off, and up from the stove, variously involved lifting wall paneling, snaking pipes through once-thought-impossible places, camouflaging pipe insulation sleeves with matching wall paint, and other strategies. On the hardware end, it was at first thought that 3/4-inch i.d. pipe (type M copper) was suitable for thermosiphon loops. Testing showed that 1-inch i.d. pipe gave higher flow rates (a 150 to 300 percent increase up to .6 gpm) and, therefore, more efficient water heating. The same is true in the case of the solar thermosiphon loop. If the layout of the thermosiphon loop didn't conform to the classic rule of thumb (straight-up-and-down), a good working flowrate could still be achieved.



Ashley stove fitted with Blazing Showers firebox coil; thermosiphon system.

In operation the increased thermosiphon flowrate afforded by the 1-inch pipe also helped put an end to a chronic "cycling" problem. In the 3/4-inch loop, water flow would nearly stagnate for a couple of minutes and then suddenly rush through the loop—it had actually steamed in the heat exchanger. The flow would return to near stagnation, and the cycle would start again. With the 1-inch pipe, there is usually one "boil off" at the start-up, which initiates flow and flow direction (sometimes the hot water wasn't sure which way it was supposed to go—some kind of static inertia), whereupon a stable, consistent flow is established. In heat exchangers with relatively high surface area-to-volume ratio (10 in a range of 2 to 10), such as a coil made from 1/2-inch i.d. type L copper, a consistently hot fire could cause infrequent local boiling. Pumped woodstove DWHS experienced none of this cycling. The 1/100 hp pumps developed 1.5 to 2 gpm flows, which effectively cleared the exchanger of heat. Consequently, the pumped system was uniformly higher than the thermosiphon efficiency in terms of hot water output.

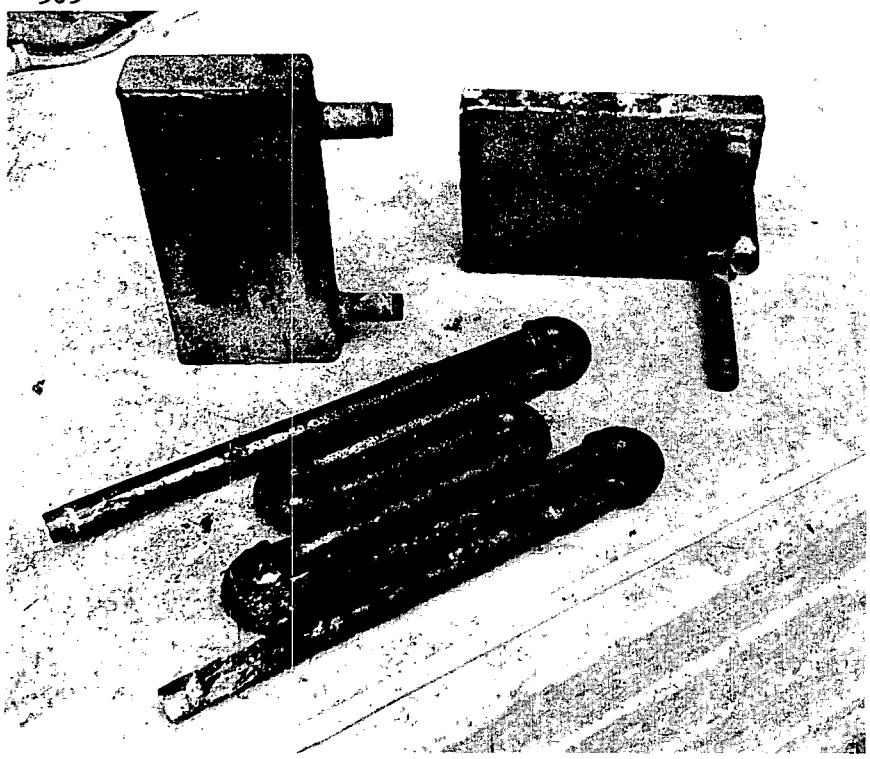
Safety

Because of high temperatures involved with the woodstove DWHS, safety is an important point. At first it was thought that a pressure-and-temperature relief valve should be installed near the thermosiphoning heat exchanger outlet as a safety precaution. But this was concluded to be unneccessary and a waste of heat energy whenever the valve might blow. The P&T relief and the air vent located at the top of the thermosiphon loop, i.e., at the top of the tank, give the system adequate protection from overpressurization, provided that the relief valve is not too far away from the heat source. Type M copper is rated to withstand pressures of 390 psi at 250°F; thicker-walled type L copper, steel-pipe and welded steel-plate heat exchanger materials are stronger still than the type M, which makes the removal of the relief valve no compromise to safety. No exchanger or plumbing failures have ever occured because of local boiling.

On the other hand, the relief valve at the pumped heat exchanger outlet is that system's primary safety feature. Pumped woodstove DWHS were generally plumbed to a lower-level storage tank. During a power outage—as might occur in a winter storm—or a failure of a pump or control, the valve is there, vented outside, to prevent overpressurization.

It has been suggested that there is danger of a "meltdown" of the heat exchanger should it lose water pressure or pumping capability. Actually, an empty heat exchanger in a hot stove simply oxidizes faster than a filled one, and the period between any such system failure and its detection at the time of refueling would not likely be long enough to cause significant damage to the exchanger.

Another caution voiced about pressurized systems is the possibility of exchanger burnout or rust-out over a long period of normal use, leading to some kind of catastrophic flooding. A few factors conspire against this eventuality. Soon after a new exchanger is put into operation, it becomes encrusted with what must be a layer of carbonized creosote. The exchanger is, after all, very cool relative to the 1000°F plus ambient firebox temperature. In freshly re-



Three shop-made woodstove heat exchangers for use inside firebox.

fueled stoves, exhaust gas condensate literally drips from the exchangers. The ensuing crust builds up to a certain thickness, about 0.10-inch, and becomes no thicker. To some extent this deposit reduces heat transfer, but it also removes the heat exchanger material from direct flame, minimizing oxidation and degradation of the exchanger. Inside rust-out of steel exchangers is possible, but only far, far into the future. Should the exchanger be corroded over time, it is highly doubtful that there would be a catastrophic failure. Most likely there would be an initial pinhole leak that could be readily detected.

Another possible safety problem with open loop systems lies with water quality. Hot water from copper, galvanized, and regular steel exchangers has been used without complaint but has not been tested for changes in purity. Finally, at the end-use, the high water temperatures (190° to 200°F) that are possible from the woodstove DWHS mean that a thermostatic tempering or mixing valve installed on the hot water supply line is a must.

Woodstove heat exchangers

The work done at the test facility has involved experimentation with different styles of heat exchangers placed in a variety of stove types. Heat-exchanger styles fall into two basic categories: pipe coils and mini-tanks. The former are fashioned from copper tubing and black, galvanized, and stainless-steel pipe. The copper coil of 1/2-inch or 3/4-inch tubing (type L) is the easiest to fabricate. A length is first filled with sharp sand to eliminate crimping during forming and then rolled into a circular coil of a desired diameter, using a large diameter pipe or other cylinder for the "die". The coil can be placed in the top rear of the firebox near the flue port or in the exhaust stack section just above the flue collar.

So as not to impede the flow of exhaust gases, stack exchangers should be installed in a larger-diameter stack section that is reduced to fit the stove's standard stack dimension. Soldered fittings should not be used in or near the coil; brass flare fittings should be used instead. Total tubing lengths for the coils used were in the 13-foot to 16-foot range. (These types of exchangers are also commercially available from the Blazing Showers Co., P.O. Box 327, Point Arena, Calif. 95469.)

Threaded-galvanized or black-pipe nipples are connected with either tight or wide return 180 degree elbows (uncommon, but eminently available fittings) to form a serpentine pattern. The nipple length for each course must be carefully planned to ensure that elbows won't hang up on other elbows or nipples during assembly. Copper tubing can also be formed into a serpentine. Dimensions of serpentine exchangers used in the project ranged from about 6 to nearly 13 linear feet (total pipe and elbow).

Mini-tanks are just that—small, flat containers fabricated from 3/16-inch or 1/4-inch-thick mild steel plate. Inlet and outlet nipples (1/2-inch or 3/4-inch) are welded over holes drilled in the side or end panels—depending on how the tank is fitted into the stove—and a single interior baffle serves to direct the flow throughout the containment and to eliminate stagnant zones. We found no difficulty in having a few units made locally at reasonable cost by using the combined capabilities of a couple of shops. The tasks involved were plate cutting (gas torch or massive shear), plate bending (massive brake) and seam welding (MIG electric arc). An exchanger manufacturer in California circumvents the need for plate bending by using standard 2-inch by 6-inch steel tubing (1/4-inch wall) cut into 12-inch, 18-inch, and 24-inch lengths. End plates with inlet and outlet ports are then welded on to seal the units. Instead of a baffle, a perforated pipe section extends into the exchanger from the inlet port. (Available from Holly HydroHeater™, P.O. Box 339, Sebastopol, Calif. 95472).

Several factors dictate the selection and sizing of the retrofit heat exchanger. The foremost is the shape of the stove.

First, the optimum heat exchanger position should be determined. Observation of what could be termed the "heat path" of the stove will serve to locate its hot spots. Heat path is primarily a function of how air flows through the unit, and properly intercepting this path can result in dramatic increases in heat extraction.

A stepped box-type stove was tested with a 2-inch by 6-inch by 12-inch mini-tank located first along the sidewall and then in front of the exhaust port (Figure 1). Maximum output at the sidewall was around 11,000 Btu/hr, yet in the baffle position output jumped to 21,000 Btu/hr.

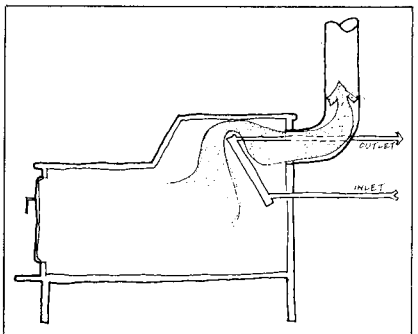


Figure 1. Mini-tank heat exchanger mounted in baffle position.

Sometimes the placement of the exchanger is a compromise between the stove's hot spots and what the shape of the stove allows. In old or low-efficiency stoves, stack-mounted exchangers are good choices for capturing otherwise wasted heat. With such a stove, there is little danger of overcooling exhaust gases to condensation temperatures (below 250°F, according to Shelton in *Woodburners Encyclopedia*, Vermont Crossroads Press, December 1976.)

Extensive testing was done with stack exchangers installed in some new-design, higher efficiency stoves. It was found that upper stack temperatures were never cooled below 300°F (an insulated chimney must be used). Stack heat extractors are not feasible in stoves that are heavily baffled (e.g., Vermont Castings, Cawley/LeMay) and force exhausts through a circuitous path before they enter the stack. Care should be taken not to oversize stack

exchangers at the risk of causing condensation problems. As mentioned, adequate heat extraction is insured by using 13 to 16 feet of 1/2-inch or 3/4-inch tubing.

Extensively baffled stoves are not likely to allow a baffle-type mount for the exchanger, which leaves backwall- and sidewall-mounting possibilities. In a box-type stove with full horizontal baffle (Figure 2), the backwall is likely to be the coolest zone —not a suitable location for the exchanger. In a performance test comparing positions, a 233-square-inch (surface area), 91-cubic-inch (volume) unit collected a maximum of

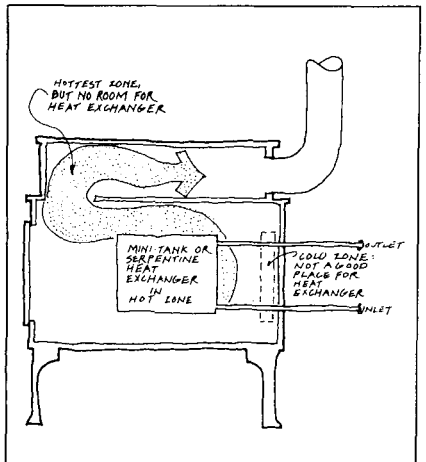


Figure 2. Box type woodstove with full horizontal baffle.

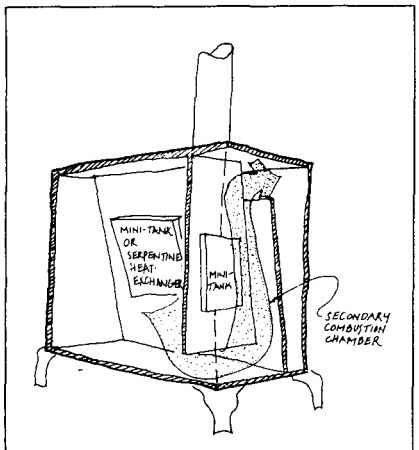


Figure 3. Franklin-type woodstove with exchanger on backwall or in secondary combustion chamber.

7,650 Btu/hr at the backwall. A smaller (184-square-inch, 100-cubic-inch) sidewall exchanger with a lower surface area-to-volume ratio captured over 14,000 Btu/hr.

A modernized, extensively baffled version of the Franklin-style stove provided two effective exchanger locations (Figure 3). A large (18-inch by 13-inch by 1 1/2-inch) exchanger mounted on the firebox backwall extracted up to 26,000 Btu/hr. A smaller unit (11 1/2-inch by 6-inch by 2-inch) located in the secondary combustion chamber extracted up to 16,000 Btu/hr. Also, since the latter unit did not take up any firebox space, wood-loading capacity was not reduced.

In terms of the actual exchanger installation, the stove owner must be prepared to accept two 5/8-inch by 1 1/16-inch holes somewhere at the back of the stove for the inlet and outlet pipes. A neat, though laborious job is done with drill bits. Torch cutting is also possible.

In a sentence, externally mounted heat exchangers give very low outputs. A mini-tank capable of capturing 14,000 Btu/hr in a firebox location only reached a 2,700 Btu/hr-maximum when mounted in contact with the outside stove wall.

When a good spot has been found for the exchanger, sizing becomes a function of available space, average hours of daily wood burning, and the domestic water heating load. In any other context these factors have little connection, but they are the critical determinants in sizing. The Btu figures given above essentially represent maximum outputs under very hot fire conditions. Under average, medium-burn conditions, heat-exchanger outputs have tended to fall in the 5,000 to 10,000 Btu/hr range, with some exceptions. Considering such an output range for eight hours of daily woodburning (a common level of use for lowland California, with cold nights and warmer days), 48,000 to 80,000 Btu would be captured. If heat loss from the plumbing and storage components amounted to 10 percent, then about 43,000 to 72,000 Btu would be the actual energy gain. With an 80-gallon tank at a "cold" start temperature of 50°F, the average tank temperature would be raised by 64° to 107°F, resulting in an average tank temperature of 114° to 157°F. (In practice, horizontal stratification made for top-to-bottom temperature differences of up to 80°F.) This range of heat exchanger output coupled with part-time wood burning produces from a nearly adequate to a full daily supply of hot water, indicating proper exchanger sizing. But in the case of full-time, 24-hour-a-day wood burning, the daily output jumps up to the 108,000 to 216,000 Btu range—a heat gain that at the upper range is too great for even a 120-gallon tank (107° to 215°F average temperature rise). Thus either the exchanger size should be reduced and/or storage capacity should be increased, along with an equivalent increase in load. Clearly, the former makes more sense.

It is indeed possible to oversize the exchanger; we did in our lust for higher output. In one experiment a pipe serpentine exchanger with tight-return, 180-degree elbows was sized to cover nearly the entire sidewall of a stepped box-type stove. Hot water output was excellent, but the radiant space heating capability of that side was greatly reduced. A not-so-mini mini-tank installed at the backwall of a Franklin-type stove introduced such a large cold mass to the firebox that it literally caused a quenching of the flame and a noticeable reduction both in the space heating capability of the stove and the wood-loading capacity. For properly sized exchangers there was no perceptible reduction in space-heating capability. If there were, it would probably go undetected, because people will burn as much wood as they need to stay warm. In the case of firebox exchangers, the woodstove DWHS does increase wood burning, perhaps by 5 to 10 percent, depending on the amount of wood used. It is clear that stack exchangers extract only waste heat.

The solar-wood fraction

The solar-woodstove contribution to the total domestic water heating load has appeared to vary somewhat among the residential installations, and continued data collection will be necessary to pinpoint the actual fraction. Limited instrumentation requires a dependence not only on numerical data, but on "smart" deduction.

Solar-wood fractions over limited (one- to two-week) periods have equalled 60 to 95 percent, depending primarily on the load. In one instance data were collected for a full week of cold nights and sunny days. Woodstove operation averaged eight hours per day, with exchanger output averaging 7,200 Btu/hr (pumped system). The solar component (72 square feet) operated about 6 hours per day and delivered about 54,000 Btu/day to storage (750 Btu/day/ft^2). The circulation freeze protection caused a heat loss of about 21,000 Btu each night as ambient temperatures consistently went below 38°F. Thus, the net energy gain was about 90,000 Btu/day—not including heat loss from storage. This is equivalent to about 26 kWh/day, worth about $1.30 per day at $.05 per kWh. For the same period, elapsed-time indicators showed that the electric water heater consumed 17 kWh/day, putting the total DHW load at 43 kWh/day and the solar-wood fraction at 26/43, or 60 percent.

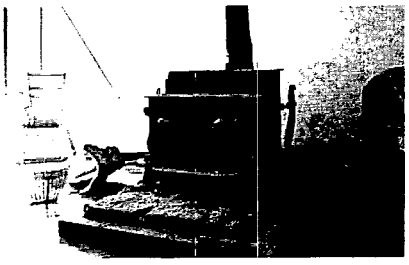
On a foggy or rainy day in which there was no solar operation and in which the house was not passively heated during the day, as it normally is, woodstove use increased to about 16 hours per day and delivered about 96,000 Btu to storage, more than making up for the loss of the solar contibution.

Costs and benefits

The woodstove DWHS is cheap. Ready-made heat exchangers can be bought for $50 to $120 in copper and steel. Homebuilt and locally shop-fabricated versions can cost $20 to $40. A complete thermosiphoning woodstove DWHS with an 80-gallon tank and all ancillary piping and fittings, plus insulation, has a materials cost of around $250. If the system output averages 7,000 Btu/hr for 8 hours per day, annual

production is 8,400,000 Btu for a 150-day heating season, or 2,560 kWh equivalent. At $.05 per kWh, $123 is saved annually for a 2-year payback (constant dollars and energy cost). Operation of the system in a colder climate (16 hours per day woodburning) could double output and halve the payback period.

The pumped woodstove DWHS has a materials cost of around $400 when a 1/100-hp pump, differential thermostat, and wiring is added. (Lower cost, less accurate thermostatic controls can be used, such as SPST snap-discs and strap-on aquastats, all in a cost range of $5 to $20.) Payback may not necessarily be extended, because the pumped system has a higher efficiency. Output was found to increase as much as 100 percent when exchangers at the test facility were switched from thermosiphon to pumped circulation (1.2 to 2 gpm). Delta-T thermosiphon systems ranged as high as 80°F, while in pumped systems temperature rise was in the 7 to 25 degree range, depending on fire condition.



Fisher "Grandma Bear" stove with factory coil; pumped system using Teel 1P760 pump and Heliotrope DTT-80 controller.

The price range of a solar DWHS is wide. We specify a 40-square-foot system of the type used in the project. The thermosiphon solar DHWS has a materials cost of around $800 (retail), and the pumped system has a cost of around $1,000. Somewhat higher efficiency can be expected from the pumped system.

It has been estimated that collectors can deliver to storage 270,000 Btu/ft^2/yr in Northern California. An owner-installed system of 40 square feet of collectors would deliver 10,800,000 Btu or 3,164 kWh, worth $158 at $.05 per kWh. Pumped systems would be paid back in about six years (constant dollars and energy cost). Thermosiphon systems, though lower in cost, would have an equivalent or even longer payback because of their lower efficiencies.

The combined solar-woodstove DWHS, using solar forced-circulation and woodstove thermosiphoning components, would have a materials cost of $1,250, and would deliver on the order of 19,000,000 Btu/yr, or about 5,560 kWh. Annual domestic water heating loads (four in the household, "average" consumption) have been estimated to be in the wide range of 16 to 27 million Btu/yr, a load to which the solar-woodstove DWHS can make a significant and cost-effective contribution.

10 Ways to Avoid Woodstove Fires

Suddenly everyone is a wood stove enthusiast. Unfortunately, every few days we hear of another house fire, sometimes fatal, caused by a wood stove that was improperly installed or operated. Read and heed!

10 Ways to Avoid WOODSTOVE FIRES

If you heat with wood, remember you're playing with fire . . . fire that can cut down heating bills . . . or burn your house down

by Ron Ross

At least 9,000 woodstove fires were recorded last year in 15 cold-weather states. At least 17 people died last winter from woodstove fires in one state alone. Stoves were not the primary cause; most blazes resulted from improper installation or careless use.

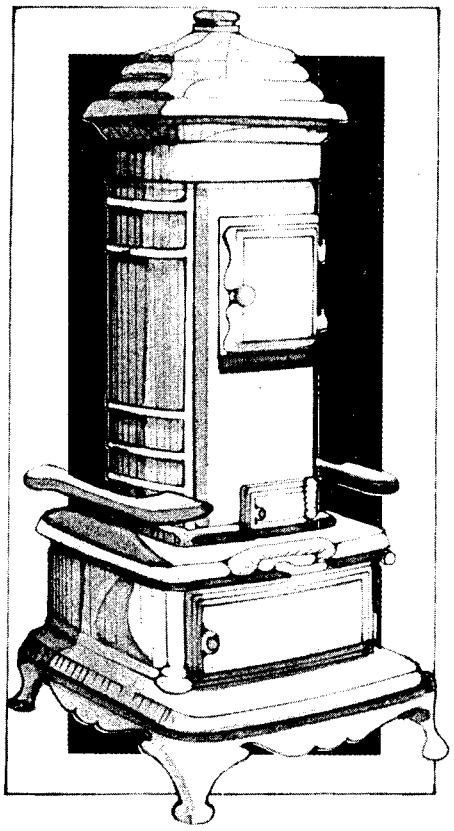
The basic rules for installing wood-burning stoves and using them are fairly simple. Unfortunately they don't allow for short-cuts, and they are not forgiving. A single mistake can cause disaster.

However, the most common causes of wood-burning stove fires are easy enough to separate out so you can avoid them in your own home. Here are the top 10, gleaned from materials provided by manufacturers, the NFPA, the New England Regional Commission Energy Program's report on woodburning safety, and other experts.

1 Cause: Stove Too Close To Wall.
Prevention: Keep at least 36″ between back and sides of stove and a combustible wall. If you can't allow 36″, put a sheet of asbestos millboard or 28-gauge sheet metal an inch away from the wall. Use non-combustible spacers, such as short pieces of metal pipe, between the backdrop and the wall.

If you use asbestos millboard (don't confuse this with cement-board or asbestos board), wear a mask during cutting and installation to avoid breathing asbestos fibers. Once installed, paint it to prevent fibers from flaking off. With asbestos millboard, the stove can be 18″ away; with 28-gauge sheet metal, 12″.

2 Cause: Insufficient Clearance Between Stove & Floor.
Prevention: Your best bet is to make a non-combustible shield under the stove that extends 12″ on all sides of the stove and 18″ in front of the fuel door (some local regulations might require more than 18″ in front; check them out). The type of base you'll need depends on the height of your stove legs. For 18″ or taller legs, 24-gauge sheet metal will do (after you've removed any carpeting). For 6″ to 18″ legs, use 24-gauge sheet metal on top of ½″ asbestos millboard. If the legs are 6″ or less, use 24-gauge sheet metal on top of 4″ of hollow masonry laid to provide air circulation through



the masonry. Note: Brick, stone or asbestos cement board alone are not effective shields. Use them with sheet metal or asbestos millboard.

3 Cause: Stovepipe Placed Through Wall.
Prevention: Don't put the stovepipe through a wall, if possible. If you must, use an insulated or ventilated wall thimble. It should be made of sheet metal or asbestos millboard and must be three times larger in diameter than the stovepipe, or use manufactured insulated stovepipe, keeping it 2″ from combustible surfaces. Don't use gas vent thimbles; they're too thin. If no thimble is used, there should be an 18″ clearance (a 6″ pipe would need a 42″ hole, closed in with masonry or other material).

4 Cause: Stovepipe Too Close To Wall.
Prevention: Keep stovepipe a distance of at least three times its diameter from a combustible surface. For an 8″ pipe that means 24″ from a wall. Too much? Remember that a chimney fire could cause the pipe to get red hot and reach temperatures of from 900° to 1,300° F., or more.

5 Cause: Collapsed Stovepipe.
Prevention: Fit stovepipe sections tightly and be sure to use two or three metal screws to lock them in place. Loose stovepipes tend to separate and collapse during a chimney fire.

6 Cause: Connection Between Stovepipe & Chimney.
Prevention: Be sure acceptable stovepipe clearances are maintained from any combustible surface. In a masonry chimney, a special connector thimble (check with your dealer) can be used to fit the stovepipe into the chimney. Use refractory cement to make a tight fit of the thimble and the chimney opening. Don't push the thimble into the flue. To prevent backdrafts, be sure the chimney flue is at least 25% larger in diameter than the stovepipe.

7 Cause: Creosote Igniting In Chimney.
Prevention: Check and clean your chimney regularly. Chimney fires are truly frightening. Temperatures of up to 3,000° F. are not uncommon during a chimney fire. Flames can shoot out of the chimney several feet into the air and fall back on the roof.

When creosote (a tarry substance that forms along with soot) ignites, drafts inside the chimney increase fast. The creosote and soot form because of incomplete combustion. Wet, green wood (especially unseasoned softwoods) and low-temperature, smoldering fires form creosote deposits faster.

Check the top or bottom of your chimney every couple weeks when you first use your stove. If creosote deposits are ¼″ thick or more, it needs cleaning. A couple of other ways to check for creosote: 1) Use the "fingernail technique." Tap the stovepipe with your fingernail. A metallic sound means it's clean; a dull sound means it's creosote dirty. 2) If you notice smoke coming out of the stove door on refueling, or an offensive odor, creosote is probably causing a slow draw.

After you get an idea of how fast creosote is

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forming, take longer between inspections. But if you change types of wood, or add a heat exchanger, go back to biweekly checks. Some chimneys will need cleaning every month. They all need it at least once a year. Clean stovepipes at the same time.

Sometimes burning an extremely hot fire briefly once each day will help clean out creosote, but could also start a chimney fire. Chemical cleaners can help, but should not be substituted for regular cleaning. Chains, small trees or sacks weighted with straw or excelsior have been used to knock creosote from inside chimneys. But a commercial chimney cleaning brush, or hiring a professional chimney sweep, is a better bet.

8 Cause: Faults In Chimney.
Prevention: If you're using a masonry chimney, makessure it has a good liner so gases and creosote don't escape and ignite before they get to the top. If you're planning to use an old chimney that doesn't have a liner, it will probably be wise to install one.

Check the chimney for cracks. One way is to build a smoky fire, cover the top of the flue, and force smoke through any cracks or holes. Repair these before using your stove regularly. Also check for loose mortar between the bricks of the chimney. If mortar crumbles when you stick it with an icepick, it needs help.

Scrape out the old mortar, remove the bricks, install new mortar and replace the brick. Be sure all chimneys extend at least 3′ above flat roofs. On pitched roofs, the chimney should be 2′ higher than any point within 10′, to prevent downdrafts and fires from sparks.

9 Cause: Petroleum Used To Light Stove.
Prevention: Don't use any petroleum product, whether it be gas, kerosene, charcoal lighter or oil. You might start a house fire, or burn yourself up in an explosion or flare-up. A sudden hot fire in a cold stove and chimney can cause a flareback, even if the starter fluid doesn't explode. Sudden heat can also crack cast iron. Let stove parts heat up and cool down gradually.

10 Cause: Ashes & Hot Embers.
Prevention: Always use a steel container to haul ashes, even if the stove has been out for several days. Hot embers may be hidden under ashes. Put ashes outside immediately, or you might have toxic fumes in the house. Bury the ashes, if possible, so winds don't blow hot sparks near buildings.

When opening the door of a wood-burning stove, have a screen handy to prevent sparks from spilling on the floor.

For tips on installing a wood stove safely, see the next page.

If You're Installing A Woodstove . . .

The woodstove fires recorded last year have more than caught the eye of fire marshals and insurance agents. Chances are there's a regulation, if you're installing a wood burner.

You might need a building permit, for example. Check first, even if it's annoying, or you could lose your homeowners insurance. Some insurance companies have flatly cancelled policies when they learned of an uninspected wood-burning stove.

More likely, if you prove to your agent or insurance inspector that your woodstove is installed according to National Fire Protection Assn. standards, your policy will probably stay in force, says Rick Baker, national sales manager, Energy Research and Development Corp., Madison, Indiana.

"Before you light the first fire, get a local building inspector and an insurance company representative to inspect your installation and *approve it in writing*," suggests Stephen Morris, customer relations manager, Vermont Castings, Inc. Randolf, Vermont.

Stoves Available. Wood-burning stoves are made from cast iron, plate steel or sheet metal. In general, the thicker the metal, the longer the stove will last. Both plate steel and cast iron retain about the same amount of heat per pound, and both stove types cost about the same, reports the New England Regional Commission Energy Program staff. Airtight models of either plate steel or cast iron are selling fastest today.

"Looking for a unit safety-tested by a private lab, such as Underwriter's Laboratory, will give you an extra margin of safety," says Baker. "Insurance companies are more likely to cover a stove that has been tested." The U.S. Consumer Product Safety Commission is currently developing a labeling rule for woodstove manufacturers.

Wood To Use. All wood has the same amount of energy per pound. Because hardwoods are more dense, there is more energy in a cord of oak, say, than a cord of white birch or white pine. A cubic foot of poplar weighs 26 lbs. compared to 39 lbs. for a cubic foot of sugar maple. Generally, unseasoned softwoods form the most creosote, (the main cause of chimney fires); "seasoned" hardwoods the least.

"Usually a minimum of nine months of air drying is required for a hardwood cut down in the winter months. A tree cut in the summer, spring or fall will require longer to season," explains Baker. Heating values by tree species are generally broken down into four groups:

- **Highest heating value** (28 to 30 million Btu per cord or about equal to 191 gal. of fuel oil). Apple, black birch, black locust, hickory, hop horn beam, white oak.
- **High heat value** (25 to 26 million Btu per cord, or about 176 gal. of fuel oil): Ash, beech, red oak, sugar maple, yellow birch.
- **Medium heat value** (21 to 23 million Btu per cord, or about 150 gal. of fuel oil): Black cherry, elm, grey birch, red maple, tamarack, white birch.
- **Low heat value** (13 to 17 Btu per cord, or about 108 gal. of fuel oil): Alder, balsam, fir, basswood, cedar, hemlock, poplar, spruce, white pine.

Combating Fires. Install a smoke detector or two in the house if it doesn't already have one, advises Baker. Also hang a good fire extinguisher with a 5-lb. minimum capacity near the stove. Fire extinguishers designed specifically for chimney fires are also available, according to Black Magic Chimney Sweeps, Stowe, Vermont. These devices resemble flares and emit large amounts of smoke and gas onto a fire to smother it. □

Don't Get Burned by Solar Rip-Offs

As with any burgeoning technology, incompetent installers and inexperienced labor can be a problem when someone buys a solar system. Use good consumer tactics, the author urges: study the kind of system you plan to buy, check with consumer agencies, look for high scores on independent tests of the system, know your materials, use a local contractor with a good reputation for performance, and get a contract and a warranty.

DON'T GET BURNED BY

Lured by growth of the solar market, hundreds of novice installers are

Abraham M. Genen bought a solar system for his Orange County, N.Y., house that didn't work anywhere near as well as it was supposed to. The contractor promised a 50-percent efficiency. The actual performance, Genen estimates, is 10 to 15 percent.

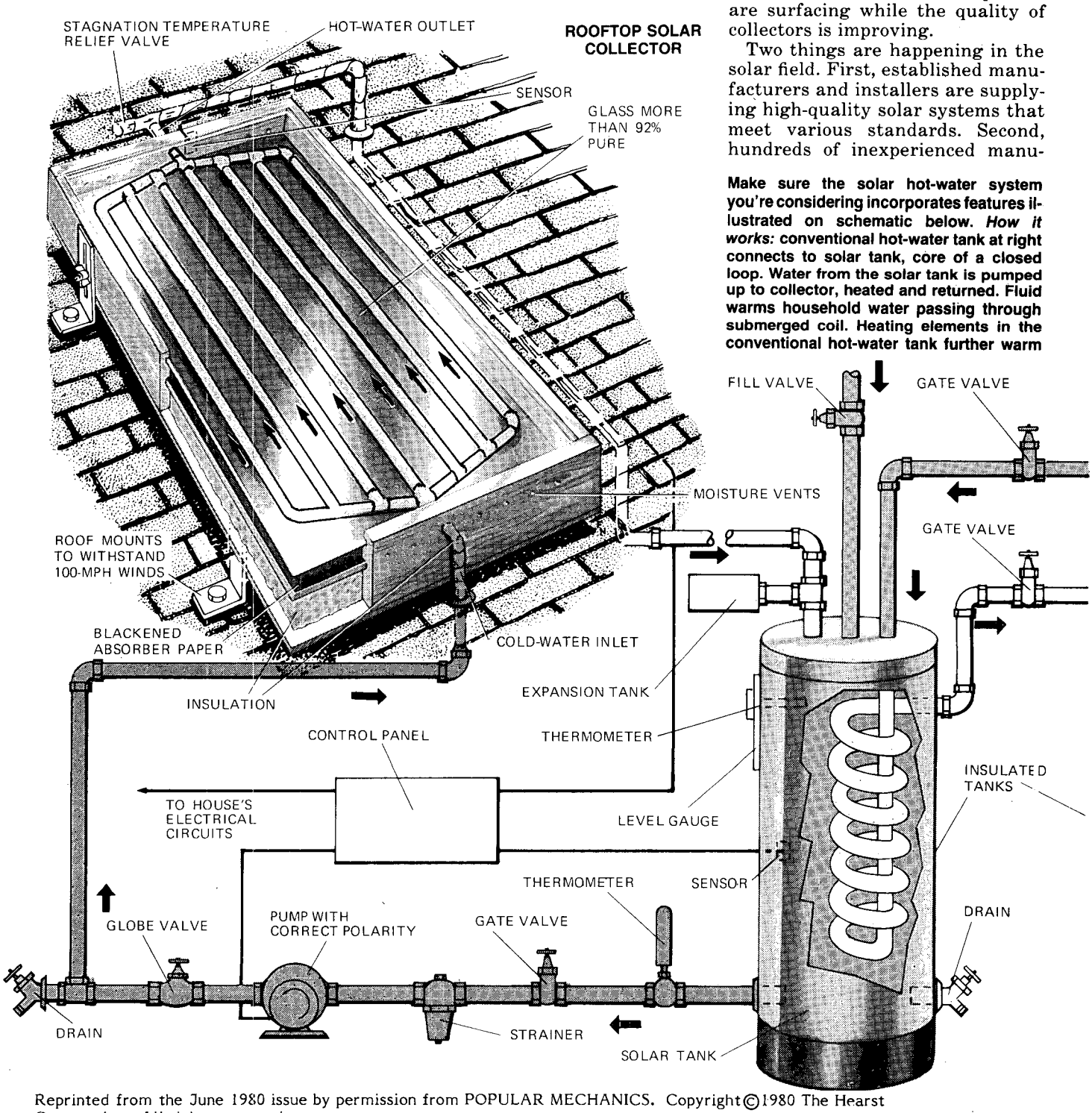
What makes Genen's experience especially illustrative is that Genen is not just any buyer. He is a senior consumer-fraud expert in the New York State Attorney General's Office. One of his specialties: solar energy. In fact, Genen, a 14-year consumer-fraud veteran, got his solar assignment about the same time he got his solar system. He could have been his first complaint.

"I asked a lot of questions," he said. "I got data and statistics. They were as phony as a $3 bill." Now he's suing the contractor. He says he would do it differently next time, but his first solar system has brought him nothing but, as he says, "tsouris," the Yiddish word for "aggravation."

Genen is part of a growing subculture that has found solar energy in practice to be far different from solar energy in theory. Even more ironic is that numerous complaints are surfacing while the quality of collectors is improving.

Two things are happening in the solar field. First, established manufacturers and installers are supplying high-quality solar systems that meet various standards. Second, hundreds of inexperienced manu-

Make sure the solar hot-water system you're considering incorporates features illustrated on schematic below. *How it works:* conventional hot-water tank at right connects to solar tank, core of a closed loop. Water from the solar tank is pumped up to collector, heated and returned. Fluid warms household water passing through submerged coil. Heating elements in the conventional hot-water tank further warm



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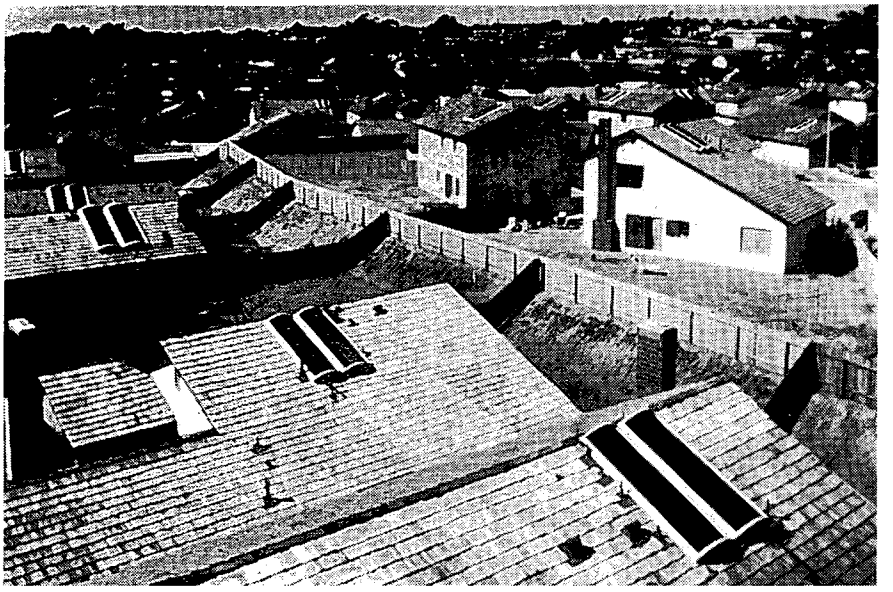
SOLAR RIP-OFFS

by Stuart Diamond

selling inferior systems.

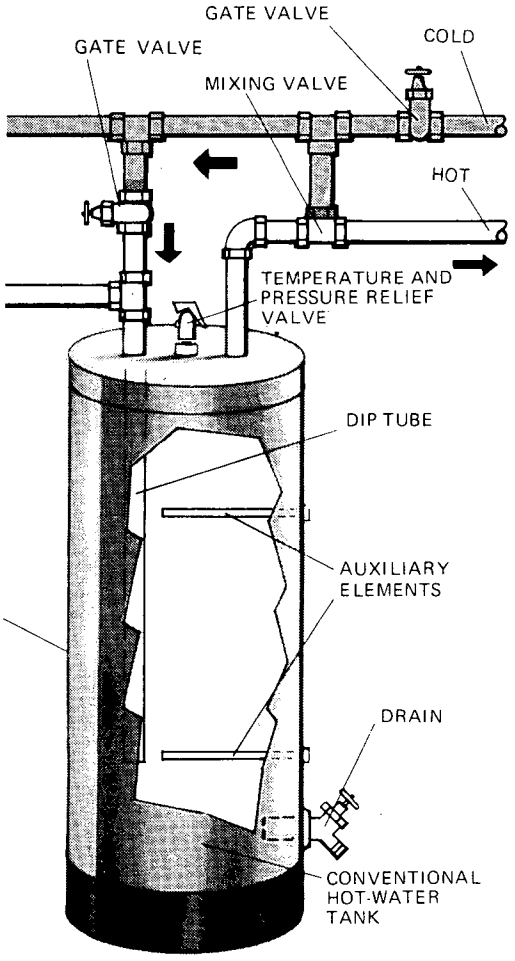
facturers and installers—attracted by the astronomical growth of the solar market—are profiting by selling inferior work. Today, perhaps 200,000 solar systems—largely domestic hot-water—dot this country, and the figure more than doubles each year. The number of competent solar firms has not kept pace with demand, experts say.

"When they opened the door, everyone came in, including the incompetents," says Edward Bohrer, president of California's Southwest Energy Management, which is highly regarded by federal officials. Bohrer said fully 20 percent of his business involves fixing systems installed by someone else.



What's wrong with the picture above? Haphazard orientation of collectors reduces efficiency. Ideally, collectors should face no more than 15° east or west of true south. Moldings lifting on collector surface (below) is evidence of poor construction.

the water as necessary. Sensors—one in the solar tank, one in the collector—turn on the pump when the collector temperature is at least 10° hotter than the temperature in the solar tank. Potential problems range from heat waste, caused by inadequate insulation on pipes or tanks, to blowouts, caused by pump failures and overheating. Good solar systems are able to save you as much as 80 percent of fuel bills.



Disheartening evidence of recent problems comes from an inspection of 60 systems early this year by the Florida Solar Energy Center, a state agency.

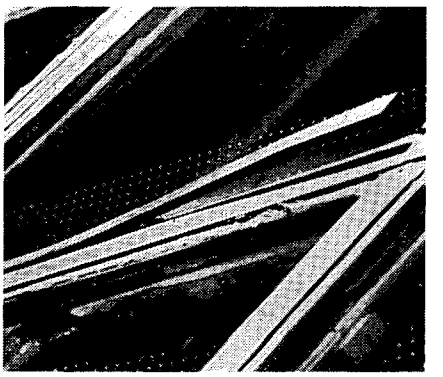
Only three of the systems checked were found to be problem-free. Fully 24 had more than routine design and installation problems, 13 had serious problems and seven didn't work at all. Even Randy Dyer, associate director of the Solar Energy Industries Assn., conceded that inexperienced labor has proven to be a serious problem in a significant number of cases nationwide.

In a number of southern California houses, workers installed systems by following the manufacturer's directions exactly: Install the collectors to the north, facing the sun. Unfortunately, the collectors came from Australia. In the United States, the sun comes from the south.

"The problems go from the ridiculous to the very subtle," observed Lynda Connor, who manages solar consumer programs at the U.S. Department of Energy.

Large rewards possible

The rewards for selecting the right system are large: A tax credit (See *How Energy-Saving Home Improvements Can Save Tax Money*, page 136, Sept. '79), thousands saved on fuel bills and a jump in a house's resale value. A problem-free solar system is completely automatic. But to reap those rewards, consumers must first use sound buying practices, as they would for any major purchase.



Here, is how to avoid getting burned when you buy a solar system.

Collecting information

The first step is to gain as much detailed information as possible on solar systems—how they work, who makes them, performance data, economics, different designs, local installers, problems. Contact the federally funded National Solar Heating and Cooling Information Center (see page 134 for the address of the Center and other helpful agencies), perhaps the world's largest such solar outlet. Almost everything they supply is free.

Make sure you ask for the *Domestic Hot Water Heater Installation Guidelines*, an invaluable document that will help you install—or scrutinize—any system.

Send for the Solar Energy Industry Assn.'s *Directory of S.E.I.A. Cer-*

tified Solar Collector Ratings, which evaluates the performance of a few dozen collectors. Contact the energy offices of any of the 10 northeastern states or Florida to find out which collectors have passed the performance standards set for the 10,000 hot-water grants of $400 each, issued in the past three years by the U.S. Department of Housing and Urban Development. The Florida Solar Energy Center also has tested more than 150 collectors made by scores of manufacturers. Send for its summary data sheet.

Fully understand a solar system before proceeding. In theory, it's simple: The sun heats a black "absorber plate" in an insulated box, covered with glass or plastic to accept light and trap heat. Water or air flows to the collector, where it picks up heat for use in your house. In practice, however, solar systems are complicated.

How systems fail

As you examine the diagram on page 84, you can begin to see where problems might develop. For example, if sensors or pumps are installed backwards, systems can heat the collector (and thus the sky) and cool hot-water tanks. It has happened. In fact, in some badly designed systems, the collector was protected from freezing by pumping up warm water from the storage tanks—water already heated by the collectors or by conventional fuel. Instead, of course, the collector should be protected with antifreeze, or be automatically emptied (through the drain) into a pail or outlet when the temperature gets too cold. It would then be filled automatically when the outside temperature increased.

Good systems include safety features such as a stagnation temperature relief valve, expansion tank, or both, in case the pump fails. Without such safety features, the sun could raise the collector temperature to 400°, blowing out the collectors or causing other serious damage.

The size of the storage tank or bin is also critical. In Roanoke, Va., one man bought a domestic hot-water system with a 2000-gallon storage tank, instead of the usual 60 to 120 gallons. The tank collected a lot of B.T.U.s of heat, but they were spread out over so much water that the fluid only increased a few degrees in temperature. The system was useless without a smaller tank.

It almost goes without saying that energy conservation comes before solar energy. For a hot-water system, insulate the tank and pipes. For heating, insulate the attic, buy storm windows and caulk and weatherstrip windows and doors.

Choosing a collector

California has a lot of swimming-pool heaters. One, a black hose, came in a coil and was installed on the roof. In one Palo Alto installation, a high wind unrolled the hose about 10 feet. It smacked into a second-floor window and emptied the pool into the bedroom.

Always choose a collector that (1) has been approved in a federal testing program, (2) looks good in the solar industry's rating booklet, or (3) is highly rated by an *independent* laboratory. All reputable collectors will have undergone stagnation-temperature tests. Ask for documentation.

First define your needs: domestic hot water, swimming pool or heating (air or water). Space heating usually requires higher collector temperatures than hot water. So heating systems often have double glazing and an electroplated black collector coating, to absorb more incoming light.

The longest-lasting collectors are copper. Galvanized steel and aluminum are subject to rusting, pitting or other corrosion. Add buffers to the water or antifreeze.

If you are a do-it-yourselfer, the specific collector you choose will probably depend on price and ease of installation. If you're hiring someone, depend on what's local: You don't want a dealer who's 200 miles away if you have a problem.

A final note on collectors: A recent study by the Solar Energy Research Institute in Colorado found a thermosiphoning system to be the most efficient of all. In such a system, the collector *and* the tank are on the roof, with the tank higher. The water circulates by siphoning; there is no pump. Of course, the system can't be used in freezing weather. But if you don't mind a tank on your roof and no solar-heated water on freezing days, consider it. The system costs less than $1500.

Picking a contractor

The best solar system in the world is thoroughly useless when installed by an incompetent contractor. In Florida, a perfectly good pump was installed upside down, so it could not be oiled—and it needed to be oiled. In Miami, a solar installer put in high-temperature collectors for a low-temperature swimming-pool system. The plastic pipes melted.

In one development near San Diego, rooftop collectors face east, west, south and in between. Installers apparently just followed the roofline, ignoring the direction from which the sun shines.

Usually, the dealer will also install the system. First, make sure he is experienced: Ask for the names of 10 customers, and *visit* at least three. If the dealer won't cooperate, leave.

Solder blocks a pipe

Grill the customers. Has the system leaked? Did the workmen kick the dog and track mud all over the carpets? Ask them how they know the system is saving money. One woman in Florida told researchers that she loved her system, but closer examination revealed it wasn't supplying any heat: A piece of solder was blocking a pipe.

Call agencies and ask for previous complaints: the local consumer affairs department and better business bureau, the state contracting license board. Consider asking your bank to do a credit check on the company principals and on the firm. The bank may do this as a courtesy or will charge a nominal fee, perhaps $20. The credit check will determine how sound the company is and whether there are any major judgments against it.

Execute a contract, specifying the type, number and price of all materials to be used. This is important: A few southwestern solar-water heater distributors were caught switching—installing cheaper and less efficient collectors than what the customer paid for.

In all cases, get a collector warranty at least as strict as the one required by the U.S. Department of Housing and Urban Development for all systems installed under its grant program. That is a full one-year warranty on minor parts such as valves and sensors, and a five-year warranty on the collector, pipes and pump. There must also be a five-year guarantee against corrosion. Try to get a full year's warranty on the installation, too—California requires it—but settle for 90 days.

And consider requesting a performance bond, in which a bonding or insurance company guarantees both the collector and the system. After all, solar companies do go out of business—in which case all their guarantees are worthless. Usually the bond costs one percent of the to-

tal bill. If bonding companies won't issue one, you know there are problems with the solar company. Get everything in writing.

You should perform several other checks to discover how good the contractor is. Ask if the firm belongs to the National Assn. of Solar Contractors, comprising 400 carefully screened and experienced solar contractors.

Check on whether the contractor's installers have taken a solar installation course approved by the federal government, major university or accredited institution.

Even for small jobs, consider paying a solar expert a small consulting fee to check plans and test data.

Above all, don't rush. *The sun will be there tomorrow.* And it's a buyer's market right now.

Having it installed

Just because the contractor has good installers, it doesn't mean they will be used on your job. Check the credentials of the *specific* installers for your collector system. At least one should be a licensed plumber and two should have solar experience.

If you can, be there when the system is installed. Bring diagrams with you. When it's finished, *inspect everything.* Have the installers walk you through the system before it's activated. Ask questions. "It takes only one small oversight to really mess up a house," says Edwin Papworth, a Virginia solar contractor.

Finally, have a checkup from the contractor after a week or two of use.

"I do believe it's possible to buy a solar system and save money," says Genen, the New York assistant attorney general. "And I'm a great believer in solar. But one thing is sure. If you don't take the time to do it right first, you may have very little recourse later." **PM**

Where to obtain further information

Florida Solar Energy Center, 300 State Road 401, Cape Canaveral, Fla. 32920. Free booklet: *Turning on the Sun.*

National Assn. of Solar Contractors, Suite 928, 910 17th St. N.W., Washington, D.C. 20006. Will send you the names of approved contractors near you.

National Solar Heating and Cooling Information Center, Box 1607, Rockville, Md. 20850.

Northeast Solar Energy Center, 470 Atlantic Ave., Boston, Mass. 02111. Free booklet: *Solar Water Heating: What's in it for You.*

Sheet Metal Workers International Assn., 1750 New York Ave. N.W., Washington, D.C. 20006. Offers written guarantee for installation on a solar system put up by its members.

Solar Energy Industries Assn., Suite 300, 1001 Connecticut Ave. N.W., Washington, D.C. 20036.

Solar energy office of the California Energy Commission, 1111 Howe Ave., Sacramento, Calif. 95825. Publishes dozens of brochures, most free. Also lists performance data on more than 100 collectors it has tested.

Solar Energy Research Institute, 1617 Cole Blvd., Golden, Colo. 80401. Its Dec. '79 *Monthly Review* contains data on relative solar system performance.

How Uncle Sam Can Help You with Your Invention

From Fulton and Bell to Kodak and IBM, American ingenuity has been encouraged by practical laws. Let's see how they can work for today's young inventor.

How Uncle Sam can help you with your invention

Henry Ford didn't work for a company the size of General Motors. Thomas Edison wasn't employed by an all-encompassing organization like Public Service Electric and Gas of New Jersey. And Alexander Graham Bell? The only Ma Bell he knew was his father's wife.

Tinkering in woodshed workshops, these "small-time" inventors helped spawn present-day giant companies. Ironically, present-day giant companies have made it difficult for inventors working on their own to get their inventions to market. For an inventor to get enough capital to develop an invention, he normally has to turn to a big company, which usually makes company ownership of the invention a condition for funding.

The government, recognizing the historic importance of the individual inventor, is bucking the trend. The Department of Energy (DOE) has two programs to fund inventions relating to energy. As this article is being written, the Department of Transportation (DOT) is developing a program to fund worthwhile inventions relative to highway, air, rail and marine transportation.

It's too soon to describe the DOT program. A PM article about that will come later, when things are more definite.

The DOE programs, on the other hand, are established. If you have an energy-related invention you think the country needs but you lack money to bring it to market, one of the programs may be worth pursuing.

The oldest of the two is called the Energy-Related Inventions Program. It was established by Congress in 1974.

According to Patrick J. Donohoe, who heads the DOE Inventions Branch, "The idea behind the program is to help individual inventors and small businesses develop, and bring to market, worthwhile inventions that are energy-related."

When an invention passes the screening process, it is funded with the hope that the inventor will be able to do one or more of these things:

- Obtain a contract from private or government sources to further develop the invention.
- Set up a company to manufacture and market the invention.
- Negotiate an agreement with a company that will manufacture and market the invention.

An inventor just doesn't walk into Donohoe's office and, zip, get a few thousand. The screening process is as tough to get through as the National Basketball Assn. playoffs. There is a limited amount of money to go around, and there are thousands of inventors, each thinking he has an answer to the energy dilemma.

Suppose you have an invention. Your first step is to apply for a patent. Then, write the Inventions Branch, Div. of Business Programs, Department of Energy, Washington, D.C. 20585, for an evaluation-request form. The evaluation request will be reviewed by the National Bureau of Standards.

At this point, over half of the applications fall by the wayside. The main reasons are incomplete, technically insufficient or hard-to-understand descriptions, and the existence of concept, rather than a working invention.

An invention may take up to a year to get through the preliminary evaluation. If it survives, it enters the next stage, which is a technical review by two specialists in the particular field. Each specialist works independently of the other. The specialists look for obvious technical flaws. This process takes about eight hours.

In 1978, over 10,000 evaluation requests were received. Only five percent of these proposals saw the light of hope at the end of the technical review.

Those inventions that do survive this phase enter the final stage of evaluation, which is in-depth testing and analysis by a staff engineer who probes both the technical and commercial feasibility of the invention.

"No energy is saved unless people are able to buy and use a device," says David G. Mello, who, along with Glen A. Ellis, works in Donohoe's of-

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fice to coordinate the evaluation process. "An invention has to be both possible and marketable to be of any value. If an invention is too expensive for people to buy, it's not practical. In other words, we are not interested in devices that use platinum ball bearings."

After this final evaluation, DOE decides the nature and extent of support each invention will receive. Of the 500 or so inventions that reached this stage in 1978, about 7 percent survived.

In terms of numbers, then, of the more than 10,000 inventions received in 1978, a scant 34 received support. But this support was to the tune of $2.3 million. The smallest award was $18,000, the largest was $170,000 and the average was $67,000.

Dollar amount is one criteria that distinguishes the Energy-Related Inventions Program from the Appropriate Technology Small Grants Program, which is the other DOE program. A cap of $50,000 is placed on funds allocated to an inventor under this program. Some inventors have received as little as $300 aid-money. However, neither extreme is the rule, since grants average about $10,000.

The Appropriate Technology Program looks for people who have energy-saving concepts (no hardware) or working inventions to meet specific needs of the local community, with a minimum expenditure of money and manpower needed to put the invention into use. In other words, under the act by Congress authorizing DOE to set up this program, DOE has been charged with providing grants for the development of "small-scale, energy-related technologies that are appropriate to local needs and skills."

In addition to individual inventors, Appropriate Technology grants are given to:

- Local nonprofit organizations, and state and local government agencies. One grant for $8500, for example, went to Nevada State University in Las Vegas, which is working with an invention that combines evaporative cooling and solar heating that uses air, instead of water, as a conductor. If successful, the equipment will be valuable to the southwestern areas of the United States should a predicted water shortage develop.
- Indian tribes. For instance, as part of a campaign to prove the effectiveness of solar energy methods, the Yavapai Council for the Aging in Prescott, Ariz., was awarded $2000 to install a solar hot-water heater in a building used by senior citizens.
- Small businesses. For example, Solar Aqua Systems, a small business firm in Encinitas, Calif., has an $8000 grant to develop a covered, solar-heated lagoon for primary anaerobic treatment of waste water that will produce methane for supplementary heating.

Screening of proposals submitted to the Appropriate Technology Program is no less rigid than those offered to the Energy-Related Inventions Program. A proposal goes through four evaluation steps:

1. A prescreening of applications.

2. A technical review by experts drawn from the region involved.

3. A review by qualified individuals from the state in which the project is to take place.

4. A final assessment by a DOE selection panel.

If you think you have an invention, or an idea for an invention, that qualifies under the Appropriate Technology Program, write the DOE regional office that serves your locality for more information and a grant application. There are 10 regional offices as follows (address your letter to the Department of Energy, Attn.: Appropriate Technology Program):

Region I: 150 Causeway St., Boston, Mass. 02114 (serving Maine, New Hampshire, Vermont, Rhode Island, Massachusetts, Connecticut).

Region II: 26 Federal Plaza, New York, N.Y. 10007 (serving New York, New Jersey, Virgin Islands, Puerto Rico).

Region III: 1421 Cherry St., Philadelphia, Pa. 19102 (serving Pennsylvania, Virginia, West Virginia, Delaware, Maryland, District of Columbia).

Region IV: 1655 Peachtree St., N.E., Atlanta, Ga. 30309 (serving Kentucky, Tennessee, North Carolina, Mississippi, Alabama, Georgia, Florida, South Carolina).

Region V: 9800 South Cass Ave., Argonne, Ill. 60439 (serving Minnesota, Wisconsin, Michigan, Illinois, Indiana, Ohio).

Region VI: 2626 West Mockingbird Lane, Dallas, Tex. 75235 (serving New Mexico, Oklahoma, Texas, Arkansas, Louisiana).

Region VII: 324 East 11th St., Kansas City, Mo. 64106 (serving Missouri, Nebraska, Iowa, Kansas).

Region VIII: Box 26247, Belmar Branch, Lakewood, Colo. 80226 (serving Montana, North Dakota, South Dakota, Wyoming, Utah, Colorado).

Region IX: 111 Pine St., 4th Floor, San Francisco, Calif. 94111 (serving California, Nevada, Arizona, Hawaii).

Region X: 1992 Federal Building, 915 Second Ave., Seattle, Wash. 98174 (serving Washington, Cregon, Idaho, Alaska).—*M.S.*

To Teachers

WHO PLAN TO USE THE READER WITH STUDENTS

Whether you are teaching young people or adults, whether you use this reader for classroom reading or for student assignments, there are a few facts that you should be aware of.

1. You have certain rights to and restrictions on your use of the material in this reader under the copyright law.

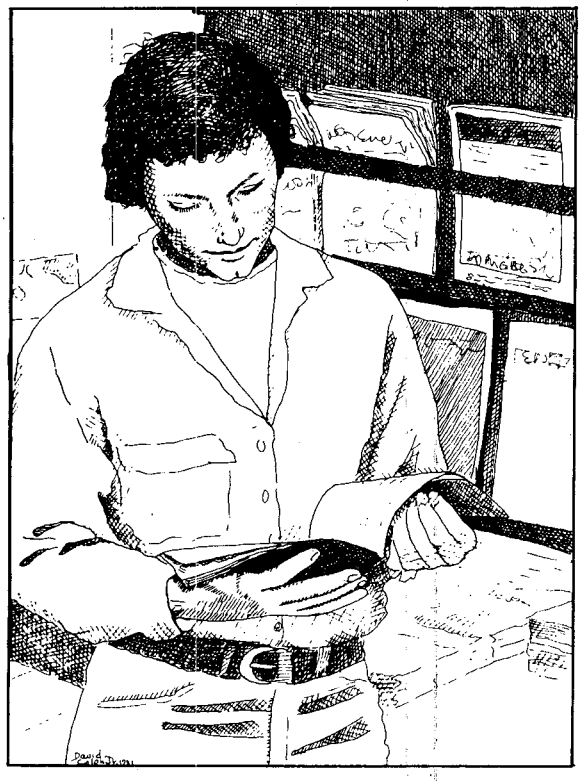
2. The statements and opinions contained in this material should be weighed and evaluated carefully.

3. In using readings with students, preparation and follow-up are as important as the reading itself.

Let's look at each of these points more closely.

Your Right to Use the Reader

The articles included in this reader are reprinted here by the generosity of a number of writers, artists, editors, and publishers. Where the material is copyrighted (and most of it is), the copyright appears with the article, poem, or story. The copyright law does allow teachers to reproduce such material; however, there are limitations on that right. To make your rights as an educator clear, and to encourage you to use the reader, we have included the Congressional Guidelines for Classroom Copying. These guidelines appear on pages 323-5.



Point of View

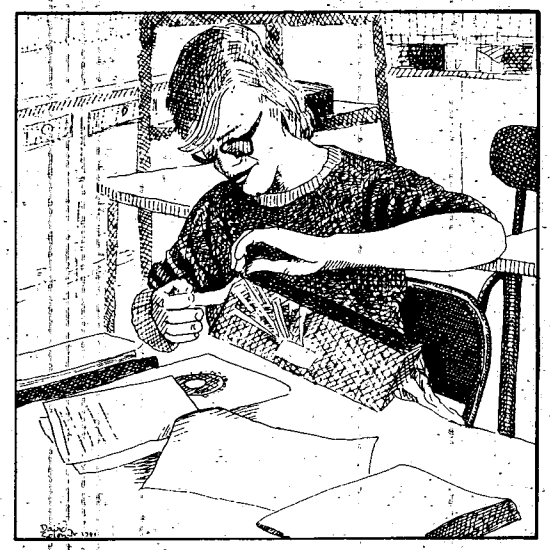
No magazine article can give you the full energy story; writers and publishers, like everyone else, have points of view. We can't guarantee that the articles included here are completely objective or all-inclusive. What this reader does attempt to do is to give a broad sampling. For suggestions on how to read thoughtfully and how to help students do the same, read on.

Reading: Preparation and Follow-Up

To profit from a reading, the person doing the reading must begin with

motivation,
background,
reading ability and vocabulary, and
critical skills

How can you be sure that you and your students get the most from your energy reading? Below are some suggestions for preparation and follow-up on reading assignments.



Motivation

Students today know that their future literally depends on energy. It's not hard to motivate them to read about energy, if you remind them that energy knowledge gives them more control over that future. To motivate,

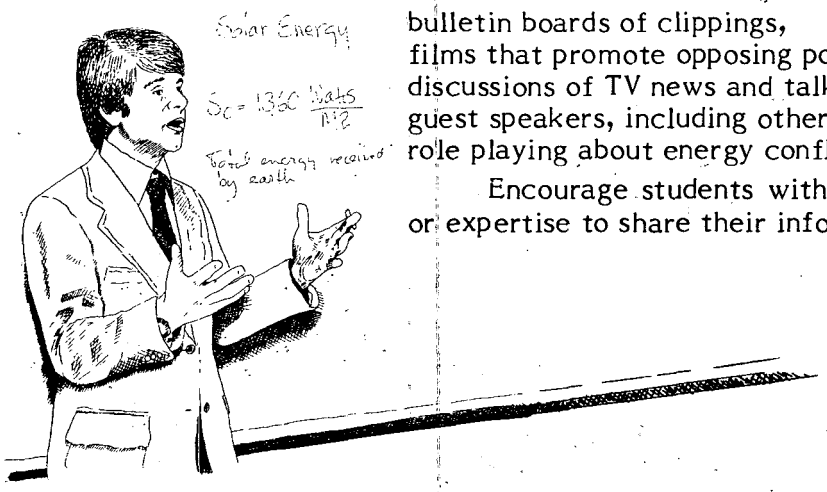
discuss sources of anxiety for them and their families, such as:
- rising costs,
- blackouts and shortages,
- political and strategic barriers to energy supply, and
- daily necessities and comforts that depend on energy;

use questions to encourage imagining and sharing, like:
- "Have you ever been in a greenhouse? What was it like?"
- "What would happen to utility companies if everyone used solar energy?"
- "Do you remember how you felt when you first became aware of an energy crisis?"
- "How do you think a person in a developing country might feel about energy use in the United States?"
- "How would you design a completely self-sufficient house?"

or do a pre-reading activity, for example:
- try a simple experiment or demonstration related to the article's subject,
- take a poll or survey,
- plan a debate or writing assignment based on the article's information, or
- consider various energy futures and raise questions about the probable outcomes.

Background

Students care about the energy future, but they often lack specific information. They tend to get their opinions by hearsay, and talk in generalities and slogans. They need more context for their reading. You can break through oversimplified thinking with



bulletin boards of clippings,
films that promote opposing points of view,
discussions of TV news and talk shows,
guest speakers, including other faculty members, or
role playing about energy conflicts.

Encourage students with special knowledge or expertise to share their information.

Reading Ability and Vocabulary

Not every reading is intended for every student. In fact, some of the articles in the reader are only appropriate for teachers and advanced students. Stack the deck for reading success:

1. Select articles at the appropriate reading level. (They are keyed in the table of contents with color tabs; one for easy, two for intermediate, and three for difficult.)

2. Introduce new words before beginning the reading. Students can use the glossary (page 327) or they can try to figure out the meanings of the words from their context.

3. Attack the reading at the easiest (informational) level first, and then lead students to the more difficult levels:
   First, search for and recall facts.
   Second, consider what the writer is trying to communicate.
   Third, apply what the writer says to one's own experience.
   Fourth, analyze how the writer presents his/her ideas.
   Fifth, suggest new ways of presenting or adding to these ideas.
   Last, evaluate and express opinions on the material.

Critical Skills

Students like magazine readings because they perceive magazines as "adult" reading. But reading like an adult requires 1) desire for objectivity and 2) tolerance for ambiguity.

Desire for Objectivity

Help students to generate questions about the reading that encourage objectivity:

- Who is the author?
- Is he/she associated with some special interest group?
- What are his/her claims to expertise?
- Where does he/she use facts and where, opinions?
- What is the quality of the evidence?
- How can the assertions be verified or compared with opposing views?
- Is the information up-to-date?
- Is the style objective and balanced?
- Does the author use propaganda techniques and emotional appeals?
- Does the article leave out or gloss over certain points?

Tolerance for Ambiguity

Encourage students to be aware of ambiguities in their reading and discuss them:

- Are there things the author has left out (intentionally or unintentionally)?
- Are there other possible points of view on the subject?
- May time and events alter the validity of what the author says?
- Is the real situation more complex than the author suggests?
- Does the author admit to uncertainty on some points?

With this kind of thoughtful preparation and follow-up, a reading becomes more than just another assignment. It becomes an opportunity to expand vocabulary, sharpen thinking, and develop more mature skills in evaluating ideas.

From Circular R21 of the Copyright Office, Library of Congress, Washington, DC 20559.

Agreement on Guidelines for Classroom Copying

in Not-for-Profit Educational Institutions with Respect to Books and Periodicals

The purpose of the following guidelines is to state the minimum and not the maximum standards of educational fair use under Section 107 of H.R. 2223. The parties agree that the conditions determining the extent of permissible copying for educational purposes may change in the future; that certain types of copying permitted under these guidelines may not be permissible in the future; and conversely that in the future other types of copying not permitted under these guidelines may be permissible under revised guidelines.

Moreover, the following statement of guidelines is not intended to limit the types of copying permitted under the standards of fair use under judicial decision and which are stated in Section 107 of the Copyright Revision Bill. There may be instances in which copying which does not fall within the guidelines stated below may nonetheless be permitted under the criteria of fair use.

Guidelines

I. Single Copying for Teachers

A single copy may be made of any of the following by or for a teacher at his or her individual request for his or her scholarly research or use in teaching or preparation to teach a class:

A. A chapter from a book;
B. An article from a periodical or newspaper;
C. A short story, short essay or short poem, whether or not from a collective work;
D. A chart, graph, diagram, drawing, cartoon or picture from a book, periodical, or newspaper.

II. Multiple Copies for Classroom Use

Multiple copies (not to exceed in any event more than one copy per pupil in a course) may be made by or for the teacher giving the course for classroom use or discussion; provided that:

A. The copying meets the tests of brevity and spontaneity as defined below; and,
B. Meets the cumulative effect test as defined below; and,
C. Each copy includes a notice of copyright.

Definitions

Brevity

(i) Poetry: (a) A complete poem if less than 250 words and if printed on not more than two pages or, (b) from a longer poem, an excerpt of not more than 250 words.

(ii) Prose: (a) Either a complete article, story or essay of less than 2,500 words, or (b) an excerpt from any prose work of not more than 1,000 words or 10% of the work, whichever is less, but in any event a minimum of 500 words.

Each of the numerical limits stated in "i" and "ii" above may be expanded to permit the completion of an unfinished line of a poem or of an unfinished prose paragraph.

(iii) Illustration: One chart, graph, diagram, drawing, cartoon or picture per book or per periodical issue.

(iv) "Special" works: Certain works in poetry, prose or in "poetic prose" which often combine language with illustrations and which are intended sometimes for children and at other times for a more general audience fall short of 2,500 words in their entirety. Paragraph "ii" above notwithstanding such "special works" may not be reproduced in their entirety; however, an excerpt comprising not more than two of the published pages of such special work and containing not more than 10% of the words found in the text thereof, may be reproduced.

Spontaneity

(i) The copying is at the instance and inspiration of the individual teacher, and,

(ii) The inspiration and decision to use the work and the moment of its use for maximum teaching effectiveness are so close in time that it would be unreasonable to expect a timely reply to a request for permission.

Cumulative Effect

(i) The copying of the material is for only one course in the school in which the copies are made.

(ii) Not more than one short poem, article, story, essay or two excerpts may be copied from the same author, nor more than three from the same collective work or periodical volume during one class term.

(iii) There shall not be more than nine instances of such multiple copying for one course during one class term.

The limitations stated in "ii" and "iii" above shall not apply to current news periodicals and newspapers and current news sections of other periodicals.

III. Prohibitions as to I and II Above

Notwithstanding any of the above, the following shall be prohibited:

A. Copying shall not be used to create or to replace or substitute for anthologies, compilations or collective works. Such replacement or substitution may occur whether copies of various works or excerpts therefrom are accumulated or reproduced and used separately.

B. There shall be no copying of or from works intended to be "consumable" in the course of study or of teaching. These include workbooks, exercises, standardized tests and test booklets and answer sheets and like consumable material.

C. Copying shall not:

(a) substitute for the purchase of books, publishers' reprints or periodicals;
(b) be directed by higher authority;
(c) be repeated with respect to the same item by the same teacher from term to term.

D. No charge shall be made to the student beyond the actual cost of the photocopying.

Publications Address List

ADIRONDACK WIND ELECTRIC, INC.
Warrensburg, New York 12885

BLAIR & KETCHUM'S COUNTRY JOURNAL
205 Main Street
Brattleboro, Vermont 05301

CIVIL ENGINEERING
345 East 47th Street
New York, New York 10017

ENVIRONMENT
Heldref Publications
Albemarle Street, N.W.
Room 504
Washington, D.C. 20016

FAMILY HANDYMAN
1999 Shepard Road
St. Paul, Minnesota 55116

FARM JOURNAL
230 West Washington Square
Philadelphia, Pennsylvania 19105

HUMAN ECOLOGY FORUM
New York State College of Human Ecology
Cornell University
Ithaca, New York 14853

NATIONAL JOURNAL
Government Research Corporation
1730 M Street, N.W.
Washington, D.C. 20036

POPULAR MECHANICS
224 West 57th Street
New York, New York 10019

POPULAR SCIENCE
380 Madison Avenue
New York, New York 10017

RODALE'S NEW SHELTER
33 East Minor Street
Emmaus, Pennsylvania 18049

SCIENCE
American Association for the Advancement of Science
1515 Massachusetts Avenue, N.W.
Washington, D.C. 20005

SIERRA
530 Bush Street
San Francisco, California 94108

SOLAR AGE
Church Hill
Harrisville, New Hampshire 03450

YANKEE
Yankee, Inc.
Dublin, New Hampshire 03444

Glossary

a

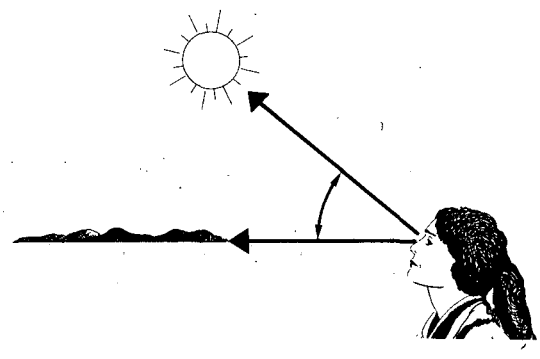
absorber
a surface, usually blackened metal, which absorbs solar radiation and converts it to heat energy in a solar collector.

active solar energy system
a system which requires external mechanical power (motors, pumps, valves, etc.) to operate the system and to transfer the collected solar energy from the collector to storage or to distribute it throughout the living units. Active systems can provide space heating and cooling, domestic hot water, and/or steam for industrial use.

air exchanges
replacement of a given volume of air in a room or an entire building over a period of time. Air exchanges (AE) are sometimes expressed as whole-volume exchanges per hour or, alternatively, as cubic feet per minute (CFM). A standard, insulated new home is expected to have 1 AE/hour; a specially constructed, energy-efficient house may have only 1/2 AE/hour. Drafty, uninsulated houses typically have 3 or more AE/hour.

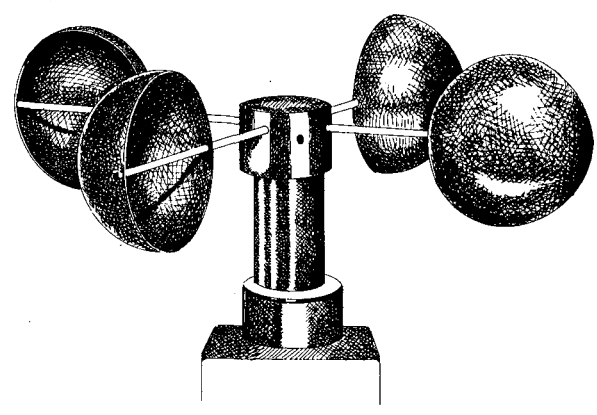
alcohol fuels
primarily grain alcohol (ethanol) and wood alcohol (methanol) which have been used for decades in some European cars and in race cars. Cheap and easy availability of gasoline in the past made them uneconomical. Engine modifications will be necessary if these liquid fuels are to be put into widespread use, but small amounts of ethanol (up to 10% mixture with gasoline, as in gasohol) can be used in most cars without alterations. Alcohol fuels can be made from a variety of materials including crop surpluses, lumber wastes, municipal sewage, and garbage.

altitude
the angle formed between the horizon and the sun.

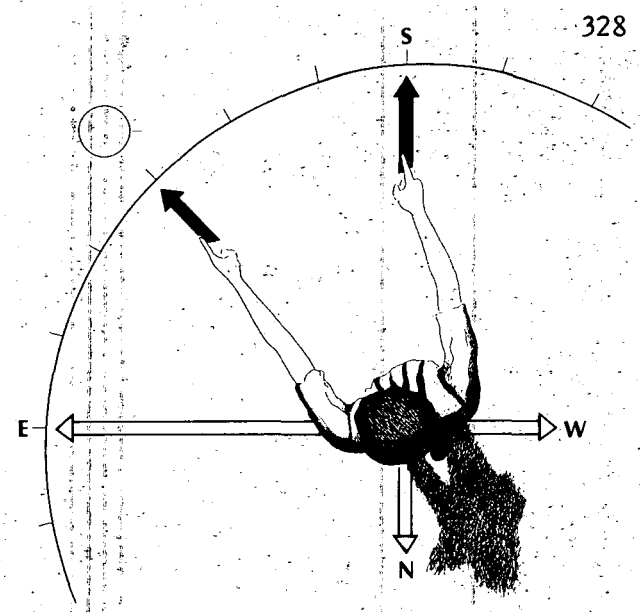


anaerobic digestion
conversion of organic material (crop residue, manure, or sewage sludge, for example) into methane by microorganisms that decompose the wastes in the absence of oxygen.

anemometer
an instrument which measures the speed of the wind.



azimuth
the angle formed between true south and the point on the horizon directly below the sun.



b

backup energy system
an energy system using conventional fuels to supply all the heating and domestic hot water during any period when the solar energy system is not operating.

bioconversion
a general term describing the conversion of one form of energy into another by living organisms. Examples are production of wood and sugars by green plants, production of alcohols and natural gases by microorganisms acting on organic materials, and transfer of energy in food chains.

biofuels
renewable energy sources produced by or from green plants. Examples are grain alcohol, wood, methane from anaerobic digesters, all foods.

biomass
a volume or amount of plant material in any form: algae, wood, plants, crop residue, animal manure, etc.

blanket insulation
cotton fiber, mineral wool, or wood fiber made into lengths of varying thicknesses.

Btu
British thermal unit, a unit for measuring heat; a Btu is the quantity of heat necessary to raise the temperature of one pound of water one degree Fahrenheit, about one-fourth of a kilocalorie (252 calories).

c

calorie (also: gram calorie)
a metric unit of heat energy; the amount of heat needed to raise the temperature of one gram of water one degree Celsius. It equals 0.0039 Btu. One thousand calories make one kilocalorie (kcal), sometimes called a Calorie or a food Calorie.

catalytic converter
a device added to an exhaust system or chimney that converts the air pollutants carbon monoxide and hydrocarbons to carbon dioxide and water. A similar conversion also removes nitrogen oxides.

caulking
a soft, semi-solid material that can be squeezed into nonmovable joints and cracks of a building, thereby reducing the flow of air into and out of the building.

clerestory
a window located high in a wall near the eaves, used for light, solar gain, and ventilation.

collector
any of a wide variety of devices (flat-plate, concentrating, vacuum tube, greenhouse, etc.) which collect solar radiation and convert it to heat.

collector efficiency
the fraction of incoming radiation converted to heat and stored by the collector. If a system captures half of the incoming radiation, the system is 50% efficient.

collector tilt
the angle, measured from the horizontal, at which a solar collector is tilted to face the sun for better performance.

compost
a mixture of decomposing plant refuse, manure, etc. used for fertilizing and conditioning the soil.

concentrator
a reflector or lens designed to focus a large amount of sunlight into a small area thus increasing the intensity of the energy collected. In wind terminology, a device or structure that increases the speed of the wind.

conduction
the transfer of heat energy through a material by the motion of adjacent atoms and molecules.

conservation
making the best use of natural resources by reducing waste, improving efficiency, and slowing the rate of consumption.

convection
the transfer of heat energy from one location to another by the motion of fluids which carry the heat.

cover plate
a sheet of glass or transparent plastic that sits above the absorber in a flat plate collector. (See also: glazing.)

cut-in speed
the wind speed at which a wind machine is activated.

cut-out speed
the highest speed which a wind machine attains, above which it shuts down; designed as a safety feature to prevent structural stresses or failures. The lower the cut-out speed, the less power generated at high wind speeds. Optimum cut-in and cut-out speeds depend on machine design and wind characteristics at the specific site where the wind machine is installed.

d

damper
a device which permits, prevents, or controls the passage of air through an air outlet, inlet, or duct.

deciduous
describes trees and shrubbery that lose their leaves during the fall season of each year and produce new foliage in the spring.

degree day
a unit which describes the severeness of a particular climate, used in the heating industry as a measure of the amount of heating needed. The number of degree days for a particular day equals 65 degrees Fahrenheit minus the average outdoor temperature for that day.

diffuse radiation
indirect sunlight that is scattered from air molecules, dust, and water vapor, and casts no shadow.

direct radiation
sunlight which casts shadows, received directly from the disk of the sun with little atmospheric scattering.

direct solar gain
a type of passive solar heating system in which solar radiation passes through the south-facing living space before being stored in the thermal mass.

draindown
a type of liquid, active solar heating system which protects collectors from freezing by automatically draining when the pump is turned off.

e

earth berm
a bank of dirt that abuts a building, used to stabilize interior temperature or to deflect the wind.

energy
the ability to do work or make things move; the application of a force through a distance. Energy exists in a variety of forms (electrical, kinetic or motion, gravitational, light, atomic, chemical, heat) and can be converted from one to another. Common units are calories, joules, Btu, and kilowatt-hours.

energy audit
the examination of a building's construction and materials, mechanical and electrical systems, energy usage patterns, and fuel history in order to identify possibilities for energy conservation.

entropy
a measure of the energy that is unavailable for use in a system, because it cannot be converted to another form; entropy therefore reflects the inefficiency of a system. The second law of thermodynamics states that the amount of entropy in the universe is constantly increasing.

eutectic salts
a group of materials that melt at a low temperature, and absorb large quantities of heat in the process.

evaporation
the change from liquid to gas which requires extraordinary absorption of heat by the material undergoing this phase change. Liquid water, for example, absorbs 540 extra calories per gram at 100° C as it vaporizes. This heat will be released again if the water vapor condenses.

f

flat-plate collector
an enclosed, glazed panel containing a dark absorbing surface that converts sunlight to heat without the aid of a reflecting surface to concentrate the rays. The collector transfers its heat to a circulating fluid.

foam insulation
styrofoam, rigid foam boards, or liquid foam, used as insulation.

force
the action on a body which tends to change its relative condition as to rest or motion.

g

gasohol
a fuel mixture composed of 90% unleaded gasoline and 10% ethanol (ethyl or grain alcohol).

Glauber's salts
sodium sulfate decahydrate, a eutectic salt that melts at 90 degrees Fahrenheit (32° C) and absorbs about 104 Btu per pound (12 kilocalories per kilogram) as it does so; fairly inexpensive, it is used for storing solar heat.

glazing
the transparent or translucent cover of a solar collector (also: cover plate), or that material which forms a window or skylight. In solar applications, glass or reinforced polyester is usually used as a glazing.

greenhouse effect
a phenomenon which converts solar radiation to heat. Sunlight penetrates glazing quite easily but, when absorbed by objects behind the glazing, is reradiated as heat which does not penetrate the glazing as easily. Heat is thereby trapped and can be used. Also: the warming effect of carbon dioxide and water in the atmosphere acting as a "lid" to slow the escape of heat from the earth's surface. Molecules of water and carbon dioxide absorb and reradiate back to earth much of the heat radiated from it.

h

heat
energy that flows between a system and its surroundings because of a temperature difference between them. Heat results from the motion of molecules of matter. Also, the word heat is often used to refer to the energy contained in a sample of matter (for example, kilocalories per unit of food).

heat capacity (specific heat)
the quantity of heat required to raise the temperature of a given volume of material by one degree in a given system of measurement.

heat exchanger
a device specifically designed to transfer heat between two physically separated fluids.

heat pump
a device that transfers heat from a colder region to a warmer one (or vice versa) by the expenditure of mechanical or electrical energy. The heat pump operates by alternately evaporating and condensing a refrigerant, or heat transferring fluid, in a closed cycle. It differs from a typical refrigeration unit in that the heat pump can reverse its cycle to provide heat instead of removing it. Heat pumps are both heaters and air-conditioners and, compared to electric resistance elements often used in all-electric homes, they are more efficient.

heat sink
a medium (gas, liquid, or solid) capable of accepting and storing heat.

heliostat
an instrument consisting of a mirror mounted on an axis moved by clockwork; used to reflect the sun's rays into a solar collector or furnace.

horizontal shaft wind turbine
a wind machine on which the shaft that the rotors are attached to is parallel to the earth.

hybrid solar energy system
a system that uses both active and passive methods to operate.

hydroelectric plant
an electric power plant in which the energy of falling water is converted into electrical energy by a turbine generator.

i

indirect solar gain
a type of passive solar heating system in which the storage is placed between the collecting and the distributing surfaces (example: Trombe wall, water wall, or roof pond).

infiltration
the uncontrolled movement of outdoor air into a building through cracks around windows and doors, and in walls, roofs and floors. (See also: air exchanges.)

infrared radiation
the invisible rays just beyond the red of the visible spectrum; their wavelengths are longer than those of the spectrum colors and they have a penetrating heating effect.

insolation
the energy received by earth from the sun, a contraction of the three words: incoming solar radiation. The total daily insolation is the equivalent of about 4.2 quadrillion kilowatt hours. Local insolation depends on the position of the earth in its orbit, the thickness and transparency of the atmosphere, the inclination of the intercepting surface to the sun's rays, and the solar constant. Weather bureaus now keep insolation data or "sunshine statistics".

insulation
material with high resistance (R-value) to heat flow. Some commonly used materials for home insulation are fiberglass, cellulose, rock wool, and styrofoam.

isolated solar gain
a type of passive solar heating system in which heat is collected in one area (sunspace, attic collector) and used in another (living spaces).

j

joule
a metric unit of work, mechanical energy, and heat; approximately equal to 0.74 ft-lbs or 0.00095 Btu or 0.24 calories. It is defined as the energy expended in one second by an electric current of one ampere with a resistance of one ohm.

k

kilowatt
a measure of power, usually electrical power or heat flow; equal to 1,000 watts or 3,413 Btu per hour.

kilowatt-hour
the amount of energy equivalent to one kilowatt of power being used for one hour; equals 3,413 Btu, or about 860 kcal.

l

langley
a unit of solar energy, its radiation intensity is equivalent to 1.0 calorie/cm^2. It can be used as a power unit when flow over time is expressed as langleys/min or langleys/hr or langleys/day. One langley/min = 221.2 Btu/hour/ft^2. One langley/min also = 697.3 watts/m^2 or 16.74 kWh.

latent heat
the amount of heat in calories or Btu absorbed when a material changes its state from a solid to a liquid or from a liquid to a gas. Latent heat is recovered by freezing a liquid or by condensing a gas.

latent heat storage
use of a heat-absorbing material's phase change behavior to design a compact thermal storage system. Unusual amounts of heat are absorbed by some solids at their melting points without causing their temperature to change. This hidden or "latent" heat is then stored in liquids until they resolidify. An example is ice, which absorbs 80 additional calories per gram after it has been warmed to 0° C and before it melts. This heat is released again only when water refreezes. Certain hydrated salts with low melting points (eutectic salts) and paraffins melt and store latent heat in the 32° C - 45° C range (90° - 113° F) easily attainable by flat-plate collectors even on cloudy days. This gives them potential for domestic heat storage. Ponds and blocks of ice are also being used for latent heat storage in some experimental heating and cooling systems.

life cycle costs
the total costs of an item including initial purchase price as well as cost of operation, maintenance, etc. over the life of the item.

loose insulation
small pieces of insulation which are blown into place.

m

megawatt
a unit of power equal to 1,000 kilowatts or one million watts.

methane gas
a colorless, flammable, gaseous hydrocarbon, emitted by marshes and by dumps undergoing decomposition; can also be manufactured from crude petroleum or other organic materials.

n

nonrenewable resources
energy resources that are not being replaced during the time span of human history. Examples are coal, oil, natural gas, and uranium.

o

ocean-thermal energy conversion (OTEC)
an energy technology in which the temperature difference (between cold deep water and the warm surface water 2,000 feet above it) in tropical oceans is used to generate electricity.

overhang
a solid horizontal or angled projection on the exterior of a building placed (ideally) so that it shades southern windows in summer only. An overhang may be fixed or movable, part of the original construction or a retrofit. Several designs are possible. An upward-tilted overhang can also serve as a reflector in winter.

p

passive solar energy system
an assembly of natural and architectural components which converts solar energy into usable or storable thermal energy (heat) without mechanical power. Current passive solar energy systems often include fans, however.

payback period
the time needed to recover an investment.

phase change
the process involved when a material changes from a solid to a liquid or from a liquid to a gas, each phase change requiring absorption of energy with no temperature change; or when the material changes from a gas to a liquid or a liquid to a solid, each phase change requiring a loss of energy with no temperature change.

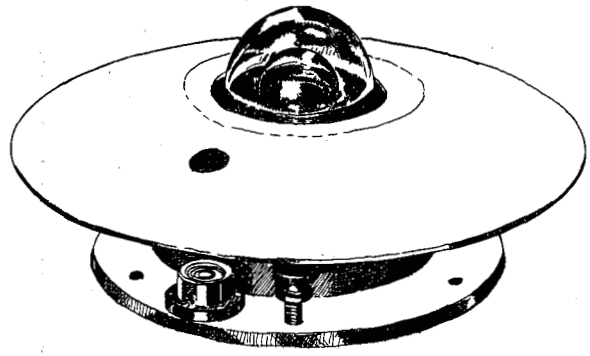
photosynthesis
green plants' process of using solar energy to convert simple molecules into complex ones with high potential energy. Carbon dioxide and water are combined, in the presence of sunlight and chlorophyll, into carbohydrates such as sugars, starches, oils and cellulose.

photovoltaic cell
a device which converts solar energy directly into electricity. Sunlight striking certain materials (silicon is most common) causes the release of electrons. The migration of these released electrons produces an electrical current. The conversion process is called the photovoltaic effect.

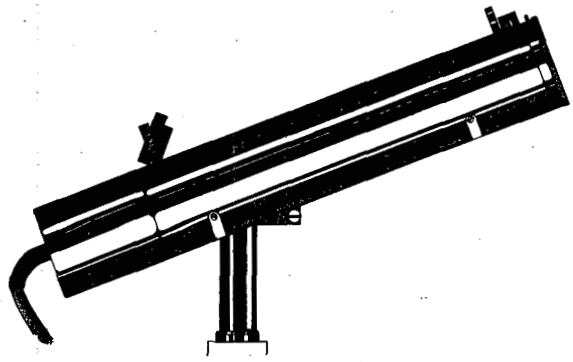
power
the rate at which work is performed. It is measured as units of energy per unit of time, for example: calories per second, watts (joules per second), or horsepower (foot-pounds per second).

pumped storage
a method whereby excess electricity produced during periods of low demand is used to pump water up to a reservoir. When demand is high, the water is released to operate a hydroelectric generator. Pumped energy storage only returns about 66% of the electrical energy put into it, but costs less than the cost of constructing the equivalent generating capacity.

pyranometer
an instrument for measuring the intensity of both direct and diffuse solar radiation.



pyrheliometer
an instrument that measures the intensity of the direct radiation from the sun; the diffuse component is not measured.



q
r

radiation
the method by which heat is transferred through open space. About 60% of the heat transferred to a room from a wood stove is by radiation. Sunlight travels to us by radiation through space at "the speed of light", 299,728 kilometers per second.

rated output
the maximum output generated by a wind machine.

rated wind speed
the speed at which a wind machine produces its maximum output.

renewable resources
materials that are recycled by natural processes within a relatively brief span of time (a human lifetime). Fresh water, wind, sunshine, and trees are some examples of resources that replace or recycle themselves within human time frames.

retrofit
to modify an existing building by adding a solar heating or cooling system or insulation to improve its energy efficiency.

rotor
a rotating blade or other surface moved by the wind.

R-value
the resistance to heat flow, reciprocal of U-value. The higher the R-value, the greater the insulating efficiency of the material. R-values are commonly stated per inch of building material. R-values are additive--thicker material or a combination of materials means increased resistance to heat flow. Some typical R-values per inch of material are 6.25 for polyurethane foam, 3.17 for fiberglass batts, 1.25 for fir and pine wood, 0.18 for plaster, and 0.08 for concrete.

S

selective surface
a special coating sometimes applied to the absorber plate of a solar collector. The selective surface absorbs most of the incoming solar energy and reradiates very little of it.

sensible heat
heat which, when gained or lost, results in a change in temperature.

shroud
a structure used to concentrate or deflect the wind.

solar access or solar rights
the right to receive direct sunlight without interference. The protection of solar access is a legal issue.

solar cell
see photovoltaic cell.

solar constant
the average amount of solar radiation reaching the earth's atmosphere per minute, 1,350 watts per square meter or 429 Btu per square foot per hour.

solar energy
the electromagnetic radiation emitted by the sun. The earth receives about 4,200 x 10^{15} kilowatt-hours of solar radiation per day.

solar furnace
a device using mirror reflectors or lenses to produce very high temperatures at a focal point or "hot spot." Small backyard furnaces generate temperatures as high as 1,100 degrees Celsius; the largest solar furnace in the world reaches 3,100 degrees Celsius.

solar greenhouse
a sunspace containing thermal mass and used to grow plants.

solar pond
a shallow pond of deliberately layered water, concentrated salt water on the bottom and fresh water on top, used to collect solar heat. The dense salt water resists rising, even when heated by the sun. When it gets hot (about 80° C), it is pumped into coils of a heat exchanger to vaporize a volatile liquid that, in turn, is directed against blades of a turbine to produce electric current. Israel has an active solar pond program. Southern California Edison plans a demonstration facility at the Salton Sea in Imperial Valley. Some home builders are also using solar salt ponds for energy storage in conjunction with heat pumps for year-round space heating and cooling.

stagnation
a high temperature condition occurring in a solar collector when the sun is shining and no fluid is flowing through the collector; temperatures range from 250 degrees Fahrenheit to 400 degrees Fahrenheit (120° - 205° C), depending on collector design. Any condition under which a collector is losing as much heat as it gains.

Stirling engine
an external combustion engine in which air (or hydrogen in the newer versions) is alternately heated and cooled to drive the piston up and down. It is claimed to be nonpolluting and more efficient than the internal combustion engine.

storage
the device or medium that absorbs collected heat and stores it for later use.

sunspace
a living space enclosed by glazing; a sunroom or greenhouse.

sun tempering
technique for taking advantage of solar radiation for winter heating but controlling solar gain for summer cooling; does not assume distribution or storage.

t

temperature
a measure of the energy of motion of the atoms and molecules of a substance. Thermometers and thermistors are used to measure an object's temperature. Temperature is not the same as heat. The tip of a burning match has a high temperature, but the object as a whole might contain very little heat due to its size.

therm
a unit used in heating calculations, equal to 100,000 Btu, the energy of approximately 100 cubic feet of natural gas.

thermal mass
mass used to store heat energy, usually collected solar energy. Insulated rock bins, sand beds, and containers filled with water or eutectic salts have been used successfully as thermal masses.

thermal pollution
degradation of water quality by the introduction of a heated effluent. Primarily a result of the discharge of cooling waters from industrial processes, particularly from electrical power generation.

thermal storage
a system which uses brick, rocks, concrete, water walls, salt ponds, eutectic salts, or other materials to store heat energy. Thermal storage is especially desirable for solar-heated homes.

thermosiphoning
heat transfer in a fluid (air, liquid) by means of currents resulting from the natural fall of heavier, cooler fluid and rise of lighter, warmer fluid.

thermostat
a temperature-sensitive device which turns heating and cooling equipment on and off at set temperatures.

tracking
for a solar collector, the process whereby the panel follows the sun.

transfer medium
the fluid that carries heat from the solar collector to storage or from storage to the living areas.

Trombe wall
masonry, typically 8 to 16 inches thick, blackened and exposed to the sun behind glazing; a passive solar heating system in which a masonry wall collects, stores, and distributes heat.

turbine
a motor, the shaft of which is rotated by a stream of water, steam, air, or other fluid from a nozzle. The fluid is forced against the blades of a wheel.

U

U-value (coefficient of heat transmission)
the rate of heat transmission measured per degree of temperature difference per hour, through a square foot of wall or other building surface; the reciprocal of R-value.

V

vapor barrier
a waterproof liner used to prevent passage of moisture through the building structure. Vapor barriers in walls and ceilings should be located on the heated surface of the building.

vertical shaft wind turbine
a wind machine on which the shaft supporting the rotors is perpendicular to the earth.

W

watt
a unit of measure for electrical power equal to the transfer of one joule of energy per second. The watt is the unit of power most often associated with electricity and is determined by multiplying required volts by required amperes. One horsepower = 746 watts.

weatherstripping
material which reduces the rate of air infiltration around doors and windows. It is applied to the frames to form a seal with the moving parts when they are closed.

WECS (wind energy conversion system)
a system which converts mechanical energy from the wind to electricity, heat, or fuel which is used directly or stored.

windbreak
a dense row of trees, or a fence or other barrier that interrupts and changes the local path of the wind.

wind charger
a wind machine equipped with a generator to produce electric power.

wind chill factor
the relationship between cooling conditions at various temperatures and wind speeds, as measured by the freezing rate of water sealed in a plastic container and exposed to winds of various speeds at a given temperature. The enclosed water models human flesh. The experiments were devised by Antarctic scientists who wanted to know how fast their faces would freeze under certain conditions. All materials and systems lose heat faster when wind is blowing, so this factor should be considered, in addition to degree days, in estimating heating requirements of buildings and machinery in windy regions.

window treatments
applications to the interior side of windows (blinds, shades, shutters, draperies).

wind turbine generator
see wind charger.

work
energy transferred from one object to another, that is, a force acting against resistance to produce motion in a body; measured by the product of the force acting and the distance moved through, against the resistance.

X Y Z

zoned heating
the control of temperature in a room, or group of rooms, independently of others.

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