Chapter XI

TECHNICAL OPTIONS

Chapter XI.--TECHNICAL OPTIONS

Page

Improved Building Envelopes. 227
Insulation 227
Interior and Exterior Cladding for Wall Retrofit 228
Installation Quality 229
Wall Sandwich Configuration. 229
Infiltration Control 229
Window Technology. 231
Improved Windows. 233
Heating and Cooling Equipment. 240
Direct Fossil-Fired Heating Equipment .. 240
Oil arid Gas Furnace Efficiency Improvements. . , ... , ...241
Advanced Fuel-Fired Equipment. 242
Pulse Combustion Furnaces and Boilers. 242
Fuel-Fired Heat Pumps 244
Electric Air-Conditioners and Heat Pumps **244**
Gas-Fired Heat Pumps and Air-Conditioners **250**
Absorption Air-Conditioners **250**
Absorption Heat Pumps **250**
Other Gas-Fired Heat Pumps. **250**
Integrated Appliances **252**
Air-Conditioner/Water Heater. **252**
Furnace/Water Heater Systems. **253**
Refrigerator/Water Heater **253**
Drain Water Heat Recovery **253**
Summary. , ...254
Controls and Distribution Systems 254
Passive Solar Design 256
Direct Gain Systems 257
Indirect-Gain Passive Buildings 259
Hybrid Passive Systems. 263
Cost of Heat From Passive Solar Heating Systems. 264
Cost of Heat From Fossil Fuels and Electricity 268
Summary. 270
Technical Notes–– Fossil Fuel Prices. 272

TABLES

Page

75 Summary of New Fenestration Technologies. .239
76 Heating Equipment and Fuels for Occupied Units in 1976............240
77 Refit Modifications for Efficiency Improvement of Oil-Fired Boilers 241
78 California Standards for Cooling Equipment 249
79 DOE Room Air-Conditioner Energy-Efficiency Improvement Target 249

Page

80. DOE Central Air-Conditioner Energy-Efficiency Improvement Target 249
81. Estimated Performance of Carrier Hot Shot® Heat Recovery Unit **With** a 3-Ton Air-Conditioner and a Family of Four. 253
82. Cost of Heat From Passive Solar Heating Installations 268
83. Cost of Heat Supplied to Houses From Fossil Fuels and Electricity 269

FIGURES

Page

22. Air Leakage Test Results for Average Home of 1,780 sq. ft. 230
23. The Double-Sided Blind 234
24. Triple Blind, Winter Day Mode. 234
25. Shades Between Glazing With Heat Recovery. 235
26. Between Glazing Convection and Radiation Control 235
27. Multilayer, Roll-Up Insulating Window Shade 235
28. Insulating Window Shade 236
29. Window Quilt Insulating Window Shade 236
30. Skylid 236
31. Beadwall. 237
32. Beam Daylighting 237
33, Selective Solar Control 237
34. Heat Mirror. 238
35. Optical Shutter 238
36. Weather Panel® 238
37. Typical Energy Flow for a Gas Furnace System. 241
38. Principles and Operation of the Hydro-Pulse Boiler Which Uses the Pulse-Combustion Process 243
39. A Typical "Split System" Heat Pump Installation 245
40. Air-Conditioning COP of Heat Pumps and Central Air-Conditioning Units Shipped in 1977 246
41. Performance of the Carrier Split-System Heat Pump 247

Page

42. The Seasonal Performance of Heat-Pump Units as a Function of Local Climate. .. 248
43. Estimated Cost of Increasing the Performance of Air-Conditioners From the Industry Average COP of 2.0 to the Performance Levels Indicated. . .249
44. Modified Saltbox Passive Solar Design Home 257
45. The Fitzgerald House Near Santa Fe, N. Mex., is 95-Percent Solar Heated by a Direct-Gain System at a 5,900 Degree Day Site 258
46. The Kelbaugh House in Princeton, N.J., Receives 75 to 80 Percent of Its Heat **From the Trombe Wall and the Small Attached Greenhouse. 260**
47. The Crosley House in Royal Oak, Md., Comblnes a Trombe Wall System With Direct Gain and a Massive Floor, to Provide 50 to 60 Percent of Its Heating Needs . . 261
48. The Benedictine Monastery Off ice/ Warehouse Near Pecos, N. Mex., Uses Direct Gain From the Office Windows and Warehouse Clerestories Combined With the Drumwall Below the Office Windows to Provide About 95 Percent of Its Heating Needs. 262
49 The PG&E Solarium Passive Solar Home in (California Uses the Large Skylight to Heat Water-Filled Tubes on Three Walls of the **Solarium . . . . , ...263**
50 This Retrofit Sunspace is Manufactured by the Solar Room Co. of Taos, N. Mex.. . .264
51 This Retrofit Greenhouse is an Example of Those Built by the Solar Sustenance Project. 265
52. The Balcomb Home Near Santa Fe, N. Mex., Combines the Use of a Greenhouse With a Rock Storage Bed to Provide 95 Percent of Its Heating Needs 266
53. This Home in Los Alamos, N. **Mex.,** Combines a Large Trombe Wall With Small Direct Gain Windows and a Rock Storage **Bed. 267**
54. Solar Feasibility for Trombe Wall With Night Insulation Alternative Fuel – Natural Gas. 271

Chapter XI

TECHNICAL OPTIONS

Technology is already available to at least double the energy efficiency of housing, but further improvements in technology promise a significant impact on savings. Conservation, possible with specific combinations of existing technology, is illustrated in chapter 11. This chapter discusses a much broader set of technical options, including many still in the developmental stage.

Design of an energy-efficient house usually starts with a tightly built and well-insulated thermal envelope (exterior walls, windows, etc.) and adds efficient equipment for heating, cooling, hot water, and other energy needs. The thermal envelope and equipment technologies, which must be combined to build an efficient house, are considered individually in this chapter. Interactions between different types of energy-using equipment, which were treated earlier, are not repeated. Additional information about most of these topics appears in volume 11 of this report.

Many improved window systems and passively heated buildings represent marked departures from present building technology and practice; most of the other technical changes identified in this chapter are incremental improvements of existing materials or equipment. This does not mean that further research and development is unimportant. Figure 14 in chapter I I shows that the total cost of owning and operating a house with energy-saving improvements changes very little over a wide range of investment, so incremental improvements in technology would substantially increase the optimum investment level and energy savings. Improvements being developed would also greatly increase the options available for meeting a performance standard, such as the building energy performance standards (BEPS). These added options could greatly increase the willingness of the housing decisionmakers to invest in energy efficiency and hence lessen the institutional resistance to building energy- efficient houses.

IMPROVED BUILDING ENVELOPES

Insulation

Minimizing the amount of heat lost from the interior is usually the first step toward constructing an energy-conserving house. This approach is almost always taken when the retrofit of a building is considered as well. It is frequently assumed that this merely means adding more insulation in the walls and over the ceilings, using storm windows and doors, and caulking and weatherstripping all of the cracks in the building. However, new ways of using these techniques are being implemented, and significant new products are being developed.

Thermal transmission through walls, ceilings, and floors is the single largest source of heat transfer in a typical house. While many older homes were built without insulation, virtually all new houses contain at least some insulation to reduce heat loss. Many different insulating materials are used including rock wool, fiberglass, cellulose, cellular plastics (such as polystyrene, urethane, and ureaformaldehyde), perlite, vermiculite, glass foam, and aluminum multifoil. The characteristics of these materials and insulation standards are discussed in appendix A. That discussion includes insulation properties, health and fire safety issues, and production capacity.

The choice of insulation depends on cost, application, availability, and personal preference. New wall cavities are generally filled with rock wool or fiberglass batts while plastic foam sheathing may be added to the exterior. Retrofit of walls built without insulation is generally accomplished by drilling holes between each pair of studs and blowing in fiberglass, cellulose, or ureaformaldehyde. Insulation is occasionally added to the exterior if new siding is installed. Attics are insulated with batts or loose-fill insulation. Fiberglass, rock wool, and cellulose are widely used, but perlite and vermiculite are also used **in attics. Floors are seldom insulated, but fiberglass batts are the most frequent choice for this application. Foams such as polystyrene** or urethane are generally used **when foundations or basements are insulated.**

Cost-effective levels of insulation can substantially reduce heat losses as illustrated in chapter II.

Thus it might seem that new insulation material and techniques would represent a new technology area of substantial importance.

It appears, however, that this is not the case. Contacts with industry and with national laboratories indicate that new technology developments will not make a large contribution to insulation materials and practices. What advances do occur by 1985-90 will primarily augment existing techniques; not represent major new directions. A basic difficulty in assessing this area is that major companies carefully keep their new product developments to themselves. Nevertheless, the following points emerge:

1. Major breakthroughs in the cost per unit of insulating value of major insulating materials are not expected, and no fundamentally new materials of high cost-effectiveness are anticipated.
2. In frame wall cavity retrofit, incremental improvements may be expected in the handling and performance characteristics of the major materials, but no fundamental breakthroughs are anticipated.
3. New systems for reinsulating the exterior surfaces of walls are being developed, but, again, no fundamental change is expected.
4. Changes in wall sandwich configurations for new buildings are being developed that will result in more efficient wall performance.
5. The quality of installation is a major problem and may be the area in which insulation effectiveness can be most improved over the next decade.

Each of these areas provides a range of new opportunities, but institutional constraints may limit implementation. The technical advances that are likely may be only incremental, but this could result in houses with substantially less energy consumption and lower lifecycle cost.

The price of insulation has increased sharply in the last 4 years, but this is largely due to a temporary lack of capacity in the industry, and future increases should be more directly related to cost increases. However, it does not appear that ways will be found to make significantly cheaper insulation, as the materials already used are quite inexpensive. **It is expected that the price of insulating materials will generally** keep pace with inflation.

Improved materials for retrofitting wall cavities would be useful since all of the materials **now in use have at least one drawback.** The labor cost is typically one to two times as great as the material cost for these retrofits. Thus, any dramatic drop in the installed price would require a less expensive material that also offered simplified installation.

Interior and Exterior Cladding for Wall Retrofit

In retrofitting exterior walls for improved thermal performance, an alternative to filling the wall cavity is the application of a layer of insulation over the exterior or interior wall surface, followed by re-covering of the wall. The advantage of this approach is that the insulation layer is monolithic (rather than broken by framing members) and that a wide range of durable and highly effective insulating materials is available for this application. This approach also has its disadvantages. If an interior insulating layer is used, the available interior space is reduced, the living space must be disrupted, and there are refinishing problems. If an exterior cladding is used, a sound weatherproof finish must be applied over it. Generally, exterior systems are more practical and have received more attention in the marketplace.

A number of complete insulation and siding systems are already on the market. None of these, however, is cost-effective purely as an energy-conserving measure; they are cost-effective only on the assumption that it is necessary to re-side the building anyway. There is no promising technical breakthrough on the horizon. Thus, it appears that wall cladding as a method of retrofit will not become a major energy strategy.

Installation Quality

It is well known that installation quality in both new and retrofit insulation application is a major and continuing problem.

In new construction, common defects include the failure to fill small or narrow cavities with insulation, the failure to pack insulation properly around and behind electrical and plumbing fixtures, and the incomplete coverage of cavities with insulation. The last problem is particularly serious if the defect extends vertically for a significant distance because convection currents are thereby set up that result in rapid heat transfer. I n general, the percentage increase of heat loss is disproportionate to the area of the defect, because of the action of air infiltration and internal air currents.

In the retrofit of existing construction, serious problems exist in reinsulation of wall cavities. As the framing pattern is not easily apparent from the outside of the building, it is common to miss small cavities entirely. Even when a cavity is located, the filling may be incomplete or the insulation may be hung up on internal obstructions. The fact that the extent of coverage of the completed installation cannot be seen results in a basic quality-control problem.

It is likely that increased understanding of these problems will result in corrective efforts by conscientious builders and inspectors. Infrared thermography can be used to detect installation defects by taking a "heat-loss picture" of a house, but the cost of the equipment and other factors have limited its use to date.

Wall Sandwich Configuration

The typical exterior residential frame wall is insulated by glass or mineral fiber insulation with a thermal resistance value of R-11 or R-13, fastened between 2x4 framing members. The interior and exterior wall surfaces and framing are composed of materials of low to moderate insulating value. Exclusive of openings, 15 to 20 percent of the area in such a wall is given over to framing. This portion of the wall area, insulated only by standard building materials, accounts for a disproportionate amount of the total wall heat loss; a framing area of 15 percent accounts for approximately 30 percent of the total heat loss through the wall.

A number of improved wall configurations and details have been developed and are finding increasing use. These, in general, involve increasing the total amount of insulation, usually from about R-1 3 to about R-20, and changing the wall sandwich to either reduce the size of framing areas or to insulate them. Several of these configurations are described on pp. 500-505 of volume I 1.

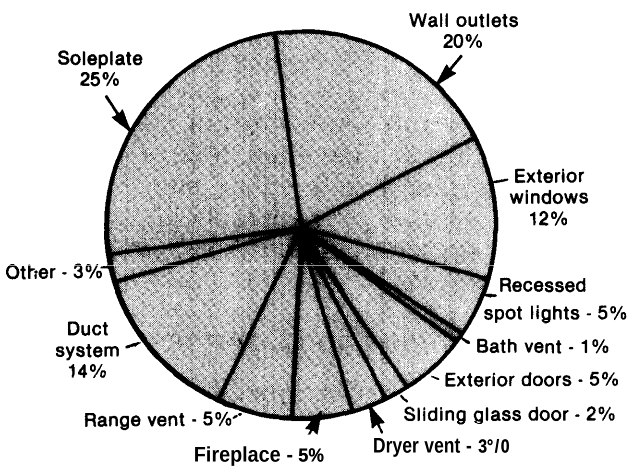
Infiltration Control

Infiltration has traditionally been a major source of thermal inefficiency in homes. According to various estimates, it accounts for between 20 and 40 percent of all heat transfer through the building envelope, in both old and new construction. While the absolute magnitude of infiltration losses has declined with the advent of tighter building components and techniques, the decline has been comparable to the reduction in conductive losses. There is clear potential for large energy savings from further infiltration control.

Infiltration depends on how a house is built and used. **It** increases whenever the wind speed or indoor-outdoor temperature difference increases and may vary from near zero on a calm spring day to several air changes per hour (ACPH) on a windy winter day. These basic facts are well known, but overall infiltration behavior is rather poorly understood and documented. A review of the literature several years ago determined that the average infiltration rate for most houses in the United States was 0.5 to 1.5 ACPH,[1] and no substantial changes have yet occurred.

The aggregate percentage breakdown of air leakage from different sources is illustrated in figure 22. This figure is based on measurements of 50 single-family homes by the Texas Power and Light Company. It shows that nearly half of the leakage occurs through electrical outlets and cracks between the foundation and the walls, with a surprisingly small contribution from windows and doors.

Figure 22.—Air Leakage Test Results for Average Home of 1,780 Sq. Ft.
(50 homes tested by Texas Power & Light Co.)



SOURCE: "Reprinted with permission from the American Society of Heating, Refrigerating, and Air-Conditioning Engineers "

It is possible to build a house very tightly if the builder uses the right materials with sufficient care. The "Saskatchewan Conservation House" in Regina, Canada, has uncontrolled infiltration of only 0.05 ACPH.[2] However, it is not known whether the average builder could build houses this tightly. The present Swedish building standard[3] requires that a house have a maximum leakage rate that corresponds to about 0.3 AC PH. It is enforced by measuring the leakage in a sample of the homes by each builder.

Insulation standards can be very specific and simple visual checks can determine whether the standard has been met. By contrast, infiltration reduction requires the use of materials and techniques in places that are inherently inaccessible and invisible. It appears that the only way to ensure compliance with an infiltration standard is to measure it as part of the inspection process.

There are two basic approaches to infiltration measurement. In the first, a small amount of sulfur hexafluoride (SF_6) or some other tracer gas is circulated through the house with the furnace blower and its concentration is measured several times during the next hour or two. Analysis of these measurements determines the infiltration rate for the specific wind and temperature conditions at the time of the measurement. The air samples can be taken in plastic bags and analyzed in a laboratory, so no elaborate equipment is required at the house. The other technique uses a large fan to suck air out of the house and measures the volume exhausted at different indoor-outdoor pressure differences (fan speeds). This provides a "leakage" measurement of the house that is relatively independent of the weather conditions and individual leaks can be located with the use of a smoke source such as incense. Several investigators[4] have attempted to correlate these measurements with actual infiltration rates. The results have been highly variable so, in a strict sense, these measurements should only be considered leakage measurements. The leakage test is used for standards enforcement in Sweden where it requires about 2 hours to test a house. [5] The equipment used in the test can be purchased for about $500.

[1] T. H. Handley and C. J. Barton, "Home Ventilation Rates: A Literature Survey" (Oak Ridge National Laboratory, September 1973), ORNL-TM-4318.

[2] Robert W. Besant, Robert W. Dumont, and Greg Schoenau, "Saskatchewan House: 100 Percent Solar in a Severe Climate," *Solar Age*, May 1979, p. 18.

[3] Svensk Bygnorm 1975, Statens Planverks Forfattningssamling, Liber Tryck Publications (Stockholm, Sweden, 1978), PFS 1978:1, 3rd edition.

[4] Investigators who have worked with air infiltration and leakage measurements include Richard Grot, National Bureau of Standards; Robert Socolow, Princeton University; Robert Sonderegger, Lawrence Berkeley Laboratory; Maurice Gamze of Gamze, Korobkin, and Caloger, Chicago, Ill.; and Gary Caffey, Texas Power and Light Company

[5] Stig Hammarsten, National Swedish Institute for Building Research, private communication, May 1979.

A house would use less energy if there were no infiltration, but the occupants would negate this strategy whenever they opened the windows. Alternatively, fresh air could be provided with very little loss of heat by a simple heat exchanger. The Saskatchewan Conservation House heats incoming air with outgoing air by running both through interpenetrating ducts made of plastic sheets separated by wooden spacers. This recovers over **80 percent of the heat. Many Swedish houses that meet the present building standard have experienced air quality problems (such as those dis**cussed in chapter X) and excessive humidity levels. The standard is presently being reviewed and, according to one observer, it will likely be modified to require the installation of a heat exchanger.[6] Minimum acceptable air change rates for homes are not well defined, but a number of people active in the field believe that heat exchangers or some other method of purification are needed if infiltration is below about 0.5 AC PH.

The "technology" for infiltration control is and will remain primarily the plugging of holes and cracks, weatherstripping, and attention to the tightness and quality of construction. Existing products are being used more extensively and others are being used in different ways; plastic sheeting is increasingly used to provide a vapor barrier instead of paper or foil insulation backing. Following the identification of electrical outlets as a major infiltration source, simple foam plastic gaskets that are placed under the outlet covers have come on the market.[7] Improved sealants and caulking materials that are easier to use have become available in recent years. A foam plastic sealant that can be squirted into a crack much like shaving cream is now available; it expands slightly as it cures to ensure a tight seal.[8] Other devices and configurations used to reduce infiltration include outside combustion air intakes for furnaces, water heaters, and fireplaces, and tightly sealable exhaust vents. Each of these changes makes it easier to build a tight house or retrofit an existing house. Further improvements of this nature are likely.

[6]Ibid

[7]Three manufacturers of such gaskets are the Vision Co in Texas, KGS Associates in Greenville, Ohio, and the Armstrong Cork Co.

[8]One manufacturer of such a foam is the Coplanar Corp , Oakland, Cal if.

WINDOW TECHNOLOGY

Windows serve multiple functions. They allow daylight to enter, provide a view of the outside with its changing weather patterns, can be opened to provide ventilation, and admit heat in the form of sunlight. They also allow heat to escape, both by infiltration around the frame and by the normal radiative/conductive/convective heat transfer processes.

From the standpoint of energy-efficient building operation, the ideal window would allow all the sunlight to enter the building whenever heating is needed, and would have very low thermal losses. During the summer when no heating is needed, it would admit only visible light, and only in the quantities needed for lighting and providing a view of the outside. All of the invisible infrared rays (over half of normal sunlight) would be excluded.

The windows in most houses are quite efficient at admitting sunlight—80 to 90 percent of the light striking them passes through. In the summer, shade trees and shades and awnings on the windows limit the heat admitted. But windows have the poorest thermal loss behavior of any part of the building shell. Typically, windows have an R-value of 0.9 to 2, while insulated walls have an R-value of 10 to 15 and insulated attics have an R-value of 15 to 20. There is clearly room for vast improvement.

Early windows were a simple hole in the wall to admit sunlight and allow the occupants to see out, or a translucent material that would admit some light and exclude cold air was used. Glass was a great advance, since it simultaneously let in sunlight and prevented drafts. Double-glazing and shutters have now been used for many years to reduce the heat loss from windows, and shades can prevent overheating in the summer. During the last few decades, most of the development of glass for architectural uses has concentrated on making windows that would admit less sunlight and heat while still providing an adequate view. The early solar control glasses simply absorbed part of the sunlight in the glass with the result that part of the heat entered the building, but much of it stayed outside. Then manufacturers began to put very thin reflective coatings on glass. These reflect most of the sunlight, and in some cases actually cut down on the winter heat loss through the glass because they also reflect the infrared heat waves back into a room. The vastly decreased amounts of sunlight admitted to the building are considered satisfactory because they still permit a good view and greatly reduce glare. These reflective glasses are marketed on the basis of their reduction of air-conditioning loads in the summer and their reduced heat loss in the winter, ignoring the fact that the additional sunlight kept out in the winter would in some cases be helpful. They are generally used on large buildings that have large air-conditioning loads in both summer and winter.

In the last 3 or 4 years, increasing attention has been devoted to new window products that will add to the flexibility of window use and substantially improve their overall effect on the energy requirements of houses. The successful commercialization of these products should make it possible for windows to generally lower the overall energy requirements of a house for space-conditioning.

Windows lose heat by all of the basic heat loss mechanisms discussed earlier: radiation, convection, and conduction. As the contribution of radiation and of convection/conduction is comparable in most windows, reduction of the losses attributable to either of these mechanisms can be important. One factor that has very little effect on heat loss is the thickness of the glass. Doubling the glass thickness has a barely perceptible effect, but the same amount of glass added as a storm window will cut the heat loss in half. The combination of an additional dead air space and layer of glass cuts both radiative and convective losses. **It is** generally true that the heat loss through a window will be divided by the number of panes (e. g., the heat loss through triple-glazing is one-third that through single-glazing).

In addition to multiple-glazing, the basic methods of conduction and convection control have been various forms of blinds, shutters, and curtains. Some sunscreen devices have the effect of baffling the outer air layer and reducing surface convection. Relatively little attention has been paid, in existing windows, to the control of convection between glazing layers. One technique that has been studied is that of filling the interglazing space with heavier molecular weight gases. Use of gases such as argon, sulfur hexafluoride, or carbon dioxide can result in a significant reduction of conduction. It is also possible to make "heat mirror" coatings that allow most of the sunlight to pass through but which reflect heat back into the room.

Room temperature radiation is a major contributor to heat loss, but sunlight has an even larger effect on the energy impact of many windows. Solar radiation at the Earth's surface is approximately 3 percent ultraviolet, 44 percent visible, and 53 percent infrared. The primary intent of glazing is to admit daylight and permit a view. Daylight is "free" lighting from a renewable source and has a more desirable "color" than most artificial light. As with artificial light sources, sunlight, both visible and invisible, is converted to heat energy when absorbed by materials. One property of sunlight, however, is that its lighting "efficiency" is higher than that of artificial light. In other words, for a given level of lighting, sunlight produces one-sixth the heat of incandescent light and slightly more than one-half the heat of fluorescent light.

The use of daylighting is particularly desirable in the summer because it can cut the use of electricity for both lighting and cooling. In winter, the heat from the lights is often useful, but daylighting is still beneficial since it reduces the use of nonrenewable sources.

In the typical design approach to small residential buildings, little attention is paid to the use and rejection of solar radiation. Windows are treated simply as sources of conductive heat loss in winter and of cooling load in summer. In reality, summer heat gain can be greatly reduced and winter heat gain can be significantly increased by appropriately specified and properly oriented windows. It is likely that the sizing and orientation of windows will be more carefully specified in the future.

Shading to keep out heat from the Sun is accomplished most effectively by an exterior shade or reflector. An outer reflective surface is almost as effective, an interior reflector (e. g., a shade) is still quite effective, and absorbing glass is generally less effective.

At night, when sunlight and view are not factors, movable insulation that cuts the heat loss to that of an ordinary wall section can be extremely useful. A single-glass window combined with nighttime insulation can exceed the overall performance of even a triple-glazed window.[9]

Many variations on these ideas are being developed and some products are already on the market.

Improved Windows

Enormous improvements in the energy efficiency of windows could be achieved through the proper use of conventional materials and components. (Some of these approaches are presented in the discussion of *Passive Solar Design* at the end of this chapter.) **In many cases "new" technologies are simply a revival of old ideas and practices. Several technologies and** devices of recent origin that appear to provide significantly improved window efficiency are illustrated and described in figures 23 through 36. These are:

- the double-sided blind,
- the triple blind,
- shades between glazing with heat recovery,
- between-glazing convection and radiation control,
- insulating shades and shutters,
- the Skylid®,
- the Beadwall®,
- beam daylighting,
- selective solar control reflective film, and
- the heat mirror (low-emissivity film),
- the optical shutter, and
- the Weather Panel®.

Some of these technologies have been developed by industry while others have been supported by the Department of the Energy (DOE) through its energy-efficient windows program managed by the Lawrence Berkeley Laboratory. This program has provided support for work on shades between glazing with heat recovery, between-glazing convection and radiation control, multi layer insulating shades, beam daylighting, selective solar control films, heat mirrors, and optical shutters. Testing and evaluation of other concepts and products has been performed.

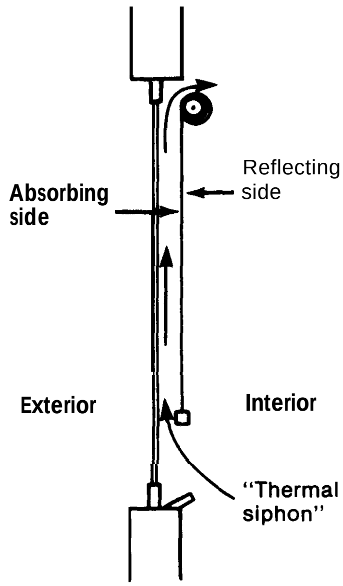
Traditional blinds provide protection from glare and overheating near the window. The blinds illustrated in figures 23 through 26 all provide this protection but also allow the heat to be used elsewhere if desired, reduce the window heat losses, or both.

The devices shown in figures 27 through 37 all serve to reduce the heat losses from windows when the Sun is not shining, and generally do it quite effectively. They can also be used as shades to exclude sunlight when it isn't wanted. The shades shown in figures 27 through 29 incorporate design features that attempt to eliminate air leakage around the edges. The same convective processes that enable the double-sided and triple blinds to distribute heat into the room will effectively cancel the insulating value of a shade if the edges are not tightly sealed. Figure 32 illustrates one approach to increased utilization of daylighting, while figures 33 through 36 illustrate the use of some highly innovative materials. The materials in figures 33 and 34 share the property of transmitting some radiation and reflecting others, but their uses are very different. The heat mirror primarily reduces cool-

[9]D. Claridge, "Window Management and Energy Savings," *Energy and Buildings 1*, p. 57 (1977).

® Registered trademark of Suntek Research Associates, Inc., Coite, Madera, Calif.

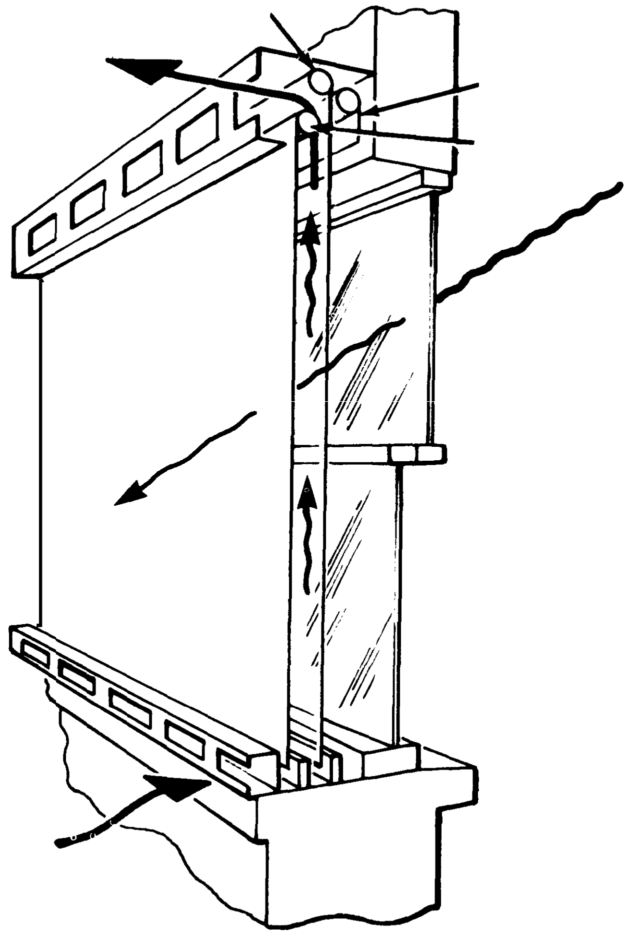
Figure 23.—The Double-Sided Blind



The double-sided blind is used on bright winter days when shading is needed to prevent overheating or glare from large windows. It absorbs and distributes to the room heat that would be reflected outside by an ordinary shade. It functions as an ordinary shade in the summer with the reflective side out.

ing loads while maintaining daylight availability for lighting. The heat mirror will be marketed by a subsidiary of Suntek Research Associates next year. The optical shutter is a passive shading material also under development by Suntek. It works well, but the economics are not considered promising if the shutter material is enclosed in glass. Some work has been done on developing a suitable method for encapsulating it in less expensive plastics. The Weather Panel® (figure 36) is a logical combination of heat mirror and optical shutter technology that could be a major advance in passive heating technology if it can be produced at low cost. A discussion of this system was presented at the Second National Passive Solar conference. '" Weather Panel® combines the advantages of high thermal resistance and shading in a completely passive system. The

Figure 24.—Triple Blind, Winter Day Mode



The triple blind is functionally similar to the double-sided blind, but the clear shade keeps more of the absorbed heat in the house. At night, thermal resistance of R5 is achieved by pulling all three shades, according to the manufacturer, *Ark-tic-seal Systems, Inc.,* **Butler, Wis.**

Cloud Gel® material can be made to turn reflective at any temperature in the range from 00 to 1000 C. (An essential requirement for systems like this is for all parts to last 15 years or more or be readily replaceable.)

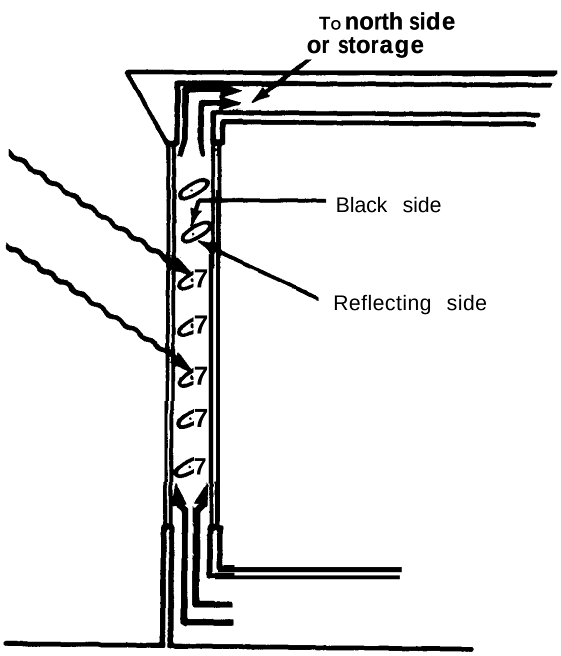
None of these new technologies is the single "best" approach for all conditions. They differ radically from each other in cost, effectiveness, and range of applicability. Table 75 summarizes the salient features of these new technologies. This table presents the performance parameters, operating requirements, estimated cost-effectiveness, applicability to retrofit, and current status of each new technology. The estimates of the level of cost-effectiveness

---

® Registered trademark **of** Suntek Research Associates, Inc., Coite, Madera, Calif.

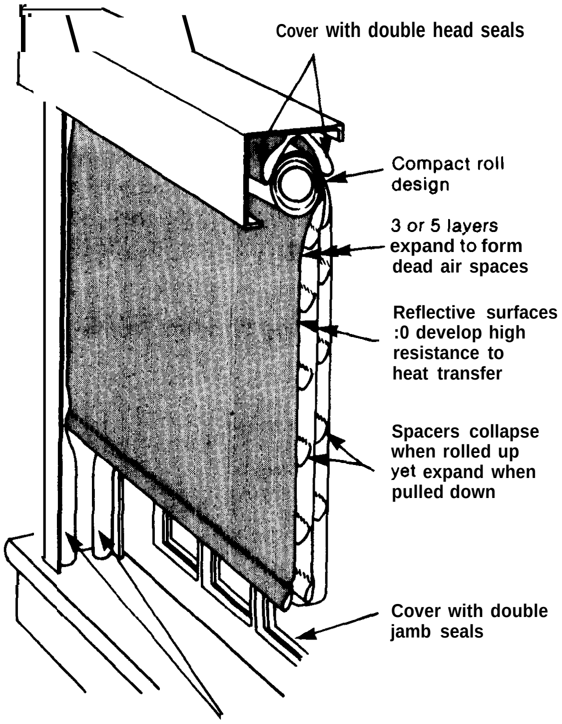
'"Day Charoudi, "Buildings as Organisms," Proceedings of **the Second National Passive Solar Conference, Mar. 16-18, 1978, p. 276 (Philadelphia, Pa.: Mid-Atlantic Solar Energy Association).**

Figure 25.—Shades Between Glazing With Heat Recovery



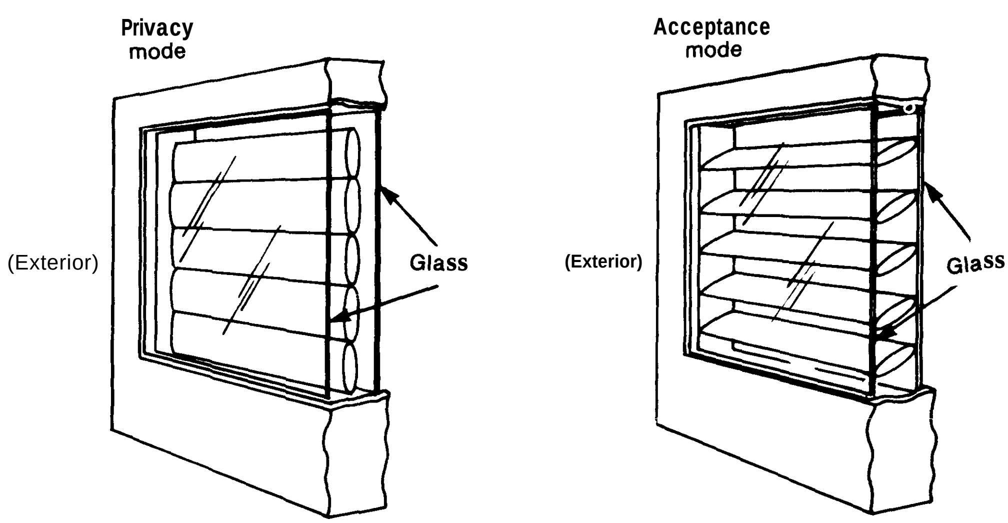
This is optically similar to the double-side blind except that heat is fed into conventional heating ducts and distributed with a blower.

Figure 27.—Multilayer, Roll-Up Insulating Window Shade



This multilayer shade stores in a compact roll and utilizes flexible spacers to separate the aluminized plastic layers and create a series of dead air spaces when in use. The five-layer shade used with double glazing offers thermal resistance of R8 according to the manufacturer, Insulating Shade Co., Guilford, Corm.

Figure 26.—Between Glazing Convection and Radiation Control



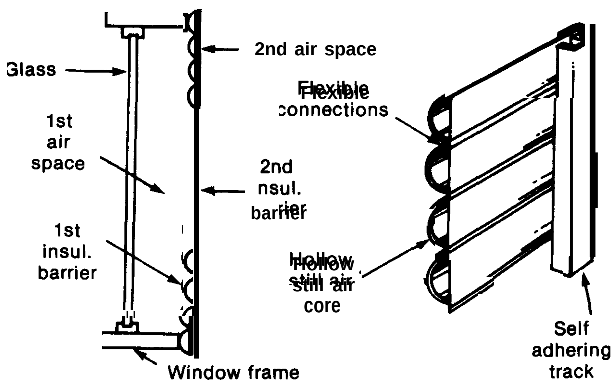
The horizontal slats between the glass suppress convective heat loss. In the "privacy mode," light is excluded and heat loss is reduced further. R3.5 has been achieved and R5 is believed possible with better design and construction.

are qualitative and approximate. They are based only on the length of payback period.

It must be remembered that windows are generally installed primarily for esthetic reasons. While there are a host of window accessories and modifications, probably only storm windows and double-glazing have historically been marketed primarily on the basis of energy savings. Many of these accessories and improvement solve one "problem" and introduce another. **Important** factors in their sale include:

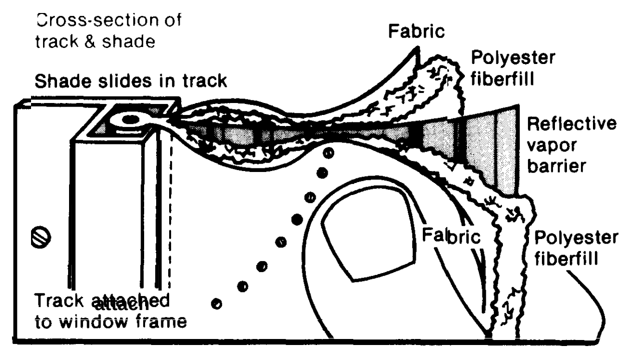
- The desire for privacy. Shades, drapes, and blinds are sold primarily for the privacy they afford. Exterior shutters such as the Rolladen, which are widely used in Europe, **offer both privacy and increased security.**

Figure 28.— Insulating Window Shade



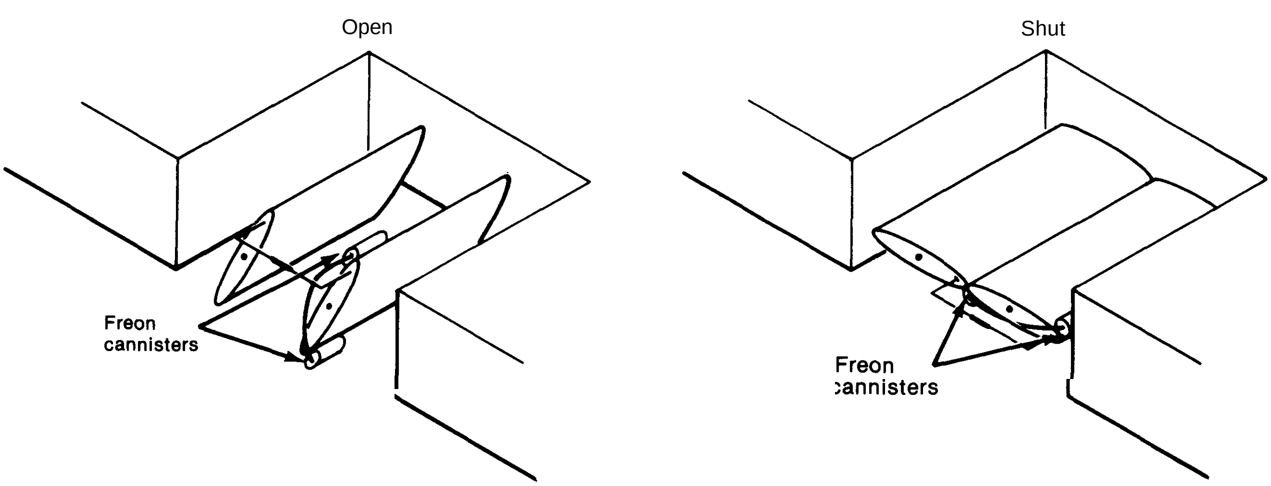
This roll-up shade is made of hollow, lens-shaped, rigid white PVC slats with minimal air leakage through connecting joints. It can be operated manually or automatically and is manufactured by Solar Energy Construction Co., Valley Forge, Pa.

Figure 29.—Window Quilt Insulating Window Shade



This roll-up shade is a fabric covered quilt whose edges slide in a track to reduce infiltration. It offers a thermal resistance of R5.5 when used with a double-glazed window according to the manufacturer, Appropriate Technology Corporation, Brattleboro, Vt.

Figure 30.–Skylid

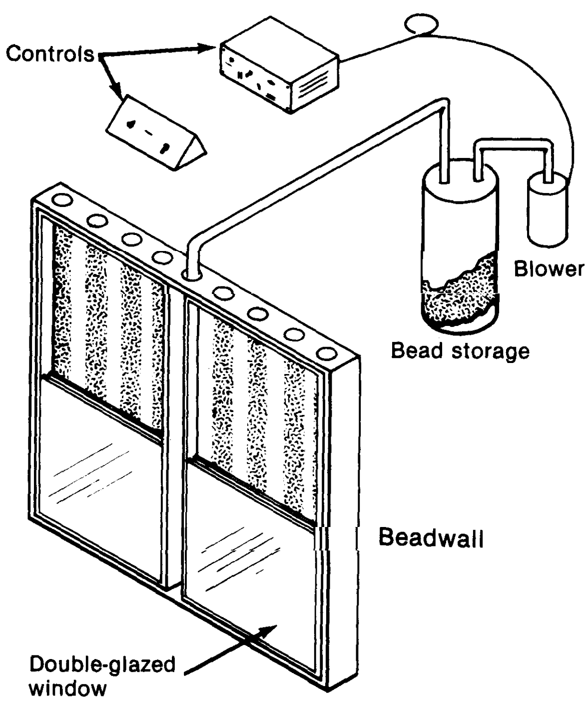


The sky lid is an insulating shutter that operates automatically. It opens when sunlight heats freon in the outer cannister causing it to flow to the inner cannister, and closes by the reverse process. It provides a thermal resistance of R3 when used with single-glazing according to the manufacturer, Zomeworks, Inc., Albuquerque, N. Mex.

- The need for improved comfort is a major factor in the sale of "solar control" glasses. While they also reduce the need for air-conditioning, it is virtually impossible to provide comfort in the full glare of the summer Sun. This is another important consideration in the purchase of shades, drapes, and blinds. The "solar control" glasses also exclude useful winter sunlight.
- The ultraviolet rays in sunlight shorten the life of fabrics and home furnishings. The opaque window covers and some coatings reduce this problem.
- Drapes, shades, blinds, and shutters are opaque. By contrast, heat mirrors, selective solar control films, and between-glazing convection/radiation control devices provide both daylighting and outlook even when in operation.

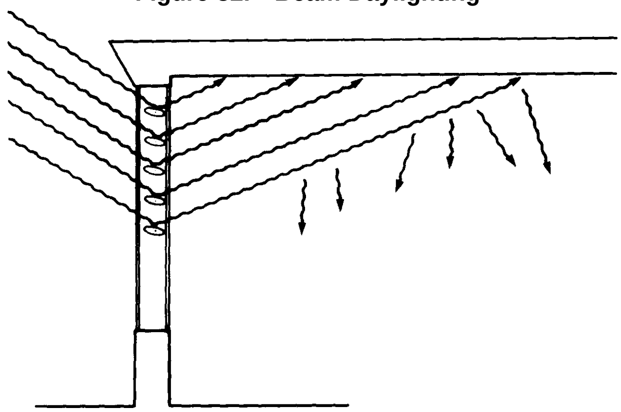
Since reduced energy consumption is only one factor in the choice of window improvements, it is entirely possible, and perhaps likely, that some of the "less cost-effective" improvements that offer other advantages will ultimately become most widely used.

Figure 31.—Beadwall



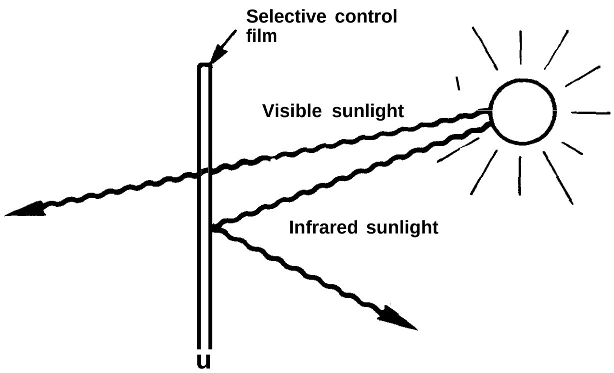
The beadwall uses automatic controls to pump small expanded polyurethane beads between the two layers of glass to provide a nighttime thermal resistance of R8. Beadwall is a registered trademark of Zomeworks, Inc.

Figure 32.—Beam Daylighting



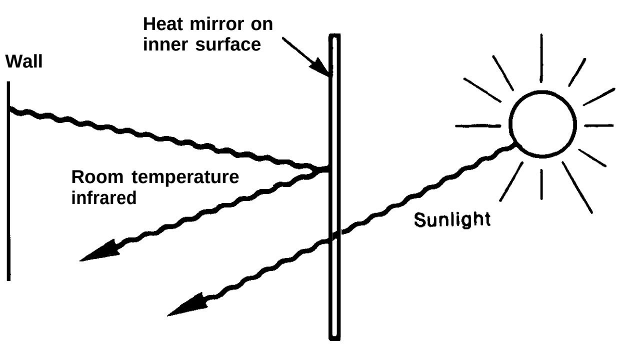
This beam daylighting approach uses adjustable reflective blinds to reflect light off the ceiling far into a room to extend the area where daylight levels are acceptably high.

Figure 33.—Selective Solar Control



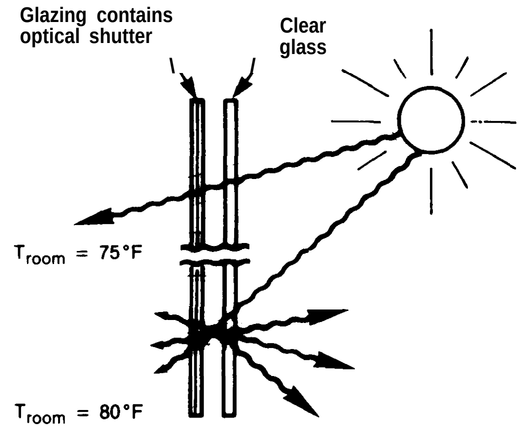
The selective solar control film transmits most of the visible sunlight while reflecting most of the infrared sunlight. This can reduce cooling loads while utilizing available daylight.

Figure 34.-Heat Mirror



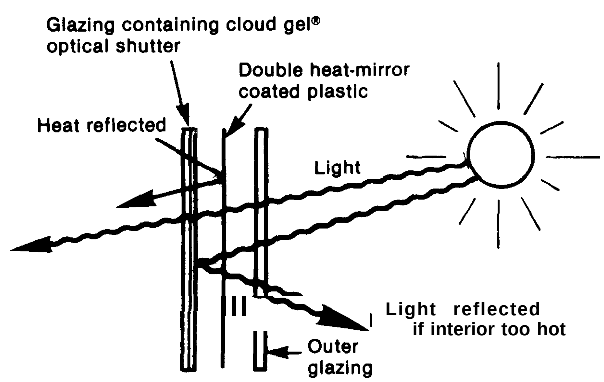
The heat mirror transmits almost all of the visible and invisible infrared sunlight but reflects almost all of the thermal infrared radiation back into the room. The overall effect can be similar to adding another pane of glass.

Figure 35.—Optical Shutter



The optical shutter is a heat-activated sunshade made from a temperature sensitive polymer material which is transparent below a critical temperature (76°F in this example) and becomes a milky-looking diffuse reflector of 80% of the sunlight above that temperature.

Figure 36.—Weather Panel®



Weather Panel[T.M.] is a passive glazing system which combines good thermal resistance (R6 claimed) with passive shading capability. It is being developed by Suntek Research Associates.

Table 75.—Summary of New Fenestration Technologies

Name of technology	Winter: Radiative gain	Winter: Heat loss (all types)	Summer: Radiative gain	Summer: Other gains	Effect on lighting/ outlook when operating	Operability	Estimated cost-effectiveness	Applicability to retrofit	Current status
1. Double-sided blind	≅ 90% of unshaded; u.v. is controlled	moderate reduction	moderate reduction	moderate reduction	no outlook, very low light	manual; seasonal reversal of blind required	very high	very high	ready for commercial i-zation
2. Triple blind	≅ 90% of unshaded; u.v. is controlled	moderate-high reduction	moderate reduction	moderate reduction	no outlook: very low light	manual, somewhat complex	high	high	on market
3. Shades between glazing with heat recovery	some loss but distribution/storage capability; u.v. is controlled	moderate reduction	moderate-high reduction	moderate reduction	some outlook; lighting possible when In operation	manual	high	low	ready commercialization
4. Between glazing convection and radiation control	≅ 90% of unshaded; slats can direct Sun away from furnishings	high reduction	moderate-high reduction	high reduction	no outlook or light: some degradation of outlook at all times	none	moderate-high	low	early R & D
5. Insulating shades and shutters	N/A	very high reduction	high reduction	very high reduction if closed	no outlook, no light	manual; or automatic	low-moderate	low-moderate	products marketed
6. Skylid®	N/A	high reduction	high reduction if closed	high reduction	no outlook, no light	automatic	low-moderate	low	on market
7. Beadwall®	N/A	very high reduction	high reduction if filled	very high reduction if filled	no outlook, no light	automatic	low-moderate	low	on market
8. Beam daylighting	beneficial distribution effects and u.v. control	N/A	no effect	reduced lighting load	Increased daylighting; affects upper part of window only	manual; only seasonal adjustment is essential	low-moderate	low	advanced R & D
9. Selective solar control reflective film	significantly reduced	N/A	moderate-high reduction	N/A	none	none	high in predom, cooling climates	very high	R & D
10. Heat mirror	low reduction	low-moderate reduction	low reduction	some reduction	none	none	moderate-high	very high	on market; retrofit package near marketing
11. Optical shutter	low reduction	N/A	high reduction	N/A	no outlook when translucent	automatic	probably low	probably low	R & D
12. Weather panel®	low reduction unless overheating occurs	very high reduction	high reduction	very high reduction	no outlook	passive/ automatic			R&D
13. Optimization of fenestration design (size, orientation)	significant optimization over current practice	N/A	high reduction through proper shading, etc.	reduction	N/A	N/A	very high	very low	early R & D

HEATING AND COOLING EQUIPMENT

Direct Fossil-Fired Heating Equipment*

Most residential and commercial buildings in the United States are heated with direct-fired gas and oil furnaces and boilers, as shown in table 76. Considerable controversy arises over the typical operating efficiencies of these

Table 76.—Heating Equipment and Fuels for Occupied Units in 1976 (in thousands)

	Number	Percent
Total occupied units.	79,316	100.0
Warm air furnace.	40,720	51.3
Steam or hot water.	14,554	18.3
Built-in electric units	5,217	6.6
Floor, wall, or pipeless furnace. . .	6,849	8.6
Room heaters with/without flu . . .	8,861	11.2
Fireplaces, stoves, portable heaters.	2,398	**3.0**
None.	**716**	**.9**
Total occupied housing unit . . .	**74,005**	**100.0**
House heating fuel:		
Utility gas.	**41,219**	**55.7**
Fuel oil, kerosene.	**16,451**	**22.2**
Electricity	**10,151**	**13.7**
Bottled gas or LP gas.	**4,239**	**5.7**
Coke or coal/wood/other	**1,482**	**2.0**
None.	**463**	**.6**
Cooking fuel:		
Utility gas.	**32,299**	**43.6**
Electricity	**35,669**	**48.2**
Other	**5,748**	**7.8**
None.	**287**	**.4**

SOURCE: Bureau of Census, Construction *Reports,* **“Estimates of Insulation Requirements and Discussion of Regional Variation in Housing Inventory and Requirements,” August, September 1977.**

systems. One reason is that remarkably little is known about their performance in actual operating environments, and the literature in the area is replete with inconsistent information. (Figure 10 in chapter **II** illustrates the problem.) Performance undoubtedly varies with the type of unit, its age, size, installation, position in the building, and a number of other variables. Another reason for the controversy is the inconsistency in the definition of efficiency. Until recently, the most common value quoted was the steady-state or full-load combustion efficiency, which is defined as the ratio of useful heat delivered to the furnace bonnet divided by the heating value of the fuel.[11] Typical values for direct-combustion furnaces are 70 to 80 percent; heat loss principally results from heated stack-gases lost during combustion. This definition does not give a complete measure of the fuel required to heat a living space over the heating season. A definition that does, and one that is increasingly being used, is the seasonal performance factor or seasonal efficiency. This measure is defined as the ratio of (a) the useful heat delivered to the home to (b) the heating content of the fuel used by the furnace over the entire heating season. Typical gas furnaces have seasonal efficiencies in the range of 45 to 65 percent (see figure 37) Seasonal efficiency accounts for all factors affecting the heating system's performance in its actual operating environment. In addition to stack-gas losses these factors include loss of heated room air through the chimney while the furnace is off (infiltration), cycling losses, pilot light (gas furnaces only), and heat losses through the air distribution ducts when in unheated spaces.[12] Cycling losses are a result of operation at part loads, which causes heat to be lost in raising the temperature of the furnace before useful heat can be delivered to the living space. Most existing homes have furnaces oversized by at least 50 percent, so they are always operating at relatively inefficient part-load conditions.[13] The oversizing is greater still in homes that have had insulation, storm windows, or other thermal envelope improvements added since the furnace was installed.

In addition to the fossil fuel required for the burner, gas and oil furnaces and boilers require electric energy to operate fans and pumps.

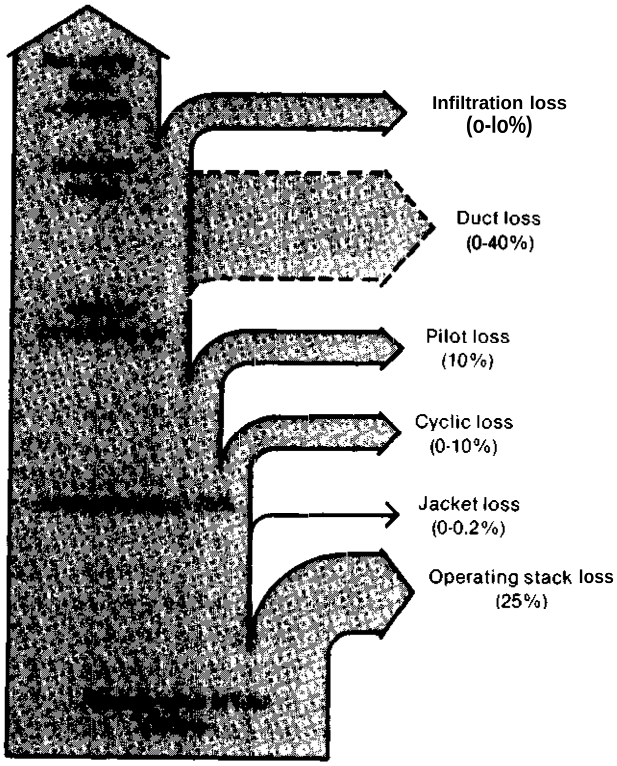
*Some parts of this section are taken from “Applications of Solar Technology to Today's Energy Needs,” Office of Technology, June 1978.

[11]E. C. **Hise and A. S. Holmn, “Heat Balance and Efficiency Measurements of Central Forced Air Residential Gas Furnaces” (Oak Ridge National Laboratory).**

[12]**C. Samuels, et al., “MIUS Systems Analysis— Initial Comparisons of Modular-Sized Integrated Utility Systems and Conventional Systems, ” ORNL/HUD/MIUS-5, June** 1976, p. 24.

[13]Hise and Holman, op. cit.

Figure 37.—Typical Energy Flow for a Gas Furnace System



SOURCE: E. C. Hise, et al., "Heat Balance and Efficiency Measurements of Central, Forced-Air, Residential Gas Furnaces," Oak Ridge National Laboratory, ORNL-NSF-EP-88, October 1975, p. 4.

Oil and Gas Furnace Efficiency Improvements

Furnaces with improved efficiency levels are now available and new devices are being developed. Table 77 summarizes the approximate energy savings and costs of a number of oil boiler improvements, most of which are now available. Corresponding tables of measured improvements for oil furnaces and gas furnaces and boilers are not available, but sim**ilar levels of improvement can be expected.**

Several of these improvements reduce the heat lost when the furnace cycles on and off frequently. As most furnaces are now sized to supply at least one and one-half times the maximum anticipated heating load, reducing the furnace capacity, either by installing a smaller nozzle or a smaller furnace, will also substantially cut off-cycle losses.

Periodic adjustment of oil burners will improve their combustion efficiency and lower flue-gas temperatures. This service is available from heating oil distributors and furnace repair services.

Variable firing rate furnaces represent an attempt to provide reduced output for near continuous operation and thus cut off-cycle losses; development of a reliable and affordable technology for accomplishing this goal

Table 77.—Refit Modifications for Efficiency Improvement of Oil-Fired Boilers

Refit action	Estimated fuel saving (%)	Approx. cost ($)	Payback period (years)
1. Reduced burner firing rate (by 25%)	8[a]	0[b] - 25	0 - 0.4
2. Boiler water temperature reduction (35 °F)	5	0[c] - 20	0 - 0.5
3. Burner efficiency adjustment	3	0[b] - 30	0 - 1.3
4. Retention-head burner[c]	16[a]	250	2.1
5. Vent damper[d]	10[a]	200	2.7
6. Stack heat reclaimer[d] (economizer)	15[a]	350	3.1
7. Low input/variable firing rate burners[e]	20	500	3.3
8. Ducting combustion air from outdoors[f]	0 - 3[g]	100	4.4
9. Modern high-efficiency burner-boiler	24[a]	1,500	8.3
10. Blue flame burner-boiler	21	1,500	9.5
11. Outdoor boiler installation	0 - 10[h]	—	—
12. Combustion air humidification	1	200	26
13. Water-fuel oil emulsion	0	—	—

NOTE: Savings from refit actions are not additive. Payback period is based on 1,500 gallons per year fuel use at $0.50 per gallon.
[a]Based on dry-based steel boiler with nonretention head burner. [b]May be included as part of annual servicing. [c]Firing-rate reduction should accompany burner installation. [d]Possible safety hazard exists—long-term testing required. [e]Commercial equipment not available at this time. [f]Including inlet air damper for burner off-cycle. [g]Will vary depending on boiler location in structure [h]Will vary with boiler—testing required.

SOURCE: J. E. Betey, T. W. Allen, R. J. McDonald, R. J. Hoppe, F. J. Salzano, and A. L. Berlad, "Direct Measurement of the Overall Efficiency and Annual Fuel Consumption of Residential Oil-Fired Boilers," Brookhaven National Laboratory, BNL 50853, under Contract No. EY-76-C-02-0016, U.S. DOE, January 1978.

has proven difficult. Such furnaces are not expected to be commercially available until the late-l 980's.

Automatic flue dampers close the flue after the furnace shuts off to drastically reduce the amount of heat that escapes up the chimney while the furnace is not operating. Flue dampers have been used in Europe for many years, but concern over safety questions delayed their acceptance in this country. They are now coming into use.

Flame-retention head burners improve combustion efficiency by causing turbulence in the combustion air, enhancing air-fuel mixing. These burners are on most oil furnaces sold now, but improved versions are being developed.

Sealed combustion units reduce flue-gas losses during both on and off cycles by using outside air for combustion. This means that the warm interior air is not exhausted up the flue. These improvements can result in furnaces with seasonal efficiencies of **75** to 81 percent.[14 15]

Advanced Fuel-Fired Equipment

Several types of equipment that should provide substantially higher seasonal efficiencies are under development. These include condensing flue-gas furnaces, pulse combustion burners, and several different fuel-fired heat pumps.

Conventional furnaces maintain flue-gas temperatures of 4000 to 7000 F to avoid condensation and attendant corrosion and to maintain the nature draft.

The near-condensing flue-gas mechanism would reduce this temperature to nearly 3000 F, and thus capture a great deal of the flue-gas heat; the condensing version would place the flue temperatures below 300° F and thus recapture the latent heat in the water vapor as well. Problems with this approach relate to corrosive flue-gas condensate and scaling on the heat exchanger. Neither version is expected to appear on the market for several years.

Pulse Combustion Furnaces and Boilers

The pulse combustion burner is a unique approach that uses mechanical energy from an explosive combustion process to "power" the burner and permit condensation of the flue gases without the need for a fan-driven burner.

The operation of the pulse combustion burner is illustrated in figure 38. Initially, a small fan drives air into the combustion chamber through flapper valves along with a small quantity of gas and the mixture is ignited by a spark plug. The explosive force of ignition closes the valves and drives the exhaust gases out the tailpipe. The combustion chamber and tailpipe are acoustically "tuned" so the exhaust process creates a partial vacuum that opens the intake valves and sucks air and gas into the combustion chamber without use of the fan. Residual heat from the previous combustion ignites this mixture without need for the spark plug. The exhaust gases are cooled to about 120° F, recovering nearly all of their heat including the latent heat in the water vapor.

The pulse combustion principle has been known for many years and some development occurred in the 1950's and 1960's. The principal problems were related to muffling the intrinsically noisy combustion process and materials problems related to the extremely high heat releases in small volumes. " While these problems were not insolvable, the promise of higher efficiency was insufficient to offset higher production costs. Further development work has occurred and Hydrotherm, Inc., has started an initial production run of 300 residential boilers with full production to begin after mid-1979.[17] Hydrotherm has measured efficiencies of 91 to 94 percent for this boiler and seasonal efficiencies are expected to be simi-

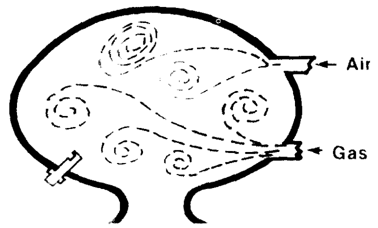
[14] J. E. Batey, et al., "Direct Measurement of the Overall Efficiency and Annual Fuel Consumption of Residential Oil-Fired Boilers" (Brookhaven National Laboratory, January 1978), BNL 50853.

"Department of Energy, "Final Energy Efficiency Improvement Targets for Water Heaters, Home Heating Equipment (Not Including Furnaces). Kitchen Ranges and Ovens, Clothes Washers and Furnaces, " *Federal Register.*

"J C. Griffiths, C. W. Thompson, and E. J. Weber, "New or Unusual Burners and Combustion Processes," American Gas Association Laboratories Research Bulletin 96, August 1963.

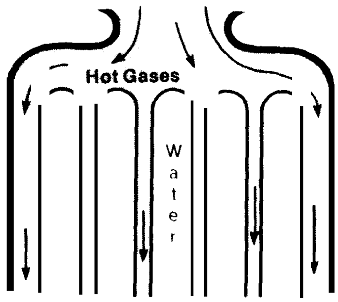
"Richard A. Prusha, Hydrotherm, Inc., Northvale, N. J., private communication, Mar. 30,1979.

Figure 38.—Principies and Operation of the Hydro-Pulse™ Boiler That Uses the Pulse-Combustion Process.

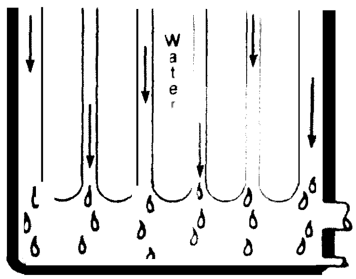


1. To start the boiler, a small blower forces outside air into a sealed chamber where it is mixed with gas.

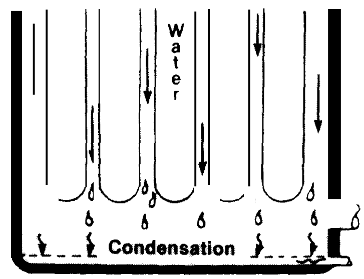
2. A spark plug is used on the first cycle only to ignite the mixture.



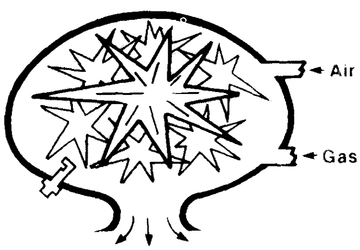
3. The pressure resulting from the combustion process forces the hot gases through tubes in the heat exchanger where surrounding water absorbs the heat.



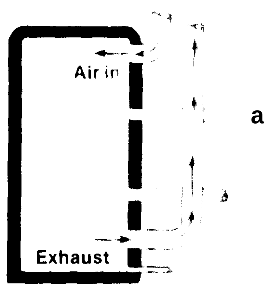
4. As the hot gases are cooled below the dew point, condensation of the water vapor in the flue gases takes place, releasing the latent heat of vaporization ...amounting to about 9% of the fuel input.



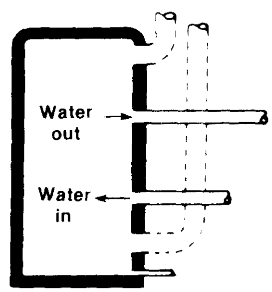
5. Condensation collects in the base of the boiler and is removed by a condensate drain.



6. Residual heat from the initial combustion ignites the second and subsequent air/gas mixtures without the need for the spark plug or blower...at a rate **in excess of 25 cycles per second.**



7. Air is drawn into the combustion chamber from outdoors by the vacuum caused by the velocity of the exiting exhaust gases...both through small diameter plastic pipe. No flue or chimney is needed



8. Water is circulated through Hydro-Pulse™ in much the same manner as in a conventional boiler.

SOURCE: Hydro Therm, Inc., Northvale, N.J. brochure for hydro-pulse boiler lar since outdoor combustion air is used and off-cycle flue losses are virtually eliminated.[18] Due to the low flue temperatures, the flue gases are exhausted through a 1½-inch PVC plastic pipe and no chimney is needed to provide natural draft. The cost of this boiler will be about twice that of conventional gas boilers. An oil-fired pulse combustion boiler is now manufactured in Europe ("TurboPuls") and the manufacturer is apparently interested in marketing in the United States if certification can be obtained.

Both the noise problem and the materials problems are more severe for hot air furnaces, but Lennox Industries is developing a pulse combustion furnace in a joint project with the Gas Research **Institute.** Laboratory efficiencies above 95 percent have been achieved and a preproduction prototype has been installed in a home but additional work on noise reduction and controls development is needed.[19] Major field testing will be conducted before the furnace is marketed, perhaps in the mid-1 980's.

Fuel-Fired Heat Pumps

Heat pumps, as their name implies, pump heat from a cooler space to a warmer space. All refrigerators and air-conditioners are actually heat pumps, but the term "heat pump" is generally reserved for a device that is designed to provide heating by pumping heat from the outdoor air or a water supply. Most heat pumps can also be reversed and used as air-conditioners. The heat pumps now on the market are electrically driven but development of gas-fired heat pumps is underway. Most gas-fired designs could be modified and produced as oil-fired units as well. The designs being developed should provide seasonal performance factors of 1.1 to 1.5 for heating, or use about half the fuel consumed by present furnace installations. Three of these designs are discussed in the *Heat Pump* section.

[18]Hydro-Pulse Boiler product literature, Hydro Therm, Inc.

[19]*1978 Annual Report* (Chicago, I Il.: Gas Research Institute).

Electric Air-Conditioners and Heat Pumps*

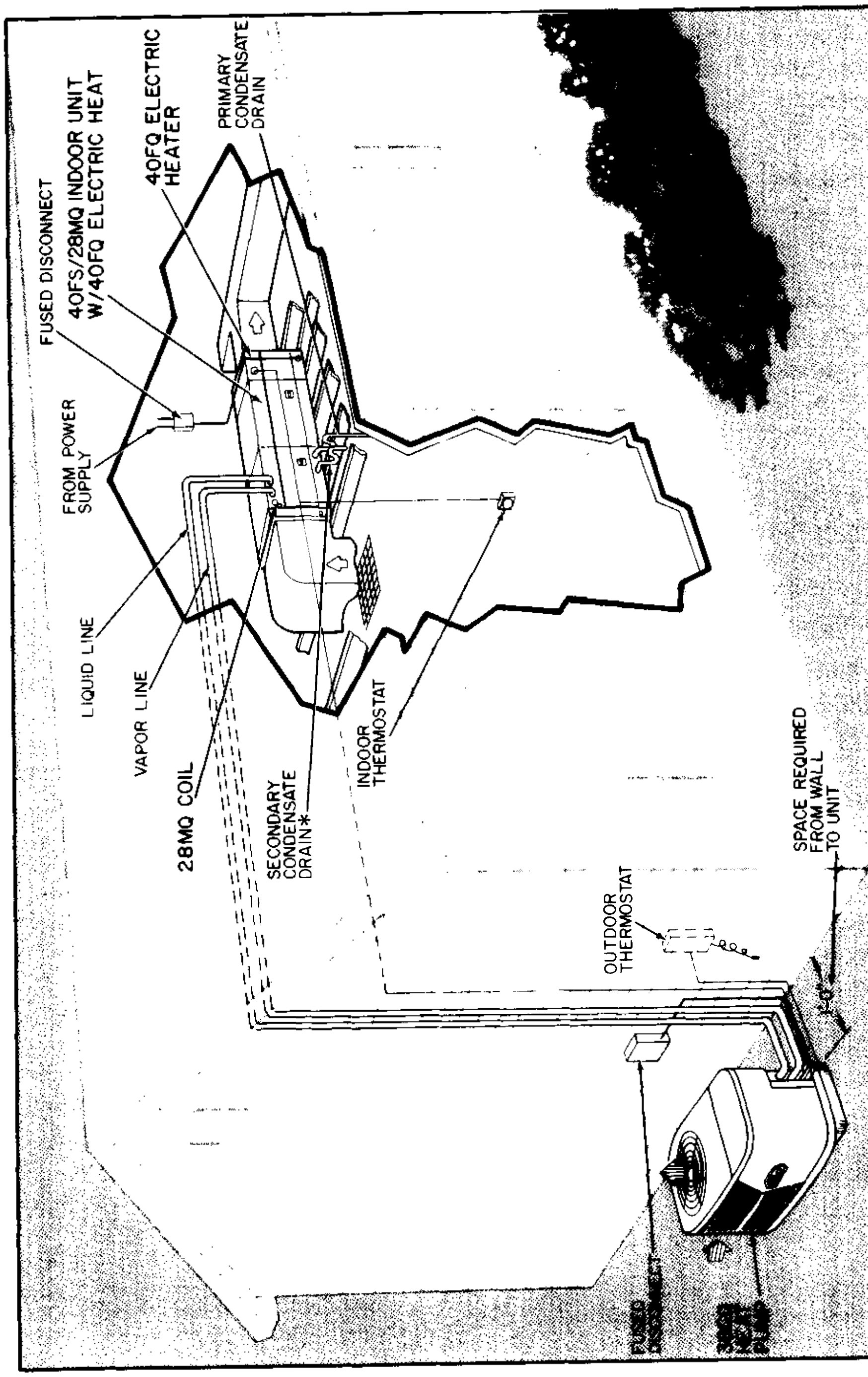
A typical residential air-conditioner/heat-pump installation is illustrated in figure 39. These systems usually cool and dehumidify room air directly while the systems used in large apartments and commercial buildings typically produce chilled water, which is piped to fan-coil units in various parts of the building. Cooling systems have three basic components: 1) a unit that permits a refrigerant to expand, vaporize, and absorb heat from the room air (or water system); 2) a compressor that compresses the heated vapor (increasing its temperature); and 3) a condenser, located outside the building that rejects the heat absorbed from the room air into the atmosphere (condensing the compressed vapor to a liquid). In "single-package" units, all three functions are provided in the same unit and can be connected directly to the ductwork (or chilled water system) of the building. In "split-system" devices, refrigerant is sent to an air-handling unit inside the building. Another distinction involves the technique used to compress the refrigerant vapor. Smaller units typically use a simple piston system for compression and are called "reciprocating" units. Larger units may use centrifugal pumps or screw compressors for this purpose.

Heat pumps use the same three basic components as the air-conditioners described above, but the cycle is reversed. In the heating cycle, the indoor air absorbs heat from the refrigerant and heat is acquired by the refrigerant from the outdoor fan unit (the "condenser" in the cooling model).

Heat pumps that can extract useful energy from outdoor air temperatures as low as 00 F are now on the market, although system performance is little better than electric furnaces at low temperatures. The electricity used by the system can be considerably reduced if a source of heat with a temperature higher than that of the outside air can be found. Lakes or

***Some** parts of this section are taken from "Application of Solar Technology to Today's Energy Needs," Of**fice of Technology Assessment, June** 1978.

Figure 39.—A Typical "Split. System" Heat Pump Installation



SOURCE: Carrier Corporation.

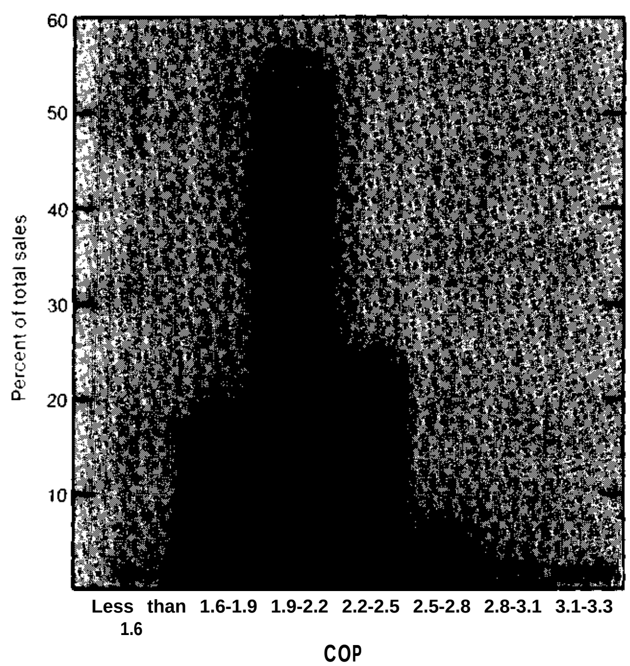
ground water, for example, are usually above ambient air temperatures during the winter and can be used to provide a source of input heat if they are available. Solar energy can also be used to provide a source of heated water. Systems that extract heat from water are called "water-to-air" heat-pump systems; units extracting energy from the air are called "air-to-air" systems. 20

In 1976, 51 percent of the housing in the United States was equipped with room air-conditioners or central air-conditioning, up from **47** percent in 1973.[21] Housing units with central air-conditioning increased from 16.8 to 21.5 percent from 1973 to 1976 while the fraction with room air-conditioners showed very little change, going from 30.1 to 29.6 percent. From 1973-77, the fraction of new homes with central air-conditioning has ranged from 46 percent in 1975 to 54 percent in 1977.22 Thus, it is difficult to say whether growth in demand for central air-conditioning in new housing was merely slowed by the Arab embargo, or whether it is approaching saturation.

Less than 5 percent of U.S. homes currently have heat pumps, but 20 to 25 percent of new housing starts in 1978 used the system, The growth of the market has been slowed by the sensitivity of buyers and builders to the initial cost of the equipment (which is higher than conventional electric-resistance heat), and by the fact that regulated gas prices and promotional electric prices have made the cost of operating competitive heating systems artificially low. Concerns about reliability have also been a problem. Some of the heat pumps marketed in the early 1960's were extremely unreliable, and sales of the units fell steadily between 1965 and 1970. While most of the reliability problems have been resolved, a recent study showed that the problem has not vanished.

The performance of heat pumps and air-conditioners now on the market varies greatly. Figure 40 indicates the performance of central air-conditioners smaller than 5 I/z tons now on the market. The difference in performance reflects both the quality of design and the cost of the unit. High-performance units may also result from a fortuitous combination of components. Manufacturers cannot afford to design condensers optimally suited for all compressors to which they may be attached, and some combinations of these units may therefore result in a high-efficiency system. As a result, while there are a few units on the market with very high efficiencies (figure 40, for example, indicates that 5 percent of the units on the market have a coefficient of performance (COP) greater than 2.5), this performance is not available in all size ranges. (The definition of COP, energy efficiency ratio, and other

Figure 40.— Air-Conditioning COP of Heat Pumps and Central Air-Conditioning Units Shipped in 1977



SOURCE Air Conditioning and Refrigeration Institute Includes only units of u rider 135,000 Btuh Data has been converted from EER to COP and values rounded to nearest tenth EER ranges were "5 4 and under 5 5-6 4 6574 75.84 85.94, 95104, and 105.11 4

[20] **Cordial Associates, Inc., "Evaluation of the Air-to-**Air That Pump for Residential Space Condition ing," prepared for the Federal Energy Administration, Apr. 23, 1976, p. 114.

[21] Bureau **of the Census,** "1976 Annual Housing Survey. "

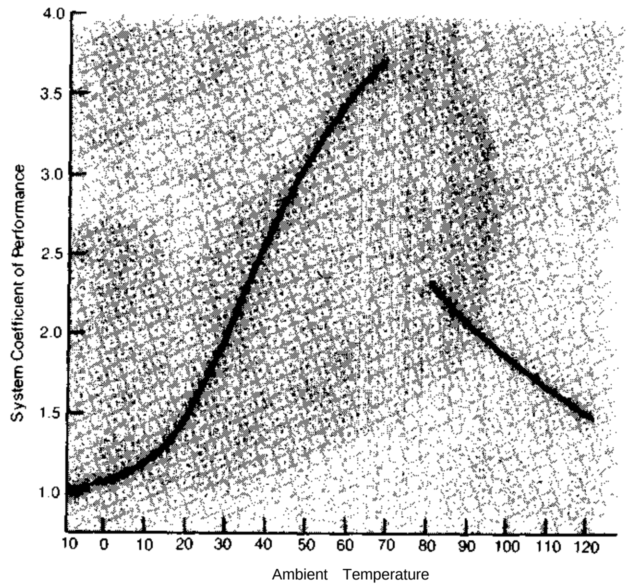
[22] Bureau of the Census, "Characteristics of New Housing: 1977, " *Construction* Reports, C25-77-13, 1978, p. 12.

efficiency measures are discussed in a technical note to chapter 1 l.) The 1976 industry average COP was 2.00.23

Heat pumps in the cooling mode were about 5-percent less efficient than the average air-conditioner, for a variety of reasons. Heat pumps cannot be optimized for maximum cooling performance as somewhat more complexity is required in the coolant piping, and the valve that switches the direction of the refrigerant when the system is changed from heating to cooling introduces some inefficiencies.

The performance of electric-cooling and heat-pump systems also varies as a function of the temperature and humidity of both the inside and outside air. This is because the theoretical capacity of a unit varies as a function of these parameters, and because most small units must be either fully on or fully off. The load control achieved by "cycling" the system from full capacity to zero output requires heating or cooling large parts of the system before useful space conditioning can be performed. Using energy to heat or cool the units decreases the system's efficiency, The dependence of a typical residential heat-pump unit COP on the outdoor temperature is shown in figure 41. The fact that the heat pumps capacity to produce heat decreases as the outside temperature decreases results in a highly temperature-dependent heating mode. A system large enough to provide 100 percent of the heating load at the lowest anticipated temperature would be prohibitively expensive in most locations, and a common compromise is to assist the heat pump with electric-resistance heat whenever its capacity falls below the heating demand. The average COP of a heat-pump system during the winter season is called the seasonal performance factor (SPF). This parameter is shown in figure **42** as a function of local climate. As expected, the average COP of heat pumps is lower in northern parts of the country. As discussed in chapter 11, the performance of heat pump installations has generally been lower than predicted.

Figure 41.—Performance of the Carrier Split-System Heat Pump



Model 38CQ020 ARI ratings:	*Heating* **mode nominal capacity 21,000 Btu/hour. COP at high temperature is 2.9, COP at low temperature IS 1.7**
	Cooling **mode** nominal capacity is 19,000 Btu/hour. COP is 2.1,
Assumptions used in computing system performance	Heating mode entering indoor air IS 70° F (db) heating demand includes energy used for defrost balance point at 30° F.
	Cooling mode entering indoor air is 80° F (db) and 67° F (wb). Fan power is 0.2 kW.

Energy use includes: compressor motor demands; resistance heat; the demands of indoor and outdoor fans, and the energy used in defrost cycles. The air-flow was assumed to be 700 cfm. Assumptions made about decrease in efficiency due to part load conditions were not explained in the literature.

SOURCE Career Split-System Heat Pump Outdoor Sections Carrier Corporation 1976 Form 38CQ-1P

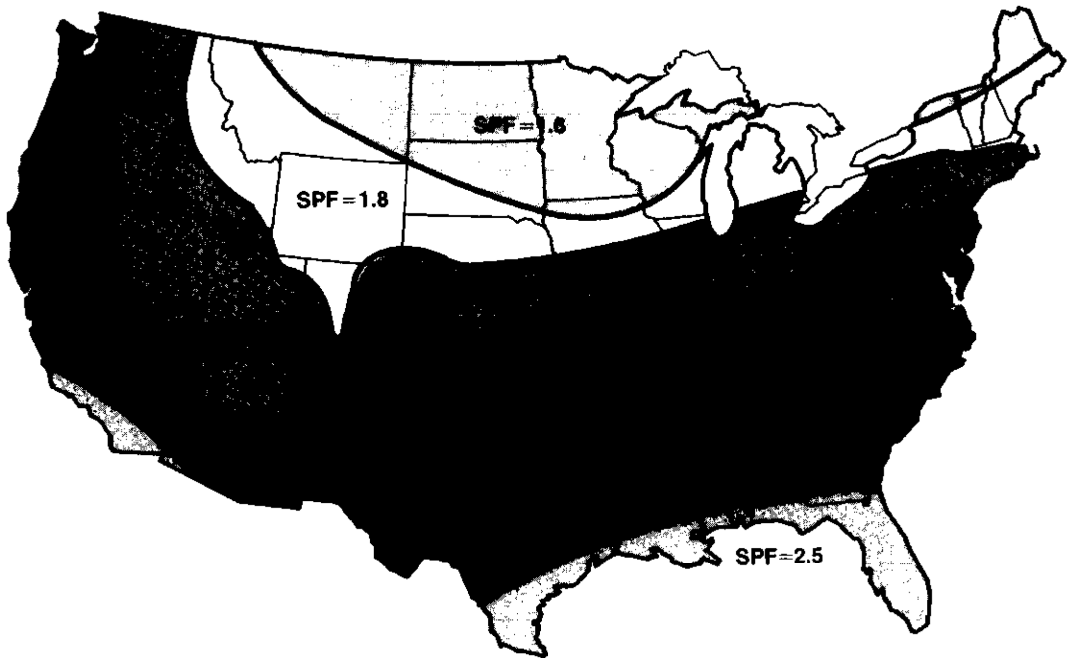
The performance of water-to-air heat-pump systems can be significantly higher than air-to-air systems if heated water is available. When 600 F water is available, most commercial units have COPS in the range of 2.5 to 3.5, but units with COPS as low as 2.0 and as high as 3.7 are on the market.

There are a number of straightforward changes that can improve the performance of air-conditioners without changing the basic design. Legislative actions and rising fuel costs have produced a number of higher perform-

---

[23] George D. Hudelson (Vice President-Engineering, Carrier Corporation), testimony before the California State Energy Resources Conservation and Development Commission, Aug. 10,1976 (Docket No. 75; CON-3).

Figure 42.—The Seasonal Performance of Heat-Pump Units as a Function of Local Climate



SOURCE: *What is a Single-Packaged Heat Pump... and How Can* it *Save You Money?,* Carrier Corporation, Catalog No. 650-069

ance units. Some of the steps being taken to improve performance include:

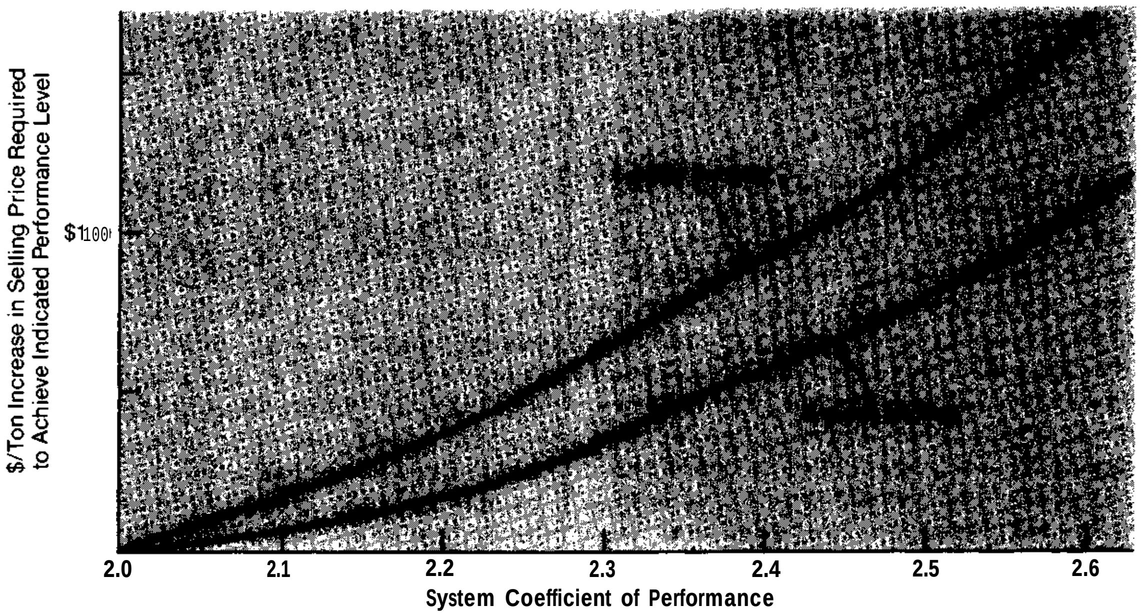
- use of more efficient compressors,
- use of two compressors or multiple-speed compressors to improve part-load efficiency,
- improved heat exchangers for both the condensor and evaporator,
- more efficient motors to drive the compressor and fan,
- automatic cycling of the fan with the compressor, and
- improved airflow.

One estimate for the cost of these incremental improvements is shown in figure 43. California has legislated performance standards in a two-step process; standards were first effective during 1977 and become more stringent in late-1979. These standards, which specify the minimum performance of any unit that can be sold in California, are shown in table 78.

The Energy Policy and Conservation Act (EPCA–- Public Law 94-163) as amended by the National Energy Conservation Policy Act (NECPA–- Public Law 95-619) required DOE to establish energy-efficiency improvement targets for appliances. These targets for air-conditioners, shown in tables 79 and 80, represent targets for the production-weighted average performance of all air-conditioners sold rather than a minimum standard. The National Energy Act has mandated the setting of efficiency standards that will be proposed in October 1979.

Looking further into the future, a number of systems have been proposed that could increase the COP of air-conditioning systems and heat pumps by as much as 50 percent. Researchers at General Electric believe that it would be possible to achieve an approximate 50-percent increase in the average COP of both heating and cooling for an increase in the initial cost of the unit of about 20 to 30 percent. It should be noted that performance can be improved by increasing low-temperature performance, high-temperature performance, or both. The speed with which these new units appear on the market will depend strongly on the company's perception of whether the public is willing to invest in equipment that can reduce their annual operating expenses over the long

Figure 43.— Estimated Cost of Increasing the Performance of Air-Conditioners From the Industry Average COP of 2.0 to the Performance Levels Indicated (estimates assume production rates equivalent to current production rates)



SOURCE George D Hudelson (Vice President—Englneerlng, Carrier Corp.) presentation to the Solar Energy Resources Conservation and Development Commission of California, Aug. 10, 1976, Docket No 75-CON-3

Table 78.—California Standards for Cooling Equipment

System type	Standard as of 11/3/77*	Standard after 11/3/79*
Central Air-Conditioners		
Heat pumps (cooling mode)	1.96	2.2
Air-conditioners	2.05	2.34
Room Air-Conditioners		
All systems with capacity greater than 20,000 Btu's	2.05	—
Other heat pumps	2.08	—
Other air-conditioners	2.20	—
All systems using voltages greater than 200 v.	—	2.40
Other heat-pump systems	—	2.43
Other air-conditioners	—	2.55

'No system may be sold in the State after this date with a COP below the standard.

Table 79.—DOE Room Air. Conditioner Energy-Efficiency Improvement Target

1972 energy-efficiency ratio Btu/watt-hour	1972 COP	1980 energy-efficiency ratio Btu/watt-hour	1980 COP
6.2	1.82	7.94	2.33

SOURCE: Department of Energy, "Energy Efficiency Improvement Targets for Nine Types of Appliances," F.R. 43, No. 70, Apr. 11, 1978, p. 15143.

Table 80.—DOE Central Air-Conditioner Energy. Efficiency Improvement Target

	1975 SEER[a]	1975 COP[b]	1980 SEER[a]	1980 COP[b]
Central air-conditioners (aggregate)	6.5	1.90	8.0	2.34
Single package	6.2	1.82	7.2	2.11
Split system	6.6	1.93	8.1	2.37

[a]Seasonal energy efficiency ratio in Btu/watt-hour as defined in chapter II.
[b]Seasonal coefficient of performance = SEER/3.413.
SOURCE: Department of Energy, "Energy Efficiency Improvement Targets for Nine Types of Appliances," F.R. 43, No, 70, Apr. 11, 1978, p. 15145.

term. These attitudes may be influenced by legislative initiatives, such as the National Energy Act.

Gas-Fired Heat Pumps and Air-Conditioners

Absorption Air-Conditioners

The only systems now available that use direct thermal input to operate a heat pump or air-conditioner are the "absorption-cycle" air-conditioners that have been used for decades. The refrigeration cycle is very similar to cycles used in other types of air-conditioning systems (vapor-compression). A chilled liquid (usually water instead of a refrigerant) is permitted to expand and cool air. This water is then recompressed and the absorbed heat is rejected into the atmosphere. The absorption cycle accomplishes this recompression by absorbing the low-pressure water vapor in a concentrated salt solution. This concentrated solution is continuously produced in a distilling unit driven by the heat from the fuel.

Absorption air-conditioners are inherently more expensive than electric systems because 1) of the larger number of heat exchangers required, and 2) the unit's cooling surface must be large enough to reflect both heat from the combustion process and heat removed from the space that was cooled. (In electric systems, the heat from generation is rejected at the electric generator site.) Absorption units had a lower operating cost than electric chillers in the era of cheap gas, and are still competitive in some areas, but their use was limited by first cost.

A typical single-effect absorption chiller has a COP of 0.52; double-effect units can have COPS of 0.88. These COPS must, however, be carefully qualified, as they do not include the electricity used for fans and pumps. They cannot be directly compared with the COPS of electric chillers since fuel costs are different and the COP of electric units does not include powerplant losses. It is reasonable to expect that improvements in current designs could lead to significant improvements in performance.

The Iron-Firemen double-effect **chiller, which was manufactured for a time, was able to achieve a COP of 1.2 (not including boiler losses and electric energy requirements). Some engineers believe it would be possible to increase this COP for double-effect absorption** devices to the range of 1.35.

Absorption Heat Pumps

An absorption heat pump is being developed for residential use by Allied Chemical Corporation and Phillips Engineering under sponsorship of the Gas Research Institute. The current goals for operating COP of this unit are 1.2 for heating and 0.5 for cooling.[24] Further improvement in heating COP could be obtained by recovering the waste heat from the generator section of the unit. It is believed that significant advances in fluids, fluid pumps, and heat exchangers have overcome problems that hindered earlier efforts to develop an absorption heat pump.

This unit has reached the preproduction prototype stage and negotiations are underway to accelerate commercialization by involving DOE and a major manufacturer in further development. After further development and extensive field testing, this system could be on the market in about 5 years.[25] Similar units are being developed in Europe by the British Gas Corporation and others.[26] This system is expected to cost about 15 percent more than a gas furnace/electric air-conditioner combination and will probably be most competitive in areas where heating is the major requirement.

Other Gas-Fired Heat Pumps

A different approach to the use of fossil fuels to operate a heat pump has been under investigation for some time. These designs burn fuel to operate a small onsite heat engine, which in turn drives the heat-pump compressor. A number of advanced, gas-fired, heat-

---

[24] James Drewry, "Gas-Fired Heat Pumps," *GRI* Digest, September 1978, pp. 1-5.

*'James Drewry, Gas Research Institute, private communication, May 1979.

*'Gerald Leach, et al., *A Low Energy* Strategy **for** the *United Kingdom* (London: **Science** Reviews, Ltd., 1979), p. 25

pump systems are being examined by the industry with the support of DOE and the Gas Research Institute. These include:

- A concept that uses a subatmospheric gas turbine is being developed by the Garrett A i Research Corp.
- A free-piston Stirling engine is being developed by General Electric.
- Systems based on diesel engines and Rankine-cycle devices are also being examined.

An interesting feature of the heat-fired, heat-pump systems is that their performance does not decrease with temperature as fast as the performance of conventional heat pumps.

The gas turbine heat pump development emphasizes commercial or multifamily applications. A "breadboard" system has been operated and development of a commercial prototype is underway. Commercial production is expected by the mid-1 980's, with units expected to range from 7.5 to 25 tons in capacity. The expected COP is 1.4 to 1.5 in the heating mode and about 1.0 in the cooling mode.[27 28] The installed cost is expected to be 15 to 20 percent higher than existing systems with payback in fuel savings in about 2 years.

The free-piston Stirling engine heat pump seems to be at a similar stage of development, but is thought to be more applicable to the residential market. One prototype has been built and another will be completed during 1979. The design goal for the prototype is a heating COP of 1.4 to 1.5 and a cooling COP of 0.9. This requires an engine efficiency of 30 percent and the present prototype operates at 22 to 25 percent. This design is potentially very reliable since there are only two moving parts in the engine and one in the compressor. It is expected to be on the market in the mid-1 980's at a price that will allow payback from energy savings in less than 3 years.[29 30]

Stirling and Ericsson cycle, free-piston devices may be able to achieve efficiencies on the order of 60 to 90 percent of ideal Carnot efficiency. An engine operating between 1,400° and 1000 F could therefore achieve a cycle efficiency of 40 to 63 percent.

ERG, Inc., has reported a measured indicated efficiency that represents 90 percent of Carnot in a free-piston device operating in roughly this temperature region. The Garrett Corp. has reportedly achieved a cycle efficiency of 38 percent, using a small regenerated gas turbine. 31

If it is assumed that seasonal performance factors for heat pumps can be in the range of 2.5 to 3.0, the overall system COP (or ratio of heat energy delivered to the living space to the heating value of the fuel consumed) of a heat pump combined with a heat engine that is 38- to 60-percent efficient can be in the range of 0.95 to 1.8. If waste heat from the engine is used, the effective COP can be as high as 2.2.

A 38- to 60-percent efficient engine combined with an air-conditioning cycle with COP of 2.5 could achieve system COPS of 0.95 to 1.5. These coefficients cannot be compared directly with COPS of electric heat pumps. In order to obtain comparable "system efficiency" for an electric system, the electric COPS must be reduced by the efficiency of converting primary fuels to electricity and transmitting this energy to a heat-pump system. The average generating efficiency of U.S. utilities is approximately 29 percent; the average transmission losses, approximately 9 percent. Under these assumptions, an electric heat pump with a heating COP of 3.0 and a cooling COP of 2.5 would have an effective "system" COP of 0.79 for heating and 0.66 for cooling. A number of

[27] Irwin Stambler, "Working on New Gas Turbine Cycle for Heat Pump Drive," *Gas Turbine World,* March 1979, pp. 50-57.

[28] James Drewry, "Gas-Fired Heat Pumps," CR/ Digest, September 1978, pp. 1-5.

[29] L. L. Dutram, J r., and L. A. Sarkes, "Natural Gas Heat Pump Implementation and Development," presented at Conference on Drives for Heat Pumps and Their Control, Haus der Technik, Essen, West Germany, Sept. 6-7,1978.

[30] James E. Drewry, op. cit.

31 Patrick G. Stone (Garrett Corporation), private communication, December 1976.

questions remain about system performance as an integrated unit: reliability, safety, noise, ease of maintenance, etc.; these can be resolved only after more experience. The devices do offer the prospect of a much more efficient approach to converting fossil fuels to useful space-conditioning.

A major question concerning any onsite system requiring oil or gas is whether they will continue to be less costly than electricity. The heat-engine devices just discussed could, at least in principle, be used in connection with a coal-burning, fluidized-bed boiler or a solar heat source, and thus might present a promising long-term alternative.

INTEGRATED APPLIANCES

Heating and water heating are the major energy users in homes today. As discussed in chapter **11,** the use of "waste" heat from other appliances already makes a significant contribution to heating and the relative contribution increases as the house is made tighter. Several sources of "waste" are not presently being used and others could be used more effectively by "integrated appliances." Most of these appliances would recover heat (that is now completely wasted) for either heating or water heating (e. g., air-conditioner/hot water heaters), while others would heat water with heat that now heats the house whether heating, cooling, or neither is needed (e. g., refrigerator/water heaters). While other applications of waste heat in the home can be imagined, cost of recovery and coincidence between availability and demand are expected to result in selected heating and hot water combinations.

Of the many possible combinations, this section discusses four systems identified in a study[32] by Arthur D. Little, Inc., as particularly promising, with brief mention of some other possibilities. The four promising systems identified are:

- air-conditioner/water heater,
- furnace/water heater,
- refrigerator/water heater, and
- drain water heat recovery.

[32] W. David Lee, W. Thompson Lawrence, and Robert P. Wilson, "Design, Development, and Demonstration of a Promising Integrated Appliance, " Arthur D. Little, Inc., performed by the Energy Research and Development Administration under contract no. EY-76-C-03-1209, September 1977.

Costs and potential savings given in the following discussion are from the Arthur D. Little study unless another source is given.

Air-Conditioner/Water Heater

This system heats water with the superheated refrigerant vapor whenever the air-conditioner operates. **It** consists of a vapor-to-water heat exchanger inserted in the refrigerant loop just ahead of the condensor (the finned radiator-like part of the air-conditioner located outside), The heat recovered is ordinarily rejected outdoors. This system can be retrofit rather easily by qualified personnel, and if added to an air-conditioner whose performance is limited by a small condensor, it can actually improve the COP by a few percent.

This system can also be used with a heat pump and when operated in the heating mode, the heat used is not waste heat, but is provided at the operating COP of the heat pump. This still offers substantial savings compared to a resistance heater.

This is the only integrated appliance that is commercially available. It is made by at least six manufacturers. The installed cost of these units ranges from $200 to $500, and several air-conditioner manufacturers allow installation of one or more of these systems without voiding their warranty.

The estimated savings expected from use of the Carrier Hot Shot® unit (about $400) with a

® Registered trademark of the Carrier Air Conditioning Corporation.

3-ton air-conditioner in each of several cities is shown in table 81. Dollar savings would be greater for a larger family that used more hot water. Most sales of these units have been in areas with high air-conditioning loads such as Florida and the deep South. Use of these units on heat pumps would probably double the savings shown for more temperate climates.

Furnace/Water Heater Systems

Combining the furnace and hot water heater offers several potential advantages. The most compelling is that it should be possible to build a high-efficiency unit that incorporates features like intermittent ignition, vent damper, and forced draft for less money than would be possible for two separate units incorporating comparable features. Some oil furnaces have been equipped with hot water heaters, but they have a reputation for high fuel use so many homes with oil heat use electric hot water. A high-efficiency combined system could provide significant savings over such systems. There is also the potential for reduced standby losses from use of a smaller storage tank (perhaps 10 to 20 gallons) since present furnaces often have 100,000 Btu per hour capacity or greater. This is more than twice the capacity of typical water heaters. This advantage could disappear as tighter houses reduce the necessary furnace sizes.

Refrigerator/Water Heater

The refrigerator generates heat that could be recovered and used to heat water. During the heating season, this helps heat the house but only part of it reduces consumption for space heating since it typically keeps the kitchen at a slightly higher temperature than the rest of the house. The Arthur D. Little study considered this fact and estimated that a hot water recovery unit on the refrigerator could save about 14 MMBtu of primary energy per year if an electric hot water heater is used with electric heat. The estimated cost of the heat recovery unit was $142 with a payback of 3 to 4 years (8 years with gas). These savings could be reduced very substantially, perhaps by a factor of two or more, by more efficient refrigerator designs.

Drain Water Heat Recovery

Most of the heat added to hot water simply runs down the drain. Existing homes mix drains from showers, sinks, and washing machines (gray water) with toilet drains (black water). It appears that heat recovery will be more practical if the "gray" water is kept separate from the "black" water since there is less difficulty with sedimentation and the black water is always cold water. One proposed system that has been tried in a demonstration house in Europe would run the gray water into a drain tank (about 50 gallons) and use a water source heat pump to extract heat. Such a system could result in primary energy savings of 46 MMBtu per year for a first cost of $440. This cost does not appear to include any additional cost for separate drain systems.

Table 81.—Estimated Performance of Carrier Hot Shot® Heat Recovery Unit With a 3-Ton Air-Conditioner and a Family of Four

City	Electric rate* (¢/kWh)	Annual electric water heating cost	Water heating cost with Hot Shot®	Savings	Savings percent
Boston, Mass. . . .	5.0	$304	$264	$39	13%
Baltimore, Md. . . .	4.0	229	170	59	26
Atlanta, Ga..	3.0	172	115	57	33
Houston, Tex.. . . .	3.0	161	78	82	51
Chicago, Ill..	4.0	243	199	44	15
Sacramento, Calif.	4.0	214	173	41	19
Boise, Idaho	2.0	61	48	13	21

® Registered trademark of the Carrier Corporation.
*The electric rate is not necessarily the rate charged in each city but is representative of the region.
SOURCE: Carrier Corporation

Summary

Many other systems are possible. One of the simplest would be a simple filter (for lint removal) and damper that would permit use of the clothes dryer output for heating during the winter months. Frequent filter changing would be required and considerable humidity would be added to the house. Freezer/hot water heaters should be similar to refrigerator systems and ingenuity may make other systems practical. All of these systems must compete with other improvements in hot water and heating as they reach the market, and it is unlikely that more than one system to augment hot water production would be practical in a single house.

CONTROLS AND DISTRIBUTION SYSTEMS

Controls and distribution systems can play a critical role in the efficiency and effectiveness with which furnaces, air-conditioners, active or passive solar systems, refrigerators, ranges, etc., function individually and as a complete system to maintain comfortable conditions and provide other amenities in a house. For purposes of this discussion, controls will be considered in two categories: 1) those that control individual equipment, and 2) those that control comfort conditions in the house.

Houses contain a surprising array of controls, some manual and some automatic. The most frequently used manual control is probably the light switch, but all of the major appliances in the home contain automatic controls and/or manual controls. Refrigerators, freezers, toasters, ovens, and water heaters all contain thermostats. Furnaces contain a thermostat (in addition to the room thermostat) that controls the blower shutoff. Furnaces and gas water heaters have flame sensors and valves to control the flow of fuel.

A number of the new or improved technologies being developed require additional control circuitry. Solar hot water heaters and active heating systems use controls of varied sophistication and several companies now manufacture these controls. Automatic flue dampers (considered under furnace improvements) are themselves a control and require additional controls and sensors for operation. The pulse combustion furnace is likely to require more sophisticated controls for safe operation since the combustion process is not continuous. Fuel-fired heat pumps can also be expected to have their own control requirements.

The discussion of indoor air quality in chapter X indicated the need for several different sensors and controls. Powered ventilation that responds to odors and other indoor pollutants is needed. Other equipment that may be adapted for residential use provides particulate control, and removes airborne chemicals and odors by means of filters, precipitators, adsorption, absorption, and chemical reaction systems.

Instruments to provide rapid feedback on the cost of consumption and to show the effect of changes initiated by the occupants are not available now. They could significantly improve occupant behavior as discussed in chapter III.

A number of the losses associated with furnaces are related to nonoptimal controls. The fans (or pumps in hydronic systems) are shut off while the furnace is well above room temperature. It is necessary to shut off fans before the air reaches room temperature to avoid uncomfortable drafts, but this contribution to off-cycle losses could be reduced. The savings that could be realized without compromising comfort by lowering these set points are apparently not known.

The only systems control found in most homes is the thermostat, which controls the heating (and possibly the cooling) system. The registers in each room usually have a damper so that the air flow in individual rooms can be shut off manually if desired, but these dampers are generally designed for infrequent use. There are at least three potential changes in thermostats. Instruments that allow one or more temperature setbacks are increasingly available; at least one of these can be set for a different temperature each hour of the week. Most thermostats contain an "anticipator" that shuts the furnace off slightly before the set temperature is reached. The heat remaining in the furnace jacket then brings the house up to the set temperature. Houses often overshoot the set temperature when the thermostat setting is increased, resulting in added losses from the house. The extent of these losses is not really known, but improved "anticipators" could reduce them. One of the sources of furnace inefficiency is the loss associated with frequent cycling of the system on and off. The frequency of this cycling is related to the temperature band within which the thermostat keeps the house. The narrower this band, the more frequent the cycling and the greater the cycling losses. This is another problem that is very prevalent, but the extent of the losses and the practical potential for reduction by changing the thermostat band-width is not known.

Heating unoccupied rooms obviously wastes energy. It may be possible to reduce this loss either through the use of timed controls or through active occupancy sensing. However, the widely varying use patterns of different rooms seem likely to limit the utility of this approach. As thermal envelopes are made tighter, the savings from such controls will also be reduced.

The rapid development of integrated circuit technology has led to sophisticated small computers that control energy use in some commercial buildings. Such systems could also be adapted for use in homes. Excess heat could be circulated from the kitchen when the range was in use, outside ventilation could be brought in through a heat exchanger as needed, an economizer unit could cool with outside air when practical, space conditioning could be provided only in occupied rooms, etc. However, the computer itself is only the "tip of the iceberg" in the cost of such systems.[33] The purchase and installation of the sensors, additional valves, and dampers that such a system would require greatly exceeds the cost of the logical unit. It seems likely that other improvements in houses will obviate the need for some of these functions while making others more acute, so it is difficult to predict the savings that could be achieved or the potential for the use of such systems.

Distribution systems transfer hot or cold air from a central furnace or air-conditioner to the rooms where heating or cooling is needed. The principal losses from these systems occur when they are run through unconditioned space in the basement, attic, or exterior walls. These losses can best be eliminated in new construction by running ducts entirely within the conditioned space. The design of such systems is facilitated if smaller ducting, designed for use with high velocity air, is substituted for standard ducting. Such ducting has been used in large buildings for many years. Smaller ducting can be readily used in tight, highly insulated houses since heating requirements are greatly reduced.

Conflicting needs suggest larger distribution systems in some cases. The heating mode efficiency of heat pumps could be improved by lower distribution temperature. Similarly, the efficiency of simple solar collectors is much higher at low temperatures than at high temperatures. The same is true of passive solar systems, where very low-temperature heat must be circulated from the rooms receiving sunlight to other rooms. Some homes are being built with most of the rooms opening onto a common area so that heating can be accomplished much as it was in homes heated only with a central wood stove in the past. It is likely that several approaches to efficient distribution will evolve to satisfy the requirements of different housing designs.

[33] Marvin L. Menka, "Controllers and Process Applications," *Proceedings of the Conference on Technical Opportunities for Energy Conservation in Buildings Through Improved Controls,* Boston, Mass., May 10, 1976, DOE publication CONF 7605138, p. 218.

PASSIVE SOLAR DESIGN

The concept of using sunlight and winds to help heat and cool houses is rapidly being "rediscovered" in the wake of today's new consciousness about the use of energy. Features that were standard construction practices before the introduction of central heating and cooling systems are making a comeback. New refinements are being added so that some houses now being built without collectors on the roof get as much as 90 percent of their heat from the Sun. As these houses generally do not use the pumps, blowers, storage tanks, and associated controls typical of solar houses, they are generally referred to as "passive" solar houses, or houses with "energy-conscious design."

These houses use natural phenomena to minimize their use of conventional fuels for heating and cooling. Overhangs are used to admit sunlight in the winter and provide shade in the summer. Deciduous trees are another reliable method of ensuring summer shade and winter sunshine. Windbreaks can be used to temper the effect of winter winds. While these techniques reduce the need for heating and cooling, the key to the success of passive solar design lies in the fact that over the course of a winter, a good south-facing double-glazed window will admit more heat from the Sun than it will lose both day and night. Thus south-facing (or nearly south-facing) windows can be used to supplement the heating requirements of homes in virtually any climate in the continental United States. The most effective use of this solar heat requires that massive components such as concrete or masonry floors or walls be incorporated into the house. These components absorb heat and thus reduce temperature swings inside the dwelling.

The benefits of proper orientation toward the Sun have been recognized for centuries; the forum Baths in Ostia (near Rome) were built with large openings to capture winter sunlight nearly 2,000 years ago.

The classic examples of ancient passive solar design in North America are the cliff dwellings of the Indians of the Southwest. They are typically situated on the south face of a rock cliff with an overhang to shade the summer sun. The dwellings, built into the wall of the cliff, use heavy adobe materials in conjunction with space hewn directly out of rock — thus providing tremendous capacity for moderating the huge swings in outdoor temperature occurring in this area.

In more recent times traditional southern architecture incorporated a variety of methods to enhance the summer cooling of homes, most prominently the use of huge porticoed porches.

With the advent of inexpensive gas and oil heating and electric cooling, these traditional regional practices were quickly discarded, as they limited design and were often less "effective" than the mechanical systems that replaced them. A few architects and engineers experimented with passive solar design in the 1940's and 1950's, but encountered problems with overheating on mild winter days. By the time OPEC tripled the price of oil in 1974, most engineers were not only unaware of passive design principles, but they believed that every window was an energy loser and that any energy-efficient building should limit the window area to the minimum level allowed by the esthetic demands of the occupants.

Following the OPEC embargo, new advocates of passive solar design appeared, many after independently rediscovering that windows really could reduce the fuel consumption of a house. These new advocates were largely people from outside the mainstream of engineers and architects—typically solar energy "nuts" with little formal training or scientists with no design experience. As in any change of technology, the early supporters received little attention or Government funding. Another complication was the "site specific" nature of these designs; as each dwelling must be defined by its site, the technology was not perceived as broadly applicable. Only very recently has passive solar design begun to receive significant research and demonstration money.

There are just about as many approaches to design of a passive solar house as there are designers; it may be as simple as planting a shade tree or so complex that it stretches the concept of "passive" design. This description makes no attempt to provide exhaustive coverage of the ideas that have been proposed or even built; rather it attempts to provide some feel for the breadth of ideas which lend excitement to the field.

Direct Gain Systems

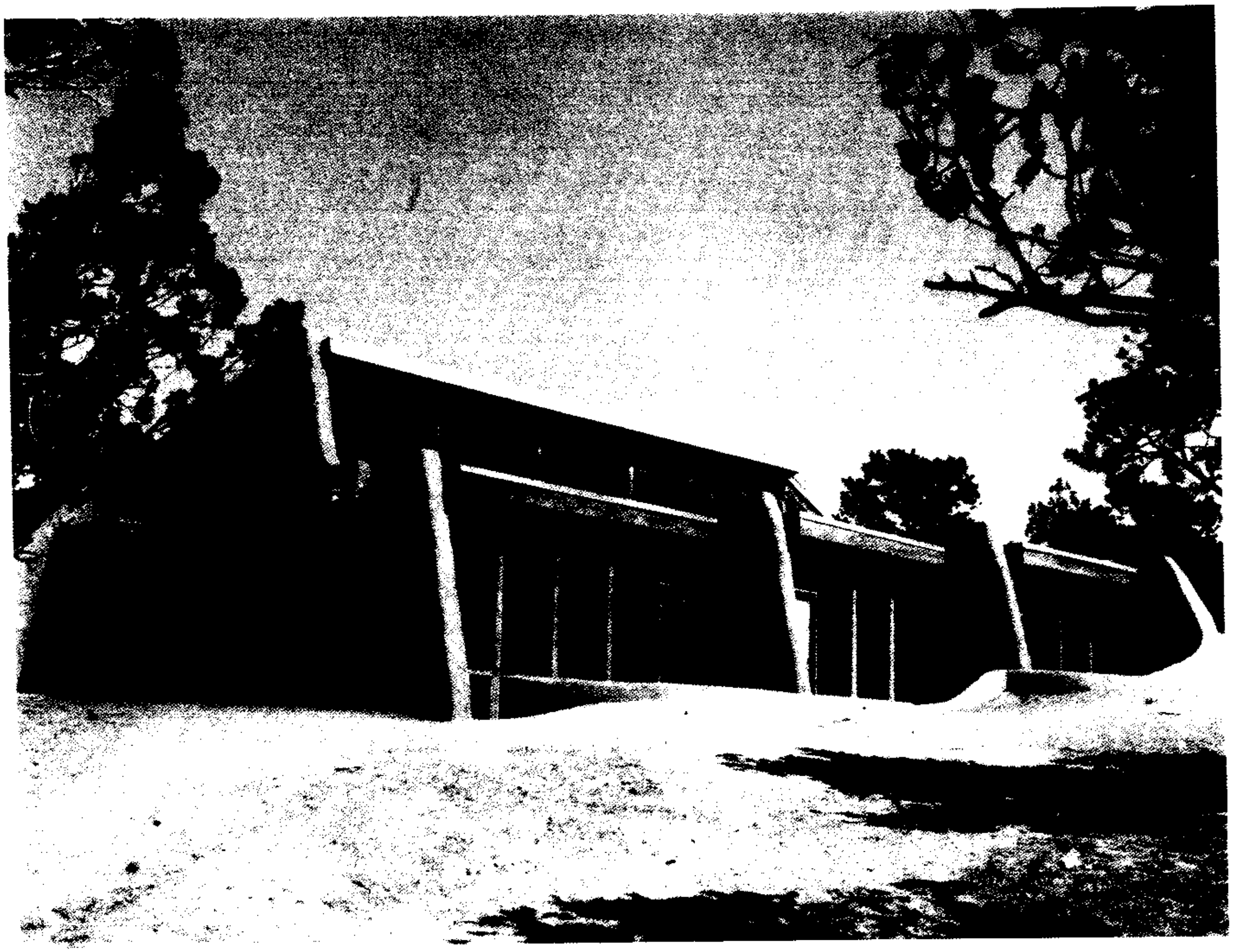
The simplest passive solar design simply adds larger south-facing windows to a house. The slightly modified saltbox design (figure 44) is a good example of the "direct gain" approach to passive solar heating. This house contains substantially larger windows on the south wall than is typical for this style of house in the New England area (Wiscasset, Maine, near Brunswick) and does not contain any fans, blowers, or heavy concrete walls to help store and distribute the heat. It does incorporate sliding insulating shutters that cover the windows at night to reduce the heat loss. The shutters also make the house more comfortable by reducing the window chill. The upstairs bedrooms have skylights angled with the roof to collect more winter sunlight than a similar area of vertical windows.

If most of the south wall were covered with windows, the typical frame house would often be too hot, even in cold weather, because of the limited capacity to absorb and store heat. As more windows are added it becomes necessary to add massive features to the construction of the house so more heat can be stored with small increases in the interior temperature The house shown in figure 45 has windows covering the entire south wall, but it also

Figure 44.—Modified Saltbox Passive Solar Design Home

Photo credit Christopher Ayres, Pownal, Maine

Figure 45.—The Fitzgerald House Near Santa Fe, N. Mex., is 95 Percent Solar Heated by a Direct Gain System at a 5,900 Degree Day Site



Reprinted with permission" William A Shurcliff, Brick House Publishing Co., Harrisville, N.H has lo-inch thick adobe walls with urethan insulation outside the adobe and a brick floor resting on 16 inches of sand. The sand has a 1-inch layer of styrofoam insulation beneath it and the house has an overhang that limits the amount of summer Sun which enters. This house, in Santa Fe, N. Mex., receives about 95 percent of its heat from the Sun. This is not an area of mild winters—the location is at an elevation of 6,900 feet and the heating requirements are comparable to those of upstate New York. Supplementary heat is provided by two fireplaces and a small electric heater in the bathroom.

Such direct-gain systems are the ultimate in simplicity as they use no fans or dampers and the heat "stays on" when the electricity goes off. However, the large windows can produce uncomfortable glare, and if the floor is to be effectively used to store heat, it must not be carpeted. If the house does not effectively incorporate massive components, the temperature swings resulting can be uncomfortably large– as much as200 to **250** F in a day.

Indirect-Gain Passive Buildings

The problems with glare and the wide temperature fluctuations experienced in many "direct-gain" buildings have led to the use of a variety of simple approaches where the Sun does not directly heat the living space.

One is illustrated in figure 46 where a massive concrete or masonry wall is placed directly behind a large glass surface. (This concept is called a thermal storage wall or a Trombe wall after its French inventor.) The sunlight is absorbed by the wall. Heat is transferred to air against the inside surface, this air becomes buoyant and sets up circulation loops that move hot air into the house through the vents. Part of the heat is stored in the wall; the interior surface of concrete walls will actually reach its highest temperature well after the Sun has set. The house in figure 47 illustrates the use of this approach in combination with direct gain. Behind the left awning is a brick wall 8 inches thick; the windows on the right-hand portion of the house have a concrete/brick floor 4 inches thick behind them. The house is 50- to 60-percent solar heated and on sunny winter days, the occupants open windows when the interior temperature reaches 86° F.[34]

Barrels of water may be substituted for the brick wall; computer calculations have shown that they will actually increase slightly the amount of heat that can be gained by a storage wall. The building shown in figure 48 is a combination off ice/warehouse used for editing and storing books by the Benedictine monastery near Pecos, N. Mex. This building combines direct gain with the use of a "water wall." The windows on the first floor and the clerestories on the second level provide direct gain. Below the windows on the first level is a window-wall with 55-gallon drums of water behind the windows. Reflective panels lying on the ground below the water wall serve to increase the amount of sunlight striking the wall. They can be closed at night to reduce the heat losses from the water barrels. This system has provided more than 90 percent of the heating needs of this large building.

A variation on the mass wall approach is the "greenhouse" or "attached sunspace" design. Sunlight provides all of the heat for the sunspace and part of the heat for the rest of the house. The sunspace is a large, live-in collector, and the storage wall is placed between the sunspace and the living quarters. The storage wall mass evens out the temperature variations for the living quarters, while the temperature in the sunspace undergoes wide swings. Such a sunspace can be used as a greenhouse, a sunny play area for children, an enclosed patio, or any use compatible with substantial temperature shifts.

Figure 49 illustrates the use of a solarium in a rather conventional appearing house specifically designed to be mass-produced in a standard California tract development. The house **incorporates direct gain through the windows on the south wall and water tubes near these windows to add storage.** The skylight in the roof lights a square solarium in the center of

[34]Andrew M. Shapiro, **"The Crosley's House–With Calculations and Results," Solar Age, November 1977, p.** 31

Figure 46.—The Kelbaugh House in Princeton, N. J., Receives 75 to 80 Percent of Its Heat From the Trombe Wall and the Small Attached Greenhouse

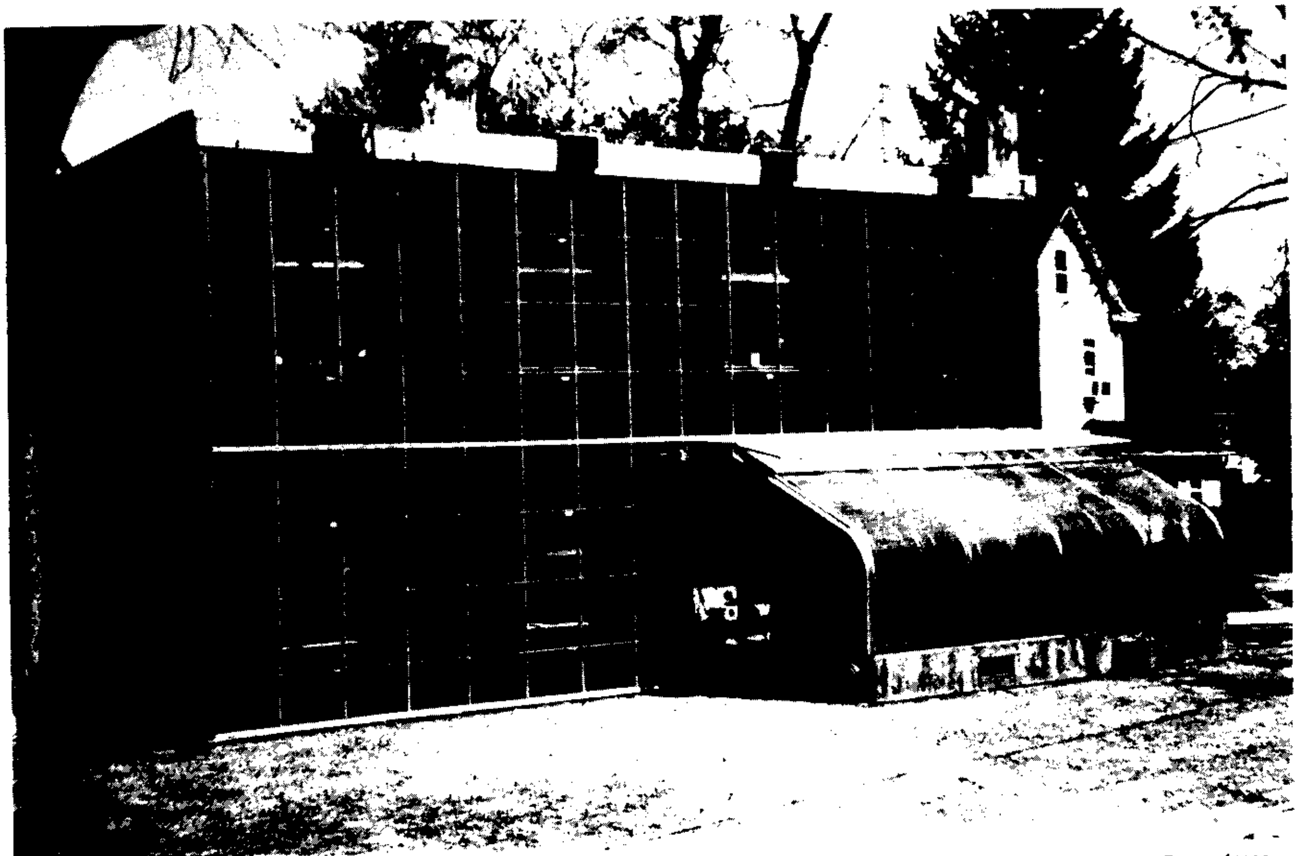
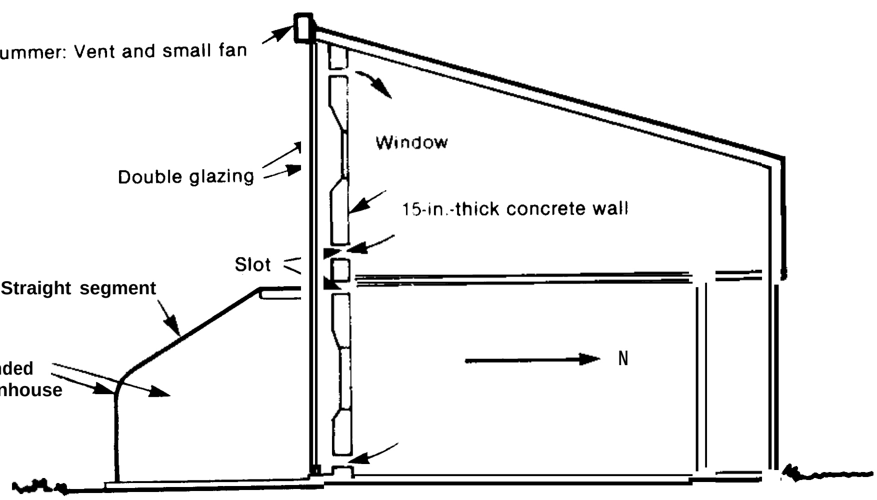
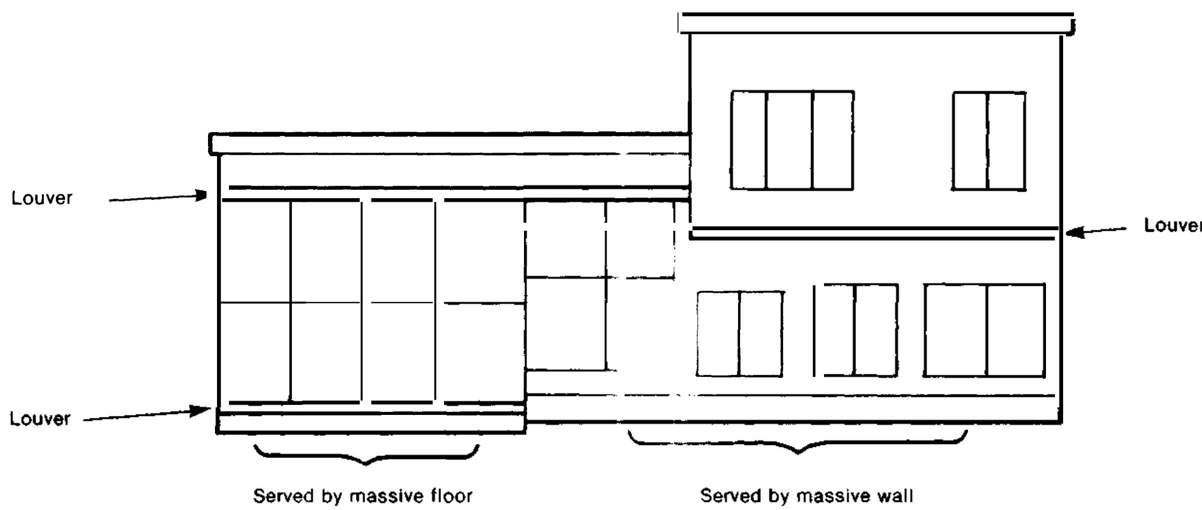


Photo credit: New Mexico Solar Energy Assoc.



Note: Omitted from this diagram are: basement under greenhouse, footings of building and many other details

Figure 47.—The Crosley House in Royal Oak, Md., Combines a Trombe Wall System With Direct Gain and a Massive Floor, to Provide 50 to 60 Percent of Its Heating-Needs



South elevation

Figure 48.—The Benedictine Monastery Office/Warehouse Near Pecos, N. Mex., Uses Direct Gain From the Office Windows and Warehouse Clerestories Combined With the Drumwall Below the Office Windows to Provide About 95 Percent of Its Heating Needs

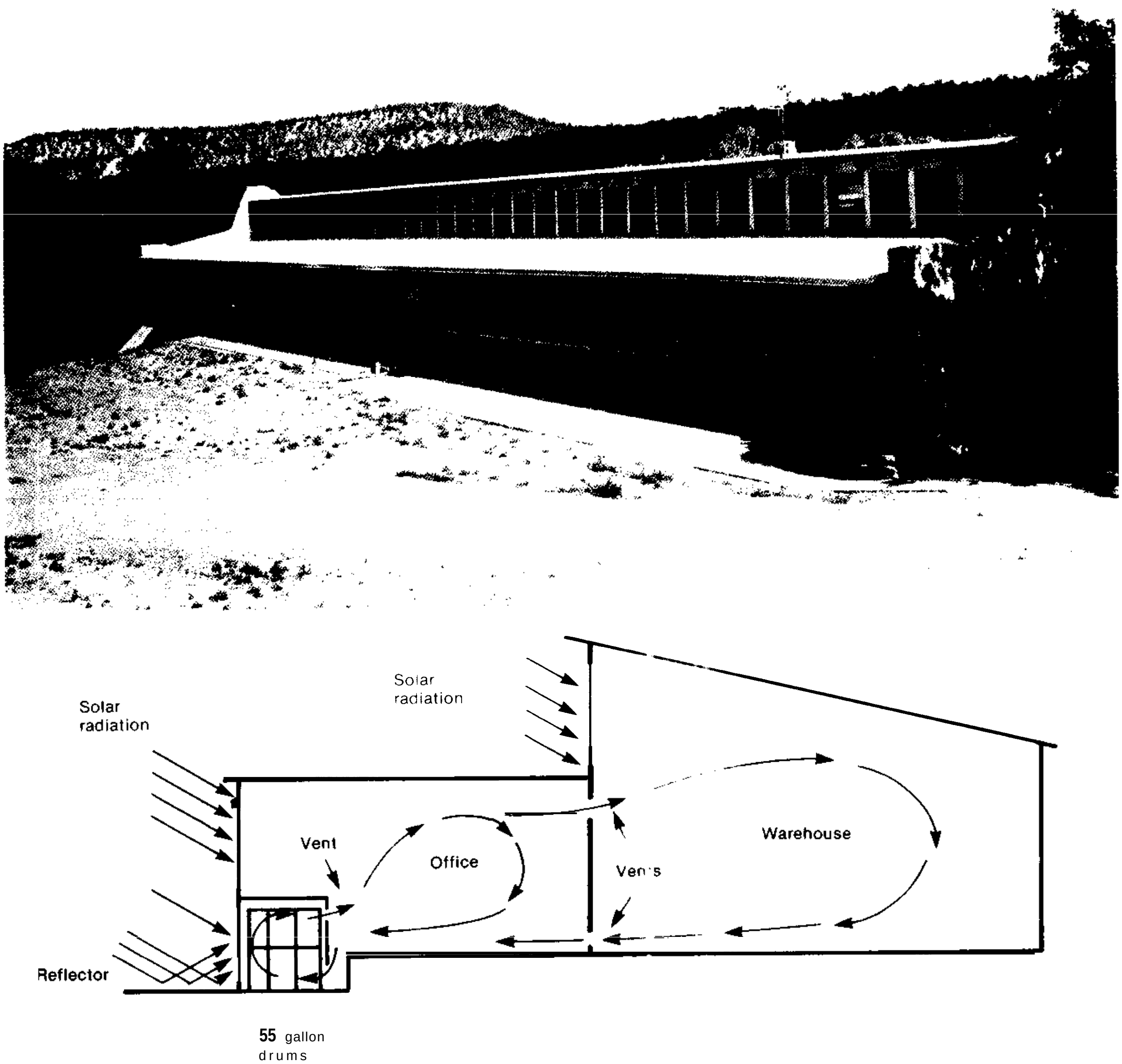


Photo credit: Sandia Laboratories

Figure 49.—The PG&E Solarium Passive Solar Home in California Uses the Large Skylight to Heat Water-Filled Tubes on Three Walls of the Solarium. The Tubes Then Radiate the Solar Heat to the Surrounding Areas

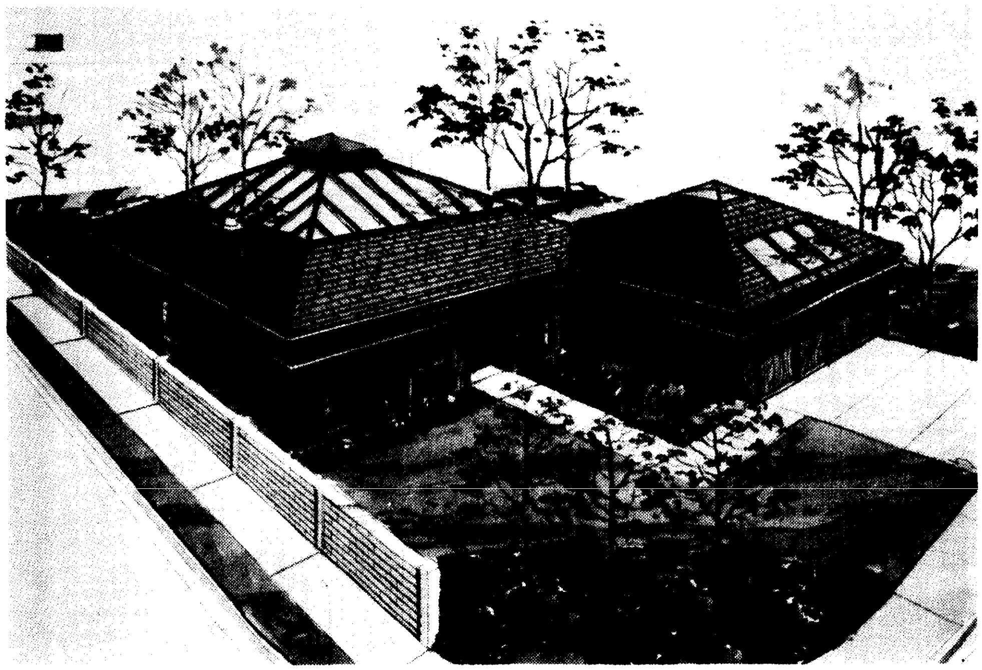


Photo credit: Pacific Gas arid Electric Company

the house. Three walls of the solarium have water-filled tubes. As this house was built in Stockton, Calif., where summer day temperatures are frequently in the 90's but night temperatures regularly drop to the 50's or low 60's, it also incorporated a gravel bed 14 inches deep under the entire house The rock bed is cooled by the earth and by circulating cool night air through it. (The use of fans to circulate the air would cause some to regard this as a hybrid passive home) Another feature of the skylight is the use of insulating panels, which are moved over the top of the solarium at night to reduce the heat loss.

An attached sunspace or greenhouse can be added to many existing homes. While most of the commercial lean-to greenhouses now available are single glazed, an increasing number of manufacturers offer double glazing. The Solar Room Co. emphasizes the heating benefits and multipurpose nature of their inexpensive double-glazed rooms (see figure 50) in their marketing. These units, which are designed for simple installation, use ultraviolet inhibited plastic coverings for extended life and can be easily taken down during the summer if desired. The Solar Sustenance Project has conducted workshops at numerous locations in the Southwest teaching simple greenhouse construction and promoting the benefits of both food and heat that can be derived from retrofit greenhouses such as the one shown in figure 51. The materials for the greenhouses built in these workshops cost from $395 to $652. Simple retrofits like those shown are generally built over an existing door or window, which can be opened to circulate heat into the house. They use the mass of the house for any storage and can supply 10 to 20 MMBtu of useful heat annually in most U.S. locations.

Hybrid Passive Systems

The definition of passive systems is the object of some controversy; the term passive implies lack of machinery and controls, but some such houses also incorporate a storage bed to

---

William F Yanda, "Solar Sustenance Project Phase I I Final Report, " proceedings of the Conference on Energy Conserving Solar Heated Greenhouses (Marlboro, Vt.: Marlboro College, Nov. 19-20, 1977), p. 16.

Figure 50.—This Retrofit Sunspace is Manufactured by the Solar Room Co. of Taos, N. Mex.

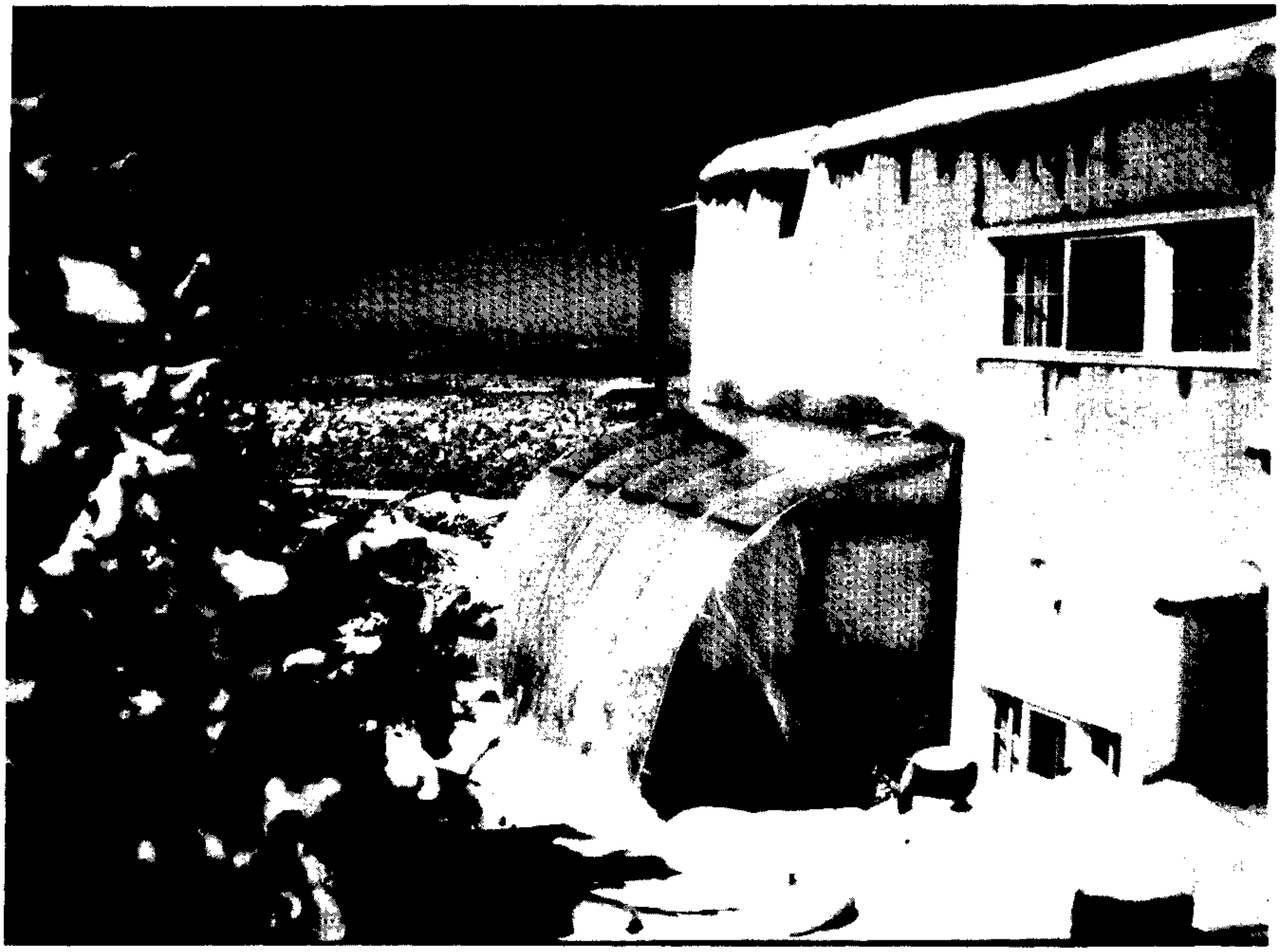


Photo credit: Solar Room Co.

improve the system's performance. Fans and controls circulate heat to and from the storage bed. Strictly speaking, the Pacific Gas and Electric house in Stockton could be considered hybrid, as it utilizes, some controls and motors.

The house shown in figure 52 successfully combines a greenhouse with a rock storage bed to provide additional heat storage. The wall between the greenhouse and the living quarters is a heavy adobe wall; blowers force air through the rock storage bed whenever the temperature in the greenhouse goes above a certain point. This heat is used to warm the house after the adobe has exhausted its heat. This house is near Santa Fe, N. Mex., where subzero winter temperatures occur; it required less than 1,000 kWh of electricity for supplementary heating (the equivalent of 30 to 40 gallons of heating oil) during a 6,400 degree-day winter).[36]

The house shown in figure 53 is an example of a dwelling with a storage wall and a rock storage bed.

Cost of Heat From Passive Solar Heating Systems

It is clear that a variety of passive heating systems are capable of providing substantial heat to buildings, that these systems are simple

[36] J Douglas Balcomb, "State of the Art in Passive Solar Heating and Cooling," proceeding of the Second National Passive Solar Conference, March 1978, p. 5-12.

Figure 51 .—This Retrofit Greenhouse is an Example of Those Built by **the Solar Sustenance Project**

Photo credit: Sandia Laboratories

and that they can be built from rather ordinary construction materials. The experience of many people who have lived **in passively heated** homes suggests that consumer acceptance can be enthusiastic, although present owners are largely a self-selected group of innovators. As with any other new energy system, the installation cost and the value of the energy savings will be a major factor in general consumer acceptance.

The cost of heat from passive solar heating systems depends on the system and the costing methodology used. As an example, consider the role of windows in a residential building. Most free-standing houses have windows on their south wall that were installed purely for the light and view they provide. If they are unshaded they will also reduce the heating bill slightly, and it can be argued that this heat is free since the windows were installed for other reasons. Similarly, some of the windows that would ordinarily be placed on the north wall of a new house can be put in the south wall, reducing the heat needed, again at no additional cost. Alternatively, the cost of this heat could be computed based on the difference between the cost of a blank wall and the cost of the wall containing windows. Attached sunspaces can be treated in the same manner in that the cost of heat they provide depends on how the intrinsic value of the sunspace is treated.

Passive systems may change the appearance of a house, and this further complicates the costing. The addition of slightly larger windows to increase heat gain may be welcomed, but if they are too large then glare becomes a problem. Inclusion of a greenhouse in a home can be a distinct plus if the owners enjoy plants and indoor gardening, but would not be a strong selling point for others. The use of massive construction to provide heat storage in the winter and retention of coolness in the summer can be done in tasteful ways that should add to the value of the home, but floors that are used for thermal storage lose efficiency if carpeted. Thus, a passive solar heating system may increase the value of a home as a heating system and for other reasons if it is

Figure 52.—The Balcomb Home Near Sante Fe, N. Mex., Combines the Use of a Greenhouse With a Rock Storage Bed to Provide 95 Percent of Its Heating Needs

Photo credit Sandia Laboratories

Photo credit New Mexico Solar Energy Assoc

The adobe wall separating the greenhouse from the interior of the house is clearly visible in this photo.

Figure 53.—This Home is Los Alamos, N. Mex., Combines a Large Trombe Wall With Small Direct Gain Windows and a Rock Storage Bed. The Interior of the Trombe Wall is a Distinctly Attractive Part of the Living Room

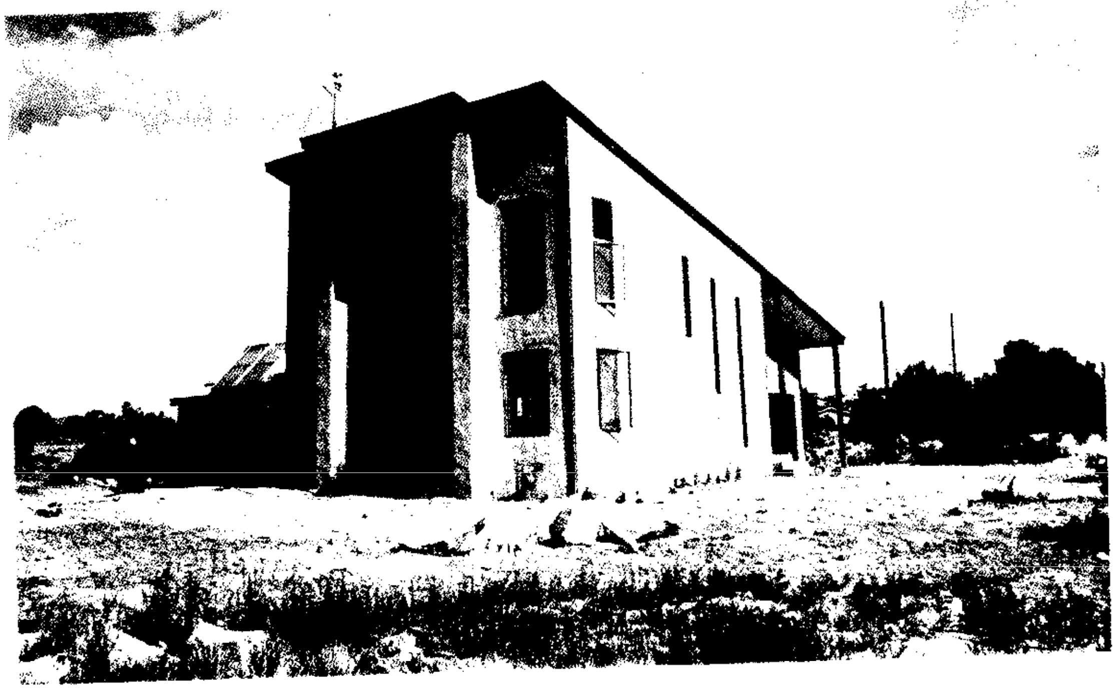


Photo credit: Sandia Laboratories

esthetically pleasing, but a poorly designed system could decrease a home's market value while reducing heating costs.

These subjective reasons make it difficult to estimate the total costs of the heat from passive solar heating systems.

The most comprehensive survey of the cost and performance of passive solar heating installations now available is that performed by Buchanon of the Solar Energy Research Institute).[37] It presents information on the installation cost and useful heat delivered by 32 actual systems and 18 simulated installations. The heat delivered by 20 of the systems was determined from monitoring of the building performance while engineering estimates have been made of the heat delivered to the other buildings. These estimates exclude heat that must be vented outdoors during the heating season because of insufficient thermal storage in the building.

Table 82 presents the cost of delivered heat for the systems surveyed. The cost of delivered heat was calculated using an annual capital charge rate of 0.094 and an annual maintenance estimate of 0.005 of the initial system cost, based on the average maintenance cost

Table 82.—Cost of Heat From Passive Solar Heating Installations

Installation type	Cost of heat ($/million Btu)
Direct gain:	
Monitored	$3.00-13.80
Unmonitored	$3.30-12.60
Thermal storage wall:	
Monitored	$3.60-24.20
Unmonitored	$8.80-15.40
Thermal storage roof:	
Monitored	$8.20
Greenhouse/attached sun space:	
Unmonitored	$1.20-11.90
Hybrid:	
Monitored	$2.60-16.60
Unmonitored	$11.90

SOURCE: Based on Deborah L. Buchanon, "A Review of the Economics of Selected Passive and Hybrid Systems," Solar Energy Research Institute publication SERI/TP-61-144, January 1979. The information on combined cost and performance has been converted to a cost of delivered heat using an annual capital charge rate of 0.094 and an annual maintenance cost of 0.005 of the initial cost.

in the survey. It is assumed that the systems have no intrinsic value other than as heating systems. (This probably overcharges for the heat from attached sunspaces.) If a single entry is given instead of a range, only one system of that type was included in the survey. Results of monitored and unmonitored systems are shown separately and there do not appear to be major discrepancies. The ranges shown reflect variation in both quality of construction and climate. The systems pictured earlier in this section span most of the range of costs shown in the table.

Cost of Heat From Fossil Fuels and Electricity

The simplest comparison for the costs shown in table 82 is against the cost of gas, oil, and electricity to residential customers. However, it is also necessary to include the effects of equipment efficiencies such as furnaces and distribution systems to provide a meaningful comparison. The policy maker may also wish to compare the costs shown in table 79 with the marginal cost of new supply such as liquefied natural gas or electricity from new generating and transmission facilities.

Table 83 shows the cost of fuels and heat supplied to houses from a variety of present and future sources of fossil fuel and from electricity. The fuel prices shown were assembled from a variety of sources as described below and reflect ranges of present or expected costs for fuel delivered to a residential customer. The cost of heat delivered to the house is the cost of a million Btu of heat delivered to the interior of the house after considering the furnace losses and ownership costs. It is thus comparable to the cost shown in table 82. It is expected that for modest increases in initial cost, the efficiency of conventional furnaces and heat pumps will be improved in the future. The third column of this table shows cost estimates for this case. The fourth column shows cost with improved equipment levelized over 30 years; fuel costs are assumed to increase at a general inflation rate of 5.5 percent. The basis for the energy prices shown and the equipment efficiencies and costs used in preparing table

[37] Deborah L. Buchanon, "A Review of the Economics of Selected Passive and Hybrid System s," Solar Energy Research Institute, SERI/TP161-144, January 1979.

Table 83.—Cost of Heat Supplied to Houses From Fossil Fuels and Electricity

	1977 residential fuel prices ($/MMBtu)	cost of heat to houses ($/MMBtu)	**cost** of heat to houses using improved equipment ($/MMBtu)	Levelized cost of heat to houses using improved equipment (5.5% inflation) ($/MMBtu)
Natural gas.	$2.00-4.00	$4.80-8.10	$4.40-6.90	$6.60-11.30
Intrastate gas.	2.50-4.00	5.60-8.10	5.00-6.90	7.80-11.30
Synthetic gas.	4.00-8.00	8.10-14.80	6.90-12.00	11.30-21.00
LNG.	3.00-6.10	6.50-11.60	5.70-9.50	9.00-16.00
Gas from "exotic" sources*. . .	3.25-7.50	6.90-14.00	6.00-11.00	9.30-20.00
Oil at 500/gallon.	3.60	9.50	8.00	12.50
Electrical resistance heat				
electricity at 3-5¢/kWh . . .	8.80-14.60	10.10-16.00	10.00-16.00	18.00-29.00
electricity at marginal cost of 7¢/kWh	20.50	21.80	21.80	40.00
Heat pumps				
electricity at 3-5¢/kWh	8.80-14.60	8.30-12.00	7.00-9.90	11.00-16.00
electricity at marginal cost of 7¢/kWh	20.50	15.80	12.90	22.00

*Gas from tight formations, Devonian shales, geopressurized aquifers, etc.

83 are discussed in a technical note at the end of this chapter.

Comparison of tables 82 and 83 show similar cost ranges that suggest that passive solar heating is now competitive with conventional heating fuels in at least some cases. It is interesting to note that the low end of the cost ranges shown for passive solar heating are lower than present cost of heat from gas. This simple comparison of costs indicates that passive systems will often be competitive, but gives no indication of the geographic range of competitive behavior. Furthermore, the cost of heat from the passive solar systems will not increase with inflation, leading to a substantial cost advantage for the passive systems after the first few years of operation. Lifecycle costing can be used to provide a better measure of the competitive advantage or disadvantage of passive solar heating systems. Most of the work in this area has been performed at the Los Alamos Scientific Laboratory and the University of New Mexico. 38 Among the more interesting of their results are those showing how a Trombe wall system will compete with gas and electricity in different parts of the country.

The group considered a double-glazed thermal storage wall with storage provided by 18 inches. of concrete. An engineering firm estimated that such a system would have an incremental installed cost of $12 per square foot. For comparison, the thermal storage wall systems used in table 82 ranged from $5 **to $21 per square foot with a single exception. A variation**

38 References **on** solar passive —

(a) **Scott** A. Nell, "A Macroeconomic Approach to **Passive Solar Design: Performance, Cost, Comfort, and Optimal Sizing,"** *Systems Simulation and Economic Analysis Workshop/Symposium,* **San Diego, Cal if.,** June 1978.

(b) Scott A. Nell, "Testimony Prepared for the U.S. House of Representatives Subcommittee on Oversight and Investigations, Committee **on Interstate and Foreign Commerce, " Aug. 11, 1978.**

(Continued)

(c) **Fred Roach, Scott Nell, and Shaul Ben-David, "The Economic Performance of Passive Solar Heating: A Preliminary Analysis,"** *AIAA/ASERC Conference,* **Phoenix, Ariz., November 1978.**

(d) **Fred Roach, Scott Nell, and Shaul Ben-David, "Passive and Active Residential Solar Heating: A Comparative Economic Analysis of Select Designs, " submitted to** *Energy,* **the International** *Journal,* **January 1979.**

(e) **Scott A. Nell and Mark A. Thayer, "Trombe Wall vs. Direct Gain: A Macroeconomic Analysis for Albuquerque and Madison," The** *Third National Passive Solar Energy Conference,* **San Jose, Cal if., January 1979.**

(f) **Scott A. Nell, J. Fred Roach, and Shaul Ben-David, "Trombe Walls and Direct Gain: Patterns of Nationwide Applicability," The** *Third National Passive Solar Energy Conference,* **San Jose, Cal if., January 1979.**

(g) **Scott A. Nell, "Thermal Mass Storage and Glazings Show Effectiveness in New Modeling,"** *Solar* **Engineering, January 1979, pp. 29-31.**

on this system was considered that assumed that the Trombe wall was equipped with movable insulation, which increases the R-value of the collector surface to R-10, between 4 p.m. and 9 a.m., at an added cost of $4 per square foot. This insulation allows a smaller system to meet the same fraction of the heating load and is often found to be cost-effective.

Results of the State-by-State analysis are shown **in figure 54, maps 1 through 5 for five different combinations of system, backup fuel, and incentives. The first two maps show that Trombe wall systems with night insulation are now feasible in three States** when natural gas is the backup and would be expected to be economic in one more within the next 10 years if no incentives are provided. The inclusion of Trombe wall systems in the solar energy tax credit contained in the National Energy Act of 1978 would make such systems economical in 29 of the 48 States shown by 1985, when natural gas is used for backup. **It is** interesting to note that the system is not economic in several Sun Belt States due to the relatively small heating requirements.

The feasibility of Trombe wall systems using electric-resistance heating as backup is examined in maps 3 through 5. Map 3 shows that Trombe wall systems are now feasible in every State except Washington, where electric rates are extremely low and there is relatively little sunshine. Systems that provide about half of the heating are feasible in California, Arizona, and South Carolina. The addition of night insulation to the system makes it feasible to increase the fraction of the heat provided by the solar system as shown in map 4. (The night insulation is generally most effective in the colder States.) The addition of the recent tax credit incentives would increase the fraction of solar heating that is feasible by 0.05 to 0.20 in about two-thirds of the States as shown in map 5.

The importance of this analysis lies not in the specific States and solar fractions shown to be feasible, but rather in the trends. Passive solar heating is shown to be marginally competitive on a lifecycle cost basis with gas heating in parts of the country. The large number of States where the addition of the tax credit incentives makes small systems competitive illustrates this. Systems that supply a significant fraction of the total heating needs are competitive with electric resistance heating in much of the country. Other passive designs such as attached sunspaces that offer other benefits in addition to heating may be more broadly applicable.

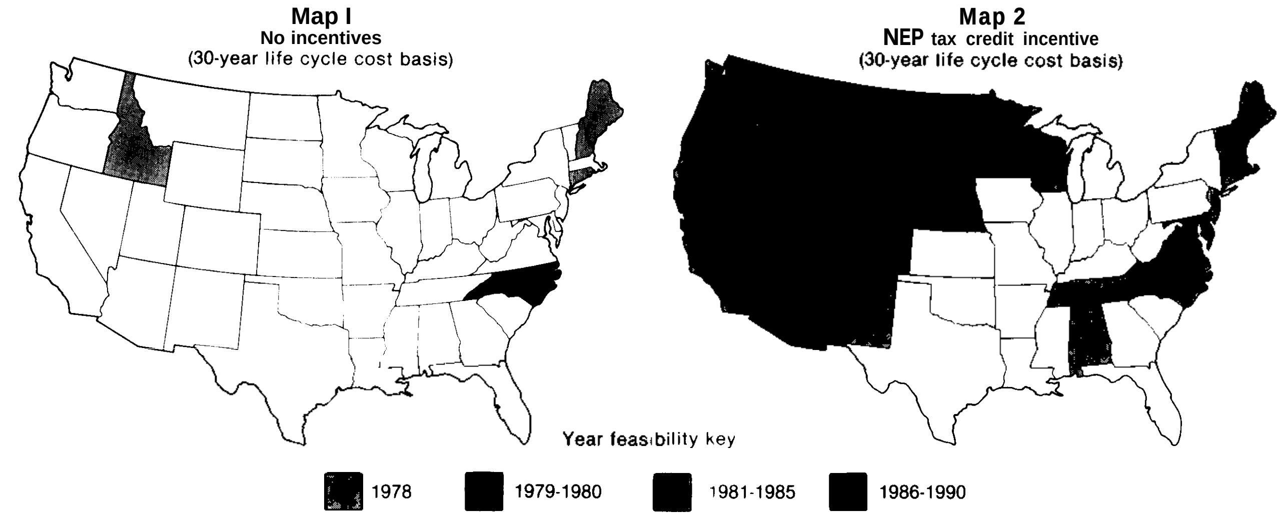
Summary

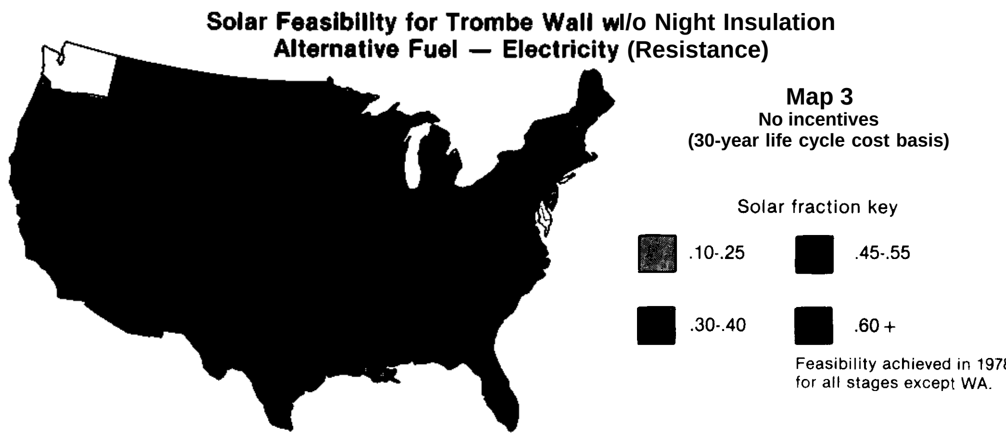
"Passive solar" buildings, which obtain 20 to 95 percent of required heat from the Sun without active solar collectors, have been built and are operating in many parts of the country. While data are sketchy, it appears that such housing is clearly competitive with electric-resistance heating in terms of cost, and is competitive with oil and gas in some parts of the country. In addition to the heat provided, many passive solar homes provide additional space, good natural light, and a pleasing view; these characteristics may be as important to homeowners as the savings in fuel costs. An additional benefit is that the systems are simply constructed and have few moving parts, so little maintenance is required. In some such homes, the daily swings in temperature are greater than commonly acceptable in houses using conventional heating/cooling systems.

Additional research and development is needed in this area, including the collection of field data on operation of homes now in place. **It** is likely, however, that the principal barriers to widespread use of these techniques (careful siting, construction, and landscaping) are institutional rather than technical. (This is generally true for home energy conservation issues.) First costs of such a system will be higher than conventional systems. Code barriers may be a problem in some areas; for instance, some code changes implemented over the past 5 years in the name of energy conservation require extensive engineering justifications of such homes on a case-by-case basis.

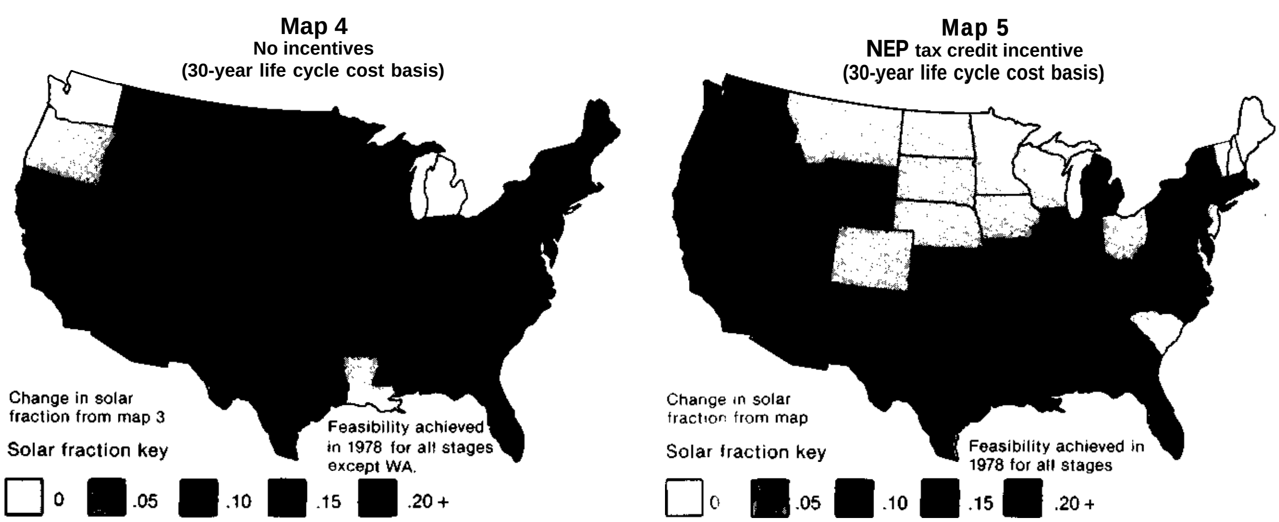
Passive heating systems are largely conventional building materials in an unconventional combination rather than new products. Accordingly, industrial promotion of passive solar has been slow to materialize. Glass and plastics industries are potential proponents,

Figure 54.—Solar Feasibility for Trombe Wall With Night Insulation Alternative Fuel—Natural Gas





Solar Feasibility for Trombe Wall with Night Insulation Alternative Fuel — Electricity (Resistance)



Source: Fred Roach, Scott Nell and Shaul Ben-David; *The Economic Performance of Passive Solar Heating: a Preliminary Analysis,* AIAA/ASERC Conference, November, 1978, Phoenix, Arizona but large industries such as these typically do not become active in a new market area until it has been established by small entrepreneurs.

Manufacturers of movable insulation are natural marketers for passive solar construction. This area is characterized by a number of small companies that have experienced difficulty in developing durable, reliable products and have not had extensive marketing experience.

The Internal Revenue Service interpretation of the solar energy tax credits (and conservation credits) recently authorized effectively excludes many passive systems. This places the passive approach, which can drastically reduce heating requirements, at a strong disadvantage to conventional supply technologies.

Accelerating the use of passive solar techniques calls for a vigorous information and demonstration effort, as the technology is not widely understood and does not have strong private sector support. Rapid and credible demonstration of a variety of systems in all regions of the country would help. These demonstrations could parallel the development and distribution of a design catalog, showing systems that have received adequate engineering analysis to meet local building code requirements. Such approaches could lead to the acceptance of "rules of thumb" for use by designers and builders in each part of the country. The recently concluded Passive Solar Design competition should provide a useful start on this task.

A number of homes could be built in varying climates and subjected to detailed and precise performance monitoring. This work could be coordinated with continued development and verification of computer programs designed to predict energy usage. Simple computer programs that are cheap and accessible are needed for field use by designers and builders; programs of greater precision and accuracy are needed for research.

Some applied research areas, such as improved glazing methods and infiltration monitoring, will be useful to passive solar. Passive cooling has received very limited attention and needs work. Possibilities for combining passive systems with active solar to further reduce dependence on conventional fuels have not been widely explored.

TECHNICAL NOTES–FOSSIL FUEL PRICES

These assumptions were used for comparing conventional fuel and solar passive heating costs in this chapter.

In 1977, natural gas prices for residential customers ranged from $2.00 per MMBtu in the Southwest to $4.00 per MMBtu in New England,[39] where gas is piped over long distances or derived from supplemental sources, such as liquefied natural gas (LNG) or synthetic natural gas (SNG) from naphtha. In comparison, the average 1977 price for wellhead interstate gas was $0.93 per MMBtu and $1.54 per MMBtu to gas distributors.[40] Although comparable average prices for wellhead intrastate gas are not known, typical new contracts ranged from $1.50 to $2.00 per MMBtu. Synthetic gas prices were compiled from a variety of sources used in the OTA solar study,[41] while LNG prices are based on current and pending LNG projects.[42] Prices for "exotic sources" are based on the OTA Devonian shale study[43] and a recent presentation by Henry Linden[44] of the Gas Research Institute.

A substantial quantity of fuel oil is imported and apparently is not affected by crude oil en-

"American Gas Association, "Quarterly Report of Gas Industry Operations– Fourth Quarter 1977 "

'"Department of Energy, April 1978.

"office of Technology Assessment, "Application of Solar Technology to Today's Energy Needs," June 1978.

[42] **American Gas Association, "Gas Supply Review, " June** 1978.

[43] Office of Technology Assessment, "Status Report on the Gas Potential From Devonian Shales of the Appalachian Basin, " November 1977.

"Henry Linden, presentation at the Second *Aspen Energy* **Conference, July 1978.**

titlements. Consequently, increasing the price of U.S. crude oil to world levels would not result in a large increase in fuel oil prices. Also, the delivered price of **$0.50** per gallon equals $21.00 per barrel delivered.

Typically, the price of electricity for residential customers ranged from 3 to 5 cents/kWh. Exceptions to this are the Northwest where electricity costs are less than 3 cents/kWh and the Northeast where it costs more than 5 cents/kWh. The delivered price of electricity from new capacity was calculated within a few mills of 7 cents/kWh for each of the four cities treated in the OTA solar report.

Different efficiency values were used for gas and oil furnaces, baseboard heaters, and heat pumps. Seasonal efficiency for gas furnaces is 60 percent; for oil furnaces, 50 percent; and 100 percent for baseboard electric heaters. Gas furnace efficiency can be increased to 80 percent at a cost of about **$400** per furnace, while oil furnace efficiency can be increased to 70 percent at a cost of about $500 per furnace. Typical heat pumps have a seasonal performance factor of 1.55–an efficiency of 155 percent — in a 5,000 degree-day climate.[45] A heat pump with "improved" installation was assumed to have a seasonal performance of 2.0 at no additional cost. The performance of the heat pump with "improved" installation corresponds to the performance of some heat pumps manufactured today and suggests that typical heat pump performance can be increased to the 2.0 level.

Conventional systems ownership costs, which include capital costs, annual maintenance costs, and a pro-rated replacement cost (for heat pumps that have a typical lifetime of only 10 years), are based on the OTA solar study.

[45] Westinghouse **Electric Corporation, "Load and Use Characteristics of Electric Heat Pumps in Single-Family Residences," EPRI EA-793, Project 432-1, Final Report, June 1978.**