NASA Technical Paper 1564

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Including Live-In Test Results

Volume I

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SUMMARY

The Technology Utilization House of the National Aeronautics and Space Administration (NASA Tech House) demonstrates the potential capability of new building construction techniques and new technologies and materials to conserve energy and water resources. As a basic goal for the house, the added investments made for energy and conservation systems were expected to be cost effective since the savings realized were expected to repay the investments within a 20-yr period.

The Tech House was designed and built at NASA Langley Research Center in Hampton, Virginia. Construction was completed during 1976. From August 1977 to August 1978, the house was evaluated under actual living conditions while serving as the residence for a family of four. During the year, performance data were automatically measured and recorded for use in evaluating the house and its technology features. In addition, daily readings were taken of total electrical energy consumption and run time of major equipment, and water usage was monitored twice a week.

The energy consumption of the house was expected to be about one-third that of a conventional house (ref. 1), whereas the water usage was expected to be reduced between 45 and 50 percent, with most of the reduction due to gray-water reuse and the remaining reduction due to water-saving fixtures.

With only minor operational problems, all house systems functioned as designed. The total energy use for the 1-yr period for the live-in family was less than half the amount estimated for the reference house. Total water use was about 33 percent less than that estimated for the reference house. Many of the new technology systems performed as expected; however, the total energy provided by solar collectors was reduced by a colder-than-normal winter, coupled with less than normal available solar energy in the fall.

Much was learned about family lifestyle and its effect on system design and component sizing. The basic project objectives were realized in that data and operational experience were obtained under normal living conditions, enabling analysis of variations from the predicted performance. The conclusions that can be drawn as to why a particular technology performed differently from expectations proved to be just as important as data which verified predicted performance.

INTRODUCTION

The oil embargo imposed by OPEC from 1973 to 1974 focused national attention on the nation's energy demands and on the need to conserve expendable fossil-fuel resources and to develop alternate sources. In examining the potential for conservation, NASA considered that the technology developed for the space programs, which involved the use of solar energy, water recycling systems, advanced materials, and electronics, should be adaptable to various public-sector problems. To illustrate the utility and benefits of these technologies, various demonstration projects were initiated. The NASA Technology Utilization House, or Tech House, was one such project. In 1974, the NASA Langley Research Center, supported by the Office of Technology Utilization, proposed a demonstration project - one that would apply new technologies, including aerospace technology, where feasible to the home-building industry. Although consideration was given to a program that would evaluate various features or subsystems independently (a normal research approach), the concept which evolved and which was accepted was that of designing and constructing a demonstration house for evaluation in a "real-world environment." The practical demonstration of solar energy systems, energy- and water-conservation design concepts, safety, and security technology was a basic objective. It was intended that the added cost of any incorporated energy- and water-conservatrion technology features would prove to be cost effective for the homeowner over a 20-yr period. In addition, all demonstrated technology was expected to be commercially available within 5 yr. With this approach, the Tech House project began in August 1974.

Project objectives, broadly stated, were (1) to design and construct a single-family detached dwelling to demonstrate the application of NASA aerospace, government, and other industrial technology to advance the building industry in residential construction and (2) to influence future development in home construction by defining the interaction of integrated energy- and water-management systems and other advanced technologies with building configurations and construction materials. Implicit in these broad objectives was the desire to reduce the annual cost of residential living by utilizing alternate energy sources which could also eliminate or reduce the demand for energy generated by fossil fuel; to reduce the consumption of water by incorporating water-reuse features; and to demonstrate the use of improved building materials and construction techniques.

Shortly after project inception, an ad hoc committee was formed to establish guidelines, assist in generating and screening ideas, and evaluate various design features. Chaired by NASA Langley personnel, the committee included representatives of the Department of Housing and Urban Development (HUD), National Bureau of Standards, Consumer Products Safety Commission, National Association of Home Builders Research Foundation, Inc., NASA Headquarters, NASA Johnson Space Center, NASA Ames Research Center, and NASA Marshall Space Flight Center. Under the general direction of the committee, university studies were conducted to evaluate candidate technology ideas. An architect-engineer contractor team was engaged to conduct trade-off studies, to assist in the selection of materials and subsystems, to prepare candidate designs, and to produce construction drawings of the selected design. Various designs were evaluated before a single-level modular home was selected in mid-1975.

It was recognized early in the project that a proper performance evaluation of the Tech House would require an extensive instrumentation and data-collection system as well as a comparison with a conventional contemporary house An existing HUD study of home energy and water use in the Baltimore-Washington area formed the basis for reference values of energy and water use in a comparably sized dwelling (ref. 1).

After construction approval was granted in November 1975, the Tech House was built during the late winter and spring. It was completed in June 1976 and was opened for public inspection in July 1976 for a 1-yr period. During this time, the house, along with its various subsystems and controls, was checked out, and changes were made as needed to assure operational readiness for the planned 1-yr live-in test (ref. 2).

In mid-August 1977, a family of four moved into the house for a 1-yr live-in experiment. Throughout the year, the house and its various subsystems and key components were monitored by an extensive data-collection system located in the garage. Although automatic data collection was interrupted briefly at times during the year, enough data were collected for satisfactory evaluation of the systems. Data from this live-in test form the basis for the performance evaluation presented in this report. After completion of the live-in test, the house was again opened to the public in October 1978 and, at this writing, continues to be available for public inspection on a daily basis.

Volume II of this report includes daily meter readings, noise-test results, weather data, and other information needed for complete analysis of the test results.

Certain commercial materials and products are identified in this paper in order to specify adequately the ones investigated in the research effort. In no case does such identification imply recommendation or endorsement of the materials or products by NASA, nor does it imply that they are necessarily the only ones or the best ones available for the purpose. In many cases equivalent materials and products are available and would probably produce equivalent results.

The requirement that the International System of Units (SI) be used in NASA reports has been waived because the house was designed and constructed using U.S. Customary Units and because the report is intended for use by the general public and the building industry, both of which use U.S. Customary Units. However, a table for conversion of U.S. Customary Units to SI Units is given as an appendix.

TECH HOUSE DESIGN

GENERAL DESCRIPTION

The Tech House is a single-level home of contemporary design, comprised of three interconnected square modules which make up the living area and an attached garage (fig. 1). Each module is covered by independent gabled roofs. The modules are interconnected by flat-roof passageways.

A floor plan of the house is shown in figure 2. The living space consists of two 729-ft^2 modules connected by a 7-ft foyer, with entry vestibules front

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Figure 1.- NASA Tech House.

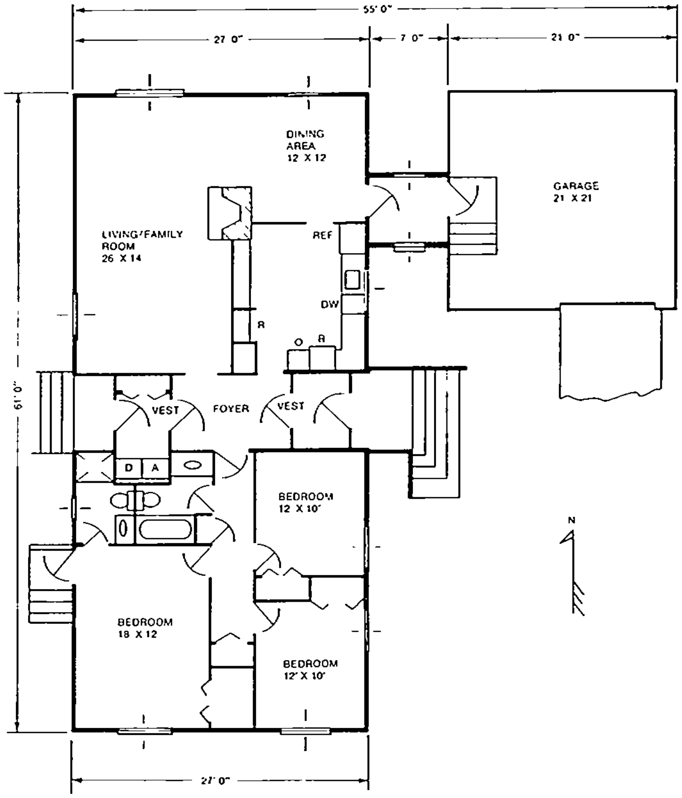

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Figure 2.- Tech House floor plan.

and rear, for a total area of nearly 1650 ft^2. The north module includes the living room, dining area, and kitchen; the south module contains three bedrooms and the two bathrooms. The garage, some 441 ft^2, is situated east of, and connected to, the north module by a vestibule.

Gable style roofs cover the three modules. Eighteen 3-ft by 8-ft solar panels (fig. 3) are mounted on the two main south-facing roof exposures to supply energy, in the form of solar-heated water, to the home's space heating system and to its domestic hot-water supply system. An array of radiator panels is placed on the north slope of the garage roof (fig. 4); these panels were provided to cool storage water heated by the heat pumps when the system is operating in the air-conditioning mode.


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Figure 3.- Tech House solar panels.

The roofs contain large louvers at either end to provide attic ventilation. Large south-facing windows allow passive solar heating in winter, and a roof overhang shades these windows in summer to reduce solar gain. Exterior retractable shutters are installed at all window locations to reduce heat loss in winter and heat gain in summer.

The featured technology includes large subsystems as well as miscellaneous items of general utility. The major technology features are integrated into the fundamental design of the house and include basic structural features, solar-energy systems for domestic hot water and space heating, and a water-reuse system. These technologies will be discussed in detail in the section entitled "Systems."

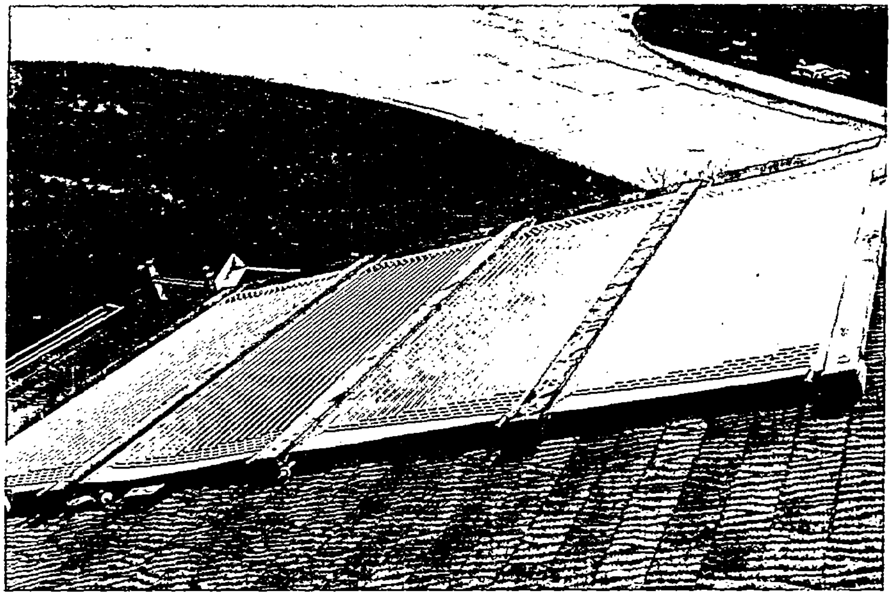

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Figure 4.- Radiator panels.

The miscellaneous technology items consist of emergency lighting, a special security system, flat conductor electrical cable, light-bulb life extenders, and a tornado-detection device. These items are not fundamental to the house design, but instead are incorporated for general demonstration and qualitative evaluation. These technology items are briefly described in the following paragraphs.

Emergency Lighting

Low-power (6-W) fluorescent lamp fixtures (fig. 5) are situated in three locations (i.e., living room, kitchen, and in the bedroom-area hallway). The emergency light system is powered by a standard 12-V automotive battery which

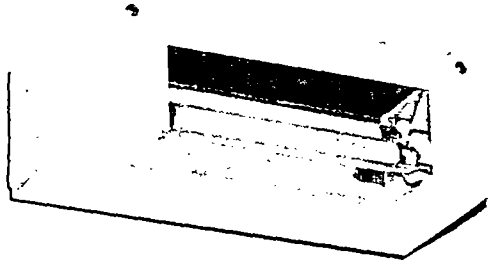

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Figure 5.- Emergency lighting fixture.

is charged by a small solar-cell array located on the garage roof (fig. 6). The emergency lights are automatically energized when local utility electrical power is interrupted.

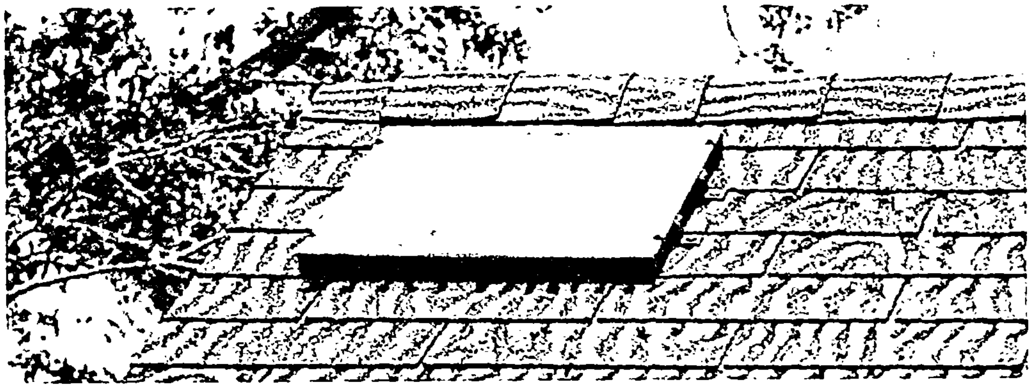

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Figure 6.- Solar-cell array for emergency lighting system.

Security

The primary system for interior security incorporates an audible alarm when there is attempted intrusion through doors or window screens or when pressure-sensitive pads (fig. 7) are treaded upon. The system is armed by entering a

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Figure 7.- Pressure-sensitive pads of security system.

coded set of numbers into one of the entrance-area digital panels (fig. 8). A preset time delay allows time for the family to exit and enter without activating the alarm. Secondary security features include seismic detectors implanted in the lawn to provide a trespass alert to an FM radio, a pocket-size sonic transmitter to remotely actuate the front-entrance light, a standard ionization-type smoke detector, and self-locking exterior door hinges which prevent doors from being removed when hinge pins are extracted.

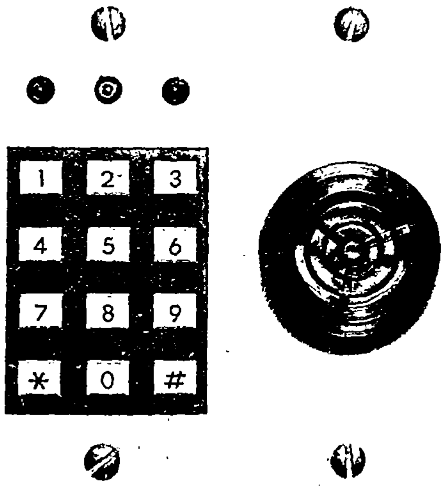

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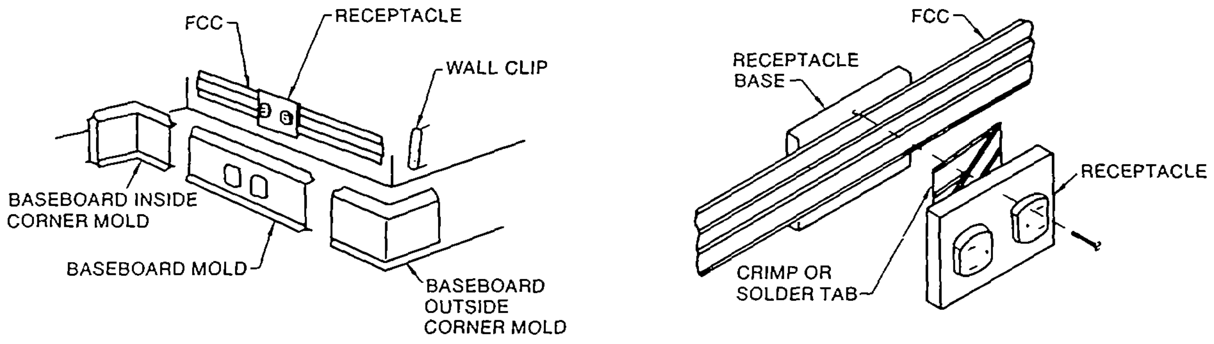
Figure 8.- Entrance-area digital control panel of security system.

Flat Conductor Electrical Cable

Baseboard-mounted flat conductor electrical wiring and receptacles (fig. 9) re installed in the living/dining area. This type wiring may be installed



Snap-on cover baseboard system

Receptacle with crimp or solder tab

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Figure 9.- Flat conductor cable (FCC).

after wall construction is finished to permit flexibility in locating outlets, make modifications easier, and allow wiring and receptacles to be removed or relocated readily.

Light-Bulb Life Extenders

Thermistor devices designed to prolong the normal life of common incandescent light bulbs are installed in some of the Tech House light fixtures (fig. 10). These devices, because of their electrical resistance characteristics, momentarily limit the initial surge of electrical current into a cold lamp, thus extending bulb life since failures frequently occur when a light is switched on.

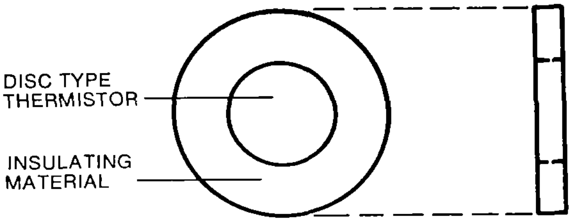

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Figure 10.- Thermistor light-bulb life extender.

Tornado Detector

The tornado detector, a light-sensitive device, is encapsulated in a suction cup and attached to the face of a television picture tube (fig. 11). Its detection threshold depends on the storm's energy level. Monitoring during a "tornado alert" is done by tuning the television to an unused channel, with the screen darkened; a tornado within a radius of 18 miles should activate the audible alarm signal.

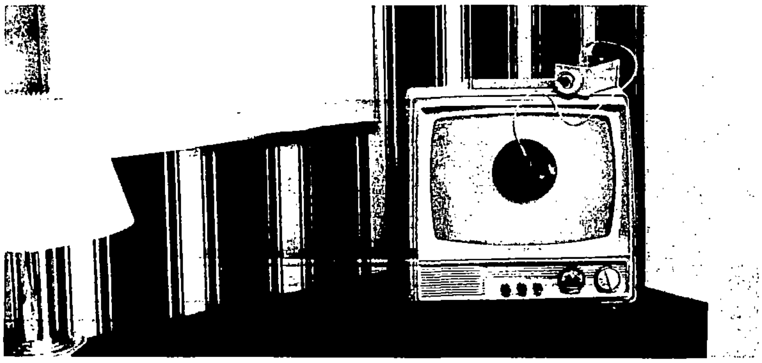

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Figure 11.- Tornado detector.

SYSTEMS

Structural

Floors

The floor structure in the Tech House is comprised of prefabricated, modular concrete slabs supported on foundation above a 3-ft crawl space. Each floor section is 7 ft by 14 ft and was set in place with a crane (fig. 12).

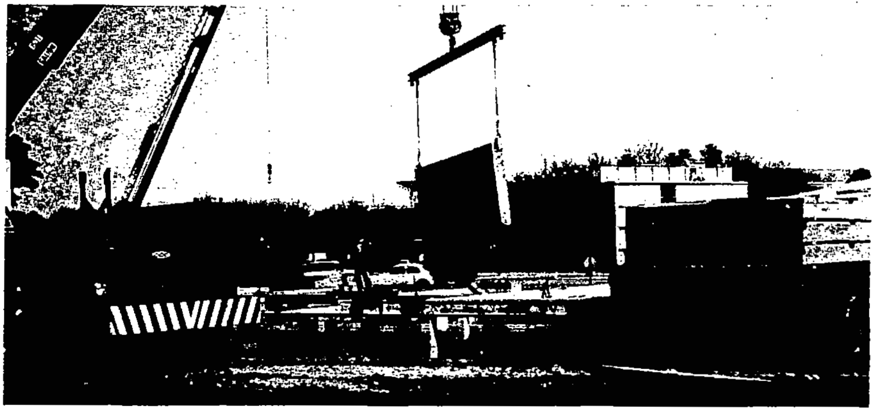

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Figure 12.- Prefabricated modular floor sections.

The sections consist of 2-in. concrete plate, reinforced by welded wire fabric, with steel joists as the supporting elements. The underside of the floor is covered with 6 in. of gypsum foam insulation held in place by wire netting (fig. 13).

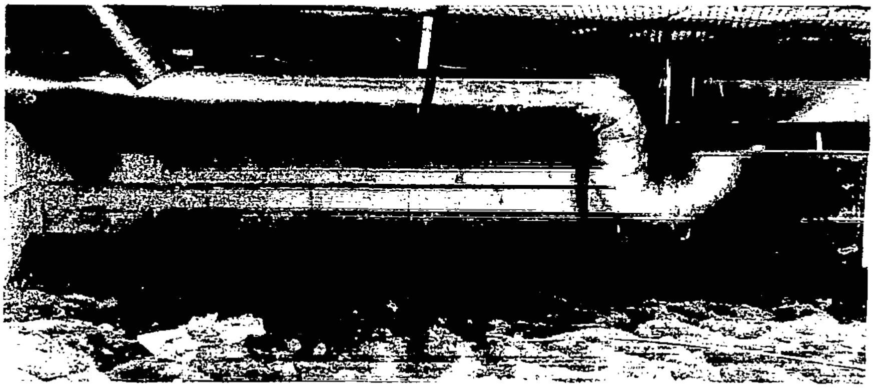

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Figure 13.- Underside of floor showing gypsum foam insulation.

Interior floor coverings vary. A foam-backed vinyl floor covering with a urethane coating is installed in the kitchen; carpeting covers the living and dining areas, the bedrooms, and hall; ceramic tile is installed in the bathrooms; and slate is used for the front entrance area and foyer. Photographs made inside the Tech House are shown in figures 14, 15, and 16.

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Figure 14.- Living-room area.

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Figure 15.- Master bedroom.

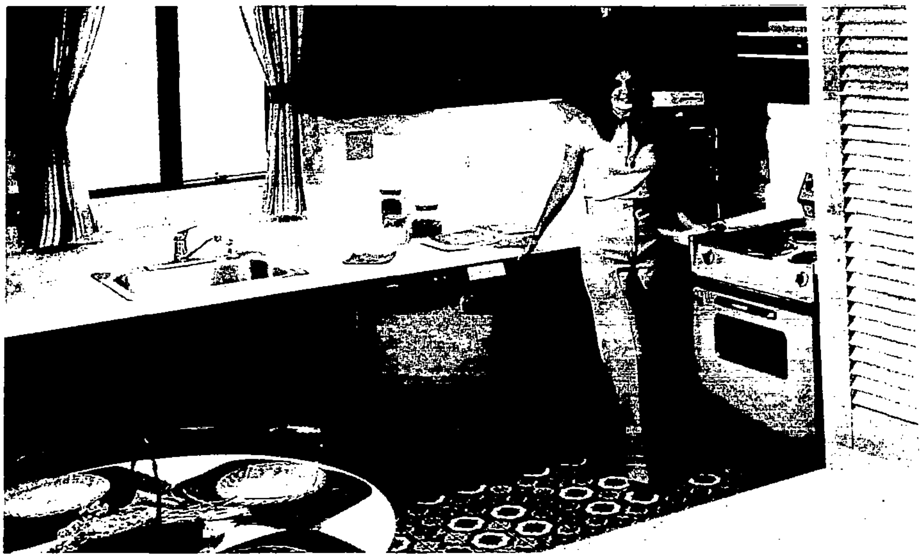

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Figure 16.- Kitchen.

Walls

The exterior wall structure (fig. 17) consists of a framework of 2- by 6-in. studs placed every 24 in.; these studs are covered with 1/2-in. sheathing and 5/8-in. fir plywood on the exterior and 1/2-in. sheet-rock panels on the inside.

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Figure 17.- Wall structure showing 2- by 6-in. studs.

Interior wall framing members (fig. 18) are 2- by 4-in. reconstituted sawdust studs placed every 16 in. These studs have thin wood facings to permit easier nailing. The interior wall between the master bedroom and bathrooms is a prefabricated section consisting of glass fiber-reinforced gypsum on the outside and sand on the inside; the entire unit is cast in a steel frame (fig. 18).

L-76-1571

Figure 18.- Reconstituted sawdust studs and precast wall.

Roof

The gable roof over each section of the house is supported by a truss structure (fig. 19) comprised of 2- by 6-in. rafters and joists that are strengthened by 2- by 4-in. bracing members. The structural framing is covered with 1/2-in. plywood sheathing, 15-lb felt insulating paper, and a final covering of standard commercial-weight (325-lb) asphalt shingles (fig. 1). A horizontal, 3-ft overhang extends the roof on the south-facing

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Figure 19.- Roof truss structure.

module to provide shade during the summer (fig. 20). The south-facing side of each gable has a slope of 58° from the horizontal, an angle which was selected for the solar panel facade for this geographic location based on regional solar insolation and historical weather patterns. The resultant north-facing roof slopes at approximately 22.5° from the horizontal. Passive summertime cooling of the attic is enhanced by large ventilation louvers at either end of the roof (fig. 20).

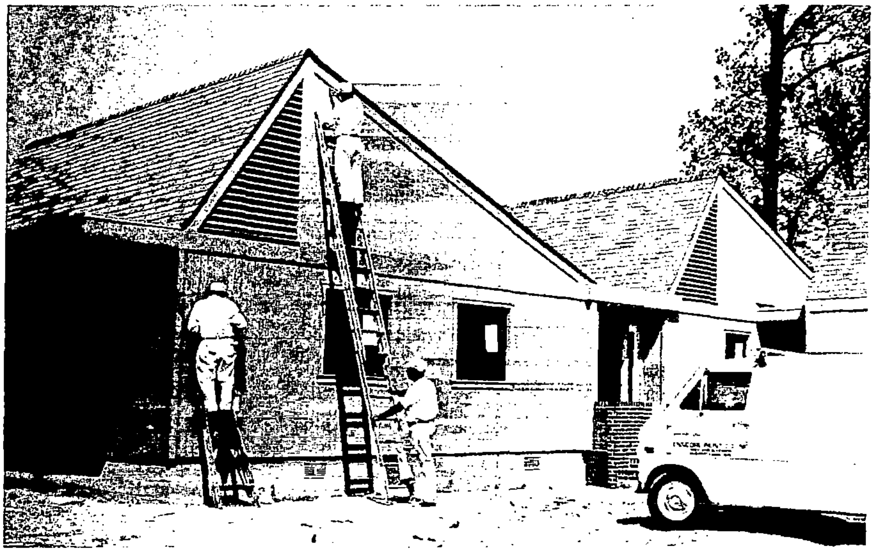

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Figure 20.- Roof showing overhang and roof ventilation louvers.

Windows and Shutters

The windows and the glass patio door are of aluminum frame construction. Energy-saving features of the windows include double glazing, low-thermal-conductivity separators between inner and outer parts of the frame, and built-in weather stripping. The window panels slide horizontally, one behind the other, to open. Screens are installed on the outside of each movable pane. An aluminized plastic sheet is installed on the glass patio door to reduce solar-heat gain in the living-room area during the summer. Retractable external shutters are provided at each window and may be operated to reduce winter heat loss at night and summer solar gain during the day (fig. 21). They also inhibit noise and provide a measure of security against storms and intruders. The shutters are manually operated from the inside, except for three of the bedroom windows which have motor-driven shutters (to demonstrate the availability of this option).

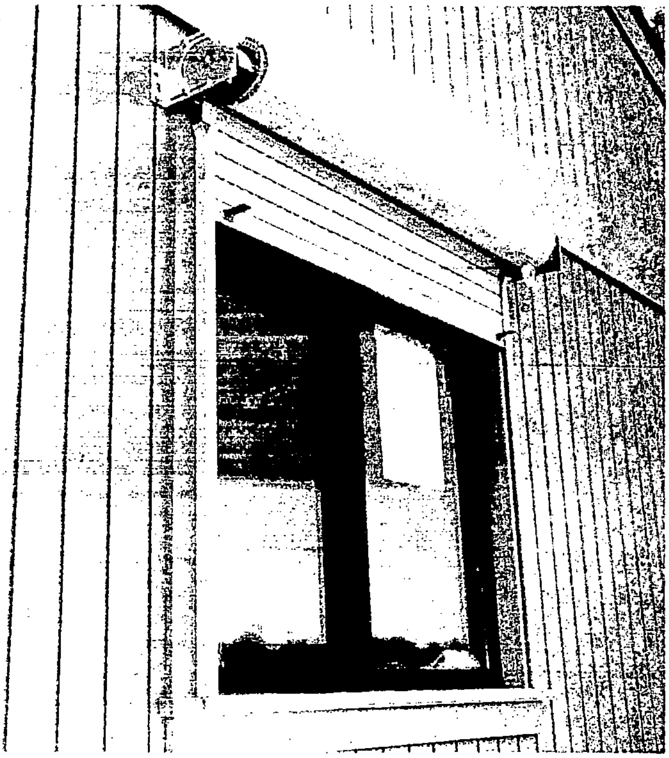

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Figure 21.- External shutters with roll-up housing removed to show how shutter is stored.

Doors and Entrances

The front and rear entrances off the foyer are provided with double-door air-lock entry vestibules to minimize heat loss in the winter and heat gain in the summer. The exterior doors are steel clad, with a solid core of insulating polystyrene foam laminated to the steel panels. Magnetic weather stripping and an adjustable sill with moisture barrier are used to further reduce heat loss or gain. Inner doors are of conventional hollow-core plywood-panel construction.

Thermal Insulation

The walls and attic floor are insulated with a urea-tripolymer foam. This type of cellular plastic is mixed at the job site and sprayed into the wall and attic cavities. It is trowel finished on walls to provide a smooth face. The foam is approximately 5-1/2 in. thick in the exterior walls and about 7-1/2 in. thick in the attic (figs. 22 and 23). A plastic film vapor barrier is installed on the interior side of the insulation in both cases.

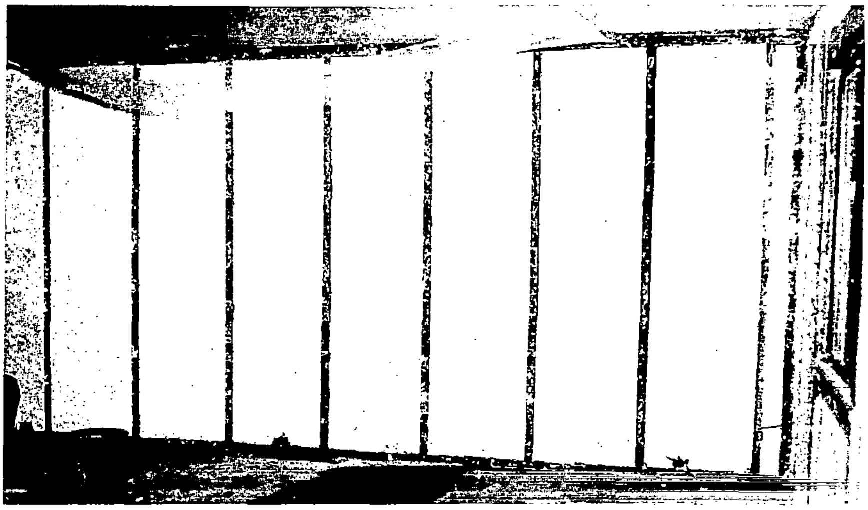

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Figure 22.- Newly installed wall insulation.

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Figure 23.- Newly installed attic insulation.

Heating and Air Conditioning

The heating and air-conditioning system schematic is shown in figure 24; for clarity, the piping, drain-down lines, and valves are not shown.

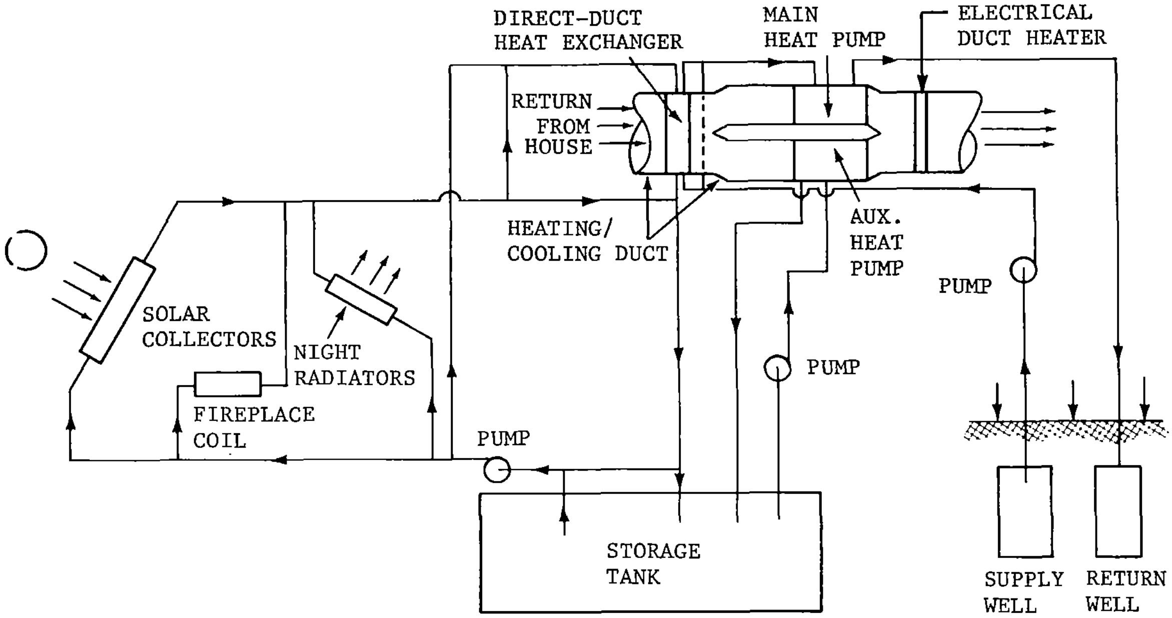

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Figure 24.- Simplified diagram of heating and cooling system.

The heating system utilizes solar energy as the primary source of heat energy and is designed to provide that energy to the house through any of three methods. First, the solar-heated hot water can be pumped through the direct-duct heat exchanger to heat the supply air. Second, excess solar-heated water can be diverted to the storage tank and later pumped to the direct-duct heat exchanger to heat the supply air during periods when the Sun is not shining. Finally, solar-heated water stored in the tank can be used as a source of energy for the heat pumps when the temperature of the stored water is too low to heat the house directly but is higher than the temperature of the well water.

As a backup, the heat pump system is designed to use well water as a source of energy when solar-heated water is unavailable (i.e., at too low a temperature). Each of the two heat pumps is rated 14 000 Btu/hr for cooling and 20 905 Btu/hr for heating. In the case of total failure of the solar and heat-pump system, an electric resistance duct heater is incorporated to provide heat to the house. To further supplement the heating system, a water-coil grate in the fireplace provides additional energy to the system when the fireplace is in use.

The design temperatures at which the system changes from one method of heating to another are as follows:

(1) When water at 110° F or more is available, the direct-duct heat exchanger is employed to transfer heat to the supply air. The water may be supplied directly from the solar collectors or from the storage tank.

(2) When the temperature of the storage tank water drops below 110° F and if the solar collectors do not add enough energy to the water to raise its temperature above 110° F, the storage water is used as the source water for the heat pumps. When the storage-water temperature falls below the temperature of the well water (about 60° F), the wells are used as the source of water for the heat pumps.

Solar Heating

The solar heating system consists of 16 solar panels with the necessary piping, valves, and pumps to collect and transport the water for space heating. Control of this system will be described in the section entitled "Instrumentation, Measurements, and Control."

The solar panels (fig. 3) are flat-plate, single-glazed collectors with a collection plate of steel covered with a selective coating to enhance efficiency. In addition to the 16 collector panels for space heating, there are two for domestic hot water. Nine collectors are mounted on the south-facing roof of each module, with two of the collectors on the north module used for domestic hot-water heating. The panels are at a 58° angle from the horizontal in order to collect the maximum amount of solar energy during the heating season. Each collector panel is 3 ft wide by 8 ft long, giving a total collection area of 384 ft^2 for space heating and 48 ft^2 for domestic hot water. The heating-system collectors on each roof section are connected in parallel such that water supplied to the group of collectors is divided among them equally. The two parallel groups of collectors are then connected in series so that water pumped through the first set of collectors must flow through the second set before returning to the storage tank. For freeze protection, the system drains automatically when not in use.

Energy Storage

The energy storage system consists of a 1900-gal concrete tank (fig. 25) installed underground and insulated with 2 in. of expanded, open-cell plastic insulation material. The insulation is sealed against ground water. The piping to and from the tank is designed so that energy collected in the form of hot water is delivered to the lower half of the tank, and the supply water used from the tank flows from the higher temperature region in the upper half of the tank.

L-76-2580

Figure 25.- 1900-gal underground storage tank.

Air Conditioning

For air conditioning the house in the summer months, the two water-source heat pumps are used in the cooling mode. The heat pumps operate by extracting heat energy from the house and rejecting it into the storage tank or into the well system.

Zone Control

The Tech House is divided into four heating and cooling zones so the heating and air-conditioning system can provide conditioned air to areas of the house as needed. Energy may be conserved by selective heating or cooling of the zones.

The four zones are shown in figure 26. Zone 1 includes the master bedroom and its adjoining bathroom; zone 2 consists of the two other bedrooms; zone 3 is the main bathroom; and zone 4 includes the living, dining, and kitchen areas. Each zone may be controlled independently. For example, the living areas would typically be heated or cooled only when occupied; the bedrooms would be heated or cooled during sleeping hours; and bathrooms conditioned shortly before awakening. Control of the zone system is described in the section entitled "Zone Control of Heating and Air-Conditioning System."

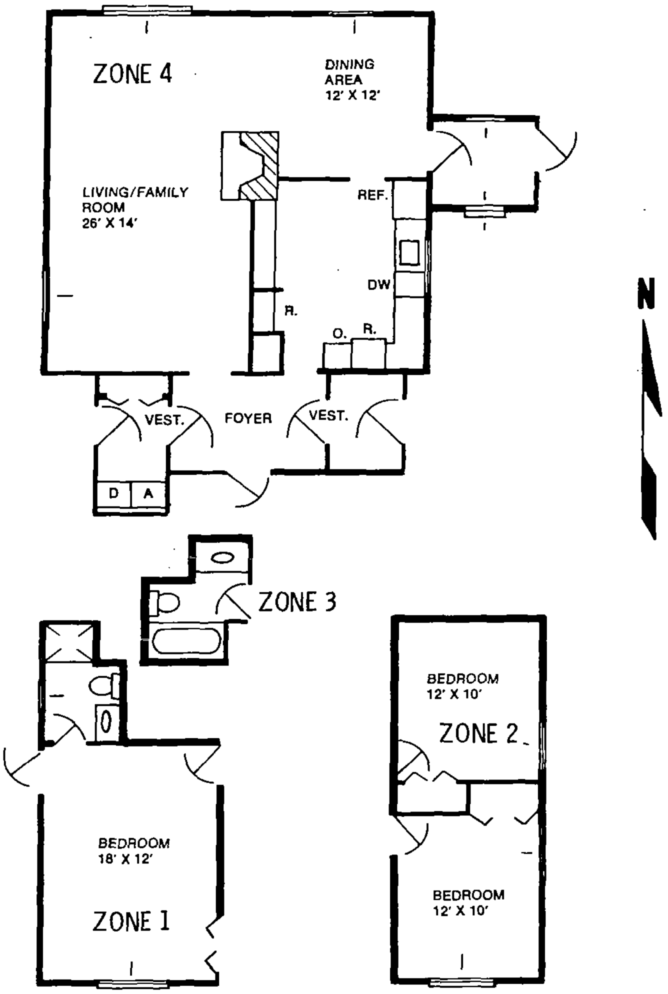

Figure 26.- Heating and air-conditioning zones.

Fireplace

The Tech House fireplace is made an integral part of the heating system by using a water-coil grate through which heating-system water may be pumped so that heat energy from the fire can be transferred to the supply water. Combustion air for the fire is obtained from ducts vented to the outside. A double-wall, steel firebox enables room air to be heated by circulating through the plenum, entering at the floor-level air intakes, and exiting near the ceiling through the warm-air outlets. A glass-door fire screen prevents room air from exiting up the chimney. Features of the fireplace are shown in figures 27 and 28.

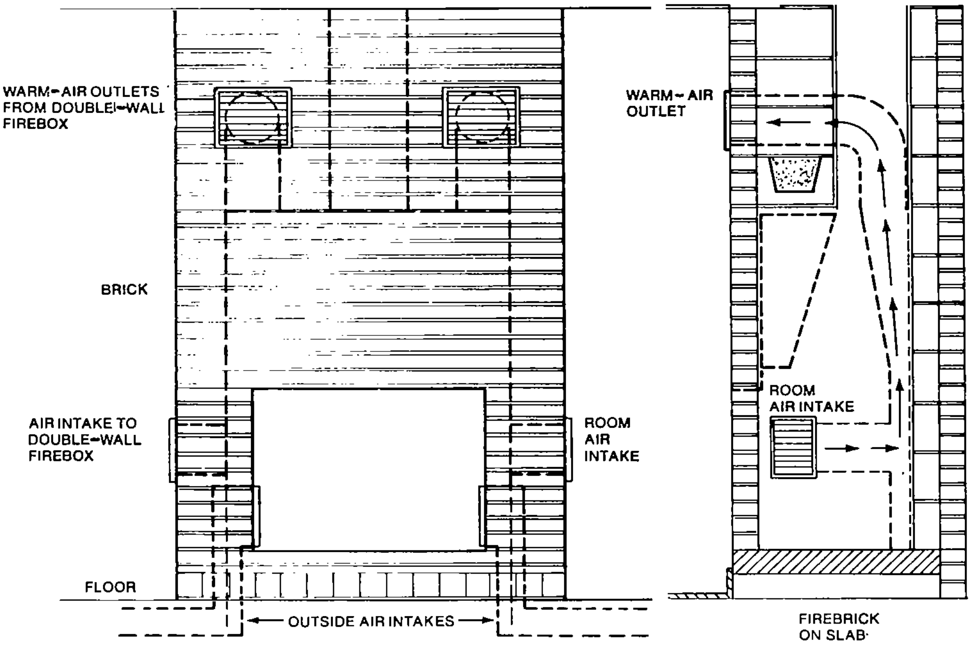

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Figure 27.- Fireplace schematic.

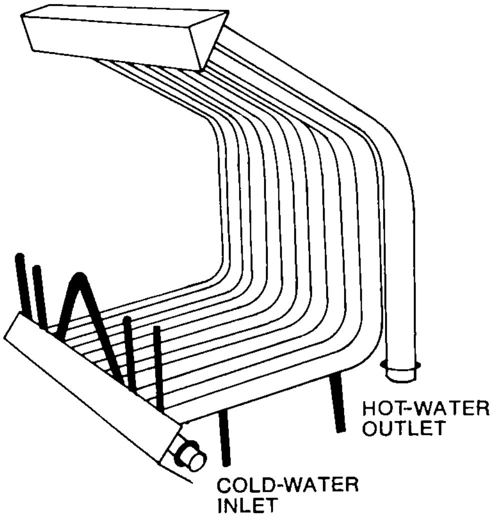

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Figure 28.- Fireplace water grate.

Solar-Supplemented Domestic Hot-Water System

The domestic hot-water system consists of a solar-heated (preheat) water tank, an electrically heated water tank, and two 3- by 8-ft solar collectors of the same design as those used in the space-heating system. The two collectors are located on the south-facing roof of the living-room/kitchen module. A diagram is shown in figure 29.

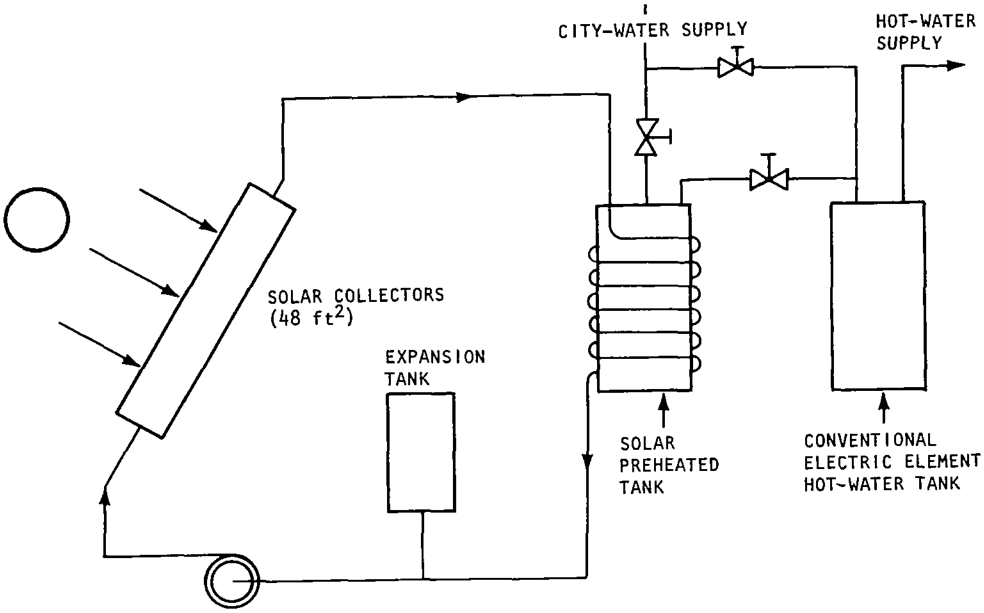

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Figure 29.- Solar domestic hot-water system.

Unlike the space-heating system, the solar domestic hot-water system has no automatic drain-down provisions to prevent freezing. Instead, a water/antifreeze mixture serves as the working fluid for transferring solar energy to the water in the preheat tank.

The preheat tank is a standard 50-gal electric hot-water tank with its resistance heaters disconnected; copper tubing is coiled around the outside of the inner water tank for transferring the collected solar energy to the potable water in the tank. An electrically heated 42-gal hot-water tank in series with the preheat tank provides backup hot water to the house. The system is designed so that city water enters the preheat tank, is heated by energy in the solar-collector loop, then flows into the electrically heated tank where it is stored for use in the house. Thus, the electrically heated tank operates only as needed to maintain the preset hot-water temperature.

Water-Reuse System

A water-reuse system using bath and laundry waste waters to provide toilet flush water was designed at the NASA Langley Research Center and is incorporated in the Tech House. A schematic diagram is shown in figure 30, and a photograph of the installed system is shown in figure 31.

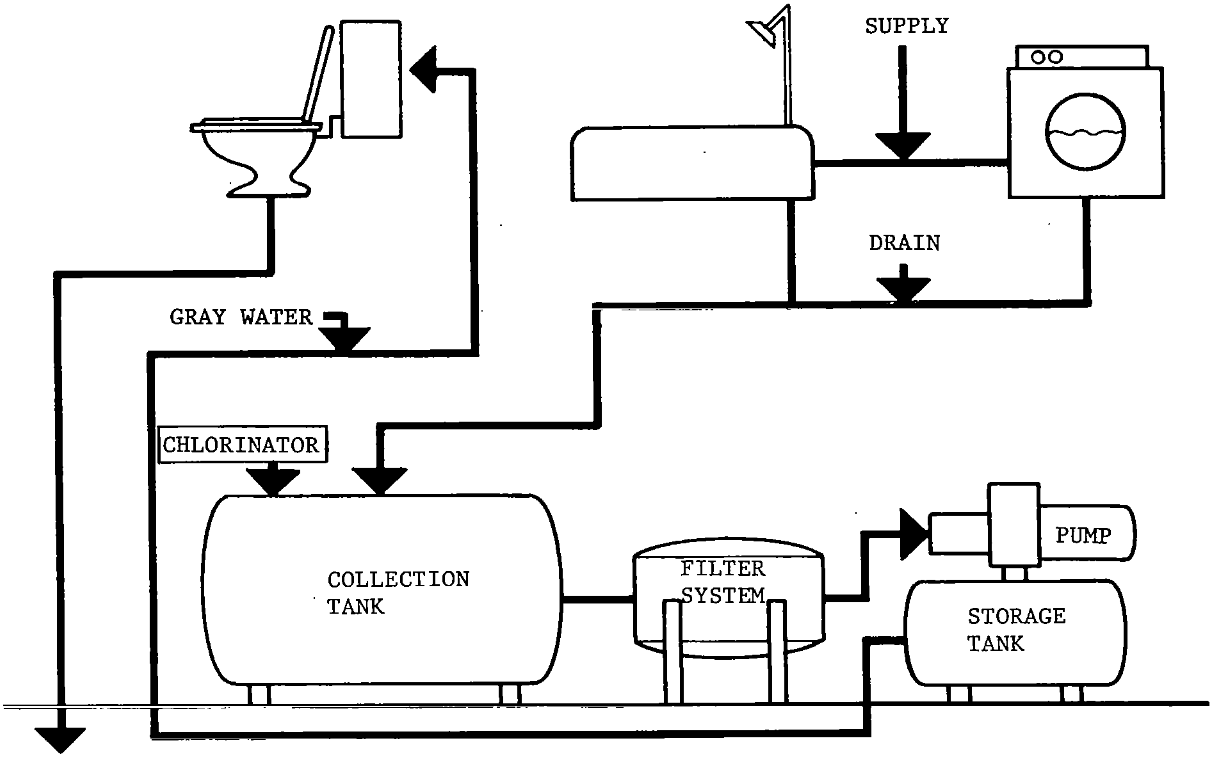

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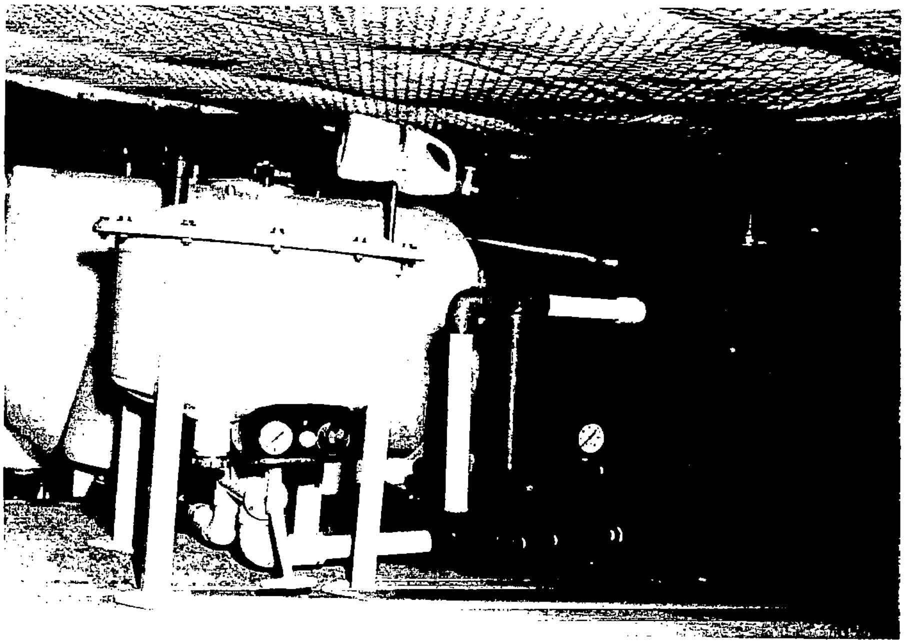
Figure 30.- Schematic of water-reuse system.



L-76-3281

Figure 31.- Water-reuse system in place.

Components include a 110-gal polyethylene collection tank, a diatomaceous earth particle filter, a shallow-well jet pump with integral 17-gal steel pressure tank, a chlorinating device, a make-up water adding valve, and an overflow to dump excess waste water to the house drain pipe.

Instrumentation, Measurements, and Control

An extensive system of instrumentation for data collection and control is incorporated in the Tech House in order to measure its status, its systems, operation, and the weather conditions necessary to the control logic. These data are used in the evaluation of house performance.

Sensors

Two types of instruments were employed for data collection: (1) instruments which display information visually for manual recording and (2) sensors that measure and transmit data for automatic recording on magnetic tape. The first group includes

- 13 water-flow meters
- 1 W-hr meter
- 5 elapsed time meters
- Various thermometers (normally used in the solar-system piping when the automatic data-recording system was down for maintenance or repair)

The second group includes a variety of sensors (flow rate, pressure, temperature, electric power, etc.), which are summarized in table 1. For further details of the sensor functions, calibrations, and accuracy, the reader is referred to Volume II of this report.

Data Collection

Each automatic data system sensor is connected to the data-acquisition system. The system scans sequentially through 100 channels (96 channels of data and 4 reference channels), converting the analog voltage signals into digital information for input to the calculator and the data-recording equipment. Each complete data scan takes 16 sec. The interval between scans is controlled by a digital clock and can be adjusted from a few seconds to several hours. A scan interval of 1 min is near optimum since shorter scan intervals do not allow sufficient time for computer control activities and longer intervals result in less favorable control of the house environment.

The data collected are recorded on magnetic tape at predetermined intervals. Only every tenth or fifteenth scan is recorded, which is sufficient for determining performance of the various systems.

TABLE 1.- TECH HOUSE SENSORS

Automatic data-system sensors		
Measurement function	Sensor type	Number used
Water flow rate	Turbine	7
Gray-water pump suction pressure	Pressure transducer	1
Electrical power	Hall effect watt transducer	12
Water temperature	Platinum resistance thermometer	25
Air velocity (duct system)	Air velocity meter (hot-wire type)	10
Air and wall temperatures	Thermocouple (type K)	39
Relative humidity	Hydrometer	1
Solar radiation	Pyranometer	1

After recording, the data are converted into engineering units and printed for review. The data are then recorded on a master magnetic tape which is used for producing daily, weekly, and monthly summaries of performance.

Control

The Tech House control system utilizes the data-collection system previously described, in conjunction with a programmable calculator and various relays. A Tektronix 4051 calculator is the heart of the system and, through its programmable features, analyzes the input data, determines the best operating mode for the house systems, and signals the relays which control the various components of the heating and cooling systems.

Information may be displayed in tabular or graphic form on a cathode ray tube (CRT) display in real time for on-the-spot monitoring of house conditions or for an assessment of systems operation so that changes in the control program may be made in a timely fashion.

A fail-safe mode is incorporated so that in the event of electrical failure or a scheduled maintenance shutdown, control of the heating or air-conditioning system switches over to the room thermostat.

A block diagram of the control system is shown in figure 32.

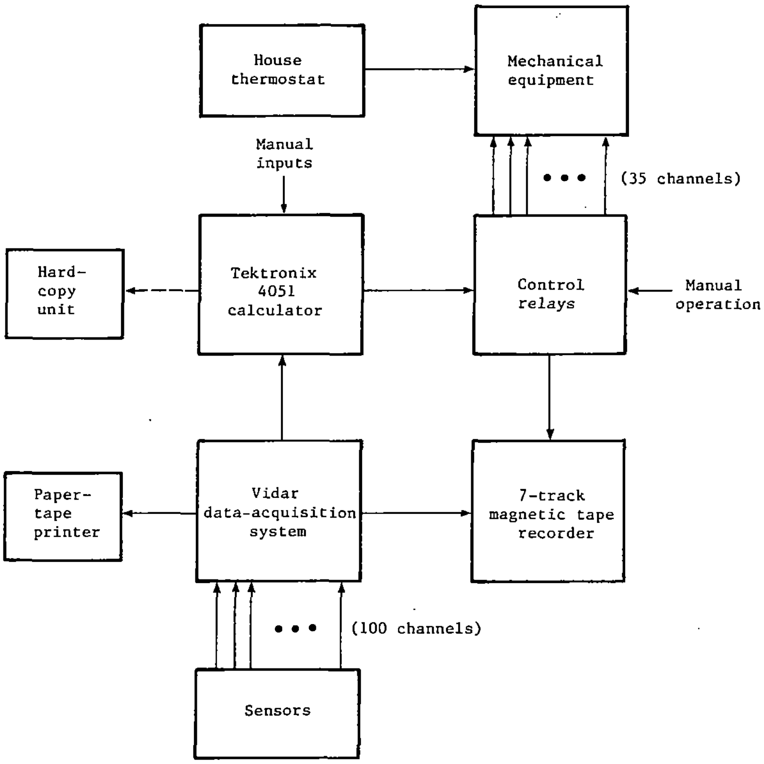


Figure 32.- Tech House control system.

GENERAL TECH HOUSE PERFORMANCE

LIVE-IN TEST

The live-in test period for the project was chosen to be one calendar year to allow the house to be tested over one complete weather cycle, during which time energy and water usage, the status of the house and its energy systems, and the external conditions (solar radiation, temperature, etc.) were monitored and recorded. During the 1-yr period, a family lived in the house and paid both rent and utility costs, the latter at rates consistent with those of the local suppliers. Their use of the house was consistent with their own life style, with as little intrusion on privacy by the researchers as possible. All data-collection and recording equipment was located apart from the living area of the house; hence, the family was not disturbed by these activities except for the collection of water samples from each water closet twice a week. The family took these samples and placed them in the garage for pick up.

LIVE-IN FAMILY

Before selecting a family to live in the Tech House for the 1-yr evaluation period, it was decided that the family should be a middle-class household with two school-age children and that the heads of the household should be nontechnical in background and profession. With these requirements in mind, NASA contacted the American Council on Education (ACE). Through an existing program that places selected teaching professionals in temporary government service positions in all parts of the country, the ACE was able to provide NASA with the names and resumes of six available candidates who met the requirements previously cited. From these, Charles W. (Bill) Swain and his family, from Tallahassee, Florida, were selected. Dr. Swain is a professor of religion at Florida State University, and his wife is a nurse practitioner. Both were employed locally during the test year. Their teenage daughter and preteen son attended local schools. The Swain family moved into the Tech House in August 1977.

TECH HOUSE PERFORMANCE VERSUS REFERENCE HOUSE

The goal to reduce energy and water consumption from the levels used by conventional homes required defining a "conventional" house for comparative purposes and establishing the average yearly usage of energy and water in such a house. The reference house also needed to be of comparable size and located in the same general geographical region, in this case the Middle Atlantic.

Description of Reference House

The reference domicile used to make annual energy- and water-consumption comparisons with Tech House is a composite, comparably sized single-family dwelling and is fully described in reference 1. Reference 1 is a study of residential energy consumption for Washington-Baltimore area homes and was prepared under the sponsorship of the Department of Housing and Urban Development (HUD).

The reference-house floor area, 1695 ft^2, is virtually the same as that of Tech House. Systems, materials, components, workmanship, and associated appliances are consistent with representative middle-income homes constructed in the early 1970's in the Baltimore-Washington metropolitan area. All energy systems and devices are electrical, with the notable exception of space heating which employs a natural-gas, forced-air system.

Annual electrical energy consumption, as estimated for the HUD reference house, is presented in table 2. The value for space heating represents the equivalent electrical energy in kilowatt-hours as derived from the Btu's required by the gas furnace. (See ref. 1.)

TABLE 2.- ANNUAL ELECTRICAL ENERGY CONSUMPTION

FOR HUD REFERENCE HOUSE

Item	Electrical energy, kW-hr
Domestic hot water	4 380
Space heating[a]	[a]29 300
Air conditioning	3 600
Base load (lights, appliances, etc.)	8 720
Total	46 000

[a]Equivalent electrical energy based on Btu required by gas furnace (from ref. 1).

Performance Comparison

Energy

A comparison of the electrical energy used during the 1-yr Tech House live-in test with the annual estimate for the HUD reference house shows that significant reductions were achieved in the Tech House. Total electrical energy used for all purposes in the Tech House was less than half that projected for the reference house. Comparative energy consumptions are given in table 3 and in figure 33.

TABLE 3.- ANNUAL ELECTRICAL ENERGY USE OF TECH HOUSE VERSUS HUD REFERENCE HOUSE

Use	Electrical energy use by HUD reference house, kW-hr	Electrical energy use by Tech House			
		Projected use, kW-hr	Projected savings, percent	Actual use, kW-hr	Actual savings, percent
Domestic hot water	4 380	1 500	66	4 167	[a]5
Heating	29 300	6 000	80	6 080	79
Air conditioning	3 600	2 100	42	2 732	24
Base load (lights, appliances, etc.)	8 720	5 400	38	7 277	17
Total	46 000	15 000	[b]67	20 256	[b]56

[a] Would be 35 percent if based on actual energy required to heat water (6392 kW-hr) at the Tech House; 4167 kW-hr of electricity, and 2225 kW-hr of solar energy.

[b] Value based on electrical energy used by HUD reference house.

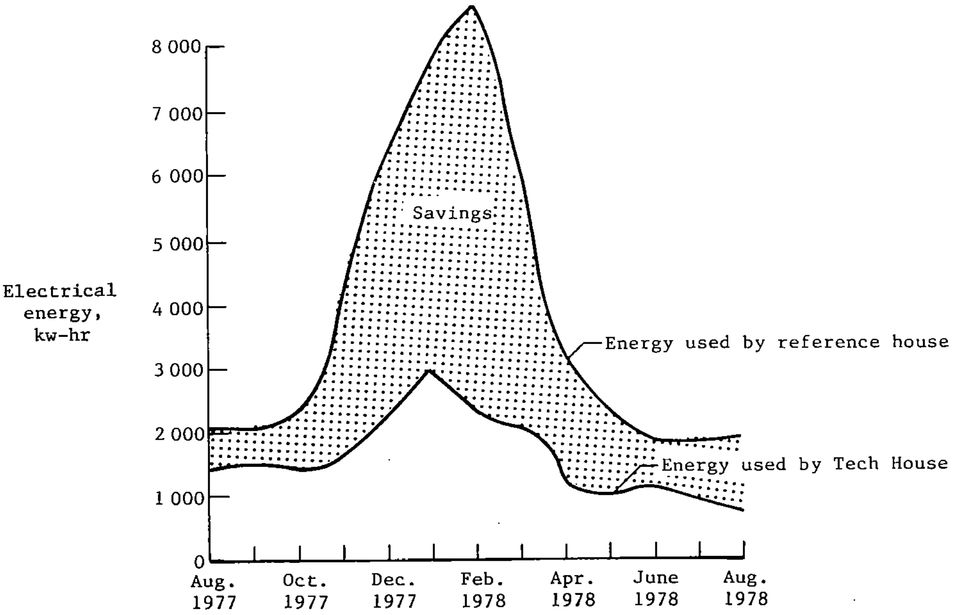


Figure 33.- Monthly electrical energy consumption of Tech House versus HUD reference house.

Significant energy savings were realized for space heating, a result of both the solar-supplemented heating system and the various thermal design features such as improved insulation, double-door vestibules, double-pane windows, window shutters, insulated floor, and insulated doors. Improvements to the house envelope accounted for approximately 60 percent of the savings in heating energy and virtually all the savings in cooling energy.

Solar energy provided approximately 35 percent of the energy required to heat the domestic hot water used in Tech House for the year. A direct comparison with the reference house cannot be made since total hot-water consumption is not available for the latter. For the Tech House, total hot-water consumption for the year amounted to 29 747 gal, or an average of about 81 gal/day.

Water

Tech House water consumption for the year totaled 61 221 gal. This was nearly 30 000 gal less than estimated use for the year without the gray-water reuse system and water-saving fixtures. This represents a 33-percent reduction in water usage, of which 24 percent is attributed to the water-reuse system and the remainder to the fixtures. Annual water use for the various functions is listed in table 4.

TABLE 4.- ANNUAL TECH HOUSE WATER USE

Water use	Water use without water-savings features, gal	Actual water use with water-savings features, gal
Bathing	[a]26 671	18 937
Dishwashing	4 601	4 601
Laundry	12 392	12 392
Lavatory	10 540	10 540
Sink	5 548	5 548
Toilet	27 777	[b]5 533
Miscellaneous	3 670	3 670
Total	91 199	61 221

[a] Estimated.

[b] Reused gray water provided 22 244 gal of required toilet flush water.

The cumulative savings resulting from the water-reuse system portion of the water-saving features are depicted in figure 34.

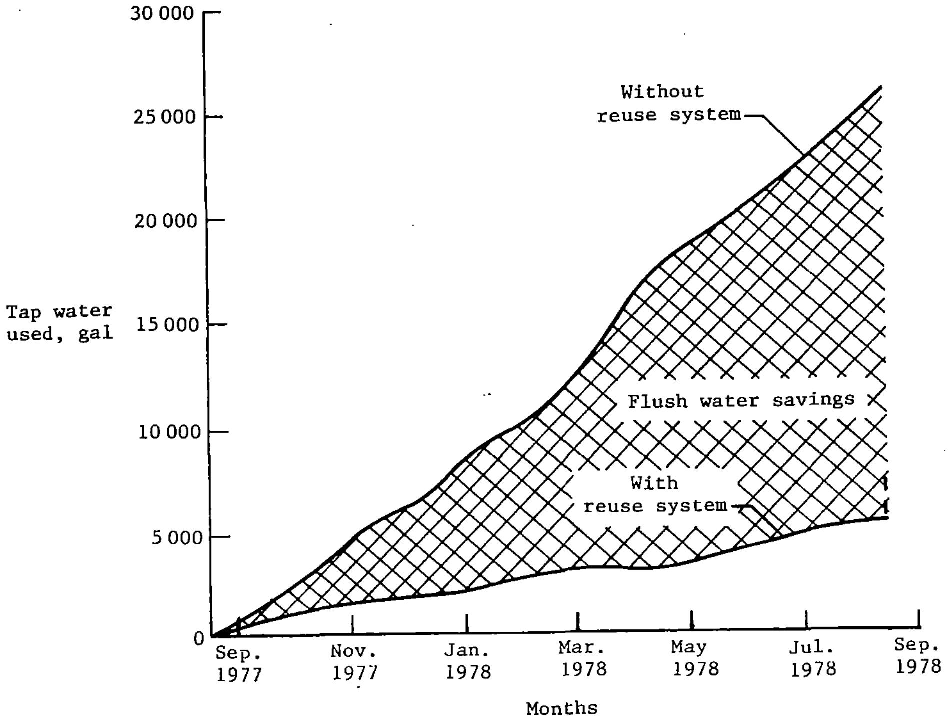


Figure 34.- Monthly flush water required and savings provided by reuse system (cumulative).

Savings in Energy and Water

As indicated in table 3, the total savings in actual electrical energy in the Tech House compared with the HUD reference house amount to an equivalent of 25 744 kW-hr. This equates to an average monthly savings of nearly 2145 kW-hr. It is to be noted that the major savings in energy result from investments in the thermal design of the house. Better insulation and other design features of the house thermal configuration account for approximately 15 900 kW-hr of the total annual savings. Solar heating and the heat-pump system account for about 7400 kW-hr of the savings; solar-heated domestic hot water accounts for some 2220 kW-hr of the savings; the remainder results from savings in lighting and energy-efficient appliances.

SYSTEMS EVALUATION

The operation of the fully instrumented Tech House under normal living conditions provided a unique opportunity to evaluate the performance of the house systems. In addition to being able to compare the energy and water usage of the Tech House with a reference house, all other systems can be studied to some extent. This section of the report evaluates the various systems and makes general observations on the performance of each.

STRUCTURAL

The structural system includes the total house envelope, that is, the floors, walls, roof, windows, shutters, doors, entrances, and insulation.

Test Method

Since controlled conditions could not be maintained during the evaluation period, the method used to evaluate the Tech House was (1) to measure the energy required to heat the house, (2) to measure the wall temperatures and the shading effects of the overhang in order to determine the heat gains and losses through the walls, and (3) to inspect the condition of the structure and insulation after the 1-yr test. The effectiveness of the attic louvers was determined by monitoring the temperature in the attic during the summer.

Data Collection

The following data were collected by the automatic data system for use in evaluating the performance of the house envelope:

(1) Attic temperatures

(2) Outside air temperatures

(3) Wall temperatures (measured at each wall exposure at the inside surface of the insulation, at a point halfway through the insulation, and at the outside surface of the insulation)

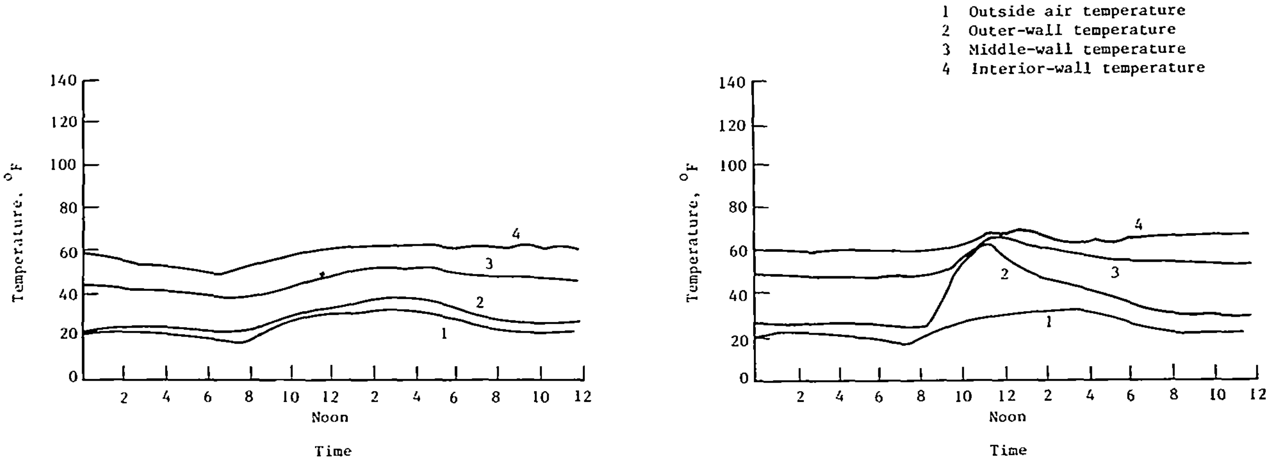
(4) Inside room air temperatures (measured at the floor, at the ceiling, and at an intermediate level in each room)

Performance

The relatively small amount of energy required for heating and cooling indicates that the structure and thermal envelope performed well. Except for insulation degradation, there were no known problems with structural components.

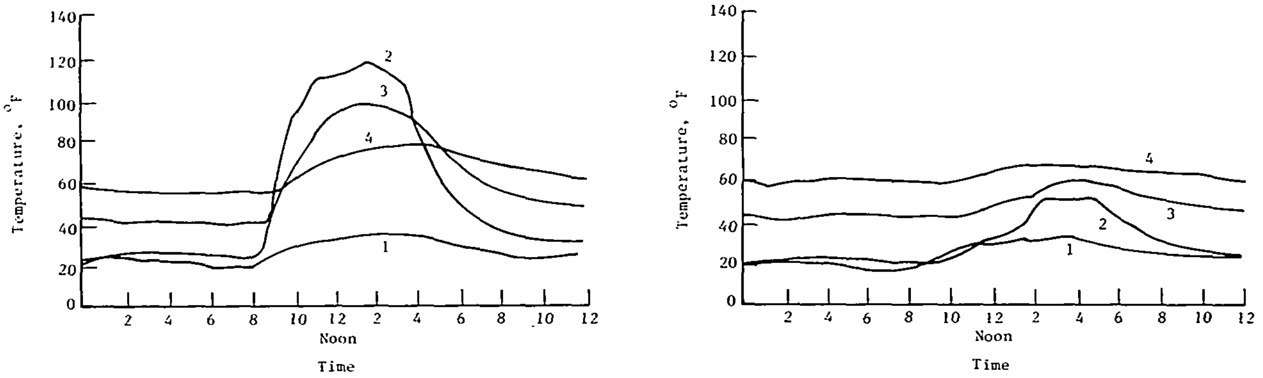
The structural features of a house are passive in that they influence energy requirements but do not themselves consume energy. These features include doors, windows, shutters, skylight, louvers, and insulation, as well as other architectural features such as overhangs, orientation, and exterior color. The orientation and general layout of the house also have a significant impact on energy demand and, in this case, was designed to limit solar gain during the summer while maximizing solar gain during the winter. Because of the site dimensions, the north- and south-facing walls are shorter than the east- and west-facing walls. Normally, these dimensions should be reversed for energy efficiency; nevertheless, because of the overall design features, the energy efficiency of the house was quite good.

The effect of the south-facing window overhang can be noted from the measured exterior-wall temperatures. Typical 24-hr temperature variations for each exterior wall are shown in figure 35 (for December 27, 1977) and



(a) North-wall temperatures.

(b) East-wall temperature.

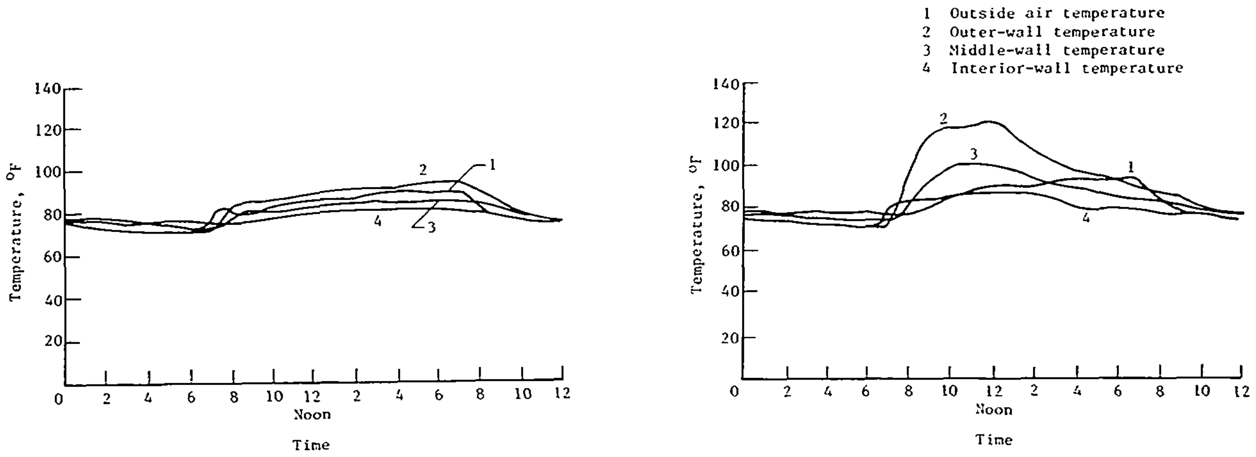


(c) South-wall temperatures.

(d) West-wall temperatures.

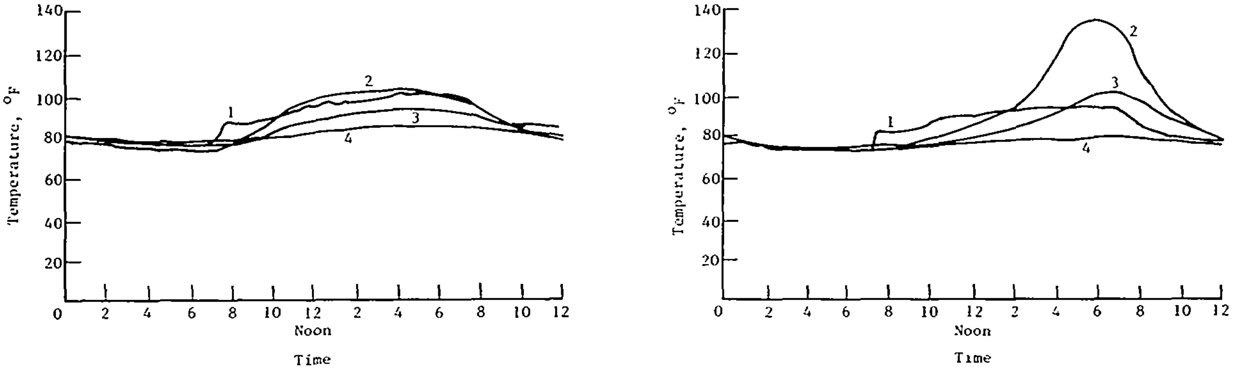
Figure 35.- Outside and wall temperatures on December 27, 1977 (clear day).

figure 36 (for July 21, 1978), with ambient air temperatures superimposed. The plots in figure 36 indicate that in the summer, south-wall temperatures were kept relatively low by the shading effect of the roof overhang. The east and west walls, which were virtually unprotected from the Sun and which in summer were subjected to exposure periods at least as long as the south face, experienced much higher afternoon temperatures. In winter, with a low Sun elevation angle, the south wall is only slightly shaded by the overhang, as is indicated by the wall-temperature data for December 27 (fig. 35).



(a) North-wall temperatures.

(b) East-wall temperatures.



(c) South-wall temperatures.

(d) West-wall temperatures.

Figure 36.- Outside air and wall temperatures on July 21, 1978 (clear day).

Thermal cycling of the walls during the course of the year was expected to have some effect on insulation. Following the live-in test, the insulation was inspected for evidence of change or deterioration.

Photographs of the wall insulation taken 30 months after installation are shown in figures 37 to 40. Some shrinkage and settling are evidenced in all


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Figure 37.- Insulation in west wall.

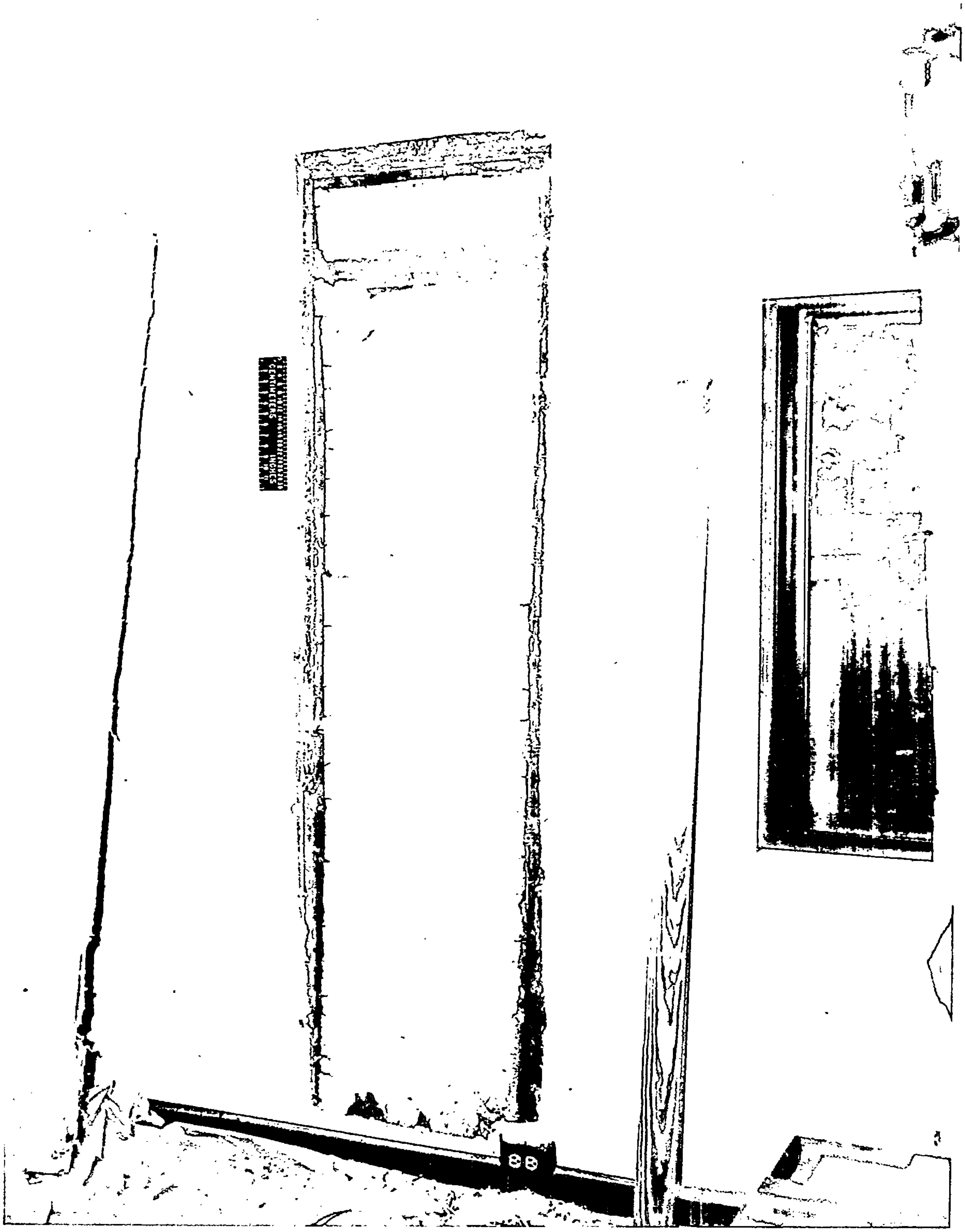

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Figure 38.- Insulation in north wall.

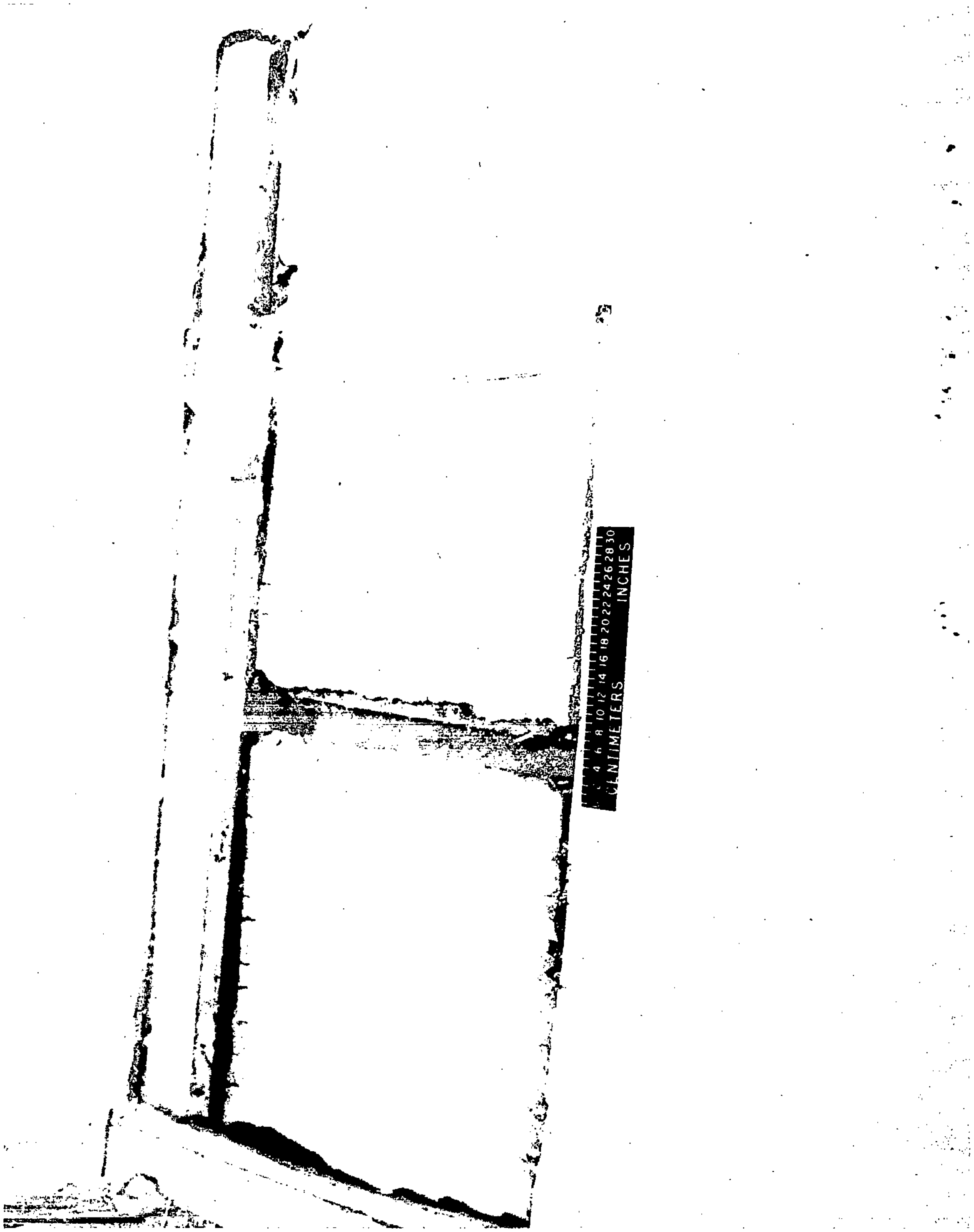

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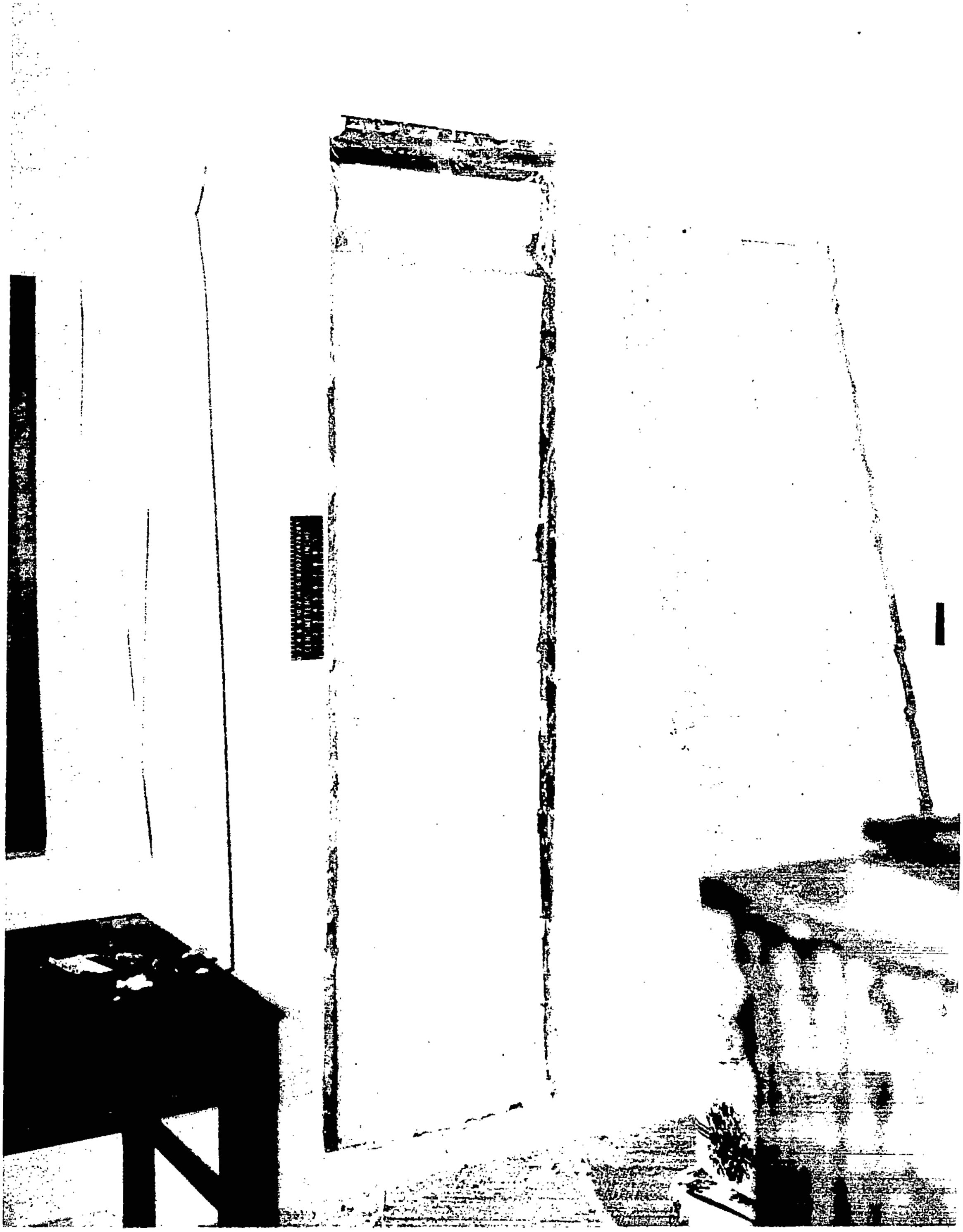
Figure 39.- Insulation in south wall.



L-78-6536

Figure 40.- Insulation in east wall.

walls. Shrinkage was most severe in the west wall (fig. 37); this correlates with typically high west-wall summer temperatures, as shown in figure 36. In addition to the visual inspection, integrity of the wall insulation was monitored by infrared thermography. The thermograms (see Volume II) show an average shrinkage of approximately 7 percent for the walls inspected by this method. Although the shrinkage and cracking was more than expected, the overall heating energy reduction indicates that the foam insulation performed satisfactorily during the test period.

The large attic louvers proved effective; attic temperatures did not rise more than 6° F above the outside air temperature during the summer months. In the winter, however, it was necessary to close off nearly 80 percent of the louver area to prevent freezing of the solar-collector drain lines.

The shutters were not evaluated under controlled conditions; however, they were effective in reducing summertime solar gain when used. Correspondingly, in the winter months, energy savings resulted by allowing sunlight in by day and closing shutters and shades at night to reduce heat losses.

The skylight was effective in providing ventilation during the spring and fall months. During winter, the heat losses appeared greater than the solar gain although no measurements were made. In the summer, it was necessary to install a plexiglass sheet faced with aluminized mylar below the skylight to reduce the solar heat load.

General Observations

To allow 6 in. of insulation, the wall was constructed of 2- by 6-in. studs on 24-in. centers. The wall was designed to be equivalent in strength to conventional walls constructed of 2- by 4-in. studs on 16-in. centers. There has been no indication of unevenness or waviness of the interior dry-wall panels due to the additional distance between studs.

The roof design has been satisfactory, although there is some concern about snow accumulation. The design provides flat areas between modules of the house where snow can accumulate or drift. Snow also can accumulate on the south window overhang. This was not a problem during the test period since snow was always quickly removed; however, in some situations, it could be a problem and should be considered in the design, particularly in those regions which experience moderate to heavy snowfall.

The windows and doors operated satisfactorily and posed no problems. The double-door entrances were an effective heat-loss barrier; vestibule temperatures were usually 10° to 15° F cooler than the living areas during most of the heating season. The large sliding glass doors in the living room were found to induce drafts which affected personal comfort in the immediate area. It is clear that large glass patio doors can be costly energy users. Locating such doors on the south side of the house would permit benefits from winter solar gain, provided that some method (such as drawn drapes) is available to reduce heat losses at night.

The skylight can present a significant energy drain in both winter and summer. Without double glazing or suitable insulation, the heat losses in winter are high. In summer, the solar gain through the skylight adds considerably to the air-conditioning load.

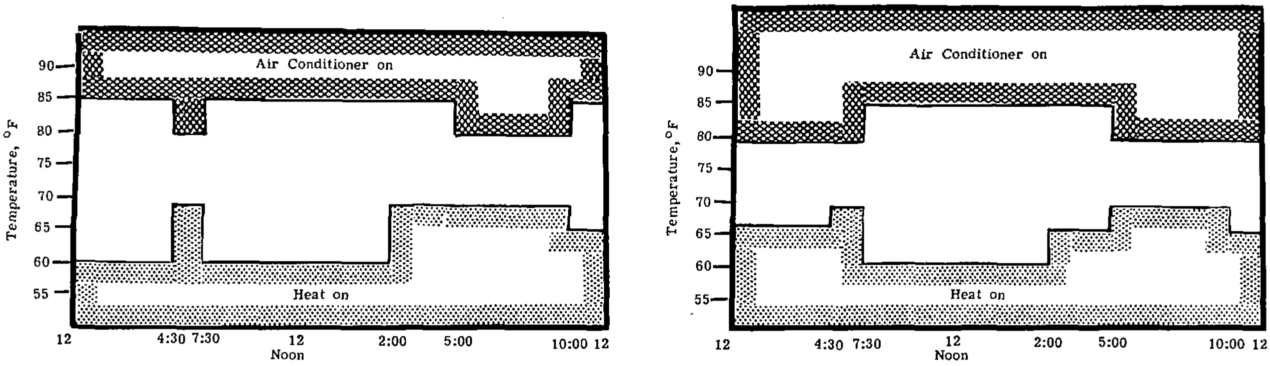
HEATING AND AIR CONDITIONING

Method of Operation

Zone Control of Heating and Air-Conditioning System

The heating and air-conditioning system supplies conditioned air to the house to comply with a time-of-day and a day-of-week schedule that was compatible with the lifestyle of the family. The house is divided into four zones, each of which can be controlled independently, with the exception, of course, that cooling and heating cannot take place at the same time. Sensors in each zone provide the data for system control. Figure 26 shows the floor plan of the house with the zone boundaries superimposed.

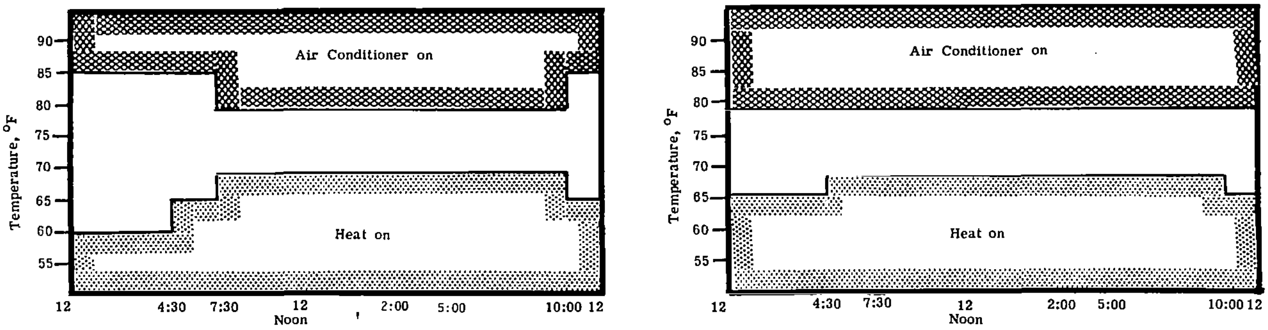
Basically, the house is zoned into living and sleeping areas. The sleeping area was further subdivided into zones, as indicated. All zones were heated to about 68° F when occupied and to about 60° to 65° F when not in use. A heating and cooling schedule was developed to meet the needs of the family. During the winter months, the low-temperature limit was set 65° F so that the morning warmup time was not prolonged. After the middle of March, this was reduced to 60° F at night. Figures 41 and 42 show the controlled temperature ranges for the zones.



(a) Living-room and kitchen zone.

(b) Bedroom zones.

Figure 41.- Weekday zone control limits.



(a) Living-room and kitchen zone. (b) Bedroom zones.

Figure 42.- Weekend zone control limits.

Mode of Operation of Heating and Air-Conditioning Equipment

The heating system can supply warm air to the house either from the heat pumps or through the direct-duct heat exchanger (fig. 24). The heat pumps use either storage-tank water or well water as a source of energy, whereas the direct-duct heat exchanger depends on the solar collectors, the fireplace coil, or the storage tank for its hot-water source. Some of the modes of operation can be used simultaneously to provide a versatile heating system with enough redundancy to greatly reduce the need for backup electric heat.

The operating modes available are summarized in the following paragraphs (the indicated mode numbers merely indicate relay numbers in agreement with the control program and have no other significance to this report). A listing of the computer program is included in Volume II of this report.

Mode 2 - Collection and Storage of Solar Energy

Water is pumped from the storage tank, through the solar collectors, and back to the storage tank.

Modes 2 and 5 - Collection of and Heat With Solar Energy

Water is pumped from the storage tank, through the solar collectors, to the direct-duct heat exchanger, and back to the tank. Blower fans provide airflow to transport the heat to the rooms as required by the zone controls.

Modes 11 and 12 - Heating With Heat Pumps (mode 11 is for heat pump 2 and mode 12 is for heat pump 1)

1. Before February 2, 1978
Heat pump 1 supplies heat to the house as required by the zone controls. The water source for this heat pump is the well. Fans in both heat pumps distribute heat to the house. If heat pump 1 is not able to supply adequate heat to the house, then heat pump 2 provides supplemental heat. Heat pump 2 utilizes water from the storage tank as its source of energy.

2. After February 2, 1978
Both heat pumps operate together with source water supplied from the wells. Fans in both heat pumps distribute the heat to the house as required by the zone controls.

Mode 1 (Manual) - Fireplace

When there is a fire in the fireplace, water is pumped from the storage tank, through the fireplace water grate, and returned to the storage tank; or it is pumped (modes 1 and 5) through the direct-duct heat exchanger to the tank, with the heat-pump fans distributing the heat to the house as required by the zone controls.

Mode 5 - Heating From the Storage Tank

Hot water is pumped through the direct-duct heat exchanger from the storage tank. Fans in the heat pumps distribute the heat to the house as required by the zone controls.

Modes 11, 12, and 14 - Air Conditioning

The heat pumps provide cooling to the house as required by the zone controls. The well supplies water flowing first through the direct-duct heat exchanger to precool the return air and then through the heat pump to remove the heat rejected by the heat pumps.

Data Collection

During the year the family lived in the house, data were collected by two means. The automatic system collected data on the operation of the solar collectors, heat pumps, and storage tank. From August 15, 1977, until January 7, 1978, data were recorded every 15 min. From January 7, 1978, until the test was completed, data were recorded every 10 min. In addition to data recorded by the automatic data system, daily meter readings were taken and recorded of the running times of major equipment and the total power usage of the house. A listing of these data is given in Volume II.

Tables 5 to 7 are a summary of the performance for the heating and air-conditioning system. Table 5 summarizes the heating requirements of the house

TABLE 5.- TECH HOUSE HEATING REQUIREMENTS AND SYSTEM PERFORMANCE DATA

Month	Total energy required, Btu	Direct solar portion, Btu	Solar portion through heat pump, Btu	Heat pump portion (solar and nonsolar), Btu	System energy usage	
					Solar, kW-hr	Heat pump, kW-hr
Oct. 1977	0.78×10^6	0.78×10^6			95.9	98.3
Nov. 1977	3.74	2.07	0.37×10^6	1.67×10^6	160.3	359.0
Dec. 1977	9.46	2.67	1.34	6.79	132.3	1224.6
Jan. 1977	11.82	3.61	1.63	8.21	197.4	1382.3
Feb. 1978	11.68	5.81		5.87	262.5	997.0
Mar. 1978	6.84	2.25		4.59	151.2	667.9
Apr. 1978	1.45	1.31		.14	151.2	87.1
May 1978	.58	.46		.12	28.7	92.0
Total	46.35×10^6	18.96×10^6	3.34×10^6	27.39×10^6	1179.5	4908.2

TABLE 6.- SOLAR-COLLECTOR PERFORMANCE DATA

Month	Total solar energy available, Btu	Operational solar energy available, Btu	Operational solar/ total solar, percent	Collected solar energy, Btu	Array efficiency (collected solar/ total solar), percent	Operational collector efficiency (collected solar/operational solar), percent
Oct. 1977	10.85×10^6	4.80×10^6	44.2	2.96×10^6	27.3	61.6
Nov. 1977	9.98	6.65	66.6	3.99	40.0	60.0
Dec. 1977	10.64	7.69	72.3	4.69	44.1	61.0
Jan. 1978	13.38	9.33	69.7	5.86	43.8	62.8
Feb. 1978	14.76	11.95	81.0	7.70	52.2	64.4
Mar. 1978	14.13	9.78	69.2	5.96	42.2	60.9
Apr. 1978	14.26	9.40	65.9	5.44	38.1	57.9
May[a] 1978	7.31	1.56	21.3	.83	11.4	53.2
Total	95.31×10^6	61.16×10^6	[b]61.2	37.43×10^6	[c]39.3	[d]61.2

[a] Only first 19 days of May.
[b] Value based on total operational energy/total solar energy.
[c] Value based on total collected solar energy/total solar energy.
[d] Value based on total collected solar energy/operational solar energy.

TABLE 7.- STORAGE-SYSTEM DATA

Month	① Energy to storage, Btu	② Energy from storage, Btu	③ Monthly change in stored energy, Btu	Storage efficiency (② + ③)/①, percent	Average temperatures of storage, °F
Oct. 1977	2.76×10^6	0.92×10^6	-0.34×10^6	21	138.2
Nov. 1977	3.99	2.07	-.54	38	116.1
Dec. 1977	3.76	2.88	-.12	73	95.7
Jan. 1978	4.84	4.09	+.21	89	86.4
Feb. 1978	5.68	4.07	+.02	72	97.5
Mar. 1978	5.20	1.49	+.51	38	103.5
Apr. 1978	5.37	.07	-.08	0	126.7
May[a] 1978	.83	.45	-.52	0	103.0
Total	32.43×10^6	16.04×10^6	-1.26×10^6	[b]49	[c]108.4

[a] Only first 19 days of May.
[b] Value based on totals of (② + ③)/①.
[c] Value average of numbers in column.

during the test period and lists the sources of energy that were used to meet these requirements. Table 6 presents the performance of the collector array. Included are total solar energy available, operational solar energy available (solar energy available while collectors are operating), collected solar energy, array efficiency (percent collected of total solar energy available), and the operational collector efficiency (percent collected of available solar energy during time collectors are operating). Table 7 is a tabulation of the data on the storage system energy with the calculated storage efficiencies.

Performance

The performance of the heating and air-conditioning system has been evaluated by two methods. The first compared the performance of Tech House with a reference house, as described in the section on general Tech House performance. The second, described here, reports how the various systems performed in the Tech House. This includes the performance of the heat system as a whole, as well as the performance of its subsystems (i.e., collector array, storage tank, heat pumps, fireplace, and zone control system).

The space-heating system provided all the heating requirements for the house from three sources:

(1) Solar energy (direct use)

(2) Heat pumps (supplied by water from the well or by solar-heated water)

(3) Fireplace

Solar energy and the heat pumps provided most the the heating for the house. The fireplace was not used enough during the live-in test to evaluate it as part of the overall system; instead, a separate test of the fireplace was conducted after the family moved out.

The preferred (and most economical) mode of heating the house was with solar-heated water circulating through the direct-duct heat exchanger. The summary of the system performance in table 8 clearly shows that heating with solar energy was more effective than using the heat pumps.

TABLE 8.- SUMMARY OF HEATING-SYSTEM PERFORMANCE

	Input, kW-hr	Output, kW-hr	Output/Input
Heat pumps	4 900	8 000	1.63
Solar heat	1 180	5 500	4.66
Total	6 080	13 550	[a]2.23

[a]Value based on total output/total input.

The tabulation shows that the total heat requirement for the live-in year was 13 550 kW-hr. To obtain that amount of energy from the heat pumps and the solar system combined required that 6080 kW-hr of energy be purchased from the utility to drive the pumps, fans, and compressors. The monthly heating energy requirements during the heating season are represented in figure 43; also shown are the amount of monthly heating provided by solar energy and the amount that could have been supplied from solar with an idealized, 100-percent-efficient storage tank.

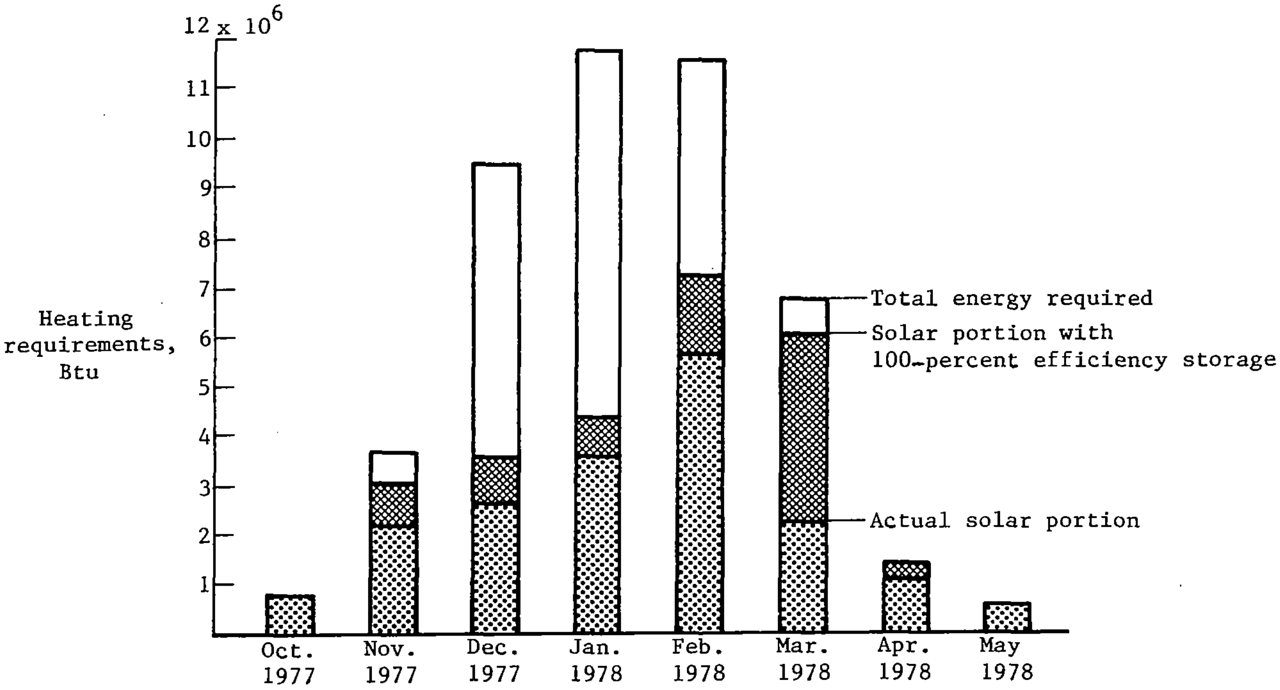


Figure 43.- Tech House heating requirements.

Collector-Array Performance

During the heating season, the 384 ft^2 of solar collectors collected 37.43 × 10^6 Btu or 80.7 percent of the energy required to heat the Tech House. During October and November 1977, and April and May 1978, more energy was collected than was required to heat the house. The overall efficiency of the solar collectors was 39 percent (table 6). The efficiency of the solar collector is determined by the percent of available solar energy that is collected. However, it must be noted that some of the time, the available solar energy was not adequate to heat the panels sufficiently to activate the control system. (The temperature of the panels had to be 10° F hotter than the water in the storage tank to turn the system on.) An alternate method to calculate the solar-collector efficiency discounts all periods when the available solar energy was not sufficient to turn the system on. Calculated in this way, the efficiency was 61.2 percent.

Storage-Tank Performance

The heating system utilizes a 1900-gal concrete underground insulated storage tank to store heated water for use by the home when solar energy is not available. The storage tank provides about 15 800 Btu (about 4.6 kW-hr) of energy to the house for each Fahrenheit degree drop in the stored-water temperature. The system is controlled so that the house can be heated with stored hot water when the temperature in the storage tank exceeds 95° F. Water can be stored up to approximately 150° F, and at this temperature, the storage system will provide about 38 hr of heat for the house when the outside temperature is about 20° F. If the stored-water temperature is between 90° F and 120° F (which is normal during cold weather), the tank can supply up to 17 hr of heat in 20° F weather. During the cold winter months of the live-in test, the storage tank provided heat on sunny days until early morning (3:00 a.m. to 6:00 a.m.) and returned about 77 percent of the stored energy to the house. However, during November and March, the system only delivered 38 percent of its stored energy to the house. This trend, shown in table 7, indicates that the tank provided efficient storage for short periods but inefficient storage for long periods when heating needs were relatively small.

Zone Control System Performance

Much of the evaluation of the zone control system is subjective in nature. During the live-in test, temperatures in the house and the energy required to heat the house were recorded. However, it is difficult to determine which mode of distributing heat was more efficient because exact heating conditions do not repeat themselves. The following observations concerning the zone control system can be made:

(1) When the zone control system was in operation, the temperature of the house stayed within 2° F of the control points in all controlled areas.

(2) When the zone control system was not in operation, temperatures in some parts of the house varied as much as 10° F from set point. Without zone control, the system provided heating throughout the house until the coolest room was heated to set point, causing other areas to be overheated by as much as 10° F at times.

(3) The bathroom zone could not be heated independently because the heat pumps would not operate with the small quantity of air flowing through the heat exchangers to the one heating outlet in the bathroom.

(4) The living room and kitchen areas required a warmup time of about 1 hr during very cold weather with a nighttime set back to 65° F in the winter and to 60° F in the spring.

(5) The zone control system, under certain conditions, adversely affected the operation of the heat pumps. Without all zones open, the heat pumps would not operate for longer than 10 min before being turned off by a protection device within the units. This occurred because some zones did not require heat and, hence, the volume of air through the heat pumps was insufficient to transfer the energy from the heat-pump coil to the air. Consequently, a protective device would turn the heat pump off to prevent damage to the unit.

Heat-Pump Performance

The heat pumps provided 59 percent of the energy required to heat the house. The 27.39×10^6 Btu of output energy provided by the heat pumps is equivalent to 8000 kW-hr. The total input energy required to operate both the heat pumps and the well pump was 4900 kW-hr; therefore, the heat pumps delivered 1.63 kW-hr of energy to the house for each kW-hr of input energy required to operate it.

For the air conditioning, the well pump and heat pumps required 2100 kW-hr of input energy. The total heat that was removed from the house (output energy from the heat pumps) was not measured because the instrumentation system did not provide a means of measuring the latent heat removed for humidity control. A significant part of the cooling was done by precooling the return air with the well water before pumping it through the heat pumps. (See fig. 24.) The direct-duct heat exchanger cooling reduced the return air temperature about 10° F, thus providing 5000 to 7000 Btu/hr of precooling. This method of precooling with well water increased the output of the cooling system by an estimated 20 to 25 percent.

General Observations

The following general observations were made concerning the operation of the heat pumps in conjunction with the solar heating system and the zoned distribution system.

(1) Use of a zone control system reduces the amount of air being delivered to the house, which has an adverse affect on heat-pump operation. The heat pumps deliver their energy to the air stream through the heat exchangers that make up the heat-pump condenser. If the airflow is not sufficient to condense the high-pressure refrigerant as fast as the compressor supplies it to the condenser, the pressure increases at the outlet of the compressor and actuates a safety switch which turns the unit off. There is also an increase in input power requirements with reduced airflow. When the heat pump kicked off, it could restart only after all power to the unit was turned off and then turned back on again. Figure 44 shows the effect of airflow on heat-pump performance. As can be seen by the curve, the coefficient of performance (COP) of the heat pump is adversely affected by a reduction of air flowing through the system. The COP is the energy delivered by the heat pump divided by the input energy required to operate it.

It was determined that the problem from reduced airflow could usually be avoided if the supply of well water to the heat pumps was limited proportionately. In addition, the control system was reprogrammed to monitor the power consumption of the heat pumps. If one or both compressors kicked off while in use, the unit was disengaged for several minutes, and then turned back on. With these modifications, the heat pumps operated without further problems from the zone control.

(2) It was initially intended that the heat pumps be supplied by solar energy when the temperature of the stored water was less than 110° F but greater than the temperature of the well water. Solar-heated water was used to supply part of the energy to the heat pumps during November, December, and January. However, water hotter than the well water had the same effect on the heat pumps as reduced airflow. In fact, water hotter than 85° F could not be used at all without tripping the heat-pump safety switch. As a result,

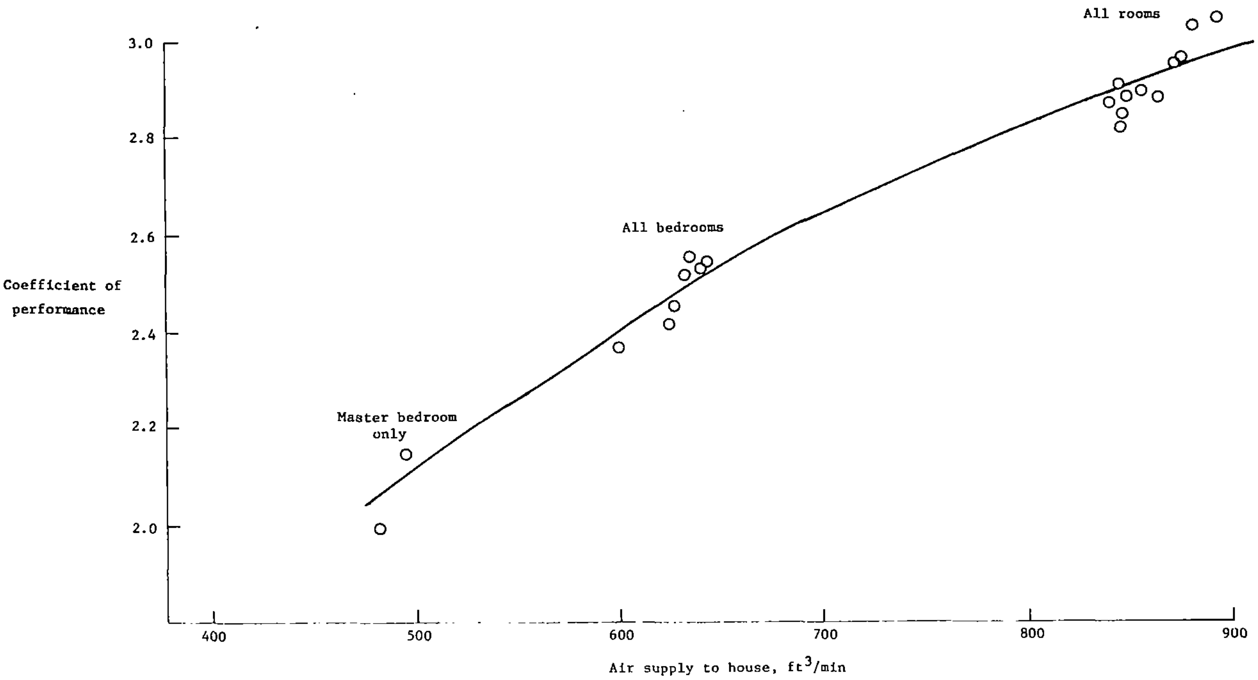


Figure 44.- Effect of zone heating on heat-pump performance.

solar-heated water was subsequently used to supply only one heat pump, and that heat pump was used only when all zones required heat.

Further experience indicated that any attempt to use solar-heated storage water as source water for the heat pump results in practical operational problems. Use of water from the storage tank to supply the heat pumps reduces the temperature of the storage tank below that required to heat the house directly. The storage tank must then be reheated before solar energy can be used to heat the house directly. It is possible to use all available solar energy through the heat pumps with no direct solar heating of the house. Evaluation of all such options indicated the preferred operation is to use solar-heated water and the storage-tank water for direct solar heating and to use only well water for the heat pumps. In this way, the overall coefficient of performance is better, primarily because the required pumping energy is less. In addition, the heat pumps as designed cannot effectively use source water at temperatures greater than about 80° F.

The air-conditioning system was designed to use nighttime radiators as an integral part of the cooling system. Heat energy removed from the house by the heat pumps would be dumped into the storage tank, elevating the water temperature. At night, the water from the tank would be pumped through the radiators to cool the water for the next day's operation. The radiators are aluminum, flat-plate solar collectors without glass covers and are mounted on the north-facing roof of the garage without back insulation. No means was provided to prevent air from circulating around the underside of the radiators.

Tests performed on the radiators showed that they will cool to about 7° F below the outside air temperature on cold, clear winter nights, and to about 4° F below outside air temperature in the summer, with no water flow through them. With water flowing through the collectors, they reject only 7000 to 10 000 Btu/hr, which is too low to be used economically. Further study is necessary to determine if a more practical method of heat rejection can be employed.

The fireplace, although thought to have considerable potential as a source of heat to the house, was not used extensively during the live-in test. As a result, there are little data on its operation; however, tests were conducted on the fireplace after the 1-yr live-in test was completed. Based on these data and experience during the live-in test, the following observations are made:

(1) The outside air vents provided adequate air supply to the fireplace for proper combustion.

(2) The water-coil wood grate was able to collect a large percentage of the heat energy produced. Figure 45 shows the amount of energy collected during a 2-hr test. The graph shows that about 35 000 Btu/hr were collected by water flowing through the grate. During the test, the fireplace was burning an average of 25 lb/hr of dry oak logs. This amount of dry oak will produce about 150 000 Btu/hr, to give an estimated efficiency of 23 percent for the grate alone. The efficiency of the fireplace water grate is difficult to determine with a high degree of accuracy. The estimate of the amount of wood burned is slightly high since the unburned wood at the end of the test was not measured. It is estimated that only about 15 percent of the wood remained unburned.

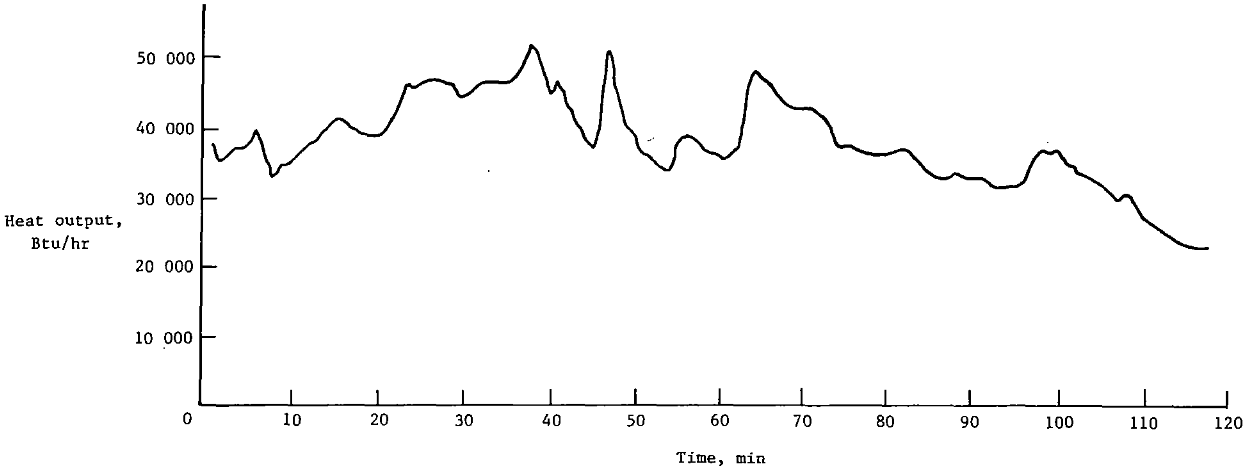


Figure 45.- Fireplace water grate output for 2-hr test.

(3) The double-walled fireplace shell provided enough energy to heat the living room and kitchen areas to 75° F when the outside temperature was 40° F. However, the family indicated that the heat delivered to the living room made that room too warm. This reason, combined with the fact that the pump supplying the water coil had to be turned off manually after use of the fireplace, discouraged its frequent use. The requirement that the pump be shut off can easily be eliminated by a design change.

(4) The glass doors on the fireplace were considered satisfactory in preventing the loss of room air up the chimney without any appreciable adverse effect on the aesthetic qualities of the fireplace.

DOMESTIC WATER

Solar-Supplemented Domestic Hot Water

Method of Operation

The solar-supplemented domestic hot-water system (fig. 29) operates in the following manner:

(1) When the surface temperature of the solar collectors is 10° F above the water temperature in the preheat tank, the solar collection system (pump) is turned on automatically and remains on for a minimum of 5 min.

(2) If the temperature of the water in the collectors is less than that in the preheat tank, or if the temperature rise of the water after flowing through the collectors is less than 2° F, the pump turns off automatically.

(3) City water enters the preheat tank as hot water is used from the electrically heated tank. The cold city water is heated as it passes through the solar preheat tank, thus supplying the electrically heated tank with water preheated by solar energy.

(4) When the temperature of the water in the electrically heated tank drops below the set point of its thermostat, the water is heated electrically.

Data Collection

Data consisted of information supplied by the automatic data-collection system, daily readings of the running time of the resistance heaters in the electrically heated hot-water tank, and the total quantity of hot water used. Detail listings of the sensors, their accuracies, and the meter readings are included in Volume II of this report.

Table 9, a summary of the 1-yr live-in test, shows the monthly use of hot water, the energy required to heat the water, and what portion of that energy was provided by solar heat. The losses in the piping from the solar collectors to the storage tank are not known. The performance of the system was determined by calculating the energy required to heat the water, including tank

TABLE 9.- DOMESTIC HOT-WATER SYSTEM PERFORMANCE

Month	Amount used, gal	Average city-water temperature, °F	Average hot-water temperature, °F	Temperature difference, °F	Energy to heat water, kW-hr (a)	Tank loss, kW-hr (b)	Total energy required, kW-hr (c)	Electrical energy, kW-hr	Solar energy, percent of total
Aug. 1977	1 177	81	135	54	154	52	206	143	31
Sept. 1977	2 040	79	133	54	268	104	372	130	65
Oct. 1977	2 046	62	135	73	360	108	468	370	34
Nov. 1977	1 911	60	138	78	354	104	458	450	2
Dec. 1977	2 232	50	135	85	408	108	516	431	16
Jan. 1978	2 889	44	140	96	676	108	784	591	25
Feb. 1978	2 608	41	140	99	629	97	726	497	32
Mar. 1978	2 952	45	137	92	662	108	770	545	29
Apr. 1978	3 031	56	125	69	509	104	613	360	41
May 1978	3 111	61	125	64	485	108	593	346	42
June 1978	2 774	72	125	53	358	104	462	199	57
July 1978	1 508	77	125	48	176	52	228	99	57
Aug. 1978	1 343	81	125	44	144	52	196	68	65
Total	29 622	62	132	69	5 183	1 209	6 392	4 229	35

[a] Calculated, not including storage losses.
[b] Estimated based on hours of operation per month of conventional hot-water heater.
[c] Calculated.

losses, and then subtracting the known electrical energy supplied to the conventional hot-water tank. The difference is the solar-energy contribution.

Performance

The cumulative total energy required for the year for domestic hot water and the savings resulting from solar energy are plotted in figure 46. Energy savings provided by solar heating amounted to 35 percent, somewhat less than predicted. Factors contributing to the lower percentage were undersized solar-collector panel area and an undersized preheat tank for the greater than anticipated daily usage of hot water, which was occasionally over 100 gal/day.

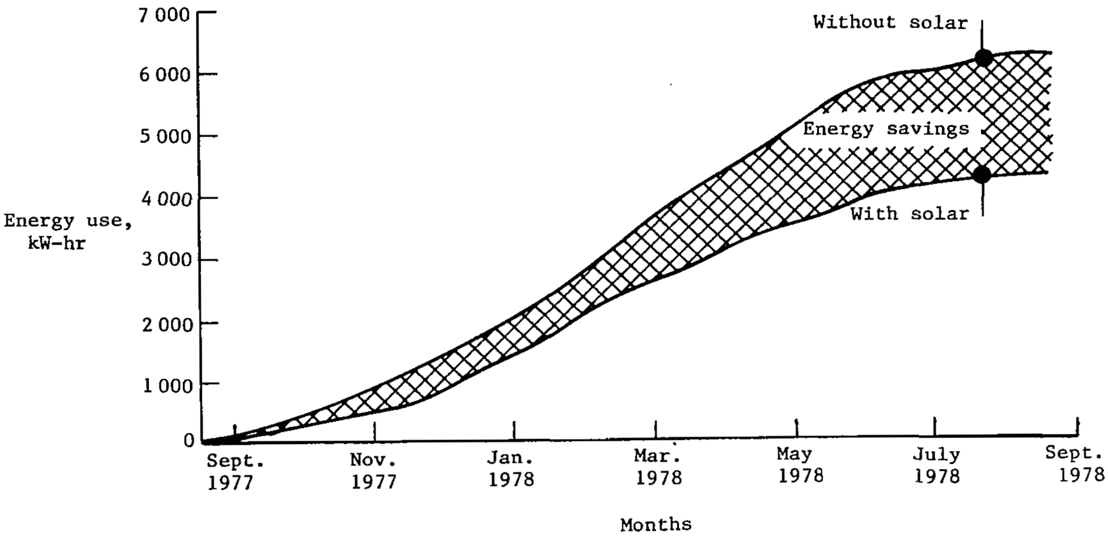


Figure 46.- Domestic hot water system energy use.

The monthly electrical energy requirements for domestic hot water, with and without solar augmentation, are represented by bar chart in figure 47.

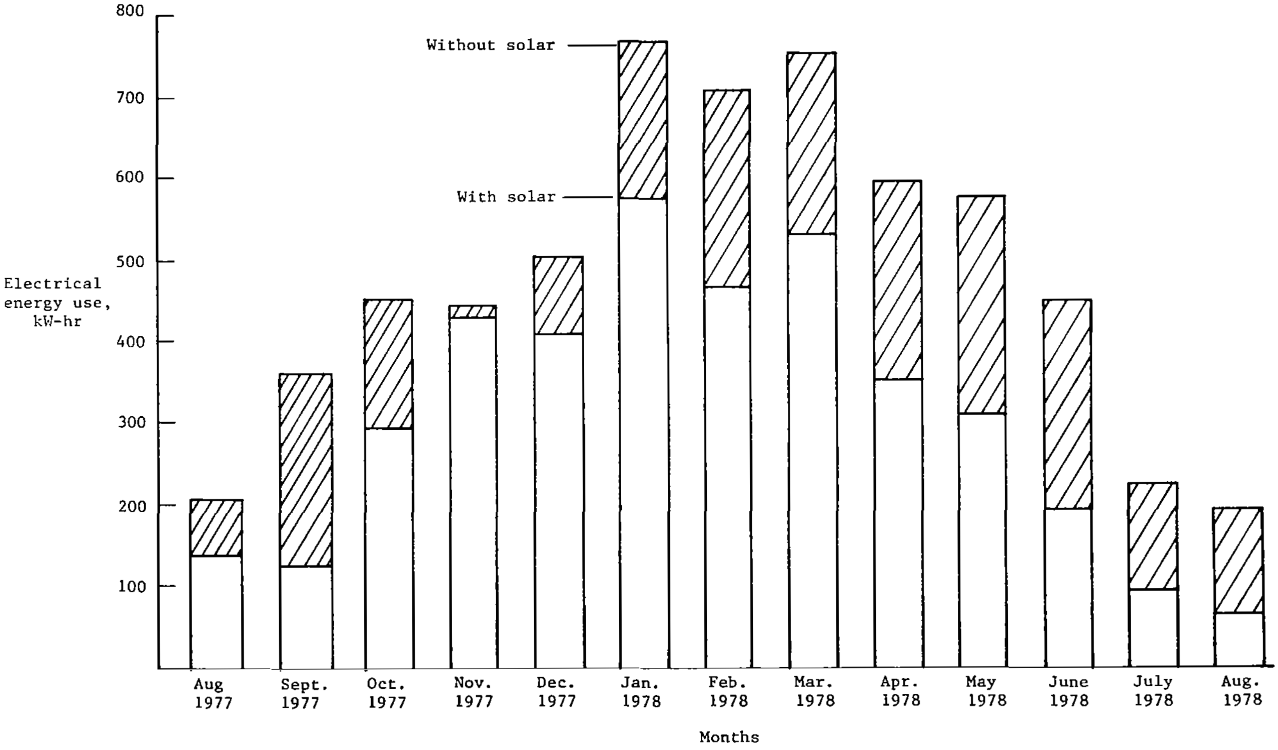


Figure 47.- Domestic hot-water system energy required.

Although hot-water usage varied from month to month, the variations in energy use result primarily from seasonal changes in temperature of the incoming tap water. The monthly energy fraction supplied by solar energy (shaded area) is indicative of the amount of sunshine available for the month. The weather during November 1977, for instance, was rainy or overcast for virtually the entire month.

General Observations

The lifestyle, habits, and schedule of a family have a significant effect on the efficiency of a solar domestic hot-water system. Unlike heating of the house, where weather is the governing factor, hot-water demand, in terms of quantity, influences the energy required by the hot-water system. Moreover, with a solar-supplemented system, the time of day that hot water is used is very critical to the energy savings. For example, if hot water is used during the daylight hours, the water in the preheat tank can normally be replenished and reheated by the solar collectors. If, however, hot-water use occurs predominantly in the evening, the preheat water is soon depleted, and all additional hot water used that day must be heated conventionally. The sizing of the preheat tank and solar-collector area, therefore, is very important in order to optimize the investment for different families and different lifestyles.

Typical performance data for the solar hot-water system are depicted in figures 48 to 53 for the period of March 15 to March 17, 1978. Figures 48 to 50 show the daily variation of water temperature in the preheat tank. The rapid temperature drops shown are normally associated with family rising, arriving home, or retiring hours. Figures 51 to 53 show the amount of solar energy collected during each of the above three days. The plots clearly indicate that March 15 was a good solar day, March 16 was very poor, and March 17

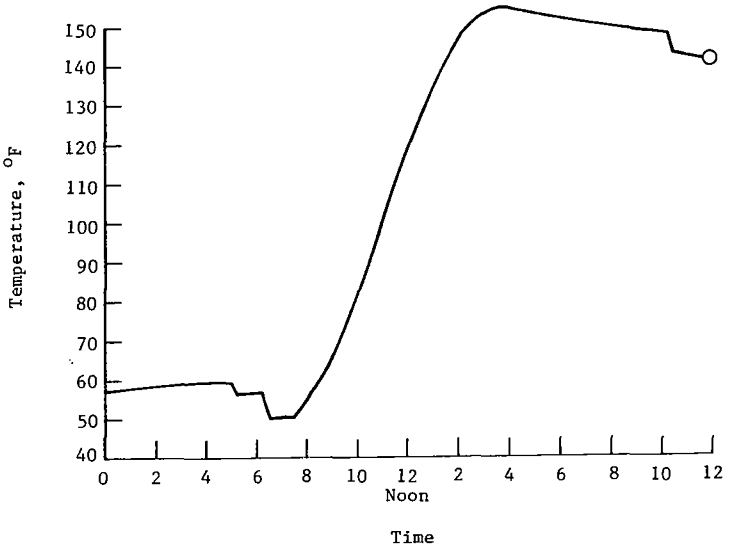


Figure 48.- Temperature in solar preheat tank on March 15, 1978.

was generally good up to 2:00 p.m., followed by cloud cover which reduced the collected energy for the remainder of the day.

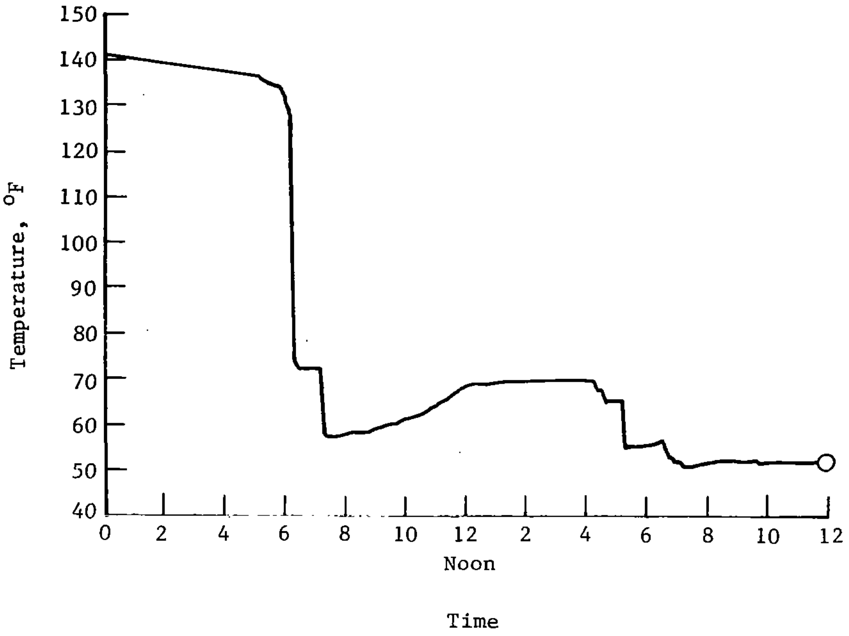


Figure 49.- Temperature in solar preheat tank on March 16, 1978.

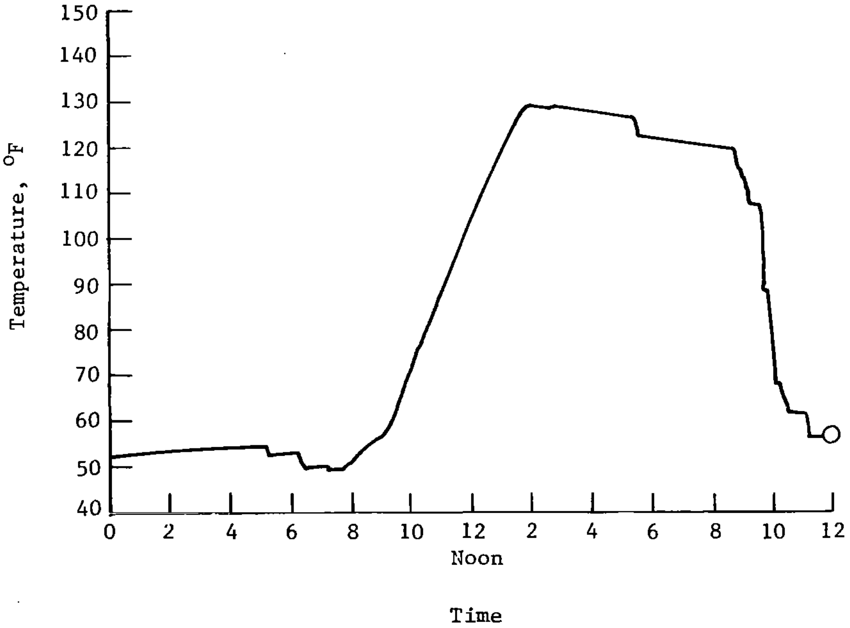


Figure 50.- Temperature in solar preheat tank on March 17, 1978.

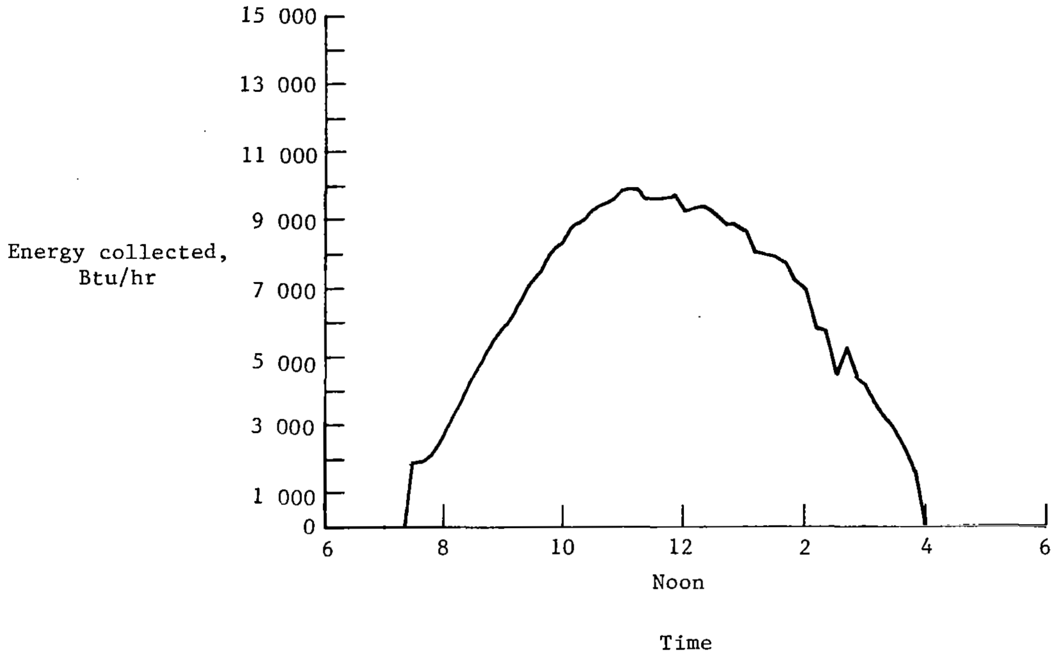


Figure 51.- Energy collected by the domestic hot-water solar collectors on March 15, 1978.

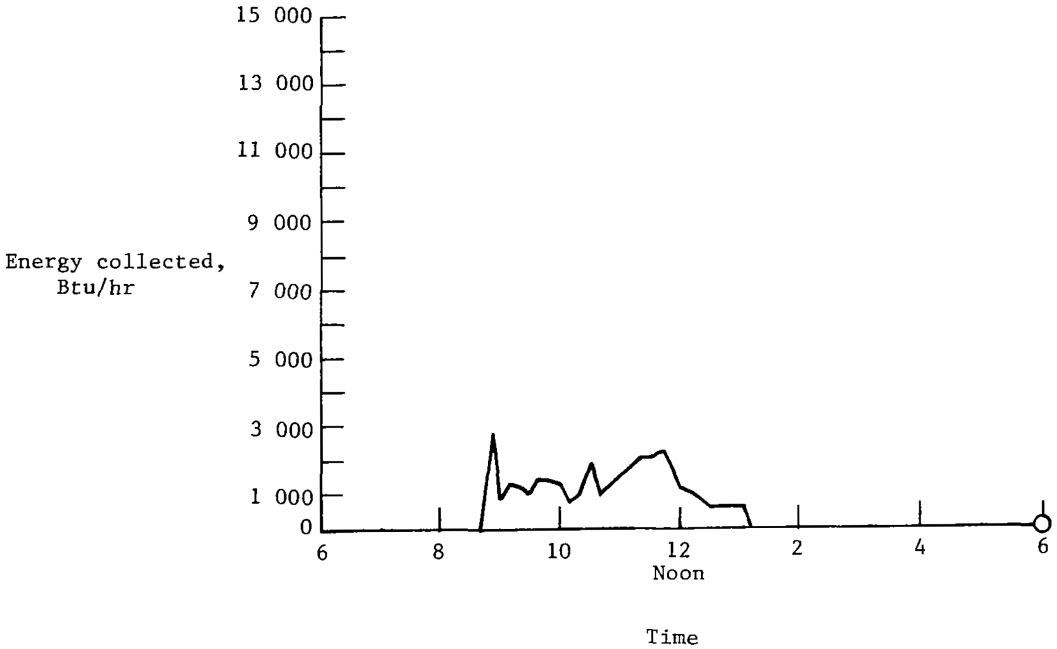


Figure 52.- Energy collected by the domestic hot-water solar collectors on March 16, 1978.

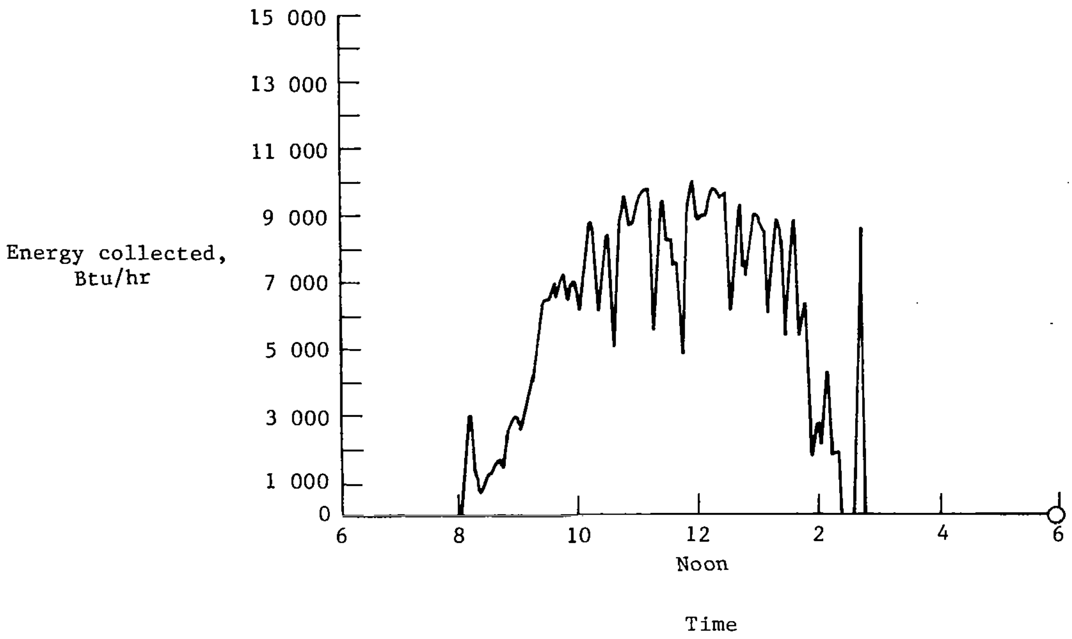


Figure 53.- Energy collected by the domestic hot-water solar collectors on March 17, 1978.

Water-Reuse System

Method of Operation

The guideline for use and evaluation of the water-reuse system throughout the 1-yr test period was that family living habits were not to be changed to enhance system performance. The house plumbing was arranged to permit easy changeover to city tap water in the event of unsatisfactory performance or failure.

In the normal operational mode, waste bath waters (two tubs with showers) and waste laundry waters were gravity drained into the collector tank located in the crawl space under the house floor. These waste waters were chlorinated in the collector tank with ordinary laundry bleach, passed through a diatomaceous earth filter, and stored in a pressure tank for use as flush water for the two toilets. The water required for the commode water closets was supplied from the pressure tank, which operated between 20 and 40 psig. When the tank pressure fell below 20 psig, the pump pressure switch triggered the pump, which sucked water from the collection tank through the diatomaceous earth filter. Thus, the waste waters made only one pass through the filter before being used. This operational procedure was a compromise of the 90- and 120-min circulating filtration period found to be optimum during previous laboratory research experiences (ref. 3). A single pass through, upon demand by the commode water closets, greatly simplified operations and system assembly.

Chlorination was selected as the means for eliminating coliform organisms in the waste water. Chlorination had proved effective during the laboratory tests and could be supplied in the form of laundry bleach, which is readily available at the supermarket. During the first 5 months of the live-in test, bleach was added by using the weight of incoming waste waters to open a plug in the end of a plastic tube that drained bleach from a container in the utility room. This method proved difficult to control, however, and was subject to failure modes that either prevented bleach from entering the tank or emptied the entire bleach reservoir into the tank. During the last 7 months, bleach was added by using the weight of incoming water to close a microswitch that triggered a small pump which pumped bleach from a reservoir on the side of the collection tank. The intent of either technique was to have bleach (chlorine) added in the proper proportion to incoming waste water at the time of collection; however, this was compromised because there were two incoming drain lines, and the weight-sensing device could only be placed under one because of crawl-space clearance limitations. The drain that delivered the laundry water and water from one tub/shower was used. When the volume of water in the tank fell below 10 gal, an automatic make-up unit would deliver tap water to the collection tank.

Clean-out and recharge of the diatomaceous earth filter was initiated when pump suction on the filter housing reached 20 in. of mercury (10 psig). The clean-out was accomplished by backwashing through the support discs upon manual movement of a built-in lever arm which, when moved, changed the direction of flow in the housing by changing valve positions.

During the first 4 months of operation, the backwash water was pulled through the jet pump directly from the collection tank. This technique proved unsatisfactory since it brought unfiltered water into the pump jet nozzle. Hair from the waste water caused pump failure and required maintenance. After 4 months, the plumbing was changed to permit backwash water to flow from the pressure tank, after passing through the diatomaceous filter. In this operational mode, unfiltered water did not enter the pump, and the pump did not need to run during backwash. In both modes of operation, the backwashed material was piped to a porous linen bag which captured the powder and particles for later disposal in a dry condition. The recasting of a new filter cake was accomplished by pouring a diatomaceous earth slurry into a reservoir valved into the suction side of the filter housing. Each recasting of the filter required 1-1/8 lb of filtering material.

Data Collection

All fixtures and appliances in the Tech House were monitored with standard rotary-disc water meters. In addition, the water flow into and out of the water-reuse system was metered. Collectively, this meter array permitted a water-use history of the Tech House family for the 1-yr period. Specific meter locations were as follows:

Meter	Location
1	Dishwasher, hot
2	Kitchen sink, hot
3	Kitchen sink, cold
4	Bath, hot
5	Bath, cold
6	Wash machine, hot
7	Wash machine, cold
8	Lavatories (2), hot
9	Lavatories (2), cold
10	Tap water make-up to reuse
11	Total flush water to closets (2)
12	Main household line

The meters were all placed in the crawl space under the house and were read and recorded every Monday morning.

Samples for determining water quality were taken each Monday and Thursday morning from the collection tank and from one of the water closets. They were collected in sterile plastic cups, carried immediately to the laboratory for processing, and were analyzed for chlorine residual, in total counts/ml and fecal coliforms/100 ml.

Performance

Water-use performance.- A water-use history for all appliances and fixtures for the 1-yr live-in test is given in table 10. The data have been totaled and averaged for the entire 367-day period of occupancy. As predicted, the single largest use of water was for toilet flush. The data also show that the combined volume of waste laundry and bath water more than equals the volume of water required for toilet flush. Thus, it is theoretically possible to furnish all of the flush water from bath and laundry waste water. This goal was not achieved, however.

TABLE 10.- HISTORY OF TECH HOUSE WATER USE - FIXTURES AND APPLIANCES

Water use	Volume used, gal															Percent of daily total
	Aug. 1977	Sept. 1977	Oct. 1977	Nov. 1977	Dec. 1977	Jan. 1978	Feb. 1978	Mar. 1978	Apr. 1978	May 1978	June 1978	July 1978	Aug. 1978	Yearly total	Average per day	
	15 days	30 days	31 days	30 days	31 days	31 days	28 days	31 days	30 days	31 days	30 days	31 days	18 days			
Dishwasher, hot	293	346	369	360	301	387	297	348	449	431	553	218	249	4 601	12.54	6
Sink, hot	128	136	228	344	257	316	250	338	313	224	266	162	160	3 122	8.51	4
Sink, cold	193	347	224	150	135	139	130	149	183	203	300	129	144	2 426	6.61	3
Bath, hot	299	412	722	851	991	1 257	1 283	1 355	1 252	1 380	1 335	643	702	12 482	34.01	16
Bath, cold	388	592	670	520	552	465	603	538	430	494	542	316	345	6 455	17.59	8
Washer, hot	128	201	275	161	209	177	168	198	219	255	276	147	141	2 555	6.96	3
Washer, cold	594	962	974	600	807	591	638	756	853	956	879	612	615	9 837	26.80	12
Lavatory, hot	264	357	506	539	455	708	496	758	846	754	577	366	361	6 987	19.04	9
Lavatory, cold	52	130	288	326	275	206	260	358	399	383	432	238	206	3 553	9.68	4
Toilets, cold	1 667	2 177	2 386	2 523	2 576	2 806	2 456	2 537	2 196	1 997	2 121	1 171	1 164	27 777	75.69	35

Table 11 summarizes the annual water-use data relative to the gray-water reuse system. The reuse system was on line for 310 of the 367 data of occupancy; however, the data in table 11 have been adjusted to the full 367-day

TABLE 11.- SUMMARY OF WATER USE AND REUSE

Water use	Yearly total, gal	Average per day, gal
Projected water use for subject family	91 199	248
Actual water used (includes tap and gray water)	83 465	227
Total tap water used	61 221	167
Total gray water available (laundry plus bathing)	31 329	85
Total flush water required	27 777	76
Total gray water reused	22 244	61
Total tap water make-up for flush use (included in total tap water used)	5 533	15

period. As shown, 22 444 gal of the 27 777 gal required for toilet flushing were supplied by the gray-water reuse system. The data also indicate that all flush water could have been supplied by gray water since a total gray-water volume of 31 329 gal was available. Unfortunately 100 percent of this volume was not collected because of losses that resulted from the relationship between collection-tank volume and family water-use habits. When large volumes of waste waters are produced in a short period of time without reuse demand, which draws down the volume in the collection tank, some water is lost to overflow. The 110-gal collection tank was found to be slightly under optimum size for the four-member family using the Tech House. A slightly larger tank (e.g., 135 gal) would have significantly improved the water savings. Other losses of water occurred when backwashing the filter and when cleaning the collection tank. It is not likely that these latter two losses can be prevented, but fortunately they are not large.

Water quality.- Reclamation of the bath and laundry gray water to a quality approaching tap water was not required. Objectives were to remove visible solids; to prevent odors; to hold turbidity, color, and foaming to aesthetically acceptable levels; and to eliminate health hazards due to possible presence of fecal coliform organisms. The diatomaceous earth filtration did a satisfactory job of holding the chemical/physical characteristics within acceptable limits. At the end of the test period, the occupant did mention that color changes were noticeable during the year but not offensive. When color changes did occur due to fabric dyes, they dissipated without a permanent effect. Odors could have been offensive, but adequate control of chlorination techniques prevented the problem. Previous laboratory tests proved that too little chlorination would lead to a putrid odor and that too much chlorination would lead to a bleach odor, either of which would have been unacceptable. Tests and observations (refs. 3 and 4) have led to the conclusion that maintenance of a chlorine concentration of approximately 0.5 ppm in the commode water closets can prevent unnacceptable odors.

Maintenance of the desired chlorination level in the water closets was achieved most of the time. The collected data show that the system operated in a satisfactory manner; these data are included in Volume II.

Maintenance and repair.- In general, the system operated satisfactorily throughout the year, as indicated by the maintenance and repair history shown in table 12. Maintenance events are those needed (although not scheduled) periodically. Repair events are unexpected and are usually the result of component failure. Prior to the live-in test, it had been predicted that the diatomaceous earth filter would need to be cleaned and recasted approximately once per month. In actuality, eight filter cleanings were necessary. The need for filter cleaning was determined by the suction required to pull water through the filter. When the suction increased to 20 in. of Hg (10 psig), the filter was cleaned. Normal suction pressure with a clean filter approximated 5 to 8 in. of Hg (2.3 to 4 psig). It had also been assumed that periodic draining of the collection tank would suffice to wash out settled particles. Draining was adequate to wash out the particles since the drain cock was at the lowest point in the tank; however, this did not adequately clean the tank. It became necessary to wash tank surfaces with a short pressure spray of clean water. It would be desirable to occasionally wipe the inside of the tank, but

TABLE 12.- MAINTENANCE AND REPAIR HISTORY OF TECH HOUSE

GRAY-WATER REUSE SYSTEM

Date	Event	Cause
Sept. 9, 1977	Cleaned filter[a]	Filter expended
Sept. 15, 1977	Opened hole/chlorinator cup[b]	Hole plugged
Sept. 23, 1977	Cleaned collect tank[a]	Residue buildup
Oct. 7, 1977	Cleaned pump jet[b]	Jet clogged
Oct. 19, 1977	Pump switch failure[b]	Switch clogged
	Cleaned collect tank[a]	Residue buildup
Nov. 10, 1977	Cleaned filter[a]	Filter expended
Nov. 28, 1977	Chlorinator failure[b]	Tension cord break
Nov. 30, 1977	Cleaned filter[a]	Filter expended
Dec. 19, 1977	Cleaned filter[a]	Filter expended
	Cleaned collect tank[a]	Residue buildup
Jan. 24, 1978	Cleaned filter[a]	Filter expended
Feb. 10, 1978	Cleaned filter[a]	Filter expended
Mar. 6, 1978	Cleaned collect tank[a]	Residue buildup
Apr. 28, 1978	Cleaned filter[a]	Filter expended
May 16, 1978	Pump failure[b]	Loose fitting
June 16, 1978	Cleaned filter[a]	Filter expended
	Cleaned collect tank[a]	Residue buildup
July 28, 1978	Cleaned collect tank[a]	Residue buildup
	Cleaned water closets[a]	Residue buildup

[a] Maintenance item.
[b] Repair item.

this was virtually impossible to do since the tank was a closed cylinder with only one small opening through which one of the drain pipes entered. As noted in table 12, the collection tank was spray cleaned periodically. Two system shutdowns occurred due to component failure, both involving the jet pump, although the pump components were not at fault. The first failure was due to particles, especially hair, which accumulated in the pump as a result of the original mode of backwashing the filter, with unprocessed waste waters passing through the pump. This problem was alleviated by backwashing with filtered water from the pressure tank without backwash water flowing through the pump. The second pump failure was due to the loosening of a threaded fitting, which caused inadequate suction on the filter; this was easily corrected. Based on the system's maintenance record and the experience of the monitoring crew, it is recommended that monthly maintenance procedures include cleaning the filter, replenishing the bleach reservoir, and generally inspecting the system. On a quarterly basis, and coinciding with a period when the water level is low in the collection tank, the system should be shut down for 15 to 30 min while the collection tank is drained and the walls spray cleaned.

Expendables used.- The two expendables in the reuse system were diatomaceous earth filter media and laundry bleach. The filter media was backwashed off the carrier screen discs eight times during the year. Each recast used 1-1/8 lb of diatomaceous earth, for a total of 9 lb during the year. The total consumption of bleach for 310 days of system operation was 4-1/2 gal. A full 365-day operational period would have required approximately 5 gal.

INSTRUMENTATION, MEASUREMENTS, AND CONTROL

Data-System Performance

The data system collected data automatically during the period of the test. All data were recorded on magnetic tape by channel number, with the times and date of each scan recorded. During the test, there were only a few times that data collection was interrupted because of problems with the sensors or with the data system itself. Problems with either the sensors or the data-collection system were easy to detect because the house control depended upon their operation. The recording and retrieval of the data did present a problem at times. The only time that a failure in collecting data could be detected was when the data were retrieved. Data retrieval was done on a weekly schedule. Therefore, when there was a problem, it could take several days to find it, and for this reason, data from two periods are limited to the daily meter readings. These periods are the first 2 weeks of the test and November 14 to December 2, 1977. During one other period, some of the data were lost, but this amounted to only one scan in thirty. This was caused when the tape recorder skipped while recording some of the scans. However, enough data were available to evaluate the systems.

A large amount of extra data was collected during the year. These data are contained on magnetic tapes in engineering units and are in blocks of 1 day each. These additional data can be used for further studies of the house.

Control-System Performance and General Observations

The control system performed very well for the live-in test, with only a short period of erratic control in early January 1978 which was caused by a component failure in the computer. This failure caused the computer to operate some of the systems, even though the data indicated they should not be operated. However, these problems were minor, and the family was unaffected by them. The computer was repaired without affecting the test.

The original computer programs written to control the Tech House were not able to operate the systems properly during the transient start-up periods each day. For example, when the solar collection system is first turned on, the panels are usually 10° F hotter than water in the storage tank. Thus, when water first reaches the panels, it cools them down. As a result, between the time that the water cools down the panels and the hot water from the panels reaches the sensors, the system is turned off by the control system. To correct this anomaly, time delays were incorporated in the programs to eliminate this transient problem.

Another problem with the software had to do with the mode of heating to be used. As first written, the program would stop heating by solar hot water if the water temperature was below a predetermined set point or if the temperature in the house did not increase after 15 min of operation. This created a problem of repeatedly switching modes. If the water temperature was above the set point but the house did not respond to heating through the direct-duct heat exchanger, the heat pumps would run for 1 min, and the control system would then try to heat by using the direct-duct heat exchanger. This was corrected by two changes in the program. First, instead of using room temperature to determine if the house was being heated, the temperature of the supply air was used. Subsequently, it was determined that if the supply air temperature could be maintained over 85° F, the house could be heated. This temperature was then used as the set point for switching from the direct-duct heat exchanger to the heat pumps. Secondly, once the heat pumps were turned on, they were used to heat the house until all zones were satisfied. Then, when a zone needed heat again, the control system would first attempt to heat using the direct-duct heat exchanger if the water temperature was over 90° F in the tank or if the water temperature of the water coming from the solar collectors was over 100° F. With these changes, the house was heated satisfactorily. A listing of the program is included in Volume II. Also included in Volume II is a detailed description of how the control points of the zone control system were included for both weekday and weekend operation and the means that were available to the family to override the system.

CONCLUDING REMARKS

The Tech House project demonstrated that the technology used in the house can reduce the consumption of energy and water. The use of the house by a family of four for a full year was a success in that data were collected on both the general operation of the various systems and the effects of living habits on the house performance. Some of the incorporated systems and items performed satisfactorily as designed, and others performed somewhat below expectations for various reasons. In either case, the unique information and experience gained from the project provided valuable insight for improvements in both systems and technology.

Total energy use at the Tech House was reduced to about one-half that projected for the reference house. Although it had been predicted that total energy use could be reduced to about one-third, because of available sunshine and other system design factors, the solar energy systems provided less energy than expected. In addition, the actual energy required for domestic hot-water use was approximately 40 percent greater than that projected for the reference house because of a higher than predicted consumption.

Solar energy provided 41 percent (5550 kW-hr) of the total heating energy (13 550 kW-hr) for the Tech House. Of the total solar energy collected and delivered to the underground storage tank only about 49 percent was later used for space heating, largely because of tank heat losses. An above-ground storage tank in the Hampton, Virginia, area would be more satisfactory since the high ground-water table contributes to premature degradation of the tank insulation.

Solar energy from the domestic hot-water solar-collector system supplied approximately 35 percent of the total Tech House hot-water requirements. This percentage was expected to be nearly twice as much, based on projected use of hot water. Factors contributing to the reduced performance, in addition to available sunshine, were the larger-than-expected consumption of hot water and family lifestyle.

The water-reuse system reduced annual water requirements in the Tech House by 27 percent. Other general conclusions of the test on the water-reuse system are:

1. The concept of using reclaimed bath and laundry waste water as a source of water for flushing toilet is feasible and practical. Water savings can vary from 25 to 40 percent, depending on system design features and family living habits.

2. Prior to reuse, waste bath and laundry water should be filtered to improve the appearance of the water and to prevent reuse-system parts from becoming fouled with particles. Filtration through diatomaceous earth media is a satisfactory method. Reuse should also include a process step for reducing microbiological contamination. Chlorination with laundry bleach is satisfactory for eliminating coliform organisms in gray-water systems, but it will not totally sterilize the water without leaving residual chlorine in the system.

3. The frequency of required maintenance is acceptable. Filter cleaning and biocide addition will be required monthly. Tank drainage and clean-out are desirable on a quarterly basis.

The actual performance of the technology items during the live-in test is perhaps not as important as what was learned that can be used to improve systems and design features for future homes. It is clear that the water-reuse system can be cost effective in many regions of the country and may have greater potential for conservation and savings than anticipated. Solar energy for domestic hot water can also be a cost-effective investment over the expected life of the system if sized and designed properly. Solar energy for space heating constitutes a sizable investment; therefore, an economic analysis should be performed before installing solar heating.

To what degree the Tech House represents a forerunner of future home design is not clear at this time. However, the project has served a prime objective as a catalyst for increased interest in new technology for residential purposes. This interest is evidenced both locally and nationally by visitors from all spectrums touring the house and the magnitude of the requests for technical information. Some design features, such as more efficient use of fireplace areas, have already advanced commercially beyond what was envisioned at the beginning of the project. Thus, there seems little doubt that, with the impetus of generally predicted increases in energy costs, many innovative technology developments will be integrated into practical home design and accepted as conventional before the end of the twentieth century.

Langley Research Center
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Hampton, VA 23665
October 1, 1979

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APPENDIX

CONVERSION TABLE

To convert from U.S. Customary Units to International System of Units (SI), use the following table:

To convert from	to	multiply by
	LENGTH	
inch	centimeter	2.54
foot	centimeter	30.48
yard	meter	0.914
mile	kilometer	1.609
	AREA	
inch squared	centimeter squared	6.45
foot squared	centimeter squared	929.03
yard squared	meter squared	0.835
	VOLUME	
foot cubed	meter cubed	0.028
gallon	litre	3.79
	WEIGHT	
pound	kilogram	0.454
	TEMPERATURE	
temperature °F	temperature °C	(°F - 32)/1.8
	PRESSURE	
pounds per inch squared	pascal	6895
inch of mercury (Hg)	pascal	3377
	ENERGY	
British thermal unit (Btu)	joule	1055
	POWER	
Btu per hour	watt	0.293
kilowatt hour	kilojoule	3600
	AIRFLOW	
foot cubed per minute	meter cubed per minute	0.283

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16. Abstract

The NASA Tech House was designed and constructed at the NASA Langley Research Center, Hampton, Virginia, to demonstrate and evaluate new technology potentially applicable for conservation of energy and resources and for improvements in safety and security in a single-family residence. All technology items, including solar-energy systems and a waste-water-reuse system, were evaluated under actual living conditions for a 1-year period with a family of four living in the house in their normal lifestyle. Results are presented which show overall savings in energy and resources compared with requirements for a defined similar conventional house under the same conditions. Also included are general operational experience and performance data for all the various items and systems of technology incorporated into the house design.

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