355
2/1/80

DR. 684

DSE-5171-2

MASTER

DESIGN, FABRICATION AND TESTING OF A MARKETABLE
WATERWALL COMPONENT

MASTER

Final Technical Report for September 1, 1978—August 31, 1979.

By
Timothy J. Maloney
Victor Habib

August 1979

Work Performed Under Contract No. EM-78-C-01-5171

One Design, Inc.
Winchester, Virginia

U.S. Department of Energy

Solar Energy

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Paper Copy \$5.25
Microfiche \$3.00

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

MASTER

DSE-5171-2
Distribution Category UC-59c

DESIGN, FABRICATION AND TESTING OF
A MARKETABLE WATERWALL COMPONENT

FINAL TECHNICAL REPORT
1 September 1978 - 31 August 1979

Timothy J. Maloney
Victor Habib
August 1979

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

One Design, Inc.
Mountain Falls Route
Winchester, Virginia 22601

Prepared for the U.S. Department of Energy
Under Contract EM-78-C-01-5171

This document is
PUBLICLY RELEASABLE

Bany Stab
Authorizing Official

Date: 7-19-07

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

TABLE OF CONTENTS

	Page
Abstract	iii
Introduction	1
One Design Products	4
Typical Applications	5
Commercial and Private Greenhouse Market	7
Physical Characteristics and Dimensions of the Waterwall Modules	11
Design Considerations	14
Manufacturing Methods	18
Unit Costs	22
Pattern Making and Fabrication	23
Preliminary Structural Testing	24
Final Structural Testing	27
Freeze and Thermal Shock Test	33
Thermal Performance	33
Economic Performance for the Homeowner	49
Testing and Evaluation of Water Purity	56
Material Evaluation Test (Creep)	56
Evaluation of Laminate Samples	57
Appendix - Princeton Energy Group Report on Instrumentation at the Star Tannery House	59

ABSTRACT

One Design, Inc., has designed and developed modular waterwall components that make up a system for passive solar space heating using a south-facing thermal storage wall. The modules can also be used as thermal mass storage for roof apertures and for greenhouse applications. The modules are constructed of fiberglass reinforced polyester and each is 95 inches long, 16.5 inches wide and 24.5 inches tall. Each module contains 94 gallons or 784 pounds of water. When stacked behind south glazing, they provide 52 Btu/^oF per square foot of net glazed area. A stack of four modules has a height of 93.5 inches, suitable for an 8-foot interior ceiling; a stack of five modules is 116.5 inches high, suitable for a 10-foot interior ceiling. The modules are designed to stack on one another without requiring additional hardware and nest inside each other to reduce shipping costs.

Prototype modules were fabricated and subjected to structural tests. They were found to be capable of supporting at least 4.8 times the load imposed by a five tank stack, well above the recommended safety factor of 2. Long term purity of the water in the containers was tested and evaluated and found to be within acceptable limits. Prototype modules were installed in One Design's Star Tannery House near Winchester, Virginia, and performance was extensively monitored from January - April, 1979. Based on the performance during the period, it has been estimated that the passive solar heating contribution would be 79.5% of the house's total heating requirement.

INTRODUCTION

One Design, Inc., is a Virginia corporation formed in May of 1977, to develop the passive solar product designs of Tim Maloney. Maloney has been designing passive solar projects since the spring of 1973. This report covers the waterwall product design carried out by Maloney and One Design under Contract No. EM-78-C-01-5171.

To date One Design has developed 15 generations of waterwall design, the last two of which are the subject of this report. The following list schematically describes One Design's waterwall systems that have been actively studied and/or monitored. (Many others have been developed on paper only.):

- 1) Monolithic heavy gauge steel, stacking - 93 lbs. water/ft.² glass.
- 2) Site built corrugated steel lined with vinyl bladder. Vertical orientation - 93 lbs. water/ft.² glass.
- 3) Horizontal FRP, one inch deep vertical ribs, monolithic - 93 lbs water/ft.² glass.
- 4) Horizontal FRP, $\frac{1}{2}$ inch deep vertical rib, monolithic - 93 lbs. water/ft.² glass.
- 5) Horizontal FRP, $\frac{1}{2}$ inch deep vertical rib, hung on steel frame - 93 lbs. water/ft.² glass.
- 6) Horizontal FRP, $\frac{1}{2}$ inch deep vertical rib, glassed on wood frame - 93 lbs. water/ft.² glass.
- 7) Horizontal steel, no ribs, non-nesting, stacking via heavy gauge steel exoskeleton welded construction - 72 lbs. water/ft.² glass.
- 8) Horizontal steel, non-nesting, stacking via light gauge steel exoskeleton, Pittsburgh lock seam construction - 72 lbs. water/ft.² glass.
- 9) Horizontal thermoplastic, nesting/stacking via steel exoskeleton - 60 lbs. water/ft.² glass.
- 10) Vertical filament wound FRP, non-nesting, rectilinear 60 lbs. water/ft.² glass.
- 11) Horizontal steel nesting/stacking, corrugated sides, site

installed ends - 72 lbs. water/ft.² glass.

12) Horizontal steel cannister/stack, corrugated sides, soldered seams - 57 lbs. water/ft.² glass.

13) Horizontal nesting/stacking, asymmetrical support, internal column support.

DOE Contract No. EM-78-C-01-5171 commenced September 1989 --

14) Horizontal FRP nesting/stacking, asymmetrical internal column support, laid up construction - 52 lbs. water/ft.² glass.

15) Horizontal FRP nesting/stacking, asymmetrical internal column support, spray/chopped construction - 52 lbs. water/ft.² glass.

Numbers (14) and (15) are identical with the exception of the production method and number (14) is the design selected for production. Number (14) has been designed, redesigned, prototyped, tested and performance monitored for application as a fiberglass waterwall module for passive solar space heating suitable for commercialization.

The design criterion was to develop a modular waterwall component that affords the ease of shipping, warehousing, installation and maintenance that builders and homeowners have come to require of building components. Further, the module should have good thermal performance and an attractive cost/energy savings ratio.

Our study indicates that all of the objectives have been met. The project led to a horizontal, rectilinear fiberglass part, 95 inches long, 24½ inches tall, and 14 inches wide (average), that provides 52 pounds of water per square foot of net south facing glass area. The parts nest one inside the other. The part weighs only 33 pounds when empty and a whole waterwall consisting of twelve modules can be installed in one hour ready for glazing.

The isophthalic polyester resin, reinforced by 3 ounce fiberglass matt, yields a part with a life expectancy well in excess of the 20-year design criterion. Through modifications, a structural safety factor of over 6 has been achieved.

The non-load bearing design allows the module to be installed at any time during construction for building schedule flexibility. Modules can be de-installed with the same flexibility. Vacuum-formed thermoplastic lids seal the units from evaporation and possible contamination. Maintenance consists of checking the water level every 24 months.

The thermal performance of six different configurations made of steel or fiberglass have been compared for nine months and the candidate design proved superior to all. The cost of an array of twelve of the mass produced parts (\$1200), when included in the mortgage of a new home, will be shown to be extremely attractive. The payback period can be zero (no negative cash flow even in the first year).

Parts are presently bid in at \$100 per laid up part. Production tooling is currently being contracted. Production capability is in excess of 2,000 parts for the first year. Greater production capacity is anticipated and can be made available at an attractive incremental cost.

One Design is presently seeking funds for full scale commercialization. A high caliber marketing director with substantial national distribution experience has been identified and only awaits finding.

Of related interest is One Design's low temperature selective surface work suitable for waterwall use. One Design, with the help of the St. Joe Mineral Company, Zinc Division, Pittsburgh, PA, has built and tested modules with a black zinc oxide coating that show promise but do need further work. The physicals of this system are not yet predictable enough to commercialize at this time. Additional work is also indicated in the area of photovoltaic waterwall design as outlined in a One Design patent disclosure. In this scenario water cooled photovoltaics produce waste heat which goes into thermal storage like a conventional waterwall. The storage medium, however, is an electrolyte which simultaneously stores electrical energy in the same medium and in the same space. The photovoltaic array is described as the luminescent flat plate concentrating type as developed by Atlantic Richfield and others.

One Design solicits the Department of Energy's attention to this unusually attractive, no-moving-parts, thoroughly passive technology. We have secured interest in this product from a photovoltaic manufacturing firm.

ONE DESIGN PRODUCTS

The products to be brought to the market by One Design make up a system for space heating using a south-facing thermal storage wall.

To summarize the benefits of this system, it has advantages over designs using either direct gain or a horizontal thermal mass mounted on the roof. A south-facing storage wall is opaque (although it can be interrupted with windows and doors as desired) and prevents the problems of huge south windows flooding the living area with direct sunlight. The direct sun causes rugs and furnishings to fade rapidly and causes discomfort to inhabitants from glare and overheating. The in-wall storage mass is preferable to a roof-mounted mass because of performance and cost factors. Performance of a vertical wall more nearly suits the heating needs of a house because an upright surface absorbs the most thermal energy in the winter and the least in the summer. Further, storage mass means weight. To suspend a significant mass overhead on the roof requires building techniques not common in the residential market and often calls for materials that significantly increase the cost of the installation.

A south-facing storage wall theoretically may be constructed of any high-mass material; in practice, only masonry and containers filled with water have been extensively tested and used. One Design's space heating system uses water rather than masonry as thermal mass for several reasons.

The thermal storage capacity (heat capacity) of water is significantly higher than that of other materials that are conventionally available for and used in construction. A cubic foot of water will absorb 62.4 Btu's when its temperature is raised 1 F. (assuming a beginning

temperature of 59°F.). Building brick, by contrast, will absorb only 24.6 Btu's for a temperature rise of 1°F. Table 1 shows the heat capacities of some other common materials.

Combined with this high heat capacity, water has the advantage of being fluid. Convection currents in water, substantially absent in masonry and other solid materials, rapidly disperse heat throughout the storage mass. For this reason, water is considered an isothermic storage medium in most practical applications.

The high heat capacity and the superior heat dispersion of water mean that its collection surface is cooler than masonry under similar conditions. This lower collection temperature makes water, (1) lose less heat to the outside air through radiation back through the glazing and, (2) collect solar energy more efficiently.

Typical Applications. In use, an appropriate number of modules are installed in the south wall of a building and filled with water to provide a thermal storage mass. The exact number of modules required for satisfactory performance in a given structure varies with a number of factors including climate, building size and design, infiltration, internal heat supplied by appliances and similar sources, insulation and others. In general, existing house designs employing the modules have specified from twelve to twenty-five modules per house with floor areas ranging from 1,200 to 1,500 square feet and with or without exterior movable insulation.

In an application in a conventional frame house, the modules may be stacked on a concrete footing exterior to a standard 2" x 4" studded wall with conventional drywall or other interior covering facing the living space. A resilient sheet, such as insulating sheathing (Celotex), is placed beneath the bottom tank in each stack. The exterior of the stacks of modules is then covered with triple glazing which admits solar radiation but serves as an insulating barrier to thermal (infrared) radiation. Heat is thus trapped for absorption by the mass of the water in the module stack.

Table 1. The Heat Capacities of Some Common Materials

<u>Material</u>	<u>Heat Capacity (Btu's/cu.ft./°F.)</u>
Water	62.4
Aluminum	36.6
Asbestos fiber	37.5
Asphalt	29.0
Brick, common	24.6
Cement, Portland	19.2
Clay	13.9
Concrete	31.7
Gypsum	20.2
Iron, cast	54.0
Lead	21.8
Marble	34.0
Sand	18.1
Stone	19.0
Wood, white oak	26.8
Wood, white pine	18.1

Source: Adapted from Bruce Anderson, The Solar Home Book. Cheshire Books, Harrisville, NH, 1976, p. 286.

The ends of the storage wall may be integrated with the floor design of the house or may be framed and finished to match the building exterior, or as desired. A floor plan compining these approaches is shown in Figure 1.

A cross section of an installed waterwall thus consists--from interior finish to exterior finish--of:

- Wallboard or other interior surface
- 2" x 4" studs 16" o.c. with air space between--no insulation
- Stack of water-filled modules
- Air space
- Triple glazing

This cross section is illustrated in Figure 2. A schematic plan view is also shown. This arrangement is detailed for slab-on-grade construction. Construction details have also been developed and are available for basements, crawl spaces and other variations.

COMMERCIAL AND PRIVATE GREENHOUSE MARKET

Space heating greenhouses by conventional means represents a significant expense to both commercial and private greenhouse owners. In some greenhouse applications, 100% of the required space heating can be supplied through passive methods, including placing water thermal mass inside. One Design waterwall modules are extremely well suited to this use.

Applications. The modules provide an effective thermal mass using relatively little floor space. They require no installation effort, shelving, supports or extra hardware or equipment; instead, they may simply be stacked in place. Steel drums have found slight acceptance in this market already as containers for thermal mass water. Although the drums are less expensive than an engineered product for the purpose, they are dangerous when stacked unless a strong rack or other support system is provided. If drums are not stacked, they require excessive floor space for an adequate amount of storage mass. Also, drums require a certain amount of hand preparation for this use and cannot simply be set into place. Even with the drums hand-coated inside

Figure 1. Integration of the waterwall with conventional floor plan.

Figure 2. A typical waterwall installation without movable insulation. Inset is schematic vertical section. 9

with a protective film, their longevity--compared with FRP--is doubtful.

Experience of experimenters with solar-heated greenhouses has indicated that 1,000 gallons of stored water will provide a significant reduction in fuel use for space heating in a greenhouse of approximately 1,600 square feet. One application in a well insulated greenhouse in a very high sun, 5,000 degree day climate achieved a 75% solar fraction with 1,000 gallons of mass. Eleven modules will store 1,034 gallons of water to meet this requirement. With an expected cost per module in this market of \$155 to the final consumer, the eleven modules will add to the cost of the greenhouse \$1.70 per square foot. Typical greenhouse square-foot construction costs are \$12 to \$20.

Even in greenhouses, whether for commercial or hobby use, where a waterwall installation is sized too small to provide large solar fractions, the use of thermal mass improves performance. An obvious problem in greenhouses is very large temperature swings that have to be controlled by venting and heating. Temperatures rise too high when the sun is out and fall quite low at night because of large losses through the glazed area. Waterwall modules help temper these conditions by acting as a high-capacity heat sink during the day and reradiating the stored heat at night.

This effect can be especially useful when provided by the One Design modules because it can easily be applied directly to plants in starting pots or trays. The 2-inch depth of the vacuum-formed module lid can contain starting soil directly or support starting containers of any common size. This use places the plants directly over the radiating thermal mass for maximum benefit.

The heating, tempering, and plant-starting uses of modules are expected to appeal to home gardeners with small greenhouses. In the size of greenhouse commonly found in this market, even one or two modules will produce improved performance. The reduction in floor space used for the thermal mass when stored in modules, as compared

with drums and other possibilities, is especially attractive in these applications where total floor space already is strictly limited.

Physical Characteristics and Dimensions. The waterwall module is made of fiberglass-reinforced polyester (FRP) in a standard size which may be specified in varying quantities to provide adequate thermal storage performance for buildings of different sizes, designs, and heat loads. Modules are shown in the accompanying photograph and drawing (Figures 3 and 4). Standard dimensions of each module are:

Length: 95.0 inches
Width: 16.5 inches
Height: 24.5 inches

The modules are designed to stack on one another when installed, as shown in Figure 3. Because the feet of an upper module recess 1.5 inches below the upper rim of the module that supports it, each upper module adds 23 inches to the height of the stack. Thus a stack of four modules has a height of 93.5 inches, suitable for an 8-foot interior ceiling; a stack of five modules is 116.5 inches high, suitable for a 10-foot interior ceiling. The modules may be placed directly inside south wall glazing or directly swept by roof aperture admitted sunlight. The greenhouse offers a third major application.

Each module contains:

12.57 cu.ft. = 94 gallons = 784 lbs. water (at 60°F)

An empty module weighs approximately 40 lbs. The area of a single module is covered by 16 square feet (gross) of glazing, giving a ratio of storage mass to glazing area of 784 lbs. of water/16 ft.² or 49 lbs./ft.². Since allowance must be made for the effective reduction in glazing area caused by the mullions that support the glazing, a net glazing area of 15.078 ft.² per module accurately reflects a true installation. Using the net glazing area yields a storage mass to glazing area ratio of 52 lbs./ft.².

the engineered waterwall

(The waterwall module is a tough, inexpensive container for water used as thermal mass in passive space heating systems. The units are a snap to install: simply stack them in place. No precision leveling is needed. Built-in water connections make filling and draining a matter only of opening a valve. The modules are puncture resistant and have been rigorously tested for strength and reliability. They are easy to specify for use because of their uniformity. Their horizontal shape, which greatly reduces the force exerted by the contained water, combined with the use of a strong FRP laminate, creates a design specifically engineered to give a long, trouble-free life.)

Specifications:

Overall Length: 95¼ inches
 Overall Width: 16½ inches
 Overall Height: 24½ inches*
 Empty Weight: 40 pounds
 Filled Weight: 824 pounds
 Contents: 12.57 cubic feet; 94 gallons; 784 pounds water
 Water per square feet of glazing: 49 pounds gross; 52 pounds net
 Heat Storage Capacity: 784 Btu's/°F. temperature rise
 Material: Fiberglass reinforced polyester

Figure 3.

one design

Mountain Falls Rt.
 Winchester, Virginia 22601

Figure 4

WATERWALL MODULE

- AS BUILT
1/2" LIP

The modules are constructed of fiberglass-reinforced polyester (FRP) with a wall thickness of approximately .065 inch. Materials requirements for a single module are:

Gel coat (interior): 3 oz./ft.² isophthalic;.015" - .020" thick--
6.8 lbs.

Glass: 3 oz. mat seamless at support feet and seats; 8½ oz.
cloth on support feet and seats--9.6 lbs.

Resin: Standard duty--23.3 lbs.

Overspray (exterior): 1½ oz./ft.² black ultraviolet screen - flat;
.0075" - .010" thick.

Design Considerations. Any product takes its final form from the solution of a variety of major and minor constraints, problems, and requirements. These constraints may be associated with performance, production, shipping, warehousing, pricing, or any number of other factors. Some of the major design criteria and considerations are described here.

1. The container should have a horizontal profile. The natural tendency of water is to lie flat. When water is mechanically held in a vertical column or tube, substantial pressures and forces develop, causing such an arrangement to be failure prone. Seam weaknesses of the water containers now on the market have been seen as a potential problem by consumers. A horizontal water container substantially reduces the force and pressure created by the contained water and reduces strength requirements for the container. Water in a container eight feet long and eight feet tall requires the side-walls to sustain a force of 21,287.6 pounds. The sidewalls of the same container only two feet tall, like the waterwall modules, must withstand a force of only 1,330.5 lbs. A similar vertical column of the same volume as the modules but two feet long and eight feet high must have sidewalls to sustain a force of 5,321.9 lbs. The lower force in the horizontal modules is expected to contribute significantly to longevity.

2. The container should be a single, uniform product for installation in varying numbers in different applications. Its size should fit a standard unit of four feet or eight feet to match glazing sheets, standard stud spacing, and interior finish sheets. An eight foot length was chosen because the material for two ends is eliminated without making the tank (when manufactured in FRP) of a weight and size to be difficult to handle by one person. The eight foot length also provides more storage mass per square foot of glazing, since there is less space lost between tanks. The stacking configuration also contributed to the goal of uniformity, since a ceiling of any common height can be accommodated by making the stack taller or shorter. Vertical storage containers must be custom manufactured and inventoried for different heights.

3. The containers should be easy to install. Racks and complex custom installation procedures have been avoided. The modules simply stack one on another. The only installation steps associated with the containers themselves are the application of struts on the top tank in a stack to prevent spread and the attachment and connection of fill/drain hoses. (The spreading of other than the top tank in a stack is prevented by the interlocking design of the tank feet and the seats into which they fit.)

4. Water capacity should provide a practical optimum of thermal capacity, mass to prevent temperature swings, container cost, and amount of floor space used. An additional consideration was the inclusion of a container wall shape to provide needed strength, as described below.

Research at Los Alamos Scientific Laboratory has indicated that a water storage mass of approximately 45 lbs./ft.² of glazing is necessary to provide economically attractive solar fractions. Increasing the mass much beyond 45 lbs./ft.² produces only negligible improvements in performance while using more floor space and increasing the cost of the container. The designed container provides 52 lbs. (net) of storage mass per square foot of glazing.

5. The containers should be capable of both nesting one within another and of stacking one on top of another with no additional hardware. Two considerations underlie this goal. The first relates to marketability, the second to physical distribution concerns. The modules have an asymmetrical wall shape. When matching ends are placed together, modules nest within each other to any desired depth. When non-matching ends are placed together--that is, when every other module in a nest is rotated 180 degrees.. the asymmetrical wall shape and the particular placement of the feet and seats cause the modules to stack rather than nest. The nesting/stacking feature of the modules accurately conveys the idea that the containers are a carefully engineered product designed for a particular application. Modules in the nested configuration are shown in Figure 1.

The second consideration related to the nesting/stacking design addresses requirements for shipping, loading, and warehousing the modules. Nesting the containers for shipment increases their on-truck density by a factor of 7.75. Manufactured of fiberglass and shipped unnested, an entire standard truckload of modules is made up of only 100 units weighing a total of 4,000 pounds. This is an unattractive shipment for most circumstances. A truck load of nested modules contains 775 units weighing 31,000 pounds. The difference in shipping costs is not compelling for regional sales, but becomes a significant factor for national sales if manufacturing is done at a single point. For a shipment from Winchester, Virginia, to Albuquerque, New Mexico, the unit shipping cost is approximately \$22.75 unnested and \$3.51 nested. These rates are based on estimated classifications but are thought to be representative of actual rates that could be obtained.

Although it should be hoped that inventories would never grow high enough for storage space to become a truly significant problem, nested modules can be stored in a much smaller space than unnested ones. In 1,000 square feet of 12 foot high clear space, 528 unnested modules can be stored, while 4,488 nested modules can be. Nested modules also have a significant advantage in loading, unloading

and internal movement. A six foot high pallet load of unnested modules would include only three modules (assuming a depth of only one module). The same six foot high, one module deep, load of nested modules would include twenty modules. Thus, to load 1,000 modules would take 334 fork-lift trips for unnested modules and only 50 trips for nested modules.

6. Modules should have an effective barrier to rapid evaporation of the water contained. Good construction practice, and building codes in many areas, attempt to eliminate the containment of moisture in closed spaces within wood frame constructed buildings. Such moisture can cause wood rot, if the wood fiber approaches saturation point, and various other potential problems in specific conditions. In addition, rapid evaporation of the water in the modules would be undesirable because it would require refilling with inconvenient frequency. To prevent rapid evaporation, the vacuum-molded lid fits the rounded top lips of a module and interlocks with the feet and seats to provide an evaporation barrier that will be effective for any expected conditions. This seal has been successful in all test conditions so far encountered. If situations are encountered where a complete seal is desired, a line of caulking between the module and its lid applied upon installation will provide complete protection from evaporation.

7. The container shape should provide a load-bearing strength of at least 2 times the load expected to be encountered in applications. The modules are designed to be installed in stacks of four high or five high under the roof trusses of a building of standard construction. The roof trusses set a physical limit on the amount of load--caused by the combined weight of contained water--that will be applied to the lower modules in a stack. In a stack five units high, the bottom module carries the weight of four containers of water ($4 \times 784 \text{ lbs.} = 3,136 \text{ lbs.}$) and the weight of the four containers themselves ($4 \times 40 \text{ lbs} = 160 \text{ lbs.}$). Thus the bottom module in a five-high stack must then be able to support 6,592 lbs. to meet the 2.0 safety factor in load-bearing capacity.

8. The containers should have a life span of at least twenty years. Two limiting factors have been identified for life span: (1) the continued load-bearing capability of the design, and (2) the continued integrity of the FRP laminate when exposed for long periods to ultraviolet radiation.

Laminate specifications indicate that long-term stress resistance will exceed that required for a 20-year life span. Tests for long-term load-bearing ability are underway. A two-high stack of modules has been carefully instrumented with strain gages and placed in a temporary load frame for a three-month period. The bottom tank is filled with water, and the second tank with sand. Concrete blocks of a weight equal to eight filled modules are stacked on the instrumented modules. Strain measurements from this test stack will provide behavior indications which, when combined with the known specifications of the laminate, can be used to model the twenty-year behavior of the modules.

Ultraviolet radiation resistance of the laminate as currently specified has been judged to be adequate by the Research and Development Division of Ashland Chemical Company, Columbus, Ohio. Their consultants have recommended changing to a less protective ultraviolet screen as a cost reducing measure. This step has not been taken and likely will not be until further assurance is gained from tests and experience with actual installations that UV resistance is adequate. Further tests are planned in this area but are not yet underway.

9. The containers should be manufacturable by several methods allowing small to large production quantities as required by sales experience. This constraint has been met, as discussed below in the section on Manufacturing Methods.

Manufacturing Methods. An important design consideration in the product evolution of the current waterwall container was the capability of being economically manufactured in varying production quantities based on stage of business development, on capital available for tooling, and on actual market demand experienced. The exact design specifications of the module, manufactured in FRP allow this.

Standard manufacturing methods suitable to the container include hand lay-up, resin transfer molding (RTM), and compression molding using sheet molding compound (SMC). Hand spray-up has not been eliminated as a product method, although specific quality control problems have been a negative factor for this technique.

1. Hand lay-up. This process applied to the container module involves creating a reinforced plastic laminate on the outside surface of a male mold. Molds may be of a number of different materials, but most commonly, the mold itself is constructed of FRP. A compressed-air-powered spray gun is used to apply a smooth finish gel coat to the mold, which has been waxed to improve separation of the finished part. This gel coat becomes the non-corrosive finish coat on the inside of the container. After the gel coat is partially cured, hand-cut fiberglass mat, and cloth where required, is applied by hand to the mold. Resin is then sprayed or brushed onto the glass and carefully rolled by hand to saturate the mat thoroughly and remove air bubbles. An overspray of black ultraviolet screen, which also improves the thermal absorbance of the exterior of the tank, is then applied. After curing, the finished part is unmolded and trimmed.

Moderate care in hand lay-up operation produces parts of adequate strength and consistency. Quality factors include acceptable variation in wall thickness, thoroughness of mat saturation, proportion of glass to resin, proper positioning of mat and cloth, consistency and coverage of gel coat thickness, and others.

Nominal output per mold is one unit per day. With multiple molds, however, task scheduling becomes more efficient and production rates can be increased. An estimate provided by a local FRP manufacturer indicated that if production were pushed, four molds could be expected to produce eight parts per day with a single extended (approximately 10 hour) shift. Multiple shifts do not necessarily increase production levels proportionately because of required curing time.

Mold costs vary considerably depending on the design life span of the mold. Estimates received from different manufacturers and mold

makers have covered a broad range. One Design is currently in the process of negotiating to have production molds made.

2. Resin Transfer Molding (RTM). This process is suitable for an intermediate production level with a corresponding mid-range tooling cost. RTM eliminates one of the critical hand steps of hand lay-up-- the application of the resin--but retains another time-consuming step--the cutting and application of the mat.

In resin transfer molding, the two molds are used: a male half and a female half, which, when clamped together, leave a cavity in the shape of the module. Molds may be of FRP, aluminum, or other materials. For the containers, a gel coat would be hand sprayed on the male mold, if further investigation indicates that the gel coat is still needed with this manufacturing method. RTM produces a smooth finish on all surfaces, and future tests may show that the gel coat is unnecessary. Glass mat is placed by hand within the female mold, the molds are clamped together and resin is injected into the mold cavity under moderate pressure. The part is left in the mold to cure. A rubber gasket shapes the outer edge of the part and trimming is minimal although not completely eliminated.

RTM has certain quality advantages over hand lay-up. The injection process, combined with the use of double molds, produces a part with walls of uniform thickness with a smooth finish inside and out. Including the ultraviolet screen in the resin is more practical with RTM, eliminating the step of spraying on a finish coat. Resin and glass usage can be better controlled, reducing waste. Hand rolling, which is a critical quality factor in hand lay-up, is eliminated. Production time is significantly reduced.

Estimates of production levels vary. A reasonably efficient process should produce four parts per day from a single mold. Multiple molds, because of specialization of labor and better task scheduling, increase output per mold. Twelve molds could be expected to produce sixty-four parts per day for an average output of 5.33 parts per mold per day.

Estimates for one set of tools--one double mold--have ranged from \$4,000 to \$10,000. Life span of the molds increases at the higher initial tooling costs. Three metal double molds with a combined cost of approximately \$30,000 are considered minimal to justify the use of RTM.

3. Compression Molding with Sheet Molding Compound (SMC).

This process is suitable for relatively high production levels for a newly introduced building product. It eliminates hand operations except for some minor finishing steps.

Sheet molding compound is a pliable sheet material of resin with fiberglass reinforcement already embedded in it. Proportion of reinforcement to resin can range from 15% to 35% with fiber lengths up to 2 inches. In compression molding, a measured section of SMC is placed between the open halves of a split mold on a press. The mold, heated to an appropriate temperature, is then closed and pressure applied causing the compound to fill the mold cavity and harden.

Compression molding produces parts of superior uniformity, surface finish, strength and overall quality. Consultants have been unanimous in recommending the process for future full-production operations.

A reasonable minimum production level with compression molding, allowing a cycle time of approximately 5 minutes per part, is 150 parts per day or 37,500 parts per year.

Tooling costs for compression molding are substantial. The molds have to withstand considerable pressure and require careful design to allow for proper and uniform heating on the press. A further consideration is that a part 95 inches long is in the upper size range for this process. A single split mold for compression molding is expected to cost approximately \$150,000 based on a fairly careful estimate by the potential supplier. Mold life span is more than adequate.

The detailed design of the module makes it suitable for any of these production methods. Drafts, radiuses, material thicknesses, edge

stiffening methods and surface requirements are all acceptable with current design specifications.

Unit Costs. Unit costs vary considerably depending on production method. This means in turn that projected sales volumes and achievable selling price interact significantly:

1. Hand lay-up parts in test quantities (1 unit per day) are currently being supplied F.O.B. factory for a \$130 unit cost. Current bids and estimates indicate that with four molds and a production level of a maximum of eight parts per day this price could be reduced to approximately \$100. The effective minimum sales level to support this production would be approximately 1,000 units per year. Discussions with potential suppliers indicate that this price could be obtained at this production level (four units per day average) because hand lay-up methods allow flexible assignment of personnel and equipment and do not require continuous production on a single product to be efficient.

2. Three RTM split molds will provide an annual production of approximately 3,600 parts or 14 to 15 parts per day. Based on current labor and materials costs, this production level produces a unit cost of approximately \$75.

3. Compression molding requires a minimum annual production of approximately 37,500 units or 150 per day for full utilization of tooling. Unit cost at this level will be approximately \$55. Estimates as low as \$45 have been received and may be achievable.

One long-term unpredictable factor in the module unit costs is the basic price of the resin component of the laminate. A petroleum-based material, resin has had a volatile pricing history. The deregulation of domestic petroleum prices combined with market and supply developments abroad, may adversely affect the future prices of resin. One offsetting factor in price rises for plastics is the fact that their production requires relatively little energy compared to other materials. Plastics require 21.03 thousand Btu's of energy to produce finished material worth one dollar; steel, by comparison, requires

32.65 thousand Btu's and aluminum 77.1 thousand Btu's, according to the U.S. Department of Commerce. Another important factor is that the pressures that might raise resin prices are the very same influences that create a greater market demand for solar heating products.

PATTERN MAKING AND FABRICATION

Based on One Design's previous experience with earlier waterwall design, it was determined that several previously studied qualities were to be retained. The part should be of horizontal orientation for long life through low stress. The part should be rectilinear for low space utilization. The part should be stackable to attain various heights.

It was decided to pursue a design that eliminated the need for any exterior support system (exoskeleton) by way of simplifying construction and reducing costs.

A self-stacking design grew out of many scenarios of integrally molded load bearing columns. Small models were built for study and visualization. The concept was then taken to full-scale drawings. Architects and builders were consulted for detailed design criteria germane to installation and building requirements. Several phases of redrawing ultimately led to a design that was executed by a pattern maker into a full-scale wooden model of a typical vertical section. Flange modifications were made and changes to the ends of the model were required to facilitate full nesting. From that model a female mold was pulled in FRP. Five parts were pulled from the female mold yielding the components of a full-scale FRP plug from which sample parts could be pulled. First, however, the feet details were modled and added to the mold.

After initial crush testing of the prototype parts, a modification was made to the laminate to reinforce the foot. (In those tests the failure mode was a line sheer load in the foot where it cantilevered off the edge of the bearing point of the module below.) This final

modification successfully moved the failure mode up to the sidewall in a generally symmetrical distribution of the column load and was retested and accepted as final. Figure 5 shows the blow off parts being installed which are used to release the finished part from the mold.

PRELIMINARY STRUCTURAL TESTING

Two preliminary rounds of structural tests were performed on the modules. In the first, a single module was slowly filled with water to a depth of 18 inches to observe the deformation behavior of the side walls and to determine if failure would occur anywhere in the tank due to hydraulic pressure. Four dial indicators were mounted perpendicular to the wall of the tank to measure lateral wall displacement. A grid of lines was drawn on the side of the tank and photographic records were made at water depths of 4, 8, 12, 14 $\frac{3}{4}$, 16 and 18 inches. The displacement-depth curve (shown in Figure 6) resulting from the test would predict a spread at the top of the tank of approximately 7 inches (3.5 inches on each side) if the top of the tank were not restrained. No apparent damage or distress was evident in the tank as a result of the load test.

In normal use, however, the modules would be stacked on top of each other, with the "feet" of the module stacking in the support area of the module below it, thus preventing the spread of the walls of the tank when filled. Five modules were stacked and filled, with a dial indicator used to monitor the lateral movement of the center column of the bottom tank. Clamps were applied to the top modules to prevent bowing of the side walls observed in the first test. Each module contained a load of approximately 94 gallons of water calculated to be 784 pounds excluding the 38 pound weight of the tank itself. The dial indicator showed virtually no displacement (less than .005") which was attributable to bending or buckling of the column element. The results indicated that the design objective of maintaining stationary column load support without resorting to a completely rigid tank had been achieved.

Figure 5

Figure 6

-Test of Water-Wall Module with Unrestrained Top

In the second round of tests two modules were subjected to extremely high loads in order to observe the most likely mode of failure. Because the tanks will be placed in house wall cavities where the potential for overloading is limited by the height of the cavity, it was recommended that the tanks be able to support a minimum of twice their normal load as a safety factor. Therefore, each tank must be able to support twice the weight of four filled tanks, or 6,576 pounds. Failure occurred at an applied load of 10,400 pounds, although an initial crack occurred at a load of approximately 5,000 pounds. The load-strain curve for the support bearing region of the upper tank is shown in Figure 7. The performance of Gage 7 in Figure 8 is an indication of the stability of the columns under high loads. The point of failure was in the foot of the upper tank. Subsequent examination revealed that the wall thickness at the point of failure was only 60% of the specified thickness. In response to this finding, additional fiberglass cloth and resin have been specified in the contact points between tanks to improve the strength characteristics of the tank without requiring a change in design of the module and with little additional material required.

FINAL STRUCTURAL TESTING

In preliminary structural tests, two modules were subjected to extremely high loads in order to observe the most likely mode of failure. The point of failure was located in the foot of the upper module, shown in Figure 9. In response to this finding, additional fiberglass cloth and resin were specified in the contact points between tanks. The modified tanks were retested at the structural testing laboratory at the University of Virginia by Dr. Fred McCormick, One Design's structural consultant. Figure 10 shows the test apparatus. A load was applied by means of hydraulic ram with the Reihle/Los control console. The load was applied to the upper module through a steel spreader beam and a wooden frame designed to bear on the seats of the module. The lower module was filled with water prior to the vertical load application. No water was placed in the upper module. All loads were applied statically to the tank stack at a reasonably uniform rate over a period of fifteen to thirty minutes.

Figure 7

Load-Strain Curves for Support Bearing Region of Upper Tank.

Figure 8

∴ Load-Strain Curves for Region at Base of Column for Lower Tank.

Figure 9

Figure 10

The following excerpts are drawn from Dr. McCormick's report of the tests:

"Structural failure of the stack occurred at a total load of 13,600 pounds. The mode of failure was the buckling of one of the center convolutes (acting as conical columns in transmitting the vertical loads) in the upper tank. The buckle initiated at approximately the mid-height of the column and formed a horizontal crease (flexural crack) which shifted the load from the highly stressed center column to adjacent columns. While the tank did not collapse nor show signs of serious distress at the 13,600 pound load, this should be considered the ultimate load capacity since leakage would occur at the point of cracking. Continued loading caused additional columns on both sides of the upper tank to buckle and then crack. A total maximum load of 16,000 pounds was reached before the test was terminated. Visual inspection of the lower tank during and after completion of the test indicated no structural damage nor distress of any kind whatsoever. It was not determined what maximum load was required to cause failure of the bottom tank."

"Safety factors for the short-term static load tests based on a waterfilled tank weighing 824 pounds are computed from the above loads and are shown as follows:

Number of Tanks in stack	Failure of second tank from bottom	Failure of Bottom Tank (minimum values)
3	16.4	9.7+
4	8.2	6.4+
5	5.5	4.8+
6	4.0	3.9+
7	3.3	3.3+
8	2.7	2.7+

The tabulated safety factors indicate that the lower tank would probably fail first in a stack of five or fewer modules, but the second tank from the bottom would probably fail first in stacks higher than five modules. The uncertainty of failure of the lower tank is due to the absence of damage to the tank at 16,000 pounds of load. The indicated safety factors (of 4.0 and greater than 3.9) for the 6-module stack are in keeping with those considered appropriate for glass-reinforced plastic composites of this type."

The safety factor is the multiple of the actual load the tanks could be expected to support. It should be noted that in most applications the height of the stack would be 4 or 5 tanks. The test results indicate that the tanks exceed this capability by far. In fact the tanks could be stacked two stories tall and would still surpass the minimum recommended safety factor of 2.

The "oil canning" failure mode shown in Figure 11 indicates that the stress which had previously applied pressure and caused failure at a point in the foot has been alleviated and that symmetrical distribution of the load has been achieved. Thus the shape of the tank helped bear the load until the structural capacity of the wall material itself was reached.

FREEZE AND THERMAL SHOCK TEST

It is virtually impossible that a backup heating system would fail and that a prolonged period of extreme cold and heavy cloud cover would cause temperatures in an insulated house to fall low enough to freeze waterwall modules. Nevertheless, a test was conducted to evaluate the impact of freezing. One module (shown in Figure 12) was subjected to a sustained temperature of 5°F. While expansion of the lid and flange around the top edge of the tank occurred, the tank itself was not damaged and no leaks were observed after thawing. Expansion of the tank is shown in Figure 13.

The tank was moved from the area of 5°F. to an outside temperature of 80°F. in direct sunlight. The sudden change in temperature caused the block of ice contained in the tank to split and a 3/4" wide fissure developed very suddenly in the ice over the full length of the tank. This caused the sides of the tank to bulge to approximately 3 inches more than normal width and cracked the top edge flange. The tank walls and bottom were not damaged. In a normal application, expansion of the sidewalls of the module would have been restrained by interlocking with the module above.

THERMAL PERFORMANCE

The basic principle of operation of a waterwall is simple. South-facing glazing creates a greenhouse effect in which heat from the sun is trapped in an air space surrounding the water storage tanks. In addition, the dark-colored surfaces of the tanks themselves are directly heated by the sun. The storage mass of the contained water absorbs and stores the heat. It is then available to heat air for the living space through radiation or through convection as air passes over the warm surfaces of the tanks. Once the stored water is heated

Figure 11: View of oil canning failure of side wall at column. The ruler indicates 4" of the side wall of the center panel is oil canning while other panels bear the load symmetrically.

Figure 12

by the sun, it acts like a large radiator installed in the wall.

Five of the nesting/stacking modules were installed with other tanks in One Design's Star Tannery House in order to monitor their performance under actual house conditions. The installation and close-ups of the various tanks are shown in Figures 14-16.

The house is of frame construction on slab-on-grade with approximately 1,250 square feet of floor space. It has three bedrooms, two baths, kitchen and a combined living room dining area. Exterior walls (with the exception of the waterwall) have 2' x 6" studding set 24" on center filled with cellulose insulation. Ceiling joists are 2" x 10" also filled with cellulose. The house has 400 square feet of south-facing triple glazing behind which test water containers (the equivalent of 25 modules) are installed, separated from the living space by a 2" x 4" studded wall covered on the interior with standard wallboard. A 115 square foot clerestory also faces south. Thirty of the fifty foot length of north wall contains a masonry mass made of 8" cinderblock grouted solid inside the exterior insulated wall. Tank water temperatures, outside ambient temperature, ground temperatures, air temperatures between the tanks and glazing, inside mean radiant temperatures, and inside dry bulb temperatures were recorded hourly. Solar radiation on the south facing vertical surface was measured by a Hollis Observatory LM-2000 Digital Integrator and auxiliary fuel meter readings and electric meter readings were maintained.

A set of larger rectangular tanks was prepared as a control group in order to compare the actual thermal performance of a tank constructed of the same material as the nesting/stacking tanks but with a mass of 93 pounds of water per net square foot of glazed area (as compared to 52). Each tank is 92 inches long, 25 inches tall and 18 inches wide, containing 165 gallons (or 1375 pounds) of water. The tanks are bolted to vertical steel supports. Tank water temperatures for both types of tanks were monitored at the Star Tannery house. Type K thermocouples were installed by Princeton Energy Group under the direction of Los Alamos Scientific Labor-

Figure 14

Figure 15

Figure 16

atories. A copy of the Princeton Energy Group report which describes the installation and placement of the thermocouples is included as an Appendix.

The thermocouples were located in the top, middle and bottom modules of each of the stacks and temperatures were recorded hourly on the Honeywell-Brown recorder provided by Los Alamos Scientific Laboratories. This instrumentation is provided for under a separate contract between DOE and Los Alamos Scientific Laboratories. One Design, Inc., is donating their time and costs to this project.

Data collected from the two sets of tanks are shown in Figures 17 and 18. Figure 17 shows water temperatures of the modules at the top and bottom of the stack during three sunny and cold days. The data provide a periodic diurnal pattern, with the top module reaching a temperature of 88° F. on February 9 and 10. The daily increases in storage temperature were 16 degrees and 13 degrees, respectively. By comparison, the top large rectangular tank peaked at 81° F. on February 9 and 82° F. on February 10. Daily increases in storage temperature were 10.5 degrees and 9 degrees, respectively.

The bottom module water temperature peaked at 75° F. on February 9 and 74° F. on February 10, with daily increases of 11.5 degrees and 9.5 degrees. Data from the bottom rectangular tank were not available during this period so the middle tank water temperatures are shown. The higher level of mass did serve to reduce the temperature swing under these sunny conditions, although it was found to keep mean radiant temperatures below comfortable levels on days with average or less than average solar radiation.

During the period January 10-14, 1979, the auxiliary heater was turned off in order to observe module and house temperatures during a cold, cloudy period with no back-up heat source. Although the outside ambient temperature remained below 20° F. on two extremely cloudy days, a mean radiant and dry bulb temperature above 50° F. were sustained in the living room. Top and bottom module water temperature and outside ambient temperature are shown in Figure 19.

Solar radiation and degree day data collected at the Star Tannery House for January through April were entered in One Design's computer program which is based on, "A Simple Empirical Method for Estimating the Performance of a Passive Solar Heated Building of the Thermal Storage Wall Type," (Balcomb and McFarland, LA-UR-78-1159, 1978). Modifications have been made for thermal storage which exceeds 45 Btu's per square foot for input of south vertical solar radiation data, for acrylic glazing systems and for the inclusion of internal gains.

The calculated auxiliary energy requirement was compared to measured fuel consumption at the Star Tannery House for the period January 29 - February 25, 1979.* Degree days for the period were derived from hourly ambient temperature readings monitored at the house and incident solar radiation on the south-facing vertical wall was measured by an integrating pyranometer. A combustion efficiency test was performed on the propane furnace at the house and efficiency was found to be 66%. The actual metered fuel consumption for the period was 2,130 cubic feet of commercial propane, providing 3.54 million Btu's of auxiliary heat. Table 2 shows that the calculated auxiliary energy requirement was only about 1% high. In Table 3 the calculated energy requirement was compared to fuel consumption for January through April, 1979. The estimate was found to be accurate within about 7% of the actual fuel consumption of 9.07 million Btu's.

Table 4 shows estimated monthly solar radiation. While the preceding two tables had been based on actual weather conditions and a mix of tank types, Table 3 is based on average weather conditions and simulates a full complement of 25 nesting/stacking modules. The annual solar heating fraction is 79.5%. The average annual heating cost for this 1250 square foot house at the current propane price of 69.6¢ per gallon would be less than \$90.00.

* It should be noted that this period included record breaking low temperatures.

Table 2. Performance of the Star Tannery House
During the Period 1/29/79 - 2/25/79.

Test Period - 1/29/79 - 2/25/79	
1198	Monthly Degree Days
11.11	Gross Thermal Load (MBtu/Mo.)
4	Internal Sources (MBtu/Mo.)
9.7	Net Thermal Load (MBtu/Mo.)
937	Daily Vertical Incident Radiation (Btu/Ft. ²)
.675	Average Transmittance
632	Daily Radiation Transmitted (Btu/Ft. ²)
8.43	Monthly Radiation Absorbed (MBtu/Mo.)
.869	Solar Load Ration
.607	Waterwall Solar Heating Fraction
.699	Direct Gain Solar Heating Fraction
.631	Weighted Average Solar Heating Fraction
3.58	Auxiliary Energy Required

Table 3. Performance of the Star Tannery House
January - April, 1979

	Monthly Degree Days	Gross Thermal Load (MBtu/Mo.)	Internal Sources (MBtu/Mo.)	Net Thermal Load (MBtu/Mo.)	Daily Vertical Incident Radiation (Btu/Ft. ²)	Average Transmittance	Daily Radiation Transmitted (Btu/Ft. ²)	Monthly Radiation Absorbed (MBtu/Mo.)	Solar Load Ratio	Waterwall Solar Heating Fraction	Direct Gain Solar Heating Fraction	Weighted Average Solar Heating Fraction	Auxiliary Energy Required
Jan.	1201	11.13	1.55	9.58	605	.72	436	6.43	.671	.478	.585	.506	4.73
Feb.	1169	10.83	1.4	9.43	939	.675	634	8.45	.895	.622	.712	.645	3.35
Mar.	648	6.01	1.55	4.46	1047	.625	654	9.65	2.167	.952	.977	.958	.19
Apr.	440	4.08	1.5	2.58	702	.525	369	5.26	2.041	.940	.969	.948	.13
Total													8.40

Table 4. Performance of the Star Tannery House Under Average Degree Day and Average Insolation Conditions.

	J	F	M	A	M	J	J	A	S	O	N	D	ANNUAL
Monthly Degree Days	1046	957	740	416	215	0	0	0	109	373	663	940	5459
Gross Thermal Load (MBtu/Mo.)	9.69	8.87	6.86	3.86	1.99	0	0	9	1.01	3.46	6.14	8.71	50.59
Internal Sources (MBtu/Mo.)	1.55	1.4	1.55	1.5	1.55	0	0	0	1.01	1.55	1.5	1.55	13.16
Net Thermal Load (MBtu/Mo.)	8.14	7.47	5.31	2.36	.44	0	0	0	0	1.91	4.64	7.16	37.43
Daily Vertical Incident Radiation (Btu/Ft. ²)	820	845	987	874	779	760	802	937	1123	1074	911	811	
Average Transmittance	.72	.675	.625	.525	.44	.4125	.44	.525	.625	.675	.72	.725	
Daily Radiation Transmitted (Btu/Ft. ²)	590	570	617	459	343	314	353	492	702	725	656	588	
Monthly Radiation Absorbed (MBtu/Mo.)	8.71	7.6	9.1	6.55	5.06	4.48	5.21	7.26	10.04	10.7	9.37	8.68	
Solar Load Ratio	1.07	1.018	1.715	2.781	11.43	-	-	-	-	5.609	2.016	1.211	
Waterwall Solar Heating Fraction	.682	.659	.867	.973	1	1	1	1	1	1	.912	.737	.781
Direct Gain Solar Heating Fraction	.756	.737	.906	.984	1	1	1	1	1	1	.941	.802	.835
Weighted Average Solar Heating Fraction	.702	.680	.878	.976	1	1	1	1	1	1	.920	.754	.795
Auxiliary Energy Required	2.43	2.39	.65	.06	0	0	0	0	0	0	.37	1.76	7.66

ECONOMIC PERFORMANCE FOR THE HOMEOWNER

Builders, contractors and developers, in particular, have made marketing decisions based on the belief that immediate economic benefits to house buyers are essential before solar will be accepted in the market. One Design's waterwall system provides these immediate economic benefits.

The calculation of savings from a solar installation is dependent on a number of factors resulting from a specific house in a specific location built and financed at a specific time. In general, there is no "typical" house because, although performance may be relatively uniform over fairly large climatic regions, local factors like property tax rates and costs of conventional fuels affect specific expenses and savings. One Design's computer analysis service will provide specific analyses of economic as well as thermal performance for houses in a range of local settings. These analyses will be used as a selling tool. A representative comparison will be described here.

The Washington metropolitan area is an important target area for early sales plans. In a typical location in this area (Fairfax County) the economic choice will be presented between an extremely well insulated house (better than current standard building practice for the region) and a comparable house with a waterwall and rolldoor installation.

A conventional oil-fired forced hot air system, based on estimates provided by a local supplier, would require an initial investment of \$2,495.00, as shown in Table 5. For purposes of comparison, the system is assumed to be installed in a 1,250 square foot house with double-glazed windows, R-19 wall insulation, R-30 ceiling insulation and 1-inch perimeter insulation. This is a more energy efficient installation than is now common in Fairfax County.

The solar system for the same 1,250 square foot house consists of three waterwall sections with a total of 12 modules. Each section is covered by an 8' x 8' rolldoor. Interior movable insulation over windows plus a vestibule door are included as standard features in the solar design (and are included in solar costs). Because of the greatly reduced conventional heating requirements an inexpensive electrical resistance back-up heater can be used economically. The costs for the solar plus electric system are also shown in Table 5. Since the installation of the waterwall system displaces part of the conventional exterior surface and insulation in the south wall, the cost of this material and labor (estimated at \$196.00) has been subtracted from the total investment cost.

The conventional economic analysis comparing these two houses assumes that the entire cost of the heating system is financed as part of the house. Table 6 shows some overall financial comparisons of the two systems. The oil system requires an additional down payment of \$499 (20% of \$2,495) over a hypothetical house with no heating system at all. The solar house requires a down payment of \$1,081 to provide a complete heating system, but the federal energy tax credit returns \$1,063.25 of this amount, as indicated in the footnote to Table 6.

Table 5. Comparison of conventional oil-fired forced air system with waterwall with roll doors and electric auxiliary.

<u>Oil System</u>		<u>Solar + Electric System</u>	
Furnace	\$805.	Truss modification	\$ 225.
Thermostat	38.	Roll doors	1,056.
Tank and piping	238.	Control Unit	100.
Ducts	665.	Modules	1,560.
Flue	<u>250.</u>	Acrylite and Support	552.
	\$1,996.	Window Quilt and Extra Insulation	461.
Contractor (25%)	<u>499.</u>	Vestibule Door	100.
Total System	\$ 2,495	Extra installation	<u>185.</u>
			\$4,239
		Less: saving on costs of conventional south wall (192 sq.ft.)	<u>196.</u>
			\$4,043.
		Contractor (25%)	<u>1,010.</u>
		Total Solar Costs	\$5,053
		Electric Back-up	<u>350.</u>
		Total System Costs	\$5,403.

Table 6. Investment and first year performance comparison,
conventional oil versus solar plus electric systems.

	<u>Oil System</u>	<u>Solar + Electric System</u>	<u>Difference (Solar-Oil)</u>
Total Amount Added to House Cost	\$2,495.00	\$5,403.00	\$2,908.00
20% Down Payment	499.00	1,081 - 1,063.25* = 17.75	(481.25)
Amount Financed	1,996.00	4,322.00	2,326.00
First Year Fuel Costs	219.75	30.19**	(189.56)
Twenty Equal Annual Mortgage Payments	234.45	507.66	273.21

* The federal energy tax credit covers nearly the entire down payment for the solar plus electric system. The credit returns 30% of the first \$2,000 invested in a solar system and 20% of the remainder of the investment up to \$8,000. Eligible items are: roll doors, \$1,056; control unit, \$100; modules, \$1,560; acrylite and supports, \$552; extra installation, \$185; contractor's fee, \$863.25. This total eligible amount of \$4,316.25 provides a credit of \$1,063.25.

** The solar house as described has an annual net heating load of 13.92 million Btu's. Of this, 11.52 million Btu's (82.8%) will be satisfied by the solar system in Fairfax County with a 4,224 degree day, moderate radiation climate.

Table 7 . Life cycle economics analysis of the extra costs and savings of a solar plus electric system versus a conventional oil system.

Year	Fuel Savings	Extra Principal	Extra Interest	Extra Insurance	Extra Property Tax	Maintenance Savings	Income Tax Savings	Down Payment Savings	Solar Savings (Losses)	Discounted Savings
1	189.56	40.61	232.60	14.54	44.78	40.00	83.21	481.25	461.49	425.34*
2	210.41	44.67	228.54	15.70	48.36	43.20	83.07		(0.59)	(0.50)
3	233.56	49.14	224.07	16.96	52.23	46.66	82.89		20.71	16.21
4	259.25	54.05	219.16	18.32	56.41	50.39	82.67		44.37	32.02
5	287.77	59.46	213.75	19.78	60.92	54.42	82.40		70.68	47.01
6	319.42	65.40	207.81	21.36	65.80	58.77	82.08		99.90	61.23
7	354.56	71.94	201.27	23.07	71.06	63.47	81.70		132.39	74.79
8	393.56	79.14	194.07	24.92	76.75	68.55	81.25		168.48	87.72
9	436.85	87.05	186.16	26.91	82.88	74.04	80.71		208.60	100.10
10	484.90	95.76	177.45	29.07	89.52	79.96	80.09		253.15	111.96
11	538.24	105.33	167.88	31.39	96.68	86.36	79.37		302.69	123.39
12	597.45	115.87	157.34	33.90	104.41	93.27	78.53		357.73	134.40
13	663.17	127.45	145.76	36.61	112.76	100.73	77.56		418.88	145.05
14	736.11	140.20	133.01	39.54	121.78	108.78	76.44		486.80	155.36
15	817.09	154.22	118.99	42.71	131.53	117.49	75.16		562.29	165.39
16	906.97	169.64	103.57	46.12	142.05	126.89	73.69		646.17	175.17
17	1,006.73	186.60	86.61	49.81	153.41	137.04	72.01		739.35	184.73
18	1,117.47	205.26	67.95	53.80	165.69	148.00	70.09		842.86	194.10
19	1,240.40	225.79	47.42	58.10	178.94	159.84	67.91		957.90	203.31
20	1,376.84	248.42	24.84	62.75	193.26	172.63	65.43		1,085.68	212.38

Total Discounted Savings = \$2,649.16

* Contrary to common practice, the entire first year amount has been discounted because the savings on the down payment are not actually realized until after the end of the year when income tax returns are prepared.

Table 7. (continued). Life cycle economic analysis: assumptions

Term of mortgage = 20 years	Discount rate = 8.5%
Extra amount financed = \$2,326	Insurance rate = 0.5%
Extra annual mortgage payment = \$273.21	Property tax rate = 1.54% (Fairfax County 1978-79)
Mortgage interest rate = 10%	Income tax rate = 30%
down payment = 20%	Fuel oil cost = 65.9¢/gal. (Fairfax County, May 15, 1979)
Fuel inflation rate = 11%	Electricity cost = 4.3¢ kwh (Fairfax County)
General inflation rate = 8%	

The effective first year cash investment thus is only \$17.75. The actual cash investment on the solar system is \$481.25 less, counting tax credit, than for the oil system. Note that the final column in Table 6 shows the extra costs or the savings resulting from the choice of the solar heating system. Thus, even though there is an initial savings of \$481.25 in cash investment with solar, there is a \$2,326 addition to the mortgage causing an annual increase in mortgage payments of \$273.21. An effective system must repay this and other extra costs and still provide enough savings in fuel cost to be worthwhile. Further analysis shows that the One Design waterwall easily meets this requirement.

Table 7 shows a life-cycle economic analysis of the savings and additional costs of choosing a waterwall system rather than conventional oil heat for this house in Fairfax County, Virginia. The analysis uses a method (part of the F-Chart analysis) developed at the University of Wisconsin by William Beckman, Sanford Klein and John Duffie. The only modification made to the model was to separate maintenance and insurance costs. The original method was designed for active solar systems and assumed that these systems would require more maintenance than a conventional heating system. The no-moving-parts design of the waterwall system reduces maintenance costs and this has been highlighted in the Table as a savings.

The analysis is given for the systems described in Tables 5 and 6. It uses an extra amount financed at 10% of \$2,326 with 20% down payment and with extra equal annual mortgage payments of \$273.21. The mortgage term is 20 years. First year fuel savings are from Table 6. Fuel costs (and thus savings) are assumed to increase at an annual rate of 11%, 3% higher than the assumed general inflation rate of 8%. The increased replacement value and tax assessment of a house with solar heating result in higher homeowner's insurance costs and in higher property tax payments. These quantities have been calculated using an insurance premium rate of .005 and a property tax rate of .0154 on the excess cost of the solar heating system over the conventional system. Both of these rates have been assumed to inflate at the general rate of 8%. Note that in a number of localities in Virginia, as well as in other states, the extra costs of solar heating systems are exempt from property taxes or receive a lower assessment. This incentive and all others except the federal energy tax credit have not been considered in the analysis. It is clear in this case that exemption from property taxes would serve as a genuine financial incentive.

The solar heating system has been credited with a savings in maintenance costs of \$40 per year, inflated at the general rate. Income tax savings are derived by multiplying the income tax rate of 30% by the sum of extra interest and property taxes resulting from the solar installation. The 30% rate is intended to reflect both state and federal taxes and is a conservative figure for typical anticipated solar buyers in most states. It also does not show the elevation to higher tax brackets as inflation makes

incomes larger. The savings on the down payment with the solar installation is a one-time item in the first year created by the federal tax credit. Solar savings for each year are the total of savings less extra costs: fuel savings - extra principal - extra interest - extra insurance - extra property taxes + maintenance savings + income tax savings.

Discounted savings in the final column show the present value of future savings. They are computed by dividing the future value by $(1 + i)^n$, where i is the discount rate and n is the number of years in the future in which the saving is realized. This adjustment allows for the time value of money by indicating the amount in current dollars that would have to be invested to be equivalent to a given income or savings in the future. A discount rate of 8.5% has been used.

Choosing a waterwall plus electric system requires the house buyer to increase the down payment by \$582 over the \$499 contribution needed for a conventional oil system. Nearly the entire amount is returned through the federal energy tax credit, though, and even with current energy costs, a significant financial benefit is realized in the first year. In the second year, extra costs for mortgage payments, insurance and property taxes slightly exceed savings on fuel, maintenance and income taxes, and there is a net extra cost of \$0.59 for the year. In every year thereafter, savings exceed extra costs. With the exception of the 59¢ in the second year, there is no point at which more money has been invested than has been immediately saved. Thus, from the cash investment point of view, payback is immediate. Buyers realize an immediate cash gain which only grows larger as the years go by.

Analyses like these, expressed simply in promotional literature and using local performance, costs and tax rates for target market areas will be an important feature of One Design's promotional efforts.

TESTING AND EVALUATION OF WATER PURITY

The waterwall modules installed at the Star Tannery House were filled with water from the house's well. After nine months, water samples were taken from the tanks and were found to have remained clear and free from odor. The following analysis performed by the laboratory of Kappe Associates in Rockville, Maryland, compares a sample of tap water from the house to a sample drawn from a fiberglass module after nine months.

	<u>House Tap Water</u>	<u>Sample From Fiberglass Module</u>
Alkalinity	77.5 mg/l	103.7 mg/l
pH	6.80	7.97
Conductivity	231 ohms	332 ohms
Total Organic Carbon	5.26 mg/l	5.37 mg/l
Standard Plate Count	70 std. plate count/ml	8,300 std. plate count/ml

The alkalinity level of 103.7 milligrams of calcium carbonate per liter of water is within acceptable limits and is merely a reflection of the calcium which precipitates out of the hard water of north-west Virginia. The pH reading is also within acceptable limits. A pH of 8 or more is found in natural water in many areas. The increase in conductivity is an indication of a slight increase in the amount of solids in the water and results again from hardness minerals precipitating out of solution. The increase in bacterial levels of the standard plate count suggests that 1-2 tablespoons of laundry bleach should be added to each tank when filled to provide an initial chlorine dosage of 2-3 parts per million. The relatively stable total organic carbon level shows that no significant amount of organic matter has built up and that the single initial application of chlorine should be sufficient.

MATERIAL EVALUATION TEST (CREEP)

When a plastic is subjected to a constant static load, there is a tendency for resin to deform slowly over very long periods. This phenomenon, which also occurs in soft metals and structural metals at very high temperatures, is called creep. In continuing research,

accelerated tests will be undertaken in which the load on the bottom unit of a stack will be increased and the highest expected service temperature will be maintained. A module has been equipped with bonded electrical strain gauges in order to measure creep deformation over the next two years.

EVALUATION OF LAMINATE SAMPLES

Laminate samples were taken from one tank and subjected to physical tests by Ashland Chemical Company of Columbus, Ohio. Results of the tests were:

Tensile strength	16,127 p.s.i.
Tensile modulus	1,068,843
Elongation	2%
Flexural strength	27,900 p.s.i.
Flexural modulus	802,534 p.s.i.
Compression strength	18,279 p.s.i.
Izod impact strength	10.7 ft. lb./in.
% glass	35.9
Barcol	45-50 rough side 30-35 smooth side

On the basis of physical test results, Ashland's engineers recommend the use of an isophthalic resin. They also recommend that the ultraviolet stabilizer that would be most reliable, easiest to apply and inexpensive is black latex paint.

APPENDIX

MALONEY INSTRUMENTATION: WINCHESTER, VIRGINIA
(STAR TANNERY HOUSE BY ONE-DESIGN, INC.)

Technical Progress Report #3

FINAL REPORT of task g, Data Acquisition System Installation covering the period
27 September 1978 through 31 April 1979

Date of Report: 31 April 1979

Reporting Organization: Princeton Energy Group
729 Alexander Road
Princeton, NJ 08540

Authors: Lawrence Lindsey
Jack B. Cooper

Research supported by the Solar Heating and Cooling Research and Development Branch,
Office of Conservation and Solar Applications, U. S. Department of Energy

Contract No. EG-77-G-04-4149, Modification A001

ABSTRACT

PEG was requested by LASL to instrument a novel passive solar house near Winchester, Virginia: the Star Tannery House by One-Design, Inc.

An instrumentation package supplied by LASL was inexpensively modified to double the number of recording channels. The data acquisition system was installed in November 1978 and has been operated successfully since that time.

Instrument modification and installation procedures are described. Suggestions for improving the effectiveness of future installations of this type are offered, from both technical and managerial viewpoints.

ACKNOWLEDGEMENTS

We thank Timothy Maloney, Maggie Maloney, Jerry Hahn, and Victor Habib for their assistance, support, hospitality, and useful critique. It is satisfying to work with such people.

This material was prepared with the support of the U. S. Department of Energy, Grant No. EG-77-G-04-4149. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the author(s) and do not necessarily reflect the view of U.S. DOE.

Recipients of this report:

U.S. DOE
ATTN: Michael Maybaum
20 Massachusetts Avenue, NW
Mail Stop 2221G, Rm. 3114
Washington, DC 20545

Los Alamos Scientific Laboratory
ATTN: Dr. Douglas Balcomb
PO Box 1663
Los Alamos, NM 87545

U.S. DOE
Chicago Operations & Regional Office
ATTN: H.N. Miller, Ass't. Mgr. for
Acquisition & Assistance
9800 South Cass Avenue
Argonne, IL 60439

Harrison Fraker
PEG Project Staff
Princeton Energy Group
729 Alexander Road
Princeton, NJ 08540

Lawrence Lindsey
PEG Project Staff
Princeton Energy Group
729 Alexander Road
Princeton, NJ 08540

Tim Maloney
One Design, Inc.
Mt. Falls Rte.
Winchester, VA 22601

Ron Lutha
U.S. DOE/CHO, Office For Acquisition
and Assistance
9800 South Cass Avenue
Argonne, IL 60439

Jack Bogert Cooper
PEG Project Staff
Princeton Energy Group
729 Alexander Road
Princeton, NJ 08540

David T. Harrje
PEG Project Staff
Princeton Energy Group
729 Alexander Road
Princeton, NJ 08540

BACKGROUND

The Star Tannery House is a novel passive solar home by One Design, Inc. It is located near Winchester, Virginia. The house employs mass wall and direct gain passive solar concepts, the latter including a clerestory roof aperture which illuminates a masonry north wall. Star Tannery House was conceived as a single family home whose size, spatial organization and appearance would suit the needs and tastes of a very large segment of the U. S. housing market. Passive solar techniques were selected for reliability and low maintenance, with conscious intent on achieving high buyer confidence in the energy aspects of the design.

Star Tannery House is currently occupied by Tim and Maggie Maloney (founders of One Design). It is also used occasionally as a demonstration/model house, and continuously as a test installation. The south-facing wall contains several generations of modular thermal (water) storage tanks which constitute a prototype history of the "Water Wall Module" developed for mass production by One Design. Tim Maloney reported on this work (including experience at the Solar Tannery House, with early performance data) at Philadelphia.¹

Tim Maloney had monitored Star Tannery House using drum-chart recording thermometers and other inexpensive devices. Aware that more sophisticated continuous-recorded data would be valuable and that passive solar monitoring efforts in the East had been sparse, Tim requested instrumentation from the Solar Group at Los Alamos Scientific Laboratory.

An instrumentation package, similar to that installed at the Kelbaugh House in New Jersey, was provided on loan. Princeton Energy Group (PEG) was asked to assist Tim Maloney in design and installation of a monitoring system using this equipment at the Star Tannery House.

DESCRIPTION OF WORK

The instrumentation package supplied by LASL for the purpose of Maloney instrumentation was a standard type which had been previously used with minor variations in passive solar experiments at LASL, and by LASL in passive solar buildings at a number of locations. The system is based on thermocouple and millivolt-readout sensors and a Honeywell "Brown" Electronik Type 153" chart recorder. Electric clock timers control recorder operation on an adjustable cycle. The Brown recorder prints outputs sequentially on a horizontal scale, with a cross symbol and corresponding channel number. With the normal 16 data points and normal timer cycle of one hour, chart advance and length allow about 2 months' data between chart renewal.

Star Tannery House drawings were mailed to PEG by Tim Maloney, with other pertinent building information (backup heat source, DHW heat source, storage component description, etc.) and data acquisition goals.

Preliminary review by PEG project staff (Lindsey, Cooper, Fraker, Harrje) indicated that at least twice the data-point capacity of the equipment supplied by LASL would be needed. Various alternative strategies and data priorities were discussed with Tim Maloney, confirming the opinion that greater capacity would provide much more useful data to Tim and to LASL's passive building monitoring program. Jack Cooper suggested a simple, cheap method for doubling the recorder capacity: introducing a Thermocouple Relay Box (see Fig. 1) to provide automatic switching between two groups of sensors.

Tim Maloney had verified by previous measurements that most of the temperatures of interest changed rather slowly. Switching between two groups of data on a 30-minute time interval was considered to introduce no significant loss in utility of the data. This is easily accomplished by changing dial setting on the timer supplied by LASL, providing hourly reading of each data group. Within the 16-point limitation, data points whose interrelationships require simultaneous reading can be grouped together.

This technique, and the considerations supporting its use in the Star Tannery House system, were discussed with Doug Balcomb and Stan Moore of LASL. PEG was authorized to make the proposed modification to expand the data system. LASL shipped additional thermocouple sensors, wire, connectors, pyranometer, and chart paper requested.

¹Maloney, Tim, "Four Generations of Waterwall Design," Passive Solar State-of-the-Art, Proceedings of the 2nd National Passive Solar Conference, Philadelphia 16-18 March, 1978, pp. 489-492. For additional information on Star Tannery House and One Design's WATER WALL MODULES, contact: ONE DESIGN, INC./Mountain Falls Route/Winchester, VA 22601/703-662-4898

Figure 1 : SCHEMATIC, Instrument Modification by PEG

11-78 JBCooper

1 - 8	Water-wall tanks, West (immersed)
9 - 16	Water-wall tanks, East (immersed)
17	Spare, unassigned
101	Concrete block, North wall, embedded 7 1/4" from inside face of block
102	Concrete block surface, North wall, inside face
103	Inside ground, 4" below slab
104	Inside ground, 28" below slab
105	Outside air (under eave, shaded and well ventilated)
106	Outside ground, 28" below surface, 30' from house
107	Living Room air, top of clerestory space, approx. 9' above floor
108	Living/Dining Room approx. mean radiant, 6' above floor
109	South Bedroom approx. mean radiant, 6' above floor
110	North Bedroom approx. mean radiant, 6' above floor
111 - 114	Water-wall air, between wd. mullion and adjacent tank
115	Inside wall surface, South Bedroom, finish surface of gypsum board
116	Wall surface, water-wall space, unfinished surface of gypsum board
117	Spare, unassigned

Figure 2 : SCHEDULE OF CHANNEL ASSIGNMENT and SENSOR LOCATION DIAGRAMS as installed 13 December 1978 by Princeton Energy Group at Star Tannery House, One Design Inc., Winchester, Virginia

When all required parts and supplies had arrived in Princeton, Jack Cooper fabricated and lab tested modification components with the recorder and timer equipment supplied by LASL. All thermocouples and connectors were assembled, numbered and tested; their readings were found to agree within 0.5°F. The complete system was temporarily assembled and operated for eight hours. The timer showed a slight discrepancy, but was considered to be close enough to allow occasional readjustment in the field. All other components functioned perfectly under lab conditions.

Jack Cooper and Lawrence Lindsey travelled to Winchester, VA on 13 November 1978. The instrumentation plan was modified extensively during the first two days at the site due to several unforeseen factors: construction details not shown on the drawings, reconsideration of wiring and sensor aesthetics, etc. During lengthy discussions with Tim Maloney and his staff, some data priorities were also revised to facilitate useful measurements of recent storage modifications and planned test activities.

Thermocouple wires were cut and bundled at the site and installed according to the listing presented in Figure 2. Cooper and Lindsey spent six days on this first visit to the site. Work proceeded more slowly than anticipated due to the revisions in instrumentation strategy, minor conflicts between sensor installation and water-wall modifications which were simultaneously underway, and mechanical fault in Lindsey's car which had to be repaired. Lindsey and Cooper returned to Princeton on 20 November. The system was substantially complete and operating; however an anomalous reading on channel #11 was left unresolved. Two pyranometers (one supplied by LASL, one by Tim Maloney) had been mounted but not connected due to construction work still underway on the south wall glazing. Tim Maloney and his staff subsequently discovered a reversed polarity in one channel #11 wiring connection, and a problem with recorder chart advance which prevented distinction between data-point groups when reading the charts. Both these problems were corrected by Jerry Hahn of One Design, in communication with Jack Cooper in Princeton.

During the first couple weeks' operation, Tim also reported to Jack an apparent fault in the recorder pen mechanism: the printing head had been observed on a few occasions to vibrate, emitting a loud hum. Tim reported that pen movement during these periods may have been sufficient to produce significant errors in printing. This vibration had not occurred during start-up tests by Cooper, nor had he observed this phenomenon during many years' previous experience with "Brown" recorders. Tim was asked to watch the machine and immediately report any recurrence of this problem.

Lindsey and Cooper returned to Star Tannery House on 13 December 1978 to make a final check of system function. Tim reported that the equipment had been operating continuously. The printer head vibration had not been observed again. Tim had determined against connecting the pyranometers. His consideration was that spot readings of insolation may be fine in New Mexico, but that passing clouds, which are common in the mountains of Virginia, render instantaneous hourly readings almost meaningless. We concur. Tim had purchased and installed an independent digital integrator. Besides providing more meaningful insolation data, this left two extra undedicated channels for use in future experimentation.

Tim had noticed several relationships between recorded data points which seemed to defy common sense, and believed that malfunction might be discovered among the corresponding channels. Suspect circuits were tested, both electronically and by stirred ice-bath immersion of the thermocouple probes, and found to be accurate. Jerry Hahn, Tim's staff engineer, observed these test procedures so that he can repeat them if questionable results appear in the future. At the end of this visit Jack Cooper made a final check of system components and found the system complete and properly operating.

The system was left with sensors located as shown in Figure 2. The four extra thermocouples, thermocouple wire, LASL pyranometer, and shielded cable were left with Tim Maloney for future experiments planned in the south-east bedroom.

OBSERVATIONS AND RECOMMENDATIONS

A number of improvements could be made based on our experience with this instrumentation task. Some expose managerial and logistic issues of a general nature; these observations are rather obvious, but worth mention for benefit of other possible installers of this type of system (and for lab personnel who deal with installers outside their own staff). Other comments deal with our opinions concerning appropriateness of this equipment and technique to LASL Solar Group's goal of obtaining useful passive building performance data.

1. In buildings which are to be occupied it is desirable that instrumentation work occur during the process of construction. Sensor locations and wiring routes may be inaccessible when construction is completed. Equipment installed during construction can be partially concealed, satisfying aesthetic concerns and providing a degree of security from accidental damage or tampering.

Nevertheless, great care should be taken to avoid conflict between construction and instrumentation operations in the same space and time. Coordinating our efforts with the water-wall modification work may have required an extra day at the site. We would not suggest, however, that instrumentation be installed without a representative of the owner (and construction personnel) present. Their knowledge of building details and use patterns is an indispensable aid to our work; their observation of our work is equally valuable in assuring subsequent protection and maintenance of the data system.

2. Two trips to site are desirable in even the simplest building instrumentation task. We approached this job intending to complete it in one site visit; we feel it could have been completed more efficiently with two trips as an initial planning assumption.

The first trip should be a reconnaissance mission with these objectives:

- a. the same persons who will perform system design and installation examine every relevant detail of the building;
- b. occupants are familiarized with the appearance and functional requirements of sensors and related equipment; final sensor and recorder locations, and wiring routes, are agreed upon with builder and occupants;
- c. measure wiring routes; this allows precutting and bundling in the lab, which is definitely preferable;
- d. clearly arrange schedule, coordination and support required for the subsequent installation trip, with both construction personnel and owner/occupant.

The second trip is to install the equipment, operate and test the system. It is recognized that last-minute changes or unforeseen problems inevitably occur in the field, and that time, tools and equipment must be planned with this possibility in mind.

3. Start-up anomalies or malfunctions are nearly inevitable regardless of skill and care applied to the installation. These problems usually appear in the first week or two of operation, but are not always manifest in initial startup and function tests. Unless the installer's home base is very near the site, teach an owner or occupant (preferably, the same person who has observed installation) about the system, its components and normal operation. This person would be designated to identify a malfunction, contact the installer, and clearly describe it by phone.

This arrangement worked beautifully in the case of our installation at the Star Tannery House, and we expect on-site knowledge of the system will minimize breaks in the flow of meaningful data from this project.

4. Clear provision should be made for ongoing maintenance on a contingency basis; our contract with LASL contains no such arrangement in connection with the Star Tannery House instrument package. Occasional scheduled inspection/testing of the equipment would be valuable, as well.
5. Clear provisions should be made for prompt analysis and feedback of data. Designers, builders, or owners/occupants always need quick feedback of data in usable form. When we first operated the Brown recorder at Star Tannery, Tim Maloney was sorely disappointed upon seeing its chart output. The drum pen recorders he had been using, despite their limited applicability and capacity, had an important advantage: their output was quickly available and could be understood visually. Tim reports that he has hired part-time assistants to translate the Honeywell chart outputs, as soon as the roll comes off the recorder, into graphic form. In this case, and typically, the data is used immediately as input to further design and experimentation. In our opinion the sponsoring agency should institutionalize a service (by its own staff or subcontract) which would rapidly process interpretation of these charts on a regular basis.

6. LASL's passive solar building monitoring program can benefit from Tim Maloney's thoughts regarding appropriate insolation measurements. In general, as the program moves outside predominantly sunny climates, this problem with instantaneous hourly readings should be recognized. We regard Tim's solution as effective, cheap, and good. Some other strategy which provided regular hard copy record of integrated data would be better.
7. When selecting building sites, passive solar enthusiasts notoriously fail to locate adjacent to recording weather stations. Many, like Tim Maloney, choose locations with special localized weather patterns which are believed to differ radically from those recorded at Weather Bureau stations in their region. The data acquisition system at Star Tannery House records very little ambient weather information. A minimal weather station, such as provided by LASL in the Kelbaugh House system, ought to be supplied whenever possible.
8. When possible, thermographic scanning and infiltration tests should be included in LASL's monitoring program. Tim Maloney has had thermographic scans performed at Star Tannery House, prior to the latest water-wall modification. Infiltration tests could reasonably be performed at the time of instrument installation; for a low cost procedure we recommend the blower door method, developed by Dave Harrje, which has been used very effectively in the residential energy research at Princeton University's Center for Environmental Studies. Such tests greatly facilitate building performance evaluation. They could also elucidate causes of strange data, and help limit variables in experimental work.

CONCLUSIONS

We applaud LASL's effort in passive building monitoring, which, as we understand it, converts stray or idle equipment into valuable project data. We are aware that re-use of instruments like the Brown recorder installed in this project may be a relatively inexpensive means to obtain useful passive solar building data. Our work shows that at least double the recorder's data point capacity can be obtained easily. Added expense for system expansion is minimal; it consists mainly in the cost of installing the additional sensors.

Installation of an expanded LASL monitoring package was accomplished smoothly. Future work of this type could be done by other private contractors with even greater ease and economy. The comments and suggestions presented above include opinions, based on our experience, concerning how this process can be improved.

Many passive buildings besides the Star Tannery House now exist outside the Southwest. They offer excellent opportunities for acquiring important data, and much experimental work is being done by organizations which cannot afford, and/or cannot specify and install, good monitoring systems.

The approach used by LASL Solar Group to obtain passive building performance data seems more effective and less costly than the larger-scale solar building monitoring efforts with which we are familiar. With a few improvements suggested in this report, LASL's monitoring program could be a very important source of information from more diverse climatic regions. We strongly urge that U. S. DOE expand the LASL passive building monitoring program, using qualified regional subcontractors for system installation and maintenance.