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**SOLAR HOUSE HEATING SYSTEM USING REFLECTIVE
PYRAMID OPTICAL CONDENSING SYSTEM**

Evaluation of Performance, June 1, 1975—December 31, 1976

January 1978
(TIC Issuance Date)

MASTER

Work Performed Under Contract No. EY-76-C-02-2769

Wormser Scientific Corporation
Stamford, Connecticut

U.S. Department of Energy

Solar Energy

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1. Introduction and Abstract

Introduction:

Wormser Scientific Corporation (WSC) received Contract E(11-1)2769 in June, 1975, to "evaluate solar energy heating and cooling systems employing a pyramidal optics solar collection system."

The Pyramidal Optics low gain optical concentrating system concept has a number of promising advantages. The principal ones are as follows:

1) The simple relatively low cost and low gain optical concentrating system reduces the amount of flat plate receivers required by a factor of three to four. This results in a significant reduction in cost for the flat plate receivers and their associated piping, reduction in use of strategic materials and reduction in weight of the solar system.

2) The system can be integrated into a roof and attic structure of conventional design and appearance.

3) By placing the flat plate collectors inside the attic of the structure, they are protected from rain, ice, snow, and dirt, and open unglazed receivers may be used. By reducing the receiver area by a factor of three to four, the temperature rise is increased by the net optical gain, which is approximately 3X in winter while the heat losses are reduced proportional to the receiver area reduction or a factor of three to four resulting in improved efficiency at higher tank and receiver temperatures with respect to outside ambient temperatures.

The objective of the contract was to evaluate the conceptual advantages of the Pyramidal Optics system in realistic settings.

Abstract

The evaluation program under this contract went through a number of phases.

First, the prototype system, previously built on Westover Road, Stamford, Connecticut, was upgraded, instrumented, and evaluated. It was found to perform essentially as expected, but the open construction shown below was found to have problems.

A fully enclosed model Pyramidal Optics house was built by Better Homes of Delaware near Rehoboth, Delaware. The solar system was instrumented as described.

After a number of significant improvements were made in the optical concentrating system and the flat plate receiver assembly, the system was monitored throughout the winter of 1976/1977 and found to perform very well. The solar contribution to heating amounted to 70 percent during the severe winter months and is expected to exceed 80 percent throughout the year.

The Pyramidal Optics system has been found to have a number of economic and operational advantages.

It is planned to evaluate additional systems in other locations and different climatic conditions.

2. Principle of Operation of the Pyramidal Optics System

The Pyramidal Optics System is a low gain concentrating system, collecting sunlight from a relatively large aperture and focusing it onto an absorber surface one-fourth the size of the entrance aperture. This is accomplished by the use of flat mirror surfaces as shown in a building cross section, Figure 1. The sun enters the "solar window" which is part of the south slope of the roof, Figure 2. Flat reflective panels cover the inside north attic slope of the roof and the floor of the attic space. The absorber panels are positioned near the intersection of the floor reflectors and the north roof slope reflector, Figure 3. At this location, if the system is properly designed, the absorbers receive all the solar energy funneled in from the solar window. The reflector surfaces describe a truncated pyramid with the absorber near the apex or focus of the pyramid, thus the name "Pyramidal Optics."

In order to maintain energy collection as the sun moves through its seasonal path, a portion of the floor reflector is hinged and is elevated to follow the solar altitude from a slope of 10° at the winter solstice to a slope of 40° at the summer solstice for 40° latitude.

The absorber panels are selectively coated, copper Rollbond through which the heat transfer fluid, pure water, is circulated. Circulation to the absorber panels occurs when a sensor on the panels detects that the absorber temperature is ten degrees higher than the tank temperature and, therefore, that heat is available for collecting. Circulation continues until the plate temperature falls to within two degrees of the tank temperature, whereupon circulation ceases. The water then drains back to the tank, providing freeze protection.

DELAWARE HOUSE FIG 1

WINTER APERTURE: $10' \times 10' = 100 \text{ FT}^2$
 COLLECTOR: $3' \times 8' = 24 \text{ FT}^2$
 GEOM. GAIN: 4.16
 NET GAIN: 3.33
 NET APERTURE: 80 FT^2

PYRAMIDAL OPTICAL SYSTEM - WITH WINDOW

DELAWARE P.O. SOLAR HOUSE

Fig. 2

DELAWARE SOLAR HOUSE
SCALE: 1/8" = 1'-0"

FIG. 3

3. Evaluation and Improvement of Pyramidal Optics Solar System

Work under this contract fell into two phases: a) Westover Road, Stamford, Connecticut, Instrumentation and evaluation of open prototype, and b) Instrumentation, evaluation, and improvement of fully enclosed full-sized unit located near Rehoboth Beach, Delaware.

a) Westover Road Prototype

At the residence of the inventor of the concept, Gerald Falbel, on Westover Road in Stamford, Connecticut, a first prototype of the system had been constructed prior to start of the contract to verify the design expectations. Under this contract a second focusing system was installed adjacent to the first unit, Figure 4. This used a 22 x 96" selectively coated, copper RollBond absorber plate with a horizontal flow pattern.

The new focusing system used the existing 5' x 24' open moving reflective flap, Figure 5 and 6.

An unfocused, standard flat plate collector was installed on the adjacent roof of the structure to provide comparative data. An improved temperature and insolation data logging system was installed which permitted recording these parameters on a continuing basis. Insolation level was measured by an Eppley total radiation pyranometer, temperature differentials were measured by ten junction, copper constantan thermopiles and absolute temperature measurements were made with Fenwall thermistor sensors. Fluid flow was measured with Bell and Gossett circuit setters, having a variable orifice, on either side of which pressure could be measured. Electrical signals from the sensors were fed into a Honeywell 20-channel analog chart recorder. The recorder operation was controlled by a 24 hour time clock, commencing recording just before sunrise and stopping just after sunset.

PYRAMIDAL OPTICS PROTOTYPE NO. 2

FIG. 4

(SECTION VIEW)

PYRAMIDAL OPTICS TEST HOUSE · OPEN

CLOSED

Fig. 6

An electro-mechanical control was developed for positioning the moving flap automatically. Testing with these improved facilities bore out previous concept hypotheses. At equal flow rates through focused and unfocused absorbers, temperature rise across the focused unit was approximately three times that of the unfocused unit, indicating a three-fold energy concentration at the focused unit, Figure 7. This was in line with expectations, in that after reflective losses were deducted, the net geometrical gain of the focused unit was three times that of the unfocused unit.

b) Problems Encountered with Westover Road Prototype

During the prototype testing at Westover Road the problem of weathering became apparent. With the system being open and exposed to moisture, temperature fluctuations and debris from trees, the optical concentrating system was subject to possible deterioration. In addition, moving and closing a relatively large and heavy waterproof reflective panel posed mechanical problems. To overcome the disadvantages of the original pyramidal optics system using an open moving flap, E. M. Wormser conceived of a fully enclosed optical design, Figure 2, using a stationary "solar window" and placing the entire optical concentrating assembly including a lightweight moving reflector inside the fully sealed enclosure.

FIG. 7 WESTOVER DATA

HEAT PUMP C.O.P.

FIG. 8

c) Delaware Fully Enclosed Model

The Better Homes Corporation of Delaware in cooperation with Wormser Scientific Corporation constructed a 1,400 sq. ft. Pyramidal Optics model ranch house on the eastern shore of Delaware, Figures 2 and 3, using private funds prior to obtaining this contract. In this house the Pyramidal Optics system is fully enclosed behind a window, which makes up the southern roof surface, Figures 9 and 10. This greatly reduces maintenance and deterioration problems as well as permitting the use of interior materials in the construction of the optical system.

FIG. 9

DELAWARE SOLAR HOUSE

SECTION THRU PYRAMIDAL OPTICS SOLAR SYSTEM

MOVING REFLECTOR IN WINTER POSITION - 10°

SCALE: $3/8" = 1' 0"$

Fig. 10 WINDOW CONSTRUCTION

4. Description of Delaware Fully Enclosed Pyramidal Optics Model

a) General Description

The Delaware Pyramidal Optics system is composed of three major subsystems :

- The Collecting Subsystem (support framing, solar window, reflectors, absorber plates, collector pump and piping, and differential controller)
- The Storage System (water storage tank and insulation)
- The Distribution Subsystem (distribution pumps, direct solar coil, heat pump, electric backup, domestic hot water preheat coil, and control components)

The materials used in each subsystem are as follows:

ITEM	DESCRIPTION
Window Support Framing	4" x 6" rafters @ 32" on center
Solar Window	1/8" Plexiglass reinforced with nylon straps
Reflectors	Aluminized mylar factory laminated to 1" urethane board panels
Absorber Plates	22" x 47" selectively coated, copper RollBond
Collector Pump	Marlowe self-priming, 1/4HP
Collector Piping	Reverse return, 1" copper with valving to equalize flow in all collectors
Piping Insulation	3/4" Armaflex
Differential Controller	RHO Sigma
Storage System Tank	Precast concrete with EPDM Water proofing bladder
Storage Tank Insulation	Sprayed on polyurethane 3"
Distribution Pumps	Marlowe self-priming 1/4HP
Direct Solar Coil	Trane, 6 row with turbulators
Heat Pump	Dual Source water to air and air to air 27,000 BTUH, Joint Development of Friedrich Division of Weillayn and WSC

Item	Description
Electric Backup	Duct heaters by INDEECO
Domestic Water Preheating	Submerged galvanized preheat tank, 40 gal.
Domestic Water Tank	42 gallon electric booster set at 125°F
Controls	Temperature sensors, relays and controls by Penn, Division of Johnson Controls

The collecting system operates in the following manner: Sun enters the south solar window and is focused on the absorber panels by the flat mirror optical concentrating Pyramidal Optical system. The concentration of rays in the horizontal and vertical planes are shown in Figures 11 and 14. Near the winter solstice (December 21) the solar rays make an azimuth angle of 42° East of South at 9 A.M. solar time and a similar angle West of South at 3 P.M. solar time. In the morning part of the rays are directly incident on the western end of the collector array, while others are incident on the collector array after one reflection from the side walls. At noon all the rays are directly incident on the collector array in the horizontal plane. In the afternoon the rays are incident on the eastern part of the array in a manner symmetrical to the morning performance. Several day long performance curves for the Pyramidal Optics system are given in Figures 12 and 13.

Performance in the vertical plane is shown in Figure 14 for solar rays at noon at the winter solstice, December 21, when the rays are 26° above the horizontal for, the equinox, March 21, and September 21 when the rays are 49° above the horizontal and for the summer solstice at June 21 when the rays are 74° above the horizontal.

The variation of optical effective gain in the vertical plane on a seasonal basis is also shown in this figure.

FIG. 11

HORIZONTAL REFLECTIONS

(PLAN VIEW)

9am Sun
Azimuth 42°
Dec.

Noon Sun

3pm Sun
Azimuth 42°
Dec.

Typical Daylong Performance

Delaware Pyramidal Optics Ray Diagram

Gross Window Width - 34.7 Ft.
 Net Window Width (rafters deleted) - 31.4 Ft.
 Receiver Area - 136.4 Ft.

Month Window Aperture Geometrical Gain

Dec.	382	2.80
Jan.	353	2.58
Feb.	302	2.21
Mar.	270	1.98
Apr.	141	1.03
May	130	0.95
June	173	1.27

Fig. 14 Vertical Reflections

The lower tracking reflective flap is moved at a slow rate by a small motor mechanism to compensate for seasonal altitude changes of the sun, as shown in Figure 9. Water is circulated through the absorber panels when their temperature is 10° above the tank temperature. Water is pumped up from the tank and circulated through the absorber in a reverse return pattern. The water flow rate is 6.4 GPM or 0.34 GPM per receiver.

The nineteen 22" wide by 48" high copper RollBond absorber plates are connected essentially in parallel as shown in the flow diagram, Figure 15, with collector water supplied from a manifold at the bottom and warmer water returned by a manifold at the top. If the absorbers were connected in parallel without any special valving, flow at the center of the 19 element array would be considerably less than at the two ends.* In order to equalize flow, the array has been divided into three sections and valves are used as shown in the flow diagram, Figure 15, to equalize the flow in the three sections.

This circulation continues until the plate temperature falls to within two degrees of the tank temperature. Drain down around the pump check valves is arranged by a normally-open solenoid on a bypass line. In the event of any electrical failure, this valve would move to its normally-open position, resulting in drainage. The control system is shown in schematic form, Figure 16.

Storage

The storage tank is fabricated from a 850 gallon precast concrete septic tank. A rubber tank liner was added to provide waterproofing. A sprayed-on 3" layer of urethane foam was applied over the outside of the tank for insulation. The domestic hot water preheat is provided by a forty gallon galvanized steel tank suspended in the main tank. The concrete of the tank contributes to the storage system heat capacity so that its specific heat

* Duffie and Beckman, Solar Energy Thermal Processes, John Wiley, 1974, pp. 261-264.

DELAWARE PYRAMIDAL FLOW SCHEMATIC

FIG.15

WORMER SCIENTIFIC CORPORATION

FIG.16 CONTROL DIAGRAM
DELAWARE SOLAR HOUSE

is:

	Volume x Specific Gravity x Specific Heat	=	Heat Capacity
Water	850gal x 8.34lbs/gal x 1BTU/lb/°F	=	7,089
Concrete	39ft ³ x 150lbs/ft ³ x 0.28BTU/lb/°F	=	1,174
TOTAL		=	8,263 BTU/°F

With a useful tank temperature differential of 100°F, this represents 800,000 BTU's of storage or enough heat to maintain the house temperature during three successive cloudy cold, winter days.

In order to minimize energy consumption through heat losses in winter and heat gains in summer, the following special energy conservation features were incorporated in the Delaware home.

The exterior wall insulation consists of 3½" of foil faced fiberglass batts (R=11) augmented by ¾" of styrofoam rigid sheet (R=3) on the outside which minimizes infiltration in addition to improving insulation.

The ceiling has 10" of loose rockwool (R=30) while the floor area has 4" of fiberglass (R=12) over a crawl space.

The windows are dual glazed throughout. The exterior doors are metal with urethane cores.

Heat loss estimates were made independently by three professional engineers resulting in a heat loss estimate of 32,000 BTU/hr ± 2,000 BTU/hr for 0°F outside temperature and 68°F inside temperature.

Usual construction procedures call for far less insulating material, typically 3 inches in the walls, 6 inches in the ceiling with limited use of insulated sheathing or glazing. The increased insulation reduces the heat losses from the structure by approximately one-half. This amount of heat saved reduces the solar equipment requirement by many times the investment

in insulation and dual glazing.

In order to accomodate the solar collection system, the height of the attic was increased to $10\frac{1}{2}'$ at the center using 10/12 (or 40°) slopes on the attic side walls.

An oversize utility room $14' \times 16'$ was added to the house to accomodate the storage tank for the solar system, in addition to space for laundry equipment, the auxiliary heat pump system, the hot water tank, as well as space for monitoring and recording equipment.

Delaware House Heat Loss Calculations

"U" Values

WALL

Outside Air	0.17
5/8" plywood	0.77
3/4" beadboard	2.68
3 1/2" R-11	11.00
1/2" gypsum	0.45
inside air	0.68
R =	15.75
U =	0.063

CEILING

Inside air	0.61
1/2" gypsum	0.45
10" R-30	30.00
Outside air	0.61
R =	31.67
U =	0.032

ATTIC ROOF

Inside Air	0.62
1/2" gypsum	0.45
5 1/2" mineral wool	18.00
1/2" plywood	0.62
shingles	0.44
outside air	0.17
R =	20.30
U =	0.049

FLOOR

Outside Air	0.25
3 1/2" R-11	11.00
3/4" air space	1.01
1/2" subfloor	0.62
1/2" finish floor	0.62
carpet and pad	1.23
inside air	0.92
R =	15.65
U =	0.064

WINDOWS

3/16" double glazing	
U =	0.69

DOORS

Urethane filled	
U =	0.40

ATTIC END WALL

Outside Air	0.17
5/8" Plywood	0.77
3/4" beadboard	2.68
3 1/2" R-11	11.00
inside air	0.68
R =	15.30
U =	0.065

Heat Loss Continued

SURFACE AREAS

Window	142 sq.ft.
wall	1104
floor	1040
main door	40
ceiling	1264
utility slab	
perimeter	60
den ceiling in	
attic	442
end wall in den	130
Building volume	11776 cubic feet

DESIGN CONDITIONS

Outside temperature = 15°F 97½ ASHRAE
 Inside 68°F
 T 53°F

Wall	(.063)(1104)(53) =	3686
floor	(.064)(1040)(53) =	3472
windows	(.69)(142)(53) =	5192
main door	(.40)(40)(53) =	848
ceiling	(.032)(1264)(28) =	1133
den ceiling	(.049)(442)(53) =	1147
end wall	(.065)(130)(53) =	448
Sensible Heat Subtotal		15926

INFILTRATION $H = 0.018$ (air volume)(air changes) T
 1.3 air changes/hr
 = (0.018)(11776)(1.3)(53)
 = 14600

TOTAL HEAT LOSS AT DESIGN CONDITIONS

15926 BTUH conduction loss
14600 BTUH infiltration loss
<u>30500 BTUH total for building</u>

The measured losses from the building are about 25 percent lower than calculations would indicate (9400 v.s. 13,800 BTU/degree day). This is mainly attributable to reduced losses due to infiltration as a result of exceptionally tight construction and very thorough and meticulous application of insulation by the builder, the Better Homes Company of Delaware. The single occupant of the house used the entrances less than would a normal family, further reducing infiltration.

b) Heat Distribution and Auxiliary System

Domestic Hot Water System

Domestic hot water is preheated in a submerged tank within the solar tank, Figure 5. Incoming well water is piped to this tank where it is held until the occupant uses water. The normal hot water heater is fed from this holding tank. When the solar tank temperature is low, the hot water heater electric coil adds additional energy as required to bring the water up to use temperature, 125°F.

As discussed further below, the method of using a 40 gallon tank as a solar preheat heat exchanger was not found to be satisfactory and extended coils of copper tubing immersed in the solar storage tank have been used in subsequent installations to provide a larger heat exchange surface. It is planned to retrofit a copper coil heat exchanger for the immersed tank.

Heating, Distribution, and Auxiliary Systems

Very careful attention has been given to the heating distribution, auxiliary and storage system. Next to optimizing the day long efficiency of the solar collection system, the design of the storage system, the distribution and auxiliary systems have the greatest influence on the overall efficiency of the solar system in providing heating energy to the building.

A storage tank of medium size (2 gallons per square foot aperture) was selected which results in median storage tank temperatures of 105°F and a temperature range from 80°F to 140°F for moderate heating requirements October, November, March, and April. (See Charts 20-24 for measured fluctuation of storage tank temperature.)

As discussed and documented further below, during these months of moderate heating requirements, a large portion of the heating is supplied by the solar heated storage via the direct "solar coil" (Figure 15) mounted in the duct plenum of the oversized hot air distribution system.

The auxiliary unit provided for this system is a dual source heat pump which was developed jointly by the Friedrich Division of Weillayn and WSC for this application.

The heat pump is a dual mode water-to-air and air-to-air heat pump. If storage tank temperature is between 80°F and 40°F, the heat pump is used in the water-to-air mode to provide hot air for heating at above 90°F. The system has a C.O.P. of between 3.0 and 2.2 resulting in solar utilization between 66 percent and 55 percent. Figure 8.

For cooling operation the heat pump is used in the air-to-air mode. It is also used in the air-to-air mode if water temperature drops below 40°F. The different operating modes are described further below.

Throughout the year as the heat load of the building and the input from the solar collection system vary greatly, the temperature of the solar storage tank fluctuates widely from a maximum around 150°F to a minimum near 40°F.

In order to provide for maximum utilization of stored solar energy over this wide storage temperature range, four modes of heat distribution and use of auxiliary energy have been provided. When the building thermostat calls for heat, the control system is activated and decides which mode of operation will provide the most efficient heating.

Mode 1

When the solar storage tank is above 80°F, space heating can be accomplished directly. When the house thermostat calls for heat, the hot tank water is circulated to the direct "solar coil" water-to-air heat exchanger located in the supply air duct. The blower of the heat pump is made to circulate the air to the living space. After passing through the solar coil, the cool water is returned to the bottom of the storage tank for reheating.

In this mode, heating is supplied 100 percent by solar minus water pump and blower energy which are relatively small.

Mode 2

If the temperature of the solar storage tank is between 40 and 80°F, the solar water cannot be used directly to produce warm air for space heating. This water, however, still contains considerable heat energy which can be utilized by means of the heat pump. Through its freon compression cycle the water-to-air heat pump extracts heat from the solar water and warms the building air supply. Between 40° and 80°F, the heat pump operates at C.O.P.'s of from 2.2 to 2.9. In this range the heating is 55 to 66 percent solar energy supplied.

Mode 3

When the solar storage tank temperature falls below 40°, little more energy can be withdrawn before ice crystals begin to form on the condenser coil. At present if the outside temperature is above 40°F, the heat pump will switch to the air heat exchanger located out-of-doors and operate in an air-to-air mode. Through use of suction accumulators and provision of defrost cycles this air-to-air mode of the heat pump will be extended to an outside ambient temperature of 0°F.

Mode 4

When the water temperature is too low to provide heat energy (below 40°F) and the outside air temperature is below 40°F, at present, the controls activate the backup electric elements located in the air duct. These resistance elements provide heat capacity to maintain comfort conditions during the rare periods of extended overcast and low outdoor temperature, or if there is a malfunction in the solar or heat pump system.

FIG17

DELAWARE INSTRUMENTATION PLAN

5. INSTRUMENTATION

An instrumentation system was designed to document the performance of the solar system. It consists of 20 channels of information provided by sensors that are recorded on an analog recorder which operates for ten daylight hours each day.

Sensor locations are marked on Figure 17, which is a schematic drawing of the Pyramidal Optics, the collector array, the auxiliary system, and the solar system fluid transport system. Channels 1 through 4 are thermistors monitoring the output temperature of the collectors. Channel 1 is attached to the top of absorber plate #2 near the western extreme of the collector array. Channel 2 monitors absorber plate #10 in the central section, channel 3 is affixed to absorber plate #19 at the eastern section, and channel 4 reads the temperature on the fluid output header, or a combined temperature for the whole collector array. Channels 5 and 6 monitor the attic air temperature with locations 12 inches from the floor in the middle of the attic and six feet from the floor immediately behind the glazing, respectively.

Location 7 reports the temperature in the duct supplying heating and cooling to the home, downstream from both the solar coil and the resistance heater. The temperature of the water leaving the heat pump is recorded on channel 9. (Channels 8, 10, and 14 are presently not used.) Channel 11 monitors the air temperature outside the building from a north-facing window-sill outside the mechanical room. A thermistor connected to channel 12 reports the temperature of the water in the storage tank. A pyranometer recording the intensity of solar radiation in the plane of the window entrance aperture at 40° to the horizontal is attached to the roof immediately

below the skylight and wired to channel 13.

Thermopiles are used for differential temperature measurement at locations 15 through 20. Temperature differences across the western, central, and eastern collector plates used in the absolute thermistor measurements are recorded at locations 15, 16, and 17, respectively. A temperature difference across all the collectors is provided by sensor 18, which is a thermopile across the inlet and outlet headers. Location 19 is a thermopile across the heat pump fluid input and output pipes, and 20 is a thermopile across the input and output of the water-to-air heat exchanger of the direct solar coil.

Samples of output of the analog recorded are shown in Figures 18 and 19, which are records of the insolation and thermal performance of the system for a clear and a cloudy day.

A clear cold day, December 5, 1976, is indicated on Figure 18 by the smooth curve of the pyranometer record (channel 13) and a steady rise of 23°F in storage tank temperature occurs from 64°F to 87°F . Channel 18 measures the temperature difference between inlet and outlet of the collector array. Its smooth curve follows the solar energy input recorded by the pyranometer.

High temperatures recorded by the thermopile at location 16 and the thermistor at location 2 indicate differences in flowrate through the eastern, central, and western collector sections. These flow differences were compensated for in January by the addition of regulating valves as shown in Figure 15, which permit control and equalization of flow rates in different sections of the collector array. The delayed rise of temperature in the eastern collector section (channel 17) and the early decrease of temperature in the western collector section (channel 15) reflect the diurnal solar movement from east to west and the corresponding illumination of various collector sections as

Fig. 18

Fig. 19

shown in Figure 11. The transition from heat pump to solar coil as the heating source at approximately 2:00 P.M. demonstrates that the change occurs at a storage tank temperature of around 80°F, in this case 79°F.

The twenty channel analog recording system provides an essentially continuous daylong record of the performance of various portions of the solar system. The information contained in the analog recording is very complete and highly information. Two problems have been encountered with the analog recording system.

The first and most serious is that complete analysis of the analog recording is very time consuming. The second is that the paper strip type analog recorder is subject to breakdown and stoppages which result in gaps in the recorded information as shown.

The twenty channel solar system instrumentation system has been supplemented by a five channel electrical energy consumption measuring system (described further below) which has been installed and is being computer analyzed on an hour-by-hour basis by the Delmarva Electric Power Company. This electrical power measuring system, furnished by Delmarva, enables us to provide complete energy balance data for this all-electric house, and further, since the data is recorded and analyzed by an independent third party, it lends authenticity and impartiality to the data.

FIG. 20

Temperature History OCTOBER '76

FIG 21

Temperature History NOVEMBER '76

FIG. 22

Temperature History DECEMBER '76

FIG. 23

Temperature History JANUARY '77

FIG. 24
Temperature History
FEBRUARY '77

TABLE 1

NUMBER OF FULL DAYS IN EACH HEATING MODE

<u>Month</u>	<u>No. of Days on Record</u>	<u>No. Days Direct</u>	<u>% Direct</u>	<u>No. Days H.P.</u>	<u>% H.P.</u>	<u>No. Days Resistance</u>	<u>% Resistance</u>
Sept.	8	8	100	0	0	0	0
Oct.	22	16	73	6	27	0	0
Nov.	27	17	63	10	37	0	0
Dec.	25	0	0	24	96	1	4
Jan.	15	0	0	15	100	0	0
Feb.	17	7	41	10	59	0	0

6. CURRENT SYSTEM PERFORMANCE

Information supplied by the instrumentation system furnishes the data for an hour-by-hour, day-by-day, and monthly computation of system performance. Peak efficiency near noon, and average daylong efficiency have been computed and are tabulated in Table 2.

An estimate of the losses occurring in various parts of the system is presented in Figure 27. It is estimated that at noon for a ΔT near 75°F , 52 percent of the incident solar energy is delivered by the solar collection system. In Figure 26 the noon time peak efficiencies range from a low of 42 percent to a high of 50 percent for fluid parameters between 0.1 and 0.3, which is in line with the loss estimates given in Figure 27.

The daylong efficiencies range from 45 percent to 30 percent for sunny days and from 39 percent to 30 percent for overcast days.

An important finding is that the daylong efficiency for overcast conditions approaches the efficiency for sunny days. The optical system has a field of view for diffuse radiation inversely proportional to the concentration ratio.

For comparison, the peak instantaneous efficiency of a good quality selectively coated flat plate is given, Figure 26.

On a sunny, cold (25°F) December day during daylight hours the solar energy is collected by the collector array and transferred to the storage tank as shown in Figure 18. The storage tank temperature rises 23°F representing a transfer of $23^{\circ}\text{F} \times 8,263^{\circ}\text{BTU}/^{\circ}\text{F} = 190,050 \text{ BTU}$ to the tank.

With an outside temperature at 25°F approximately 50,000 BTU were used for direct solar 2 P.M. to 4 P.M. and solar heat pump heating 8 A.M. to 2 P.M. from sunrise to sunset.

TABLE 2
System Efficiencies

DATE	Daylong Efficiency (%)	ΔT ($T_{plate} - T_{amb}$)	$\frac{T_{fluid} - T_{amb}}{Q_{incident}}$ % BTU/Ft ² -hr	Peak Instantaneous Efficiency (%)
10- 3-76	33	11	.03	50
11-13-76	37	35	.12	44
11-14-76	41	40	.14	48
11-16-76	41	35	.13	48
11-18-76	38	31	.11	48
11-20-76	39	47	.16	46
11-25-76 (partly cloudy)	27	34	.16	50 (clear period)
12- 1-76	36	52	.18	45
12- 3-76	37	66	.23	46
12- 4-76	41	34	.13	46
12- 5-76	40	48	.17	44
12-16-76	37	32	.12	49
1-11-77	35	31	.11	47
1-26-77	45	22	.07	46
<hr/>				
Good Quality selective flat plate, not including fluid transport losses	47 27	75 120	.25 .40	50 32

$$\text{Efficiency} = 49.1 - 16.3 \frac{\Delta T}{Q_{incident}}$$

Fig. 26
DELAWARE PYRAMIDAL OPTICS

FIG. 27

Energy Attrition Model

However, a high percentage of 250,000 BTU (80 percent) of the total solar energy collected was transferred to storage.

a) Monthly Plots

One of the most meaningful day-to-day indicators of system performance is storage tank temperature. This quantity as well as the outside air temperature have been plotted against time for the months of September, October, November, December, January, and February of the 1976-77 heating season. These graphs (Figures 20-24) include daily relative solar intensity by the addition of circles of different size below the day of the month on the horizontal axis. The pyranometer record was used to measure the intensity of solar radiation, with each day being assigned a rating between one and five. One represented a completely overcast day and is shown by the smallest circle, while five, a day of practically uninterrupted sunshine, is depicted by the largest circle.

Much may be inferred about the system performance from this plot of solar intensity, tank, and ambient temperature. Weekly cycles of clear and cloudy weather are reflected by tank temperature changes. In addition, the time that the system was in each of the three operating modes may be deduced from the amount of time spent above and below the temperature cutoff transition points.

Eighty degrees Fahrenheit marks the transition from heat pump operation to direct solar heating. When the storage tank is in the range 42° - 80° F, (50° F prior to Jan.), the home is heated by the heat pump, and when the storage temperature falls below 42° F, auxiliary electric resistance heating is used. Using these transition temperatures, the number of days spent in each mode has been found, and is tabulated in Table 1. It can be seen that direct solar heating predominates during the fall months of September, October, and November, while the heat pump provides the biggest fraction of the heat.

required by the building during December, January, and February.

Practically all the electric resistance heating used during the 76-77 severe winter heating season was used during periods of system malfunction, repair, or modification.

b) Efficiency Calculations

To permit comparison of the Pyramidal Optics solar system with other designs, efficiency calculations have been made. Efficiency is defined as the ratio of heat energy delivered to storage and available for house and hot water heating to the solar energy incident on the net optical aperture for the particular operating month, since this quantity varies throughout the year as shown in Figure 14. Several days have been analyzed for each month of the heating season.

Table 2 lists the efficiencies that have been calculated. Instantaneous noontime efficiencies are seen to lie between 42 percent and 50 percent, while daylong efficiencies of 35 percent to 45 percent prevail. Two methods of calculating the system efficiency are used. The method and merits of each are discussed in the Appendix.

To permit the prediction of system efficiency, an energy attrition model was constructed (Figure 27) which accounted for energy losses at the various system interfaces. Transmission losses at the glazing, reflective losses at the mirror surfaces, absorptive loss at the Rollbond receiver, as well as convective, conductive, and radiative heat losses from the plate were considered. Figure 28 shows how this predicted efficiency compares to the measured performance of the system after the former is corrected for diurnal geometrical and optical reductions.

c) Energy Consumption

The evaluation of energy balance for the Delaware P.O. solar home has been made possible by the assistance of the local electric utility, Delmarva

FIG. 28

Observed vs Predicted

Power Company of Salisbury, Maryland. Delmarva Power has furnished five magnetically recording watt meters for the house and has provided hour-by-hour computer analysis of these meters monthly. These monitor the five major power consuming segments of the home, which are:

1. The total electric consumption of the building.
2. Power consumption of the heat pump, including its blower.
3. The electricity used to operate the water pumps and solar system controls.
4. The current used by the auxiliary resistance heaters.
5. The power consumption of the electric booster heat in the domestic hot water tank.

Original data from the first two of these segments is shown in Figures 29 and 30. Figure 29 shows the electric consumption of the entire building for the interval, November 15-22. The date is shown in the left margin and the time from left to right across the page. The amounts displayed are the number of kilowatt hours consumed in a one hour period. On Figure 30 the record for the heat pump, the difference in consumption clearly marks the times when only the fan was operating as opposed to the entire heat pump.

The record provided by these meters has enabled us to compute an energy balance for the home. An example of this for a clear day is shown in Figure 31, an energy breakdown of November 6, 1976. The type of energy distribution that prevails on a cloudy day is shown on Figure 32, for December 10, 1976. It can be seen that on a clear day the solar contribution to space heating is about 91 percent while on a cloudy day that percentage drops to 56 percent.

Energy consumption on a monthly basis has also been computed. Figures 33, 34, and 35 show this consumption for the months of October, November, and December, 1976.

DATE	TIME	1	2	3	4	5	6	7	8	9	10	11	12
11 15 76 MON	AM KW	.62	2.02	1.69	1.33	1.67	1.74	1.59	1.98	2.90	1.52	1.59	1.52
	PM KW	1.36	1.49	1.15	1.89	1.71	1.25	1.36	2.91	2.23	3.67	1.38	1.13
	DAILY LOAD FACTOR	.474		HIGH KW		3.67		HIGH KVA					
11 16 76 TUE	AM KW	1.40	1.44	1.95	1.70	1.61	1.77	1.85	1.75	3.69	.33	.48	1.18
	PM KW	.41	.49	.58	.63	.28	.22	.24	1.55	2.18	3.28	2.12	1.70
	DAILY LOAD FACTOR	.376		HIGH KW		3.69		HIGH KVA					
11 17 76 WED	AM KW	1.82	1.83	1.71	1.74	1.72	1.78	2.36	2.53	1.64	.38	.31	.43
	PM KW	.45	.33	.31	.24	.46	1.15	.96	2.93	2.77	2.27	1.98	1.85
	DAILY LOAD FACTOR	.484		HIGH KW		2.93		HIGH KVA					
11 18 76 THU	AM KW	1.85	1.93	1.69	1.80	2.38	1.72	1.66	1.64	2.79	.36	.46	.54
	PM KW	.41	.51	.51	.99	.47	.21	.21	.15	3.12	1.77	.86	1.22
	DAILY LOAD FACTOR	.391		HIGH KW		3.12		HIGH KVA					
11 19 76 FRI	AM KW	.61	.74	2.03	1.96	1.84	1.83	1.72	1.89	3.42	1.15	.38	.51
	PM KW	.49	.56	.51	.42	.47	.27	.13	.49	1.50	1.49	.78	.62
	DAILY LOAD FACTOR	.316		HIGH KW		3.42		HIGH KVA					
11 20 76 SAT	AM KW	.46	.46	.52	.59	.48	.59	.66	1.29	1.79	1.69	1.08	.64
	PM KW	.78	.73	1.56	.56	.85	.79	1.30	.59	.56	.54	.55	.64
	DAILY LOAD FACTOR	.476		HIGH KW		1.69		HIGH KVA					
11 21 76 SUN	AM KW	.64	.59	.61	.66	.67	.64	.92	1.45	.78	2.04	.87	.89
	PM KW	1.59	.48	.69	.53	.54	.30	.57	.48	.97	.47	.94	1.02
	DAILY LOAD FACTOR	.396		HIGH KW		2.04		HIGH KVA					
11 22 76 MON	AM KW	.51	.53	.63	.53	.62	.68	.65	1.28	1.80	.24	.42	.47
	PM KW	.28	.46	.88									
	DAILY LOAD FACTOR	.213		HIGH KW		1.80		HIGH KVA					

FIG. 29

HOUR	1	2	3	4	5	6	7	8	9	10	11	12
11 15 76 MON AM KW	.87	1.31	1.39	1.37	1.26	1.00	1.37	1.11	1.00	1.04	1.10	1.20
PM KW	.79	1.14	1.12	.82	1.07	1.14	1.24	.72	.66	.62	.68	1.10
DAILY LOAD FACTOR	.754		HIGH KW		1.39		HIGH KVA					
11 16 76 TUE AM KW	.75	1.15	1.56	1.06	1.36	1.46	1.49	1.38				
PM KW							.19	1.79	1.46	.87	1.21	1.25
DAILY LOAD FACTOR	.395		HIGH KW		1.79		HIGH KVA					
11 17 76 WED AM KW	1.14	1.24	1.39	1.39	1.35	1.35	1.39	.88				
PM KW					.42	.52	.82	2.72	1.46	1.26	1.39	1.42
DAILY LOAD FACTOR	.308		HIGH KW		2.72		HIGH KVA					
11 18 76 THU AM KW	1.36	1.36	1.35	1.32	1.20	1.16	1.33	1.29	.38			
PM KW								.20	.20	.16	.17	.19
DAILY LOAD FACTOR	.357		HIGH KW		1.36		HIGH KVA					
11 19 76 FRI AM KW	.22	.83	1.59	1.46	1.49	1.44	1.40	.48				
PM KW								.10	.03	.08	.12	.13
DAILY LOAD FACTOR	.246		HIGH KW		1.59		HIGH KVA					
11 20 76 SAT AM KW	.16	.17	.14	.19	.20	.21	.22	.23	.15	.14		.11
PM KW	.09	.08		.02	.01	.03	.14	.09	.14	.15	.12	.14
DAILY LOAD FACTOR	.547		HIGH KW		.23		HIGH KVA					
11 21 76 SUN AM KW	.17	.18	.21	.22	.22	.24	.24	.25	.24	.25	.16	.14
PM KW			.01							.15	.19	.18
DAILY LOAD FACTOR	.507		HIGH KW		.25		HIGH KVA					
11 22 76 MON AM KW	.14	.19	.21	.22	.24	.24	.24	.24	.04			
PM KW												
DAILY LOAD FACTOR	.309		HIGH KW		.24		HIGH KVA					

FIG. 30

November 6, 1976

21 Degree Days — Clear

Total Building Energy

214×10^3 BTU

Space Heating

161×10^3 BTU

FIG 31 BUILDING ENERGY BALANCE

December 10, 1976

25 Degree Days - Cloudy

Total Building Energy

209×10^3 BTU

Space Heating

161×10^3 BTU

FIG 32 BUILDING ENERGY BALANCE

October '76

(9-23-76 to 10-22-76)

253 Degree Days (134%)

Total Building Energy

316×10^6 BTU

Space Heating

1.31×10^6 BTU

FIG 33 BUILDING ENERGY BALANCE

November '76

(10-22-76 to 11-22-76)

654 Degree Days (17%)

Total Building Energy

6.91×10^6 BTU

Space Heating

5.12×10^6 BTU

FIG.34 BUILDING ENERGY BALANCE

December '76

(11-22-76 to 12-22-76)

832 Degree Days (+4%)

Total Building Energy

8.54×10^6 BTU

Space Heating

6.69×10^6 BTU

FIG.35 BUILDING ENERGY BALANCE

d) Domestic Hot Water Preheating

The performance of the hot water preheating tank immersed in the main storage tank cannot be precisely determined because temperature sensors for the component are not included in the current instrumentation package. However, an examination of the electric consumption record for the hot water heater indicates that the preheating tank for domestic hot water performs inefficiently. In a subsequent system designed by Wormser Scientific for installation in Columbia, South Carolina, lengths of copper pipe immersed in the storage tank were used for DHW preheating. Tests on this configuration confirm a much more satisfactory performance. Preheaters of this sort, which have much greater effectiveness as heat exchangers, are recommended in future installations and will be retrofitted in this installation.

7. Planned Improvements

Since the completion of the Delaware Pyramidal Optics house a number of design improvements have been made in the system. These improvements will be incorporated into a 4-unit townhouse condominium located in Columbia, South Carolina and in other projects. Improvements will be made in the optics and in the distribution systems.

a) Optics Improvements

Solar Window

The thickness of the glazing sheet will be increased to 1/4" and the size of each pane will be 48" x 48" to improve the structural characteristics of the window. A neoprene zipper gasket will be used to provide a superior weather seal and is expected to lower installation costs.

Reflectors

The flat mirror surfaces are under redesign. The latest development is a paper-backed, aluminized polyester film laminated to a corrugated board substrate. This forms a lightweight, easy-to-install, durable mirror surface of high optical quality.

Tracking Mechanism

The moving flap mechanism for the fully enclosed Pyramidal Optics system is being improved to provide a reliable, yet low cost, device that will periodically reposition the flap in accordance with the solar altitude changes.

b) System Improvements

Heat Pumps

The existing heat pump design restricts the use in the air-to-air mode to air temperatures above 40 °F. Lowering this temperature limit to 0 °F is planned by the inclusion of a suction accumulator in the freon line to prevent

slugging of liquid freon at low temperature and by adding a defrosting cycle to clear possible frost accumulation from the condenser coil. Prototypes are being constructed which have the direct solar coil, the resistance backup heating, and the mode switching controls installed inside the heat pump cabinet as well as incorporating the above improvements.

Water Pumps

Through analysis of electric power consumption records and additional engineering, the required size and design of the pumps have been refined. The 1/4 HP Marlowe pumps will be replaced by 1/12 HP Grundfos pumps which perform more efficiently and are expected to adequately perform the circulation tasks.

Domestic Hot Water

The thermal and electric records indicate that the submerged tank is a relatively unsuccessful preheating method. Engineering analysis reveals that the heat transfer is poor from the solar tank to the DHW preheat tank due to a high resistance from a low film efficiency and because of limited flow duration through the heat exchanger. Improved performance will be attained from a coiled tube-type heat exchanger with more surface area. The heat transfer will be further increased by the installation of a small circulator in a closed loop between the solar tank and the DHW tank. This pump will operate whenever the solar tank is warmer than the DHW tank.

Monitoring System

The monitoring system presently installed in the Delaware house consists of thermistors (absolute temperature measurement), thermopiles (temperature change measurement), and a pyranometer (insolation measurement). Voltages from these sensors are conditioned as required and fed to a 20 channel analog chart recorder which records at five minute intervals. This method of

data logging results in continuous graphic representation of the twenty parameters being monitored and makes trends which might not be immediately detected in digital type recording systems highly evident. Data reduction of the analog data records and any mathematical manipulation of the recorded data is difficult and time consuming using the analog data records of the type shown in Figures 18 and 19.

Recording and analysis of detailed performance parameters has been found to be most valuable and, in fact, essential in the further development and optimization of sophisticated solar heating and hot water systems, such as the system described in this project.

Over a period of several months, prior to the data period reported on in this report, the efficiency of the Delaware Pyramidal Optics solar collection system was nearly doubled. This was only feasible because detailed performance data were available on the operation of the various components and subsystems. This permitted comparison with the theoretically predicted performance and provided guidance for the upgrading of these parts of the system.

To provide continuing, detailed performance monitoring of the Delaware P.O. solar house and of a number of additional P.O. solar houses in other locations, a digital recording system is planned. It would be composed of an on-site commutator and digital recorder logging the data onto a magnetic cassette tape. This tape will be sent weekly to the central facility for analysis. Here, the data will be read into a small computer and analyzed according to requirements. With this configuration, required data manipulation can be performed with minimal effort. The data can be automatically

plotted in graph form when required. Trends and abnormal conditions can be quickly and accurately surveyed providing for a much better understanding of the system performance thus leading to further improvements in system design.

8. Conclusions

a) Optical Concentrating System and Receiver Assembly Performance

After a number of modifications were made in the optical concentrator design and the flat plate receiver assembly, the system is now performing close to the predicted levels (Figures 27 and 28). The overall daylong efficiency of the P.O. collector experimentally evaluated on a clear day is 40 percent. (This efficiency is defined as the ratio of solar energy incident on the optical aperture to the heat energy transmitted to the storage tank.) The peak efficiency of the system at noon is near 50 percent. The overall system performance is equivalent to an area of high quality flat plate collectors equal to the aperture area or four times the receiver area used, whose cost would be much higher, more difficult to fit in architecturally and aesthetically less pleasing.

The relatively conventional appearance of the Pyramidal Optics unit as demonstrated in the photographs of the Delaware P.O. solar house, Figure 2 and the four Townhouse Condominium, Figure B2 of Appendix B have been found to be most important in enhancing the acceptability and saleability of the P.O. solar units.

As shown in Figure 26, the performance of the P.O. solar system is relatively insensitive to outside temperature differentials and, hence, is particularly suitable for use in cold climates.

b) Auxiliary and Distribution System

The coupling of the P.O. solar system to a storage tank of medium capacity (2 gallons per square foot of aperture) and to a dual source water-to-air and air-to-air heat pump has resulted in a highly efficient overall system performance, as documented in the performance data for the

very severe winter months of the winter of 1976-77.

Using the solar heated water in the direct heating mode through a solar coil (100 percent solar heating) when tank temperature is above 80°F and using it with the water-to-air heat pump for upgrading when the tank temperature is between 80°F and 40°F has provided us with a system which essentially satisfied the heating requirements of the house throughout a severe winter. This was accomplished with a collecting system of moderate aperture, 382 sq. ft. in December, amounting to only 27 percent of the heated area of the building. The overall solar contribution amounted to 70 percent of the space heating requirement for the months of November and December and is expected to average above 80 percent throughout the year.

The operating cost for the Delaware solar house from October to December 1976, based on recordings and billings of Delmarva Power Company, are shown in Table 3. The total cost of auxiliary space heating power during these three severe winter months amounted to \$35.50 or less than 40 cents per day or \$12 per month.

c) General Conclusions

The ERDA evaluation program has provided a thorough understanding of the design and performance parameters of low gain optical concentrating systems, such as the Pyramidal Optics system, and will enable us to proceed with design of these systems with much greater knowledge and confidence.

In order to further this growing understanding of this type of solar system and to extend our ability to design these systems and to improve their performance, further performance monitoring of the Delaware P.O. house and of several other P.O. solar houses in other climatic locations should be undertaken.

TABLE 3 - ENERGY USED FOR SPACE HEATING-DELAWARE SOLAR HOUSE

[illegible]

9. Appendix A

a) Efficiency Calculations

1. Hourly Average Method

The efficiency of a solar system is defined as the ratio of useful energy extracted from the sunlight to the total energy which the sun presents to the aperture of the solar system. The most commonly used formula for evaluating this quantity is to divide the term (flowrate X specific heat X temperature rise across the collectors) by the term (solar insolation in BTU/ft² X aperture area).

This method has been used to evaluate both a noontime instantaneous efficiency and a daylong system efficiency, which is an average of all the hourly efficiencies computed for the day. Figure A1 illustrates this method. Both the solar insolation and the temperature rise across the collector array are found by graphical integration of the curves plotted on the analog recorder (channels 13 and 18, and Figures 18 and 19). For the day used as an example, November 14, 1976, the values of these variables at 12:30 P.M. were used to find a middle of the day peak efficiency of 48 percent. A daylong efficiency is found by summing the hourly totals of solar intensity and temperature rise, obtaining 1755 BTU/ft² and 80°F, respectively. These figures are then used in the equation:

$$\text{Efficiency} = \frac{\text{Flowrate} \times \text{specific heat} \times \text{temperature rise}}{\text{solar insolation} \times \text{aperture area}}$$

to obtain a daylong efficiency of 41.3 percent.

Figure A1

Efficiency Calculations Using Collector ΔT Date: 11-14-76
Location: Delaware

Hour	Average Insolation BTU/ft ² /hr	$^{\circ}$ F Average ΔT
7-8	-	-
8-9	99	-
9-10	187	8.0
10-11	243	12.0
11-12	280	15.0
12-13	294	15.5
13-14	277	14.5
14-15	237	11.0
15-16	138	4.0
16-17	-	-
17-18	-	-
TOTAL	1,755	80.0

Aperture: 353 Ft²

$$\text{Day Long Efficiency} = \frac{\text{Collected Energy}}{\text{Incident Energy}}$$

$$= \frac{\sum \Delta T \times \text{GPM} \times \text{Lbs/gal} \times \text{Cp} \times \text{Min/hr}}{\sum \text{BTU/ft}^2 \times \text{ft}^2}$$

$$= \frac{80^{\circ}\text{F} \times 6.4 \text{ GPM} \times 8.3 \text{ Lbs/gal} \times 1 \text{ Cp} \times 60 \text{ Min/hr}}{1755 \text{ BTU/ft}^2 \times 353 \text{ ft}^2}$$

$$= 41.3\%$$

Instantaneous Efficiency at 12:30 P.M.

$$\frac{15.5^{\circ}\text{F} \times 6.4 \text{ GPM} \times 8.3 \text{ lbs/gal} \times 1 \text{ Cp} \times 60 \text{ min/hr}}{294 \text{ BTU/ft}^2 \times 353 \text{ ft}^2} = 48\%$$

2. Tank Temperature Method

As a check on the accuracy of the efficiency calculated by the average of hourly efficiencies, a second method is employed. This is to compare the energy absorbed by the storage tank to the energy incident in the sunlight. This method is used by measuring the temperature rise occurring in the storage tank (channel 12) over the course of a day.

An example is presented in Figure A2. The solar radiation is evaluated identically to the hourly average method. The energy absorbed by storage is found by multiplying the rise in tank temperature by the specific heat of the storage system. In the case of January 26, 1977, these quantities have values which reduce to a daylong average efficiency of 45.6 percent.

This method has one serious disadvantage. Energy given up by the tank to heat the building reduces the temperature rise of the tank during the day but is not accounted for in the efficiency calculation. On cloudy days this drawback becomes particularly noticeable. In the case of a cloudy day on which heat gains from the sun are exactly equalled by the heating demand of the house, the tank temperature remains constant, yielding an "efficiency" of zero in the calculation but disregarding the fact that the sun is still imparting energy to the system with some finite efficiency.

A means of correcting the expression for heat given up by the tank to bring this calculation into agreement with the results of the hourly average method would extend the usefulness of this construct.

Figure A2

STORAGE ΔT EFFICIENCY CALCULATIONS

Date: 1-26-77 (Clear)

Hour Ending:	8	9	10	11	12	1	2	3	4	5
Solar Radiation BTU/ft ²	44	135	215	272	305	303	256	228	122	18
TOTAL:	1,898									

$$\begin{aligned}
 \text{Daylong Efficiency} &= \frac{\text{energy absorbed by storage}}{\text{sunlight incident on system}} \\
 &= \frac{(\text{storage heat capacity}) (\Delta T)}{\text{incident sunlight}} \\
 &= (8263 \text{ BTU/}^\circ\text{F}) (1/353 \text{ ft}^2) (72-35^\circ\text{F}) (1 \text{ ft}^2/1898 \text{ BTU}) \\
 &= 45.6\%
 \end{aligned}$$

$$\begin{aligned}
 \text{Noontime Peak Efficiency (11AM-1PM)} &= (8263 \text{ BTU/}^\circ\text{F}) (1/353 \text{ ft}^2) (58-47^\circ\text{F}) (1 \text{ ft}^2/608 \text{ BTU}) \\
 &= 42.3\%
 \end{aligned}$$

10. Appendix B: Application of Pyramidal Optics Solar Collection System to Multiple Family Residences

The Pyramidal Optics solar collection system evaluated under this contract is being applied to solar heating of a four townhouse condominium as described below.

Description of Solar Heated Four Townhouse Condominium In Columbia, S.C.

Pyramidal optics solar concentrating type systems similar to the Delaware units are being used to provide heat and hot water to a model four townhouse condominium building which is part of a 400 unit project at Yacht Cove on Lake Murray outside Columbia, S.C. The first solar unit has been supported by a HUD grant. The four townhouse building shown in Figure 10 (south elevation) consists of two two-story 2,530 sq. ft. end units and two three-story 1,570 sq. ft. middle units for a total heated building area of 8,200 sq. ft. The solar system uses two pyramidal optics concentrating type solar collectors which have been fitted into the unused attic space of the two end units, of the four unit building (Fig. 11(104-4)). The solar system has been incorporated into the building design without significantly effecting the architectural design and blends in aesthetically into the 400 unit Yacht Cove townhouse project.

In modifying the building design to use a solar energy system for heating a total approach to minimizing energy consumption for heating and cooling has been taken by first reducing the heat losses and heat gains of the building. In the Yacht Cove design we were able to achieve a 45% reduction in winter heat losses through improved insulation and dual glazing and a similar reduction in summer heat gains through use of overhangs in addition to the above steps. The Yacht Cove management adopted these energy conservation steps for all new construction starting in 1976.

Description of Solar System

Solar heated water is pumped to a single 2,500 gallon segmented storage tank located in the enlarged basement of one of the end buildings. Heat is distributed to the four townhouse units from this central storage as further described below. Significant economies in system cost and advantages in system operation are achieved through this central storage approach.

Each solar collection system (Fig. 12) consists of an optical window or skylight of plexiglass 36'x16'=576 sq. ft. for a total collection area of 1,152 sq. ft. which is 14% of the total area of 8,200 sq. ft. to be heated. Optical concentrators using aluminized mylar reflectors concentrate the solar energy by a factor of nearly four onto an array of flat plate collectors 35'x4'=140 sq. ft. The flat plate collector array is made up of 19 specially designed copper rollbond collectors with black chrome selective black coatings similar to the collectors used in Delaware. The solar system is very similar to the system used in Delaware. The optical design was adjusted for the change in latitude and the size of the system is determined by the local climatic conditions.

The overall performance is expected to be very similar to the performance of the Delaware system providing in excess of 70% of the heat and hot water requirements.

We hope to provide monitoring instrumentation in cooperation with the local electric company before next winter season.

In addition to the technical advantages of the pyramidal optical system. The use of a skylight for the solar collection system at an angle of 32° to the horizontal matching the existing roof slopes of the project and blending in with the existing architecture was considered of particular importance by the developers.

Initial reaction from potential purchasers has confirmed that the normal appearance enhances the public acceptability of this type of solar house and increases its marketability.

Auxiliary and Distribution System

Solar heated water from the two collector arrays is piped to the central two compartment 2,500 gallon concrete storage tank as shown in Figure 13. The two compartment tank is arranged to provide maximum stratification of hot water returning from the collectors and cold water which is used to feed the collectors.

A dual source type heat pump unit, is located in each of the four townhouses. The heat pump is capable of operating either in the water-to-air or the air-to-air mode. The fan sections of the heat pumps are used to distribute heating or cooling through the duct systems of the respective townhouses.

Each townhouse is equipped with a direct "solar coil" and a dual source heat pump, a resistance backup heater, and a domestic hot water heater similar to the Delaware system. The mode of operation is also patterned after the Delaware system.

The use of a central tank and only two sets of solar collectors and a single control system result in the economies which will result in the capital cost of systems beyond the first unit amounting to about \$24,000 per four townhouse building which results in a payback of $7\frac{1}{2}$ years again equating fuel escalation and interest cost.

SECTION AT DOWNHILL SOLAR UNIT: TYPE 2

$$\frac{1}{4}'' = 1'-0''$$

FOUR HOUSE FLOW SCHEMATIC

NORNER SCIENTIFIC

S. ELEV. 4-UNIT TOWNHOUSE

S.W. VIEW 4 UNIT SOLAR TOWNHOUSE

11. Appendix C - Costs

Estimates of Cost of Delaware P.O. Solar House (390 sq. ft. winter aperture)

Records were kept of the material cost and labor hours used to construct the Delaware P.O. solar house. From these records a detailed estimate has been prepared of what the repeat costs would be estimated to be for a P.O. solar house of comparable size and design to be built at the present time.

The estimated cost of the complete solar system is \$9,425 or \$24 per square foot of aperture for the complete system.

The added cost of the additional insulation and dual glazing is estimated to amount to \$1,050 for a total cost of \$10,500 for energy conservation and solar heating.

As shown in Table 3, the extrapolated yearly cost of auxiliary electric energy for heating is \$93 and for water heating is \$40 at present. The water heating auxiliary cost can be expected to be significantly reduced by a better heat exchanger to around \$20/year for a total auxiliary electric cost of \$110.

The Delaware house with improved insulation is estimated to cost \$308/year for resistance heating and \$120 for water heating. The house without improved insulation is expected to cost \$560 for resistance heating and \$120 for water heating for a total cost of \$780.

The estimated cost with a solar system and improved hot water heat exchanger is \$110 resulting in a savings of $\$780 - \$110 = \$670$ per year. Taking into account fuel cost escalation and possible tax credits, the solar and insulation system will pay for itself in seven to ten years.

DELAWARE SOLAR HOUSE

Cost Analysis:

ITEM	COSTS		TOTAL
	MATERIAL	LABOR	
Collectors	1311		1311
Collector Frames	81		81
Collector Piping	160		160
Fittings & Valves	228		228
Collector Pump	128		128
Pipe Insulation	180		180
Collector Insulation	75		75
Heat Trace Tape	14		14
Thermometers & Gauges	30		30
Plexiglass Window	345	355	700
Gasketing	100	-	100
Caulking, Caps & Nailers	150	-	150
Flashing	75	-	75
Reflective Panels	398	160	558
Reflective Panel			
Supports	70		70
Moving Panel Frame	76		76
Associated Hardware	90		90
Solar Coil	400		400
Piping	70		70
Fittings & Valves	150		150
Circulating Pump	128		128
Pipe Insulation	69		69
Thermometers & Gauges	30		30
Solar Storage Tank	400		400
Butyl Liner	150		150
Tank Insulation	100		100
Resistance Heat	150		150
Heat Pump	1,200		1,200
Circulating Pump	128		128
Thermometers & Gauges	30		30
Piping	70		70
Pipe Insulation	69		69
Domestic Hot Water			
Preheat Tank	80		80
Control Panel	600		600
Motor for Seasonal Flap	400		400
Asjustment Pulley System	75		75
Carpentry Labor		600	600
Plumbing Labor		500	500
TOTAL SOLAR SYSTEM COST			\$9,425.

Cost of Added Insulation and Dual Glazing:

Additional Cost of Insulating Glass -

Approximately 132 sq.ft. of total glass
area @ \$2.67 of additional material cost = \$ 352.00

Additional Cost of 1" rigid styrofoam board on
exterior of stud wall, 1436 sq.ft. of
styrofoam sheathing =

215.00

Additional crawl space insulation

1625 sq. ft. of 3½" batt insulation
additional cost =

195.00

762.00

Added Installation of Insulation =

285.00

Total Cost of Added Energy Conservation

\$1,047.00