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SUNCATCHER MONITORING PROJECT

**FINAL REPORT
FOR PERIOD SEPTEMBER 1, 1977 1977 — DECEMBER 31, 1978**

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AUGUST 1979

**EARTH INTEGRAL OF LIVING SYSTEMS
(NOW DAVIS ALTERNATIVE TECHNOLOGY ASSOCIATES)
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**PREPARED FOR THE
U.S. DEPARTMENT OF ENERGY
SOLAR HEATING AND COOLING, RESEARCH AND
DEVELOPMENT BRANCH
OFFICE OF CONSERVATION AND SOLAR APPLICATIONS**

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ABSTRACT

The Suncatcher Monitoring Project has to date accumulated a wide variety of data on the Nittler/Maeda Suncatcher house in Davis, California, designed by Living Systems. Highlights of the data indicate 70% solar heating during 1978 despite unusually adverse winter weather conditions, and a 40% increase of solar energy in winter through clerestory glazing as compared to ordinary south glazing.

Because of various problems, the data acquisition system (DAS) only worked intermittently during 1978, but hourly data was gathered during several intervals and daily data was virtually continuous. As a back-up to this hourly gathering of data, hand read data was taken daily from September 1977 to the present. This manually collected data has allowed a reliable estimate of the Suncatcher house's performance.

Summer data on Suncatcher window performance has been collected for comparison purposes, but budget constraints have delayed completion of computer modeling of the Suncatcher performance. This modeling will be carried out during the grant extension period. Comparison of the overall Suncatcher's performance with the estimation models, SOLEST & LASL6, and simulation model, SOLSIM, appear accurate, although completion of the reflector enhancement algorithm remains desirable.

Experiments such as the radiant isolation experiment, the special short wave radiation monitoring, and basal energy use have been rescheduled for completion during the grant extension period. Preliminary results indicate a 3°F gradient of the radiant temperatures from the mass storage water cylinders to north windows during summer periods.

1. INTRODUCTION

1.1. Purpose

The purpose of this project is to monitor the thermal performance of an innovative passive design, Living System's Suncatcher House, and to provide detailed, quantitative data on the performance of the Suncatcher's reflective roofing design and house's breadbox solar hot water system. An additional purpose is to compare the house's thermal performance to a computer simulation program (SOLSDIM) previously termed HEAT. Performance has also been compared to two design evaluation programs: SOLEST, which estimates energy performance, solar contribution, and natural cooling; and LASL6, which uses Doug Balcomb's passive solar load ratio estimating technique.

1.2. Location & Climate

The monitored Suncatcher is situated in Davis, California, about fifteen miles southwest of Sacramento. The elevation of the site is approximately 60 feet above sea level. The Lower Sacramento Valley, where Davis is located, enjoys a mild climate and abundant sunshine most of the year, cloudless skies prevailing during the summer and for most of the spring and autumn. Summers are remarkably dry, with warm days and pleasant nights. In the "rainy season" (November - March) over three-fourths of the total annual precipitation falls, yet rain in measurable amounts occurs only on nine days monthly during this period. Mountains border the valley to the west, north, and east. The Sierra Nevada snow fields are only 70 miles east of Sacramento and usually supply plentiful water to the valley streams during the dry season. Because of the shielding influence of the high mountains around the valley, winter storms reach valley districts in modified form. Excessive rainfall and damaging windstorms are rare.

Prevailing winds at Davis are southerly every month except November, when they are northerly. This pattern is due to the north-south direction of the valley and the deflecting effect of the towering Sierra Ranges on the prevailing oceanic winds which move through the Carquinez Straits at the confluence of the Sacramento and San Joaquin Rivers. No other tidewater gap exists in the coastal mountains to admit marine air into the Sacramento or the San Joaquin Valley. Occasionally, a steep northerly barometric pressure gradient develops and air is forced over the Siskiyou Mountains to the north,

warmed as it descends, and reaching the valley floor as a warm, dry, north wind. These occasional disagreeable winds, known as "northers" in the valley, are the counterpart of the well-known "chinook" winds of the Rocky Mountains, and they, or their modifications, produce pronounced heat waves in summer. Fortunately, northers occur infrequently and are usually followed within two or three days by the normally cool southerly breezes, especially at night. Summer nights in the lower Sacramento Valley are, with few exceptions, cool and invigorating, the result of the prevailing oceanic influence. While "northers" cause dry, hot weather for brief periods during the summer, they also moderate cold waves in the winter. The winter northers, with only a few exceptions, are comparatively warm, drying winds.

As is well known, relative humidity is a marked influence on the reaction of plants and animals to temperature. The extremely low relative humidity that accompanies high temperatures in the Central Valley should be considered when comparing temperatures here with those of cities in more humid regions, since discomfort is likely to be less in the valley at high temperatures.

Thunderstorms are few, usually mild, and occur mainly in the spring. Snow falls so rarely and in such small amounts that it may be disregarded as a climatic feature. Heavy fog occurs mostly in midwinter, never in summer and seldom in spring or autumn. Light and moderate fog is more frequent, and may come anytime during the cold, wet season. Valley fog is usually the radiational cooling type confined to the early morning hours. An occasional winter fog, under stagnant atmospheric conditions, may continue for several days.

Davis has 2819 heating degree days and in summer 1063 cooling degree days with 815 average annual hours over 80°F. Various tabulations of monthly climate factors for Davis and Sacramento appear in table 1 and figures 1 to 8.

DAVIS	TEMPERATURE (°F)								Mean Degree Days **	PRECIPITATION TOTALS (INCHES)				MEAN # OF DAYS			
	MEANS			EXTREMES						Mean	Greatest Daily	SNOW, SLEET		TEMPERATURES			
														Max		Min	
	Month	Daily Maximum	Daily Minimum	Monthly	Record Highest	Year	Record Lowest	Year		Mean	Greatest Daily	Mean	Maximum Monthly	Greatest Daily	90° and Above	32° And Below	32° and Below
(a)	30	30	30	30		30		30	30	30	30	30	10	10	10	10	
Jan	54.1	36.5	45.3	74	1948	18	1937	611	3.29	2.72	0.1	3.5	2.0	0	0	0	
Feb	59.4	39.2	49.3	77	1932	22	1948	440	3.25	2.92	T	T	T	0	0	3	
Mar	65.2	41.6	53.4	83	1960	26	1939	360	2.14	1.98	0.1	2.5	2.5	0	0	1	
Apr	73.2	44.5	58.9	98	1931	29	1953	198	1.36	2.17	T	T	T	1	0	*	
May	80.5	48.9	64.7	104	1950	33	1933	87	.57	1.50	0	0	0	5	0	0	
June	88.4	53.4	70.9	112	1934	39	1939	0	.13	.50	0	0	0	13	0	0	
July	95.1	55.3	75.2	113	1950	44	1955	0	T	.04	0	0	0	24	0	0	
Aug	93.3	53.2	73.3	112	1950	40	1939	0	.01	.08	0	0	0	22	0	0	
Sept	89.8	52.4	71.1	112	1950	38	1934	9	.17	1.42	0	0	0	15	0	0	
Oct	79.4	47.0	63.2	102	1933	26	1946	87	.76	1.39	0	0	0	4	0	0	
Nov	66.1	40.1	53.1	88	1949	23	1931	357	1.37	1.88	0	0	0	0	0	2	
Dec	55.5	37.0	46.3	75	1958	12	1932	580	3.41	3.01	0	0	0	0	0	6	
Year	75.0	45.8	60.4	113	July 1950	12	Dec 1932	2729	16.46	3.01	0.2	3.5	2.5	84	0	17	

Table 1

(a) Average length of record, years
 T Trace, an amount too small to measure
 ** Base 65° F
 * less than one half
 † Also on earlier dates, months, or years

Latitude 38° 32' N
 Longitude 121° 45' W
 Elev. (Ground) 51 feet

MEANS AND EXTREMES FOR PERIOD 1931 - 1960 FOR YOLO COUNTY

University of California Agricultural Extension Service - 1971

SUNCATCHER MONITORING PROJECT

Figure 3

Figure 4

SUNCATCHER MONITORING PROJECT

CLEAR AND CLOUDY DAYS

Figure 5

-7-

HOURS OF SUNSHINE

Figure 6

Figure 7

Figure 8

1.3. Solar and Energy Conserving Design of the House

1.3.1 Suncatcher System

The Nittler/Maeda Suncatcher was designed by Jim Plumb of Living Systems and is located in Davis' Village Homes, a subdivision featuring a variety of active and passive solar home designs. The Suncatcher design is characterized by a reflective overhang and north sloping roof surface. This configuration provides enhanced collector area for reflective solar heat gain through 96 square feet of clerestory windows. The roof and overhang surfaces form a cavity that increases winter solar gain, while preventing overheating in the summer (see figures 9, 10 & 11). Manually operated insulated shutters (R-6) inside the house reduce winter heat losses, and also decrease cooling loads by reflecting diffuse solar gain away from their exterior-facing reflective surfaces.

The water Trombe collector consists of seven galvanized steel culverts two feet in diameter and ten feet high, located eight feet behind the clerestory windows.

The water-filled tubes, centrally located within the living space, remain at temperatures within the comfort range (65-78°) and help moderate temperatures in the living, dining and hallway portions of the residence.

1.3.2 Direct Gain Components

Three south facing bedrooms are heated by direct solar gain through the windows, completely shaded in summer by a grape arbor. Heat storage in the bedrooms is provided by thermal mass in 55 gallon water filled drums and the parquet covered slab floor. The location of these drums is indicated in figure 14, in section 2.1.

1.3.3 Natural Cooling System

To reduce the Davis climate's severe cooling requirement (over 800 hours annually above 80°F) the house uses heavy wall insulation, double glazing and well-shaded, draped windows. Additional cooling needs are met with daytime heat storage in water mass and later heat rejection by cross ventilation through the south windows above the collector/storage tubes and the north side windows. Relatively consistent, cool evening and night breezes from the Carquinez Straits provide the driving force for nighttime ventilation.

1.3.4 Breadbox Solar Hot Water Heater

The breadbox solar water heater has a net collector area of 36 square feet of double glazed, tempered glass. The system heats water through a total of four tanks. The two middle tanks are parallel to each other, and in series with an inlet tank and a fourth tank for final solar heating (see figures 12 & 13).

1.3.5 Other Energy Efficient Features

Other energy efficient features include natural lighting with a light shelf above a south bedroom closet, an interior clerestory window providing additional light into the living room (on the north side of the house), and a ceiling to north wall hot air circulation duct and fan. The house has fewer than normal appliances, the residents using only a stove, washer, refrigerator, and several small electric appliances. There is no dishwasher, clothes dryer (except solar), garbage disposal or trash compactor. The residents' demand for hot water and electricity is modest.

Suncatcher Ray Tracing

Figure 9

Suncatcher Ray Tracing

Figure 10

Figure 11

Suncatcher Two Point Perspective

BREADBOX HOT WATER HEATER

SCHEMATIC

Figure 12

BREADBOX HOT WATER HEATER

ISOMETRIC VIEW

Figure 13

2. DATA ACQUISITION SYSTEM AND PROCEDURES

2.1. Sensors and Equipment

The Nittler/Maeda Suncatcher has over 130 temperature sensors located throughout the house as shown in figure 14. Non-shielded type T iron-constantan thermocouples were used because they were installed before the grant award and were available at no cost. Although these thermocouples are not as accurate as we would like, they are adequate for measuring air temperatures. The mass temperatures especially for the water tubes are more crucial and may require thermistor installation for monitoring during the grant extension period. The installed sensors terminate at a reference junction with a precision thermistor monitoring the reference temperature. Additional equipment includes maximum/minimum thermometers made by Taylor instruments and purchased from Weathertronics of West Sacramento, California. These instruments are reset by a simple push button device rather than a magnet.

There are two comfort measuring stations also shown in figure 14, both located near the interior maximum/minimum thermometer in the study and in the living room. These stations monitor wet bulb, dry bulb, and black globe temperatures (the equilibrium temperatures within a black enclosure used as an indication of the average temperature at which the walls and roof are radiating). These temperatures will be combined in the final reduced data to standard comfort indices. Wind speed is taken by a Weather-measure model W121 recording system. Data is taken manually once a day and combined with Davis daily data. A Hersey BTU flow meter is installed in the output taken manually once a week. Solar radiation is measured on a vertical plane directly behind the clerestory windows. The thermopile-type pyranometer is double-dome, Eppley model PSP. Its output is recorded hourly by the DAS. Two additional gas and watt hour meters were provided by Pacific Gas and Electric, the local utility. The gas meters separately monitor the space heater and hot water heater, leaving the stove as residual value. The two additional watt hour meters measure the lighting circuits and the refrigerator energy use.

2.2. Daily Data Acquisition

Daily monitoring began on November 2, 1977 and included data from three maximum/minimum thermometers, three electronic temperature sensors for the water tubes, and the gas and electric meters. In

Figure 14

SUNCATCHER MONITORING PROJECT

c - COMFORT MEASURING STATION: WET BULB, DRY BULB, BLACK GLOBE

g - GROUND THERMOCOUPLE

n - MAX/MIN THERMOMETER

s - SLAB THERMOCOUPLE

t - WALL/WINDOW THERMOCOUPLE

NOTE: SUBSCRIPTS INDICATE HEIGHT IN FEET.

addition, weather data from the Davis benchmark weather station (located approximately one mile south of the house on an open site) at the University of California at Davis, is incorporated into our data. The monitoring procedure has been modified (three times since November 2, 1977) to improve data gathering and make the data more representative. The first modification, on November 25, 1977, consisted of several small practical adjustments. On February 2, 1978, the additional gas meters provided by the local utility were finally installed, but only recently, July 1979, was any data received from Pacific Gas and Electric Company (PG&E). There has been no hourly analysis of this data because of PG&E's delays. The additional electric meters were finally received and installed on March 4, 1978. These instruments were on loan from PG&E and the project had no power over the local utility's delivery schedule, nor sufficient funds for purchasing more equipment; hence the delays. Two daily maximum/minimum stations were shifted on March 1, 1978 to more representative locations and closer to the comfort monitoring indicators of the DAS. In the summer of 1978 several daily maximum outside temperatures appeared erroneous due to early morning and late afternoon sunlight on the thermometer. A shading device was made and fitted, but proved inadequate. A louvered box, similar to a Stevenson screen, was devised to house this thermometer and installed on August 1, 1978. Although some light still penetrates, the thermometer now reads more accurately. D.A.T.A. does, however, rely on the U.C. Davis station for accurate outside daily temperatures as a back-up for the DAS. The current, revised monitoring procedures and locations have been in effect since August 1, 1978. A list of daily data gathered and available appears below:

1. Total gas usage (100's of cu.ft.)
2. Furnace gas usage (cu.ft.)
3. Hot water gas usage (cu.ft.)
4. Total electric usage (kwh)
5. Refrigerator usage (kwh)
6. Lights usage (kwh)
7. Outside max/min and 8:30am temperatures
8. Living room max/min and 8:30am temperatures
9. Study max/min and 8:30am temperatures
10. Outer tube temperatures at 0.5, 5, and 9ft. at 8:30am
11. Wind speed at 8:30am

We have not always been successful at monitoring temperatures at the same time every morning, but over 95% are monitored at 8:30am. Daily data since March 1978 has been reduced, combined and compared to various forms of Davis data by a computer program. A sample of one month's data reduction is included here; complete copies will be sent to Michael Holtz at the Solar Energy Research Institute and Michael Maybaum of the Department of Energy in Washington, D.C. Not all of this data has been presented graphically because of its bulk, time constraints, and our judgement of its utility. The computer program analyzes enough to give a selection of data to present. Additional data analyses will be added to the computer program for daily data reduction during the grant extension period. Currently,

SUNCATCHER UTILITY DATA FOR DEC - 1970

	MAIN GAS CU. FT.		FURNACE GAS CU. FT.		HEAT GAS CU. FT.		STOVE GAS CU. FT.		KWH TOTAL		KWH REFRIGERATOR		KWH LIGHTS		KWH PLUGS	
DATE	READ	DELTA	READ	DELTA	READ	DELTA	DELTA	READ	DELTA	READ	DELTA	READ	DELTA	DELTA	READ	DELTA
1	26390.0	80.0	2075.0	0.0	3336.0	50.0	10.0	2731.0	5.0	853.0	2.0	445.0	1.0	2.0		
2	26390.0	80.0	2075.0	0.0	3336.0	50.0	10.0	2731.0	5.0	853.0	2.0	445.0	1.0	2.0		
3	26430.0	40.0	2075.0	0.0	3380.0	44.0	14.0	2745.0	14.0	858.0	5.0	452.0	7.0	3.0		
4	26480.0	50.0	2075.0	0.0	3410.0	30.0	24.0	2751.0	6.0	861.0	3.0	454.0	2.0	1.0		
5	26510.0	30.0	2075.0	0.0	3440.0	30.0	8.0	2756.0	5.0	863.0	2.0	456.0	2.0	1.0		
6	26570.0	60.0	2075.0	0.0	3475.0	35.0	25.0	2762.0	6.0	864.0	1.0	458.0	2.0	1.0		
7	26630.0	60.0	2075.0	0.0	3520.0	45.0	15.0	2769.0	7.0	868.0	4.0	460.0	2.0	3.0		
8	26730.0	100.0	2115.0	40.0	3560.0	40.0	20.0	2779.0	10.0	871.0	3.0	465.0	5.0	3.0		
9	26900.0	170.0	2210.0	95.0	3615.0	55.0	25.0	2789.0	10.0	873.0	2.0	469.0	4.0	4.0		
10	26940.0	40.0	2240.0	30.0	3640.0	25.0	44.0	2797.0	8.0	874.0	1.0	470.0	1.0	2.5		
11	27140.0	200.0	2325.0	85.0	3705.0	65.0	32.0	2805.0	8.0	879.0	5.0	474.0	4.0	2.5		
12	27230.0	90.0	2355.0	30.0	3715.0	10.0	5.0	2811.0	6.0	881.0	2.0	476.0	2.0	2.0		
13	27350.0	120.0	2430.0	75.0	3750.0	35.0	10.0	2819.0	8.0	884.0	3.0	479.0	3.0	2.0		
14	27390.0	40.0	2430.0	0.0	3790.0	40.0	0.0	2825.0	6.0	886.0	2.0	481.0	2.0	2.0		
15	27410.0	20.0	2430.0	0.0	3820.0	30.0	10.0	2831.0	6.0	889.0	3.0	483.0	2.0	1.0		
16	27470.0	60.0	2430.0	0.0	3835.0	15.0	25.0	2837.0	6.0	890.0	1.0	484.0	1.0	0.0		
17	27510.0	40.0	2490.0	60.0	3890.0	55.0	12.0	2847.0	10.0	894.0	4.0	490.0	6.0	4.0		
18	27550.0	40.0	2540.0	50.0	3950.0	60.0	40.0	2856.0	9.0	897.0	3.0	493.0	3.0	3.0		
19	27630.0	80.0	2740.0	200.0	4015.0	65.0	40.0	2865.0	9.0	899.0	2.0	496.0	3.0	4.0		
20	2770.0	140.0	2890.0	150.0	4060.0	50.0	30.0	2872.0	7.0	902.0	3.0	498.0	2.0	2.0		
21	28320.0	50.0	2875.0	85.0	4085.0	25.0	-10.0	2877.0	5.0	904.0	2.0	501.0	3.0	0.0		
22	28380.0	60.0	2875.0	0.0	4110.0	25.0	35.0	2882.0	5.0	906.0	2.0	503.0	2.0	1.0		
23	28770.0	390.0	3210.0	335.0	4125.0	15.0	10.0	2889.0	7.0	909.0	3.0	506.0	3.0	1.0		
24	28850.0	80.0	3540.0	330.0	4180.0	55.0	25.0	2908.0	19.0	912.0	3.0	512.0	6.0	2.0		
25	28880.0	30.0	3680.0	140.0	4260.0	80.0	110.0	2908.0	0.0	914.0	2.0	514.0	2.0	2.0		
26	28930.0	50.0	3675.0	5.0	4310.0	50.0	5.0	2915.0	7.0	916.0	2.0	519.0	5.0	2.0		
27	29040.0	110.0	4150.0	470.0	4335.0	25.0	10.0	2922.0	7.0	919.0	3.0	521.0	2.0	2.0		
28	29580.0	540.0	4545.0	395.0	4410.0	75.0	30.0	2929.0	7.0	921.0	2.0	524.0	3.0	0.0		
29	29810.0	230.0	4740.0	195.0	4410.0	0.0	5.0	2935.0	6.0	923.0	2.0	529.0	5.0	1.0		
30	30100.0	290.0	5000.0	260.0	4490.0	80.0	20.0	2940.0	5.0	926.0	3.0	530.0	1.0	1.0		
31	30260.0	160.0	5120.0	120.0	4520.0	30.0	10.0	2945.0	5.0	928.0	2.0	532.0	2.0	1.0		
TOT	4970.0		3045.0		1240.0		645.0		219.0		77.0		88.0		53.0	
MEAN	160.3		98.2		40.0		22.1		7.1		2.7		3.0		1.8	
ST DE	127.5		115.0		15.6		23.3		1.6		0.9		1.7		1.1	
MAX	460.0		355.0		75.0		110.0		11.0		3.0		6.0		4.0	
MIN	30.0		0.0		15.0		-10.0		5.0		2.0		1.0		0.0	
SUNX2	1706700.0		701825.0		56200.0		31375.0		1641.0		120.5		249.0		136.5	
SUNYEN	487494.0		402727.0		7340.0		14238.7		93.9		8.2		40.4		35.8	

Table 2

Table 3

SUNSHINE TEMPERATURE DATA FOR DEC - 1978

LIVING ROOM			STUDY		OUTSIDE		DAYS STATION		TUBES		
DATE	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	9 FT.	5 FT.	.5 FT.
1	68.0	64.0	68.0	66.0	53.6	48.2	53.0	48.0	72.0	71.0	70.0
2	72.0	64.0	74.0	66.0	59.0	53.6	61.0	41.0	75.0	71.0	69.0
3	72.0	64.0	76.0	65.0	59.0	50.0	59.0	33.0	76.0	71.0	69.0
4	73.0	64.0	74.0	64.0	55.4	37.4	58.0	32.0	75.0	71.0	68.0
5	73.0	67.0	76.0	63.0	53.6	44.4	58.0	34.0	74.0	70.0	68.0
6	70.0	62.0	74.0	64.0	53.6	37.4	54.0	36.0	72.0	69.0	68.0
7	69.0	58.0	73.0	64.0	48.2	37.4	49.0	32.0	70.0	67.0	66.0
8	69.0	58.0	72.0	64.0	46.4	26.6	48.0	26.0	70.0	67.0	64.0
9	69.0	67.0	74.0	64.0	44.6	20.0	48.0	27.0	71.0	67.0	65.0
10	70.0	63.0	72.0	64.0	50.0	33.0	51.0	28.0	71.0	64.0	65.0
11	72.0	64.0	74.0	65.0	53.6	39.2	53.0	30.0	72.0	68.0	64.0
12	70.0	64.0	72.0	64.0	55.4	42.0	56.0	34.0	70.0	68.0	64.0
13	70.0	64.0	71.0	64.0	59.0	46.4	60.0	33.0	70.0	68.0	64.0
14	72.0	64.0	75.0	64.0	51.8	41.0	62.0	32.0	70.0	64.0	64.0
15	73.0	64.0	76.0	65.0	50.0	46.4	62.0	29.0	72.0	69.0	66.0
16	72.0	63.0	74.0	64.0	60.8	30.0	61.0	24.0	71.0	68.0	64.0
17	70.0	63.0	71.0	64.0	50.0	37.4	49.0	40.0	70.0	64.0	64.0
18	71.0	64.0	69.0	64.0	50.0	41.0	50.0	34.0	69.0	68.0	64.0
19	70.0	63.0	74.0	64.0	46.4	35.6	48.0	34.0	70.0	68.0	66.0
20	71.0	67.0	75.0	64.0	48.2	34.0	48.0	28.0	71.0	69.0	67.0
21	72.0	62.0	75.0	62.0	46.4	30.0	47.0	29.0	70.0	68.0	64.0
22	72.0	62.0	74.0	63.0	51.8	30.0	54.0	28.0	70.0	67.0	65.0
23	69.0	62.0	68.0	61.0	41.0	32.0	38.0	30.0	70.0	68.0	66.0
24	70.0	62.0	66.0	61.0	41.0	35.6	39.0	33.0	71.0	68.5	66.0
25	70.0	64.0	67.0	63.0	41.0	38.3	40.0	34.0	70.5	68.5	64.5
26	69.0	62.0	66.0	61.0	41.0	35.6	40.0	35.0	70.0	68.0	65.5
27	69.0	63.0	64.0	61.0	40.1	35.6	38.0	34.0	69.5	67.4	65.0
28	70.0	62.0	64.0	61.0	42.8	37.4	40.0	35.0	70.0	68.0	64.0
29	70.0	63.0	66.0	61.0	42.8	39.2	44.0	34.0	69.0	67.0	66.0
30	70.0	67.0	71.0	61.0	52.7	30.0	41.0	27.0	70.0	68.0	65.0
31	69.0	67.0	74.0	61.0	42.8	26.6	43.0	24.0	72.0	69.0	65.0

TOT	2184.0	1944.0	2927.0	1970.0	1517.0	1137.6	1552.0	1010.0	2203.0	2118.0	2051.0

MEAN	70.5	62.0	71.8	63.5	49.4	37.3	50.1	32.0	71.1	68.3	66.2

ST OF	1.4	1.0	4.0	1.7	8.1	7.0	7.9	5.4	1.0	1.3	1.5

MAX	73.0	64.0	76.0	66.0	60.8	53.6	62.0	48.0	74.0	71.0	70.0

MIN	68.0	58.0	64.0	41.0	46.1	26.6	38.0	24.0	64.0	64.0	64.0

SUNNY	15420.0	12250.0	16043.0	12520.0	74035.4	44602.7	79354.0	34230.0	154640.5	144757.5	135769.5

SUNNY%	50.7	46.2	46.2	41.7	119.2	145.6	105.0	93.4	94.4	90.3	64.7

HOURS	3.0		10.0		670.7		731.0				

C00A9	55.0	93.5	0.0	0.0
H0067	20.5	28.5	732.2	793.0
C0067	10.5	46.0	0.0	0.0
H0070	103.0	73.5	825.2	896.0
C0070	0.0	4.0	0.0	0.0
H0075	180.5	149.0	987.7	963.5
C0075	0.0	0.0	0.0	0.0
AVE	66.7	67.7	43.4	41.4

Table 4

.....
 --- SUNCATCHER TEMPERATURE AND RADIATION DATA FOR DEC , 1978

.....
 -- TQAVIS STATION-FLYING ROOM HORIZONTAL RAD. VERTICAL RAD.

DATE	MAX	MIN	AVE	BTU/SQ.FT.	BTU/SQ.FT.
1	+13.0	-10.0	-15.5	879.3	1507.1
2	-11.0	-23.0	-17.0	850.8	1683.6
3	-13.0	-31.0	-22.0	868.2	1719.0
4	-15.0	-32.0	-23.5	850.0	1711.2
5	-15.0	-18.0	-16.5	810.9	1504.2
6	-16.0	-26.0	-21.0	956.7	1883.3
7	-20.0	-26.0	-23.0	936.2	1992.5
8	-21.0	-32.0	-26.5	855.1	1748.2
9	-23.0	-35.0	-29.0	746.2	1449.2
10	-19.0	-35.0	-27.0	855.1	1764.0
11	-19.0	-34.0	-24.5	711.4	1361.7
12	-14.0	-30.0	-22.0	543.9	977.2
13	-10.0	-31.0	-20.5	780.3	1342.3
14	-10.0	-34.0	-22.0	644.1	1764.0
15	-11.0	-35.0	-23.0	748.8	1602.0
16	-11.0	-39.0	-25.0	581.3	828.8
17	-21.0	-21.0	-22.0	309.6	374.2
18	-21.0	-26.0	-23.5	387.0	551.2
19	-22.0	-29.0	-25.5	851.4	1606.0
20	-23.0	-34.0	-28.5	803.5	1658.6
21	-25.0	-33.0	-29.0	840.4	1772.3
22	-18.0	-34.0	-26.0	741.7	279.0
23	-31.0	-32.0	-31.5	261.7	278.8
24	-11.0	-29.0	-20.0	226.5	214.3
25	-30.0	-30.0	-30.0	280.1	314.5
26	-29.0	-27.0	-28.0	217.5	194.0
27	-31.0	-29.0	-30.0	213.0	189.2
28	-30.0	-27.0	-28.5	405.4	508.3
29	-26.0	-27.0	-26.5	457.1	710.0
30	-29.0	-35.0	-32.0	748.2	1446.7
31	-26.0	-38.0	-32.0	718.8	1378.7

TOT	+634.0	+932.0	-783.0	19670.1	34786.0
MEAN	-20.5	-30.1	-25.3	672.9	1186.7
ST DF	7.0	5.2	4.5	252.2	675.9
MAX	-10.0	-18.0	-15.5	936.2	1992.5
MIN	-31.0	-39.0	-32.0	213.0	189.2
SUMMY	18456.0	28816.0	20379.0	10375194.5	55405569.7
SUMMYR	1449.7	704.9	601.9	1907522.5	1751721.7

Table 5

the program outputs an echo of the raw data files for error checks, the actual daily data of each of the daily measurements indicated above including actual meter readings and daily differences. Other electric usage and stove gas usage are calculated as residuals. Davis temperature data is used for the outside temperatures. The difference between living room temperatures and Davis stations data is calculated for maximum, minimum and average temperatures. The sum and the sum of the squares are calculated for all appropriate variables. Daily insolation data for a horizontal surface is directly input from U.C. Davis data and output. The radiation is converted to south vertical insolation on a daily basis and statistics are provided on south vertical as well as horizontal radiation. Using daily average temperatures heating degree days and cooling degree days to bases 65°, 67°, 70°, 72.5°F are calculated for inside and outside temperatures. Much of this data is used as an intermediate step in the graphic presentations.

2.3. Hourly Data Acquisition and DAS

After a variety of complications, the DAS started gathering data in August 1978, but despite several debuggings, system problems continued through May 1979; hourly data was gathered only sporadically, but with increasing reliability during this period. The DAS now functions well with only sporadic, routine problems.

2.3.1 Data Acquisition Equipment

A single board microcomputer does all the necessary collecting, storing, and initial processing of the data gathered from temperature sensors within the house. The central processing unit is an IMSAI 8048 computer controller interfaced to multiplexing, analog to digital conversion and amplification circuits for the respective sensor input signals. The 75 channels are first selected by a CMOS analog multiplexer, then amplified with a high performance modular CMOS chopper, and finally converted from analog to digital form using a monolithic successive approximation A/D converter with 8-bit resolution. The computer controls the multiplexing, amplification and conversion, and receives the 8-bit data words through its I/O PORT. Data is temporarily stored in random access memory (RAM) and later transferred to a paper tape punch. This microcomputer system is well suited to the relatively simple tasks required of it. Pre-processing of data is kept to a minimum since all programming is in machine language. Since interrupt capabilities of the 8048 have been pre-empted by a PROM monitor, the on-board timer is not available for providing the time during the data logging. Real time is provided by an external crystal controlled clock that is interrogated by the computer.

Figure 15

Figure 16

The paper tape is later transferred to magnetic tape for further reduction and analysis on the Burroughs B6700 computer at U.C. Davis.

The hardware configuration is illustrated in figure 15. All input channels are connected through the analog multiplexer to either the CMOS chopper amplifier, selected for low offset and high stability, and thence to one of three amplifiers, or straight through as in the case of the thermistor channel. One of the four modes is selected for input to the analog-to-digital converter (ADC). The ADC's output is connected to an 8048 I/O port. All the control and address lines (indicated in figure 16) are connected to the 8048 board. The 8048 instruction set and the large number of I/O lines make this microprocessor very useful for this data acquisition application. The board has 2000 bytes of random access memory, about half for storing the program and half for data.

2.3.2 The Data Acquisition Procedure for the DAS

The data acquisition proceeds as follows: the I/O select lines are set to the clock. Data from the clock is continuously brought in, displayed, and checked to see if minute is equal to 00. i.e., it is the hour. At the hour, the time is stored in the next location in the RAM buffer. The clock calendar mode is then selected and the data is likewise stored.

The following sequence occurs for each data channel. The channel address is selected using the seven address lines connecting the desired channel to the circuitry following. The mode (see table 6) for the selected channel is read from a table and then put out on the mode select lines to route the signal to the proper amplifier. Next, the system waits a few seconds to permit settling. The conversion begins as the computer sends a start (STRT) pulse to the ADC and waits for the end-of-conversion (EOC) response. The data is now stored in RAM, and also displayed in hexadecimal form as shown in figure 17. This process continues until the desired set of data channels is exhausted.

At this point the clock is interrogated again. If the hour is 09 or 21 (shortly after 9am or shortly after 9pm PST), the data for the previous 12 hours stored in RAM will now be punched out.

MODE NUMBER	AMPLIFIER SELECTED
0	Straight Through
1	Pyranometer
2	Copper-Constantan
3	Iron-Constantan

Table 6

Figure 17

The I/O select lines are set to paper tape punch. Data is retrieved from the buffer, a punch pulse is sent and then the computer waits for a punch ready signal before sending out the next data byte. The process continues until the buffer is emptied. When the buffer is emptied, a complete cycle of data acquisition and storage is completed.

2.4. Special Experiments

2.4.1 Suncatcher Radiation Mapping

Five times during the year, radiation mapping of the Suncatcher internal configuration and storage mass was carried out. At twelve stations (shown in figure 18) located in the hallway of the Suncatcher house, solar radiation was monitored hourly on the following days:

1. January 10, 1978
2. May 9, 1978
3. June 26, 1978
4. September 21, 1978
5. December 7, 1978

The data was taken in a vertical plane using a hand held Eppley double dome PSP pyranometer, except for locations number 10, 11 and 12 in figure 18, where radiation was measured in a horizontal plane.

Figure 18 Location of Radiation Measurements

2.4.2 Water/Tube Stratification

On the days of solar radiant mapping of the Suncatcher cone, hourly temperature data was taken for the water storage tubes from 8am to 6pm or later to determine the extent of thermal stratification of the water in the thermal mass storage closets. This data is presented in the next section, Performance Results .

3. PERFORMANCE RESULTS

3.1. Monthly Performance

Since the quickest overview of a solar house's performance can be given on a monthly and annual basis, we present the monthly data analyses of the Suncatcher's performance in three major graphs with a brief description of the analysis methodology.

3.1.1 Temperatures

The daily data is reduced to monthly averages by a computer routine which calculated monthly mean minimum, maximum and average temperatures for both inside and outside. The data presented in figure 19 below gives the monthly mean maximum, minimum and average, and extreme temperatures for the living room (see figure 4 also) and the Davis benchmark weather station. The graph also gives estimated, or when available, actual gas furnace usage in therms and monthly outside heating degree days to base 65°F. Generally, the temperatures inside the house were quite comfortable, although early morning low temperatures were noticeably cool in summer and winter. The worst winter low occurred in October 1978, when a low of 58°F was recorded on the living room max/min thermometer. This low occurred only when the occupants neglected to turn on the thermostat during a cold snap. The extreme maximum was 85°F and occurred only once. The temperature peaked at over 83°F on three to four separate days which proved to be uncomfortable in the early evening, primarily due to stagnant air conditions within the house. To account for variation in interior comfort conditions, a simplified, modified performance estimation technique has been developed to accommodate this data, but it has not yet been applied. This new technique will be explained and used in presenting 1979 performance estimates.

3.1.2 Utilities

Utility data for 1978 is shown in figure 20. This data includes both total therms and kilowatt hours for all uses including space heating and cooling. The dollar amount of the utility bills from Pacific Gas and Electric is also given and represents about one-fourth the average bill of a Davis single-family home. Note that gas usage in the summer is limited to the oven pilot, gas stove and oven usage, since hot water is exclusively supplied by the solar breadbox system.

Figure 19

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DAVIS ALTERNATIVE TECHNOLOGY ASSOCIATES

SUNCATCHER TEMPERATURES

1-3-79

A	~46	~33	7	0.8	0	0	0	0	0	0	11.7	30.5
B	443.5	426.5	257	282.5	39.5	0.5	0	0	13.5	49.5	460.5	731

C	73	61	73	69	79	77	77	82	81	94	83	106	83	104	84	108	80	96	78	96	78	81	73	62
D	70	56.6	70.6	57.6	73.7	66.5	73.2	66.6	76	80.6	77	87.6	78.5	93.3	77.5	92	76	85	75	85	72.0	61.3	70.5	50.1
E	66.6	50.7	67.6	49.8	70.7	56.7	70	58.6	71.1	66.3	78.9	70.7	73.3	74.5	73	74	71.6	69.4	70.3	66.3	69.5	49.4	66.7	41.5
F	63.1	44.9	64.5	41.9	67.7	66.9	66.8	44.6	66.2	51.9	66.9	53.8	66.2	55.8	68	56	67	54	65	48	66.1	37.5	62.0	32.0
G	60	33	62	33	63	37	63	35	60	42	63	47	63	49	61	50	62	44	58	40	64	28	50	24

A - AUX GAS USED

C - EXTREME MAXIMUM

E - AVERAGE

G - EXTREME MINIMUM

B - HEAT'G DEGREE DAYS

D - AVERAGE MAXIMUM

F - AVERAGE MINIMUM

SUNCATCHER MONITORING PROJECT
Utility Usage and Bills
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Figure 20

3.1.3 Monthly Solar Insolation

The monthly values of solar insolation for a horizontal and vertical surface are presented in figure 21, with normal average daily values included for comparison. The horizontal insolation is the average daily insolation for each respective month. The vertical values for both actual and normal are calculated for the horizontal values using the Liu-Jordan technique. In both cases the insolation was somewhat below normal, particularly for early 1978 during the anomalous winter of 1977-1978. December 1978, however, was above normal and solar performance of the Suncatcher reflects the additional solar heat gain during that month.

3.1.4 Overall Performance

The monthly solar contribution for solar heating is graphically depicted and tabulated in figure 22. The heating load is determined by multiplying the total heat loss coefficient of the house times the heating degree days for the month times twenty-four. (The heat loss coefficient changed during 1978 because of various improvements, such as Roman shades and a high quality thermal cat door). The internal load was determined from the data; estimates of metabolic heat from the human (and animal) occupants were deducted from the load. The furnace gas usage delivered was determined (with the application of 70% efficiency factor) from the data after March 1978. Before March 1978, the values were estimated from total gas usage and average heating; the winter of 1978-1979 appears to indicate an even higher percentage of solar heating attributable to thermal improvements during the summer of 1978. November and December achieved 81% and 71% solar respectively.

3.2. Daily Performance

The daily maximum and minimum values of inside (living room) and outside (Davis Weather Station) air temperatures plotted in parallel with the daily values of insolation on a horizontal surface appear in a combined graph in figure 24. This graph gives a quick overview of day to day performance as it relates to solar input. Solar radiation on a vertical facing plane is indicated from March 1978 to December 1978.

MONTHLY SOLAR INSOLATION

	(%) of <u>Normal</u>	<u>Measured</u> <u>Horiz.</u>	<u>Normal</u> <u>Horiz.</u>	(%) of <u>Normal</u>	<u>Calculated</u> <u>South Vert.</u>	<u>Normal Average</u> <u>South Vert.</u>
Jan	(86.9)	561	645	(87.9)	851	968
Feb	(72.9)	645	885	(61.6)	654	1062
Mar	(59.8)	849	1419	(54.2)	665	1226
Apr	(58.4)	1128	1933	(59.8)	658	1100
May	(71.1)	1650	2322	(78.8)	737	935
Jun	(89.9)	2279	2533	(93.8)	813	867
Jul	(98.5)	2509	2548	(101.3)	915	903
Aug	(97.2)	2194	2258	(99.9)	1096	1097
Sep	(94.4)	1731	1833	(97.5)	1333	1367
Oct	(96.8)	1249	1290	(105.1)	1458	1387
Nov	(86.1)	689	800	(90.4)	1055	1167
Dec	(109.1)	633	580	(127.0)	1187	935
Total	(84.6%)	16117	19046	(87.8)	11422	13014

Units are BTUs/ft.²/day

Figure 21

Figure 22

suncatcher Load and performance data

1978

- annual solar performance 69.7% of net Load

total Load
 internal gains
 % of total
 solar
 % of total
 % of net Load
 Furnace gas
 % of total
 % of net Load

6.86	6.58	3.97	4.36	0.92	0.88	0.00	0.00	0.16	0.60	5.67	8.85
1.28	1.10	1.09	1.10	1.00	0.88	1.14	1.14	0.98	1.13	1.28	1.44
19	17	27	25	100	100	100	100	100	100	23	16
2.39	3.37	2.40	3.20	0.00	0.00	0.00	0.00	0.00	0.00	3.56	5.28
35	51	61	74	0	0	0	0	0	0	62	60
45	61	83	98	0	0	0	0	0	0	81	71
3.19	2.11	0.48	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.83	2.13
46	32	12	1	0	0	0	0	0	0	15	24
57	39	17	2	0	0	0	0	0	0	19	29

- Inside daily maximum, degrees Fahrenheit
- Inside daily minimum
- Outside daily maximum
- Outside daily minimum

Figure 23

3.3. Hourly Performance

Although a great deal of hourly data has been collected, only small amounts have been reduced this year. We present here reduced data from December 7 and 8, 1978, which was gathered and reduced for comparisons to computer simulations.

3.3.1 Air Temperatures

Figure 24 gives interior air temperatures in the living room and the ceiling peak above the back-up heater, outside air temperature, and the mid-height temperature of the thermal mass storage wall. The interior temperatures were allowed to free-float on December 7 until 2200 when the back-up heater was turned on. Usually the back-up heater's operation can be inferred by the sharp spikes in the peak ceiling temperature. December 7 and 8 were both quite clear and cold days for Davis, California, the outside temperature reaching a low near the median of extremes for this climate. The clear skies assured a good solar input to the passive heating system. After 2200 on December 7, the back-up heater thermostat was set at 60°F for the night. This setting usually maintained a temperature of 62°F-63°F inside. During waking hours on December 8, the thermostat was reset to 65°F which would maintain 67-68°F minimum inside temperatures. Solar heating and stratification contributed to a steady temperature rise during daylight hours at the ceiling peak. Interior temperatures from midnight until 1000 were cool, but from 1000 to 1800 became quite comfortable with no back-up heating required.

3.3.2 Shell Surface Temperatures

The graphs that follow (figure 25,26,27) give the south wall interior and exterior temperatures, the Suncatcher aluminum roof temperature and the ceiling surface temperature directly below it, and the window interior and exterior surface temperature for a double-glazed north casement window during December 7 and 8, 1978. The temperatures display generally expected results. The exterior south wall heats dramatically during daylight hours as a result of the (solar energy) absorption on its light colored exterior. The unusual dip around noon is attributed to the shadow of part of the trellis crossing the sensor location. The temperatures indicate little or no heat loss from south walls between 1000 and 1500 on sunny winter days. The rise and drop off curves are sharp, because the walls are lightweight and the magnitude of the heat gain and losses are large relative to the wall's storage capacity. The interior wall temperature maximums are approximately

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Figure 25

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30°F above the outside wall surface temperature minimums because of high insulation R values (R-19 batts). These temperatures are generally within the comfort range, falling only slightly below it during early morning hours. The roof temperatures present a very similar picture, except that the external temperatures do not exceed the internal surface temperatures. This is a result of angle of incidence of the winter sun on the roof surface combined with the roof's reflective character. The difference in minimum temperatures remains close to 30°F even though the roof has more insulation (R-30 fiberglass batts). The window temperatures are also expected and their pattern similar, but offset by 8-10°F. The temperature pattern follows the outside with virtually no lag. Minimum internal surface temperatures are about 43-44°F for the double glazed windows.

3.3.3 Mass Temperatures

A. Water Wall

The water columns absorb solar energy and release it as heat during the course of a day. On December 7, 1978, the middle tube of the seven water filled, galvanized steel culverts absorbed 7425 BTUS and released 6030 BTUS for a net gain of 1396 BTUS. On December 8, 1978, this tube had a net gain of 4230 BTUS of energy due to solar and back-up heat input. The top of the tube reached a temperature maximum of 78.7°F while the bottom reached a maximum of 67.7°F on the same day, resulting in an 11°F stratification. This design thus has a carryover of about 24 hours if the temperatures of the house must be maintained above 63°F. Greater internal temperature fluctuations would increase the heat delivered by the mass and the storage time. Plots of the middle tube on December 7 and 8 are given in figure 29 along with a plot for a summer day for comparison, (figure 28).

B. Slab Temperatures

Slab temperatures are relatively dull, changing only a few degrees Fahrenheit at most. The slab in the hallway at the center of the house was the warmest, fluctuating between 67° and 70°F, an expected result due to the slab's solar exposure and central location. Although there were other slab sensors in the south study, furniture and other objects blocked the sun on those locations. Representative temperature plots for December 7 and 8, 1978, are given in figure 30.

JUNE 26, 1978
TEMPERATURE

WATERWALL TEMPERATURES **Suncatcher Monitoring Project**

Figure 28

9 FOOT WATERWALL TEMPERATURE
 5 FOOT WATERWALL TEMPERATURE
 0 1/2 FOOT WATERWALL TEMPERATURE
 STUDY TEMPERATURE
 OUTSIDE TEMPERATURE

Figure 29

Figure 30

3.4. The Suncatcher Reflective System

3.4.1 Description of Stations

The monitoring and radiation mapping procedure, described in section 2.3.2, was also used to monitor the Suncatcher reflective system. For a description of the procedure and instrument stations review section 2.3.2.

3.4.2 Hourly Graphic Results

The Suncatcher roof system performs well, showing substantial increases in the radiant energy transmitted through its clerestory double glazing as compared to a normal south facing double glazed window. This concentration of radiant energy peaked dramatically near solar noon, showing almost a doubling at that time. This result is to be expected from a reflective surface much more than twice the size of the glazing. The theoretical and experimental work of D.P. Gimmer et al.⁽¹⁾ documents this. Living Systems' staff anticipated these results in their design of the Suncatcher before the Gimmer article was published. Even at low, off axis angles at 4 hours from solar noon, the increase was 800 per cent over the south study windows. Summer data is interesting, but not crucial to overall performance because of the reflective, operable shutters. These shutters work quite well in summer, because of their reflective surfaces, even when not fully closed. In winter, shutters are more important for insulating.

3.4.3 Conclusions

The conclusions are summarized graphically in figure 32. This figure indicates:

- Winter energy increases of 40% over standard vertical south facing double glass
- Doubling of the diffuse sunlight in summer, i.e. over twice as much energy transmitted in summer when both Suncatcher windows and the south study windows are shaded from direct insolation by overhangs. This indicates a need for operable reflectors for the Suncatcher windows in summer to prevent overheating problems.
- The doubling of the diffuse sunlight in summer probably means similar gains in winter, although winter gains were not measured. This assumption implies positive heat balance in very cloudy weather for the Suncatcher windows. This will be measured during the grant extension period.

SUNCATCHER MONITORING PROJECT
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Figure 31

SUNCATCHER PERFORMANCE

Figure 32

REFLECTIVELY ENHANCED SOUTH CLERESTORY GLAZING

DOUBLE GLAZED WINDOWS
MEASURED DAILY TRANSMITTED RADIATION TOTALS

Generally, the Suncatcher design has many benefits in climates with little or no snow loads on roofs, although special care must be taken to avoid leaks because of the unusual roof configuration.

3.5. Breadbox Performance

3.5.1 Results

The breadbox solar water heater provided 100% of the hot water for three adults from June through October. During the rest of the year the breadbox heater acted as a preheater to the auxiliary gas domestic hot water heater. When the breadbox alone was used, the hot water temperature was occasionally cooler than desired (98-105°F or 37-40°C) for morning showers; for afternoons and evenings water temperatures were quite adequate, ranging from 112-130°F (44.4-54°C). Monitored temperatures on two sunny winter days, December 7 and 8, 1978 indicate input temperatures of about 62°F and water delivery temperatures to the water heater of 68-86°F, depending on the time of day of the usage. This indicates that substantial morning hot water needs preclude the use of breadboxes without nighttime insulation in the Davis climate in winter; however, an afternoon and evening load usage pattern would allow good winter preheating performance for this particular system. Increased gain by reflector and lowered losses by low emissivity coating of tanks are probably indicated, but further study of the breadbox design is needed. Computer simulations for other projects have indicated that lower temperatures are due to undersized glazing collector area for the breadbox relative to its tank's storage heat capacity, currently 3.30 gallons per square foot (136 lm^{-2} collector) would provide for higher temperatures without significantly greater losses, though it might lessen the ability of the system to withstand temperatures below freezing in winter.

3.5.2 Breadbox Performance Plots

Breadbox hot water temperature at the top rose from 95°F to 120°F on July 19-20th 1979. The measurements required running hot water and doubled the hot water demand of the household to 75 gallons for July 19. On July 20 measurements were taken less frequently to reduce the measurement load demand; performance was noticeably better, with a minimum of 113°F the morning after. The glazing of the breadbox was also quite dirty and cleaning it substantially improved performance. Since this particular system is under-glazed or over-massed, keeping the glazing clean is crucial. Performance results appear in figure 33.

Figure 33
SUNCATCHER MONITORING PROJECT
Breadbox Performance

4. PERFORMANCE VS. SIMULATION ESTIMATION METHODS

4.1. SOLSIM

4.1.1 Program Description

The thermal analysis program, SOLSIM, is based upon the same algorithms for shell heat transfer as the National Bureau of Standards Load Program, NBSLD, the GARD-GATX Post Office Program, and DOE1; however, there are differences. Unlike the two government programs, SOLSIM is primarily a design tool developed to:

- Ensure flexibility of usage
- Allow for expansion
- Evaluate solar system and energy conservation features of building design
- Allow for adaptability to different climatic conditions and usage schedules

SOLSIM can analyze any conventional building in virtually any climate zone, but its primary purpose is to analyze the thermal performance of passive solar systems in the climate of California's Central Valley. Other climates can also be easily analyzed by the input of readily available local weather information. The program simulates the internal air temperatures, mass storage temperatures, solar energy input through glazing, shutter, or drapery operations, internal heat and light loads, internal heat loads due to people, infiltration and ventilation, and response to external weather conditions.

The program outputs hour-by-hour temperature and heat flow analyses. These are again displayed in daily summaries for each building or floor as appropriate. The daily thermal exchange of each building elevation is printed separately to evaluate that elevation's performance. The heat storage is given for each type of heat storage device. If a multi-floored building is simulated, a summary of the daily performance for the whole building is printed at the end. A graph of external and internal air temperature along with storage temperatures may also be plotted at the user's option. Exterior shell elements are characterized by:

1. Opaque wall area
2. Transparent glazing area
3. R value of wall
4. R value of glass
5. Daily average shading coefficient of the wall

6. Daily average shading coefficient of the glazing
7. Orientation according to azimuth and tilt of the element
8. Construction type (TETD type from ASHRAE Handbook of Fundamentals)
9. Portion of glazing shuttered or thermally draped
10. R value of shutter/drape
11. Shutter schedule code

Various heat storage elements such as water cylinders, barrels, concrete slab, roof ponds, or Trombe walls may be investigated. Storage devices may be shuttered, exposed to the exterior, or totally enclosed within the building shell. They may vary in number and several characteristics:

1. Associated solar radiation element glazing, which tells the program where the sunlight is coming from
2. Number of identical units
3. Surface area of each unit
4. Location flag
5. Exterior insulation R value (operable)
6. Interior insulation R value (operable)
7. Portion of surface exposed to solar radiation (avg.daily)
8. Portion of surface exposed to interior
9. Portion of surface exposed to exterior
10. Portion of surface exposed to lighting
11. Portion of surface exposed to north sky
12. Mass of each unit
13. Specific heat of mass
14. Density of mass
15. Mass thickness (primarily for slabs)
16. Emissivity of mass surface

There may be up to five types of storage mass elements differing in any of these characteristics.

One of SOLSIM's unique features is its internal heat balancing sub-routine, TEMS, which allows evaluation of passive solar buildings or other buildings using thermal mass for heat storage. After determining the shell load, the external gain or loss is distributed among the various storage elements and the room air in a routine that calculates air, storage, and collector glazing temperatures. In order to maintain stability in the air temperature calculations, the time step had to be reduced to one-one hundredth of an hour. This is because small amounts of heat transfers to air can raise air temperatures substantially.

Recently, fluid transfer between storage elements was incorporated into the program to allow for more accurate evaluation of solar "breadbox" hot water heaters. This improvement allows the calculation of rock bed thermal performance using air as a heat transfer fluid. As is always true with computer programs, SOLSIM could be further improved. Its current weaknesses include single zone air temperatures, expensive calculations for more than a few days simulation,

and poor documentation. More validation is certainly desirable, especially for both energy conserving and passive solar houses in a variety of climates.

4.1.2

SOLSIM FLOW CHART

Figure 34

4.1.3 Results

On December 7 and 8, 1978, two cold but clear days in Davis, California, the DAS and D.A.T.A. staff recorded 43 hours of intensive measurements. These measurements were then compared to hour-by-hour simulations of the Suncatcher house. The simulation program, originally called HEAT, is currently termed SOLSIM, for solar thermal performance simulator. The simulator is not an electric analog model, but rather a finite difference physical analog using parameters related to actual construction or geometric qualities. A series of ten simulations was integrated against the full spectrum of temperature data to simulate performance. The final simulations mock the temperature performance of the thermal water mass quite well. The slab mass temperatures appear to be accurate, but the average slab temperatures is difficult to compare to the geometric temperature distribution of the slab. Air temperatures in the simulation cycle with a maximum of 6°F higher than measured temperature. This may be due to the program's assumption of full mixing of interior air, but any assumption changes likely to make the simulation more realistic would most likely also result in increasing the differences between the simulation and measured interior air temperatures. One possible explanation for the deviation is the chosen formulation for the convective film coefficient of vertical cylinders. If this coefficient does not accurately account for heat flows, the amount of heat from the mass to the air may change, but the heat transfers may make only small differences in mass temperatures. However, the same is not true of air temperatures, for small additions of heat to the air mean substantial temperature rises. The transfer coefficient dramatically affects the equilibrium temperatures of air.

The coefficient used assumes smooth surface cylinders. The actual surfaces of the water tubes are corrugated, and this may create turbulence at the boundary layer, thus increasing the convective heat transfer from the air to the water columns.

Other researchers have given verbal indications that even the plane vertical air film coefficient formulations in ASHRAE may be incorrect for surfaces within enclosures; however, it is not within the scope of this study to investigate this particular heat transfer coefficient. Hence, we can only suggest that further research needs to be done to investigate actual heat transfer coefficients. Our simple investigation seems to imply an increase by a factor of two. The true coefficient variation may be due to an incorrect exponent rather than the constant coefficient; thus a wide range of temperature differences need to be investigated, since

$$h_{air} \propto \Delta T^{\alpha} \text{ or } a \left[\frac{\Delta T}{L} \right]^{\alpha}$$

per ASHRAE Handbook of Fundamentals.

4.2. SOLEST

4.2.1 Program Description

This computer program uses a degree day method to estimate monthly and annual energy use for space heating and cooling. Degree day data is readily available for many localities. Degree-days to base 65°F are well correlated with the amount of natural gas used for space heating.

The algorithm used in the computer program for estimating energy consumption multiplies the monthly normal degree days times the "thermal area" of the residence times twenty-four to yield the monthly heat loss. However, this calculation does not account for the useful heat gain due to solar energy. Since all solar energy incident on glass is not usable for heating, the program calculates only the appropriate portion of average solar gain transmitted through south or nearly south glazing by first determining the "justified solar glass". Solar glass is vertical glass that faces within 90 degrees of south, or tilted glass within 50 degrees of south. Solar glass may be considered "justified solar glass" under two conditions.

1. Some of the heat from solar glass is needed to balance heat loss even on sunny days in the winter (usually cold and clear). This solar glass may be "justified" by the daytime heat loss of the structure.
2. Any additional heat from solar glass to be useful must be stored for later use in "thermal mass" in order to be "justified".

Thus solar glass may be "heat loss justified" or "thermal mass justified".

Some types of thermal mass may "justify" more glass than others. The program distinguishes the following general thermal mass types:

1. Sunlit water mass in containers
2. Shaded water mass in containers
3. Trombe walls (sunlit concrete walls 12" thick with sunlit side dark colored)
4. Shaded concrete wall
5. Sunlit concrete slab, covered by hard-surfaced floor
6. Shaded concrete slab, covered by hard-surfaced floor
7. Concrete slab, rug-covered or insulatively covered

Slab thickness is assumed to be at least 4 inches. Greater thicknesses are assumed to be beneficial in the short run (daily) only if both sides of the slab are available for heat exchange.

After the total amount of justifiable solar glass is determined, the minimum of the justifiable solar glass and actual solar glass is taken to be the "justified solar glass". The average insolation of vertical south glazing is used to determine the heat gain through the justified solar glass.

Other glazing orientations are weighted differently in calculating solar glass. The winter heat gain due to non-solar glass is ignored to allow a margin for error on the conservative side. The winter heat gain through the justifiable solar glass is deducted from the heat loss of the structure.

The method for estimating space cooling load is somewhat different. The heat gain calculation assumes a 90 degree outside temperature. It includes heat gain from "unshaded afternoon glass", which is west-facing glazing, skylights, a portion of the unshaded south glass and, "equivalent unshaded glass", which is the sum of all glazing areas times their respective mean daily summer shading coefficients, element by element.

This gain is reduced by the "peak cooling potential" of the thermal mass heat storage of the structure. The "peak cooling potential" is based on assumed temperature differentials between the various storage types and the design temperature of the air inside the house, usually 78°F. The surface area of the exposed thermal mass is used to calculate the "peak cooling potential." The assumed temperature differentials are based on empirical data derived primarily from the climate of California's Central Valley. The cooling credit is modified by other factors as well. One factor accounts for the estimated minimum temperature on a summer's day whose peak temperature reaches the summer design hour peak. Another is the ratio of heating degree to cooling degree days in the month under consideration. The exact weight of these factors is not known, but in practice the general trend and order of magnitude is realistic and probably within the limits of error of the other calculations. These formulations are used:

$PKCR_0 = \text{peak cooling credit due to cooled mass}$

$$PKCR_1 = PKCR_0 * \left[\frac{80^\circ\text{F} - \text{expected summer minimum daily temp.}}{20^\circ\text{F}} \right]$$

$$PKCR_2 = PKCR_1 * \left[1 + \frac{\text{monthly heating degree days}}{\text{monthly cooling degree days}} \right]$$

These factors are rationally based, but not experimentally demonstrated. To ignore them because they are not experimentally demonstrated would be to assume their effect to be zero, an assumption which would certainly result in a greater error than the one induced by the errors present in our assumptions.

The heating load annualization methodology resembles short calculation annualization used by public utilities and by solar researchers, and is based on degree days and "thermal areas." The solar contribution aspect of this calculation methodology has been ignored in traditional usage. Our methodology uses average monthly radiation incident on south-facing glazing to determine the solar contributions to heating. It would be better to use solar radiation deviation measures rather than averages, but this data is either unavailable or at best very difficult and expensive to obtain. To allow for the error introduced by the use of averages, the program reduces the collected solar energy by ten percent (10%). The cooling annualization is based on the number of annual dry bulb hours greater than 80°F or the number of annual wet bulb hours greater than 73°F. This measure has proven to be a reliable estimate of the relative cooling needs based on climate.⁽²⁾ Residential structure solar radiation loads will, however, vary the energy budget more than the climatic factor. Thus, the program calculates a "full load" cooling hour using both outside temperature and radiation factors, then annualizes this "full load" hour by using dry bulb hours over 80°F or wet bulb hours over 73°F.

4.2.2 SOLEST FLOWCHART

Figure 35

4.2.3 Results

The estimation program predicted a performance of 83% solar heating and 100% natural cooling for the Suncatcher. The house design analyzed was a thermally tight version with insulated shutters, some drapes, and low infiltration. Predicted gas usage for heating was 86.4 therms while 78.2 therms were actually used by the furnace. This prediction, however, ignores two facts: one, internal gains were not included in the usage estimate; and two, the house was not actually operated as designed. Using a more realistic evaluation of the house as operated with real weather data and subtracting internal heat gains for the heating season, yielded an estimate of 76 therms for November 1977 to January 1978. The estimate is quite good, although it is difficult to determine its accuracy except on this limited basis. Limitations notwithstanding, performance estimates for water walls and energy conserving houses in real operation can achieve reasonably good accuracy for California climates. Larger errors than design characteristic prediction errors will occur because of the differing lifestyles of building occupants. To evaluate this estimation procedure fully, more complete comparisons need to be done. The cooling estimate appears slightly high but still close to reality. It is more difficult to judge this estimate accurately due to lack of an important input, the annual hours over 80°F, for estimating the cooling load.

4.3. LASL6

4.3.1 Program Description

LASL6 is a microcomputer-based interactive program written in BASIC. It uses Balcomb's solar load ratio methodology for passive solar system types, such as mass storage walls and direct gain systems.(3)

LASL6 calculates the heat load, the estimated solar performance and also does an energy cost analysis. The program is documented in two parts. The users' package contains an input data sheet with references, a sample output and how to interpret it. The program package includes a flowchart, a listing of the program, a dictionary of variables used and other useful documentation. The losses from convection and conduction are given by the building skin conductance value, calculated from the areas and R-values or lengths and F-values. The losses due to infiltration (cracks, open doors, etc.) are calculated using the volume of the house and the design air changes per hour and are given by the infiltration load value. The building loss coefficient, the sum of the building skin conductance and the infiltration load, is displayed by the program. The thermal storage ratio, the mass times its heat capacity divided by the glazed collector area is used to calculate the adjusted solar absorptance value. This value is less

than the solar absorptance value for ratios less than 45, and greater for ratios larger than 45. The adjusted solar absorptance value is simply a convenient way to modify the method of handling buildings with thermal storage ratios different from 45 BTU/Ft.*degree F. The program lists the following input quantities: heating degree days, internal gains, and the calculated net load. The net load is estimated by multiplying the building heat loss coefficient times the heating degree days, and subtracting the internal gains of the building from people, stoves, dryers, etc. The net load represents the amount of heat needed to keep the building interior between 65-75°F. The solar radiation absorbed by a passive system depends on the sun's position, the actual radiation, the thermal mass, the solar absorptance and the latitude. The solar declination is given for the sun's position at midmonth at noon. The solar radiation data available is usually for a horizontal surface, and the program converts this value for a vertical surface. The thermal mass and solar absorptance are considered in the adjusted solar absorptance value. All of these factors are used to calculate the solar radiation absorbed by the Trombe wall, which determines the amount of heat available for heating the building.

The program also lists the calculated quantities solar load ratio, solar heating fraction and auxiliary energy. The solar load ratio is defined in the program as the solar radiation absorbed divided by the net load. The solar load ratio is used to determine the solar heating fraction which is the percent of the total load provided by the passive solar system. The auxiliary energy is the amount of heat that must be provided by an auxiliary source to meet the building's heating need. The last output section gives an estimate of the energy costs for the building. The fuel usage is the amount of gas that must be delivered to the heater to provide heat equivalent to the net load. The costs with solar and without solar represent the costs of heating the building in each case.

4.3.2 LASL6 FLOWCHART

Figure 36

4.3.3 LASL 6 Results

The designed version of the Nittler/Maeda house was run using the LASL6 program, which evaluates the house's passive performance using Balcomb's solar-load ratio technique. Using average climatic data, a solar heating performance rating of 84% was achieved. Comparing the house with actual 1978 data, a rating of 68% was found for that year which agrees well with the actual data; however, the house was not entirely finished with regards to its thermal performance for the winter months of early 1978. Hence this methodology appears to underestimate performance in this particular case. Two separate runs were combined to yield an auxiliary heating energy prediction for 1977. This is shown for both SOLEST and LASL6 and compared to the actual gas furnace output for 1978.

Table 7

Predicted Vs. Actual Auxiliary Energy Usage
(in Therms)

	Predicted (70% furnace efficiency)		Actual
	SOLEST	LASL6	
JAN	33.9	35.1	46
FEB	50.4	37.5	33
MAR	6.1	8.7	7
APR	14.1	14.3	0.8
Subtotal	105.3	95.6	86.8
NOV	4.0	16.8	11.7
DEC	38.1	50.7	30.5
Subtotal	42.1	67.5	42.2
TOTAL	147.4	163.1	137.6

Both SOLEST and LASL6 underestimated actual performance; however, in both cases night setback of temperatures are not accounted for by the programs. It is difficult to assess the effect of this on either program. SOLEST overestimates auxiliary energy use by 7.1%; LASL6 by 18.5%. It would appear that SOLEST is more accurate, but because of effects that cannot be readily evaluated, no firm conclusions can be made. In either case both are reasonably close to the inherent error in such calculations due to problems with estimating the infiltration load ($\pm 15-20\%$). Also in both cases, it appears that the programs can readily evaluate passive designs without the complexity of full year simulation.

5. GENERAL CONCLUSIONS

It is quite evident that the Suncatcher design provides a high percentage of solar heating, around 70%, and a high percentage of natural cooling, about 99.5%, at very low additional construction costs. When compared to similar sized houses built in Davis, the Nittler/Maeda Suncatcher had no additional costs, although the owners did help with construction and this may have reduced costs. Despite the relatively poor solar economics of the Davis area - a mild climate having low loads and available, cheap natural gas - the Suncatcher design has proven cost effective.

In addition to economics, the Suncatcher's comfort in terms of space conditioning is, according to its residents, exceptional. Although there were times when the house was noticeably uncomfortable, these periods were fewer than in other houses the residents had occupied. The quality of comfort provided was also distinctive and both Davis Alternative Technology Associates and the residents feel that the house's performance can and will be improved.

Perhaps, the following figures of energy use for the Nittler/Maeda Suncatcher (figure 37) are the best summary of our conclusions. Utility data for the Suncatcher was from September 1977 to September 1978. Davis' energy usage rose during 1978, but exact figures were not available when the following graph was drawn. Data for Village Homes was only available for 1977 and applies only to the first phase of the development's construction.

Although the residents do not have a full range of appliances, their lifestyle is quite comfortable. They are careful about their energy use, and the solar design makes it possible for them to achieve substantial energy savings without compromising their comfort.

Due to these results and solar design calculations for over 350 passive solar houses all around the country, including Alaska and California, and from the work of others in passive solar energy, Davis Alternative Technology Associates feels that all new housing (everywhere in the United States including Alaska) can achieve over 60% solar heating and natural cooling over and above the effects of good insulation alone. This can be done cost effectively using any of a variety of passive solar designs. We feel that this can be done as long as the political will exists to achieve such goals, people are given appropriate information and choices, and a carefully designed regulatory strategy is implemented.

Figure 37

6. ACKNOWLEDGEMENTS

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7. FOOTNOTES

- (1) "Augmented Solar Energy Collection Using Different Types of Planar Reflective Surfaces: Theoretical Calculations and Experimental Results" by D.P. Grimmer, K. Zinn, K.C. Herr, and B.E. Wood, presented to International Solar Energy Society, American Section Annual Meeting, "A Solar World" June 1977.
- (2) Designing, Building, and Selling Energy Conserving Houses, NAHB Research Foundation, Inc.
- (3) Program method from: Balcomb, J.D., and McFarland, R.D., "A Simple Empirical Method for Estimating the Performance of a Passive Solar Heated Building of the Storage Wall Type". Printed in the proceedings of the Second National Passive Solar Conference, Philadelphia, Pa., March 16-18, 1978.