392
11-20-80
v
SAND80-0599
Unlimited Release
UC-62b

Dr. 2028

1

Performance of a Solar-Heated Assembly Building at Sandia National Laboratories

Dale E. Haskins

MASTER

Prepared by Sandia National Laboratories, Albuquerque, New Mexico 87185 and Livermore, California 94550 for the United States Department of Energy under Contract DE-AC04-76DPO0789

Printed September 1980

Sandia National Laboratories

DISCLAIMER

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

DISCLAIMER

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

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

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

Printed in the United States of America

Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes

Printed copy: \$6.00

Microfiche copy: A01

SAND80-0599
Unlimited Release
Printed September 1980

Distribution
Category UC-62b

PERFORMANCE OF A SOLAR-HEATED ASSEMBLY BUILDING AT
SANDIA NATIONAL LABORATORIES

Dale E. Haskins
Experimental Systems Operations Division 4721
Sandia National Laboratories
Albuquerque, NM 87185

ABSTRACT

This report describes the passive solar-heating system of the assembly building at Sandia National Laboratories' Photovoltaic Advanced Systems Test Facility, and gives the thermal analysis of the building. Performance predictions are also given, and actual performance for December 1979 and January 1980 are shown.

DISCLAIMER

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

ACKNOWLEDGMENT

The performance of the assembly building's passive heating system described in this report is the result of the work of several people and organizations.

The architectural and engineering firm of Gordon Herkenhoff & Associates made the initial building design tradeoffs which led to the selection of the water wall passive solar heating system for the building. They also generated the additional building structural cost data used in this report as the basis for cost tradeoffs in their design studies. These same data, with adjustments to correct for late design changes, are used to determine the cost of the water wall addition to the building.

Personnel in the Plant Engineering Department at Sandia National Laboratories contributed to the final building design by participating in the decision-making processes during the design tradeoff stages.

The research and technical writing for this report were done under contract to Sandia National Laboratories by Tech Reps, Inc. of Albuquerque, New Mexico.

CONTENTS

	<u>Page</u>
Introduction	9
Description of the Building	9
Plans	9
Walls	10
Roof and Ceiling	14
Floor and Foundation	14
Water Wall (Thermal Storage System)	15
Auxiliary Heat	15
Lighting	15
Domestic Hot Water	17
Operation	17
Climate	18
Thermal Analysis	20
Building Load Coefficient	20
Performance Estimate	21
Standard Metal Building Option	24
Effect of Asphalt Apron on Thermal Performance	24
Possible Methods of Improving Solar Heating Performance	24
Costs	26
Performance	30
APPENDIX A--Method of Correction for Change in Ground Reflectance	35
APPENDIX B--Cost Evaluation Method	41
References	45

ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Floor Plan of Assembly Building	11
2	South Elevation of Assembly Building	12
3	Cross Section of Assembly Building	13
4	Completed Assembly Building	13
5	Detail of Foundation Footing	14
6	Water Storage Tubes Set in Place Prior to Installation of Glazing	16
7	View of Base of Containers Before Painting	16
8	Completed Installation of Water Tubes	17
9	Temperature Distribution Pattern for Albuquerque	18
10	Annual Degree Days as a Function of Base Temperature (Albuquerque Data)	20
11	Electrical Energy Price Rise Predictions	29
12	Data Recorded at Assembly Building, December 24-29, 1979	31
13	Data Recorded at Assembly Building, January 20-25, 1980	31
14	Number of Hours Within Each 5°F Temperature Bracket for December 1979	32
15	Number of Hours Within Each 5°F Temperature Bracket for January 1980	32

TABLES

<u>Table</u>		<u>Page</u>
1	Basic Information	10
2	Climate and Insolation Summary	19
3	Degree Days per Month, 10°C (50°F) Base Temperature (Albuquerque Data)	20
4	Building Load Coefficient Computation	21
5	Computations for Annual Solar Heating Fraction	23
6	Effect of Asphalt Apron (Reflectance = 0.05) on the Annual SHF	25
7	Effect of Specular Reflector ($\rho = 0.8$) on the Annual SHF	25
8	Maximum Effect of Whitewash ($\rho'_g = 0.6$) on the Annual SHF	26
9	Cost Estimate for Standard Metal Building	27
10	Cost Estimate for Solar-Heated Building	28
11	Levelled Annual Energy Cost for Electric- Heated, Standard Metal Building	29
12	Computation of Solar Heating Fraction for December 1979 and January 1980	33

8a

PERFORMANCE OF A SOLAR-HEATED ASSEMBLY BUILDING AT SANDIA NATIONAL LABORATORIES

Introduction

The assembly building at Sandia National Laboratories' Photovoltaic Advanced Systems Test Facility derives all its space heat from passive solar energy. The building does not have an auxiliary heating system.

The great potential for energy conservation offered by passive solar systems makes the thermal performance of the building a matter of special interest. The purposes of this report are to describe the design of the building, review the thermal analyses used to predict the performance of the building, make a cost comparison with a standard metal building, and present performance data for the first winter. Basic information is given in Table 1.

Description of the Building

Plans

The floor plan, south elevation, and a cross section of the building are shown in Figures 1, 2, and 3, respectively. The building is a standard, preengineered, metal structure (butler building) erected on a concrete floor slab on grade. Figure 4 is a photograph of the completed building.

Walls

The steel frame walls are sheathed on the outside with 26-gauge, galvanized steel panels with a prefinished exterior surface. The inside is sheathed with 29-gauge, prefinished, white liner panels. The wall cavity is insulated with 7.5-cm (3-in.) fiberglass batt taped to the inside face of the metal siding. The west wall is penetrated by one 0.9 x 2.1-m (3 x 7-ft) hollow, metal frame door and one 2.7 x 3.7-m (9 x 12-ft) insulated, metal overhead door. The east wall is penetrated by one 0.9 x 2.1-m (3 x 7 ft) hollow, metal frame door. There are no penetrations in the north wall. The south wall incorporates the solar collector described below.

Table 1

Basic Information

Type of Construction	Preengineered, metal, highbay butler building
Dimensions	7.6 x 15.2 x 4 m high (25 x 50 x 13 ft high)
Floor Area	116 m ² (1250 ft ²)
Heating System	Passive solar water wall
Auxiliary Heating System	None
Location	Photovoltaic Advanced Systems Test Facility Sandia National Laboratories Albuquerque, NM
Geographic Coordinates	35°03'N, 106°33'W
Elevation	1676 m (5500 ft)
Architect/Engineer	Gordon Herkenhoff & Associates, Inc
Owner	Sandia National Laboratories, Albuquerque, NM

Figure 1. Floor Plan of Assembly Building

Figure 2. South Elevation of Assembly Building

Figure 3. Cross Section of Assembly Building

Figure 4. Completed Assembly Building

Roof and Ceiling

The roof is 26-gauge galvanized steel with a prefinished, colored exterior. The roof has a 0.9-m (3-ft) eave extension overhanging the south wall to shade the solar collector during the summer. The suspended ceiling is insulated with 15-cm (6-in.) fiberglass batts.

Floor and Foundation

The floor slab is 15-cm(6-in.)-thick reinforced concrete to support vehicle loading. The concrete foundation footing is insulated with 5 cm (2 in.) of expanded polystyrene board which extends above the grade to meet the wall panels. The polystyrene board is protected from the weather by a 2.5-cm (1-in.) layer of stucco. A detail of the foundation design is shown in Figure 5. This design reduces thermal losses around the perimeter. However, no thermal break is provided in the concrete floor slab where it passes under the overhead door.

Figure 5. Detail of Foundation Footing

Water Wall (Thermal Storage System)

The solar collector for the assembly building is a water wall built as an integral part of the building's south wall. Two 3 x 6-m (10 x 20-ft) openings are cut into the south wall. The openings are glazed with SUNWALL[®] panels manufactured by the Kalwall Corporation, Manchester, N.H. Extruded aluminum grids form the cores of the panels. Sheets of fiber-glass-reinforced polymer, 1 mm (0.04 in.) thick, are pressure-bonded on each side of the grid cores. Each panel measures 1.2 x 3.0-m (4 x 10 ft).

The panels are 3.8 cm (1-1/2 in.) thick. Ten of these panels are mounted in the water wall for a total area of 37 m² (400 ft²). The solar transmissivity of this panel is reported to be

77% at 0-deg angle of incidence

73% at 30-deg angle of incidence

65% at 45-deg angle of incidence

48% at 60-deg angle of incidence

The water storage tubes are mounted directly behind the glazing panels. Each tube is nominally 46 cm (18 in.) in diameter and 3 m (10 ft) tall, with a storage volume of 0.5 m³ (17.67 ft³). There are 26 of these water storage tubes, giving a total storage capacity of 13,000 kg (28,660 lb) of water. The tubes are made of fiberglass-reinforced polymer sheets with sealed bottoms and fiberglass caps and are painted on the exterior with flat black latex paint. Photographs of the water storage tubes as seen during the construction of the building are shown in Figures 6, 7, and 8.

Auxiliary Heat

The assembly building does not have an auxiliary heating system.

Lighting

Six halogen lamps light the interior. They consume approximately 100 W each.

Figure 6. Water Storage Tubes Set in Place Prior to Installation of Glazing (Tubes are not yet painted black. Fiberboard shipping containers are lying in the foreground.)

Figure 7. View of Base of Containers Before Painting

Figure 8. Completed Installation of Water Tubes

Domestic Hot Water

The bathroom in the northeast corner of the building includes a hot water heater. In accordance with Sandia's energy conservation policies, the hot water heater has been turned off and consumes no energy.

Operation

Solar radiation transmitted through the glazing on the south wall is absorbed on the black-painted surfaces of the water storage tubes. The heat is conducted through the tube wall to the water within the tube. Convection currents move the heated water so that the tube surfaces facing the interior work space become warm. Heat is transferred to the workspace by radiation and by air convection currents. There are no temperature controls for the system. Temperature moderation is dependent on the design and balancing of the thermal components (e.g., the glazing area on the south wall, the thermal mass in the water tubes, building insulation and heat loss rate, ambient temperature, and solar insolation).

Climate

The design of a solar-heated building is strongly dependent on the local weather conditions and on the availability of solar energy. Table 2 is a climate and insolation summary extracted from References 1 and 2.

The "degree days" (DD) shown in Table 2 refer to a base temperature of 18°C (65°F). Because of the working environment, the design temperature selected for the interior of the building was 10°C (50°F), so new degree-day data was computed. Ambient temperature data for this purpose was extracted from Reference 3. A yearly summary of the hourly temperatures is shown in Figure 9.

Figure 9. Temperature Distribution Pattern for Albuquerque

The number of degree days rapidly decreases as the base temperature is reduced. The relationship is shown in Figure 10. The degree days per month for the months November through April (the heating season in Albuquerque) for a 10°C (50°F) base temperature are given in Table 3.

Table 2
Climate and Insolation Summary

Site Name--Albuquerque, N.M.				Latitude--35.050				Longitude--106.620					
Ashrae* Design Condition													
Winter 97-1/2%													
Dry bulb (DB) temp 8.3°C; 94°F													
Wind speed low													
Summer 2-1/2%													
DB temp 34.4°C; 94°F													
Wet bulb temp 18.3°C; 65°F													
Design Relative Humidity 20°													
Degree Days													
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Heating	°C	513	389	331	156	32	0	0	0	4	121	342	496
	°F	924	700	595	282	58	0	0	0	7	218	615	893
Cooling	°C	0	0	0	3	37	162	236	200	89	4	0	0
	°F	0	0	0	6	67	291	425	360	160	7	0	0
Percent Possible Sunshine													
		70	72	72	76	79	84	76	75	81	80	79	70
Average Ambient Temperature Range													
Max DB	°C	8.0	11.2	14.9	20.6	25.7	31.4	32.9	31.1	27.9	21.5	13.4	9.1
	°F	46.4	52.2	58.8	69.1	78.3	88.6	91.2	88.0	82.3	70.7	56.1	48.3
Min DB	°C	-4.7	-2.5	0.4	5.7	11.1	16.2	18.8	17.9	14.2	7.4	-0.5	-3.6
	°F	23.5	27.5	32.7	42.2	51.5	61.1	65.8	64.3	57.6	45.3	31.1	25.6
Average Daily Incident Radiation													
Horiz.	kWh/m ²	3.58	4.50	6.00	7.30	8.29	8.63	7.39	7.23	5.87	6.23	3.80	3.48
	Btu/ft ²	1136	1427	1903	2116	2630	2738	2343	2292	1861	1658	1205	1105
Direct	kWh/m ²	6.77	7.11	8.48	9.10	10.00	10.40	8.43	8.90	7.37	8.19	6.90	7.23
	Btu/ft ²	2149	2254	2591	2887	3172	3299	2691	2824	2337	2599	2189	2292
Effective Atmosphere Factors													
Clearness No.		0.96	0.87	0.99	0.92	1.17	1.17	1.03	1.10	0.93	1.05	0.97	1.14
Cloud Factor		0.84	0.85	0.85	0.87	0.89	0.92	0.87	0.866	0.90	0.89	0.89	0.84
Average Daily Incident Radiation on a South-Facing Wall													
kWh/m ²		5.72	5.33	4.78	3.56	2.70	2.46	2.66	3.48	4.77	5.49	5.47	5.77
Btu/ft ²		1814	1691	1515	1130	859	780	844	1103	1512	1742	1736	1829

*American Society of Heating, Refrigerating, and Airconditioning Engineers

Figure 10. Annual Degree Days as a Function of Base Temperature (Albuquerque Data)

Table 3

Degree Days per Month, 10°C (50°F) Base Temperature (Albuquerque Data)

	<u>Nov</u>	<u>Dec</u>	<u>Jan</u>	<u>Feb</u>	<u>Mar</u>	<u>Apr</u>	<u>Annual*</u>
°C	131	244	253	173	118	37	987
Degree Days							
°F	236	439	455	312	212	66	1777

*Includes degree days not shown in Nov-Apr columns

Thermal Analysis

Building Load Coefficient

The building load coefficient (BLC) quantifies the rate at which a building loses heat or the additional energy required to increase the building temperature one additional degree. The BLC for the assembly

building is 8052 W·h/DD (15 264 Btu/DD). The computations are shown in Table 4.

Table 4
Building Load Coefficient Computation

Surface	Area		U-Value		U x A	
	m ²	(ft ²)	W/m ² .°C	(Btu/ft ² .°F.h)	W/°C	Btu/°F.h)
Water wall	37	(400)	1.87	(0.33)	70	(132)
Opaque walls	129	(1388)	0.51	(0.09)	66	(125)
Ceiling	116	(1250)	0.28	(0.05)	33	(63)
Floor*	--	--	--	--	--	--
Rolling door	11	(120)	0.62	(0.11)	7	(13)
Personnel doors	4	(42)	1.36	(0.24)	<u>5</u>	<u>(10)</u>
Building skin conductance = 181						(343)

*The floor is not considered a load at a building working temperature of 50°F.

Because of the difficulties associated with sealing the rolling door, building infiltration is expected to be one air change per hour.

$$\begin{aligned} \text{Infiltration} &= 16,250 \text{ ft} \times 1 \times 0.018 = 155 \quad (293) \\ &= 336 \quad (636) \end{aligned}$$

Modified BLC = 8064 Wh/DD (15,264 Btu/DD)

Unmodified BLC = 6384 Wh/DD (12,096 Btu/DD)

Performance Estimate

Los Alamos Scientific Laboratory has developed methods for estimating the annual solar heating performance of a building using a water wall thermal storage system.⁴ The method has been applied to the assembly building and indicates that 91% of the annual building heat load will be provided by solar heat. Conversely, 9% of the annual building heat load

must be supplied by auxiliary heating sources. Since the building does not have an auxiliary heat source, the temperature is expected occasionally to fall below the design temperature of 10°C (50°F.) The computations for this estimate are given in Table 5. The column entries in Tables 5 through 8 are described below:

- Column 1: The month of the year
- Column 2: The number of degree days in the month. In this case, a 10°C (50°F) base temperature is used.
- Column 3: The building heat load for the month, obtained by multiplying Column 2 by the BLC (in this case, BLC = 15 264 Btu/DD). It should be noted that Reference 4 defines the load coefficient for the entire building as the "MODIFIED BLC." If the losses through the solar collector are ignored, the resulting coefficient is defined as the "UNmodified BLC."
- Column 4: The total monthly solar radiation incident on 1 ft² of horizontal surface. This figure is extracted from available tables.
- Column 5: The latitude (L) at the location of the building minus the sun's declination (δ) at midmonth.
- Column 6: The solar radiation absorbed by the solar collector. This entry is derived from the entries in Columns 4 and 5 by an empirical relationship given in Reference 4.
- Column 7: The ratio of the entry in Column 6 to the entry in Column 3.
- Column 8: The fraction of the monthly heating load (Column 3) supplied by solar heat. This entry is derived from the solar load ratio (SLR) (Column 7) by a second empirical relationship given in Reference 4.
- Column 9: The energy needed from an auxiliary heating system to keep the building at the design temperature of 10°C (50°F).

Table 5

Computations for the Annual Solar Heating Fraction

<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>8</u>	<u>9</u>
Month	Degree Days °C (°F)	Monthly Load kWh/mo (MBtu/mo)	Total Solar Radiation on Horizontal Surface kWh/mo·m ² (Btu/mo·ft ²)	Latitude Minus Sun Declination (Degrees)	Solar Radiation Absorbed by Solar Collector kWh/mo (MBtu/mo)	Solar Heating Fraction SHF	Auxiliary Heater Required kWh/mo·m ² (MBtu/mo)
Nov	131 (236)	1055 3.602	117 (36,960)	53.66	45,552 (14.44)	0.998	0.3 (0.001)
Dec	244 (439)	1963 6.701	100 (31,558)	58.18	44,637 (14.15)	0.883	230 (0.784)
Jan	253 (455)	2035 6.945	110 (34,375)	56.50	46,909 (14.87)	0.887	230 (0.785)
Feb	173 (312)	1395 4.762	126 (39,872)	49.07	42,429 (13.45)	0.954	64 (0.219)
Mar	118 (212)	948 3.236	184 (58,466)	37.89	42,208 (13.38)	1	0 (0)
Apr	37 (66)	295 1.007	216 (68,400)	25.95	31,767 (10.07)	1	0 (0)
	956 (1 720)						524.3 (1.789)

$$\text{Annual SHF} = 1 - \frac{\text{Annual Auxiliary Energy}}{(\text{Annual DD})(\text{UNmodified BLC})} = \frac{1.94}{1\,720 \times 12\,096} = 0.91$$

Standard Metal Building Option

If the solar heating option had not been selected for the building, a standard metal building of the same dimensions would have been used. The BLC for such a building would be 6836 W.h/DD (12,960 Btu/DD), assuming the solar collector is replaced with wall panels. Annual fuel consumption for this building would be 6533 kW.h (22.3 MBtu). Because no auxiliary heating system is included in the assembly building, this figure represents the annual energy savings. However, it is expected that the assembly building occasionally may drop below the design temperature while the "standard" metal building would not, at least as long as fuel is available.

Effect of Asphalt Apron on Thermal Performance

An extensive area of black asphalt paving lies on the south side of the assembly building. The reflectance of the asphalt (ρ_g) is estimated at 0.05 which is less than the ground reflectance of 0.3 used in Reference 4. Columns 2, 3, 4, and 5 are omitted from Table 6 because the data in those columns are identical to those in Table 5. The data show a reduction of only 2% in the annual solar heating fraction (SHF) due to the poor reflectance of the asphalt. However, the annual auxiliary heating requirement is increased by 30% which would be significant if the assembly building were provided with auxiliary heat.

Possible Methods of Improving Solar Heating Performance

Reference 4 furnishes a method for estimating the enhancement of performance when specular reflectors are placed on the ground in the front of the solar wall. The reflectors considered must be the same dimensions as the glazing on the solar wall and must be placed horizontally, adjacent to the vertical glazing. The reflectance is specified as 0.8. For the assembly building, these standards require that two reflectors, each 3 x 6.1 m (10 x 20 ft), be placed flat on the asphalt on the south side of the solar wall. The results of applying this correction are shown in Table 7. The reflectors increase the amount of radiation absorbed by the wall (Appendix A). The computation indicates an annual SHF of 96%, an increase of 7% over the plain asphalt case (Table 6).

Table 6

Effect of Asphalt Apron (Reflectance = 0.05) on the Annual SHF

<u>1</u>	<u>6</u>		<u>7</u>	<u>8</u>	<u>9</u>	
Month	Solar Radiation Absorbed by Solar Collector		Solar Load Ratio	Solar Heating Fraction	Auxiliary Heating Required	
	kWh/mo	(MBtu/mo)	(SLR)	(SHF)	kWh/mo	(MBtu/mo)
Nov	3 850	(13.14)	3.65	0.990	11	(0.036)
Dec	3 821	(13.04)	1.95	0.858	279	(0.952)
Jan	4 000	(13.65)	1.96	0.861	283	(0.965)
Feb	3 531	(12.05)	2.53	0.931	96	(0.329)
Mar	3 323	(11.34)	3.50	0.985	14	(0.049)
Apr	2 247	(7.67)	7.62	1	0	(0)
					683	(2.33)

$$\text{Annual SHF} = 1 - \frac{2.33 \times 106}{1\,720 \times 12\,096} = 0.89$$

Table 7

Effect of Specular Reflector ($\rho = 0.8$) on the Annual SHF

<u>1</u>	<u>6</u>		<u>7</u>	<u>8</u>	<u>9</u>	
Month	Solar Radiation Absorbed by Solar Collector		Solar Load Ratio	Solar Heating Fraction	Auxiliary Heating Required	
	kWh/mo	(MBtu/mo)	(SLR)	(SHF)	kWh/mo	(MBtu/mo)
Nov	5 324	(18.17)	5.04	1	0	0
Dec	5 125	(17.49)	2.61	0.938	122	(0.415)
Jan	5 470	(18.67)	2.67	0.942	118	(0.403)
Feb	4 984	(17.01)	3.57	0.987	18	(0.062)
Mar	4 644	(15.85)	4.90	1	0	0
Apr	2 792	(9.53)	9.46	1	0	0
					258	(0.880)

$$\text{Annual SHF} = 1 - \frac{0.880 \times 10^6}{1\,720 \times 12\,096} = 0.96$$

Since the asphalt apron is a working area for the photovoltaic test facility and is subject to traffic, it may not be practical to lay specular reflectors there. An alternate method of improving the SHF is to whitewash the asphalt in front of the solar wall. Since reflection in this case would be diffuse, a very large area would need to be whitewashed to be effective. The maximum possible improvement attainable by whitewashing can be estimated by assuming the ground reflectance to be the same as for whitewash. Table 8 summarizes the computations for the annual SHF assuming a ground reflectance (ρ'_g) of 0.6. A maximum increase of approximately 4% is indicated for the whitewash modification over the plain asphalt case.

Table 8

Maximum Effect of Whitewash ($\rho'_g = 0.6$) on the Annual SHF

<u>1</u>	<u>6</u>		<u>7</u>	<u>8</u>	<u>9</u>	
<u>Month</u>	Solar Radiation Absorbed Solar Collector kWh/mo	(MBtu/mo)	Solar Load Ratio (SLR)	Solar Heating Fraction (SHF)	Auxiliary Heating Required kWh/mo	(MBtu/mo)
Nov	4685	(15.99)	4.44	1	0	0
Dec	4533	(15.47)	2.31	0.908	180	(0.616)
Jan	4785	(16.33)	2.35	0.913	177	(0.604)
Feb	4430	(15.12)	3.18	0.973	38	(0.129)
Mar	4641	(15.84)	4.89	1	<u>0</u>	<u>0</u>
					395	(1.349)

Annual SHF = 0.935

Costs

Prior to construction of the assembly building, cost estimates were made for a standard metal butler building with an electric heating system and for several alternate forms of solar-heated buildings. The water wall solar-heated building was shown to be the least costly of the alternate forms. The cost estimates for the standard building and the water wall

solar-heated building are shown in Tables 9 and 10. Common items (e.g., foundation, slab floor, grading) have been omitted from these estimates since they do not affect the cost differential between the two types of buildings. The tables show that the solar option cost \$4511.00 more than a standard metal building with electric heat.

The standard building costs less to build but there is an annual heating bill which must be paid over the lifetime of the building. An evaluation of the economics of buying the solar option instead of the standard building (with electric heat) must consider both the additional capital costs of the solar option, \$4511.00, and the annual heating costs for the standard building. The method chosen here to make the comparison is the one used by the Office of Technology Assessment, Congress of the United States.⁵ The essential aspects of the method are shown in Appendix B.

Table 9

Cost Estimate for Standard Metal Building

<u>Item</u>	<u>Unit</u>	<u>Quantity</u>	<u>Unit Price</u>	<u>Amount</u>
Building Shell consisting of steel frame, metal siding, wall and roof insulation, and metal liner panel	ft ²	1 250	\$ 7.50	\$ 9,375.00
Electric unit heaters (complete)	Ea	2	830.00	1,660.00
SUBTOTAL				\$11,035.00
5% Contingency				<u>552.00</u>
SUBTOTAL				\$11,587.00
25% Overhead, profit, tax, and bond				<u>2,897.00</u>
TOTAL				\$14,484.00

Table 10

Cost Estimate for Solar-Heated Building

Item	Unit	Quantity	Unit Price	Amount
Basic building shell (see Table 9, building shell)	ft ²	1 250	\$ 7.50	\$ 9 375.00
Deduct south wall panels	ft ²	525	-1.30	-683.00
Deduct south wall insulation	ft ²	525	-0.40	-210.00
Deduct south wall liner panel	ft ²	400	-1.00	-400.00
3-ft 0-in. roof overhang	Linear feet	50	13.83	692.00
Solar thermal storage tubes, 10 ft long by 18 in. diameter	Ea	26	91.50	2 379.00
Caps for tubes	Ea	26	7.00	182.00
SUNWALL® glazing panels 4 ft by 10 ft	Ea	10	131.50	1 315.00
Painting of tubes	Ea	10	12.00	120.00
Glazing of frame and installation	Linear feet	228	7.47	1 703.00
SUBTOTAL				\$14 473.00
5% Contingencies				<u>724.00</u>
SUBTOTAL				\$15 197.00
25% Overhead, profit, tax, and bond				<u>3 799.00</u>
TOTAL				18 996.00
Less basic metal building				<u>14 484.00</u>
COST DIFFERENTIAL FOR SOLAR HEATED BUILDING				\$ 4 511.00

The levelled capital costs of the solar option are \$529.86 per year over a period of 20 yrs. The 20-yr period for evaluation is arbitrarily selected. A discount rate (d) of 10% was used, as recommended for government agencies by the Office of Management and Budget.⁵

The levelled purchased energy costs were computed for two different inflation rates (6% and 12%) and for two different energy price escalation rates (2X and 5X). The 2X energy price escalation rate assumes that energy prices expressed in constant 1976 dollars will eventually stabilize at a price twice what they were in 1976 (Appendix B). A similar assumption pertains for the 5X rate, with energy prices, expressed in constant 1976 dollars, projected to stabilize at 5 times their 1976 level. Both of these price projections are plotted in Figure 11 for 1980 through 2000, the 20-yr evaluation period. The resulting levelled purchased energy costs over the 20-yr evaluation period for each case considered are shown in Table 11.

Figure 11. Electrical Energy Price Rise Predictions

Table 11

Levelled Annual Energy Cost for Electric-Heated, Standard Metal Building

Fuel Cost Escalation Rate	Inflation Rate	
	6%	12%
2X	\$433.34	\$ 782.29
5X	\$762.15	\$1427.43

Comparing the levelled capital cost for the solar option, \$529.86, with the levelled fuel costs for the standard building shows that the solar option is an economically justified choice in all cases except one: the case of combined low inflation rate and low energy cost escalation.

Performance

Temperature measurements were made at the assembly building to determine the actual building performance. The inside air temperature was measured by a thermocouple on the north side of the building. This thermocouple was shielded from the water wall so that radiation from the water wall would not affect the measurement. The outside ambient temperature was measured by a thermocouple (shielded from the sun) located on the north side of the building. Measurements were recorded on a chart recorder approximately every 20 min from December 1979 to January 1980. Samples of the recorded data are shown in Figures 12 and 13. The solar input scale in Figure 12 is uncalibrated. In Figure 13 the solar input is the record from a calibrated pyranometer (Eppley PSP) mounted between the windows on the south wall.

An analysis of the ambient temperatures showed there were 489 degree days at base temperature 10°C (50°F) during December 1979 and 420 degree days during January 1980. The number of hours within each 5°F temperature bracket is shown in Figures 14 and 15.

Solar radiation data were obtained from the U. S. Weather Bureau located at the Albuquerque airport, only a few miles from the solar facility location. Because of equipment failures, some of the daily total horizontal radiation measurements were missing. Estimates for these missing measurements were made based on the percent sunshine measurements which were available for the entire month.

Figure 12. Data Recorded at Assembly Building, December 24-29, 1979

Figure 13. Data Recorded at Assembly Building, January 20-25, 1980.

Figure 14
Number of Hours Within Each 5°F
Temperature Bracket for December
1979

Figure 15
Number of Hours Within Each 5°F
Temperature Bracket for January
1980

With the above figures as input data, the solar heating fraction for the month of December 1979 and January 1980 were computed. The results are shown in Table 12.

Table 12

Computation of Solar Heating Fraction
for December 1979 and January 1980

	Dec 1979	Jan 1980
Degree days, °C (°F)	272 (489)	233 (420)
Monthly load, kWh/mo (MBtu/mo)	2,186 (7.46)	1,878 (6.41)
Horizontal solar radiation, kWh/m mo (Btu/ft mo)	86.1 (27,288)	78.73 (24,957)
Latitude minus declination, deg	58.18	56.50
Solar radiation absorbed, kWh/mo (MBtu/mo)	3,305 (11.28)	3,118 (10.64)
Solar load ratio	1.51	1.66
Solar heating fraction	0.76	0.80
Auxiliary heating required, kWh/mo (MBtu/mo)	524 (1.79)	375 (1.28)

These results indicate that auxiliary heating should have been required to keep the building temperature above 10°C (50°F) or, because no furnace was installed, the room temperature should have dropped below 10°C (50°F). A review of the temperature records shows that the room air temperature did not go below 10°C (50°F) at any time during these months; the minimum temperature was 10.6°C (51°F). The unexpectedly efficient performance of the passive solar heating system can probably be attributed mainly to the high thermal mass of the water wall and to the added thermal mass of the bare concrete floor.

The December 1979 weather characteristics (increased degree days and reduced solar insolation) are a severe test of a passive solar heating system. The ambient temperature data show that no severely cold days occurred in December 1979. However, in New Mexico severe cold is accompanied by clear weather and high insolation, and the assembly building heating system responds favorably to such conditions as shown by the January 1980 performance data.

The performance data confirm the practicality of the passive solar heating system for the photovoltaic facility assembly building.

APPENDIX A

Method of Correction for Change in Ground Reflectance

APPENDIX A

Method of Correction for Change in Ground Reflectance

SYMBOLS

H = daily total radiation incident on a surface

τ = transmission coefficient

α = absorption coefficient

ρ = reflectance coefficient

L = latitude in degrees

δ = sun's declination in degrees

$F(L - \delta)$ = the vertical wall absorptance factor defined in Reference 4

SUBSCRIPTS

FIRST SUBSCRIPT

D -- indicates direct radiation

d -- indicates diffuse radiation

r -- indicates reflected radiation

T -- indicates total radiation

g -- indicates ground

SECOND SUBSCRIPT

h -- indicates horizontal surface

v -- indicates vertical surface

The total radiation on a vertical surface, H_{Tv} , is

$$H_{Tv} = H_{Dv} + H_{dv} + H_{rv} ,$$

where

$$H_{dv} = 1/2 H_{dh} \text{ and } H_{rv} = 1/2 \rho_g H_{Th} ;$$

∴

$$H_{Tv} = H_{Dv} + 1/2 H_{dh} + 1/2 \rho_g H_{Th} .$$

$F(L - \delta)$ is defined as

$$F(L - \delta) = \frac{\tau \alpha H_{Tv}}{H_{Th}} ,$$

where

τ = fraction transmitted

and

$$\alpha = 1 .$$

The energy transmitted through the glazing and absorbed is

$$F(L - \delta) H_{Th} = \tau H_{Tv} = \tau_D H_{Dv} + \tau_d (1/2 H_{dh} + \tau_d (1/2 \rho_g H_{Th})) ,$$

where

τ_D = transmittance of direct radiation and is dependent on angle of incidence

and

τ_d = transmittance of diffuse radiation.

Reflection is assumed to be diffuse reflection, not specular. Reference 4 used $\rho_g = 0.3$ for the ground reflectance. If the ground reflectance is changed to ρ'_g , then the energy transmitted through the glazing is

$$F'(L - \delta) H_{Th} = \tau_D H_{Dv} + \tau_d (1/2 H_{dh} + \tau_d (1/2 \rho'_g H_{Th}))$$

The difference in energy absorbed by the wall due to a change in ground reflectance is

$$F(L - \delta)H_{Th} - F'(L - \delta)H_{Th} = 1/2 \tau_d H_{Th} (0.3 - \rho'_g) ,$$

which gives

$$F'(L - \delta) = F(L - \delta) - 1/2 \tau_d (\rho_g - \rho'_g)$$

for

$$\rho'_g = 0.05 \text{ (black asphalt)}$$

$$\tau_d = 0.70 \text{ (estimated hemispherical diffuse transmittance for standard SUNWALL® panel)}$$

$$F'(L - \delta) = F(L - \delta) - 0.0875$$

APPENDIX B
Cost Evaluation Method

APPENDIX B

Cost Evaluation Method

SYMBOLS

CRF(d, L) -- capital recovery factor for a loan at interest d over L years

d -- consumer's discount rate

i -- annual rate of inflation

K -- initial cost of facility expressed in current dollars

L -- period over which system costs are evaluated

P(t) -- unit fuel cost in year t

P -- assumed stable fuel cost in future

t -- the year of system operation under consideration

t_0 -- an adjustable constant for P(t)

T_r -- an adjustable constant for P(t)

The "capital recovery factor," CRF(d, L), is the ratio between the annual payments on a loan and the initial value of the loan if it is for L years and pays an interest rate d.

$$CRF(d, L) = \frac{d(1 + d)^L}{(1 + d)^L - 1}$$

The levelized annual capital cost = CRF(d, L) x K where K is the initial cost.

The form used to predict fuel cost, $P(t)$, is

$$P(t) = P_{\infty} \left[1 - \exp\left(\frac{t_o - t}{T_r}\right) \right]$$

For the 2X fuel cost escalation model, the values for the parameters are

$$P = 0.0608 \text{ (\$/kWh) ,}$$

$$t_o = 1956.4, \text{ and}$$

$$T_R = 28.334 .$$

For the 5X fuel cost escalation model, the values of the parameters are

$$P = 0.1522 \text{ (\$/kWh) ,}$$

$$t_o = 1969.7, \text{ and}$$

$$T_R = 28.334 .$$

The value of $P(1976)$ is \$0.03044 for both the 2X model and the 5X model. The year 1976 is the base year. Fuel costs given by this model are expressed in constant 1976 dollars.

The levelized annual fuel cost, P_L , is found from

$$P_L = CRF(d, L) \sum_{t=1}^L P(t) \left(\frac{1+i}{1+d} \right)^t .$$

This appendix was extracted from Reference 5.

References

- ¹Handbook of Fundamentals (New York: American Society of Heating, Refrigerating, and Airconditioning Engineers, 1977).
- ²T. Kusuda and K. Ishii, Hourly Solar Radiation Data for Vertical and Horizontal Surfaces on Average Days in the United States and Canada, U. S. Department of Commerce, NBS Building Science Series 96 (Washington, D.C.: Government Printing Office, 1977).
- ³Engineering Weather Data, Department of the Army Technical Manual 5-785 (Washington, D.C.: Government Printing Office, 1978).
- ⁴J. D. Balcomb and R. D. McFarland, A Simple Empirical Method for Estimating the Performance of a Passive Solar Heated Building of the Thermal Storage Wall Type, LA-UR-78-1159 (Los Alamos, NM: Los Alamos Scientific Laboratory, 1978).
- ⁵U. S., Congress, Office of Technology Assessment, Application of Solar Technology to Today's Energy Needs (Washington, D.C.: Government Printing Office, September 1978).

DISTRIBUTION:

TID-4500-R68 UC-62b (333)

American Section of the International
Solar Energy Society, Inc.
P. O. Box 1416
Killeen, TX 76541
Attn: J. Kincel

Honorable Pete V. Domenici
Room 405
Russell Senate Office Bldg.
Washington, D. C. 20510

EPRI
3412 Hillview Avenue
Palo Alto, CA 94303
Attn: J. E. Bigger

Georgia Institute of Technology
Atlanta, GA 30332
Attn: J. D. Walton

Georgia Power Company
Atlanta, GA 30302
Attn: Mr. W. Hensley
Vice President Economics Services

Green Mountain Homes
Royalton, VT 05068
Attn: J. Kachadorian

Mike Hansen
Pecos Benedictine Abbey
Pecos, New Mexico 87552

Bruce Hunn
300 Valle Del Sol
Los Alamos, New Mexico 87545

Mark Jones
P. O. Box 892
Santa Fe, New Mexico 87501

Kalwall Corp.
P. O. Box 237
Manchester, N.H. 03105
Attn: S. Keller

Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720
Attn: M. Wallig

Lawrence Livermore Laboratory
University of California
P. O. Box 808
Livermore, CA 94500
Attn: W. C. Dickinson

Los Alamos Scientific Laboratory (10)
Los Alamos, NM 87545
Attn: J. D. Balcomb
C. D. Bankston
D. P. Grimmer
S. W. Moore
R. D. McFarland

Honorable Manuel Lujan
1324 Longworth Building
Washington, D. C. 20515

New Mexico State University (5)
Las Cruces, NM 88001
Attn: E. Lumsdaine
H. Zwibel (NMSEI)

Office of Technology Assessment
Old Immigration Bldg., Rm. 722
119 D. Street, N. E.
Washington, D. C. 20002
Attn: H. Kelly

One Design, Inc.
Mountain Falls Route
Winchester, VA 22601
Attn: T. J. Maloney

Parallax, Inc.
P. O. Box 180
Hinesburg, VT 05461
Attn: D. C. Taff

Honorable Harold Runnels
1535 Longworth Building
Washington, D. C. 20515

Honorable Harrison H. Schmitt
Room 1251
Dirksen Senate Office Bldg.
Washington, D. C. 20510

Shepley Bulfinch Richardson & Abbott
1 Court Street
Boston, MA 02108
Attn: G. W. Zwart

DISTRIBUTION: (cont)

New Mexico Engineering Research Institute
University of New Mexico
P. O. Box 25
Albuquerque, NM 87131
Attn: G. Leigh

Solar Energy Research Institute (11)
1536 Cole Blvd.
Golden, CO 80401
Attn: C. J. Bishop
K. Brown
B. L. Butler
K. Haggard
M. Holtz
F. Kreith
C. Grosskreutz
B. P. Gupta
A. Rabl
Library (2)

TEA, Inc.
Church Hill
Harrisville, NH 03450
Attn: B. Anderson

Tech Reps, Inc. (10)
540 Chama, N.E., Suite 1
Albuquerque, NM 87108

Thayer School of Engineering
Dartmouth College
Hanover, NH 03755
Attn: A. O. Converse

Office of Solar Applications (4)
for Buildings
U. S. Department of Energy
Washington, D. C. 20545

U. S. Department of Energy (5)
Albuquerque Operations Office
P. O. Box 5400
Albuquerque, NM 87115
Attn: B. Barattino

U. S. Department of Energy (50)
Division of Passive Heating
and Cooling
20 Massachusetts Avenue
Washington, D. C. 20585

U. S. Department of Energy (4)
Division of Photovoltaics
Energy Systems
Washington, D. C. 20545

University of New Mexico (2)
Department of Mechanical Engineering
Albuquerque, NM 87113
Attn: W. A. Cross
M. W. Wilden

Edward Maeria & Associates
400 San Felipe Rd, NW
Albuquerque, NM

1000	G. A. Fowler
1100	C. D. Broyles
1230	W. L. Stevens
1232	S. D. Spray
1472	L. G. Rainhart
1500	W. A. Gardner
1540	R. L. Brin
1550	F. W. Neilson
1552	O. J. Burchett
1714	R. E. Reed
1714	B. G. Prentice
2300	J. C. King
2320	K. Gillespie
2323	C. M. Gabriel
2326	G. M. Heck
2532	R. A. Hayenga
2533	J. K. S. Walters, Jr.
3161	J. E. Mitchell
3162	C. J. Mora
3600	R. W. Hunnicutt
	Attn: H. H. Pastorius, 3640
3650	R. E. Hepplewhite
3651	S. L. Johnson
3652	V. O. Ealey
3700	J. C. Strassell
4000	A. Narath
4200	G. Yonas
4231	J. H. Renken
4311	W. J. Shock
4332	J. M. Parvin
4337	W. C. Nickell
4362	W. W. Wagoner
4500	E. H. Beckner
4700	J. H. Scott
4710	G. E. Brandvold

DISTRIBUTION: (cont)

4713 B. W. Marshall
4714 R. P. Stromberg
4715 R. H. Braasch
4719 D. G. Schueler
4719 D. E. Haskins (25)
4720 V. L. Dugan
4721 J. V. Otts
4722 J. F. Banas
4723 W. P. Schimmel
4725 J. A. Leonard
4725 F. F. Rush
4730 H. M. Stoller
4740 R. K. Traeger
8100 W. J. Spencer
8112 J. D. Gilson
8200 A. N. Blackwell
8250 L. E. Davies
8400 L. Gutierrez
8450 R. C. Wayne
8452 A. C. Skinrood
8453 W. G. Wilson
8266 E. A. Aas
3141 T. L. Werner (5)
3151 W. L. Garner (3)
for DOE/TIC (Unlimited Release)