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Passive Test-Cell Experiments During the Winter of 1979-8

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Passive Test Cell Experiments During the Winter of 1979-80

Jack C. Hyde

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PASSIVE TEST CELL EXPERIMENTS DURING THE WINTER OF 1979-80

by

Jack C. Hyde

ABSTRACT

During the winter of 1979-80 the Los Alamos National Laboratory Solar Energy Group monitored the performance of a variety of passive solar heating configurations in 14 passive test cells. The cells included attached greenhouses, masonry and water walls with black-chrome absorber surfaces, night insulation, and phase-change thermal storage walls. The results of these side-by-side tests allowed us to make quantitative comparisons of the delivered performance of these configurations for the conditions under which they were tested.

I. INTRODUCTION

The Solar Energy Group at the Los Alamos National Laboratory built its first passive test building in 1976 (Refs. 1 and 2). The building had two side-by-side rooms, 5 ft wide by 8 ft deep, each having 45 ft² of south-facing glazed area. One cell had a Trombe wall and the other had a water wall. The cells ran without auxiliary power and served to provide experimental data for validating passive solar computer performance simulation models. Because the results of one winter of testing were very useful, six additional buildings were constructed in 1977 (Ref. 3). This brought the total number of cells to 14. During the winter of 1977-78, we tested several night insulation methods, various storage walls, and several glazing configurations. The results from these tests indicated that we could obtain information that was more useful if the test buildings had auxiliary heating systems and thermostats. We made these additions in 1978. In 1979, all cells

were equipped with measured, forced infiltration that effectively eliminated varying infiltration loads due to varying wind conditions.

In 1980 we developed quantitative comparisons between several passive concepts on the basis of the experimentally derived net solar energy delivered and the solar savings fractions (SSFs). We experimented with black-chrome absorbers on Trombe walls and water walls, allowing us to intercompare the performance of selective absorbers, flat-black absorbers, and night insulation. For example, the results show, under particular testing conditions, whether a masonry wall with black chrome and a single glazing performs better than a flat-black wall with double glazing, or how a black-chrome wall without night insulation compares to a flat-black wall with night insulation.

We also tested phase-change storage materials. The main questions were: After many cycles, will these materials provide the useful thermal storage when placed in a wall that would be expected from laboratory behavior? How does the energy delivery of a phase-change storage wall compare to that of a masonry wall under the same weather conditions?

II. DESCRIPTION OF THE PASSIVE TEST CELLS

A. Construction

The test buildings are small, wood frame structures divided into two equal-sized cells by a wall running north to south. All of the buildings are identical, except for the original building housing Cells 1 and 2. This original building is slightly different in size and was built by a different contractor so that some construction features are different from the other cells. None of the differences is significant. Figure 1 shows dimensions of the standard test building as configured for the 1979-80 winter. The floors are 3/4-in. plywood over 2-by-6 joists running east and west. The first four joists from the south wall are on 6-in. centers, and the rest are on 16-in. centers. The floor is insulated with two layers of R11, 3-1/2-in. fiberglass with foil backing. The ceiling has 2-by-6 rafters running east and west on 16-in. centers and is insulated with two layers of the R11 fiberglass. The outside walls consist of 2-by-4 studs on 16-in. centers with 5/8-in. plywood on the outside and insulated with one layer of R11 fiberglass covered on the inside with a sheet of 1-in.-thick rigid polystyrene. The interior wall

DIMENSIONS IN INCHES

$A - \text{GLAZED} = 44 \text{ ft}^2$
 $A - \text{FLOOR} = 40 \text{ ft}^2$
 $L_C = 28 \text{ Btu/h } ^\circ\text{F}$
 (3 AIR CHANGES / HOUR)
 $LCR = 15$
 $T_{\text{ref}} = 80 \text{ } ^\circ\text{F}$

Fig. 1.
Passive test building dimensions.

separating the two test cells is made of 2 by 4s on 16-in. centers with one layer of R11 fiberglass, sandwiched between two 1-in. rigid polystyrene sheets.

B. Glazings

The south-wall apertures of all of the cells, except Cells 11 and 13, were glazed with 1/8-in. Acrylite[®] (acrylic). We used acrylic because it is lightweight, less fragile than glass, and has the same transmittance. It is, however, more expensive than glass and scratches easily. Cell 11 was glazed with Acrylite[®] SDP, which is a commercial double glazing. Cell 13 had no transparent wall. The unshaded, glazed area of all of the cells was 44.2 ft², except for the cells with Beadwall[®] insulation (Cells 7 and 8), which had 41.0 ft² of glazed area, and Cell 11, which had an area of 45.9 ft².

C. Test Configurations

We set up the initial configurations in October 1979 and made small changes during the heating season. Table I lists the configurations tested. The Trombe walls were stacks of 16-in. by 6-in. by 8-in. solid concrete blocks weighing 56 lb each. The blocks were about 5 years old and were well cured.

Cell 1 was a Trombe wall with a flat-black surface. Cell 2 was identical to Cell 1, except that a selectively absorbing surface, Berry Solar Products black-chrome-coated foil, was glued onto the concrete with Devcon F epoxy cement. After two years of testing the black-chrome foil, we removed it from the wall to change the wall configuration for a new test. Inspection showed that the adhesive-to-concrete bond left numerous voids when it was originally applied. Voids of 1 in. diam were seen; 50 to 75% of the applied area was bonded. We saw no evidence of the adhesive failure except around the edges, which showed some tendency to peel off. Manufacturers of the black-chrome foils have been studying the problem of attaching the foil to concrete surfaces during the past several years and will supply recommendations regarding their products to potential users. Cell 1 served as a reference cell against which we could compare the performance of Cell 2, thereby obtaining quantitative comparisons between a new concept and a well-understood reference. All of the other cells were tested in pairs. Cells 5 and 6 had storage walls consisting of three 18-in.-diam tubes, filled with water to a depth of 9 ft. The absorbing surface on the tubes in Cell 5 was black chrome, and Cell 6 had a flat-black absorber. We used a high-temperature contact cement to attach the foil to the fiberglass tubes. It was very difficult to obtain a wrinkle-free surface; however, the resulting contact area was about 90% of the cemented surface, and the bond obtained did not fail during the period observed. Cells 1, 2, 5, and 6 were tested with single and double glazing, both with and without polystyrene-board night insulation on the flat-black cells.

Cells 3 and 4 each had identical, attached greenhouses built as add-ons to the basic cells with Trombe walls. Cells 7 and 8 had Beadwall[®] night insulation systems. The beads in Cell 7 were cycled in at 4:30 p.m. and out at 8:00 a.m. We did not operate the bead insulation system in Cell 8 in order to evaluate the performance increment due directly to the bead insulation.

TABLE I
TEST CELL CONFIGURATIONS FOR 1979-80

<u>Cell</u>	<u>Configuration</u>	<u>Storage</u>	
1	Flat-black Trombe wall	2 rows of 9 blocks 12 rows of 10 blocks	7590 lb concrete
2	Black-chrome Trombe wall	Same as 1	
3	Attached greenhouse	Same as 1	
4	Attached greenhouse	Same as 1	
5	Black-chrome water wall	3 Kalwall 18-in. tubes 9 ft high	2980 lb water
6	Flat-black water wall	Same as 5	
7	Flat-black Trombe wall with Beadwall [®] insulation	2 rows of 9 blocks 12 rows of 11 blocks	8250 lb concrete
8	Same as 7		
9	Flat-black Trombe wall Double glazed	Same as 7	
10	CaCl ₂ ·6H ₂ O tube wall Double glazed	29 3-1/2-in. tubes	725 lb CaCl ₂ ·6H ₂ O
11	Direct gain Acrylite SDP	not recorded	
12	Flat-black Trombe wall Double glazed	Same as 7	
13	Reference cell, no transparent area	No storage	
14	4-in.-thick CaCl ₂ · 6H ₂ O wall, double glazed	21 rows, 5 boxes per row	1020 lb CaCl ₂ ·6H ₂ O

Cell 10 had a phase-change storage wall consisting of a set of commercially available units of CaCl₂·6H₂O encased in 3-in. PVC tubes. Cell 9 was a reference Trombe wall, operated at the same conditions as Cell 10. Cell 11 was a direct-gain cell, and Cell 12 was another reference Trombe wall. In Cell 13, we installed an insulated stud wall on the south side in place of the glazed aperture and storage wall that we had on the other cells.

Cell 13 was, therefore, identical to the other cells, but without the solar feature, and served as a reference for all of the solar configurations. Cell 14 had a phase-change storage wall consisting of a slurry of $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ and diatomaceous earth in 5-in. by 5-in. by 12-in. rectangular, plastic, "bread boxes."

Each cell had an auxiliary power system consisting of six 100-W light bulbs and a thermostat to turn on the power when the cell temperature dropped below a selected level. We also installed a small blower to force outside air into each test cell. The air passed through a calibrated flow nozzle used to monitor the flow rate of air forced into the cell. Forcing a measured amount of air into the cells with the blowers caused cracks and holes in the cells to be exit leaks, and only the known flow rate from the blowers entered the buildings. This resulted in a known infiltration rate at all times.

D. Instrumentation

The data logging system consisted of a Hewlett-Packard 9820 desk-top calculator, two HP3495A scanners, an HP3490A digital volt meter, and two HP9875 tape drives. The scanners sequentially connected inputs from 160 data channels to the voltmeter, which read the inputs and fed them into the calculator. The calculator retained running sums of the key measurements and calculated averages each hour. At the end of each hour, the calculator stored all of the data on a magnetic tape.

The most important measurements for calculating performance from the test cells were the cell globe temperature, T_{cell} , the outside air temperature, T_{∞} , the total insolation on a vertical surface, I_v , and the auxiliary energy used, q_{aux} . We used Type K thermocouples (Chromel Alumel) in black plastic bulbs to measure T_{cell} and an Epply PSP pyranometer to measure I_v . We measured q_{aux} using a device that emitted a 1-V signal when the lights were on and no signal when they were off. During each scan, the calculator logged whether or not the power was on at the instant a cell was interrogated. If it was on, we assumed that the power was on for the complete time increment of approximately 1 minute since the last scan. The energy used each hour was taken to be 0.6 kWh, multiplied by the number of scans during which the auxiliary system was on, and divided by the total number of scans. This method assumes that each light bulb produced exactly 100 W and that all of the light bulbs were working. The test cells had watt-hour meters to provide an independent measure of the auxiliary energy. Each morning we checked to see if any bulbs were burned out and recorded the watt-hour meter reading.

In addition to cell temperature and q_{aux} , each cell had eight other data channels available for measurements such as temperature profiles within Trombe walls. We used Type K thermocouples for these measurements.

The accuracy of the results of the test program was directly dependent on the accuracy of the auxiliary energy measurements. Over a large number of scans (for example, 1 day--1440 scans) the calculation integration itself is sufficiently accurate. We measured current and line voltage for a group of light bulbs selected at random. The hot-filament resistance of individual bulbs computed from these measurements varied less than 0.5% from the mean.

Variations in line voltage can produce significant errors because the power output of the bulbs is proportional to the line voltage. Normal line voltage variations produce the largest error in instantaneous power measurements, but should have a minor effect on the integrated results. We checked the accuracy of the auxiliary energy measurements directly by comparing the integrated output from the calculator to the energy recorded by the watt-hour meters on each of the cells from 8:00 a.m. on February 29 to 8:00 a.m. on March 31. Table II summarizes the results. The calculator results agreed very well with the watt-hour meters on all cells except Cells 4 and 11, which had failures in the measurement system during this period. The two methods agreed within 1% for half of the cells.

TABLE II

AUXILIARY ENERGY MEASUREMENT CHECK FROM
8:00 A.M., FEBRUARY 29 TO 8:00 A.M., MARCH 31

Cell	Calculator Method (kWh)	Watt-Hour Meter (kWh)	Calculator/Meter
1	542.5	556.9	1.027
2	487.9	487.3	0.999
3	95.5	93.2	0.976
4	218.4	264.0	1.211
5	358.3	360.8	1.007
6	528.8	543.0	1.027
7	481.1	478.9	0.995
8	528.9	533.0	1.008
9	Power off		
10	Power off		
11	75.1	63.2	0.842
12	522.0	541.2	1.037
13	996.3	1002.3	1.006
14	68.2	68.3	1.001

III. TEST PROGRAM

We began data acquisition in early November. Most of November was devoted to checking the system changes that were made during the summer and to measuring load coefficients. The load coefficient, L_c , is defined as the power required to maintain a unit temperature difference between the heated space and ambient atmosphere, in the absence of any gains or losses through the solar aperture of the cell. In order to measure load coefficients, we covered the south wall of the test building housing Cells 11 and 12 with a 12-in.-thick polystyrene wall ($R \approx 6$ per in.), sealing the edges carefully to eliminate air leaks between the insulation and glazing. With the glazed area covered, the total energy input to the cells was the auxiliary energy. Figure 2 shows the measured load coefficients for Cells 11, 12, 13, and 14 from November 22 to December 8. These tests directly measured the auxiliary energy required per degree difference between cell temperature and outside temperature for losses through all surfaces except the south wall, which had essentially infinite insulation during the tests. Thus, L_c was directly measured. The infiltration blowers were off during these measurements. At that time, Cell 14 was identical to Cell 13, except that the insulation was removed between two studs on the north wall to increase the load coefficient.

Fig. 2.
Load coefficient comparison between Reference Cell 13 and
Test Cells 11 and 12 with insulated cover on south wall.

The results show that the load coefficients (L_c) for Cells 11 and 12 are about the same as for Cell 13, but the data varies considerably from day to day for all of the cells. On December 11, we turned on the infiltration blowers on Cells 13 and 14 and set the flow to give 2.8 air changes per hour. The cell volume is 400 ft³. L_{c13} increased from 21 to 28 Btu/h⁰F. This is illustrated in Fig. 3. The change in L_c , ΔL_c , due to infiltration is the product of infiltration rate, cell volume, specific heat of air, and air density (at the Los Alamos altitude of 7000 ft).

$$\Delta L_c = 2.8 \frac{\text{changes}}{\text{h}} \times 400 \text{ ft}^3 \times 0.24 \frac{\text{Btu}}{\text{lb}^0\text{F}} \times 0.057 \frac{\text{lb}}{\text{ft}^3} = 15.4 \text{ Btu/h}^0\text{F}.$$

The measured increase in L_c was 9 Btu/h⁰F, indicating that about one air change per hour had been leaking into the cells before we turned on the blowers. The blowers replaced all of the small leaks with one large, known leak. An interesting side effect of using the blowers was that the L_c variation from day to day was much smaller than had been observed with the blowers off. We measured the flow rate in the blower flow nozzles each day and adjusted the blowers to maintain 2.8 air changes per hour.

On December 22, we covered the glazing in Cells 1, 2, 5, and 6 with 1-in.-thick polystyrene to compare the load coefficients of these cells. The L_c of all the cells agreed closely with one another and with that of Cell 13.

We conducted these tests to confirm that the L_c s of Cells 1, 2, 5, and 6 were essentially equal. If, for example, one cell had large air leaks or poor insulation relative to the others, it would have produced a larger L_c than the others. The fact that the L_c for the cells with 1 in. of polystyrene ($R = 6$) over the glazing was the same as Cell 13 with an R20 wall shows that, because the glazed area is relatively small, the energy required to heat the cell is not greatly affected by changing the amount of insulation used over the glazed area from R20 to R10. Increasing the conduction through the 44-ft² glazed area by replacing the R20 wall with an ~R10 wall (glazing and polystyrene and storage) only increases the calculated L_c from 28 to 30.

Fig. 3.
Load coefficient tests in Reference Cells 13 and 14,
with blowers off (before Dec. 11) and on (after Dec. 11).

The test results discussed below were obtained with the air infiltration blowers set at 2.8 changes per hour and the thermostats set at 80°F, unless otherwise stated. We assumed $L_c = 28$ for all cases. The Load Collector Ratio⁴ was about 15 Btu/DD ft² (DD = degree days), which is lower than would occur in a normal home. The high thermostat setting increased the degree days by about 60%. With the thermostat set at 80°F, the auxiliary energy used by the cell was roughly equal to the net solar energy delivered by the glazed area during a 24-hour period with a clear day and an average ambient temperature of ~30°F. With a thermostat setting of 65°F, little or no auxiliary energy was used under these conditions.

IV. SUMMARY OF RESULTS

One relative measure of the performance of various passive solar configurations is a comparison of the net solar energy, q_{solar} , delivered to each cell over a period of time when the configuration was unchanged, all systems functioned properly, and the weather provided significant insolation

and loads. We did not measure q_{solar} directly. It was computed using measured parameters and a simple energy balance,

$$q_{\text{solar}} + q_{\text{aux}} = q_{\text{load}} ,$$

in which $q_{\text{load}} = L_c \times (T_{\text{cell}} - T_{\infty})$,

L_c = the measured load coefficient,

T_{cell} = the measured time average cell temperature for the cell for which q_{solar} is being computed,

T_{∞} = the measured time average ambient temperature, and

q_{aux} = the measured auxiliary energy to the cell.

For example, assume we want to measure q_{solar} for Cell 1 for a 10-day period. First we compute the average cell temperature using the average daily cell temperatures that were computed from measured average hourly temperatures. For the example, assume we compute $T_{\text{cell}} = 82^{\circ}\text{F}$ for the 10-day period. Next compute the average outside ambient temperature from measured hourly average temperatures. Assume we calculate $T_{\infty} = 32^{\circ}\text{F}$ for the 10-day period. We use the measured L_c of 28 Btu/h $^{\circ}\text{F}$ and the two temperatures to compute the load

$$q_{\text{load}} = \frac{28 \text{ Btu}}{\text{h } ^{\circ}\text{F}} \times \frac{24 \text{ h}}{\text{day}} \times (82 - 32) ^{\circ}\text{F} = 33 \text{ 600 Btu/day} .$$

Assume we measure an average auxiliary energy input to the cell of 10 000 Btu/day. The net solar input to the cell is

$$q_{\text{solar}} = 33 \text{ 600} - 10 \text{ 000} = 23 \text{ 600 Btu/day} .$$

The load is the energy lost for all surfaces except the glazed area. The auxiliary energy is the total energy input by the heating system and must equal the net energy transported across all of the surfaces. The only surface not accounted for by these two terms is the glazed area. The q_{solar} term

is, therefore, the net energy across the glazed area consisting of both the energy in from the sun and the energy lost to the cold outside air. The q_{solar} term can be negative or positive, depending on whether the glazed area gains more or less than it loses. In the example, the glazed area produced a net gain and provided about two-thirds of the energy needed to heat the cell.

Figure 4 shows the daily q_{solar} values for Cells 1, 2, 5, 6, 7, and 8 from January 23 to March 20. The daily insolation on a vertical surface and the daily average ambient temperatures on these plots are included to illustrate how the cells react to changes in weather. The difference in performance between cells was fairly constant day to day, indicating good accuracy and consistency in the test measurements.

One disadvantage of using q_{solar} is that it credits overheating; that is, solar energy that keeps the cell temperature above the thermostat setting is included in q_{solar} . A configuration that produced very large temperature swings may have a higher q_{solar} than a second configuration that did not. The second configuration may provide a much better environment for a living space, but it may appear to be inferior if judged only on the basis of q_{solar} . A second approach is to make comparisons based on SSF, where

$$\text{SSF} = 1 - \frac{q_{\text{aux}}}{q_{\text{load, reference}}},$$

where $q_{\text{load, reference}} = L_c (T_{\text{reference}} - T_{\infty})$

$T_{\text{reference}}$ = the thermostat setting.

The SSF is a measure of the reduction in auxiliary energy consumed compared to that of a nonsolar system that maintains the room temperature at the same thermostat setting. It does not directly credit or penalize for overheating. The difference between q_{load} and $q_{\text{load, reference}}$ is a direct measure of the amount of energy delivered while the room temperature was above the thermostat setting.

Returning to the preceding example, we will compute SSF for the assumed data used in the q_{solar} calculation. The only measured quantity required to compute SSF is q_{aux} (10 000 Btu/day, in our example). We need to know

Fig. 4.
Test cell daily performance comparisons.

$T_{\text{reference}}$, which is the average temperature at which we would like to keep the building over the test period. $T_{\text{reference}}$ is usually taken to be the thermostat setting, assuming an ideal thermostat that delivers a room temperature equal to its setting. For our tests, we used a $T_{\text{reference}}$ of 80°F and adjusted the thermostat settings in an attempt to obtain a cell temperature of 80°F while the auxiliary system was running. The reference load for the example is

$$q_{\text{load, reference}} = \frac{28 \text{ Btu}}{h^{\circ}\text{F}} \times \frac{24 \text{ h}}{\text{day}} \times (80 - 32)^{\circ}\text{F} = 32\,300 \text{ Btu/day},$$

$$\text{and SSF} = 1 - \frac{10\,000}{32\,300} = 0.690.$$

For the same example, the solar fraction is

$$\text{Solar fraction} = \frac{q_{\text{solar}}}{q_{\text{load}}} = \frac{23\,600}{33\,600} = 0.702.$$

The small difference is due solely to the slight overheating generated during the test period ($T_{\text{cell}} = 82^{\circ}\text{F}$, $T_{\text{reference}} = 80^{\circ}\text{F}$).

In order to present quantitative evaluations, we have selected data from sets of days when the weather was mostly clear and cold, and then computed average q_{solar} , q_{aux} , q_{load} , t_{∞} , and I_v (daily total insolation on a vertical surface) for each set. We used a measured load coefficient of $28 \text{ Btu/h}^{\circ}\text{F}$ and a reference temperature of 80°F (the thermostat setting for the cells) to compute $q_{\text{load, reference}}$. By using measured load coefficients, we eliminated the major uncertainty associated with calculated load coefficients. Table III is a compilation of the comparison data.

The last column in Table III compares the performance of the cells normalized by the performance of Cell 8 (a double-glazed Trombe wall) for the complete test series. The glazed areas for Cells 7 and 8 were 41.0 ft^2 each. Each of the other cells had a glazed area of 44.2 ft^2 . For the last column in Table III, the q'_{solar} for each cell was normalized by q_{solar} for Cell 8, where q'_{solar} is defined as q_{solar} per square foot of glazed

TABLE III

PERFORMANCE SUMMARIES

Test Period	Cell	q_{solar} KBtu/Day	q_{aux} KBtu/Day	Load KBtu/Day	Average Ambient Temp. °F	Vertical Insolation Btu/ft ² /Day	SSF ^d	$q'_{\text{solar}}/q'_{\text{solar } 8^e}$
1	1 Trombe wall, flat black, SG ^a	11.4	19.7	31.1	32.4	1630	0.38	0.63
	2 Trombe wall, black chrome, SG	19.1	13.1	32.2			0.59	1.05
	5 Water wall, black chrome, SG	25.5	10.1	35.6			0.68	1.40
	6 Water wall, flat black, SG	15.2	20.4	35.6			0.36	0.83
	7 Trombe wall, flat black, DG ^b , NI ^c	22.1	10.5	32.5			0.67	1.31
	8 Trombe wall, flat black, DG	16.9	15.4	32.3			0.52	1.0
2	1 Trombe wall, flat black, SG, NI	13.7	14.6	28.3	37.6	1214	0.49	0.91
	2 Trombe wall, black chrome, SG	15.1	12.8	27.9			0.55	1.01
	5 Water wall, black chrome, SG	17.8	12.5	30.3			0.56	1.19
	6 Water wall, flat black, SG, NI	22.8	9.9	32.7			0.65	1.52
	7 Trombe wall, flat black, DG, NI	18.2	11.2	29.4			0.61	1.31
	8 Trombe wall, flat black, DG	13.9	13.6	27.6			0.52	1.0
3	1 Trombe wall, flat black, DG	11.4	17.2	28.6	37.4	1430	0.40	0.92
	2 Trombe wall, black chrome, DG	14.7	13.1	27.8			0.54	1.19
	5 Water wall, black chrome, DG	19.9	10.1	30.0			0.65	1.61
	6 Water wall, flat black, DG	14.4	15.9	30.3			0.44	1.16
	7 Trombe wall, flat black, DG, NI	MALFUNCTION IN BEAD SYSTEM						
	8 Trombe wall, flat black, DG	11.5	16.2	27.7			0.43	1.0
4	1 Trombe wall, flat black, DG	22.4	16.4	38.8	23.5	1950	0.57	1.00
	2 Trombe wall, black chrome, DG	28.5	10.4	38.9			0.72	1.27
	5 Water wall, black chrome, DG	40.0	3.5	43.5			0.91	1.78
	6 Water wall, flat black, DG	37.4	6.7	44.1			0.82	1.67
	7 Trombe wall, flat black, DG, NI	29.9	10.0	39.8			0.74	1.44
	8 Trombe wall, flat black, DG	20.8	18.0	38.8			0.53	1.00

^aSG--single glazed^bDG--double glazed.^cNI--night insulation.^dSSF--solar savings fraction.^e q'_{solar} -- $q_{\text{solar}}/\text{glazed area (Btu/day } \cdot \text{ft}^2)$.

area. This assumes that q_{solar} is proportional to glazed area and corrects for cell-to-cell differences in glazed area.

A. Test Period 1: January 22 to February 4, 1980

During the thirteen-day period from 8:00 a.m. January 22 to 8:00 a.m. February 4, Cells 1, 2, 5, and 6 were single glazed and tested without night insulation. During that time, the systems worked properly and the weather provided an average ambient temperature of 32.4°F and an average daily vertical-surface insolation of $1630 \text{ Btu/ft}^2 \text{ day}$ (about 70% possible sunshine). The black-chrome-covered Trombe wall (Cell 2) delivered an average q_{solar} of 19 100 Btu/day compared to 11 400 Btu/day for the flat-black wall (Cell 1). Therefore, the single-glazed wall with selective surface delivered 69% more net energy than the flat-black wall under identical conditions. The SSF for the selective surface wall was 0.59 compared to 0.38 for the flat-black wall, which represents a 55% advantage for the selective wall.

During the same period of time, the black-chrome, water-wall cell delivered an average q_{solar} of 25 500 Btu/day, compared to 15 200 Btu/day for the flat-black water wall (68% higher q_{solar} from the selective-surface wall). The SSFs were 0.68 and 0.36 for the selective and nonselective configurations, respectively ($\text{SSF}_{\text{selective}}/\text{SSF}_{\text{nonselective}} = 1.89$). Both of the water-wall cells overheated about 10% ($q_{\text{load actual}}/q_{\text{load ref}} \approx 1.10$).

The Beadwall[®] cell with the bead system operating (Cell 7) produced an average $q_{\text{solar}} = 22\ 100 \text{ Btu/day}$ and a solar fraction of 0.67 compared to Cell 8 (beads not operating), which produced $q_{\text{solar}} = 16\ 900 \text{ Btu/day}$, $\text{SSF} = 0.52$. These cells produced essentially no overheating (for example, for Cell 7 $q_{\text{load, actual}}/q_{\text{load, ref}} = 1.003$).

Comparing the double-glazed, flat-black wall (Cell 8) to the single-glazed, black-chrome wall (Cell 1), we find that the black-chrome wall delivered 5% more energy per square foot of glazed area, in spite of its single layer of glazing. (The glazed area of the double-glazed Beadwall[®] cells was 41.0 ft^2 compared to 44.2 ft^2 for all of the other cells.) On the same basis, the double-glazed, flat-black Trombe wall delivered 60% more energy per square foot of glazed area than the single-glazed, flat-black Trombe wall.

B. Test Period 2: February 5 to March 7, 1980

During Test Period 2, we compared the performance of single-glazed cells using black chrome to the performance of cells using flat-black absorbers with night insulation. The night insulation was 2-in.-thick polystyrene, which we installed manually at 4:00 p.m. Monday, Tuesday, Wednesday, and Thursday and removed at 8:00 a.m. the following mornings. The cells were not insulated on Friday, Saturday, and Sunday nights because the test technicians did not work on weekends.

In our first attempt to analyze the test results, we tried using all of the days that cells were insulated for the night insulation test period. After further investigation, we discovered that during the first day after a weekend when the cells had had no night insulation, the auxiliary energy used by the insulated cell was considerably higher than the energy used by the black-chrome cell. After several days of cycling the night insulation, this difference was much smaller, as the insulated wall reached a new equilibrium level. This trend occurred each week of the night insulation test period. In order to minimize the effects of the weekends, we used only the last two days of each work week for the data set used in Test Period 2. We would have had a much better study if we had installed night insulation every night consecutively for several weeks to eliminate the transients introduced by not insulating on weekends.

Cell 8 performed essentially the same during Test Periods 1 and 2. During Test Period 1, the Beadwall[®] cell with the bead system inactive (Cell 8) delivered an average q_{solar} of 16 900 Btu/day. The average insolation, I_v , was 1630 Btu/ft² day. During Period 1, the solar efficiency for Cell 8 was 0.25, where solar efficiency is defined as q_{solar} divided by the product of I_v times the glazed area. During Test Period 2, q_{solar} for the same cell was 13 900 Btu/day, I_v was 1214 Btu/ft² day and solar efficiency was 0.28. Also, $q_{\text{solar 7}}/q_{\text{solar 8}}$ was 1.31 during both Periods 1 and 2. The erratic time intervals in Period 2, therefore, did not appear to have any large effect on the measured results.

During Period 2, the single-glazed Trombe wall with a black-chrome surface and no night insulation (Cell 2) produced 10% more energy than the single-glazed, flat-black Trombe wall with the 2-in.-thick polystyrene night insulation. However, the night insulation was more effective on the water walls. During

Period 2, the black-chrome water wall delivered 22% less energy than the flat-black water wall with night insulation. During this period the single-glazed, black-chrome Trombe wall produced 1% more energy per square foot than the double-glazed, flat-black wall (compared to 5% more during Test Period 1).

The double-glazed, flat-black wall without night insulation (Cell 8) produced 10% more energy per square foot than the single-glazed, flat-black wall with night insulation (Cell 1). The double-glazed, flat-black wall with night insulation (Cell 7) produced 44% more energy per square foot than the single-glazed, flat-black wall with night insulation.

C. Test Periods 3 and 4: December 31, 1979, to January 4, 1980, and March 22-26, 1980

Cells 1, 2, 5, and 6 were double glazed during Test Periods 3 (late December) and 4 (late March). The black-chrome Trombe wall (Cell 2) delivered 29% more energy per square foot in Period 3 and 27% more in Period 4 than the flat-black wall with double glazing. The double-glazed, black-chrome water wall produced 7% higher q_{solar} than the double-glazed, flat-black water wall during Period 4 compared to 38% during Period 3. The small performance increment delivered by the black-chrome water wall during Period 4 does not appear to be correct, but we were unable to find anything obviously wrong with the measurements during either period.

V. DISCUSSION OF RESULTS

A. Errors Associated with Comparing Measurements from Different Test Periods

The largest uncertainty that we face in interpreting the results of these tests occurs because we are attempting to compare different configurations tested at different times. Ambient conditions, especially sun angle and weather, were not identical from test period to test period. By comparing results from configurations that remained unchanged from period to period, we can see if the differences in test conditions produced significantly different results. Test Cells 7 and 8 were the Beadwall[®] cells with double glazing. Cell 7 used the beads in place at night, but Cell 8 did not use the beads at all. These configurations were the same throughout all of the test periods. Cell 8 was, therefore, simply a flat-black Trombe wall with double glazing,

and it apparently functioned correctly throughout the tests. Recall that the glazed areas of Cells 7 and 8 were 41 ft² each, compared to 44.2 ft² for the other cells. Figures 5 and 6 show a summary of the q'_{solar} delivered by each configuration normalized by the q'_{solar} from Cell 8, where q'_{solar} is q_{solar} per square foot of glazed area.

During Test Periods 3 and 4, Cell 1 was double glazed and similarly configured to Cell 8, except for glazed area. The ratio of $q'_{\text{solar}}/q'_{\text{solar } 8}$ was 0.92 for Test Period 3 and 1.0 for Period 4. This indicates that correcting for glazed area gives satisfactory results. During Periods 1 and 2, the ratio $q'_{\text{solar } 7}/q'_{\text{solar } 8}$ was 1.31, indicating that relative performance did not change from test period to test period. It would have been interesting to compare Cells 7 and 8 during

Fig. 5.
Summary of storage wall comparison tests.

Fig. 6.
Storage wall performance with 1 and 2 glazings.

Periods 3 and 4, but the bead system of Cell 7 malfunctioned during these periods.

The configuration of the black-chrome cells (single glazed) did not change between Periods 1 and 2 and between 3 and 4 (when they were double glazed). Therefore, $q'_{\text{solar } 2}/q'_{\text{solar } 8}$ and $q'_{\text{solar } 5}/q'_{\text{solar } 8}$ should not change between Periods 1 and 2 and between Periods 3 and 4. For Period 1, $q'_{\text{solar } 2}/q'_{\text{solar } 8} = 1.05$, and for Period 2 it was 1.01. All the preceding comparisons show that variables that should have remained constant between test periods apparently did so; comparisons between unknowns should be

valid. One apparent error is obvious from the calculated results in Table III. The performance of the water walls during Test Period 4 was much higher than the results from the other periods, whereas the performance of the Trombe walls was only slightly higher. Test Period 4 was very cold (23°F average) and very sunny (1950 Btu/ft² day) compared to the other periods. Either these conditions were too different from those of the other periods to make accurate comparisons possible, or we made some measurement errors that were not detected. In any case, we consider the water-wall data from Period 4 to be questionable.

B. Errors Due to Thermostat Temperature Differences

We have learned from previous experiences with interpreting and applying experimental results from passive test cells the advantages of testing with thermostatically controlled, auxiliary power systems. Using auxiliary heat introduces new questions about comparing data from two test cells. How significant are differences in the thermostat turn-on temperatures and dead bands from cell to cell? How can results from several cells be corrected for differences in thermostat turn-on temperatures? Complete answers to these questions are not simple. The following brief analysis illustrates the magnitude of the errors associated with differences in turn-on temperatures.

We compared the performance of various cells on the basis of q_{solar} , which is the total energy entering through the glazed area minus the total energy out through the glazed area. The energy in (q_{in}) is clearly independent of the thermostat temperature. The energy out (q_{out}), however, is at least somewhat dependent on the cell temperature, which is, in turn, related to thermostat temperature. If we assume that q_{out} is proportional to cell temperature minus ambient temperature, then $q_{\text{out}} = U_L (T_{\text{cell}} - T_{\infty})$, where U_L is a loss coefficient that is assumed to be constant. (This assumption is very approximate, and, for this reason, the following results must be considered to be approximations.) For our tests, solar efficiency, η , was about 25%, where

$$\eta = \frac{q_{\text{solar}}}{q_{\text{in}}} = \frac{q_{\text{in}} - q_{\text{out}}}{q_{\text{in}}}$$

First consider a test period where the average ambient temperature, T_{∞} , was 30°F. Assume that the thermostat was set at 80°F but actually came on at

78°F. If the cell did not overheat at all, the average cell temperature would exactly equal the thermostat turn-on temperature of 78°. Then q_{out78} would be less than q_{out80} if $T_{cell80} = 80^\circ$.

$$\frac{q_{out78}}{q_{out80}} = \frac{T_{cell78} - T}{T_{cell80} - T} = \frac{78 - 30}{80 - 30} = 96\% ;$$

q_{out} would be 4% less than it should have been.

Also, if $\eta = 25\%$, $Q_{out} = 3 \times q_{solar}$. Because q_{out} is much larger than q_{solar} , a small change in q_{out} yields an even smaller change in q_{solar} . A 4% decrease in q_{out} corresponds to a 1.2% increase in q_{solar} . For this example, if the thermostat comes on 1° lower than its set value, the q_{solar} would be 0.6% higher than it would have been if the thermostat had performed perfectly. The solar efficiency increases as T_{cell} decreases, and this effect becomes important for large thermostat errors.

If the cell were solar heated to the extent that temperature remained higher than the thermostat set temperature throughout the test period, the thermostat would have no influence on q_{solar} . For $\bar{T}_{cell} > T_{thermostat}$, the effect of $T_{thermostat}$ decreases as $\bar{T}_{cell}$ increases. On the other hand, as $\bar{T}_{\infty}$ increases, the effect of thermostat error is greater. For example, if in the preceding case T_{∞} were 50°F instead of 30°F,

$$\frac{q_{out78}}{q_{out80}} = \frac{78 - 50}{80 - 50} = 0.933 .$$

This corresponds to a 2% increase in q_{solar} for each 1° the thermostat turns on below the set temperature.

During the test program, we monitored cell temperature in each of the cells to detect differences in thermostat turn-on temperatures and kept these temperatures matched as closely as possible (about 1°F). When the thermostats in several of the cells became erratic, they were replaced with high-quality temperature controllers. In passive cell testing, the temperature at which the auxiliary heat turns on must be closely matched from cell to cell to make meaningful performance comparisons without complicated

and questionable data manipulation. The thermostats can never be matched exactly and represent a potential source of error in any passive experiment.

C. Performance of Selective Absorbers

Figure 4 summarizes the test results. The major results from Fig. 4 are listed in Table IV. For a single-glazed Trombe wall, a selective absorber increased the net solar energy delivered by about 70% for the conditions under which we tested. The performance of a Trombe wall with single glazing and a selective absorber is about the same as for a flat-black wall with double glazing and no night insulation. The improvement gained from using a selective absorber on a Trombe wall with double glazing was 20 to 30% (Period 3 or 4), which is also about the same as the improvement observed using night insulation in Periods 1 and 2. The water walls produced similar results. The results indicate that the night insulation increased the delivered energy from the flat-black Trombe wall by 44% for single glazing (which appears to be low) and 30% for double glazing (which looks about correct). The 44% performance improvement from night insulation on a single-glazed cell appears to be low because the performance improvement from using black chrome compared to flat black was about equal to the performance improvement from using night insulation in the tests with double glazing. The tests with single glazing showed a 70% improvement from black chrome, but only a 44% improvement from night insulation; the night insulation should have produced a performance improvement of 60-70%.

TABLE IV

PERFORMANCE OF SELECTIVE ABSORBERS AND NIGHT INSULATION

			<u>q_{solar} ratio</u>
Trombe Wall			
Single glazed	BC/FB ^{a, b}		1.68
	NI/FB ^c		1.44
Double glazed	BC/FB		1.25
	NI/FB		1.30
Single glazed BC/Double glazed FB			1.02
Water Wall			
Single glazed	BC/FB		1.69
	NI/FB		1.85
Double glazed	BC/FB		1.39
	NI/FB		Not available
Single glazed BC/Double glazed FB			1.21

^aBC--black chrome.^bFB--flat black.^cNI--night insulation.

The auxiliary energy consumption measurements show that the selective surface Trombe wall delivered about 70% more net energy to the room than the similar flat-black Trombe wall during Test Period 1. Wall-temperature profile measurements support this observation. Figure 7 shows wall-temperature histories for both Trombe walls during three sunny days during Period 1. On

Fig. 7.
Wall-temperature histories in flat-black- and black-chrome-covered concrete walls.

each of the days shown, the black-chrome wall started to warm up sooner and reached a higher maximum temperature than the flat-black wall. The temperature at the center of both walls peaked at the same time, but the temperature at the center of the black-chrome wall was 12° hotter. Also, the temperature near the interior surface of the black-chrome wall was $4-6^{\circ}$ higher than the corresponding temperature for the flat-black wall. If we assume a linear temperature distribution in the wall, heat flux from the hot exterior wall to the cell of the wall is

$$q_{\text{wall}} = \frac{K}{x/2} (T_1 - T_5) ,$$

and

$$\frac{(T_1 - T_5) \text{ black chrome}}{(T_1 - T_5) \text{ flat black}} = \frac{160 - 90}{130 - 90} = 1.75 ,$$

where T_1 is the temperature at thermocouple (T/C) No. 1 (1 in. inward from the exterior wall surface), T_5 is at T/C No. 5 (1 in. outward from the interior surface), K is the thermal conductivity of the wall, and $x/2$ is the wall thickness. The selective wall, therefore, delivers a higher heat flux when the exterior wall temperature is at its peak.

At 4:00 a.m., the temperature at the center of the wall is higher than the cell temperature and the walls conduct heat from the warm center to both the interior and exterior surfaces. Comparing the heat flux from the center to the exterior surface of the wall for the black-chrome and flat-black walls, we find

$$q_{\text{black chrome}}/q_{\text{flat black}} = \frac{(T_3 - T_1) \text{ black chrome}}{(T_3 - T_1) \text{ flat black}} = \frac{106 - 99}{91 - 85} = \frac{7}{6} = 1.17.$$

This shows that during the night, the heat flux from the center of the wall to the exterior surface is roughly the same for the selective and flat-black absorbers. Therefore, most of the benefit from the black chrome is apparently due to reduced heat loss from the wall during the day when its exterior surface temperature is the highest.

Figure 8 shows wall temperature profiles for a flat-black wall with night insulation and a black-chrome wall without night insulation. During the 24 hours from 8:00 a.m. on February 13 to 8:00 a.m. on February 14, the interior-surface wall temperatures of the two walls were almost identical. At 6:00

a.m., the temperature at the interior surface of the flat-black wall was 94°F , compared to 92°F for the black-chrome wall. During the 24-hour period ending at 8:00 a.m. on January 27, when the flat-black wall was not insulated at night, the temperature at the interior surface of the wall with the black-chrome absorber was $4\text{--}8^{\circ}\text{F}$ higher than the temperature at the same location on the wall with the flat-black absorber. At 6:00 a.m. on January 27, the temperature at the interior surface of the wall with the black-chrome absorber was 95°F , compared to 89°F for the nonselective wall. The night

Fig. 8.
Wall-temperature histories with night
insulation on the flat-black wall.

insulation increased temperatures at the center and interior surface of the flat-black wall. It, of course, had no effect on the losses while the sun heated the wall. The black-chrome wall absorbed more heat during the day than the flat-black wall. In fact, the peak, exterior-surface temperatures of the flat-black wall were about the same with and without night insulation. The most obvious effect of night insulation was the higher temperature measured late at night at the exterior surface of the wall. Without night insulation, the temperature at the exterior surface of the flat-black wall dropped to 80°F at 6:00 a.m., compared to 85°F at the center of the wall. The exterior-surface temperature of the black-chrome wall dropped to 95°F , compared to 100°F for the center. With night insulation, the temperature of the exterior surface of the flat-black wall at 6:00 a.m. was equal to the temperature at the center of the wall (100°F). At the same time, the temperature at the exterior surface of the black-chrome wall was 93°F , compared to 99°F at the center of the wall. Comparing temperature gradients from the center of the wall to the outside, we find that the night-insulated wall lost less heat at night than the black-chrome wall, but gained less during the day, when the night insulation was not a factor and the low emissivity of the black chrome became dominant.

The preceding indicates that the primary benefit from the selective absorber on a Trombe wall occurs when the temperature at the exterior surface of the wall is the highest, which happens during the daytime hours on sunny days. The night insulation is effective only during the night hours when the selective surface is least effective. It appears that a Trombe wall with a selective absorber and night insulation would perform considerably better than either a wall with only a selective surface or a flat-black wall with night insulation. This would be an interesting subject for future tests.

Figures 9 and 10 show water-tube temperature histories for the same time periods shown previously for the Trombe walls in Figs. 7 and 8. The differences between the temperature profiles for the selective and nonselective tubes are not nearly so dramatic as we observed with the Trombe walls. Without night insulation, the water simply got hotter during the day and stayed hotter all night in the selective-surfaced tubes. The hotter tubes gave higher room temperatures and delivered 70% more q_{solar} . The water tubes had about 3-in.-wide spaces between them that allowed air convection among the room, the space between the tubes, and the glazing. Night

insulation was especially effective on this configuration. The room-temperature plots in Fig. 10 show that the night insulation kept the room temperature about 5 degrees warmer at night than the uninsulated black-chrome room next to it. During the day, both rooms reached the same temperature. The water was a little hotter in the night-insulated cell. This agrees with the power measurements, which showed that the night-insulated water wall with single glazing performed about 10% better than the single-glazed, black-chrome water wall.

D. Phase-Change Material (PCM) Tests

Two of the test cells, Cells 10 and 14, had storage walls comprised of $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$, which dissolves in its water of hydration at 81°F . These

Fig. 9.
Water-wall temperature histories.

walls use heat from the sun to dewater the salt, thereby storing energy in the latent heat of fusion of the phase-change material (82 Btu/lb). The wall in Cell 10 consisted of 29 "heat rod" tubes. Twenty-five of the tubes were manufactured by PSI, Inc., and four were made by Energy Materials, Inc. (EMI). The rods have polyvinylchloride tubes, 3-1/2-in. o.d. by 60 in. long, each filled with 30 lb of salt. The tubes were stacked horizontally with 1/2-in.-wide gaps between them. The material in the tubes was $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$, seeded with Dow Chemical's nucleating formulation to inhibit supercooling (cooling below 81°F before solidification starts). We built the storage wall in Cell 14

Fig. 10.
Water-wall temperature histories
with night insulation.

by stacking rectangular, plastic "bread boxes" filled with a mixture of $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ and diatomaceous earth (a formulation developed by a French solar group).⁵ The wall consisted of 105 boxes 12 in. by 4 in. by 5-1/2 in., each containing 9.7 lb of $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$. The air gaps between the boxes were sealed. The diatomaceous earth mixture had been designed to both contain the nucleating agent and fix it in suspension, well distributed relative to the salt. In this mix, the nucleating agent cannot settle out of solution and become ineffective, a problem in other applications. We did not observe any failures of either formulation in freezing at or within a few degrees of the ideal freezing point of 81°F .

Each of the tubes stored 2400 Btu of latent energy of fusion. The tube wall had a latent heat capacity of 70 000 Btu. The bread-box wall had a latent heat capacity of about 77 000 Btu. We operated Cell 9, a conventional, flat-black Trombe wall, as a reference cell for the two phase-change cells. The Trombe wall was made of concrete weighing 8250 lb with a specific heat of $0.15 \text{ Btu/lb}^\circ\text{F}$, for a heat capacity of $1240 \text{ Btu/}^\circ\text{F}$. The Trombe wall had a capacity to store 37 000 Btu on a sunny day, with 30° wall-temperature increase, or about half as much energy as the total capacity of the phase-change walls. The PCM wall temperature would remain constant at 81°F throughout the charging and discharging process. We did not use auxiliary heat in either of the phase-change cells or the reference cell because we wanted to allow the cells to cool sufficiently to allow the PCM to freeze. On cold nights, the tube wall cell temperature dropped to about 60°F while the salt was freezing. If we had used a thermostat setting of 65°F , the auxiliary power would have come on about the time freezing began; thus, the stored energy could not be effectively used. One alternative strategy would be to use a low night-setback thermostat temperature (like 60°F), together with whatever daytime temperature is desired. The low night temperature would permit all of the phase-change energy to be extracted before the heaters come on. If we were to install night insulation over the PCM wall, the difference between room temperature and storage temperature would decrease and a possibly higher night thermostat setting could be used effectively. A phase-change material with a higher melting temperature would work better in many passive solar applications. We could have reduced the temperature swing in the tube wall cell by sealing the gap between the tubes. This would probably have been difficult to do because the slope of the tubes changed considerably after many

cycles of heating and cooling. A better method of stacking and supporting the tubes would have been needed before the gaps could be sealed effectively.

One of the disadvantages of phase-change storage is that as soon as all of the material becomes solid or liquid, the heat capacity of the wall suddenly drops to a fraction of its value while a two-phase mixture exists. For example, after several cloudy days, all of the salt solidifies and the wall heat capacity is $0.34 \text{ Btu/lb}^{\circ}\text{F}$ (about twice that of concrete). When the salt is solid, the tube wall heat capacity is only $250 \text{ Btu/}^{\circ}\text{F}$, compared to $1240 \text{ Btu/}^{\circ}\text{F}$ for the concrete wall in Cell 9. Figures 11, 12, and 13 show how the PCM tube wall compares with the concrete wall during both sunny and cloudy conditions. By noon on January 13, the temperature of the material in the center of a tube in the PCM tube wall had risen above the melting material temperature, indicating that all of the material had melted. The cell temperature was 80°F . As soon as the clouds cut off the insolation, the material temperature began to drop, leveling off at the melting temperature, while the material solidified and released its stored heat of fusion. From 6:00 p.m. on January 13 to 6:00 p.m. on January 14, the wall exhibited ideal behavior, maintaining a constant temperature both while giving up stored energy and storing energy. January 14 was a cloudy day with a total, vertical-surface insolation of only 366 Btu/ft^2 . The tubes were not well charged at the end of the day, and they completely solidified early in the evening. During the night of January 14, the tube temperature dropped rapidly, and the PCM cell was colder than the reference cell with concrete wall.

January 15-19 were cloudy (average insolation about half the clear-day value) and the wall was never fully charged. In fact, on January 18 and 19, the highest salt temperature measured was 5° less than the melting temperature of the material, and the PCM wall acted like a thin mass wall. During this period, the slope of temperature vs time during the night was much steeper for the low-heat-capacity PCM wall than the mass wall, and Cell 10 was much colder than Cell 9. The period January 20-23 was very sunny. The PCM wall fully charged during January 20 and stayed near the melting temperature all night. During January 21-23, the tube completely melted and overheated, producing daily maximum cell temperatures of 80°F , compared to maximum temperatures of $60\text{-}68^{\circ}\text{F}$ for the reference cell with the concrete wall. The PCM cell was colder than the reference cell most of the night, with both cells

Fig. 11.
Temperature comparisons for the phase-change
material tube wall tests.

Fig. 12.
Temperature comparisons for the phase-change
material tube wall tests.

Fig. 14.
Temperature histories in the phase-change walls.

the PCM walls almost every day during this period. The average q_{solar} for the PCM walls was the same, about 11% higher than the mass wall.

The bread-box wall probably produced the best overall performance of the three during this period. The temperature variations in the walls and cells for one day, shown in Fig. 14, illustrate this. Cell 10 (the tube wall) overheated, hitting a peak temperature of 78°F . The bread-box wall produced about the same amount of temperature swing as the mass wall, but it also produced the highest minimum cell temperature. All of the cell temperatures were nearly the same during the night. Characteristic temperatures in the storage walls are also shown. The curves show the temperatures of the concrete wall at the center of the wall half-way between the top and bottom, the center of PCM Tubes 13, 19, and 26 from the bottom of a stack of 29, and the center of a bread box in Rows 1, 14, and 20 in a stack of 21.

Fig. 15.
Performance comparison between
the tube wall and bread-box wall.

The temperatures measured in the tubes were not well ordered with respect to height. This occurred because the thermocouples were installed in dry wells and not in good contact with the material measured. More consistent results were obtained from the boxes, where the thermocouples were directly immersed in the PCM.

The PCM tests show that the material behaved as we expected, changing phase at 81°F and storing large amounts of energy in the process. The PCM cells did not perform much better or worse than the mass wall cell, except when several sunny days or several cloudy days occurred in a row, in which cases they performed worse than the mass wall. Numerical modeling based on

these experiments confirms that the phase change wall gives roughly the same SSF as a masonry or water wall, but with much less thickness and mass of wall.⁶ PCM walls offer a weight and space savings that would be an advantage in some circumstances, especially in retrofits. They cannot serve the dual purpose of load-bearing structure and storage that can be provided by concrete.

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