Solar Energy Vol. 38, No. 5, pp. 303–309, 1987
Printed in the U.S.A.

0038-092X/87 \$3.00 + .00
Pergamon Journals Ltd.

COMPARISON OF EXPERIMENTAL AND CALCULATED PERFORMANCE OF INTEGRAL COLLECTOR-STORAGE SOLAR WATER HEATERS

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(*Received* 30 *April* 1986; *accepted* 8 *October* 1986)

Abstract—Experimental measurements of the monthly performance of an integral collector-storage solar water heater for a one-year period are compared with performance predictions using the method of Zollner. The prediction method requires two parameters which were obtained from indoor experiments with a solar simulator. The experimental measurements are also compared with predictions in which the two parameters were obtained from short-term outdoor tests.

1. INTRODUCTION

The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) has established a short-term test method for solar domestic hot water (SDHW) systems[1]. Test conditions, such as irradiance profile, ambient temperature, windspeed, etc., are prescribed by a rating agency such as the Solar Rating and Certification Corporation (SRCC)[2].

The results from short-term tests do not necessarily reflect the performance of SDHW systems in either an absolute or relative sense. The SRCC test results only allow a comparison of the thermal performance of various systems at the prescribed rating conditions. The economic merit of an SDHW system can be established only by examining its long-term performance. The long-term performance depends on both its design and the climate in which it is operated.

Methods of estimating the long-term performance of several types of SDHW systems using local climatic data have been developed. The *f*-Chart method[4–5] is applicable to several generic types of forced circulation systems. A technique for predicting the long-term performance of forced-circulation SDHW systems based on short-term test data has been developed[6]. A performance estimation method for integral collector storage (ICS) systems has recently been developed by Zollner *et al.*[3].

Performance prediction methods for solar energy systems necessarily rely on data generated by computer simulations since long-term performance data are difficult to obtain and not widely available. The computer simulation models incorporate numerous simplifications. Further approximations are made in developing correlations of long-term performance from the simulation data. Comparisons with experimental data are needed to establish the validity of the performance predictions methods. The *f*-Chart method has been the subject of numerous validation efforts[7–9]. The method developed by Zollner *et al.* for ICS systems has not been validated due to a lack of published experimental data.

The purpose of this paper is to compare the monthly and annual performance estimates from the Zollner method with experimental data collected at the National Bureau of Standards (NBS). A second purpose of the paper is to investigate whether the two parameters needed in the prediction method can be obtained from short-term outdoor tests instead of indoor tests with a solar simulator.

2. LONG-TERM PERFORMANCE PREDICTION PROCEDURE

The long-term performance prediction technique employed in this study is semi-empirical and based on simulation results obtained using the TRNSYS[10] simulation program. Reference [3] includes a description of the model and details concerning the development of the performance prediction technique. A summary of the performance prediction technique is provided below.

A monthly energy balance on an ICS system, assumed to have a fully mixed storage tank and subjected to a continuous water draw, results in a simple expression for the fraction of the load supplied by solar energy:

$$f_{m,c} = \frac{\overline{T}_D - T_m}{T_s - T_m}. \quad (1)$$

The subscripts m and c indicate a fully mixed system subjected to a continuous draw. T_m is supply water temperature (assumed constant over the month), T_s is the hot water set temperature, and $\overline{T}_D$ is the monthly average temperature at which water exits the ICS unit. Performing an energy balance on the ICS unit and ignoring changes in stored energy results in the following expression for $\overline{T}_D$:

$$\overline{T}_D = \frac{A_c(\overline{\tau\alpha})\overline{H}_T + M_D C_P \overline{T}_M + U_L A_C \overline{T}_e \Delta\tau}{M_D C_P + U_L A_C \Delta\tau}. \qquad (2)$$

$\overline{H}_T$ is the monthly average daily solar radiation per unit area incident on the ICS aperture of area A_c during the month, $(\overline{\tau\alpha})$ is the monthly average transmittance-absorptance product, which is the product of $(\tau\alpha)_n$, the normal incidence transmittance-absorptance product, and $\overline{K}_{\tau\alpha}$ the incidence angle modifier for the month. M_D is the average daily mass of water withdrawn from the ICS unit. $\overline{T}_e$ is defined as the effective sink temperature which accounts for radiation losses to the sky. Zollner *et al.*[3] suggests that the following expression be used to compute the effective sink temperature:

$$\overline{T}_e = \overline{T}_a - 1/4(\overline{T_a - T_{sky}}). \qquad (3)$$

The overall heat loss coefficient, U_L, and monthly average transmittance absorptance product $(\overline{\tau\alpha})$, are computed from short-term test results in the manner described in Section III.

Equation (2) is valid for fully mixed ICS systems in which thermal stratification within the storage tank cannot occur. Thermal stratification is modelled by dividing the ICS tank into a number of equal-volume segments, (or nodes) each of which is assumed to be fully mixed. Computer simulations[3] show that the effect of stratification is a function of the solar fraction and the ratio of storage tank volume to the average daily water use. Systems which meet only a small fraction of the load do not show significant performance improvements when the number of tank sections is increased because there is little energy in the tank at any time and thus little possibility to benefit from stratification. The ratio of the average daily water use to the storage volume is defined as TT, the average daily tank turnovers. Stratification is reduced as the number of tank turnovers is increased due to increased draw-induced mixing. The following correlation for the solar fraction of a stratified ICS system was developed from simulation results:

$$\frac{f_{s,c}}{f_{m,c}} = 1 + \frac{a}{TT}(1 - f_{m,c}). \qquad (4)$$

In eqn (4), $f_{s,c}$ is the fraction of the thermal load met by a system having a continuous water draw and a stratified storage tank. However, computer simulations have shown the thermal performance of ICS systems to be relatively insensitive to the water draw profile. Zollner *et al.*[3] found only small differences in the annual thermal performance obtained using the SRCC, RAND, and continuous draw profiles: differences of 10–20% were noted between the extremes of evening- and morning-weighted profiles. The coefficient, a, in eqn (4) is dependent on the number of nodes used to model stratification. For a two-node tank, Zollner *et al.*[3] found the numerical value of a to be 0.17, compared to a value of 0.326 for a 10-node tank. The value of a cannot easily be determined from short-term experiments and thus must be assumed. However, the assumed value of a has only a small effect on the long-term performance of the system[3].

3. SHORT-TERM TEST RESULTS

Test data from five short-term tests, conducted in accordance with ASHRAE Standard 95-1981[1], for an ICS unit identical to the units tested outdoors at NBS were provided by the Florida Solar Energy Center. Each of the five tests were conducted indoors using a solar simulator to irradiate the ICS unit and repeated on a daily basis until periodic steady-state performance was achieved. Test conditions are given in Table 1. The insolation intensity was varied by changing the incident angle while maintaining the simulator lamp intensity constant. The integrated daily solar radiation level, listed in Table 2, was varied by changing the time duration at each insolation level. In addition to the irradiated tests, an additional test was conducted in accordance with SRCC Standard 200-82[2] to determine the heat loss coefficient of the ICS units. A heat loss coefficient of 1.44 W/m$^2\cdot$°C (based on ICS aperture area) was obtained from this 16-hour non-irradiated test. The average transmittance-absorp-

Table 1. Indoor test conditions

Test number	Daily simulated solar radiation (Wh/m^2)	Ambient temperature (°C)	Mains water temperature (°C)	Daily draw (l/day)
1	3940.4	22	22	375
2	5516.6	22	22	375
3	6304.7	22	22	375
4	4728.5	22	11.1	270
5	4728.5	22	22	375

Table 2. Indoor solar simulator irradiance profiles

Irradiance $I(t)$, W/m^2	Incident angle degrees	Test 1 daily incident radiation 3940.4 Wh/m^2 Solar time	Test 2 daily incident radiation 5516.6 Wh/m^2 Solar time	Test 3 daily incident radiation 6304.7 Wh/m^2 Solar time	Tests 4, 5 daily incident radiation 4728.5 Wh/m^2 Solar time
315.2	60	0840–0930	0640–0830	0640–0800	0800–0900
472.9	45	0930–1020	0830–0940	0800–0920	0900–1000
567.4	30	1020–1110	0940–1050	0920–1040	1000–1100
662.0	15	1110–1200	1050–1200	1040–1200	1100–1200
693.5	0	1200–1250	1200–1310	1200–1320	1200–1300
662.0	15	1250–1340	1310–1420	1320–1440	1300–1400
567.4	30	1340–1430	1420–1530	1440–1600	1400–1500
472.9	45	1430–1520	1530–1640	1600–1720	1500–1600
315.2	60	1520–1600	1640–1750	1720–1840	1600–1700

tance product, $(\overline{\tau\alpha})$, for each of the five tests was computed by rearranging eqn (2) to yield

$$\overline{\tau\alpha} = \frac{M_D C_P[\overline{T}_D - T_M] + U_L A_C \Delta_T[\overline{T}_D - \overline{T}_e]}{\overline{H}_T A_C}. \qquad (5)$$

The results, Table 3, show a variation of less than 2.6% in the value of $(\overline{\tau\alpha})$ in spite of the fact that the test conditions varied widely. The $(\overline{\tau\alpha})$ value resulting from the SRCC Standard 200-82 test conditions, .44, was used to predict the long-term performance of the ICS units tested at NBS.

4. NBS EXPERIMENTAL APPARATUS

A solar hot water system employing commercially available integral collector storage units was fabricated at the National Bureau of Standards Solar Hot Water Test Facility in order to obtain long-term outdoor performance data. The system consisted of two identical integral collector storage units connected in series. The ICS systems have reflective polyisocyanurate insulation with one glass and two fiberglass covers. The systems were installed on a fixed test stand with the axis of the 355.6-mm-diameter tank along an east-west line in the horizontal plane. The rack was set to provide a tilt angle of 39°. Complete materials and dimensions for the ICS systems are given in Table 4.

Instrumentation was used to measure the total irradiance, effective blackbody sky temperature, ambient temperature, wind speed, internal tank water temperatures, and the temperature of the water entering and leaving each integral collector storage unit. The total solar radiation and infrared sky radiation were measured normal to the aperture plane of the ICS systems using an Eppley model PSP pyranometer and an Eppley model PIR pyregeometer, respectively. A four-vane anemometer was used to monitor wind speed. A type-T thermocouple was mounted in a small, white ventilated box near the test stand to measure ambient air temperature. Thermocouple probes were constructed for measuring the temperature of the water inside the storage tank of each system at five vertical heights within each tank. The junctions of these type-T thermocouple probes were electrically insulated from the water using silicone rubber sealant and heat shrink tubing to prevent the occurrence of ground loops. Six-junction thermopiles were fabricated to measure the temperature differential between the inlet and outlet port of each of the two units and across both ICS units.

All measurements were taken at one-minute intervals using a microcomputer-controlled data acquisition system. Fifteen minute averages of the data were stored on flexible media disks for final data reduction and analysis. In addition to data acquisition, the microcomputer initiated and controlled the hot water draws. The draw schedule,

Table 3. Computation of normal transmittance–absorptance product from indoor test results

Test number	Average transmittance–absorptance product during test $(\overline{\tau\alpha})$	$\overline{K}_{\tau\alpha,\text{test}}$	$(\tau\alpha)_n$
1	.440	.948	.464
2	.440	.948	.464
3	.447	.948	.471
4	.451	.948	.476
5	.444	.948	.468

Table 4. Dimensions and properties of integral collector storage systems tested at NBS

Nominal capacity (m^3)	0.121
Aperture area (m^2)	1.317
Length (m)	1.62
Width (m)	1.04
Tank diameter (mm)	355.6
Outer cover	Low iron glass
Inner covers (2)	Fiberglass acrylic
Insulation	Reflective polyisocyanurate

identical to the one used during the indoor tests, consisted of three draws which occurred daily at 8:00, 12:00, and 17:00. Each draw consisted of water entering the solar system at approximately 23°C at a flow rate of 2×10^{-4} m^3/s. The microcomputer terminated the draw when approximately 14,100 kJ of energy were removed from a downstream conventional hot water tank. The quantity of energy removed was computed by numerically integrating the product of mass flow rate through the solar system, the temperature differential across the system, and the specific heat of water.

5. PREDICTED VERSUS MEASURED OUTDOOR PERFORMANCE

The performance of the ICS system, subjected to outdoor conditions at the NBS Test Facility, was monitored from November 1, 1984, through October 31, 1985. A summary of the monthly experimental data appears in Table 5. The second column indicates the number of days in which complete data existed for each of the 12 months. Missing data were caused by downtime for instrument calibration, power and water supply failures, data acquisition equipment failures, and the freezing of the supply and return pipes leading to and from the ICS system. Columns 3 and 4 list the average ambient and effective sky temperatures, respectively. The fifth column represents the daily average mass of water withdrawn from the ICS unit. The inlet temperature represents the measured average inlet temperature during the data collection period. Column 7 gives the daily solar radiation per unit area measured at the tilt angle of the ICS unit.

The values of $\overline{K}_{\tau\alpha}$, column 8, are computed using the technique outlined in Ref. [11] with the assumption that the monthly incident angle modifier varies in the same manner as a flat-plate collector with three covers. The monthly value of $(\overline{\tau\alpha})$, column 9, is computed by multiplying the monthly values of $\overline{K}_{\tau\alpha}$ in column 8, by $(\tau\alpha)_n$ which in turn is computed by dividing the value of $(\overline{\tau\alpha})$ obtained from the short-term indoor tests (Column 1, Table 3) by $\overline{K}_{\tau\alpha,\text{test}}$ in column 2, the value of incidence angle modifier for the test day. Since the irradiance angle of solar radiation is known throughout the short-term indoor test, $\overline{K}_{\tau\alpha,\text{test}}$ can be computed using the procedure described in Ref. [11].

The experimental average outlet temperature of the ICS system, $\overline{T}_D$, and solar fraction, columns 10 and 11, may be compared to the predicted values given in the remaining columns. The predicted monthly solar fraction values are in close agreement with the experimental values. Agreement is within three percentage points for each of the 12 months with the exception of January. The five-point discrepancy noted in January may be due to snow which occurred during the 18-day test period. Snow on the ICS glazing would decrease the performance of the SDHW system and would not be accounted for in eqn (2) since the value of incident solar radiation, $\overline{H}_T$, was measured using a radiometer cleaned on a daily basis. Additionally, one hot water draw did not occur during the 18-day period due to a frozen inlet water supply line. The predicted annual solar fraction, 33%, is in excellent agreement with the measured value of 32%.

The above prediction results are based on indoor experiments to determine needed parameters. The second objective of this investigation was to determine if short-term outdoor monitoring could be used to determine the parameters required for the long-term performance predictions. Two distinct tests were required to obtain the required parameters, similar in this respect to the method of Reichmuth and Robison[12]. The first experiment, used to determine the overall heat loss coefficient, was conducted in the following manner. A radiation shield was placed above the ICS unit to block incoming radiation. An air space between the radiation shield and ICS glazing was maintained for adequate air circulation. The ICS unit was filled with 60°C water and subjected to outdoor environmental conditions. The resulting overall loss coefficient, U_L, and average environmental conditions which existed during each of two tests are tabulated in Table 6.

The second experiment consisted of measuring the incident solar radiation, ambient temperature, effective sky temperature, inlet and outlet temperatures of the ICS unit during hot water draws, and the mass of water removed during each draw. These data were already in hand as a result of the long-term monitoring effort previously described. Equation (5), in conjunction with an average overall heat loss coefficient value of 1.73 W/m^2·°C, (Table 6), resulted in the $(\overline{\tau\alpha})$ values tabulated in Table 7 for 10-day periods during the months of April, June, and November. Table 7 also gives the transmittance-absorptance product at normal incidence, $(\tau\alpha)_n$, for each 10-day test period calculated as the ratio of $(\overline{\tau\alpha})/\overline{K}_{\tau\alpha}$, where $\overline{K}_{\tau\alpha}$ is evaluated using the average conditions for the 10-day test period. One would expect that the accuracy and consistency of the $(\tau\alpha)_n$ value to improve as the number of consecutive days used in the computations increase due to the lack of a storage term within eqn (5).

Using the $(\tau\alpha)_n$ values in Table 7 and the outdoor measured value for the overall-heat loss coefficient, 1.73 W/m^2·°C, the predicted monthly and annual solar fraction for the ICS system was calculated for each of the three sets of outdoor test data. Table 8 compares the predicted performance using the outdoor and indoor (SRCC) test results to the measured monthly solar fractions.

The annual solar fraction predicted using the short-term outdoor test results varies from a value of .31 to .35 in comparison to the measured value of .32. The annual predicted solar fraction is within one percentage point when the short-term testing was conducted during the months of April and No-

Table 5. Monthly measured and predicted integral collector storage system performance—National Bureau of Standards data

									Experimental values		Predicted values	
Month (−)	Days (−)	Average ambient temp. (°C)	Average effective sky temp. (°C)	Average daily mass withdrawal (kg)	Average ICS inlet temp. (°C)	Average daily solar insolation (kJ/m²)	$\overline{K}_{\tau\alpha}$ (−)	$(\overline{\tau\alpha})$ (−)	Average delivery temp. (°C)	Solar fraction (−)	Average delivery temp. (°C)	Solar fraction (−)
11/84	29	6.0	−4.8	384	22.2	13,696	.93	.43	27.8	.21	27.7	.23
12/84	31	6.4	−2.2	389	21.9	9,738	.93	.43	25.1	.12	25.0	.13
1/85	18	9.7	−11.0	379	21.2	10,892	.93	.43	23.9	.10	25.1	.15
2/85	25	2.2	−9.1	380	21.8	15,731	.92	.43	28.5	.24	28.0	.25
3/85	20	6.9	−4.0	402	22.9	17,395	.91	.42	31.1	.31	30.4	.31
4/85	27	14.1	1.3	422	22.9	21,026	.91	.42	33.4	.40	33.6	.43
5/85	28	18.8	5.1	415	22.9	18,420	.88	.41	33.1	.39	32.5	.39
6/85	28	27.1	11.5	431	23.0	19,182	.87	.40	33.8	.42	34.0	.45
7/85	21	25.8	16.9	429	23.1	19,530	.87	.40	35.2	.47	34.4	.46
8/85	31	23.7	14.5	420	22.8	17,407	.89	.41	33.4	.41	32.9	.41
9/85	28	20.2	8.2	432	23.1	19,783	.90	.42	34.3	.43	33.9	.44
10/85	28	15.4	5.4	407	22.9	13,596	.92	.43	29.3	.25	29.7	.26
Annual solar fraction										.32		.33

Table 6. Measured overall heat loss coefficient for integral collector storage unit subjected to outdoor environmental conditions

Test number	One	Two
Duration (hrs.)	18	9
Average ambient temperature (°C)	−4.5	−0.4
Average effective sky temperature (°C)	−6.5	−2.2
Average effective sink temperature (°C)	−5.0	−0.9
Average wind speed (m/s)	0.10	0.02
Overall heat loss coefficient ($W/m^2 \cdot °C$)	1.73	1.73

Table 7. Computed $\overline{\tau\alpha}$ values from outdoor short-term test data

Number of consecutive days used in computation	Computed ($\overline{\tau\alpha}$) value using data collected during		
	April	June	November
1	.35	.42	.47
2	.41	.47	.43
3	.42	.44	.42
4	.41	.44	.44
5	.41	.44	.44
6	.42	.44	.45
7	.44	.44	.47
8	.43	.44	.47
9	.44	.44	.46
10	.43	.44	.46
$(\tau\alpha)_n$	.47	.51	.50

vember. Using the short-term results collected in June resulted in a difference of four percentage points between the measured and predicted annual performance.

It is interesting to note that although a 20% difference existed between the indoor measured value of U_L, 1.44 $W/m^2 \cdot °C$ and the outdoor measured value of 1.73 $W/m^2 \cdot °C$ the resulting predicted annual performance using both values is in good agreement with the measured values. The same observation was made by Zollner *et al.*[3], who found, using computer simulations, that the determination of ($\overline{\tau\alpha}$) using eqn (5) will tend to compensate for errors in the experimentally determined value of U_L. Zollner's results show a difference in predicted annual performance of less than 5% results for an error of 30% in the experimental determination of U_L. The reader is cautioned against assuming that measurement errors and/or environmental conditions accounted for the 20% difference in U_L. Neither of the ICS units tested at NBS was the same unit for which the indoor testing was conducted for the Florida Solar Energy Center.

6. CONCLUSIONS

The performance of solar hot water systems depends on their design and the climate to which they are subjected. Thus, test results obtained for a given set of meteorological conditions, such as those used by SRCC[2], can only be used to compare system performance at the selected set of meteorological conditions. The ultimate objective, however, is the ability to accurately predict system performance for all climatic conditions.

Klein and Fanney[6] previously conducted an analytical and experimental investigation to show how the yearly performance of forced circulation SDHW systems can be obtained with a minimum of two indoor tests in accordance with ASHRAE Standard 95-1981. The research described in this investigation extends the ability to predict long-term performance based on short-term test results to integral collector storage systems. The technique requires two system parameters, $(\tau\alpha)_n$ and U_L, which are readily computed from the Solar Rating and Certification Standard 200-82[2] test results or from short-term outdoor test results. The predicted performance obtained using this technique is in excellent agreement with a carefully monitored experiment at the National Bureau of Standards.

Table 8. Predicted versus measured solar fraction using SRCC and outdoor test results for integral collector storage systems tested at NBS

Month	Measured solar fraction	SRCC test results	April outdoor test results	June outdoor test results	November outdoor test results
11/84	.21	.23	.19	.22	.21
12/84	.12	.13	.09	.12	.11
1/85	.10	.15	.13	.15	.14
2/85	.24	.25	.25	.28	.27
3/85	.31	.31	.28	.32	.30
4/85	.40	.43	.42	.44	.45
5/85	.39	.39	.38	.41	.37
6/85	.42	.45	.44	.48	.46
7/85	.47	.46	.45	.49	.48
8/85	.41	.41	.40	.43	.42
9/85	.43	.44	.42	.46	.45
10/85	.25	.26	.26	.29	.28
Annual	.32	.33	.31	.35	.33

Acknowledgements—The authors wish to acknowledge the numerous contributions made by Charles Terlizzi of the NBS Solar Equipment Group. Preparation of the manuscript by Mrs. Flora Parsons is gratefully acknowledged. The authors extend their appreciation to Dr. David Block of the Florida Solar Energy Center who graciously provided the indoor test data utilized in this investigation. The research described in this report was supported by the Office of Solar Heat Technologies, U. S. Department of Energy, Washington, DC.

NOMENCLATURE

a parameter used in eqn (4)
A_c aperture area
C_p specific heat of water
$f_{m,c}$ monthly solar fraction with ICS tank fully mixed and operating under a continuous draw
$f_{s,c}$ monthly solar fraction with ICS tank fully stratified
$\bar{H}_T$ monthly average daily solar radiation per unit area on a tilted surface
$\bar{K}_{\tau\alpha}$ monthly average incidence angle modifier
$\bar{K}_{\tau\alpha,test}$ average incidence angle modifier during test period
$\bar{M}_D$ average daily mass of water withdrawn from the ICS system
$\bar{T}_a$ monthly average ambient temperature
$\bar{T}_D$ monthly average temperature of water exiting the ICS system
$\bar{T}_e$ effective temperature for computing ICS thermal losses
T_m average cold water supply temperature
T_s hot water set temperature
T_{sky} effective sky temperature
U_L heat loss coefficient
TT ratio average daily water use to storage volume
$(\overline{\tau\alpha})$ monthly average transmittance-absorptance product
$(\tau\alpha)_n$ transmittance-absorptance product for solar radiation at normal incidence
$\Delta\tau$ number of hours or seconds during the month or test period

REFERENCES

1. Methods of testing to determine the thermal performance of solar domestic water heating systems. ASHRAE Standard 95-1981, ASHRAE, New York (1981).
2. Test methods and minimum standards for certifying solar water heating systems. SRCC Standard 200-82, Solar Rating and Certification Corporation, Washington, DC (Revised February 1985).
3. A. Zollner, S. A. Klein and W. A. Beckman, A performance prediction methodology for integral collection-storage solar domestic hot water systems. *ASME J. Solar Energy Engng* **107**(4), 265–272 (1985).
4. W. A. Beckman, S. A. Klein and J. A. Duffie, *Solar Heating Design*. Wiley–Interscience, New York (1977).
5. W. E. Buckles and S. A. Klein, Analysis of solar domestic hot water heaters. *Solar Energy* **(25)**, 417 (1980).
6. S. A. Klein and A. H. Fanney, A rating procedure for solar domestic water heating systems. *ASME J. Solar Energy Engng* **105** (November 1983).
7. J. A. Duffie and J. W. Mitchell, F-Chart: Predictions and measurement. *ASME J. Solar Energy Engng* **105** (February 1983).
8. A. H. Fanney and S. T. Liu, Performance of six domestic hot water systems in the mid-Atlantic region. In *Conference Proceedings—Solar Heating and Cooling Systems Operation Results*, p. 25 (1979).
9. A. H. Fanney and S. A. Klein, Performance of solar domestic hot water systems at the National Bureau of Standards—measurements and predictions. *ASME J. Solar Energy Engng* **105** (August 1983).
10. S. A. Klein *et al.*, TRNSYS—A transient system simulation program. Engineering Experiment Station Report 38-12, Solar Energy Laboratory, University of Wisconsin–Madison (1984).
11. S. A. Klein, Calculation of the monthly-average transmittance-absorptance product. *Solar Energy* **23**, 547 (1979).
12. H. Reichmuth and D. Robison, An analytical model and associated test procedure for predicting the performance of batch type solar DHW systems. *Proceedings of 1982 Passive Solar Conference, ASES* (1982).