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Comparison of Short-Term Testing and Long-Term Monitoring of Solar Domestic Hot Water Systems[1]

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This paper reports on the results of a comparison between short-term indoor testing and long-term outdoor monitoring of solar domestic hot water systems. Five solar-preheat systems were monitored under side-by-side conditions of irradiance and load, for a period of two years. The systems were then tested according to a standard day test, using a solar simulator, and a load schedule identical to that imposed on each system during the monitoring. The systems were found to deliver 19.7 MJ–25.8 MJ daily in the test, compared to a two-year average of 19.1 MJ–26.0 MJ (1.5 to 2.0 GJ/m² annually) outdoors. System rank was reasonably well preserved. Comparison of results on the basis of efficiency and solar fraction suggests that good correspondence exists between long-term outdoor results and those of indoor testing, at least for systems with stable controllers. Selected systems were also tested at different load schedules and radiation levels. Methods of predicting the performance of a solar-preheat system from the results of a standard day test are discussed, and the possibility of reducing testing time to a single day is explored.

1 Introduction

For several years, monitoring was the only method by which solar domestic hot water (SDHW) system performance could be assessed. Monitoring, by its nature, requires substantial time, and comparison of different sets of results is difficult. More recently, short-term sytems tests, such as those based on the American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) Standard 95-1981 [1], have been developed. Several authorities have adopted, or are proposing SDHW systems' certification according to the results of such tests; Fanney [2] provides a review of some of these. A major hurdle to SDHW performance assessment is comparison of results under one set of conditions of radiation and load to another. Balon et al. [3] and Klein and Fanney [4] have proposed simple methods of performance prediction, based on the results of a number of tests. It has also been suggested that the results of a single carefully devised standard day can adequately be used to characterize a SDHW system. In either case it is tacitly assumed that there is a correspondence between the results of indoor tests and long-term time-averaged values.

The National Research Council of Canada (NRC) undertook a program of comparison of the results of long-term monitoring and short-term testing of five SDHW systems: A quantitative comparison of delivered energy and an analysis of the overall behavior of the systems was made, to determine the validity of short-term testing. The effects of irradiation and load on the system output were also examined. The results may be used to critically appraise the rating of SDHW systems, confidence with which system performance can be predicted, and provide a data base for future research.

Table 1 Rating conditions for CSA standard F379.1 thermal performance test

Time	G_T	θ	Load Schedule		
			Size A	Size B	Size C
(h)	(W/m²)	(°)	(L)	(L)	(L)
0000–0700	0	–	0	0	0
0700–0800	0	–	5	10	10
0800–0900	337	61.9	25	25	25
0900–1000	396	49.3	0	5	25
1000–1100	435	38.1	45	45	45
1100–1200	494	30.1	0	5	25
1200–1300	768	28.3	5	10	10
1300–1400	413	33.5	0	5	5
1400–1500	346	43.3	0	0	0
1500–1600	284	53.3	0	0	0
1600–1700	0	–	0	10	15
1700–1800	0	–	5	25	25
1800–1900	0	–	15	45	45
1900–2000	0	–	30	25	25
2000–2100	0	–	20	10	30
2100–2200	0	–	0	5	10
2200–2300	0	–	0	0	5
2300–2400	0	–	0	0	0
	12.5 MJ/m²		150	225	300

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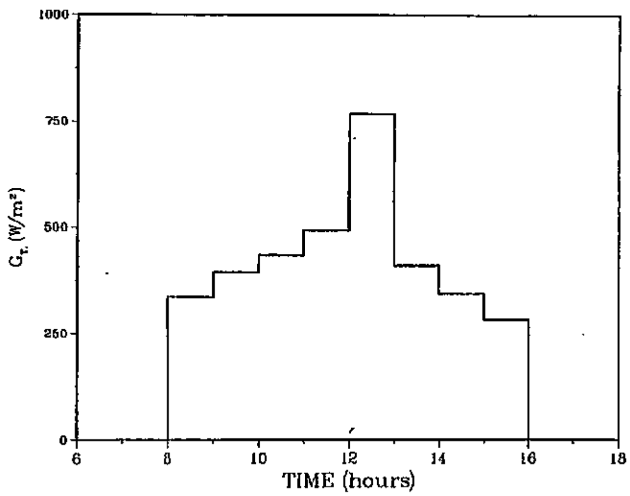

Fig. 1 Irradiance profile for CSA standard F379.1 thermal performance test

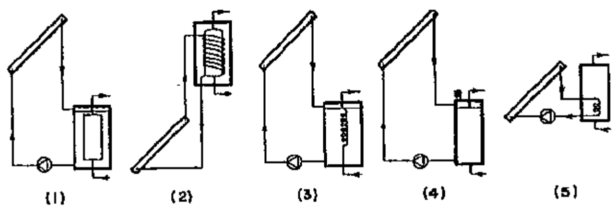

Fig. 2 Schematic of SDHW systems

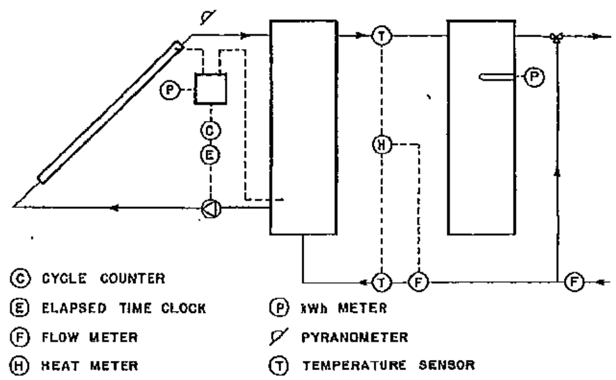

Fig. 3 Schematic of outdoor setup

2 Systems' Testing and Monitoring

2.1 CSA Standard F379.1. The Canadian Standards Association (CSA) Standard F379.1-M1984 [5] is a SDHW systems test based substantially on ASHRAE 95-1981 [1], with a specified test day to be repeated until the 24 hour sum of delivered net solar energy is within 5 percent of the previous 24 hour value. Table 1 shows the thermal performance rating conditions for the test day. The 12.5 MJ/m²•day (±10 percent hourly, ±5 percent daily) irradiance profile, shown in Fig. 1, was developed by Unies Ltd. [6] using the computer program TRNSYS: hourly irradiance values were specified to minimize the deviation between standard day solar fraction and annual-average solar fractions, at various locations across the country. All draws commence on the hour at a rate of 10±1 L/min. The load may be one of three, corresponding to daily withdrawals of 150±5 L, 225±5 L, or 300±5 L. These schedules were developed as a result of a study of water usage in Canada by the IBI Group and Watershed Ltd. [7]. The test stipulates that the draw be tempered should the delivery temperature exceed 55°C. Wind conditions for the test are 4.5±1 m/s with collector ambient temperature 15±2°C while the array is being irradiated and 21±2°C at all other times. Inlet water temperature is 9±2.5°C with tank ambient 20±2°C. CSA Standard F379.1 [5] requires that each solar preheat system be rated according to the net daily solar energy, $Q_{\rm NET}$, given by,

$$Q_{\rm NET} = Q_s - Q_{\rm PAR} \tag{1}$$

where the daily solar energy Q_s is defined by,

$$Q_s = \sum_{j=1}^{n} m_{s,j} c_{p,w} (t_{s,j} - t_{{\rm main},j}) \tag{2}$$

and $Q_{\rm PAR}$ is the daily energy consumed for parasitic power in the SDHW system. $m_{s,j}$ is the mass of the jth withdrawal of potable water, $c_{p,w}$ is the specific heat of water, and $t_{{\rm main},j}$ and $t_{s,j}$ are the system inlet and outlet temperatures, averaged over the draw. Certain issues of design, construction, and matters of health and safety are also addressed in the standard; these were not investigated in this project.

2.2 SDHW Systems Description. Five solar-preheat systems, illustrated in Fig. 2, were used in the research program: (1) A drainback system with a load-side tank-in-tank heat exchanger; (2) a water-propylene glycol thermosyphon (1:1 by volume) with a coil wrapped around a load-side tank-in-tank heat exchanger; (3) a drainback system with a load-side coil-in-tank heat exchanger; (4) a direct pressurized drain-

Nomenclature

a = constant
A = area, m²
b = constant
c_p = specific heat, J/kg•K
f = theoretical solar fraction
F_R = collector heat removal factor
G = irradiance, W/m²
H = daily irradiation, J/m²
I = hourly irradiation, J/m²
j = summation index
$K_{\tau\alpha}$ = incidence angle modifier
m = mass, kg
$\dot{m}$ = mass flow rate, kg/s
n = number of draws per day
N = daily pump on cycles
Q = daily energy, J
t = temperature, °C
U_L = collector overall heat loss coefficient, W/m²•K
$(UA)_T$ = tank conductance, W/K
V = tank volume, m³
η = system efficiency
θ = angle of incidence, deg
λ = system function
ξ = nondimensional temperature
τ = time
$(\tau\alpha)_e$ = effective transmittance-absorptance product

Subscripts

a = ambient, aperture
c = collector, critical
e = exit
f = collector fluid
g = gross
i = incident, inlet
main = mains
n = normal
NET = net
on = on
PAR = parasitic
s = solar system
set = set point (55°C)
T = tilt, tank
u = theoretical useful
w = water

Superscripts

$-$ = two-year daily average

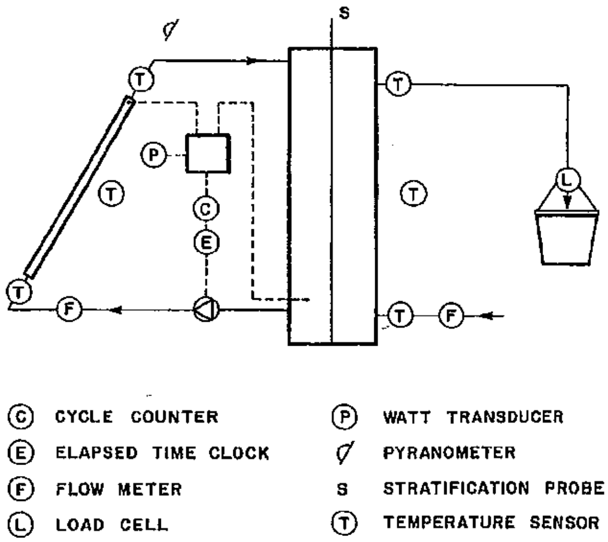

Fig. 4 Schematic of indoor testing setup

back system; (5) a water-propylene glycol system (1:3 by volume) with a collector-side coil-in-tank heat exchanger. All systems had three single-glazed flat-plate collectors.

2.3 Outdoor Monitoring. The water heaters were monitored for a period of two years at the NRC SDHW test facility located in Ottawa, Ontario. The facility, and the results of this monitoring work were discussed by Shewen et al. [8] and Beale and Sibbitt [9] and are briefly summarized below. Figure 3 is a schematic of the monitoring setup. An integrating heat meter connected to precision temperature detectors and flowmeter recorded solar system output. Parasitic and auxiliary energy were measured with kWh meters. A programmable dump controller imposed the daily 225-L load schedule B on each system; this being monitored by an additional flow meter. The auxiliary tank controller was set at 55°C; a tempering valve set at 60°C prevented overheating. Daily pump run-time and cycles were measured by means of a timer and counter. Horizontal and tilt radiation were measured using precision pyranometers.

2.4 Indoor Testing. The systems were then tested at the National Solar Test Facility (NSTF), located near Toronto, Ontario. Norgate [10] and Pullan and Neilsen [11] describe the capabilities of NSTF, which is operated by the Ontario Research Foundation on behalf of NRC. CSA Standard F379.1 [5] permits systems' testing by means of full irradiation (using a solar simulator), partial irradiation (in conjunction with a slave heater), or with a nonirradiated array (in series with a heater). The tests described below were conducted using arrays fully irradiated by means of a 150 kW Vortek single-source argon arc lamp. Care was taken to ensure that original collectors, controllers, sensors etc. were used; occasionally where this was not possible replacements were obtained from the manufacturer: Systems 1, 2, and 3 had identical collectors, and only a single array was built for the tests. The same collector-to-tank height was maintained throughout the testing as in the field; in addition, pipe connections of the same diameter were used.

Figure 4 is a schematic of the set-up for a solar-preheat test. The array and tank were maintained at the prescribed conditions in separate chambers. Load-side mass flow was measured by means of a load cell and computer clock, with a flow meter as backup; all other flow meters and temperature sensors were duplicated (not illustrated) using dissimilar instruments to facilitate error checking, as is the policy of NSTF. Parasitic energy was measured by means of a power transducer. Conditioned mains water was circulated in a continuous loop at the entrance to the system. Stratification probes inserted in the preheat tank(s) measured tank temperature profiles. Data were monitored on a computer-based data acquisition system; summaries being written to a file every 30 minutes. Tempering was achieved in software by shutting off the load early. In addition to the instrumentation required for the tests, daily pump run-time and cycles were measured by means of a counter and timer. In some cases an auxiliary tank was also monitored.

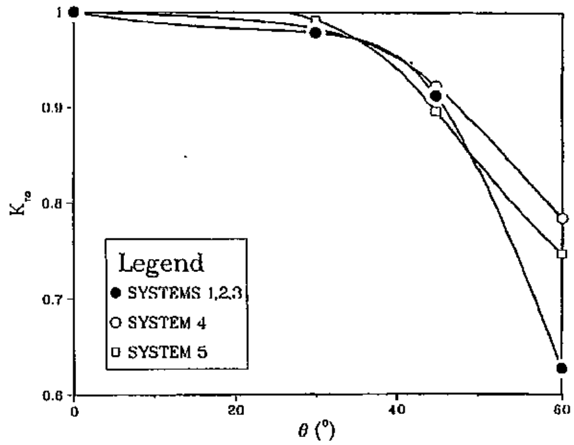

Fig. 5 Collector incidence angle modifiers

Table 2 SDHW Systems' descriptions

No.	$\frac{A_a F_R(\tau\alpha)_{e,n}}{A_g}$	$\frac{A_a F_R U_L}{A_g}$	$\frac{A_a}{A_g}$	A_g (m^2)	V (m^3)
1	0.711	4.53	0.907	5.26	0.454
2	0.520*	3.31*	0.907	5.26	0.454
3	0.711	4.53	0.907	5.26	0.454
4	0.708	4.51	0.918	5.15	0.273
5	0.694	4.49	0.902	5.69	0.303

* At a measured mean mass flow rate of 3.14×10^{-3} kg/s.

The low flow rates associated with the thermosyphon system 2 prevented the use of collector-loop test equipment and an Intek Rheotherm™ flow instrument was used instead. The flow-meter injected 0.5 W into the collector-loop. Physical constraints required that the instrument be located closer to the tank than the collector array.

Prior to conducting the system tests, at least one collector from each array was tested using the simulator, for incidence angle modifier, pressure drop, and efficiency according to CSA Standard F378-M1982 [12]. Incidence angle modifier, $K_{\tau\alpha}$, is shown as a function of angle of incidence, θ, in Fig. 5. This is a prerequisite requirement for the systems test, as the angle of incidence of the radiation in the collector plane, θ, specified in Table 1 is not physically achieved by relative rotation of the lamp and collector array; rather the hourly irradiance, G_T, is multiplied by the value of $K_{\tau\alpha}$ corresponding to the angle given in Table 1, to obtain the equivalent normal irradiance, G_n, which is the actual value to which the lamp is set. Values of $F_R(\tau\alpha)_{e,n}$ and $F_R U_L$, corrected for flow rate differences between the collector and system tests, as outlined in Duffie and Beckman [13], are shown in Table 2.

3 Results and Discussion

3.1 Comparison of Indoor and Outdoor Results. Tests were conducted on all five systems using load Schedule B. Table 3 is a summary of these results: Table 4 is an equivalent summary of the average daily values for the two years of out-

Table 3 Indoor results, load schedule B, $H_T = 12.5$ MJ/m^2, $\bar{t}_{main} = 9$°C (nominal)

No.	$\dot{m}_c$ (kg/s)	Q_c (MJ)	Q_s (MJ)	Q_{PAR} (MJ)	Q_{NET} (MJ)	η_n	η_T	η_T'	f	f'	ξ	N	τ_{on} (h)
1	0.133	28.2	24.3	1.9	22.4	0.43	0.39	0.33	0.52	0.45	0.46	4	5.7
2	9.42×10^{-3}	26.8*	25.8	0.0	25.8	0.48	0.43	0.37	0.60	0.52	0.34	N/A	-
3	0.133	28.0	21.6	1.9	19.7	0.37	0.33	0.28	0.47	0.40	0.57	5	5.9
4	0.120	34.1	27.8	3.3	24.5	0.44	0.41	0.39	0.56	0.52	0.49	15	6.0
5	0.060	30.4	23.2	2.3	20.9	0.35	0.32	0.29	0.49	0.45	0.35	5	6.6

* Assuming pipe losses of 1.3 MJ.

Table 4 Outdoor monitoring results, all systems load schedule B: $\bar{H}_T = 14.7$ MJ/m^2, $\bar{t}_{main} = 10.4$°C

No.	$\overline{Q}_s$ (MJ)	$\overline{Q}_{PAR}$ (MJ)	$\overline{Q}_{NET}$ (MJ)	$\overline{\eta}_T$	$\overline{f}$	$\overline{N}$	$\overline{\tau}_{on}$ (h)
1	23.3	0.9	22.4	0.32	0.54	8	2.6
2	26.0	0.0	26.0	0.37	0.62	N/A	-
3	20.1	1.0	19.1	0.27	0.46	3	2.9
4	24.6	2.3	22.3	0.32	0.53	29	3.8
5	23.8	1.4	22.4	0.30	0.54	19	3.8

door monitoring. Daily values of Q_{NET} range from 19.7 to 25.8 MJ in the indoor test compared to two-year averages of 19.1 to 26.0 MJ (1.5–2.0 GJ/m^2 annually). Agreement between the two sets of results is better than 1 percent for systems 1 and 2, with systems 3 and 4 overperforming by 3 percent and 10 percent, respectively, and system 5 underperforming by 7 percent in the indoor test. The results are shown pictorially in Fig. 6, with performance rank by both Q_{NET} and Q_s indicated in the Figure. Ranking the systems by Q_{NET}, then, it can be seen that system 2 was the best and system 3 the worst performers both indoors and outdoors, with order preserved except for systems 4 and 5. Actual energy extracted from the collector, Q_c, was measured indoors only. This is defined by,

$$Q_c = \int_{\tau}^{\tau + 24\,\text{hrs}} \dot{m}_c c_{p,f} (t_{f,e} - t_{f,i}) d\tau \qquad (3)$$

where $\dot{m}_c$ is the collector-loop mass flow rate, $c_{p,f}$ is the specific heat of the collector fluid, and $t_{f,i}$ and $t_{f,e}$ are the instantaneous collector fluid entry and exit temperatures. Top ranking system 2 appears to have actually collected the least energy, due to the effects of low flow on collector properties (see Table 2). Systems 1 and 3, also with identical collectors and storage volumes, collected about the same energy, but delivered substantially different contributions to the load.

Q_{PAR} was substantially greater during the indoor testing as a result of run-times being approximately double, suggesting that a more extreme radiation profile might be more representative (of Ottawa). Experiments at NRC suggested that significant fractions of pump energy may be added to the collector-loop fluid. The number of pump cycles indoors were typically half of outdoor values, probably as a result of the monotonically increasing and decreasing day.

Comparison of the results of Tables 3 and 4 on the basis of dimensional quantities, such as Q_{NET}, is of limited use due to the difference in irradiation and mains water temperature. Efficiency, η, based on daily irradiation, H, and aperture area, A_a, is defined by,

$$\eta = Q_{NET} / A_a H \qquad (4)$$

Theoretical solar fraction, f, is defined by,

$$f = Q_{NET} \Big/ \sum_{j=1}^{n} m_{s,j} c_{p,w} (t_{set} - t_{main,j}) \qquad (5)$$

where $m_{s,j}$ is the mass of the jth withdrawal, $c_{p,w}$ is the specific heat of water, $t_{main,j}$ is the system inlet temperature averaged over the draw, and t_{set} is by assumption 55°C. Note that this definition differs from that given by Beale and Sibbitt [9].

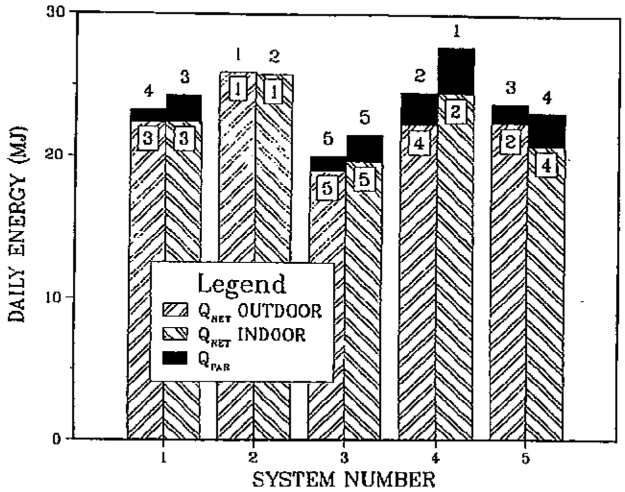

Fig. 6 Results of indoor and outdoor tests

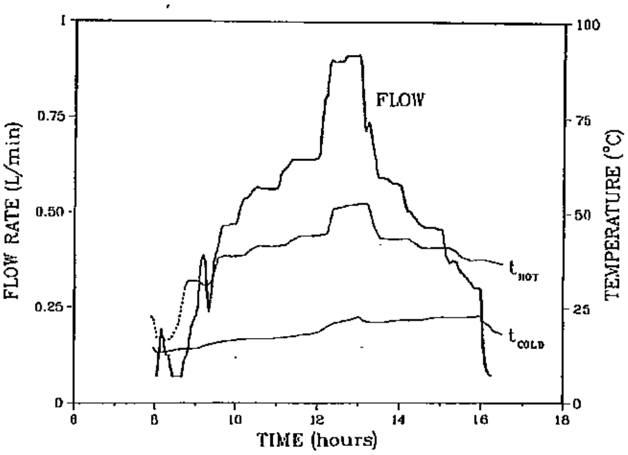

Fig. 7 Collector-loop flow rates and temperatures for a thermosyphon SDHW system

Efficiency values based on both H_n and H_T are tabulated in Table 3 as η_n and η_T. It can be seen that while there is good agreement between indoor and outdoor solar fractions, values of η_T are systematically higher for the results of the indoor tests. This is because CSA Standard F379.1[5] specifies only the total irradiance from [6], where tilt radiation data was broken down into beam and diffuse components. Since the simulator radiation is direct, lamp intensities based on [6] would have been less than those in the test. Moreover, the relative magnitude of system inputs would have been different, due to the different $K_{\tau\alpha}$ profiles in Fig. 5. An estimate of what the system efficiencies might have been is obtained by assuming constant output versus input, i.e., constant η_n (estimates require a second order correction because of

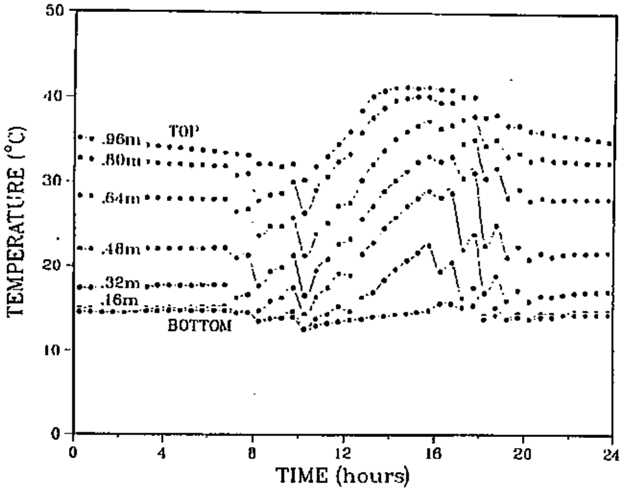

Fig. 8 Tank temperature profile of a thermosyphon SDHW system

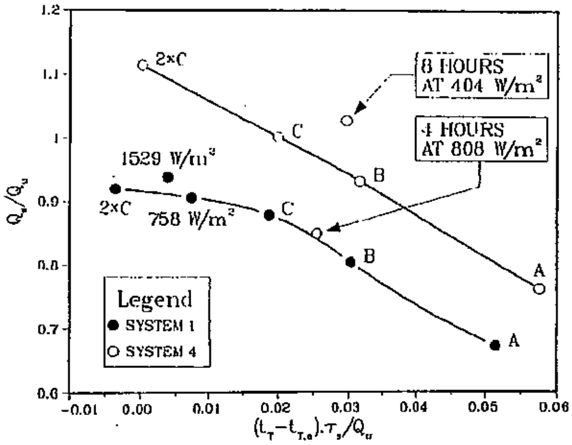

Fig. 9 Correlation of the results of SDHW systems tests

Table 5 Indoor test results, systems 1 and 4, various load schedules

No.	Load	Q_C (MJ)	Q_S (MJ)	Q_{PAR} (MJ)	Q_{NET} (MJ)	η_m	f	N	τ_{on} (h)
1	A	25.5	18.6	1.7	16.9	0.32	0.59	4	5.3
1	B	28.2	24.3	1.9	22.4	0.43	0.52	4	5.7
1	C	31.8	28.2	2.1	26.1	0.50	0.46	1	6.9
1	2xC	35.4	34.1	2.1	32.0	0.61	0.28	1	6.7
4	A	29.4	20.1	2.6	17.5	0.32	0.61	23	4.7
4	B	34.1	27.8	3.3	24.5	0.44	0.56	15	6.0
4	C	34.9	31.6	3.5	28.1	0.51	0.48	14	6.5
4	2xC	38.3	39.1	3.6	35.4	0.64	0.30	14	6.6

Table 6 Effect of radiation intensity on system 4

Description	Q_c (MJ)	Q_u (MJ)	Q_c/Q_u	N	τ_{on} (h)
CSA Schedule B	34.06	29.79	1.14	15	6.0
404 W/m² for 8 hrs	34.42	28.69	1.20	10	7.4
808 W/m² for 4 hrs	37.64	36.62	1.03	1	4.1

changes in average collector inlet and tank temperature) and furthermore that the diffuse component specified in [6] were isotropic and incident at 60 deg. These values are listed in Table 3, as $\eta_{T'}$ and f'. Values of $\eta_{T'}$ show almost perfect agreement with η_T based on monitored results, with the exception of one system, the direct drainback system 4, which substantially overperformed indoors. Theoretical solar fraction values f' are systematically lower than values based on outdoor data. This may be because of the intrinsic sensitivity of solar fraction to changes in inlet temperature and irradiance, or because of uncertainty in the value of t_{main} associated with preheating of inlet lines to the systems between loads at the NRC SDHW test facility (where values of t_{main} were measured and recorded on a daily basis only). While the correspondence between the two sets of results demonstrates that the standard day rating method generally works well, the apparent disparity between indoor-test and outdoor-monitoring results for system 4 should not be overlooked: As will be shown below the implications of this result are serious, both for the proponents of the standard day concept as a rating method, and for simple performance prediction methods based on collector theory. There is some possibility that a beam-diffuse component of solar radiation will be included in a future version of CSA Standard F379.1 [5].

3.2 Effects of Stratification, Load, and Radiation Intensity on System Performance. Collector-loop flow rate and temperatures for the final 24 hours of the indoor test conducted on the thermosyphon (system 2) are shown in Fig. 7 (values of flow rate below 160 mL/min. are not meaningful). Due to problems with a chart recorder, the first hour of the hot (collector outlet) temperature was estimated from the previous day. The starting transients occurred in the absence of any check valves. This system exhibited excellent thermal stratification in storage as shown in Fig. 8, which shows the 30 minute average temperatures measured by the tank probe for the final 24 hours. This is due to the low flow rate and the presence of the outer tank containing stagnant water. All systems stratified to some extent at night but system 5 (with a relatively low flow rate) was the only other system capable of maintaining more than 6°C difference between top and bottom in the daytime. The effect of stratification is to lower the nondimensional daily average bulk tank temperature, ξ, defined by,

$$\xi = (t_T - t_{main})/(t_{set} - t_{main}) \tag{6}$$

i.e., high solar fraction does not necessarily imply high bulk tank temperature. System 4 did not stratify at all during the day; in fact, daytime temperatures were actually a little higher at the bottom than at the top of the tank, probably as a result of repeated draining. Excessive cycling of this system, where the collector sensor was thermally isolated from the collector, was caused by a high controller differential off temperature. Significant cycling was also observed in system 5.

The effects of load on system performance were investigated by imposing all three CSA load schedules and an additional 600 L/day (twice schedule C) on the direct system 4 and the tank-in-tank drainback (system 1). The results are shown in Table 5; the effects of increasing load are to increase η, but decrease f. With lower tank temperatures associated with larger loads, controller cycling decreased, and run-times increased.

A number of authors have discussed the effects of load distribution on water heaters; it now being generally agreed that performance is not a strong function of load distribution for systems with adequate storage. This is not true for system 3, with the load-side heat exchanger, which displays a marked transient (drop) in delivery temperature when loads of 10 L or more are imposed on it. The impact of tempering on the outdoor test results was small; tempering did not occur at all during the indoor testing.

The effects of radiation intensity distribution, at constant load, were also investigated. System 4 was retested using the same daily irradiation as in the standard day (11.6 MJ/m^2) but (*a*) at 404 W/m^2 for 8 hours and (*b*) at 808 W/m^2 for 4 hours. The results are shown in Table 6. Q_u the theoretical useful energy from the collector is calculated as,

$$Q_u = \sum_{j=1}^{24} A_a [F_R (\tau\alpha)_{e,j} I_{T,j} - F_R U_L (t_{f,i} - t_{c,a})_j \cdot \Delta\tau]^+ \qquad (7)$$

where $(t_{f,i} - t_{c,a})_j$ is the difference in temperature between collector fluid inlet and collector ambient for hour j, and the superscript "+" indicates values are summed only when the hourly irradiance, I_T, exceeds a critical value, I_c, given by,

$$I_{c,j} = \frac{F_R U_L}{F_R (\tau\alpha)_{e,j}} (t_T - t_{c,a})_j \qquad (8)$$

$(t_T - t_{c,a})_j$ is the hourly-average difference between the bulk tank temperature and the collector ambient.

This theoretical critical level was always exceeded throughout the indoor tests. Unfortunately $t_{f,i}$, though measured, was not reported, and an estimate of Q_u had to be made on the basis of the temperature at the bottom of the tank as measured by the stratification probe. The effect of pipe losses on $t_{f,i}$ is small, but values of Q_c/Q_u greater than unity suggest that this bottom centerline tank temperature is not entirely representative of the average inlet temperature of the (flowing) fluid. Although τ_{on} for the 4-hour high-irradiance case was at least 100 percent compared to 75 percent of the possible run-time for CSA Schedule B, there is no increase in Q_c/Q_u (in fact there is a slight reduction in Q_c/Q_u as Q_u increases), suggesting that the system can operate effectively (under test conditions at least) in a transient mode as a drainback batch heater! The sensitivity of this system to variation in utilizable incident energy distribution explains the disparity between indoor and outdoor results.

3.3 Rating SDHW Systems from the Results of Indoor Tests. Although CSA Standard F379.1 [5] appears to rank the majority of the systems (excluding system 4) well relative to NRC measurements, it cannot be used to rate systems under every possible combination of load and climate. Before attempting to predict system performance on the basis of tests, it is necessary to have a means of correlating the results of indoor tests. Assume then that some fraction, λ, of the theoretical useful energy is delivered to the tank (due to controller hysteresis, pipe losses, injection of parasitic energy into the collector-loop, heat exchanger ineffectiveness, stratification, etc), also some energy will be lost from the preheat tank. Then Q_s defined in equation (2) is given by,

$$Q_s \doteq \lambda Q_u - (UA)_T (t_T - t_{T,a}) \cdot \tau_s \qquad (9)$$

where t_T and $t_{T,a}$ are the daily average bulk tank and tank ambient temperatures, $(UA)_T$ is the tank conductance, and τ_s is the length of the test cycle (e.g., 24 hours). If λ and $(UA)_T$ are constant and the results of two or more tests are available, they may be calculated using the method of least squares (depending on the data supplied by the testing laboratory, they may also be estimated from the results of a single test, if necessary).

Figure 9 is a graph of Q_s/Q_u against $(t_T - t_{T,a}) \cdot \tau_s / Q_u$ for the results of tests on systems 1 and 4. Values of Q_u are again based on bottom (outer) tank temperature. The line drawn through the results of Table 5 for the direct system 4 is quite straight suggesting that $(UA)_T$ (the slope) and λ (the intercept) are indeed constant. This is consistent with the results of Klein and Fanney [4]. In the case of system 1, nonlinearity associated with the heat exchanger ineffectiveness is apparent.

With reference to Fig. 9, the linearity of the results of Table 5 for the direct drainback system is indeed remarkable, as large deviations from the correlation line are apparent when the results of Table 6 are included in this graph. Standard day rating of this system, by means of CSA Standard F379.1 [5], is in error due to controller-related effects on system performance. Any simple predictive method which does not take this into account will also fail. This does not preclude the possibility of developing a standard day which would be more realistic (of Ottawa weather) for all systems, stable or otherwise. Indoor test results, for SDHW systems which are not sensitive to irradiance and load distributions, may be used as a rating method. For other systems (e.g., system 4), if the energy actually delivered to the preheat tank were measured, variation in λ could be investigated and correlated.

SDHW system testing requires 3 to 5 days of testing, and costs are substantial. By judiciously increasing irradiance and load schedules, it should be possible to maintain the same load-side temperature, while decreasing test time, at least for fully mixed systems with good controllers. Experiments aimed at investigating this hypothesis were performed. System 1 was retested at a continuous 758 W/m^2 with a draw of 30 L every 30 minutes. As can be seen by inspection of Fig. 9, agreement is excellent. Despite careful preheating of the tank the system barely reached equilibrium after 10 hours. In order to further decrease the convergence time, it would have been necessary to increase the irradiance beyond the limits of the lamp. Time prevented a complete range of tests from being conducted using an inline heater in conjunction with a nonirradiated array, however, one final test was conducted by disconnecting the collector and supplying heat equivalent to an irradiance of 1529 W/m^2, based on equation (7), and a draw of 75 L every 30 minutes. Convergence without preheating was reached after 10 hours.

These preliminary results are encouraging, and suggest that a reduction of testing time might be possible. The reader will note that a constant value of $F_R U_L$ was assumed throughout this paper. Calculations indicate that values of $F_R U_L$ based on the identity,

$$F_R U_L = a + b(t_{f,i} - t_{c,a}) \qquad (10)$$

are substantially lower than the values given in Table 2 for the collectors used in this program, operating under typical standard day conditions.

The results of Fig. 9, though instructive, may not be used to predict field performance, unless some reduction of parameters is achieved. Many approaches are possible. The simplest method would be to substitute the daily average system outlet temperature, t_s, for both $t_{f,i}$ and t_T and equate equations (2) and (9). Following a procedure similar to that outlined by Klein and Fanney [4], by direct substitution of monthly-average values of incidence angle modifier, and employing the concept of utilizability to estimate Q_u, a value of Q_s could be obtained by iteration, e.g., using the secant rule, on trial values of a monthly-average daily system temperature, t_s. Values of λ and $(UA)_T$, not necessarily constant, could be obtained from a correlation of the test results. However, a utilizability-based method may not be appropriate for climates where there are significant random variations in t_s. In the case of indirect systems, an alternative procedure could be developed by rewriting equation (9) in terms of a collector-side equation and a load-side equation, introducing a heat exchanger overall heat transfer coefficient.

While it was once true that design methods were required because of the expense associated with computer simulation, this is probably less true nowadays. Computer simulations are currently available which use typical meteorological data, account for changes of internal energy in the system, and contain subcomponent models based on engineering principles. The problem with present-day software is that the results are not "tied" to empirical results. Future computer simulations should contain flexible models, which can be adjusted using the results of one or more indoor tests. Current simulations are typically based on the results of a collector test. Future simulations based on additional systems test results should yield precise performance prediction figures.

The CSA standard day test [5], [6] was based on TRNSYS simulations of various SDHW systems across the country. While the single standard day could represent a range of conditions, it cannot account for all possible environmental extremes. It is therefore necessary to be able to predict/simulate system performance based on test results. The advantage to using a simpler, more direct "synthetic" test (not representative of typical conditions) is that one does not have to specify a unique procedure for every new generic system type. However, even if precise performance prediction were possible, to the authority seeking to rate or certify systems, it would still be necessary to define the standard application. Also since some systems (e.g., systems 2 and 3) do not lend themselves well to simulation, the use of a "natural" standard day is not without merit.

4 Conclusions

The solar simulator is a useful research tool, capable of generating precise, repeatable results and obviating much of the need for time-consuming SDHW system monitoring. The standard day concept has proven itself to be as good a method of rating SDHW systems as any other in existence. Five solar preheat systems testing according to CSA Standard F379.1 [5] were found to deliver from 19.7 to 25.8 MJ daily, compared to two-year daily averages of 19.1 to 26.0 MJ operating outdoors under identical conditions of load. Ranking systems by net delivered energy, order was reasonably well preserved.

The existing standard [5] accounts for the directional properties of solar radiation associated with the apparent motion of the sun, but not the beam-diffuse nature of insolation. The latter should be included in (or the former excluded from) the standard day. Dimensionless quantities such as system efficiency and solar fraction allow for meaningful comparison of results. On this basis it was shown that good agreement existed between indoor-test and outdoor results for all but one of the systems used in this project. The standard day was found to overestimate the performance of this system, due to controller-related effects. Notwithstanding the above, the test results were correlated in a fashion which suggest that (*a*) for many systems, the results of indoor testing can and should be used to predict SDHW system performance and (*b*) simple one-day tests could possibly replace existing SDHW tests at substantial cost savings. More research is required to adequately characterize systems with poor controllers. However, it should be noted that if the results of short-term tests cannot be used to estimate the performance of an SDHW system, it is unlikely that system performance can ever be estimated.

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References

1 ANSI/ASHRAE Standard 95-1981, "Methods of Testing to Determine the Thermal Performance of Solar Domestic Water Heating Systems," ASHRAE, Atlanta, GA, 1981.

2 Fanney, A. H., "A Review of Solar Domestic Hot Water System Test and Rating Procedures," *Proceedings of the ASME Solar Energy Division Fifth Annual Conference*, Orlando, FL, Apr. 1983, pp. 169–177.

3 Balon, R. J., Wood, B. D., and Nelson, D. J., "Performance Testing and Rating of Solar Domestic Hot Water Systems," CR-820390, College of Engineering and Applied Sciences, Arizona State University, Tempe, AZ, June 1982.

4 Klein, S. A., and Fanney, A. H., "A Rating Procedure for Solar Domestic Hot Water Heating Systems," JOURNAL OF SOLAR ENERGY ENGINEERING, Vol. 105, Nov. 1983, pp. 430–439.

5 Canadian Standards Association Standard F379.1-M1984, "Solar Domestic Hot Water Systems (Liquid-to-Liquid Heat Transfer)," Rexdale, Toronto, Canada, 1984.

6 Unies Ltd., "Report of the Computer Simulation Study to Develop a Standard Day Test for Solar DHW Systems," Final Report, Contract 04SX.31155-2-2794, Solar Energy Program, National Research Council Canada, Ottawa, Canada, Dec. 1982.

7 IBI Group and Watershed Energy Systems Ltd., "Hot Water Load Profiles," Solar Energy Program Report No. SOLWAT-4, National Research Council Canada, Ottawa, Canada, Aug. 1982.

8 Shewen, E. C., Sibbitt, B. E., and Chamberlain, M. J., "Examination of S.D.H.W. System Performance," *Proceedings of the 9th SESCI Annual Conference*, Windsor, Canada, Aug. 1983.

9 Beale, S. B., and Sibbitt, B. E., "Monitoring of Solar Domestic Hot Water Systems at the National Research Council of Canada," *Proceedings of ISES Congress*, Montreal, Canada, June 1985, pp. 868–872.

10 Norgate, G., "Canada's National Solar Test Facility," *Proceedings of ISES Congress*, Perth, Australia, Aug. 1983, pp. 858–865.

11 Pullan, H., and Nielsen, V. H., "Ongoing Developments at Canada's National Solar Test Facility," *Proceedings ISES Congress*, Montreal, Canada, June 1985, pp. 1248–1252.

12 Canadian Standards Association Standard F378-M1982, "Solar Collectors," Rexdale, Toronto, Canada, 1982.

13 Duffie, J. A, and Beckman, W. A., *Solar Engineering of Thermal Processes*, 1st Ed., Wiley, New York, 1980, pp. 266.