

CALIBRATED SIMULATION OF THE DEGRADATION OF A SOLAR HOT WATER SYSTEM PERFORMANCE OVER A 22-YEAR PERIOD OF OPERATION

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ABSTRACT

This paper reports on the measured performance of a residential solar water heater system over a period of 22 years and the modeling of the system to simulate its degradation over that period. The system consists of three fixed flat-plate collectors with a total of 5 m² of double-layer glass cover plates and black aluminum fin-tube absorber plates. The solar storage tank capacity is 303 liters, which is used as a pre-heater to a 114-liter conventional electric water heater. Measurements and simulations indicate that the degradation is mainly due to fogging of the glass cover plates, reducing the transmissivity by around 63 percent over the 22 years.

INTRODUCTION

This study concerns the author's residence, which housed a family of five from 1982 to 1985, three people from 1985 to 1998 and two people from 1998 to 2005. The home had two storage-tank type water heaters serving two sections of the house. Both tanks contained two electric resistance 4500-W heating elements. One tank, 197 liters (52 gal.), served the laundry area and two bathrooms. The second tank, 114 liters (30 gal.), served the master bathroom and kitchen (with dishwasher). The solar system was originally installed to serve only the larger tank. Though the total daily hot water consumption for five people was around 379 liters (100 gal.) per day, only 325 liters (86 gal.) were used through the tank being served by solar and 54 liters (14 gal.) by non-solar.

On 12 June 1982, the Sun-Pride solar system, manufactured by Revere Solar Products, was purchased for US\$1160 and installed. No state sales tax was charged due to state law exempting energy devices. The closed-loop system included check valves, a tempering valve, pressure gauge and relief valve, pump, differential thermostat controller, shut off valves, air expansion tank, air vents, two 1.6 m² (17.2 ft²) collectors, and a 303-liter (80-gal.) storage tank with a heat exchanger near the bottom of the tank. The system is depicted in the schematic diagram in Figure 1. The collector heat transfer fluid is a 50:50 mix of ethylene glycol and water.

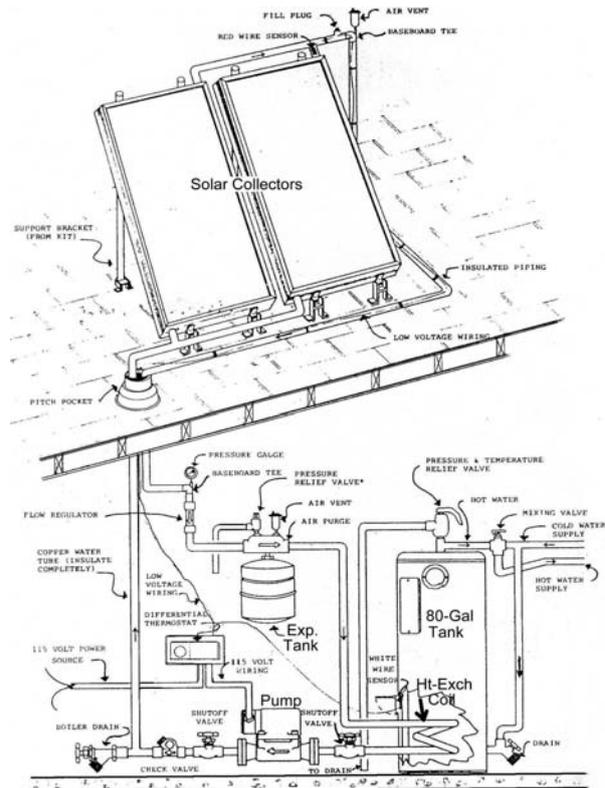


Figure 1 The Revere Sun-Pride system

Led by the 1 m² (10 ft²) of collector per person rule-of-thumb, a third collector panel was purchased and installed along with the other two, resulting in a total collector area of 5 m² (53.7 ft²), or about 1 m² (10.7 ft²) per person. The solar storage tank provided about 60 L/m² (1.49 gal./ft²) storage/collector ratio. The final collector array is shown in Figure 2.



Figure 2 Final collector panel arrangement

The roof is oriented to true South and has a pitch of 36 degrees, which is about 6 degrees higher than the site latitude of 30°N. This was considered to be ideal, so no further added tilt was necessary. There are no trees or other objects shading the collector panels. After all expenses were accounted for, the total cost of the system was US\$1,500. A 40% income tax rebate made the effective cost just \$900, labor excluded, or \$180/m² (\$16.76/ft²). Using typical-year weather data, a software model (described later) was run to predict the solar heating contribution (around 80%) and the payback on the investment (about 2.9 years.)

In order to see if the computer simulation prediction was valid, kWh consumption records were made for one year prior to the installation of the solar system and for the year following the installation. The heating element at the top of the hot water heater was left activated at all times, but only turned on when there was not enough solar energy to preheat the water. In the first summer of operation, the electric element never turned on and showed consumption only after mid-October. After one year of operation, the measured electric use was 790 kWh compared to the prior year of 5011 kWh when no solar system was installed. The solar system was therefore giving slightly better performance than predicted, yielding about 84% of the annual needs and saving \$312.34 a year. Since the total investment was \$900, the payback is computed to be 2.88 years, approximately what the software had predicted. No attempt was made to correct for possible weather differences in the two years that were evaluated; however, when the simulation was performed, identical weather data were used for both years.

In 1985, the smaller “non-solar” water heater was removed, and the plumbing was rerouted so the solar system would serve all hot water use in the house through the 197-liter tank. In 2004, this tank failed, was discarded, and the smaller water heater was installed in its place. Since this heater is much smaller than the previous one, both of the 4500-Watt heating elements were left activated.

For the 1982 to 2005 period, an estimate was made of the total savings in water heating energy. First, the base consumption was based on the consumption rate in 1981 with 5 persons present. This established a “daily-use-per-person” rate that was applied over the 22 years, during which three of the occupants left the household. Once the yearly consumption was determined, a cost savings estimate was calculated from known electric rates that increased only modestly from \$0.074/kWh in 1982 to \$0.08/kWh in 2005. The actual costs were determined precisely from the measured kWh consumption. The solar system netted an electric savings of about 44,647 kWh, for a cost savings of around US\$3440.

PROCEDURES

During one year prior to the collector installation plus the first two years of operation, the kWh use was measured by use of a system-on timer. This enabled the calculation of kWh energy savings from the solar system. In the 22nd year, the water temperatures were measured by time-dependent portable data loggers; thus, both water temperatures and system on-time usage could be analyzed. In the software simulations, hourly weather records were used to determine the incident solar radiation values and the ambient dry-bulb temperatures. By adjusting the collector cover plate transmission factor, the simulated annual water heating energy could be calibrated against the measured kWh consumption. Once the simulated energy consumption matched the measured results, monthly, daily and hourly values were also checked for agreement. Graph plots were then made of hourly measured and predicted tank temperatures for several week-long periods. This permitted the inspection of aggregate energy savings as well as time-dependent performance characteristics.

THE SOLAR SIMULATION MODEL

A FORTRAN program was written by the author, based on flat-plate solar collection methodology developed by Duffie and Beckman (1974.) The program was designed to use either “typical” weather (see Degelman 2004, 1991) or recorded weather records. In 1982, the program was run using typical weather data and a collector efficiency equation published by the collector manufacturer. In 2005, locally recorded weather data were used, because the objective was to calibrate between measured performance and the simulated performance by adjusting the solar collector efficiency parameters.

Though the model can accommodate a variety of collector types, it is intended mostly to handle the category of flat-plate water-cooled collectors with tank storage. Sun angles and direct normal and diffuse insolation are derived on an hourly basis within the model, so concentrating and tracking collector systems may also be modeled with little extra effort. (See Degelman 1991.)

The solar collection model computes the thermal energy output from the collector, after which the net useful energy is computed by doing a thermal balance on the storage tank. This is done by adding the collector heat minus the building’s hot water demand and tank losses. The tank water temperature is never permitted to exceed boiling, 100°C (212°F).

The collector’s useful energy output is modeled using the equation:

$$Q_u = F_R [Q_T - U_L (t_{f,i} - t_a)] \dots\dots\dots (1)$$

Since F_R and U_L are themselves dependent on Q_u , the precise establishment of Q_u is an iterative process. The program was originally devised to iterate a series of equations to converge on an acceptably low error in Q_u , but repeated runs with the program revealed that a substitute one-pass series of computations would result in an acceptably accurate solution. This technique has resulted in a very useful procedure for flat-plate collector output computations (Degelman 1977), the steps of which are delineated below:

Step 1: Given I_{DN} , I_{df} , and sun angles, compute Q_T .

$$Q_T = \tau (I_{DN} \cos(\Theta_T) \text{Trans}(\Theta_T) + I_{df}) \dots\dots (2)$$

Step 2: Set $t_{f,i}$ equal to the storage tank temperature.

Step 3: Set a temporary value of U_L at $4.0 \text{ W/m}^2 \text{ K}$, (or $0.7 \text{ Btu/ft}^2 \text{ F h}$.)

Step 4: Set a temporary value of F_R at 0.9.

Step 5: Compute a temporary value of Q_u by Eq. 1.

Step 6: Compute mean fluid temperature based on a specified fluid mass flow rate:

$$t_{f,m} = t_{f,i} + Q_u / (2 \dot{R} C_p) \dots\dots\dots (3)$$

Step 7: Compute mean plate temperature:

$$t_{p,m} = t_{f,m} + Q_u / U_p \dots\dots\dots(4)$$

Step 8: Compute the cover plate heat transmission coefficient (U_C). This is a function of number of glass cover plates, emissivity of absorber plate, wind speed, $t_{p,m}$ and t_a . For empirical equation, see Duffie and Beckman (1974), pages 132 - 135.

Step 9: Compute the overall heat loss coefficient:

$$U_L = U_C + U_B \dots\dots\dots (5)$$

Step 10: Compute the collector heat removal factor:

$$F_R = (\dot{R} C_p / U_L) [1 - \exp(-F' U_L / \dot{R} C_p)] \dots\dots (6)$$

Refinements in the value of Q_u can be obtained by iterating the above sequence beginning at step 5 and going through step 10; however, it was determined after several computer runs that a one-pass process may result in sufficiently accurate results.

Step 11: Compute final value of Q_u , by using Eq. 1

The above steps are utilized by the computer program if a certified and published efficiency graph is not available for the collector. If an efficiency plot is available, then it can be used to compute Q_u in lieu of iterating the 11 steps shown above. The form of the efficiency equation is:

$$\text{Eff} = A - B x - C x^2 \dots\dots\dots (7)$$

Where, Eff = collector efficiency
 x = the fluid parameter
 A, B, C = regression coefficients.

For the Sun-Pride system, the published equation (in inch-pound units) was:

$$\text{Eff} = 0.77 - 0.549 x - 0.3 x^2 \dots\dots\dots(8)$$

Step 12: Compute storage tank losses: The hot water demand is determined from an hourly use pattern, thus drawing in new supply water and lowering the tank's temperature. The tank's stand-by losses are determined by multiplying the tank's surface area by the shell's U-factor and the temperature difference to the room's ambient temperature. The tank's surface area is 2.35 m^2 (25.33 ft^2) and the U-factor is estimated to be $0.57 \text{ W/(m}^2 \text{ K)}$, or $0.1 \text{ Btu/(hr ft}^2 \text{ F)}$.

A plot of the performance curve is shown in Figure 3. This is a typical shape of an efficiency plot, showing that as a collector's temperature is increased, the efficiency decreases because of increased heat losses to the ambient air. The intercept on the y-axis (0.77) is essentially the collector's efficiency when the collector's temperature is equal to the outside air temperature; i.e., no heat losses from the collector. This intercept is, therefore, a close indicator of the cover plate transmissivity. The fluid parameter on the horizontal axis is actually the temperature difference between the incoming water and the outdoor ambient air divided by the incident solar radiation flux.

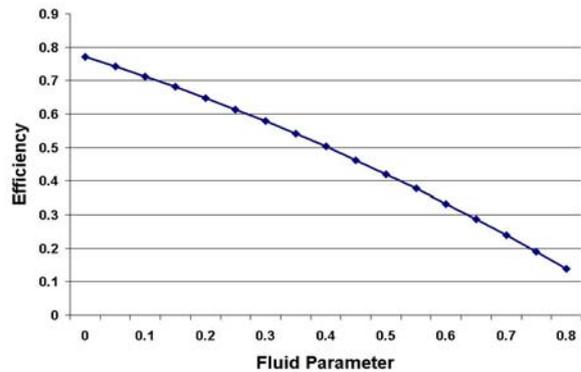


Figure 3 Original Sun-Pride efficiency curve

MEASUREMENT RESULTS

Detailed temperature measurements were made throughout 2004 at three-minute intervals by portable data loggers. Recorded data included the temperature of the fluid returning from the collector, water temperature near the top of the storage tank, and the room temperature where the storage tank and water heater were located. This is a small room with an outside door that has 0.28 m^2 (3.03 ft^2) of glass facing due south. This aperture allowed for natural solar heating of the space surrounding the solar storage and water heater tanks, typically keeping the room around $27\text{-}29\text{C}$ ($80\text{-}85\text{F}$) throughout the day and night and thus minimizing the standby heat losses from the tanks. A typical plot of temperature data from December 2004 are shown in Figure 4.

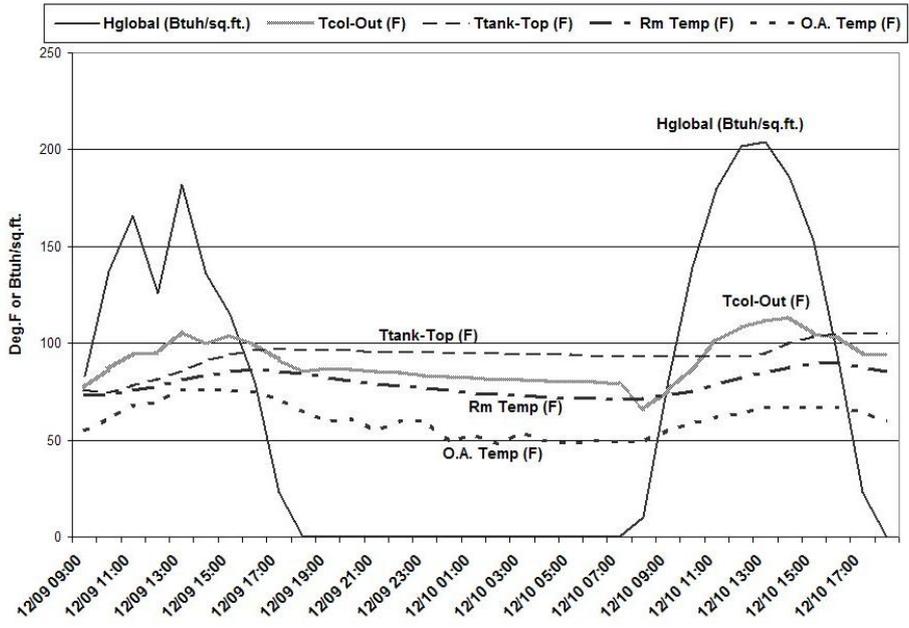


Figure 4 Typical plots of measured data, 9-10 Dec 2004

This plot shows temperatures for outdoor, tank room, water in top of storage tank, and water returning from the collector. In addition, it shows hourly horizontal global insolation for a two-day period. (Inch-pound units, °F and Btuh/ft², were used for this graph so the values for both temperature and insolation could be scaled easily on the same axis.) From the graph, it can be seen that the room temperature is typically 20-25F (11-14C) warmer than the outdoor temperature. This is due to the solar gain through the south-facing window in the door, as the room is neither heated nor cooled by the house HVAC system. In addition to temperature data, the electricity consumption was monitored continuously through the use of timers attached to both heating elements in the water heater. The kWh consumption was then derived by multiplying the timer hours by 4500 Watts (the actual rating of each element.) Hot water usage was measured over a period one month to determine the typical consumption pattern for the two residents of the house in 2004. The consumption rate was 136 liters (36 gallons) per day, or 68 liters (18 gallons) per person per day. The temperature rise was typically from 20C (68F) incoming temperature to about 54C (129F) outgoing temperature. This resulted in a temperature of about 51C (124F) at the faucet.

Using the measured base data, an annual consumption was calculated to be 49,871 liters (13,176 gallons). The annual heating of this water was computed to be 2414 kWh, or about US\$193, if no solar system were present. The measured consumption, with solar present, was 1060 kWh, or about US\$84.80. This means that the annual solar contribution is 56% as compared to the 84% solar contribution during the system's first year of operation 22 years earlier.

SIMULATION RESULTS

The simulation model was run for the year of 2004 using actual outdoor temperature and solar radiation data recorded at a local site. Using repeated computer runs, it was possible to match the annual 56% solar contribution by varying the collector's efficiency by successively lowering the A-coefficient in the efficiency equation, which approximates the actual transmissivity of the cover plate. An annual energy match was made when the A-coefficient was 0.28. This is a radical reduction from the original 0.77 value when the collector was first installed. This can be supported somewhat by visual confirmation that the cover plates are no longer transparent. Instead, they have been severely whitened by a chalk-like substance on their interior. At this point, no effort has been made to remove the plates, clean and re-seal them. The new efficiency curve is therefore:

$$Eff = 0.28 - 0.549 x - 0.3 x^2 \dots\dots\dots(9)$$

To show the magnitude of this degradation from the original performance, a plot was made (Figure 5.)

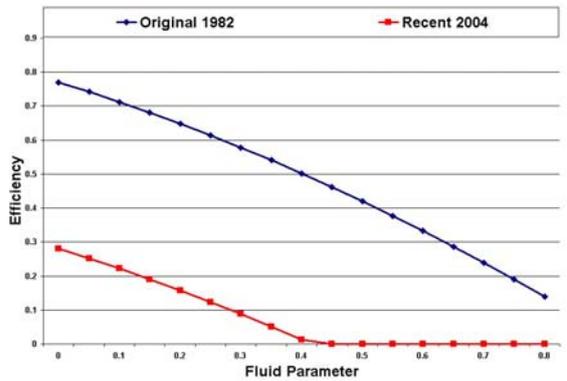


Figure 5 Efficiency curves – year 1982 vs. 2004

In order to confirm that the new efficiency equation would satisfactorily predict hourly energy collection performance, several plots were made of selected periods of the year, specifically, early August, mid September, and mid December. These plots are 6 to 9 days in length and show hourly results for

calculated temperatures in the storage tank and recorded temperatures for tank (top), collector out, and outdoor ambient. Hourly global insolation values are shown as well. These plots are shown in Figures 6 through 8. Once again, Inch-pound units are used for scaling reasons.

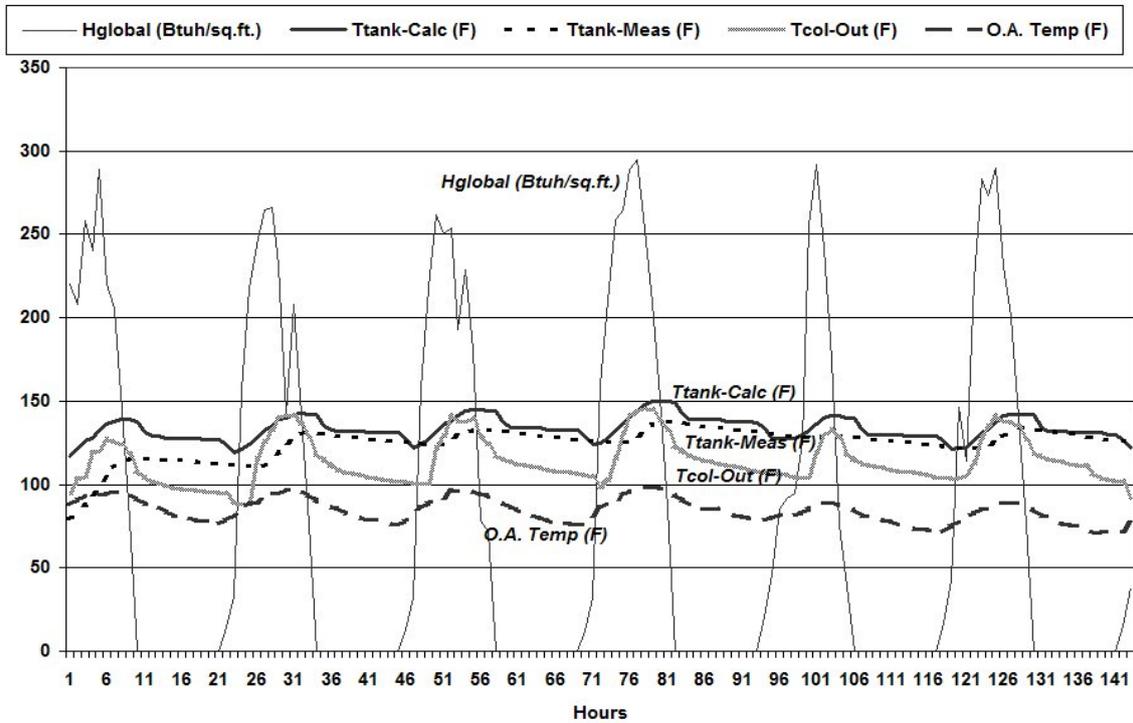


Figure 6 Calculated & measured temperatures (2-8 August 2004)

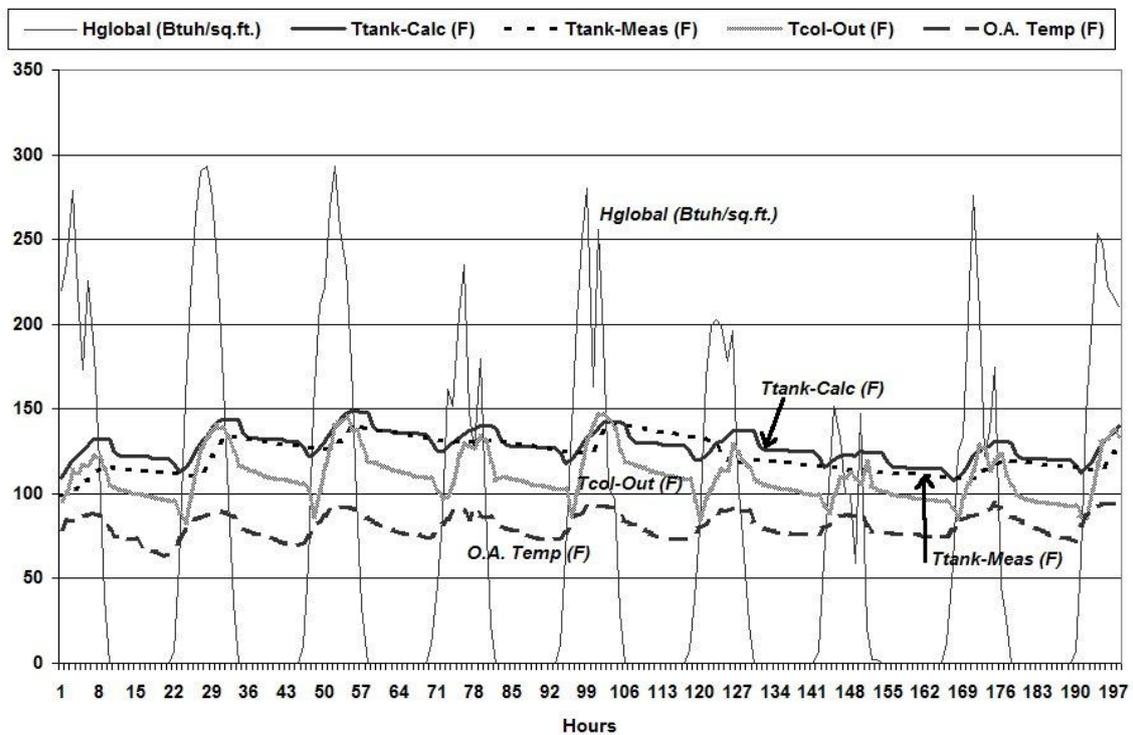


Figure 7 Calculated & measured temperatures (8-16 September 2004)

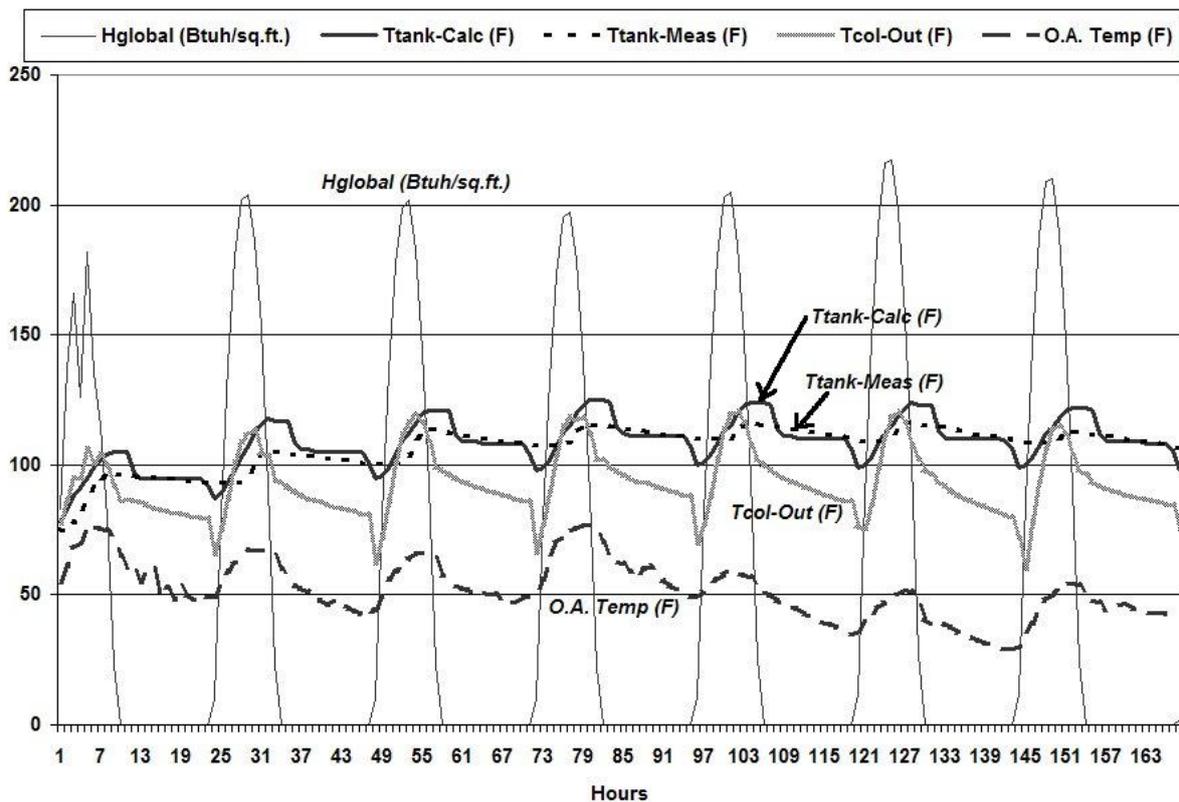


Figure 8 Calculated & measured temperatures (9-16 December 2004)

The previous three figures show hourly values of measured outdoor dry-bulb temperatures, horizontal global insolation, water temperature leaving the collector, and temperature in the storage tank. Included is also the simulated tank temperature, for comparison to the measured tank temperature. Since the simulated tank temperature is a “mixed” temperature, it should not be compared directly to the measured value of “top of tank” temperature. These do have a close relationship, but because of tank stratification, the “top of tank” temperatures will tend to reach a higher value than the mixed tank temperature. Another factor in trying to make exact comparisons of hourly temperatures is that the real hot water use pattern will not follow the assumed use pattern that is in the computer program. The average daily use in the simulation is the same as the actual average daily use, but the day-to-day use amounts were not measured. This will cause the comparison to be high on some days and low on others, as can be seen in the plots in Figures 6 through 8.

In addition to comparing hourly temperatures and annual energy consumption, it is of interest to observe some of the monthly statistics of weather, solar and water heating energy supplied by solar. To observe this, a plot was made of the monthly percent load supplied by solar energy in both the original

1982 scenario and the one existing in 2004. The plot also includes the monthly percentage solar energy utilization efficiency by the collector. (See Fig. 9.)

In Figure 9, the percent utilization efficiency (**% util 1982**) is quite different than the percent of load supplied by solar energy (**% load 1982**), and these are both different than the collector’s output efficiency. The percent of load supplied by solar is the total solar energy delivered divided by the total water heating demand by the household. The utilization efficiency is the amount of collected solar energy used divided by the total energy incident on the collector. The latter is influenced not only by the collector’s efficiency (ability to convert incident energy into usable heat), but also by the hot water demand by the household. If a collector is large and the demand is small, then the utilization efficiency will be small. Such is the case for this experiment. When the collector was initially installed the household consisted of 5 users and the utilization efficiency was high, around 50-90%. In 2004, there were only two users, so the demand was smaller and the utilization efficiency reduced to 15-17%. The smaller demand coupled with the fact that the collector’s performance has been degraded over the years has resulted in low utilization efficiency. This became quite evident in the plot shown in Figure 9.

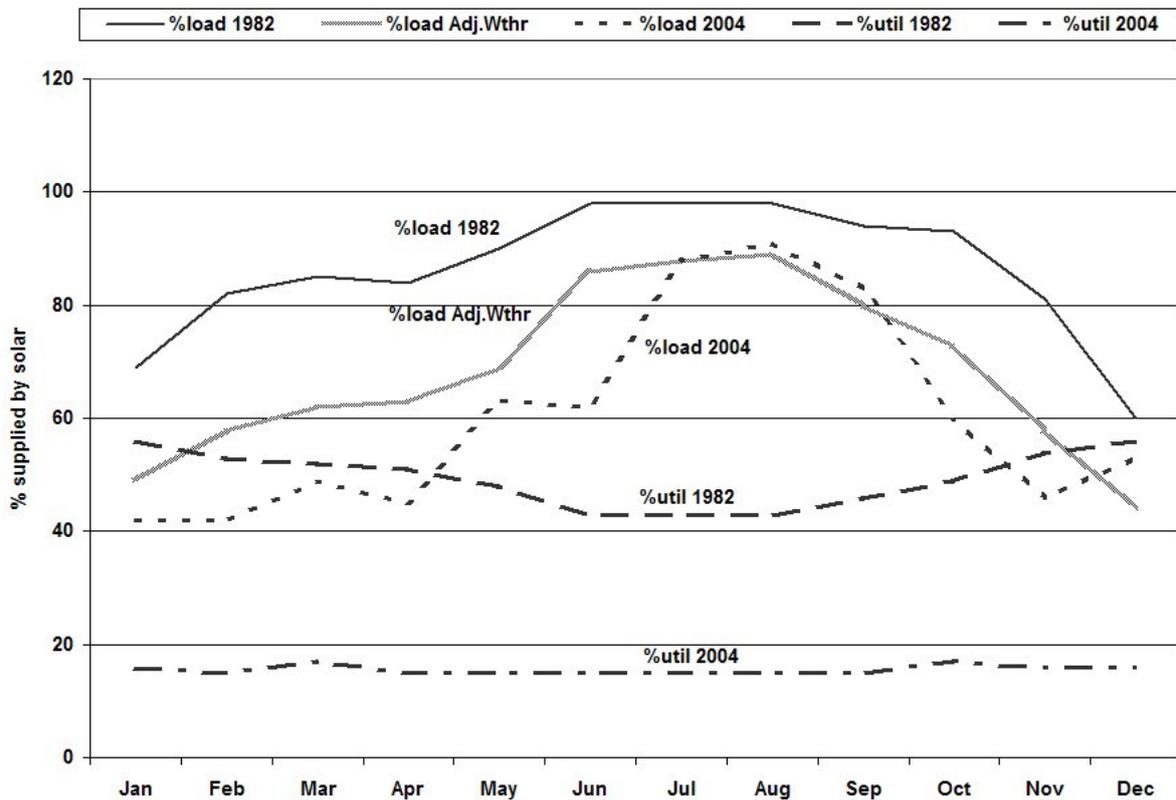


Figure 9 Monthly percentage load supplied by solar and collector energy utilization efficiency

Figure 9 also shows that the solar system’s monthly contribution to the water heating load varied between 60 & 98% in 1982 and from 41 to 91% in 2004. Had the collector performance not degraded, one would expect the heating load contribution to actually increase on a percentage basis, since the hot water demand had been reduced from 5 people to 2 people over during this period. However, the collector performance was severely degraded, so the energy contribution was lessened. It is noteworthy to point out a weather-related factor -- the annual solar radiation in 2004 was just 86% of that used in the calculations for 1982. To get a more accurate picture of the collector’s performance in 2004, the same weather data used in 1982 was then applied to the year 2004. The results of that simulation are shown in Figure 9, and are labeled as “% load Adj.Wthr.” This curve shows a somewhat better performance in 8 months, one equal, and 3 less (August, September and December.) The low and high values are similar to before (about 42 to 90%), but when summed on an annual basis, the annual water heating supplied by solar increased to 65% from the previous value of 56%.

CONCLUSIONS

In general, the simulated hourly temperatures do align adequately with the measured values, at least enough

to not have serious doubts about anomalies in the simulation process. Furthermore, the annual energy results show very close correspondence between measured and simulated values.

The study made it quite obvious that the collector performance has deteriorated markedly over its 22-year life. The first assumption made in this study was that this deterioration was due to clouding of the collector plates. By lowering the transmissivity only, and leaving all other factors in tact, the simulations seem to closely corroborate the measured results of annual energy predictions. Furthermore, the model seems to have fair success in tracking the hourly temperature data.

There are other factors that could contribute to lowering of collector performance. Since the collector panels are arranged in parallel, it is not known whether there may be dirt stoppage in one or more of the pipes serving the three collector panels. If that were the case, it could also explain some of the degradation in performance, but from a simulation perspective, the lowering of cover plate transmissivity seems to also provide an adequate explanation of the degraded performance.

The next step in this study will be to remove and clean the cover plates and measure the performance for another year. It will be of interest to see if much

of the losses can be recovered by restoring some of the cover plates' original transparency.

REFERENCES

Degelman, Larry 2004. "Simulation and uncertainty: weather predictions", *Advanced Building Simulation*, (Malkawi and Augenbroe, Ed.), Spon Press, New York and London, Chapter 3, pp 60-86.

Degelman, L.O. 1991. "A statistically-based hourly weather data generator for driving energy simulation and equipment design software for buildings", *Proc. Building Simulation '91*, International Building Performance Simulation Assoc. (IBPSA), Nice, Sophia-Antipolis, FRANCE, 20-22 Aug., pp 592-599.

Degelman, L.O. 1977. "Computer optimization of solar collector area based on life-cycle costing", *Proc. 1977 Annual Meeting of the Int'l. Solar Energy Society (ISES)*, Orlando, FL, June 16-19, Vol. 1, pp 8-11 to 8-15.

Duffie, J.A. and Beckman, W.A. 1974. *Solar Energy Thermal Processes*, John Wiley & Sons, Inc.

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NOMENCLATURE

C = temperature, Celsius

C_p = mass specific heat, 4184 J/kg K (1 Btu/lb °F) for water

D_i = inside diameter of aluminum tube, = 0.016 m (5/8 inch or 0.052 ft.)

Eff = solar collector efficiency (dimensionless)

F = temperature, Fahrenheit

F_R = Collector heat removal factor (dimensionless)

$F' = U_o/U_L$ = collector efficiency factor, the ratio of heat conductance factors for "fluid to ambient air" to "absorber to ambient air." The F' factor is mostly dependent on the absorber fin geometry and material,

but it is not a strong function of plate temperature. For the collector plates in this study, the values for single plate vs. double plate covers were 0.94 and 0.97 respectively. These are based on values from page 145 in Duffie and Beckman (1974) for aluminum absorber plates with 15 mm tube spacing.

$h_{f,i}$ = forced fluid heat transfer coefficient inside the tubes, = 1500 W/m² K (264.2 Btu/ft² °F h)

I_{DN} = Incident direct normal insolation (W/m²)

I_{df} = Incident diffuse insolation (W/m²) on tilt

I_T = insolation on collector tilt = $I_{DN} \cos(\Theta_T) + I_{df}$

K = temperature, Kelvin

L = Total length of tube per collector area, = 6.67 m per m² (2.05 ft/ft²), for a tube spacing of 0.15 m (6 inches)

Q_T = Solar radiation transmitted through the collector cover plates (W/m²)

Q_u = Useful energy out of collector (W/m²)

\dot{R} = mass flow rate, = 0.02 kg/m² s (14.7 lb/ft² h)

t_a = Temperature of outside air (°C)

$t_{f,i}$ = Temperature of heat transfer fluid at collector inlet (°C)

$t_{f,m}$ = mean fluid temperature (°C) in collector

τ = transmissivity of cover plate.

Θ_T = solar angle of incidence to collector panel

Trans (Θ_T) = transmittance parameter at angle, Θ_T

U_B = heat transfer coefficient for collector bottom, typically about 0.3 to 0.45 W/(m² K)

U_C = heat transfer coefficient for cover plate, typically around 7 W/(m² K) for single plate and 3.7 W/(m² K) for double cover plates.

U_L = Overall heat loss coefficient (W/m² K)

U_p = heat transfer coefficient between the plate and the fluid, equal to: $h_{f,i} (\pi) D_i L$, = 503 W/m² K (88.5 Btu/ft² °F h)

x = collector fluid parameter, $(t_{f,i} - t_a) / I_T$