Spring 1979

Validation of a Transient Simulation Program (TRNSYS)

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VALIDATION OF A TRANSIENT SIMULATION PROGRAM (TRNSYS)

BY

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B.S.A.E., University of Kansas, 1973

RESEARCH REPORT

Submitted in partial fulfillment of the requirements for the degree of Master of Science in the Graduate Studies Program of the University of Central Florida at Orlando, Florida

Spring Quarter
1979

ABSTRACT

Although a Transient Simulation Program (TRNSYS) has become a widely used model for simulating a solar energy system, there has not been extensive work done in validating this model with actual data. The approach used to validate this model consisted of a modular build-up of components with validation for each module.

Extreme care was taken in choosing the necessary parameters to model each component. Where parameters were not given, they were either derived or reasonable values were selected based upon general conditions prevailing in Central Florida or conditions which are generally true for certain solar hot water systems. The intent of this approach was to avoid forcing the model to fit experimental data. Such forcing can cause present results to correlate favorably, but gives no assurances for model performance in future simulations which may be made for varying conditions or completely different systems.

TRNSYS compared favorably with experimental data. The average error for an entire 8 hour simulation with 15 minute intervals was only 3.39 percent for the entire tank and collector combination. The model's major deviations were in the start-up collector outlet temperature and rapid changing in actual hot water demand which the model could not match primarily in amplitude and not phase.

ACKNOWLEDGEMENTS

Space does not permit me to express thanks to every person whose direct or indirect assistance was used in the preparation of this report. I would like to thank my graduate committe, and in particular my advisor, Dr. Klee, for the guidance and invaluable assistance in preparing this paper.

Special thanks also go to the U.S. Army Project Manager for Training Devices and Naval Training Equipment Center for their support and constant encouragement of work leading to this effort.

Also, special thanks to Lyette Coggins for an excellent job of typing. Her ability and promptness are appreciated.

Finally, a thank you goes to my family for their understanding and moral support during the preparation of this paper. These members include my wife, Audrey, and my children Alison, Robert, and one soon to be named.

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I

INTRODUCTION

Although a Transient Simulation Program (TRNSYS) has become recognized and accepted as a good approach for simulating various solar energy systems, this program has not been validated using actual experimental data [1]. To evaluate the model's accuracy, actual data was used and compared to predicted values obtained from TRNSYS [2]. The United States National Bureau of Standards is currently conducting a similar effort to validate TRNSYS. This effort utilizes two approaches. One is to use TRNSYS to predict performance of several solar hot water systems. This effort will entail gathering data for approximately one year and then modeling performance. No data is presently available for this approach. The second approach involves a shorter term solution where a laboratory model is used and compared to TRNSYS. The results of this effort are available, but do not represent an actual solar hot water system.

The solar energy system selected to be modeled consisted of a forced circulation solar hot water system (depicted in Figure 1). This type of system with an auxiliary heater in the storage tank is typical of solar energy systems used in many homes today. The solar energy system investigated consisted of a solar collector, pump, and hot water storage tank with an auxiliary heater in the tank.

This investigation was performed in conjunction with the work done by Pearce [2]. Duplication of effort was avoided, but some additional system characteristics were needed to describe the solar energy system in a format compatible with TRNSYS. These additional system characteristics were either derived, or reasonable values were used which are typical for Central Florida. All assumptions will be so noted in the following text.

The text is organized such that the collector characteristics and assumptions used are first presented and following this is a similar discussion on the tank characteristics. Following these two sections is a section on the results of the simulation runs

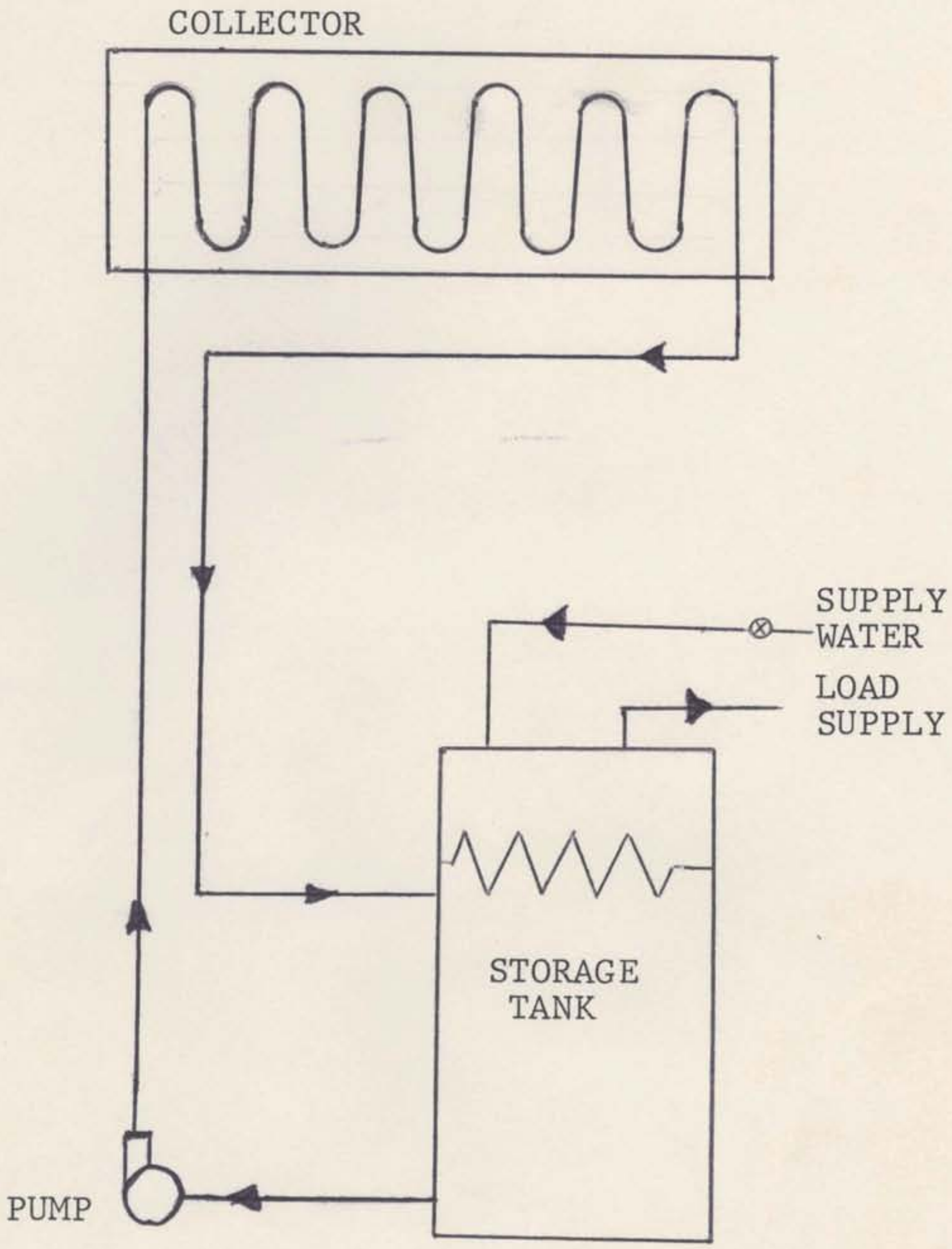

Figure 1. Solar Hot Water System

and a comparison with actual data. The final section analyzes these results with the actual data to make an assessment of TRNSYS performance.

Many given data values required conversion from English units to SI (modified metric) units. The metric units which use seconds for time are modified by using the hour as the time unit in the SI system. Several constants within the TRNSYS model, such as the solar constant, are given in SI units and parameters which interact with these must of course conform dimensionally. For ease of interpreting results, the SI units were used throughout the simulation.

II

THE COLLECTOR

The collector to be modeled is depicted in Figures 2 and 3. Figure 2 depicts the collector with the parameters provided by Pearce, while Figure 3 depicts a block diagram format of the collector with the parameters necessary for the TRNSYS simulation [2]. As can be noted from these two figures, some of the parameters needed by TRNSYS were not provided by Pearce in his data.

Mode 2 was selected for use in the TRNSYS model for the collector. This mode was selected because it provides a better solution than Mode 1 by calculating the loss coefficient U_L. Modes 3 and 4 were not selected because in these modes, the transmittance, τ, is determined by the equation:

II.1

$$\tau = H_B/H_T[\tau'_{\theta T} e^{-KL/\cos\theta_1}] + H\ /H\ [\tau'_{60^o} e^{-KL/\cos\theta_2}]$$

where

τ'_x is the transmittance of an N-glass cover surface at an angle x. τ'_x can be found in Figure 6.1.3 of Duffie and Beckman [3].

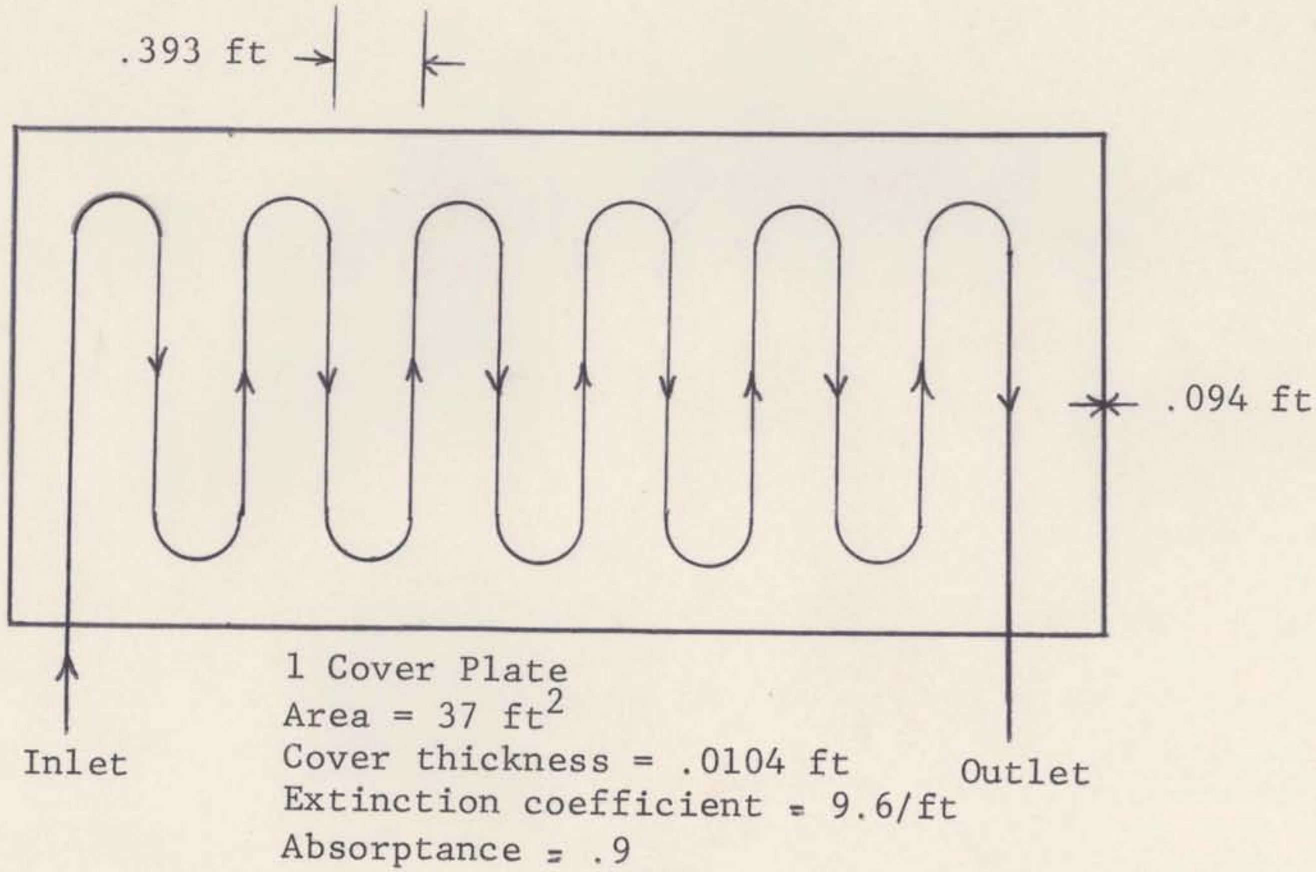

Figure 2. Given Collector Characteristics

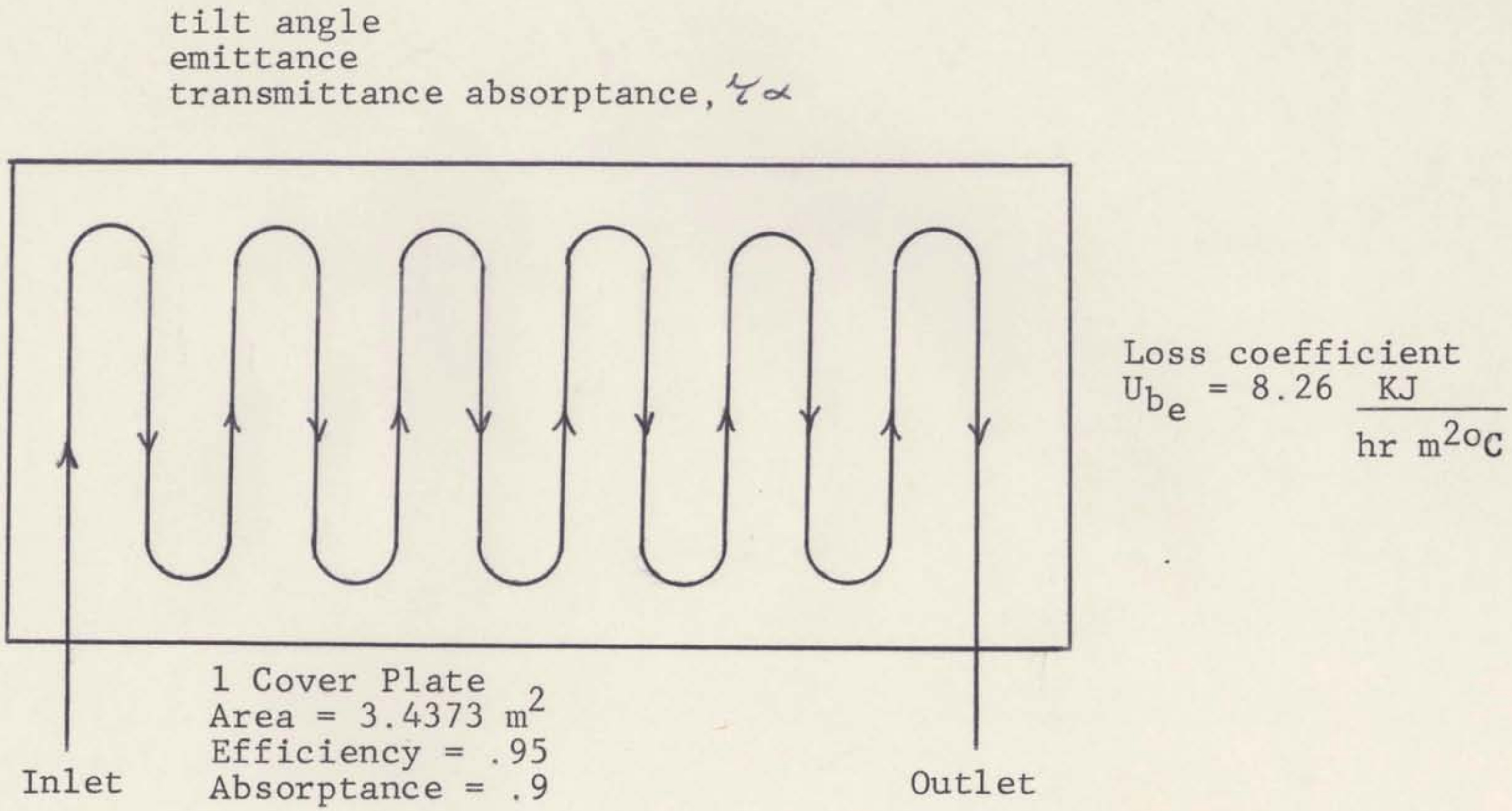

Figure 3. TRNSYS Mode 2 Collector Characteristics

$$\theta_1 = \arcsin [\sin \theta_T / n_g]$$

$$\theta_2 = \arcsin [\sin 60^o / n_g]$$

As can be readily seen from equation II.1, τ is highly dependent upon the incidence angle of beam radiation on the collector, which in turn is dependent upon collector tilt angle. Collector tilt was not given as a collector parameter and τ can be assumed to be relatively constant over tilt angles from 0^o to 40^o. Therefore, Modes 3 and 4 were not used to model the solar collector.

The collector area used for the simulation was 37 ft^2 or 3.4373m^2. This area represents the net absorbing area of the collector panel. The gross collector area is 40 ft^2, which represents the absorbing area in addition to the framing structure necessary to support the collector panel. The net absorbing area was used in the TRNSYS program because this area should present a more accurate measure of collector performance.

Several parameters and calculations were necessary to determine the collector efficiency factor, F'. This factor is dependent upon the characteristics of the working fluid, collector materials, and collector construction. Basically, though, this parameter can be expressed as a ratio where the numerator represents the gain in useful energy and the denominator represents the useful energy gain if the collector absorber and working fluid in the collector were at the same temperature. This, of course would be the ideal case because when both collector and fluid are at the same temperature no convention losses occur as long as the fluid flow rate is maintained. In determining F', the values of collector tube spacing (12 cm), plate thermal conductivity (223 W/m ^{o}C), and plate thickness (.0013m) were given and F' was graphically determined to be approximately equal to .95 [3].

The next parameter which needed to be calculated was the bottom and edge loss coefficients for the collector. These factors are dependent upon materials selection for the edge and back of the collector. The loss coefficient is the ratio of the thermal conductivity of the material divided by the thickness of the material. Expressed in equation form:

II.2

$$U_{b,e} = \frac{K}{L}$$

where

K = insulation thermal conductivity

$$= .019 \frac{BTU}{hr\ ft\ {}^oF} \times 1.7307 \frac{J}{S\,m\ {}^oC} \frac{hr\ ft\ {}^oF}{BTU}$$

$$\times\ 3600 \frac{S}{hr} \times \frac{KJ}{1000J}$$

$$= .1184 \frac{KJ}{hr\ m\ {}^oC}$$

and

$$L = .094\ ft \times .3048 \frac{m}{ft} = .0287m$$

From these terms and also from the fact that loss coefficients are additive, the loss coefficient for bottom and edge losses, U_{be} can be expressed as

II.3

$$U_{be} = U_b + U_e = 2(U_b)$$

$$= \frac{(2)(.1184)}{.0287}$$

$$= 8.2636 \frac{KJ}{hr\ m^2\ {}^oC}$$

Collector tilt was assumed to be equal to 40°. This angle was not given in the original experimental data, and several attempts to determine this proved to be fruitless. Collector tilt angle is highly dependent upon application of the collector and the time of the year when maximum performance is desired. For example, when good collector performance is desired in the winter months, the sun is lower in the horizon and collector tilt must, therefore, be increased to capture incident solar radiation. Of course, with a solar hot water heating system, demand is essentially uniform throughout the year, so that tilt angle can be chosen without regard to seasonal variations in the sun angle. Also, collector performance for hot water applications is relatively insensitive to tilt variations in the range of latitude plus or minus fifteen degrees. This was borne out by making a simulation run with collector tilt at 25°, with no appreciable difference in results with a 40° tilt angle. Finally, tilt angle was not an important parameter for this simulation because the data provided was for solar radiation incident on the collector, so that a solar radiation processor was not needed. In other words, the pyranometer used to collect solar insolation data values was mounted on the collector so that collector tilt angle was implicitly accounted for in the data provided.

The final factor which needed to be determined was the transmittance absorptance product $(\tau\alpha)$. This factor combines some of the characteristics of the collector cover with the back plate. This term provides a measure of how well the collector cover allows light to pass through it, how well the collector back plate collects the energy and reflects it back to the cover, and how well the cover can reflect the energy back. This is illustrated in Figure 4. Another explanation of $(\tau\alpha)$ is the collector's ability to capture solar energy and retain that energy within the structural confines of the collector box.

The product $(\tau\alpha)$ can be determined through a mathematical expression.
The equation for this product can be expressed as [3]
II.4

$$(\tau\alpha) = \frac{\tau\alpha}{1-(1-\alpha)\rho_d}$$

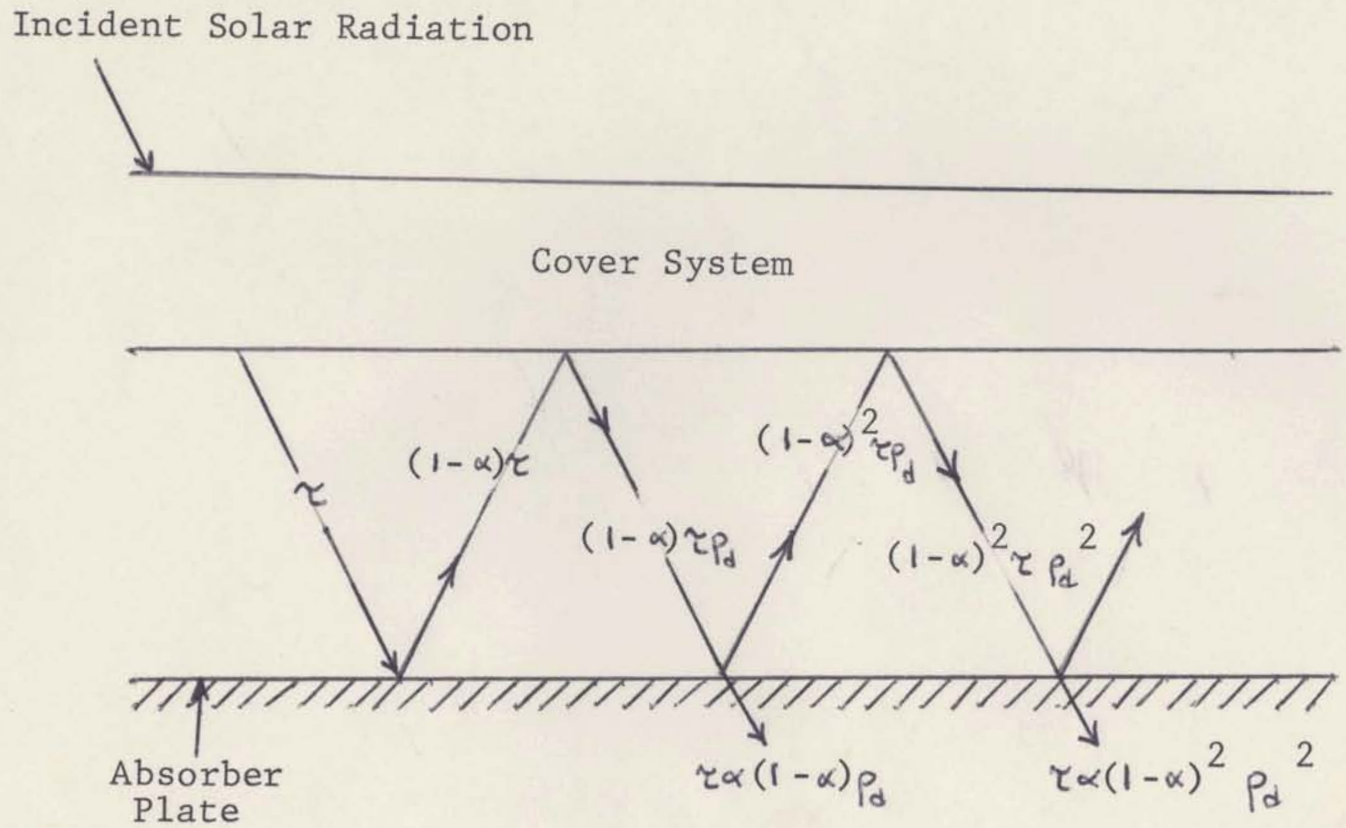

Figure 4. Absorption and Retention of Solar Radiation by a Collector

where

$(\tau\alpha)$ = transmittance absorptance product

τ = transmittance

α = absorptance

ρ_d = diffuse reflectance

The term α is given as 0.90. To determine the value of the transmittance, τ, a cross plot was made reflecting τ as a function of AT (the product of the extinction coefficient, and the optical path length of the incident radiation, respectively) [3]. This cross plot is represented in Figure 5. The optical path length is approximately equal to the plate thickness of .317 cm (.0104 ft). The value of the extinction coefficient is equal to 9.6/ft or .315/cm. For glass the value of the extinction coefficient, A, varies between 0.04/cm for good "water white" glass to about 0.32/cm for poor glass (that with a greenish edge color). As can be seen, the glass cover of this collector falls into the lower quality end of glass. From Figure 5, the value of the transmittance, τ, is equal to 0.84.

The remaining term of equation II.4 which needs to be determined is the diffuse reflectance, ρ_d. The sum of absorptance, reflectance, and transmittance

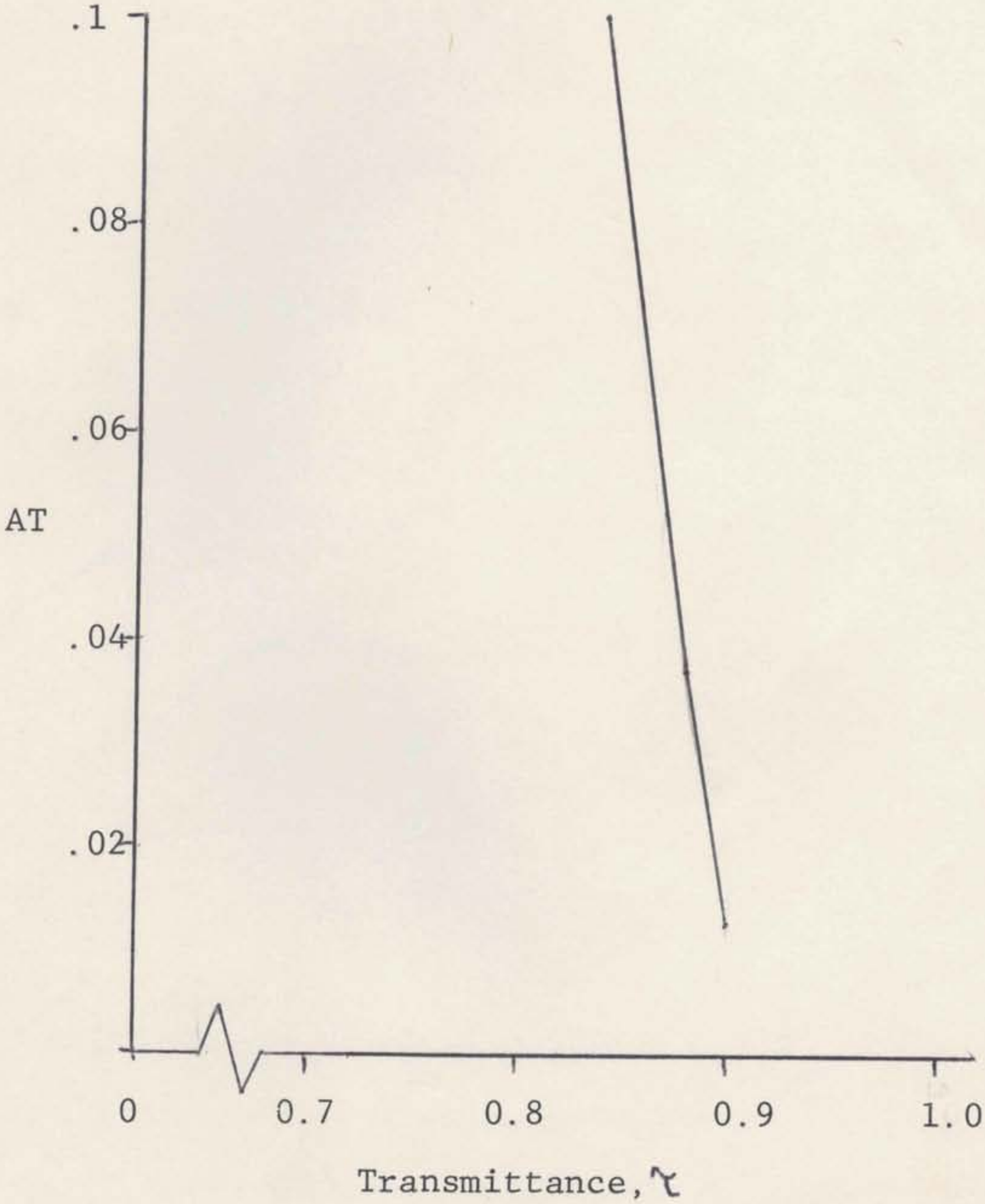

Figure 5. Transmittance as a Function of Extinction Coefficient and Optical Path Length (One Cover, tilt = 40°)

must be equal to unity. These terms simply can be expressed as the percentage of the radiation which is absorbed by the surface, reflected by the surface, and transmitted through the surface. Nothing more can happen to the radiation striking the surface. The quantity ρ_d, refers to the relationship just expressed. It represents the reflection of the cover plate of incident and/or diffuse radiation that may be partially polarized due to reflections which may have occurred within the cover system. The diffuse reflectance can be expressed as:

$$\rho_d = 1 - \tau_d$$

where

τ_d the lumped absorptance and transmittance of the cover plate.

The value of τ_d is 0.92 yielding a value of 0.08 for ρ_d [3].

As noted previously, the value of transmittance, τ, is equal to 0.84, absorptance, α, is equal to 0.90, and diffuse reflectance, ρ_d, is equal to 0.08. Substituting these values into equation II.4 the transmittance absorptance product $(\tau\alpha)$, is equal to 0.762.

A methodology for determining the collector parameters has been given for those parameters that were not provided as given data. Extreme care and consideration must be made in choosing assumptions to follow. These parameters can have a significant impact on collector performance. The important point to be made is that in the initial stage of simulation verification, data choices must be carefully made and documented for traceability and verification of the simulation's effectiveness. Chapter IV further expands on the results of the simulation run to model the collector performance.

III

THE TANK

In any solar hot water system a storage device is needed to store collected energy and deliver it on an as-needed basis. This storage device or tank can be configured into the solar hot water system in many different ways. The configuration used in this model is typical of many low cost solar hot water systems used today. In this system, the working fluid, water, is also the medium where solar energy is stored. This system has no heat exchangers or preheat tanks for energy storage. This type of system is one that could be readily implemented with a slightly modified conventional hot water heater.

The modeling of the tank requires the user to specify the number of stratified layers of fluid within the tank. Each stratified layer is assumed to be completely mixed (i.e., constant temperature) and an energy balance must be written at the boundary of each layer to obtain thermal equilibrium. It has been reported from several sources that dividing the storage tank into more than three sections does not significantly alter results obtained from using a three section storage tank [1][2]. Nevertheless, the tank to be modeled was divided into four sections for comparability purposes to a previously developed model [2].

The TRNSYS model has fixed sections for supply and return lines from the collector, to the load, and replacement fluid. This arrangement is illustrated in Figure 6, along with given and determined values of tank parameters. The arrangement of the various lines is illustrated in Figure 7 for the actual storage along with given characteristics of the storage tank. The only difference is that hot water supplied from the collector is deposited in the second section of the actual storage tank and into the top section of the simulated storage tank. The effect of this difference in position of this line cannot be readily determined, but could account for some deviation between predicted and actual results. It was originally thought that this problem could be overcome by dividing the actual tank into four separate, fully mixed storage tanks. This would allow for placement of supply and return lines in

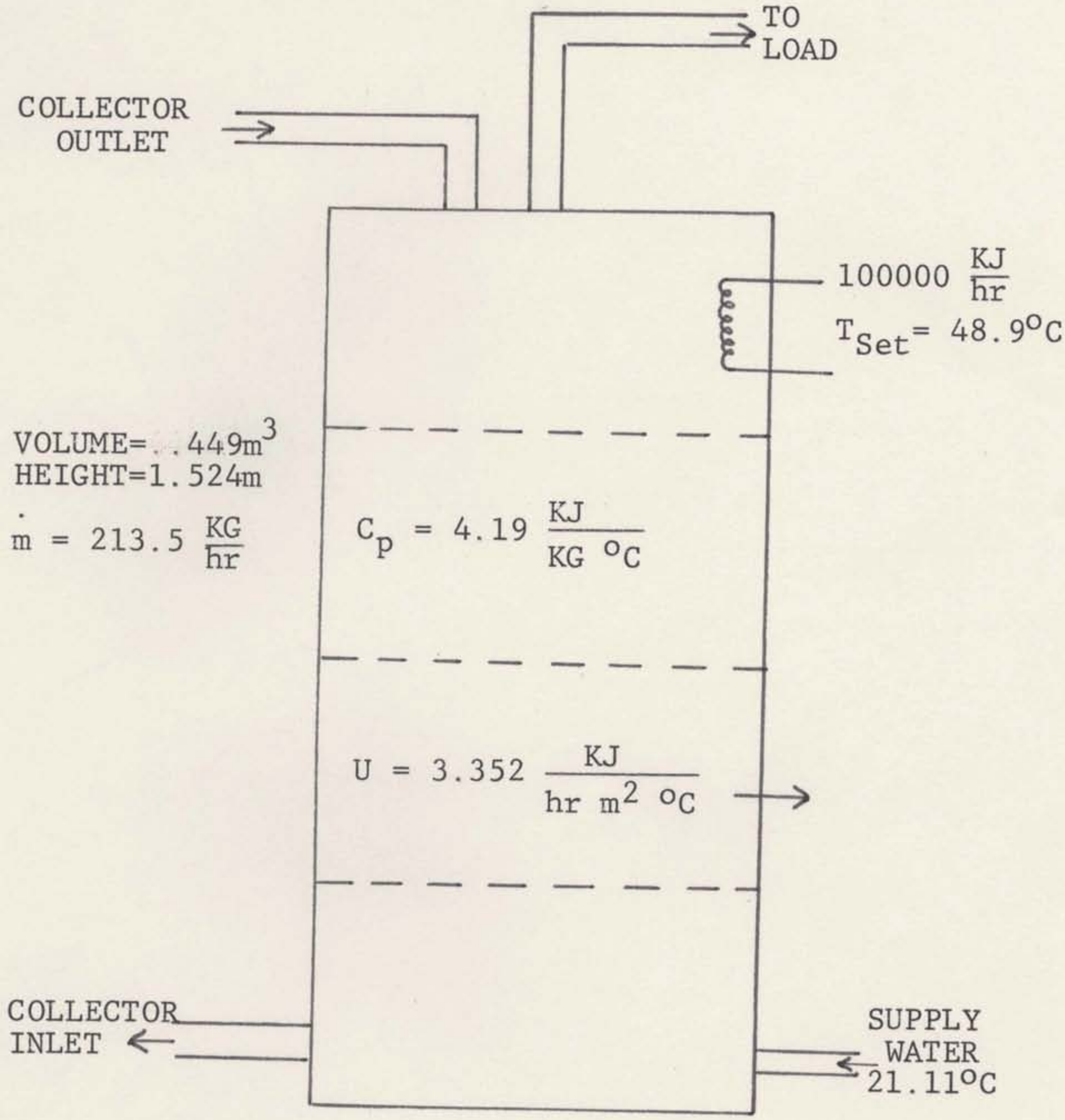

Figure 6. TRNSYS Tank Characteristics

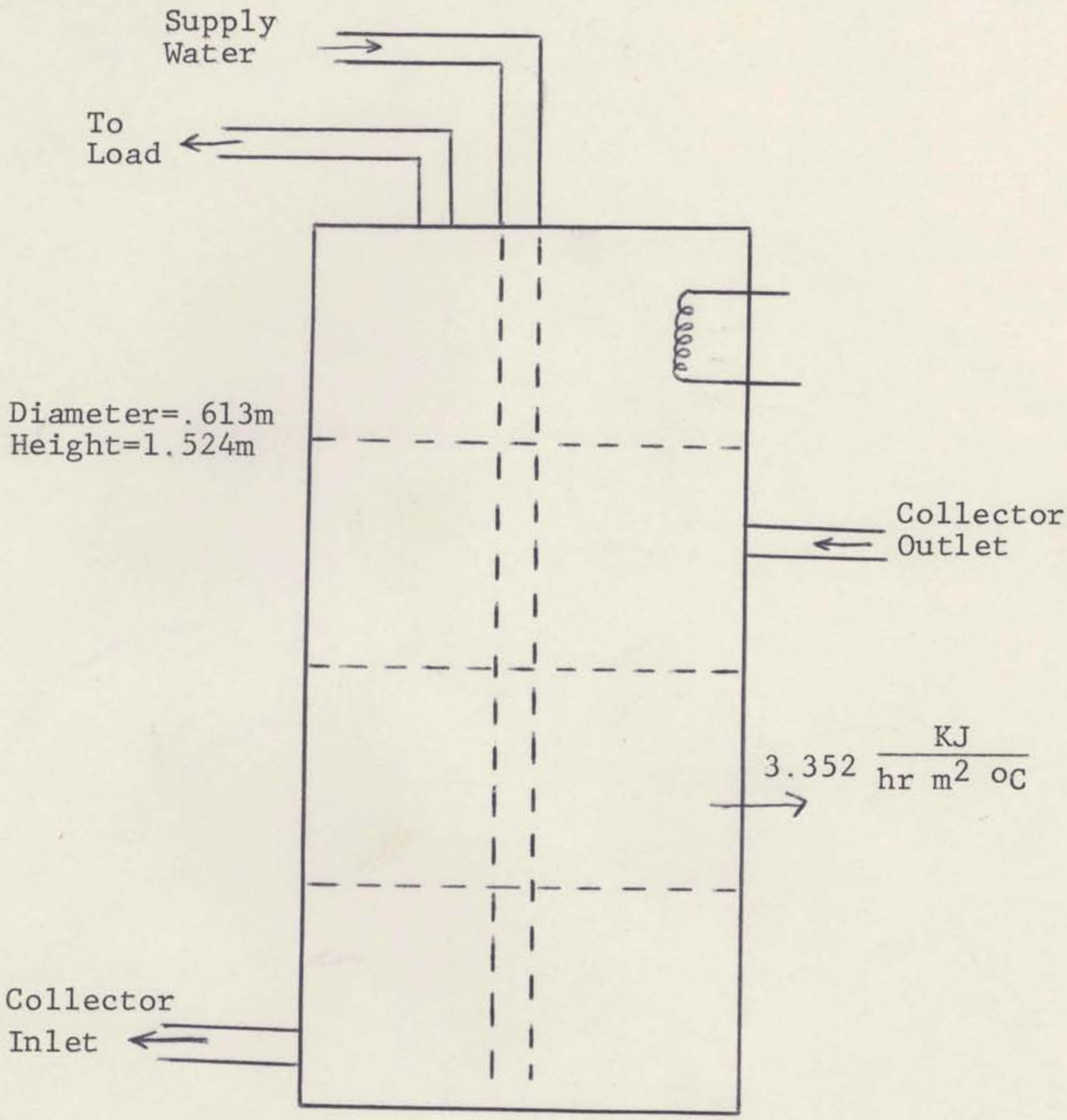

Figure 7. Given Tank Characteristics

any section, but would not allow the layer mixing which the model allows. Therefore, this approach was discarded.

It could prove useful for future revisions to TRNSYS to allow user selection of supply and return line placement within existing tank sections. This approach would allow more flexibility in modeling various storage tank configurations and allow possible increase in model fidelity.

Storage tank volume was easily determined from given characteristics as

$$\text{Volume} = \frac{\pi}{4}(\text{Diameter})^2(\text{Height}).$$

Storage tank volume is equal to 0.449 m^3 or approximately 120 gallons.

The loss coefficient, U, given need only be converted to SI units to make it compatible with TRNSYS. This is accomplished as follows:

$$0.164 \frac{\text{BTU}}{\text{hr ft}^2\ {}^o\text{F}} \times 5.67826 \frac{\dfrac{\text{KJ}}{\text{m}^2\ {}^o\text{C}}}{\dfrac{\text{BTU}}{\text{hr ft}^2\ {}^o\text{F}}} \times \frac{3600\text{s}}{\text{hr}}$$

$$= 3.352 \frac{\text{KJ}}{\text{hr m}^2\ {}^o\text{C}}$$

The maximum rate of energy input by the auxiliary heating element ($\dot{Q}_{HE}$) was not given as data on the actual storage tank. This rate was estimated using available experimental raw data [2]. It was discovered that by scanning the raw data that the maximum auxiliary energy input occurred at 10:45 A.M. on 9 September 1976. This data value was then converted to proper units using the following equation:

$$\text{III.1} \quad \dot{Q}_{HE} = \left(2.534 \ \frac{\text{Volt}}{.25\text{hr}}\right)\left(8700 \ \frac{\text{BTU}}{\text{Volt}}\right)\left(1.054 \ \frac{\text{KJ}}{\text{BTU}}\right)$$

$$= 23236 \ \frac{\text{KJ}}{.25\text{hr}} = 92944 \ \frac{\text{KJ}}{\text{hr}}$$

This value used in the simulation model was 100,000 $\frac{\text{KJ}}{\text{hr}}$, because this represents a more common energy input and there is no indication that the maximum data value found among the data is truly the maximum rate the system is able to deliver.

The only other parameter which needed to be determined was the set temperature of the heating element thermostat, T_{set}. Again, by examining raw data, this value could be determined. By watching where the auxiliary heater turned on and noting the water temperature in the storage tank, T_{set} was determined to be equal to 120^oF (48.89^oC).

Finally, no differential controller was indicated as being a part of the solar hot water system. The auxiliary heater control was assumed to be water temperature sensitive with no hysterisis so that a differential controller was not employed. Differential controllers are almost always used to activate the pump on typical solar hot water heaters. This model did not use one though. Experimental data provided indicated that the pump was always on during data collection periods.

The constant running of the pump can have negative effects on total system performance. Differential controllers are normally used to sense the temperature difference between the water temperature in the collector and that in the storage tank. When the temperature differences exceed certain user defined thresholds the pump is either turned on or off. These controllers normally have a hysterisis loop to avoid rapid cycling of the pump motor. If a differential controller is not used (i.e., the pump runs continuously), no problems result as long as the tank temperature is lower than the fluid temperature in the collector. But when the collector fluid temperature drops below the storage tank temperature, energy is released from the tank to the environment through the collector. Clearly, this is an unacceptable occurrence which should be avoided.

IV

PERFORMANCE OF SIMULATION

The simulated solar hot water system was modeled using a build-up of the system components. The collector was modeled alone using experimental data, then the storage tank was added so that a system simulation could be run to compare to the actual system's performance.

There is a fundamental approach for simulation validation which is discussed at this time. This concerns the use of "tweeking" the simulation model to allow predicted output and actual output to match within a given tolerance. This type of approach is felt to be unacceptable to show the math model's ability to duplicate the real-world. The reason for this is that for a given set of data, any reasonable model can be forced to correlate well with the experimental data. But when conditions change or the system to be modeled changes, the simulation must be such that an accurate result will follow. Therefore, much effort was devoted to the front-end analysis of component parameters to avoid any "tweeking" of parameters.

The first simulation made was of the collector alone. All data values used were experimental data from September 8, 1976, except for the fluid mass flow rate through the collector [2]. The mass flow rate of 213.5 Kg/hr was chosen because this represents the average flow rate from the pump through the collector when the pump is on. The error when using this average flow rate is 1.5 percent.

Solar radiation which was originally given in the data at fifteen minute intervals needed conversion. Data values needed to be multiplied by a factor of four to be put in a per-hour format. Also, original solar insolation was taken using a pyranometer on a cumulative basis. Differences were taken between data points to get rate values which are necessary for TRNSYS. Solar insolation was initially set equal to zero.

Finally, inlet fluid temperature to the collector, ambient temperature, and wind speed were initially set at 27.11°C, 27.22°C, and 0.0 Km/hr, respectively. Actual experimental data was then used to drive these parameters.

The simulation was run with the values noted above. Table 1 is a listing of the data values used in this simulation. Table 2 presents the results of the simulation run. Figure 8 is a similar, but graphical presentation of the data in Table 2. Appendix A is the complete TRNSYS listing with the accompanying output. TOUT corresponds to the collector outlet temperature in degrees centigrade. USED is the total energy incident on the collector. DEL is the amount of this total energy which is delivered to the working fluid. The ratio of energy used to the total insolation is the average efficiency of the collector (η). For this simulation, η is equal to 0.50. An attempt was made to make a plot of collector efficiency versus the difference between the collector inlet temperature minus ambient temperature divided by solar insolation. The efficiency curve was constructed for the collector only. It was felt that this type of method would be better than a curve constructed for

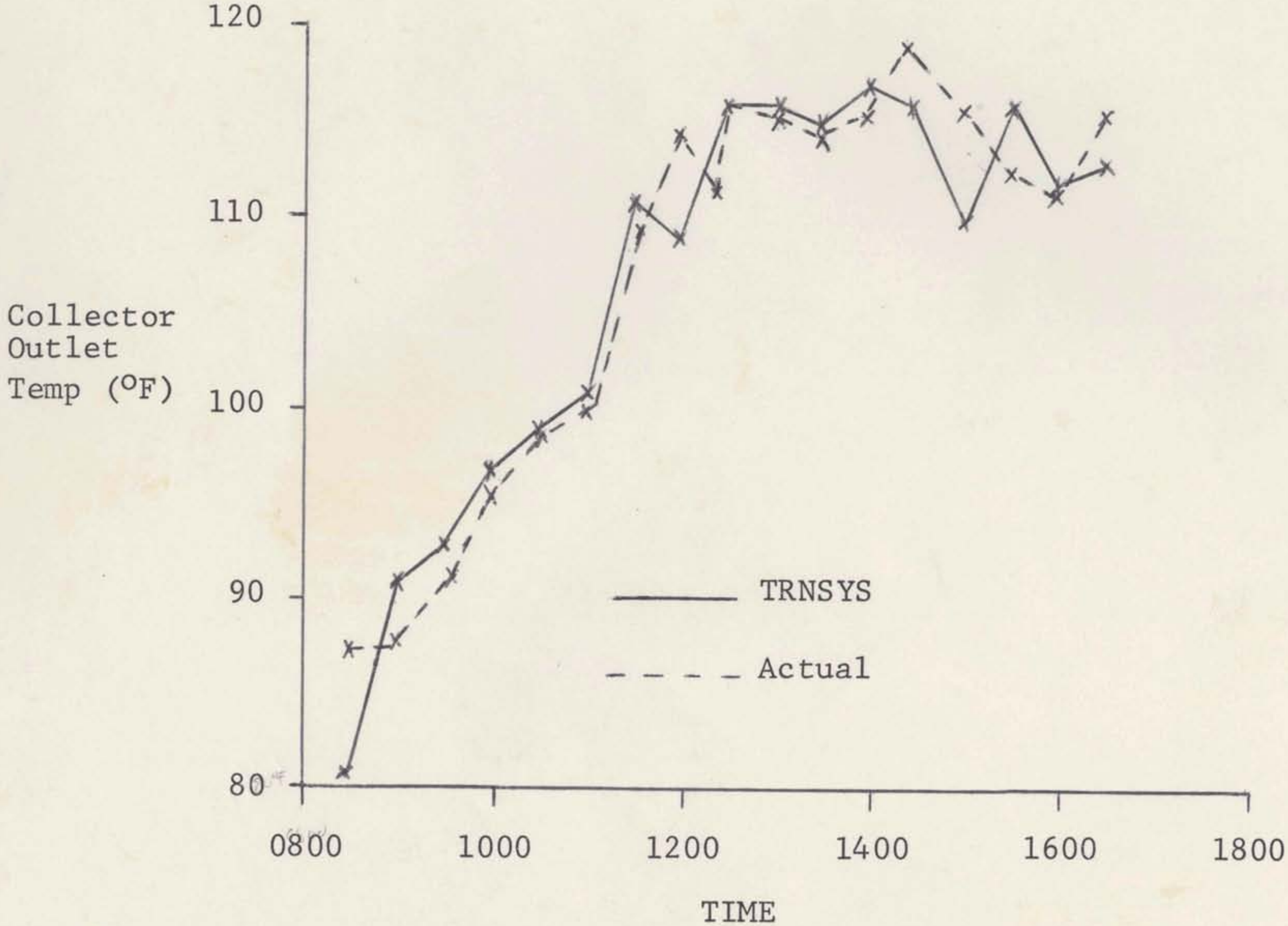

Figure 8. Simulated Collector Performance

the entire system because when the tank is used, inlet water temperature to the collector is constant (120°F) and a good apread in data values might not be reflected. The values used to construct this curve can be seen in Table 3. The only value which required calculation was the column labeled E (collector energy gain). This value of E was determined using the equation

$$\text{IV.1} \qquad E = \dot{m}\, C_p\, \Delta T/S$$

where

$\dot{m}$ = fluid mass flow rate (213.5 Kg/hr)

C_p = specific heat $(4.19 \frac{KJ/}{Kg^{o}C})$

ΔT = temperature rise across the collector (°C)

S = collector absorbing area $(3.4373 m^2)$

The data values in Table 3 are plotted in Figure 9.

The simulated collector used 16520 KJ/m^2 of the energy delivered compared to 17096 KJ/m^2 from the experimental data. This is equivalent to a 3.37 percent error. Many factors can influence this difference, even though it is small in magnitude. Such factors as collector tilt and the assumptions used in Mode 3 of the TRNSYS model of the collector can cause these slight deviations to occur. Also, initial condition variations can have a significant impact on TRNSYS stability [4].

TABLE 1

DATA VALUES - COLLECTOR ONLY

TIME	INLET TEMPERATURE (^oC)	AMBIENT TEMPERATURE (^oC)	SOLAR RADIATION (KJ/hr m^2)	WINDSPEED (m/s)
0830	27.11	27.22	903.1	0.0
0845	29.22	27.22	1102.8	0.0
0900	29.50	27.77	1302.5	0.0
0915	29.61	27.77	1502.1	0.0
0930	29.89	28.33	1701.8	0.0
0945	30.22	28.33	1901.5	0.0
1000	31.11	28.89	2101.2	0.72
1015	31.17	29.44	2300.9	0.0
1030	31.28	30.00	2500.6	0.72
1045	31.28	30.56	2700.2	0.0
1100	31.28	31.11	2900.0	2.17
1115	31.39	31.11	3100.0	0.0
1130	36.00	31.11	3308.4	0.0
1145	36.78	31.67	3508.0	0.0
1200	38.06	32.22	1987.7	0.0
1215	38.67	32.78	2455.2	0.72
1230	39.50	33.33	3104.1	3.62
1245	41.72	33.33	3185.8	0.0
1300	42.89	33.33	1751.8	0.0
1315	43.17	32.78	1683.7	0.0
1330	43.39	33.33	1370.5	3.62
1345	44.67	33.89	984.8	0.0
1400	45.61	34.44	916.7	0.0
1415	39.39	33.89	3217.6	0.72
1430	38.00	34.44	3600.3	2.53
1445	36.72	35.00	3204.0	3.87
1500	38.39	34.44	2069.4	0.0
1515	43.67	34.44	767.0	0.0
1530	44.61	32.22	1125.5	6.88
1545	44.50	30.56	1565.7	4.35
1600	43.39	30.00	698.7	2.50
1615	44.67	28.33	1148.2	2.17
1630	44.67	27.77	635.3	6.52
1645	44.67	27.77	462.9	0.0

TABLE 2

COLLECTOR ONLY SIMULATION -
COLLECTOR OUTLET TEMPERATURES

TIME	TRNSYS °F	ACTUAL °F	Δ °F	% DIFFERENCE
0830	81	87	-6	-7.4
0900	91	88	3	3.5
0930	93	91	2	1.9
1000	97	96	1	1.6
1030	99	98	1	0.9
1100	101	100	1	1.0
1130	111	110	1	1.4
1200	109	115	-6	-5.1
1230	116	112	4	4.0
1300	116	115	1	0.6
1330	115	114	1	1.0
1400	117	115	2	1.5
1430	116	119	-3	-2.6
1500	110	116	-6	-5.1
1530	116	112	4	3.2
1600	112	111	1	0.6
1630	113	116	-3	-2.3

NOTE: TRNSYS, ACTUAL, and Δ columns have been rounded to integer values for tabular purposes only.

TABLE 3

COLLECTOR EFFICIENCY DATA

TIME	$T_{inlet}-T_{amb}$ (ΔT_1) (°C)	I $\frac{KJ}{hr\ m^2}$	$\frac{\Delta T_1}{I}$ ($x10^3$)	$T_{out}-T_{in}$ (ΔT_2) (°C)	E $\frac{KJ}{hr\ m^2}$	η
0900	1.73	1302.5	1.33	3.08	801.6	.62
0930	1.56	1701.8	0.92	4.06	1056.6	.62
1000	2.22	2101.2	1.06	4.99	1298.7	.62
1030	1.28	2500.6	0.51	6.02	1566.7	.63
1100	0.17	2900.0	0.06	7.05	1834.8	.63
1130	4.89	3308.4	1.48	7.77	2022.2	.61
1200	5.84	1987.7	2.94	4.51	1173.7	.59
1230	6.17	3104.1	1.99	7.14	1858.2	.60
1300	9.56	1751.8	5.46	3.71	965.5	.55
1330	10.06	1370.5	7.34	2.68	697.5	.51
1400	11.17	916.7	12.19	1.58	411.2	.45
1430	3.56	3603.3	0.99	8.53	2220.0	.62
1500	3.95	2069.4	1.91	4.82	1254.4	.61
1530	12.39	1125.5	11.01	1.90	494.5	.44
1600	13.39	698.7	19.16	0.85	221.2	.32
1630	16.90	635.3	26.60	0.38	98.9	.16

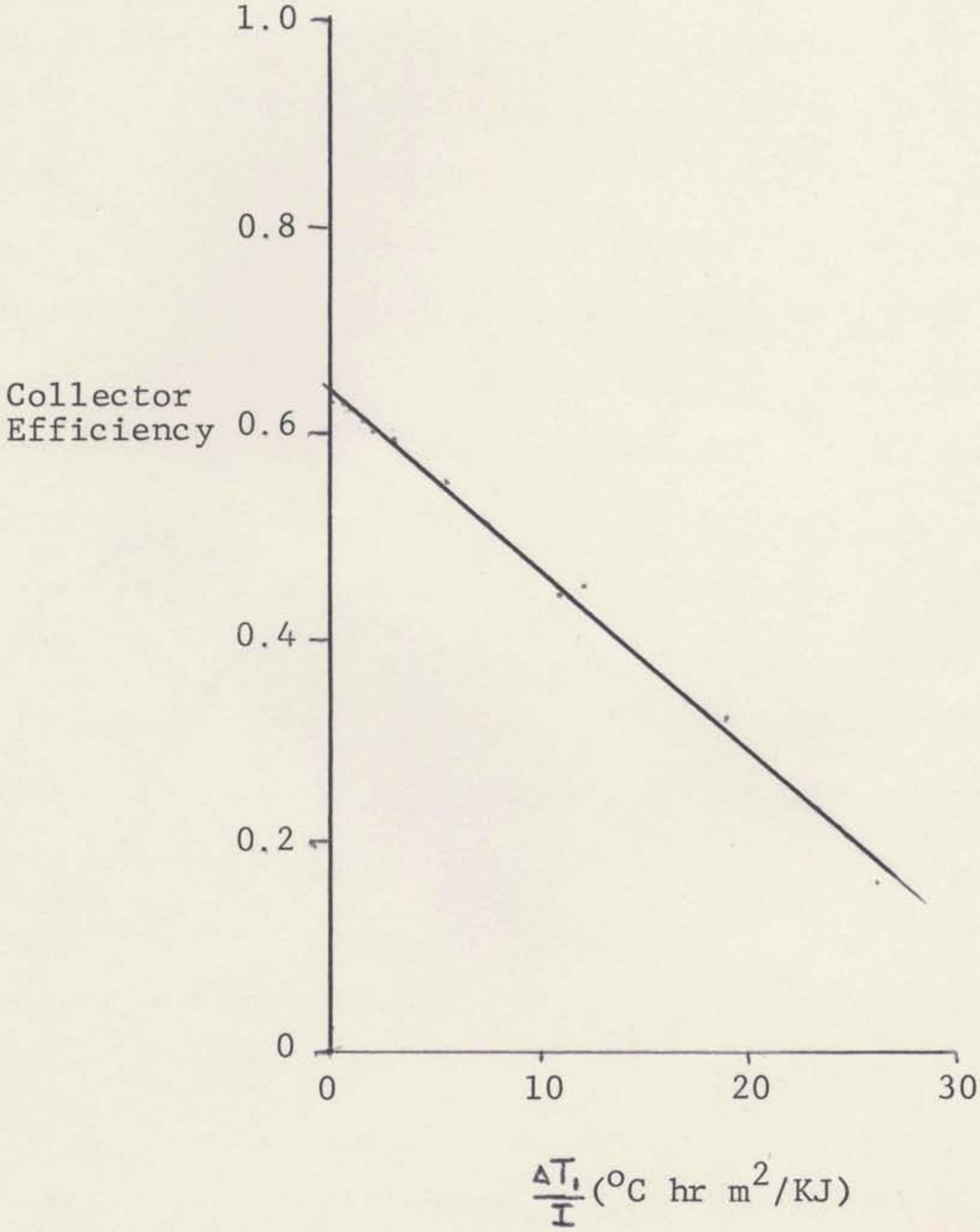

Figure 9. Collector Performance

Collector outlet temperature is tracked in Table 2, as previously noted. This data reveals several interesting facts about the TRNSYS model. Primarily, the largest deviations from experimental data occur during the simulation starting time. The first two data points in Table 2 show a -7.4 percent and -3.5 percent deviation at 0830 and 0900, respectively. Perhaps if steady state conditions had been tracked during the previous evening and had been incorporated into the model, a better correlation would have resulted. Unfortunately, this type of experimental data was not available. The TRNSYS evidently requires a fixed period of time for the model to stabilize before high fidelity results occur. This fact has been substantiated by independent studies of the time necessary for TRNSYS to stabilize [4]. These studies showed TRNSYS required up to three simulated days of operation for the model to stabilize.

Another interesting point to note in Table 2 is other data points where larger than normal deviations occur between experimental data and simulated results. In general, rapid changes in temperatures or conditions (such as a sudden cloud cover) cause fidelity problems in the model. These rapid changes cause the model to start fluctuations in an attempt to keep up with the driving force of this change (in this case, the solar insolation is the driving force influencing the collector outlet temperature). The model will stabilize once the rapid change subsides. This problem is not necessarily the cause of the TRNSYS program. If the update rate of the data values is increased, the model should produce more acceptable results. Unfortunately, experimental data was only provided four times per hour and this was the only data used in the simulation model. Another possible, but less likely cause of the model's inability to follow rapid data changes could be attributed to the integration routines within the TRNSYS program. This is less likely to cause problems when an adequate update rate is used. But it must be noted that TRNSYS uses a modified Euler integration routine, and although this is a good integration routine, there are other routines which are more accurate (e.g., Runge Kutta), but are not as computationally efficient. An Euler integration has reasonable accuracy if a small step size is used. This model, with a step size of 0.25 hours, could have produced more accurate results if the step size was shortened. A word of caution is necessary on computational step sizes. Although accuracy is improved, step sizes that become too small become computationally inefficient and can cause round-off errors to become more noticeable.

The method which is used to measure the accuracy of the simulated results when collectively compared to the experimental data is an absolute average value. Taking the absolute value of each individual percent deviation at each data point and averaging these values, one gets a measure of the absolute percent deviation of the simulation. This value can be expressed as

IV.2 $$|\text{Average}| = \frac{\sum |\text{percent deviation}|}{n} = 2.7 \text{ percent}$$

where n = the number of data points

A measure of the standard deviation can be found using the expression

IV.3 $$\sigma_{MOD} = \frac{[\sum(\text{Percent Deviation-Net Average})^2]^{\frac{1}{2}}}{n} = .78 \text{ percent}$$

The net average is found using the expression

$$\text{IV.3} \qquad \text{Net Average} = \frac{\sum \text{Percent Deviation}}{n} = -.6 \text{ percent}$$

It can be concluded that the TRNSYS modeling of the collector is quite accurate for the given experimental data. The next area to be investigated is the collector and tank simulated performance as an entire system.

For the system model using TRNSYS, collector initial conditions and data values remained the same as they were for the collector alone (refer to Table 1). For the tank, fluid temperature from the heat source (i.e., the collector) and mass flow rate from the heat source (collector) were taken from the collector outputs. The initial conditions for these items were the same as the corresponding initial conditions from the collector. The third tank input, the temperature of the replacement fluid (T_L), was not given as experimental data. This value was assumed to be constant at 21.11^{o}C (70^{o}F). This is a reasonable value for cold water supply temperature in Central Florida, and was measured at several residential sites to confirm the temperature value to be generally acceptable. This value does vary somewhat seasonally.

In addition to the collector data presented in Table 1, Table 4 exhibits the time varying data values pertinent to the tank. Table 5 exhibits system performance, with Figure 10 as a graphical representation of system performance. Appendix B is an entire listing and results of the TRNSYS model for the entire solar hot water system simulation.

The total system simulation exhibited much of the same general characteristics as the collector alone. The largest errors occurred in system start-up similar to when the collector alone was run. Errors generally were higher with the tank added than when it was not attached. Also, as with the collector alone, rapid fluctuations in the forcing function caused larger model deviations to occur. The model was attempting to track sudden changes, but began oscillating with what appeared to be little damping when these changes occurred.

The same measures of total system fidelity were used for the total system as were used for the collector alone. The absolute average percent deviation in data values was 3.39 percent (2.7 percent for the collector alone). Finally, the modified standard

TABLE 4

TIME VARYING TANK VALUES

TIME	AMBIENT TEMPERATURE AT TANK (°C)
0830	25.47
0845	25.01
0900	23.54
0915	22.69
0930	20.36
0945	23.00
1000	26.00
1015	28.16
1030	27.01
1045	27.01
1100	27.22
1115	27.32
1130	26.59
1145	26.48
1200	26.90
1215	28.16
1230	28.89
1245	28.05
1300	27.74
1315	28.18
1330	28.37
1345	29.27
1400	28.05
1415	28.16
1430	28.68
1445	28.78
1500	32.11
1515	32.32
1530	30.24
1545	30.97
1600	30.56
1615	30.56
1630	30.56
1645	30.56

TABLE 5

SYSTEM SIMULATION -
COLLECTOR OUTLET TEMPERATURES

TIME	TRNSYS (°F)	ACTUAL (°F)	Δ (°F)	% DIFFERENCE (%)
0830	81	88	-7	-12.1
0900	91	88	3	4.9
0930	93	91	2	3.1
1000	97	96	1	2.3
1030	99	98	1	1.6
1100	101	100	1	1.6
1130	111	109	2	1.8
1200	109	115	-6	- 7.2
1230	116	111	5	5.8
1300	116	115	1	0.9
1330	115	114	1	1.5
1400	117	115	2	2.2
1430	116	119	-3	- 3.6
1500	110	116	-6	- 7.0
1530	116	112	4	4.3
1600	112	111	1	0.6
1630	113	115	-2	- 2.9

NOTE: TRNSYS, ACTUAL, and Δ columns have been rounded to integer values for tabular purposes only.

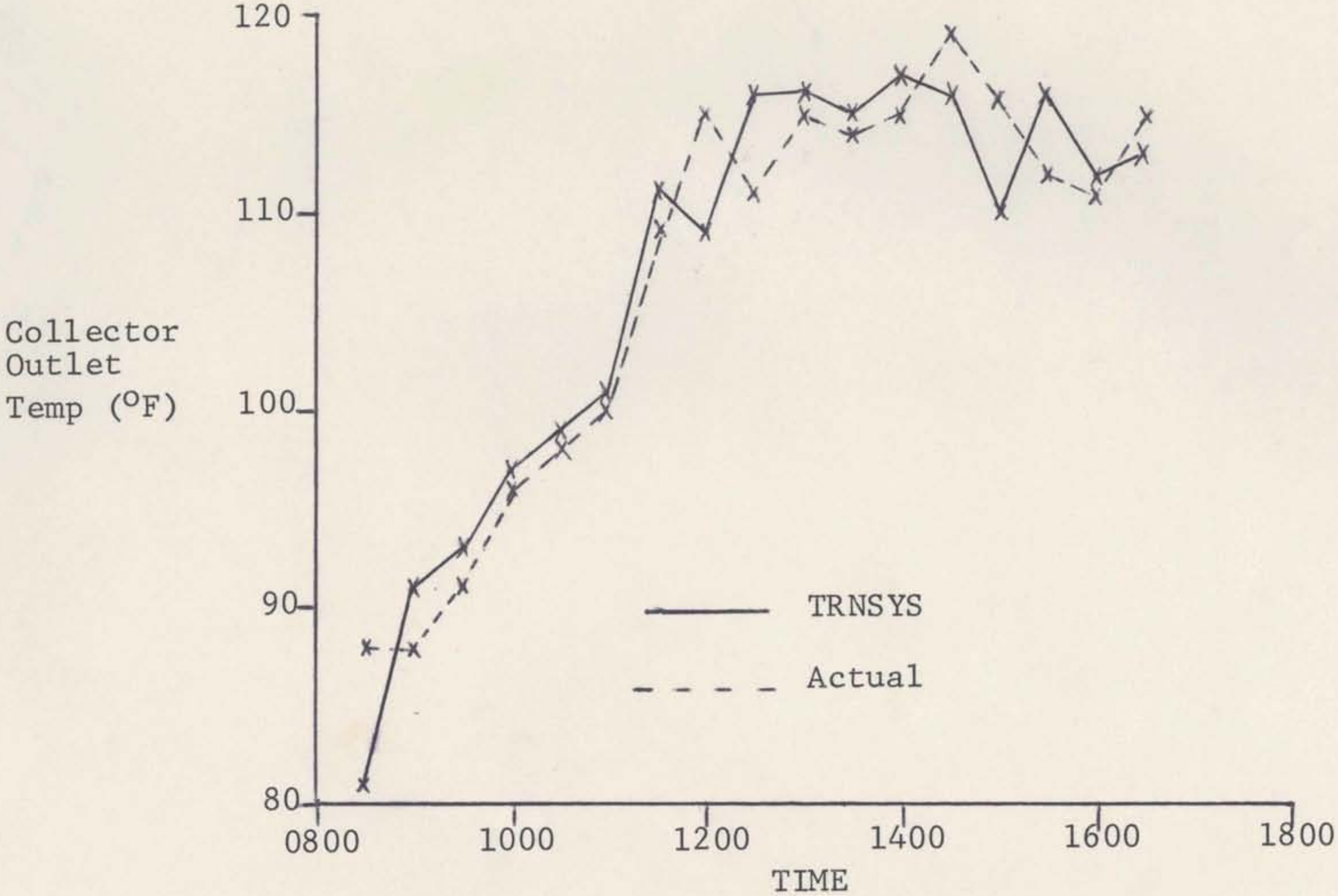

Figure 10. Simulated System Performance

deviation, σ_{MOD}, for the entire system was 1.16 percent (.78 percent for the collector alone) which shows a higher amount of data scatter for the system when compared to the collector alone.

The increase in the average starting error which comes about when the storage tank is added to the system is probably due to assumptions used for stratification by TRNSYS [4]. The TRNSYS model assumes that water returning from the collector will go to the stratified layer with the closest temperature to the incoming flow. The model further assumes that the fluid flow coming from the collector will go through any other stratified layers without distrubing them. The initial conditions for the storage tank for this model assumed all stratified layers were at 48.89°C (120°F). Therefore, the first stratified layer must become warmer than the other layers before the next layer can be warmed. This cascading effect can cause delays and an inability for the system to respond in sufficient time when rapid changes occur. Even smaller changes in collector outlet temperatures can cause longer than normal lags in storage tank response. For example, even though collector outlet fluid flows into the first stratified layer of the tank in the simulation model, the impact could be first felt in another layer whose temperature more closely matches the inlet temperature. Therefore, the effect on the top layer might not appear at the proper sequence in time. This problem primarily occurs when the inlet water temperature is below that of the first stratified layer. Unfortunately, TRNSYS does not allow the display of storage tank temperature for each stratified layer.

There is some valid reason why the collector outlet temperature was the one parameter scrutinized so closely. One reason is that by investigating this parameter for the collector only and for the entire system, relative differences would be easily distinguished. Another reason is that this value gives a valuable insight into the total system operation. If demand from the load increases which causes an initial drop in tank outlet temperature, this is always reflected in the value of the collector outlet temperature. Also, other parameters are often not a singularly good measure of system performance. For example, fluid temperature delivered to the load is not a good measure of system performance in this simulation, because the auxiliary heater will tend to maintain this temperature, and therefore, the heater input must be considered. Outlet fluid temperature from the collector was both a convenient and accurate measure of system performance.

The system performance as modeled by TRNSYS was quite accurate on a macro level. There were individual areas or certain times when performance was degraded, but these were the exception rather than the rule.

V

CONCLUSIONS

The simulated results from the TRNSYS model generally agree and track very well with experimental results. Deviations occurred, but on an overall basis, the model accurately reflects the actual system it models. System characteristics, when not given, were chosen with great care to accurately reflect a component's actual characteristics. In some cases, representative values for parameters were chosen to represent general characteristics of a solar hot water system operating in Central Florida.

Both the collector alone and the total system performance when measured against actual collector outlet temperature showed very close agreement. Both simulations showed larger than average deviations during initial start-up in the morning and when rapid changes in the forcing function (solar insolation and/or hot water load demand) occurred. If ample stable system data for the previous evening had been available, start-up errors could have been reduced. As the data was presented, slight imbalances in data values at the start of the simulation run can cause the TRNSYS model to also be imbalanced and present erroneous results. As time progressed, the TRNSYS model began to react to the forcing functions and responded in a similar manner as the actual system responded. This trend held true until a rapid change in either solar insolation or hot water demand occurred. In the case of a sudden cloud cover, solar insolation was reduced in a short period of time causing the TRNSYS model again to begin oscillating in an attempt to keep up with the forcing functions. When the forcing function ceased oscillating, simulated performance again matched the actual system performance. As noted, this problem could have been minimized if a smaller integration step size was used (data points were unavailable) or if another integration routine was used in place of the modified Euler technique in TRNSYS.

This study also discovered several parts of the TRNSYS model where flexibility could be enhanced. As noted above, a choice of integration routines available to the user for various time steps could enhance simulation fidelity. Another area for increased flexibility and fidelity would be to have the user specify line locations in the hot water storage tank. Finally, increased guidance is necessary for the user to implement multiple data readers.

The above discussion has indicated areas where TRNSYS might be improved, but emphasis should also be placed on the TRNSYS model's accuracy. Given good data and system characteristics, this model can provide a good overall assessment of an actual system's performance. Individual data points might have diverged, but it has been shown that overall performance of TRNSYS matched actual data quite well.

Finally, this investigation was limited in scope in that a simple system with few components and relatively few data points were used. As system complexity increases, either with new components being added or a different solar application causing changes in system layout, a reassessment is necessary to verify and validate results. The results presented must be qualified by the above statements to provide a limit to the work which has been done and a starting point for future work.

APPENDIX A

TRNSYS Run - Collector Only

```
          TRNSYS - A TRANSIENT SIMULATION PROGRAM
    FROM THE SOLAR ENERGY LAB AT THE UNIVERSITY OF WISCONSIN
                   VERSION  9.2   2/1/78

SIMULATION          8.500E+00     1.675E+01     2.500E-01

WIDTH     72

UNIT  1     TYPE  1      COLLECTOR
      PARAMETERS 10
      2.000E+00     3.437E+00     9.500E-01     4.190E+00     9.000E-01
      1.000E+00     1.000E-01     8.264E+00     4.000E+01     7.620E-01
      INPUTS  5
       6, 1          0, 0          6, 2          6, 3          6, 4
      2.711E+01     2.135E+02     2.722E+01     0.0           0.0
UNIT  6     TYPE  9      READER
      PARAMETERS 16
      4.000E+00     2.500E-01     1.000E+00     1.000E+00     0.0
      2.000E+00     1.000E+00     0.0           3.000E+00     1.000E+00
      0.0           4.000E+00     1.000E+00     0.0          -1.000E+00

      3.000E+00
       (4F10.3)

UNIT 24     TYPE 24      INTEGRATOR
      INPUTS  2
       1, 3          6, 3
      0.0           0.0
```

```
UNIT 25      TYPE 25      PRINTER
     PARAMETERS  4
     8.250E+00     1.675E+01     1.675E+01    -1.000E+00
     INPUTS  2
     24,-1           24, 2
     USED            DEL

UNIT 10      TYPE 25      PRINT
     PARAMETERS  4
     2.500E-01     8.500E+00     1.675E+01    -1.000E+00
     INPUTS  1
      1,-1
     TOUT

END
```

```
      TRANSIENT SIMULATION      STARTING AT TIME = 8.500E+00
                                STOPPING AT TIME = 1.675E+01
                                        TIMESTEP = 2.500E-01
          DIFFERENTIAL EQUATION ERROR TOLERANCE = 1.000E-02
              ALGEBRAIC CONVERGENCE TOLERANCE = 1.000E-02
***LTOP***

      TIME =     8.5000
    TOUT
 2.712E+01

      TIME =     8.7500
    TOUT
 3.180E+01

      TIME =     9.0000
    TOUT
 3.258E+01

      TIME =     9.2500
    TOUT
 3.317E+01

      TIME =     9.5000
    TOUT
 3.395E+01

      TIME =     9.7500
    TOUT
 3.475E+01

      TIME =    10.0000
    TOUT
 3.610E+01

      TIME =    10.2500
    TOUT
 3.668E+01
```

TIME = 10.5000
TOUT
3.730E+01

TIME = 10.7500
TOUT
3.782E+01

TIME = 11.0000
TOUT
3.833E+01

TIME = 11.2500
TOUT
3.893E+01

TIME = 11.5000
TOUT
4.377E+01

TIME = 11.7500
TOUT
4.502E+01

TIME = 12.0000
TOUT
4.257E+01

TIME = 12.2500
TOUT
4.429E+01

TIME = 12.5000
TOUT
4.664E+01

```
     TIME =   12.7500
  TOUT
4.898E+01
     TIME =   13.0000
  TOUT
4.660E+01
     TIME =   13.2500
  TOUT
4.666E+01
     TIME =   13.5000
  TOUT
4.607E+01
     TIME =   13.7500
  TOUT
4.644E+01
     TIME =   14.0000
  TOUT
4.719E+01
     TIME =   14.2500
  TOUT
4.689E+01
     TIME =   14.5000
  TOUT
4.653E+01
     TIME =   14.7500
  TOUT
4.440E+01
     TIME =   14.9999
  TOUT
4.321E+01
```

```
        TIME =     15.2499
   TOUT
4.501E+01
        TIME =     15.4999
   TOUT
4.651E+01
        TIME =     15.7499
   TOUT
4.737E+01
        TIME =     15.9999
   TOUT
4.424E+01
        TIME =     16.2499
   TOUT
4.640E+01
        TIME =     16.4999
   TOUT
4.505E+01
        TIME =     16.7499
  USED              DEL             TOUT
3.285E+04       1.652E+04      4.479E+01


                    UNIT   1 WAS CALLED      34 TIMES
                           6                 35
                          24                 35
                          25                  1
                          10                 34
```

APPENDIX B

TRNSYS Run - System Simulation

```
          TRNSYS - A TRANSIENT SIMULATION PROGRAM
    FROM THE SOLAR ENERGY LAB AT THE UNIVERSITY OF WISCONSIN
                   VERSION  9.2   2/1/78


SIMULATION          8.500E+00     1.675E+01     2.500E-01

WIDTH     72

UNIT   1      TYPE  1      COLLECTOR
       PARAMETERS 10
       2.000E+00     3.437E+00     9.500E-01     4.190E+00     9.000E-01
       1.000E+00     1.000E-01     8.264E+00     4.000E+01     7.620E-01
       INPUTS   5
        6, 1          0, 0          6, 2          6, 3          6, 4
       2.711E+01     2.135E+02     2.722E+01     0.0           0.0

UNIT   6      TYPE  9      READER
       PARAMETERS 19
       5.000E+00     2.500E-01     1.000E+00     1.000E+00     0.0
       2.000E+00     1.000E+00     0.0           3.000E+00     1.000E+00
       0.0           4.000E+00     1.000E+00     0.0           5.000E+00
       1.000E+00     0.0           0.0           1.000E+00
        (5F10.3)

UNIT 24       TYPE 24      INTEGRATOR
       INPUTS   3
        1, 3          6, 3          4, 8
       0.0           0.0           0.0
```

```
UNIT 25      TYPE 25      PRINTER
     PARAMETERS  4
     8.2 0E+00      1.675E+01      1.675E+01      -1.000E+00
     INPUTS   3
     24, 1          24, 2          24, 3
     USED           DEL            AUXE

UNIT 10      TYPE 25      PRINT
     PARAMETERS  4
     2.500E-01      8.500E+00      1.675E+01      -1.000E+00
     INPUTS   3
      1, 1           4, 1           4, 3
     TOUT           TCOLL          TLOAD

UNIT  4      TYPE  4      TANK
     PARAMETERS  9
     4.490E-01      1.524E+00      4.190E+00      1.000E+03      3.352E+00
     1.000E+05      1.000E+00      1.000E+00      4.889E+01
     INPUTS   5
      1, 1           1, 2           0, 0          14, 1           6, 5
     2.711E+01      2.135E+02      2.111E+01      0.0            2.700E+01
     DERIVATIVES  4
     4.889E+01      4.889E+01      4.889E+01      4.889E+01

UNIT 14      TYPE 14      FORCING FUNCTION
     PARAMETERS 74
     8.500E+00      0.0            8.750E+00      2.810E+00      9.000E+00
     6.194E+01      9.250E+00      6.242E+01      9.500E+00      8.894E+01
     9. 50E+00      1.178E+02      1.000E+01      1.767E+02      1.025E+01
     1.997E+02      1.050E+01      2.550E+02      1.075E+01      3.093E+02
     1.100E+01      3.421E+02      1.125E+01      3.426E+02      1.150E+01
     3.432E+02      1.175E+01      3.450E+02      1.200E+01      3.480E+02
     1.225E+01      3.527E+02      1.250E+01      3.533E+02      1.275E+01
     3.559E+02      1.300E+01      3.559E+02      1.325E+01      3.559E+02
     1.3 0E+01      3.560E+02      1.375E+01      3.560E+02      1.400E+01
     3.560E+02      1.425E+01      1.916E+02      1.450E+01      3.862E+01
     1.475E+01      7.762E+01      1.500E+01      7.781E+01      1.525E+01
     7. 78E+01      1.550E+01      7.878E+01      1.575E+01      8.594E+01
     1.600E+01      9.736E+01      1.625E+01      9.736E+01      1.650E+01
     9.736E+01      1.675E+01      9.746E+01      1.700E+01      9.862E+01
     1.725E+01      9.997E+01      1.750E+01      1.432E+02

END
```

```
TRANSIENT SIMULATION     STARTING AT TIME = 8.500E+00
                         STOPPING AT TIME = 1.675E+01
                                 TIMESTEP = 2.500E-01
   DIFFERENTIAL EQUATION ERROR TOLERANCE = 1.000E-02
        ALGEBRAIC CONVERGENCE TOLERANCE = 1.000E-02
***LTOP***
```

TIME	TOUT	TCOLL	TLOAD
8.5000	2.712E+01	4.889E+01	4.889E+01
8.7500	3.180E+01	4.716E+01	4.886E+01
9.0000	3.258E+01	4.355E+01	4.879E+01
9.2500	3.317E+01	3.912E+01	4.869E+01
9.5000	3.395E+01	3.569E+01	4.844E+01
9.7500	3.475E+01	3.284E+01	4.799E+01
10.0000	3.610E+01	3.014E+01	4.758E+01
10.2500	3.668E+01	2.719E+01	4.631E+01

```
        TIME =    10.5000
   TOUT            TCOLL           TLOAD
3.730E+01     2.485E+01     4.515E+01

        TIME =    10.7500
   TOUT            TCOLL           TLOAD
3.782E+01     2.308E+01     4.445E+01

        TIME =    11.0000
   TOUT            TCOLL           TLOAD
3.833E+01     2.216E+01     4.399E+01

        TIME =    11.2500
   TOUT            TCOLL           TLOAD
3.893E+01     2.156E+01     4.365E+01

***** WARNING *****
              THE INPUTS TO UNITS           4
              DIFFERENTIAL EQUATIONS        1
   WERE NOT CONVERGED WITHIN THE SPECIFIED TOLERANCE AT TIME=   11.5000


        TIME =    11.5000
   TOUT            TCOLL           TLOAD
4.377E+01     2.122E+01     4.363E+01

***** WARNING *****
              THE INPUTS TO UNITS           4
              DIFFERENTIAL EQUATIONS        1
   WERE NOT CONVERGED WITHIN THE SPECIFIED TOLERANCE AT TIME=   11.7500


        TIME =    11.7500
   TOUT            TCOLL           TLOAD
4.502E+01     2.117E+01     4.541E+01

        TIME =    12.0000
   TOUT            TCOLL           TLOAD
4.257E+01     2.115E+01     4.442E+01
```

```
     TIME =     12.2500
  TOUT           TCOLL            TLOAD
4.429E+01     2.112E+01       4.423E+01

     TIME =     12.5000
  TOUT           TCOLL            TLOAD
4.664E+01     2.114E+01       4.431E+01

     TIME =     12.7500
  TOUT           TCOLL            TLOAD
4.898E+01     2.113E+01       4.486E+01

     TIME =     13.0000
  TOUT           TCOLL            TLOAD
4.660E+01     2.113E+01       4.416E+01

     TIME =     13.2500
  TOUT           TCOLL            TLOAD
4.666E+01     2.113E+01       4.436E+01

     TIME =     13.5000
  TOUT           TCOLL            TLOAD
4.607E+01     2.113E+01       4.340E+01

     TIME =     13.7500
  TOUT           TCOLL            TLOAD
4.644E+01     2.113E+01       4.408E+01

     TIME =     14.0000
  TOUT           TCOLL            TLOAD
4.719E+01     2.113E+01       4.374E+01

     TIME =     14.2500
  TOUT           TCOLL            TLOAD
4.689E+01     2.114E+01       4.566E+01

     TIME =     14.5000
  TOUT           TCOLL            TLOAD
4.653E+01     2.134E+01       4.777E+01
```

```
       TIME =    14.7500
  TOUT              TCOLL            TLOAD
4.440E+01     2.200E+01     4.772E+01

       TIME =    14.9999
  TOUT              TCOLL            TLOAD
4.321E+01     2.286E+01     4.724E+01

       TIME =    15.2499
  TOUT              TCOLL            TLOAD
4.501E+01     2.410E+01     4.694E+01

       TIME =    15.4999
  TOUT              TCOLL            TLOAD
4.651E+01     2.552E+01     4.820E+01

       TIME =    15.7499
  TOUT              TCOLL            TLOAD
4.737E+01     2.696E+01     4.826E+01

       TIME =    15.9999
  TOUT              TCOLL            TLOAD
4.424E+01     2.807E+01     4.800E+01

       TIME =    16.2499
  TOUT              TCOLL            TLOAD
4.640E+01     2.905E+01     4.790E+01

       TIME =    16.4999
  TOUT              TCOLL            TLOAD
4.505E+01     2.985E+01     4.816E+01

                          TIME =    16.7499
  USED            DEL              AUXE             TOUT            TCOLL
3.285E+04     1.652E+04     4.162E+04     4.479E+01     3.068E+01
  TLOA
4.819E+01
```

```
UNIT  1 WAS CALLED     34 TIMES
      6                35
     24                35
     25                 1
     10                34
      4               150
     14                35
```

FOOTNOTES

[1]Solar Energy Laboratory, University of Wisconsin, A Transient Simulation Program TRNSYS (Madison: University of Wisconsin, 1978).

[2]Jeffrey B. Pearce, "Analytical and Experimental Investigation of Pumped Solar Hot Water Systems" (Master's thesis, Florida Technological University, 1975).

[3]John A. Duffie and William A. Beckman, Solar Energy Thermal Processes (New York: John Wiley and Sons, 1974).

[4]U.S., Department of Energy, Proceedings of the DoE Symposium on Systems Simulation and Economic Analysis for Solar Heating and Cooling (San Diego, June 1978).

BIBLIOGRAPHY

Duffie, John A., and Beckman, William A., Solar Energy Thermal Processes. New York: John Wiley & Sons, 1974.

Gibra, Isaac N. Probability and Statistical Inference for Scientists and Engineers. Englewood Cliffs, NJ: Prentice-Hall, 1973.

Honeywell Corporation. Transportable Solar Laboratory Workshop, prepared for the United States Energy Research and Development Administration. Minneapolis, 1977.

Lapin, Lawrence L. Statistics for Modern Business Decisions. New York: Harcourt Brace Jovanovich, 1973.

Pearce, Jeffrey B. "Analytical and Experimental Investigation of Pump Solar Hot Water Systems," Master's thesis, Florida Technological University, 1975.

Solar Energy Laboratory, University of Wisconsin. A Transient Simulation Program TRNSYS. Madison: University of Wisconsin, 1978.

U. S., Department of Energy. Proceedings of the DoE Symposium on Systems Simulation and Economic Analysis for Solar Heating and Cooling. San Diego, June 1978.