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**COLORADO STATE UNIVERSITY PROGRAM FOR
DEVELOPING, TESTING, EVALUATING
AND OPTIMIZING
SOLAR HEATING SYSTEMS**

**PROJECT STATUS REPORT FOR THE MONTHS OF
OCTOBER AND NOVEMBER 1995**

Prepared for the

**U.S. Department of Energy
Conservation and Renewable Energy
Under Grant DE-FG36-95GO10093**

Submitted by

**SOLAR ENERGY APPLICATIONS LABORATORY
COLORADO STATE UNIVERSITY**

December 1995

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UNIQUE SOLAR SYSTEM COMPONENTS

INTEGRATED TANK/HEAT EXCHANGER MODELING/EXPERIMENTS

As noted in previous reports, we have decided to commit to using TRNSYS 14 for the development of a new wrap-around heat exchanger/tank model. The failing health of our DEC 5000 and discrepancies between the results produced by the DEC 5000's fortran compiler and the Microsoft Powerstation fortran compiler on our PC's (see AUG/SEP 1995 Progress Report) have prompted a decision to move the development of future wrap-around heat exchanger tank models to the PC. As a first step, a set of data manipulation utility programs has been written using the PERL programming language have been ported to the PC. These PERL language programs and scripts have proven very useful in automating the process of reducing experimental data, updating the corresponding TRNSYS simulation decks and normalizing the simulation results to the experimental data.

The most recent version of the "old" CSU wrap-around heat exchanger model using the new version of the TRNSYS Type 4 Thermal Storage Tank Model developed by B. J. Newton (1995) at the University of Wisconsin for TRNSYS 14 has not yet been tested. Jeff Miller is currently focusing most of his efforts on completing the literature review chapters for his dissertation. Final documentation of all of experimental results obtained to date is waiting on the completion of the new version of the wrap-around tank model.

References

Newton, B. J., Schmid, M., Mitchell, J. A., and Beckman, W. A., "Storage Tank Models," *Proceedings of the 1995 ASME Solar Energy Conference*, March 19-24, Maui, Hawaii, pp. 1111-1116, 1995.

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conf'd*

RATING AND CERTIFICATION OF DOMESTIC WATER HEATING SYSTEMS

October/November 1995

A paper accepted for the 1996 International Solar Energy Conference in San Antonio, Texas has been completed and the final version is included here.

Current work involves moving the tank-in-tank heat exchanger portion of the system under investigation indoors for further testing. The portable testing apparatus described in the April/May, 1995 Progress Report will be used for the tests. An attempt is being made to obtain the same results presented in the attached paper using a much simpler method. By outlining a simple and relatively fast method to arrive at the same results, system simulations of thermosyphon solar domestic hot water systems may be performed expeditiously and more accurately. This should simplify the rating and certification of such systems.

MASTER

A SYSTEMATIC APPROACH TO IMPROVING THERMOSYPHON SDHW MODEL PERFORMANCE

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ABSTRACT

A systematic procedure is used to calibrate a computer model of a thermosyphoning, solar domestic hot water heating system with a tank-in-tank heat exchanger using data from an indoor solar simulator experimental performance test. Excellent agreement with the experimental collector useful energy gain and the energy delivered during a draw is achieved by ensuring that the model gives an accurate prediction of the temporal history of both the system flow rates and temperatures. The calibrated simulation model is then compared to two additional one-day outdoor tests. Simulation accuracy is greatly improved and confidence in an annual performance prediction is increased.

INTRODUCTION

The simulation of solar domestic hot water (SDHW) system performance is important to enable efficient and reliable energy saving predictions. The Solar Rating and Certification Corporation (SRCC) has chosen to use the TRNSYS (1992) simulation software to rate SDHW systems sold in the United States under its OG300 Protocol (Solar Rating & Certification Corporation, 1995). These ratings are used by utilities, governmental agencies, and consumers to evaluate the thermal and economic value of different systems. Thus, ensuring that simulated performance matches experimental results is an important and ongoing area of research (Burch 1993).

Model development and calibration becomes especially difficult for thermosyphon SDHW systems. The performance of these systems is dependent on the complex thermal interaction between the collector and the combination of heat exchanger and thermal storage tank which determines the thermosyphon flow rate at various operating conditions. This makes simulation of these systems more complex than constant flow rate pumped systems. Several sources of modeling uncertainties can be identified. First, the flow in the collector loop is typically laminar. Pressure drops due to pipe fittings and developing flow are significant and must be taken into account (Morrison and Ranatunga, 1980). As a result, accurate estimation of friction loss coefficients in thermosyphon systems is difficult and largely uncertain. Second, the heat exchanger is integrated with the storage tank. Natural

convection driven flows on both sides of the heat exchanger make the performance of the combined system extremely difficult to model. These combinations of heat exchanger and tank have not been studied as extensively as in forced flow situations. Finally, vertical temperature stratification in horizontal tanks is not as well understood as it is in vertical tanks and has a major effect on both collector inlet temperature and thermosyphon flow rate (Morrison and Braun, 1985). Tank destratification due to conduction between the fluid layers and in the tank wall is simulated in the current model, but destratification due to convective mixing in the tank, likely more significant than that due to conduction, is not currently modeled.

BACKGROUND

Bickford and Hittle (1995) recently reported experimental measurements on the performance of a thermosyphon SDHW system with

Figure 1. Thermosyphon System Overview

an annular tank-in-tank heat exchanger along with comparisons of their experimental results with predictions using a TRNSYS simulation model. The predicted total energy delivered by the collector agreed reasonably well with the experiment, however, the total energy delivered to the load was much larger than measured. The results of their comparison are summarized below.

The experiments were performed using the indoor solar simulator at the Solar Energy Applications Laboratory (SEAL) at Colorado State University. The solar simulator is a unique facility that allows for full-size SDHW systems to be tested under constant irradiation conditions over extended periods of time (Kenny, 1993).

Figure 1 is a schematic of the thermosiphon SDHW system tested. The system was fully instrumented with special-limit, T-type thermocouples to measure the fluid temperatures ($\pm 0.3^\circ\text{C}$). A low-pressure-drop Coriolis-effect mass flow meter was used to measure flow in the collector loop (± 0.2 kg/h). The collector performance parameters and the tank heat loss coefficient were determined from separate tests and are noted in Figure 1. A variety of four and eight hour constant irradiation tests with and without draws were performed. Figures 2 thru 5 show the results of a four-hour test with a 420 second draw at an average flow rate of 0.21 liters per second at two hours. The draw volume was about one-half of the total tank volume. Draw flow rate was controlled with a pressure control valve and was measured with a turbine flow meter (± 0.01 l/s).

Bickford and Hittle simulated the results of this experiment using the solar simulation program TRNSYS (Klein, 1992) with a recently updated thermosiphon system model originally developed by Morrison and Braun (1985). The model calculates the thermosiphon flow rate by requiring the sum of changes in pressure around the collector heat exchanger loop due to buoyancy forces and frictional losses to be zero. Recent upgrades (Morrison, 1994) allow the simulation of several different kinds of heat exchangers, including an annular tank-in-tank arrangement. The model now also calculates conduction between adjacent water layers in the tank and along the tank wall.

Figure 2. Collector Inlet (Bottom) and Outlet (Top) Temperature vs. Time For Four Hour Test With Draw.

Figure 2 shows a comparison of the collector inlet and outlet temperatures during the four hour test. The predicted temperature rise

Figure 3. Collector Flow Rate vs. Time For Four Hour Test

across the collector is larger than in the experiment. Figure 3 shows the predicted and actual collector flow rate. The qualitative shapes of these curves have been discussed previously (Bickford and Hittle, 1995), but note that the model predicts significantly lower flow than observed which counteracts the overprediction of the collector temperature rise in a calculation of collector useful energy. Over the four hour experiment, the predicted collector useful energy is 21053 kJ which is about seven percent larger than the experimental value of 19626 kJ. Although this agreement is reasonable, it arises due to compensating errors in the model.

Figure 4 compares the average tank temperature as a function of time over the four hour test. The experimental average temperature is computed as a volume weighted average of the temperatures of four thermocouples placed in a vertical tree near the center of the tank as described by Bickford and Hittle (1995). The TRNSYS average temperature is computed as a weighted average of the tank node temperatures. The simulation predicts a

Figure 4. Average Tank Temperature vs. Time For Four Hour Test With Draw.

higher average tank temperature before the draw with a larger drop during the draw.

Figure 5 shows the tank draw temperature as a function of fractional tank volume over the 420 second draw. The predicted draw temperature starts off higher and then drops faster than the corresponding experimental draw temperature. This indicates that there is a higher degree of vertical stratification in the model tank than in the experimental tank. The measured energy delivered during the 420 second draw is 7412 kJ. The model predicts an energy delivery of 9503 kJ which is 28 percent larger.

With no adjustment, the TRNSYS Thermosyphon System model is not effectively simulating this four hour solar-only constant irradiation test with a fixed volume draw.

This work seeks to improve the accuracy of the simulation by systematically identifying and adjusting key parameter inputs and requiring that the model output better match the time evolution of the collector and heat exchanger/tank temperatures and flow rates. This is accomplished using the TRNSYS program to first examine the accuracy of individual component models and then check the results of the simulation as a whole. Finally, as a test of the accuracy of the adjusted model, the performance of two additional one-day outdoor tests made at SEAL is predicted and compared.

Figure 5. Draw Temperature vs. Fractional Volume During the 420 Second Draw.

IMPROVING THE SIMULATION

By adjusting one parameter such as the tank heat loss (UA) value or the collector heat loss parameter ($F_{sh}U_L$), the simulation model could be "calibrated" to match any single experimental outcome, such as the draw energy. However, if the model does not match the details of the development of the system temperatures and thermosyphon flow rate there can be little confidence in the simulation model's ability to predict system performance under widely varying conditions. More likely, several parameters will have to be adjusted in order to obtain a more accurate match between the simulation and the experiment.

In this case, the thermosyphon model consists of a standard flat plate collector that is coupled to a heat exchanger and a thermosyphon calculation. The performance of the individual components is highly coupled and modification of any one of them will affect the others making

multiple parameter adjustment difficult. For example, adjusting the overall heat transfer coefficient (UA) value of the heat exchanger will affect the thermosyphon flow and collector outlet temperature. Therefore, in the procedure used here, the thermosyphon flow calculation in the collector loop is disabled and the collector model is forced to exactly follow the measured collector inlet temperature and flow as shown in Figures 2 and 3. The accuracy of the collector and heat exchanger/tank models can then be assessed and, if necessary, adjusted individually. The thermosyphon calculation is then enabled and performance of the entire model is checked and adjusted if necessary. By using this approach, several adjustments can be made to the model in logical succession allowing the experiment to be simulated more accurately.

DECOUPLED MODEL SIMULATION RESULTS

Figure 6 shows the predicted and experimental collector outlet temperatures when the measured experimental flow rate and collector inlet temperature shown in Figures 2 and 3 are used as inputs to the model (this is called the "forced model" hereafter). With two exceptions, the predicted collector outlet temperature is within about one half of one degree of the experimental collector outlet temperature. The discrepancies at the

Figure 6. Collector Outlet Temperature vs. Time With Forced Collector Flow Rate and Inlet Temperature.

beginning of the test and during the draw occur because the TRNSYS model does not account for the thermal capacitance of the system. The experimental flow rate, being forced into the model, is very low at the start of the test (Figure 3), which causes the model to immediately predict a very large collector temperature rise. In reality, the collector takes some finite time to respond to the step change in irradiation and does not experience a large temperature rise immediately.

Examination of Figure 3 shows that the measured (and predicted) thermosyphon flow increases as the average temperature of the fluid in the collector/heat exchanger loop increases with time (due to a decrease in fluid viscosity). During the draw, the average temperature in the collector/heat exchanger loop will drop as the cold water enters the tank. The thermosyphon flow predicted by the model immediately predicts a corresponding drop in flow. In the experiment, the flow first responds to

Figure 7. Collector Inlet Temperature vs. Time With Forced Collector Flow Rate and Inlet Temperature.

only a drop in the collector inlet temperature which causes the flow rate to increase. The eventual drop in the average loop temperature and corresponding drop in flow rate is delayed to well beyond the end of the draw. The current model (and TRNSYS in general) will not reproduce this same trend.

Even with the discrepancies mentioned above, the experimental and predicted total collector useful energy differ by less than one percent indicating that the previously measured collector gain ($F_{av}(\tau\alpha)$) and loss parameters ($F_{av}U_L$) are appropriate.

After the fluid leaves the collector, it passes through the heat exchanger and then goes back to the collector inlet. Figure 7 compares the collector inlet temperature predicted by the forced model with the experiment. The predicted temperature out of the heat exchanger is significantly lower than

the measured value. Since the measured and predicted temperature entering the heat exchanger are essentially the same, this result implies that the predicted heat transfer to the tank water is larger than in the experiment. This suggests that the model overestimates the performance of the heat exchanger and a modification of the heat exchanger overall heat transfer coefficient (UA) calculation is required.

Figure 8 shows the average tank temperature for the model and the experiment. As discussed in relation to figure 4 in the previous section, the temperature rises at a greater rate in the model than in the experiment. Since, in this case, the predicted collector energy output is very close to the experimental value, the predicted heat exchanger UA value must be larger than the experimental value (assuming correct thermal capacity in the tank).

Figure 9. Draw Temperature vs. Volume Fraction With Forced Collector Flow Rate and Inlet Temperature.

Again, this suggests a modification of the heat exchanger UA value.

Figure 9 shows the predicted and actual draw temperature over the 420 second draw. The model predicts higher draw temperatures and higher stratification as discussed in relation to Figure 5. The predicted draw energy of 9896 kJ is about thirty percent larger than the experimental value of 7412 kJ. A modification of the destratification calculation in the tank model may also be required.

ADJUSTMENTS USING THE DECOUPLED MODEL

The decoupled thermosyphon model is used as a starting point for adjustment of the original model parameters. The amount of heat transferred through the heat exchanger is first reduced and then the tank stratification problem is considered.

Since the predicted inlet temperature profile to the heat exchanger (collector outlet) is very close to the experimental profile, adjusting the UA value of the heat exchanger until the heat exchanger outlet temperature (collector inlet) profile matches the experimental profile will ensure that the model heat exchanger is transferring the correct amount of energy into the tank water. To do this, a previous eight hour warm-up test with no load draw made by Bickford and Hittle (1995) is used. This is to avoid the complications associated with the capacitance in the system during the

Figure 8. Average Tank Temperature vs. Time With Forced Collector Flow Rate and Inlet Temperature.

draw. The eight hour test is modeled by forcing the flow rate and collector inlet temperature as with the four hour test. The heat exchanger UA value is adjusted until the predicted collector inlet temperature profile matches the experimental profile as closely as possible. A multiplicative factor of 0.7 applied to the heat exchanger UA calculation in the model minimizes the RMS error in the prediction.

Note, an attempt was made to adjust the heat exchanger UA until the experimental and simulation tank average temperature profiles (specifically, slope of the temperature rise) matched. The new predicted temperature at the heat exchanger outlet was much lower than the experimental value. The experimental value of the average tank temperature is calculated on a volume weighted average of only four temperature measurements. As a result, the uncertainty in the experimental average is large and thus this temperature may not be the best value to use to characterize the heat transfer to the tank.

Having modified the heat exchanger calculations, the tank stratification problem is considered. Tank destratification in the model includes conduction along the tank wall and between adjacent water layers. These two effects are combined into an equivalent conductivity term. There is currently no convective destratification mechanism modeled. To decrease tank stratification, a multiplicative factor is applied to the equivalent conductivity term and adjusted until the 420 second draw temperature profile is matched as closely as possible. A factor of 27 is required to minimize the RMS error in the temperature profile. Two causes have been suggested previously for the large size of this adjustment. First, an assumption is made in the model that the collector fluid rises without mixing to the top of the annular space in the heat exchanger. Measurements show that this is not the case (Bickford and Hittle, 1995) and mixing will decrease tank stratification. Second, there may be a convective mixing process occurring in the potable water inside the tank (Bickford and Hittle, 1995).

FINAL SIMULATION RESULTS

The modifications calculated using the forced model are applied to the non-forced model. The heat exchanger UA value is multiplied by 0.7 and the equivalent conductivity term is multiplied by 27 throughout the simulation. When this is done, collector and draw energy quantities match very well, but the collector flow rate is still underpredicted and the

Figure 10. Collector Inlet (Bottom) and Outlet (Top) Temperature vs. Time For Final Model.

Figure 11. Collector Flow Rate vs. Time For Final Model.

temperature rise is overpredicted (once again resulting in good agreement in integrated collector energy prediction). A final adjustment is made by reducing the total friction factor in the collector loop piping until the flow rate (and thus temperature rise) match. This requires that the friction factor be reduced by approximately 40 percent.

Figure 10 shows the collector inlet and outlet temperatures for the final model and the experiment. The profiles match within two degrees except at the start of the experiment and during the draw. Figure 11 shows the collector flow rate. Again the profiles match very well. Figure 12 shows the predicted and actual draw temperature profiles. The predicted temperatures in the profile have an RMS error of 1.9 degrees C compared to the original RMS error of 5.6 degrees C (Figure 5). The energy results are summarized in Table 1.

Figure 12. Draw Temperature vs. Volume Fraction For Final Model.

Table 1. Comparison of Integrated Energy Simulation Results for Indoor Test

	Experiment	Original Model	Adjusted Model	% Error Original Model	% Error Adjusted Model
Coll. Energy (kJ)	19626	21053	19828	+ 7	+ 1
Draw Energy (kJ)	7412	9503	7445	+ 28	+ 0.4

SIMULATION OF OUTDOOR TESTS

In an effort to test the robustness of the model with the adjusted parameters, the thermosyphon system was mounted on the outdoor testbed at SEAL and two one-day tests were conducted. The first test occurred on a very clear day and the second occurred on a partly cloudy day. A 420 second draw at a flow rate of approximately 0.2 liters per second was made sometime after noon and a complete three volume draw off was made later in the afternoon for each test. Horizontal radiation, ambient temperature, and tank inlet and outlet temperatures were recorded and used to construct TRNSYS input decks to simulate the outdoor experiments. The simulations were run with the adjusted model parameters and the unadjusted original parameters. Figures 13 and 14 show the experimental, unadjusted, and adjusted model results for the draw temperature profiles for both draws of the first test and Figures 15 and 16 show the same information for the second test. In all cases, the adjusted model greatly increases the accuracy of the temperature predictions and the integrated energy results. Table 2 summarizes the integrated energy results for the outdoor tests.

Figure 14. Draw Temperature vs. Volume Fraction For Long Draw of First Outdoor Test.

Figure 13. Draw Temperature vs. Volume Fraction For Short Draw of First Outdoor Test.

Figure 15. Draw Temperature vs. Volume Fraction For Short Draw of Second Outdoor Test.

Table 2. Comparison of Integrated Energy Results for Outdoor Tests

	Experiment	Original Model	Adjusted Model	% Error Original Model	% Error Adjusted Model
Test #1					
Short Draw Energy (kJ)	4551	7368	5371	+ 62	+ 18
Long Draw Energy (kJ)	26383	25042	26249	- 5	- 0.5
Test #2					
Short Draw Energy (kJ)	6534	8466	6140	+ 30	- 6
Long Draw Energy (kJ)	10774	8984	11030	- 17	+ 2

Figure 16. Draw Temperature vs. Volume Fraction For Long Draw of Second Outdoor Test.

CONCLUSIONS

The performance of the TRNSYS simulation model for a thermosyphon SDHW system with an integral tank/heat exchanger has been significantly improved by using systematic comparisons between model and experiment to identify and calibrate three model parameters. Before calibration, the collector useful energy, tank stratification, and draw energy are all overpredicted by the model. Integrated energy quantities and

temperature profile predictions improve greatly with a systematic multiple parameter adjustment of the model. Further, agreement between the calibrated model and two independent outdoor tests was improved.

The required reductions of about 30 percent in the heat exchanger UA value and 40 percent in the collector loop friction factor are physically realistic and justifiable based upon the uncertainty in their modeling. However, the required adjustment to the effective conductivity term is too large to be realistic and it is probable that other physical processes are occurring in the experiment that are not included in the model. Mixing of the fluid in the collector loop as it rises in the annulus of the heat exchanger and convective mixing of potable water in the tank may explain the observed reduction in stratification compared to the original model prediction.

In future testing of thermosyphon systems, experimental tests that disable one portion of the system would be beneficial in the modeling process. For example, forcing the closed loop flow rate and the heat exchanger inlet temperature experimentally would provide a data set with only the heat exchanger performance and tank stratification as parameters.

The general importance of this work lies in the logical progression of the procedure that is used. First, the inlet conditions to the collector are forced to examine the performance of the collector model and to adjust the heat exchanger to match experimental temperature data. Then, using a forced model, the tank water stratification is adjusted to match the experimental draw temperature profile. Finally, with no model forcing, the collector friction factor is adjusted to match experimental collector flow rate. By following this logical progression around the system, the model can be adjusted to match time dependent temperature profiles very well and the original indoor experimental integrated energy values to within one percent. Use of the adjusted parameters in two additional outdoor tests confirms that the adjusted model is significantly better at predicting system performance than the original model.

REFERENCES

- Bickford C., and Hittle, D. C., 1995, "Short Term Performance Comparisons Between A Solar Thermosyphon Water Heater and Two Numerical Models." *Proceedings of the 1995 International Solar Energy Conference*, March 19-24, Maui, Hawaii, pp 1079-1092.
- Burch, J. D., Wood, B. D., Huggins, J. C., and Thornton, J. W., 1993, "Simulation-Based Ratings for Solar Hot Water Systems," *Proceedings of the 1993 American Solar Energy Society Annual Conference*, Washington, DC, April 22-28, pp 316-321.
- Kenny, S. P., and Davidson J. H., 1994, "Design of A Multiple Lamp Large Scale Solar Simulator," *Proceedings of the 1994 International Solar Energy Conference*, March 27-30, San Francisco, California, pp 7-12.
- Klein, S. A., et al., 1992, "TRNSYS 13.1 Manual," University of Wisconsin-Madison Solar Energy Lab, Madison, WI.
- Morrison, G. L., 1994, "TRNSYS Extensions For Australian Solar Water Heating Systems (TRNAUS)," Report 1994/FMT/1. School of Mechanical and Manufacturing Engineering, University of New South Wales, Kensington, New South Wales, Australia.
- Morrison, G. L., and Braun, J. E., 1985 "System Modeling and Operation Characteristics of Thermosyphon Solar Water Heaters," *Solar Energy*, Vol. 34, No. 4-5, pp. 389-405.
- Morrison, G. L., and Ranatunga, D. B. J., 1980, "Transient Response of Thermosyphon Solar Collectors," *Solar Energy*, Vol. 24, pp. 55-61.
- SRCC, 1995, Solar Rating & Certification Corporation 1995 Directory of SRCC Certified Solar Collector and Water Heating System Ratings. Washington, D.C.

ADVANCED RESIDENTIAL SOLAR DOMESTIC HOT WATER (SDHW) SYSTEMS

This report is for October and November, 1995. Experimental tests are being conducted on three side by side systems: ASN, NEG and Thermodynamics.

Experimental Work

Continued performing normal operation tests and "continuous operation" tests on the three systems. A "normal operation" test allows the systems to function as per the manufacturer with three 20 gallon draws a day; at 8:00 a.m., noon, and 5 p.m. For "continuous operation" test the pumps on the systems are set to run 24 hours a day. This test is done with and without draws and with and without auxiliary heaters. These tests will enable us to isolate collector performance characteristics.

The manifold on the NEG collector was re-plumbed. Originally the two collector panels were plumbed to operate in series, they are now plumbed to operate in parallel. The Micro Motion flow meter was removed from the Thermo Dynamics natural convection line. Selected tests will be performed with the new configuration. The testing will not commence until spring; or until the weather is warm enough to not have to worry about the pipes freezing.

While analyzing the reduced data from previous tests, it was discovered that the Thermo Dynamics main solar storage tank was missing a "dip-tube." This was discovered by following the temperatures in the tanks during the draws, see the attached figures. A dip-tube was installed. The tests for Thermo Dynamics will be re-run. The performance characteristics of the heat exchanger and collector are not affected by the missing dip-tube, but overall system performance will be improved.

Work continues towards completion of my dissertation. The literature search is still in progress.

Optimization of Evacuated Tube Collectors

The installation and instrumentation of the NEG Sun Family collector with 8 ICS collector tubes and a stainless backplane reflector was completed. The instrumentation set-up is as described in the previous report. Initial tests have been performed with the following procedure.

- a • cover the collector
- b • flush water through the collector until $(T_{\text{coll,out}} - T_{\text{coll,in}}) < 1^{\circ}\text{C}$
- c • remove the cover
- d • collect energy for a number of hours
- e • cover the collector
- f • flush water through the collector until $(T_{\text{coll,out}} - T_{\text{coll,in}}) < 1^{\circ}\text{C}$
- g • Stop

Using the steps from the above procedure, the following equations have been derived. The collector's performance will be evaluated by measuring the change in capacitance of the collector, (ΔE_{coll}) , while the cover is removed (steps c through e). This is determined using equation 1. Q_u is the collector useful energy drawn off and Q_{loss} is the collector thermal losses to ambient

$$1) \quad \Delta E_{\text{coll}}|_c^e = Q_u|_e^g + \Delta E_{\text{coll}}|_c^g + Q_{\text{loss}}|_e^g$$

where:

$$2) \quad Q_u|_e^g = \int_e^g \dot{m}_{\text{coll}} c_p (T_{\text{coll,out}} - T_{\text{coll,in}}) dt$$

$$3) \quad \Delta E_{\text{coll}}|_c^g = M_{\text{coll}} c_p (T_{g,\text{avg}} - T_{c,\text{avg}})$$

$$4) \quad T_{c,\text{avg}} = \frac{(T_{\text{coll,out}} + T_{\text{coll,in}})|_c}{2}$$

$$5) \quad T_{g,\text{avg}} = \frac{(T_{\text{coll,out}} + T_{\text{coll,in}})|_g}{2}$$

$$6) \quad Q_{\text{loss}}|_e^g = UA_{\text{coll}} \int_e^g (T_{\text{coll,avg}} - T_{\infty}) dt$$

The average collector temperature in equation 6 is not an easy value to determine. Without the use of a thermocouple tree in each collector tube, an analytical approach is required. A first order approximation would be to assume a linear decrease in the collector temperature between steps 5 and 7.

Thermo System Temperatures, August 30, 1995

Thermo Auxiliary Tank Temperatures, August 30, 1995

Thermo Main Tank Temperatures, August 30, 1995

MANAGEMENT AND COORDINATION OF COLORADO STATE/DOE PROGRAM

Coordination of research activities continued on the three technical research tasks under the DOE grant, and accounts were maintained and updated. Financial and technical reports were submitted as required.

U. S. DEPARTMENT OF ENERGY
RECOMMENDATION FOR THE ANNOUNCEMENT AND DISTRIBUTION
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Disclosure
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PART I (DOE, DOE Contractors, Grantees, and Awardees complete)

A. Product/Report Data

1. (Award) Contract No. DE-FG36-95G010093

2. Title Developing, Testing, Evaluating and
Optimizing Solar Heating Systems

3. Product/Report Description

☒ a. Report (Complete all that apply)

(1) ☐ Print ☐ Nonprint (specify) _____

(2) ☐ Quarterly ☐ Semiannual ☐ Annual ☐ Final

☐ Topical ☐ Phase I ☐ Phase II

☒ Other (specify) Bimonthly Progress Report

Dates covered _____ thru _____

☐ b. Conference/Meeting/Presentation (Complete all that apply)

(1) ☐ Print ☐ Nonprint (specify) _____

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☐ c. Software—Additional forms are required. Follow instructions on the back of this form.

☐ d. Other (Provide complete description) _____

B. Patent Information

Yes No

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If yes, identify page numbers _____

☐ ☐ Has an invention disclosure been submitted?
If yes, identify the disclosure number and to whom it was submitted. Disclosure number _____
Submitted to _____

☐ ☐ Are there patent-related objections to the release of this STI product? If so, state the objections. _____

C. Contact (Person knowledgeable of content)

Name Dr. Douglas C. Hittle

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Position Director

Organization Solar Energy Applications Laboratory
Colorado State University

PART II (DOE/DOE Contractors complete/or as instructed by DOE contracting officer)

A. DOE Identifiers

1. Product/Report Nos. G0-10093-3

2. Funding Office(s) (NOTE: Essential data) Golden Field Ofc.

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☐ d. Translations of copyrighted material

☐ e. Small Business Innovation Research (SBIR)

☐ f. Commercializable information

☐ (1) Proprietary

☐ (2) Protected CRADA information

Release date _____ / _____ / _____

☐ (3) Other (explain) _____

☐ 4. Program Directed Special Handling (copy attached)

D. Releasing Official

A. Patent Clearance ("X" one)

☐ Has been submitted for DOE patent clearance

☐ DOE patent clearance has been granted

B. Released by

(Name) _____

(Signature) _____

(Phone) _____

(Date) _____