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TO DEVELOP A DYNAMIC MODEL OF A COLLECTOR LOOP FOR PURPOSE
OF IMPROVED CONTROL OF SOLAR HEATING AND COOLING

MASTER

Final Technical Report

By
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Work Performed Under Contract No. EG-77-S-02-4512

Drexel University
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U.S. Department of Energy

Solar Energy

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FINAL TECHNICAL REPORT

TO DEVELOP A DYNAMIC MODEL OF A COLLECTOR
LOOP FOR PURPOSE OF IMPROVED CONTROL OF
SOLAR HEATING AND COOLING

submitted by:

P.R. Herczfeld and R. Fischl

Contract EG-77-S-02-4512.M001

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1. INTRODUCTION

This report presents the work done on DOE Contract No. E-8-77-5-02-4512. This final report consists of two major parts: (a) TRNSYS program modifications (Section II) and (b) the development of a dynamic model of solar liquid flat plate collectors for control of the solar collector loop, (Section III). This section reviews the project objectives and gives a brief summary of the accomplishments.

A. Contract Objectives

The original objective of the proposed work was to evaluate the proportional flow control system employed in the RKL solar heating and cooling system supported under DOE's demonstration program. The RKL system uses a real-time computer control throughout the entire system and one of its special features is the proportional flow control (using a pinch valve) for the collection and distribution of solar energy. The scope of this work was to use the TRNSYS simulation computer program in evaluating the performance of the RKL system. The performance evaluation scheme is depicted in Fig. 1.1. Note that one of the goals was to compare and validate the performance using the TRNSYS simulation model with that obtained from the measured data. Since the RKL system was not built and since problems were encountered with using the TRNSYS program for control studies, the scope of the project has changed in the middle of the project. This change has been approved and encouraged by the DOE contract monitors and is summarized below.

The new objectives of the project are:

1. Assess the feasibility of using the TRNSYS computer code for control studies and modify it wherever possible.
2. Develop a new dynamic model of the solar collector which properly reflect the performance of the collector under transient conditions such as those encountered under on/off controller operation. In addition, study the sensitivity of the performance of this model to the various system parameters

Fig. 1.1: PERFORMANCE EVALUATION

such as collector time constants, flow rates, turn-on and turn-off temperature set points, solar insolation, etc.

This report summarizes the work done in meeting these objectives.

B. Summary of Accomplishments

The most important accomplishments of the work completed under this contract are :

1. Development of a number of modifications to the TRNSYS simulation code so as to make it suitable for control studies. The major accomplishment is the implementation of a new stable and accurate numerical integration method which improves the accuracy of the results obtain from TRNSYS when performing control studies (see Section II).
2. Development of a dynamic distributed parameter model of the solar collector loop which accurately describes the performance under control actions including such instabilities as cycling (see Sections II-A and III-B).
3. Performed an initial sensitivity study to determine the effect of the various system parameters (such as collector time constants, controller set points, etc.) on the pump cycling and energy collected (see Section III-C).

In addition work has been initiated to determine the optimal control strategy using the distributed parameter collector loop model. This work is concerned with establishing the best theoretical control strategy when considering the pump losses but neglecting the pump cycling phenomena. It is felt that this work will identify some of the critical theoretical and practical conditions which are needed for designing the optimal feedback controller.

Based on these accomplishments we presented six papers at various meetings (see Appendix A for a complete list of publications resulting from work sponsored under this contract).

II TRNSYS PROGRAM MODIFICATIONS

In order to evaluate the performance of the RKL solar system using the TRNSYS computer simulation program, the computer code had to be modified. The major problems encountered in using the TRNSYS code involve the inability of the existing code to simulate accurately the performance of solar system when the controller is active, specifically:

- (1) The inability of the predictor-corrector integration method to accurately predict the temperatures under load switching and/or mass flow rate changes.
 - (2) In order to simulate the RKL's flow control system, new component models had to be developed and some of the existing ones had to be modified.
- In the following a brief description of these modifications is given.

A. Numerical Integration Method Modification

The problem with TRNSYS' numerical integration routine is manifested in the inaccurate updating of temperatures, flows, etc. (although the relative errors were within the specified tolerance limits) when short term performance of the system is of interest (such as one or two days).

The numerical integration method used in the TRNSYS program is depicted in Fig. 2.1. The method is of the predictor-corrector type, using a forward Euler predictor and a trapezoidal corrector described by the following equations:

$$\begin{aligned}\text{Predictor: } T_m^{(0)} &= T_{m-1} + \Delta t \left. \frac{dT}{dt} \right|_{m-1} \\ \text{Corrector: } T_m^{(i)} &= T_{m-1} + \frac{\Delta t}{2} \left[\left. \frac{dT}{dt} \right|_{m-1} + \left. \frac{dT^{(i-1)}}{dt} \right|_m \right]\end{aligned}\tag{2-1}$$

where T is the temperature; Δt is the integration step; the subscript m denotes the current time step, t_m ; and the superscript i is the corrector iteration index.

One of the difficulties with this integration method is that at the point when the pump is turned on or off (i.e. the switching point) an inherent delay of Δt is introduced as shown in Fig. 2.2. This figure depicts the results of using Eq.(2-1) to solve the differential equation which simulates the operation of a solar tank to load loop, namely

$$\frac{dT}{dt} = \begin{cases} -10T + 2500 & 0 \leq t \leq .05 \text{ hrs.} \\ -30T + 2500 & .05 \text{ hrs.} \leq t \end{cases} \quad (2-2)$$

Two time steps $\Delta t = .01$ hrs. and $\Delta t = .005$ hrs. are considered. It should be noted that at the switching point (i.e. when a load is connected to the tank) the exact solution indicates that the temperature $T(t)$ starts to decay. On the other hand the TRNSYS solution continues to rise to the next time step (although the rate of rise is slower). Clearly, this yields erroneous temperature profiles and also fails to maintain the energy balance at each time step. Furthermore, in terms of control, it gives the wrong switching times as to when the pumps are turned on or off (if the pumps are controlled by the various temperatures sensors in the system). Similar effects are observed in the collector loop.

To correct this problem, we have studied various numerical integration method [1] and selected the Weighting - Factors (W.F.) method (which is a modified version of Brandon's methods) because it can be easily implemented in the TRNSYS algorithm. The W.F. predictor-corrector method, implemented in TRNSYS, is as follows:

Fig. 2.2: AN EXAMPLE OF SOLVING SYSTEM EQUATIONS.
TRASYS VS. BACKWARD EULER METHOD.

$$\text{Predictor: } T_m^{(0)}(k) = T_{m-1}(k)$$

$$\text{Corrector: } T_m^{(i)}(k) = T_{m-1}(k) + \Delta t \left\{ (1-W(k)) \left. \frac{dT(k)}{dt} \right|_m + W(k) \left. \frac{dT(k)}{dt} \right|_{m-1} \right\} \quad (2-3)$$

where $W(k)$ is a weighting factor given by

$$W(k) = \begin{cases} 0, & \text{when a discontinuous derivative is encountered} \\ 1/2, & \text{otherwise} \end{cases}$$

Note that the W.F. is a combination of the trapezoidal method and backward Euler's method. That is, when $W(k) = 0$ then the corrector of Eq.(2-3) is identical to that of the backward Euler method, and when $W(k) = 1/2$, then the corrector is identical to that of Eq.2-1. Hence, the W.F. method is attractive because its accuracy is similar to that of trapezoidal method and it can handle the discontinuous derivatives (which is the feature of the backward Euler method). A detailed analysis of the W.F. method has been reported in papers [1] which are included in Appendix A.

In order to incorporate the W.F. method into TRNSYS a detailed flow chart of the TRNSYS computer code Version 9.2 was made. This is given in Appendix B. The W.F. method was incorporated in subroutine SIMUL.

B. TRNSYS Component Modeling

In addition to the modifications to the TRNSYS numerical integration procedure various component models have been modified and new ones developed. Table 2.1 summarize these models while Appendix C gives the detailed component descriptions. The auxiliary heater (Type 6) has been modified so that it can deliver different rates of energy and thus take advantage of any off-peak energy utility rates. The rate of heat delivery is controlled by the on/off controller for off-peak energy utilization (Type 33). In addition, this controller (Type 33) manages the supply of energy from two storage tanks where one tank is dedicated to storing solar energy while the other is

Type No.	Name	Purpose
6	Modified Auxiliary Heater	Modified Type 6 Auxiliary heater for use with the new Off-Peak Energy Controller (Type 33).
30	Proportional Pump Controller	Controls the collector loop pump so that the flow rate is proportional to the collected energy.
33	Controller for Supplying load from two storage tanks and off-peak energy utilization	Designed to control the supply of the load from two storage tanks, i.e. solar tank and auxiliary tank. In addition it controls the charging of the auxiliary tank.

Table 2.1: SUMMARY OF TRNSYS COMPONENTS MODIFICATIONS

dedicated to store the auxiliary energy. The control strategy is design to supply the load from the solar tank as long as its temperature is above some set value and then switched over to the auxiliary storage tank. In addition the auxiliary storage is controlled to guarantee that there is sufficient back-up during a cloudy day which is based on an estimate of the heating load per day. This controller generates the control function to accomplish this via the auxiliary heater.

In order to evaluate the performance of the solar system operation under continuous flow control strategy, a proportional flow controller module was developed. This controller is designed to generate a control function for the pump so that the fluid flow is proportional to the rate of collected energy. This control function is also designed to take into account the pump losses and the maximum flow through the collector. That is, the pump is not turned on until some minimum energy is collected and if the collected energy exceeds some maximum value then the flow is constrained to its recommended maximum value.

III. DEVELOPMENT OF A DYNAMIC MODEL OF A COLLECTOR LOOP FOR SOLAR HEATING AND COOLING SYSTEM CONTROL.

A. Problem Definition

Control strategies are usually developed and evaluated by analytic and/or computer simulation techniques based on control models which must accurately reflect the behavior of real systems. A typical system is shown in Fig.3-1. Central to this setup is the solar energy system itself, consisting of the individual components (collector, load, storage, etc.) and their integration. The system is driven by external driving functions such as the solar flux and ambient temperature. The state of the system is monitored by sensors placed at key locations throughout the system. These measurements are used to evaluate the performance of the system and to actuate the controllers. The control strategy determines the controller actions (i.e. determines set points, flow rates, off-peak power utilization, etc.). The controllers execute the control strategy based on the measured state of the system.

The control model is used to simulate the behavior of the real system. For control studies it is imperative that the simulation accurately track the instantaneous performance of the real system including short term transients (such as cycling). Failure to do so results in improper control strategies.

In the control model the solar energy system components are represented by a set of equations describing the dynamic behavior of the components and their system integration. The system is driven by the disturbance functions, such as solar flux ambient temperature, which are entered as input data. The computer simulates the time evolution of the system under various control objectives which are then evaluated and synthesized into a comprehensive control strategy.

Fig. 3.1: CONTROL BLOCK DIAGRAM OF A SOLAR ENERGY SYSTEM

===== THERMAL
——— ELECTRICAL

Fig. 3.2: BLOCK DIAGRAM OF A SOLAR ENERGY SYSTEM.

Fig. 3.3: COLLECTOR LOOP

In order to study control problems by computer simulations it is important to recognize that any control modeling must depend on the following five items:

1. The model of the system;
2. The disturbance functions;
3. The measured state of the system;
4. The control objective; and
5. The simulation technique.

Each of these five items are discussed below.

1. Model of the System

By the model of the system is meant the characterization and mathematical description of the components of the system and their inter-connection. In general; one has to consider the entire system; from energy inputs to load, as shown in Fig. 3-2. The present report is limited to the collector loop shown in Fig. 3-3 and discussed in more detail below.

The liquid flat-plate collector can be described by distributed parameter [3], lumped (uniform-temperature) [4,5] and steady state (zero-capacitance) [6,7] models. Most control studies to date are based on a steady state collector model. The zero capacitance model does not describe the system accurately, in particular, it does not explain cycling and other related phenomenon associated with collector capacitance.

During the course of this work we considered a distributed parameter model.

$$W C_A \frac{\partial T_{fc}}{\partial t} = F_c W \{ (\tau \alpha)_c I - U_L (T_{fc} - T_a) \} - \dot{m}_c c_p \frac{\partial T_{fc}}{\partial x} \quad (3-1)$$

The normalized (with respect to length of collector tubing) form of eq.(3-1) is given:

$$\frac{\partial T_{fc}(\xi, t)}{\partial t} = (1-\gamma) \frac{1}{\tau_{fc}} [\alpha_c f(t) - (T_{fc}(\xi, t) - T_a(t))] + \gamma \frac{1}{\tau_{fc}} [\alpha_c f(t) - (T_{fc}(\xi, t) - T_a(t))] - \gamma \frac{1}{\tau_{tc}} \frac{\partial T_{fc}(\xi, t)}{\partial \xi} \quad (3-2)$$

The definition of the various coefficients appearing in Eqs. (3-1) and (3-2) are summarized in Table 3.1. T_{fc} is, of course, the fluid temperature in the collector and $f(t)$ and $T_a(t)$ are the climatic forcing functions due to solar radiation and ambient temperature, respectively. Finally γ , is a control function; $\gamma=1$ for flow condition and $\gamma=0$ for stagnant condition. Equation(3-2) is a baseline equation for the collector, together with the appropriate boundary conditions it describes the dynamics of the collector.

2. The Disturbance (or Forcing) Functions

The disturbance functions drive the system. They can be identified in this model as the solar flux, $I(t)$ (or $f(t)$) and the ambient temperature, $T_a(t)$. Both of these functions are stochastic in nature and their prediction in the short-term scale (0.1 hr. or less) is difficult. A useful, practical control strategy must take into consideration the stochastic nature of these forcing functions but must depend on the determination of the state of the system for the implementation of the control strategy. The report is limited to "clear sky" studies, where the solar flux is approximated by a sinusoidal function.

3. The Measured State of The System

Since the driving (disturbance) functions are non-deterministic, the control decisions have to be based on the determination of the state of the

SYMBOL	DESCRIPTION	UNITS	BASELINE VALUE
A_c	- Area of collector plate	m^2	2
C_A	- Lumped thermal capacitance of collector per unit area	$\frac{kJ}{^\circ C \cdot m^2}$	10.22
C_p	- Specific heat capacitance of fluid	$\frac{kJ}{kg \cdot ^\circ C}$	4.19
F'_c	- Collector geometry efficiency factor	—	.95
I_o	- Amplitude of the sinusoidal solar intensity	$\frac{kJ}{m^2 \cdot hr}$	3000
t_o	- Time of Sunrise	hr	6.0
ω	- Radian frequency of sinusoidal solar radiation	rad	.2618
I	- Magnitude of solar sinusoidal radiation	$\frac{kJ}{m^2 \cdot hr}$	—
U_L	- Overall heat loss coefficient of collector.	$\frac{kJ}{hr \cdot ^\circ C \cdot m^2}$	18.65
T_a	- Ambient temperature	$^\circ C$	0
$\dot{m}$	- Collector loop mass flow rate	kg/hr	227.19
W	- Collector width	m	1
γ	- Pump control variable $\gamma=0$ pump-off $\gamma=1$ pump-on	—	—
L	- Collector Length	m	2
$\xi = \frac{x}{L}$	- Normalized distance variable along the collector	—	—
$\tau_{fc} = \frac{C_c}{\dot{m} C_p}$	- System static time constant	hr	1.425
$(\tau\alpha)$	- Collector's transmittance absorbance product	—	.8281
$\sigma_c = \frac{I_o(\tau\alpha)}{U_L}$		—	133.2
$f(t) = \frac{\int_{t_o}^t I(t) dt}{I_o} = \cos \omega (t - t_o)$		—	—

TABLE 3.1: NOMENCLATURE AND BASELINE VALUES OF COEFFICIENTS IN EQNS. (3-1) and (3-2)

system. This is usually measured by temperature sensors placed at various key locations throughout the system. Since the controllers are actuated by the sensors, their accuracy in determining the state of the system is crucial.

4. Control Objectives

The control strategy is based on an optimization problem which determines the set-points and flow control.

- * Optimization. The system performance is optimized with a performance index which is defined in terms of energy collection, economic considerations, and/or stability.

- * Control Strategy. The Control Strategy dictates the mass flow-rate in the collector loop, $\dot{m}_c$, as a function of sensor outputs. In this report we consider only on/off controls, where the flow rate is binary, having a fixed value $\dot{m}_c^*$, or zero. Those values are dictated by the two control set points, T_{on} and T_{off} , at which the pumps turn on and off.

5. The Simulation Technique

The performance evaluation of the solar energy system requires computer simulation. Such a simulation program must be capable of solving accurately and efficiently the set of differential and algebraic equations describing the system model.

B. Analytic Solution

This section presents the analytic solution to Eq.(3-2). First it should be noted that when the pump in the collector loop is switched on ($\gamma=1$) or off ($\gamma=0$) the system undergoes a fundamental change. This change is reflected in the form of Eq.(3-2) which is different when $\gamma=1$ and when $\gamma=0$. The most important requirement for the solution is that it be continuous at all times and at all points around the loop under both flow ($\gamma=1$) and stagnant ($\gamma=0$) conditions. The initial and boundary conditions must be set up so as to ensure continuity under this sudden change (i.e. switching from $\gamma=0$ to 1 and vice versa). In the next paragraphs the solution as well as the use of initial and boundary conditions are discussed.

Note that the solution of Eq.(3-2) is given by $T_{fc}(\xi, t)$, which is the temperature profile at any time t . The initial condition represents the temperature profile at time $t=0$, which is given by

$$T_{fc}(\xi, 0) = A_1(\xi) \quad (3-3)$$

Although (3-3) is valid for either flow ($\gamma=1$) or stagnant ($\gamma=0$) condition, we assume that $t=0$ occurs at midnight so that the collector loop is under stagnant condition. Hence Eq.(3-3) is the initial condition when $\gamma=0$. Such a spatial temperature profile is illustrated in Fig. 3-4, which depicts various $T_{fc}(\xi, t)$ under stagnant conditions around the collector loop when neglecting the transport piping. In effect the storage temperature is considered to be constant at T_s and the temperature across the collector is also assumed to be isothermal. Note however that these temperatures will vary with the solar insolation (if any) incident on the collector. For example, the collector temperature at $t = t_1$ maybe greater than that at $t=0$ as shown in Fig. 3-4.

Fig. 3.4: TEMPERATURE IN COLLECTOR LOOP AS A FUNCTION OF SPACE AT $t=0$ AND $t=t_1$ with $\gamma=0$.

Let us now consider the boundary condition at the collector - storage interface. Under stagnant condition the collector and storage temperature can be substantially different, nevertheless, the physical conditions dictate that there must be a smooth transition across the interface. This implies that the temperature and its spatial derivative must be continuous over the boundary region as shown in Fig. 3-4. This can be written formally as

$$T_{fc}(\Delta \xi, t) = A_2(\Delta \xi, t) \quad (3-4)$$

where $\Delta \xi$ is the boundary region. By selecting $A_2(\Delta \xi)$ to be a third order polynomial in $\Delta \xi$ one obtains the desired smoothness across the boundary.

The solution of Eq.(3-2) in terms of generalized initial (3-3) and boundary (3-4) conditions is found by using Green's function techniques [2].

$$\begin{aligned} T_{fc}(\xi, t) = & \gamma_1 \{ F'(t) - e^{-\beta \xi} F'(t - \tau_{fc}) \} U(t - \tau_{tc}) \\ & + e^{-t/\tau'_{fc}} A_1(\xi - t/\tau_{tc}) U(\xi - t/\tau_{tc}) \\ & + e^{-\beta \xi} A_2(t - \tau_{tc}) U(t - \tau_{tc}) \\ & + (1 - \gamma_1) \{ F(t) + e^{-t/\tau_{fc}} A_1(0) \} \end{aligned} \quad (3-5)$$

where

$$\begin{aligned} \beta &= \tau_{tc} / \tau'_{fc} \\ F(t) &= \frac{1}{\tau_{fc}} \int_0^t [a_c f(\lambda) + T_R(\lambda)] e^{-\frac{-(t-\lambda)}{\tau_{fc}}} d\lambda \end{aligned} \quad (3-6)$$

Equation (3-5) describes the temperature in the collector loop as a function of time under either flow or stagnant condition. Note that τ_{tc} represents the time delay, namely the transit time of a slug of fluid from inlet to outlet of collector.

It is useful to examine Eq.(3-5) in somewhat more detail from the point of view of controller action. At $t=0$ we have the initial condition as discussed before. For $t>0$, the system is initially in no flow stage ($\gamma=0$), the collector is slowly warming up (see Fig. 3-4). If one observes the collector outlet temperature, $T_{co}(t) = T_{fc}(1,t)$, as a function of time, the temperature increases from pt. A to pt. B in Fig. 3-5. When $T_{co}(t)$ reaches the upper control set point ($T_{co} = T_{on}$), the pump turns on (i.e. $\gamma=1$). During this transient period, the solution is continuous and the inlet collector boundary condition propagates through the collector and arrives at the outlet ($\xi=1$) after a time delay τ_{tc} . If after this time delay T_{co} remains above the controller turn-off setpoint, T_{off} , then steady state will be reached. If however, T_{co} decreases below T_{off} then the pump turns off. During this off switching process care must be taken to preserve continuity. To do this, the temperature profile in the collector loop just prior to turn-off is noted and used as a new initial condition i.e. $A_1(\xi)$ in Eq.(3-5). This technique ensures continuity and smooth tracking of the temperature profile.

In summary, the solution, Eq.(3-5) is in the desired form:

- * It depends explicitly on the disturbance functions $f(t)$ and $T_a(t)$.
- * It is continuous at all times and all places under both stagnant and flow conditions.
- * It displays time delays, as expected.
- * It is suitable for control studies.

To perform a sensitivity analysis of the cycling phenomena and energy collection with respect to the system parameters and set points we have developed a simple computer simulation based on the above equation. This is discussed next.

Fig. 3.5: CHARACTERISTIC TIME PERIODS OF COLLECTOR OUTLET FLUID TEMPERATURE, $T_{co}(t)$.

C. Computer Simulation

1. General Discussion

In order to perform parametric studies of the dynamic collector model a computer simulation was developed. The simulation is based on Eq.(3-5), i.e. the solution to Eq.(3-2). As mentioned earlier, this study was limited to clear sky solar fluxes only so that the solar forcing function $f(t)$ of Eq.(3-6) can be written as

$$f(t) = \frac{I(t)}{I_0} = \sin \omega(t - t_0)$$

where

$$I_0 = 3000 \text{ Kj/hr} \cdot \text{m}^2$$

$$t_0 = \text{time of sunrise (hrs)} \quad (3-7)$$

$$\omega = 2\pi/24 \text{ (rad)}$$

In addition, we assume that the ambient temperature T_a is constant during the simulation. Under these two conditions, the disturbance function $F(t)$ of (3-6) can be written explicitly in terms of a transcendental algebraic expression.*

For control we are interested in the collector outlet temperature $T_{co}(t) = T_{fc}(1,t)$. The algebraic expression for $T_{co}(t)$ can be divided into three physically meaningful time periods, shown on Fig. 3-5, which are named: I initial warm up, II initial transient (delay) and cool-off time periods. The computer program is based on these three time periods which are discussed below.

i. Initial warm up period $t_0 \leq t \leq t_{on}$

This is the period in which the collector warms up under stagnant condition, ($\gamma_1 = 0$). The expression for $T_{co}(t)$ as obtained from Eq.(3-5) when $f(t)$ is given by Eq.(3-7).

* Note that if the ambient temperature is not constant but a known function of time, the integration of Eq.(3-6) can still be carried out.

$$T_{co}(t) = T_{fc}(1,t) * [T_i - T_a + b_1] \exp [-(t - t_o)/\tau_{fc}] \\ + \frac{b_1}{\omega \tau_{fc}} \sin[\omega(t - t_o) - \phi_1] + T_a \quad (3-8)$$

where

$$T_i = T_{co}(t_o) \\ b_1 = \frac{a_c \omega \tau_{fc}}{[1+(\omega \tau_{fc})^2]^{\frac{1}{2}}} \quad ; \quad \phi_1 = \tan^{-1}(\omega \tau_{fc})$$

Eq.(3-8) is valid in the time period ranging from t_o to t_{on} where t_{on} is the time when T_{co} reaches the turn-on set point T_{on} (i.e. $t = t_{on}$ when $T_{co} = T_{on}$).

The next two periods are under flow conditions.

ii. Initial transient - time delay $t_{on} \leq t \leq t_{on} + \tau_{tc}$

This is the time period which corresponds approximately to the time delay or transit time for a slug of water at the collector inlet to travel through the collector to the outlet. Since we are under flow condition, then, so that Eq.(3-5) yields .

$$T_{co}(t) = T_{fc}(1,t) = T_{on} - b_2 \sin[\omega(t_{on} - t_o) - \phi] \exp\left[-\frac{(t - t_{on})}{\tau_{fc}}\right] \\ + b_2 \sin[\omega(t - t_o) - \phi_2] + T_a \quad (3-9)$$

where*

$$b_2 = \frac{a_c}{[1+(\omega \tau_{fc}')^2]^{\frac{1}{2}}} \\ \phi_2 = \tan^{-1}(\omega \tau_{fc}')$$

* Note the τ_{fc}' denotes τ_{fc} under flow condition. The distinction is necessary because the effective collector capacitance is a function of flow.

iii. Cool-off Period

$$t > t_{on} + \tau_{tc}$$

During this time period colder fluid from storage passes through the collector cooling it off. If the collector output temperature falls below the control turn off temperature, T_{off} , the pump turns off and the sequence of the three successive time periods is repeated. This is cycling. If, however, the collector output temperature remains above T_{off} , steady state is attained and the pump remains on. The expression for the collector outlet temperature is given by:

$$T_{co}(t) = T_{fc}(1, t) = P(z) + T_s + b_3 \{ \sin[\omega(t - t_o) - \phi_3] - \exp[-(\tau_{tc}/\tau'_{fc})] \sin[\omega(t - t_o - \tau_{tc}) - \phi_3] \} \quad (3-10)$$

where

$$b_3 = \frac{\alpha}{\sqrt{1 + (\omega \tau'_{fc})^2}}$$

$$\phi_3 = \arctan(\omega \tau'_{fc})$$

The function $P(z)$ represents the effect of the boundary condition at the collector inlet which appears at $t = t_{on} + \tau_{tc}$ at the collector outlet. Recall that since the boundary condition has to be continuous, the function $P(z)$ matches the two solutions given by (3-9) and (3-10) at $t = t_{on} + \tau_{tc}$. This matching is achieved by a third order polynomial in time over an interval Δt_f (which is specified) starting at $t = t_{on} + \tau_{tc}$. Therefore the matching polynomial is given by

$$P(z) = \begin{cases} (T_{on} - T_s) \exp(-\tau_{tc}/\tau'_{fc}) (z^2(1-2z) + 1) & 0 \leq z \leq 1 \\ 0 & \text{otherwise} \end{cases} \quad (3-11)$$

where

$$z = \frac{t - (t_{on} + \tau_{tc})}{\Delta t_f} \quad (3-12)$$

If there is no cycling, then the simulation gives the steady state solution, i.e. Eq.(3-10) with $P(z) = 0$. If there is cycling, then the state of the system, i.e. $T_{fc}(t = t_{off}, \xi)$ becomes the initial condition, T_i , of the solution given by Eq.(3-8) for the initial warm-up period. Note that this preserves the continuity of the solution for all time.

In summary, the computer simulation evaluates either one of the three solutions given by Eqs.(3-8), (3-9) or (3-10) depending on which state the system is in.

2. Computer Program for Distributed Parameter Collector Model

A. Overview

This program is written for the express purpose of performing parametric sensitivity studies of the collector system performance with respect to the following parameters.

1) System Parameters

- a) System static ($\gamma=0$) time constant, τ_{fg} [hrs]
- b) System dynamic ($\gamma=1$) time constant τ_{tc} [hrs]

2) Control Parameters

- a) Pump turn-off temperature, T_{off} [$^{\circ}\text{C}$]
- b) Pump turn-on temperature, T_{on} [$^{\circ}\text{C}$]
- c) Collector fluid flow rate, $\dot{m}$ [kg/hr]

3) Climatic Parameters

- a) Peak solar insolation, I_0 [$\text{kJ}/\text{m}^2\text{-hr}$]
- b) Ambient temperature, T_a [$^{\circ}\text{C}$]

The computer code is set-up to model the system shown in Fig. (3-3). This system is comprised of a thermal collector, a pump controlled by a standard on/off controller, and a large storage. Note that the model neglects the transport piping. The large storage is modeled by maintaining the collector inlet fluid temperature at a constant value over the simulation. The collector is modeled by Eqns. (3-8), (3-9), and (3-10). The equations are used to compute the collector outlet fluid temperature, which in turn is used to evaluate system performance e.g. pump cycling and energy collected.

B. Program Description

The program written consists of a main routine and four subroutines. The four subroutines compute the collector outlet temperature $T_{co}(t)$, using Eqs. (3-8), (3-9) and (3-10). Each subroutine represents one of the characteristic time periods* discussed in section III-C-1. The main routine; (1) sets up the parameters for these equations; (2) turns the pump on and off [i.e., controls which subroutine is to be used to compute $T_{co}(t)$]; (3) computes the energy collected; (4) and prints the results.

A simplified flow chart of simulating program is shown in Fig. (3.6), a detailed explanation is given in Appendix (D). Starting at BLOCK A the program reads a set of constants and parameters**, $\underline{\phi}$, from a data file. This feature is provided as a convenience so that the data need not be manually entered each time. If it is desired to change this data, a provision is made in the code (see BLOCK B).

BLOCK C is concerned with setting up the parametric sensitivity study. If a sensitivity study is desired, then one must specify the parameters to be varied and the magnitude of their variation, viz. $\Delta\phi_i$.

BLOCK D depicts the evaluation of the coefficients of Eqs. (3-8), (3-9) and (3-10). Block E initialize time, t , to t_0 (hrs) i.e. the time of sunrise.

* Note that Equ (3-8) is valid for all stagnant conditions($\gamma=0$); however, the initial conditions differ depending upon the existance of pump cycling. Therefore, two subroutines are used for $\gamma=0$, one handles the initial warm up period, while the other handels warm up after each pump turn off.

** For brevity, the vector $\underline{\phi}$ represents the set of constants and parameters which specify the system under study.

FIG. 3.6: SIMPLIFIED PROGRAM FLOW CHART

At this point the simulation problem is set-up and is ready to compute the collector outlet temperature, $T_{co}(t)$.

BLOCK F decides which one of the characteristic time periods the system is in and selects which subroutine is to be used to compute $T_{co}(t)$. This is accomplished by comparing $T_{co}(t)$ to the two control set points T_{on} and T_{off} based on the pump, namely ($\gamma=1$) or ($\gamma=0$). BLOCK G computes $T_{co}(t)$ from eqns. (3-8), (3-9), or (3-10) depending upon the decision made in BLOCK F. This temperature is printed out (BLOCK H) and the energy supplied to storage is computed (BLOCK I) if the pump is running. Note that the computation performed in BLOCK F through BLOCK I represent the evaluation of $T_{co}(t)$ at time step t (hrs). This process is repeated by interactively incrementing time, t , by Δt until specified final time, t_{max} .

If a parametric study has been specified then the program automatically sets up a new set of parameters as depicted in BLOCK K. Note that for each new set of parameters the program will automatically give a new temperature profile over the time period t_0 (hrs) to t_{max} (hrs).

3. Program Results

Recall that the computer program output consists of the collector outlet temperature $T_{co}(t)$ and the energy collected at the desired time step. This output is summarized by generating figures similar to Fig.(3.7). This example, Fig.(3.7), represents the case when the system parameters values are set at their baseline values (see Table 3.1). The time period covered is from 6:00 a.m. which corresponds to sunrise (t_0), until 10:30 a.m. Clearly, the model and the computer code are capable of handling the entire day, but most of the important control problems occur during this time period.

In the following, the results shown in Fig.(3.7) are discussed in detail. The Curve labeled COLLECTOR OUTLET FLUID TEMPERATURE gives the instantaneous value of the collector output temperature $T_{co}(t)$ in °C as a function of time. There are three horizontal lines of significance. The one labeled STORAGE (at 40 °C) gives the temperature of the mixed storage tank, which is assumed to be constant with respect to time. (This assumption corresponds to a very large storage tank.) The remaining horizontal lines are labeled TURN-ON (at 45 °C) and TURN-OFF (at 42 °C). These are the upper and lower hysteresis temperatures of a standard on/ off thermostat which controls the pump. By observing the COLLECTOR OUTLET FLUID TEMPERATURE curve, we see that the pump first turns on when the collector outlet fluid temperature intersects the TURN-ON line, as expected. The three characteristic time periods discussed in Section III-C.1 (i.e., initial warm-up time delay and cooling-off periods)

Fig. 3.7: BASELINE SYSTEM PERFORMANCE

are observed. This particular run shows cycling which continues until steady state is attained, i.e., until the time at which the outlet fluid temperature at the end of the cool off period remains above the TURN-OFF curve. Recall that under clear sky conditions this condition will be met at sometime and no further cycling happens, i.e. steady state condition.

The curve labeled ENERGY COLLECTION RATE represents the energy collected within either each cycle or a specified time interval (0.1 hour) after steady state has been achieved. The curve label TOTAL ACCUMULATED Energy represents the total energy supplied to the storage upto the time.

In summary, we see from Fig. (3.7), that for this particular run a total of four pump cycles occurs between the time of first turn-on and steady state. A total of 4550 Kj of energy was supplied to the storage upto 10.5 hrs. Furthermore, it is interesting to note that energy is being collected during cycling.

Finally, it should be noted that for the sensitivity studies, similar curves to that discussed above are obtained for each parameter variation in order to accurately predict their effect on the cycling phenomena and energy collection.

D. Parametric Sensitivity Studies

1. General Discussion

Parametric sensitivity studies were performed using the digital computer program described in Section (III C-2). The coefficients in the equations used to compute the collector outlet fluid temperature are calculated from a set of parameters which are inputted into the program. Let this parameter set be denoted by the vector $\underline{\psi}$.

The components of the vector $\underline{\psi}$ belong to one of two subclasses of parameters; viz., those which are varied during the simulation study, denoted by the vector $\underline{\phi}$, and those which are maintained constant throughout the study, denoted by the vector $\underline{\xi}$. The vector of parameters varied, $\underline{\phi}$, is comprised of three types of parameters as shown below.

$$\underline{\phi} = \begin{cases} \underline{\phi}_c & \text{- Control Parameters} \\ \underline{\phi}_s & \text{- System Parameters} \\ \underline{\phi}_w & \text{- Climatic Parameters} \end{cases}$$

where

$$\underline{\phi}_c = \begin{cases} T_{\text{off}} & \text{- pump turn-off set-point (°C)} \\ T_{\text{on}} & \text{- pump turn-on set point (°C)} \\ \dot{m} & \text{- collector fluid flow rate (kg/hr)} \end{cases}$$

$$\underline{\phi}_s = \begin{cases} \tau_{tc} & \text{- system dynamic time constant when } \gamma=1 \\ \tau_{fc} & \text{- system static time constant when } \gamma=0 \end{cases}$$

$$\underline{\phi}_w = \begin{cases} I_0 & \text{- peak solar insolation (kJ/m}^2\text{-hr)} \\ T_a & \text{- ambient temperature (°C)} \end{cases}$$

The vector $\underline{\xi}$ is given by:

$$\underline{\xi} = \begin{cases} \omega & - \text{Radian frequency of solar insolation (rad)} \\ T_i & - \text{Initial temperature of collector (°C)} \\ t_o & - \text{Time of sunrise (hr)} \\ T_s & - \text{Mixed storage temperature (°C)} \\ \tau\alpha & - \text{Collector Transmittance absorptance product} \end{cases}$$

The parameter set vector $\underline{\psi}$ may be now expressed as:

$$\underline{\psi} = \begin{cases} \underline{\phi} & - \text{varied parameter vector} \\ \underline{\xi} & - \text{constant parameter vector} \end{cases}$$

The effect of variations in the components of the vector $\underline{\phi}$ upon system performance was evaluated in terms of two performance indices. The first performance index, J_1 , is the number of pump cyclings; J_2 , is the useful energy collected. Both J_1 and J_2 are function of $\underline{\psi}$. A performance index vector $\underline{J}$ is defined as:

$$\underline{J}(\underline{\phi}, \underline{\xi}) = \begin{cases} J_1(\underline{\phi}, \underline{\xi}) & - \text{Number of Pump Cycles} \\ J_2(\underline{\phi}, \underline{\xi}) & - \text{Collected Energy} \end{cases}$$

To facilitate the parametric sensitivity studies a base line system was defined for which

$$\underline{\psi}_0 = \begin{cases} \phi_0 \\ \xi_0 \end{cases}$$

where ϕ_0 and ξ_0 are given in Table 3.2 .

2. Results (Typical Sample Runs)

The sensitivity of the system performance was investigated by a systematic variation of each parameter in $\underline{\phi}$ about the base line system $\underline{\psi}_0$. This was accomplished by first obtaining the variation of the solar energy system performance in terms of the collector outlet temperature as

$$\underline{\phi}_0 = \begin{bmatrix} \phi_C^1 = 42^\circ\text{C} \\ \phi_C^2 = 45^\circ\text{C} \\ \phi_C^3 = 227.19 \text{ kg/hr} \\ \phi_S^1 = .0125 \text{ hr} \\ \phi_S^2 = 1.425 \\ \phi_W^1 = 3000 \text{ kj/m}^2\text{-hr} \\ \phi_W^2 = 0^\circ\text{C} \end{bmatrix}$$

$$\underline{\xi}_0 = \begin{bmatrix} \xi_1 = .2618 \\ \xi_2 = 0^\circ\text{C} \\ \xi_3 = 6.0 \text{ hr} \\ \xi_4 = 40^\circ\text{C} \\ \xi_5 = .8281 \end{bmatrix}$$

Table 3.2: BASELINE VALUES OF THE PARAMETER VECTOR $\underline{y}_0$.

a function of time for each parameter value. Samples of these results are shown in Figs.(3.8) to (3.25). Note that these figures are similar to those discussed in Section B , and they represent the results of variation in each and every parameter in ϕ . Based on these runs a set of graphs was developed to summarize the dependence of the pump cycling (J_1) and useful energy collected J_2 as a function of each parameter in ϕ . These curves are shown in figures. In the following paragraphs, we shall discuss the results shown in these figures, in terms of the three sets of parameters, namely the control, system, and climatic parameters:

(a.) Control Parameters - ϕ_c

The first control parameter investigated was the pump turn-off temperature set point T_{off} . As seen from Figs.(3.7), (3.8) and (3.9), as the turn-off set point approaches the storage temperature both performance indices, J_1 and J_2 greatly improve , i.e., the number of cyclings decreases and energy collection increases. A summary of a number of computer runs is synthesized in Figure 3.10 . This figure presents total accumulated energy (J_2) and the number of pump cyclings (J_1) as functions of the turn-off temperature set point. As the curves indicate both performance indices are extremely sensitive to even a slight variation in the turn-off set point.

The second parameter studied was the pump turn-on temperature set point, T_{on} . As the turn-on set point is increased both cycling and energy collected decreased as shown in Figures (3.7), (3.11) and (3.12) The reduction in cycling with increasing value of T_{on} is due to the fact that the first pump turn on time occurs at a later time, i.e., at a higher solar insolation level. However, the higher the turn-on set point results in a higher mean collector temperature during the stagnant warm-up period, thus increasing thermal losses which in turn reduces the collector efficiency and the energy collection.

Figure 3.8: RESULT OF VARIATION IN TURN OFF TEMPERATURE ($T_{off} = 41.7^{\circ}\text{C}$)

Figure 3.1: RESULT OF VARIATION IN TURN OFF TEMPERATURE ($T_{off} = 10.5^{\circ}\text{C}$)

Figure 3.10: TOTAL ENERGY AND NUMBER OF PUMP CYCLINGS AS A FUNCTION OF TURN OFF TEMPERATURE

Figure 3.11: RESULT OF VARIATION IN TURN ON TEMPERATURE ($T_{on} = 52.0^{\circ}\text{C}$)

Figure 3.12: RESULT OF VARIATION IN TURN ON TEMPERATURE ($T_{on} = 47.0^{\circ}\text{C}$)

Figure 3.13: TOTAL ENERGY AND NUMBER OF PUMP CYCLINGS AS A FUNCTION OF TURBINE TEMPERATURE

Figure(3.13),which summarizes these results, indicates that the pump cycling (J_1) is more sensitive to variations in the turn-on set point than the total accumulated energy (J_2). In general the effect of the turn-on set point upon cycling and energy collection was much less dramatic than that of the turn-off set point.

The third and final control parameter investigated was the collector fluid flow rate, $\dot{m}$. Typical results of the collector performance due to changes in flow rate are shown in Figures(3.7), (3.14)and (3.15).As seen from these figures cycling increases monotonically with flow rate while energy collection does not. This phenomenon is more clearly illustrated in the summary of results given in Figure (3.16).

At low flow rates there is no cycling but the collection efficiency is low. As the flow rate increases the collection efficiency improves since the collector mean temperature and therefore, thermal losses are lower. As the flow rate is increased above a certain value cycling begins which is accompanied by a reduction in the collector efficiency.

In summary the following statements can be made regarding the control parameter:

First, system performance depends on all three parameters: turn-off and turn-on set points and flow rate. Performance optimization with respect to only one of these parameters such as flow rate is meaningless!

The most critical control parameter with respect to both stability (cycling) and energy collection is the turn-off set point. It is clear that for best performance, this should be set to as close to the storage temperature as possible. The second most important control parameter is the flow rate. This value should be relatively high for good collection efficiency. Finally the turn-on set point should be set high to minimize cycling, although this leads to a modest decrease in collection efficiency.

Figure 3.14: RESULT OF VARIATION IN COLLECTOR FLUID FLOW RATE ($\dot{m} = 75.73 \text{ kg/hr}$)

Figure 3.15: RESULT OF VARIATION IN COLLECTOR FLUID FLOW RATE ($\dot{m} = 302.92 \text{ kg/hr}$)

Figure 3.16: TOTAL ENERGY AND NUMBER OF PUMP CYCLINGS AS A FUNCTION OF COLLECTOR FLUID FLOW RATE.

(b.) System Parameters - $\dot{Q}_s$

The first system parameter studied was τ_{fc} , the system static time constant. From figures (3.7), (3.17) and (3.18) it is seen that as τ_{fc} increases cycling substantially subsides, while the amount of useful energy collected is modestly decreased. This result is accounted for by the fact that τ_{fc} significantly changes the first pump turn-on time, while having little affect upon the steady state time (which is determined primarily by τ_{tc} , the system dynamic time constant). A summary is presented in Fig. (3.19)

It may be recalled that τ_{fc} is defined in terms of the collector capacitance C_c and overall heat loss coefficient U_L as given below:

$$\tau_{fc} = \frac{C_c}{U_{LC} F'} \quad (3-13)$$

It is seen that collectors with low thermal capacitances would have a tendency to cycle and therefore require a different control set points than collectors with higher capacitances. The effect of the overall thermal loss coefficient, U_L , on the control performance is the reverse.

Figure 3.17: RESULT OF VARIATION IN SYSTEM STATIC TIME CONSTANT ($\tau_{fc} = 1.625$ hr)

Figure 3.18: RESULT OF VARIATION IN SYSTEM STATIC TIME CONSTANT ($\tau_{fc} = 1.825$ hr)

Figure 3.19: TOTAL ENERGY AND NUMBER OF PUMP CYCLINGS AS A FUNCTION OF SYSTEM STATIC TIME CONSTANT

The second system parameter considered is, τ_{tc} , the dynamic system time constant. However, τ_{tc} , is also a control parameter since it depends on the flow rate:

$$\tau_{tc} = \frac{C_c A_c}{\dot{m}_c C_{pf}} \quad (3-14)$$

Thus, with appropriate change of variable, figures (3.7), (3.17) and (3.18) describe system performance with variation of τ_{tc} .

(C) Climatic Parameters

Finally the effects of changes in the climatic conditions upon the system performance were studied. The climatic changes investigated include system performance with different ambient temperatures and during uniformly hazy days (i.e., under variations in peak solar insolation)

Figures (3.7), (3.20) and (3.21) depict typical results for changes in ambient temperature. The results are summarized in Figure (3.22). It is seen that collected energy increases with increasing temperature. However, the pump cycling tends to increase when the difference between the ambient and storage temperature becomes very high, i.e. $|T_A - T_S| \gg 0$. The increase in cycling when $T_A \ll T_S$ is due to the increase in collector losses which result in reduced collector output temperatures. On the other hand, the increase in cycling with high ambient temperatures (i.e. $T_A \gg T_S$) is explained by considering the pump first turn-on time. With elevated ambient temperature, the static collector attains turn on temperature very early in the day when there is insufficient insolation to maintain the collector temperature above turn-off under flow conditions. Thus additional pump-cycling will occur during the early morning hours when the ambient temperature is significantly above the storage temperature.

The other climatic parameter considered was the peak solar insolation. Figures (3.7), (3.23) and (3.24) depict typical variations in this parameter. The results are straight-forward. It is seen that the larger the peak solar the better is the system performance. The results are summarized in Figure (3.25). It is seen that for even modest reductions in peak solar insolation there is a pronounced increase in cycling reduction of collected energy. Thus during even slightly hazy days system performance is appreciably decreased.

TEMPERATURE (°C)

Figure 3.21: RESULT OF VARIATION IN AMBIENT TEMPERATURE ($T_a = -15.0^\circ\text{C}$)

TEMPERATURE (°C)

FIGURE 3.21: RESULT OF VARIATION IN AMBIENT TEMPERATURE ($T_a = -5.0^\circ\text{C}$)

Figure 3.22:: TOTAL ENERGY AND NUMBER OF PUMP CYCLINGS AS A FUNCTION OF AMBIENT TEMPERATURE
3.4'

Figure 3.23: RESULT OF VARIATION IN PEAK SOLAR INSOLATION($I_o=2500 \text{ KJ/m}^2\text{-Hr}$)

Figure 3.24: RESULT OF VARIATION IN PEAK SOLAR INSOLATION ($I_o=3500 \text{ KJ/m}^2\text{-Hr}$)

Figure 3.25: TOTAL ENERGY AND NUMBER OF PUMP CYCLINGS AS A FUNCTION OF PEAK SOLAR INSOLATION

E. Optimal Control

This study is concerned with obtaining the optimal control strategy of the fluid flow rate in the solar collector loop. Specifically, the goal is to obtain the optimal control strategy of the distributed parameter model of Eq. (3.1) which maximizes the net energy collected (i.e. gross energy collected minus energy required to pump the fluid).

Recall that the studies reported in Section III-D are concerned with the cycling problem encountered when using an on/off feedback controller in the solar collector loop. In order to establish that such a controller structure is indeed the optimum controller in terms of maximizing the net energy collected, it is essential that one determine the optimum control strategy for the solar collector model of Eq. (3.1). This is the object of the study reported here.

Consider the collector model of Eq. (3.1), which is rewritten as

$$\frac{\partial T_{fc}(x,t)}{\partial t} + u(t) \frac{\partial T_{fc}(x,t)}{\partial x} + a T_{fc}(x,t) = v(t) \quad (3.30)$$

where

$$a = \frac{F_c U_L}{C_a}$$

$$v(t) = a \left\{ \frac{(T_a)}{U_L} I(t) + T_a(t) \right\}$$

$$u(t) = \left(\frac{C_p}{W C_A} \right) \dot{m}_c(t)$$

Note that in Eq. (3.30), $u(t)$ is the effective velocity of the fluid through the collector and is the control variable which is constrained by $0 \leq u(t) \leq M$, where M is the specified maximum effective fluid velocity dictated by the pump.

The optimum control problem which has been considered initially can be stated as follows:

Given $v(t)$, find the fluid velocity $u(t)$ which maximizes the net energy collected, given by

$$J(u) = \int_0^{t_f} c_p u(t) [T_{fc}(L,t) - T_{in}(t) - c] dt \quad (3.31)$$

subject to the state equation (3.30) and the constraints:

$$T_{fc}(0,t) = T_{in}(t) \quad , \quad 0 \leq t \leq t_f \quad (3.32)$$

$$T_{fc}(x,0) = T_o \quad , \quad 0 \leq x \leq L \quad (3.33)$$

$$0 \leq u(t) \leq M \quad , \quad 0 \leq t \leq t_f \quad (3.34)$$

where

$T_{in}(t)$ = specified collector inlet fluid temperature

T_o = specified constant initial fluid temperature
across the collector

t_f = final time (i.e. 24 hrs)

c = measure of the efficiency of the pump.

Note that this problem assumes that the inlet temperature, $T_{in}(t)$, is independent of the outlet temperature $T_f(L,t)$ i.e. the case encountered when the storage is large.

The solution of this problem states that the optimal control policy is one in which the fluid flow is instantly switched between zero and maximum flow, M . That is, the optimum policy is bang-bang where the switching times depend on a priori knowledge of the solar intensity $I(t)$ and ambient temperature $T_a(t)$ for each day.

One of the major findings of this work has been that the switching function^{*} for the open-loop bang-bang control can be decomposed into two terms* [7]:

- (i) A measurable quantity which depends on the states; and
 - (ii) A quantity which depends on the a priori knowledge of the daily weather.
- That is, the optimum switching function, $S(t)$, can be written as

$$S(t) = C_p [T_f(L,t) - T_{in}(t) - C] - D(t) \quad (3.35)$$

where $D(t)$ is the weather dependent function. It can be shown that this function is identically zero (i.e. $D(t) = 0$) when only two switches (i.e. one switch turns the pump on and the other turns it off) occur during the period $[0, t_f]$. Note that this situation occurs during a clear day but may not occur during periods of cloudiness.

Based on this result, a suboptimal on/off feedback-type controller which depends on the measurable states can be designed. This type of controller implements the switching function.

$$\hat{S}(t) = C_p [T_f(L,t) - T_{in}(t) - c] \quad (3.36)$$

It should be noted that this control policy is similar to that investigated in Section III-D. The difference is in the selection of the on and off set points T_{on} and T_{off} , respectively. Eq (3.36) states that

$$T_{on} = T_{off} = [T_{in}(t) - c] \quad (3.37)$$

In the studies performed in Section III-D, we assume that

$$\begin{aligned} T_{on} &= [T_{in}(t) - c] + \Delta T_1 \\ \text{and} \\ T_{off} &= [T_{in}(t) - c] - \Delta T_2 \end{aligned} \quad (3.38)$$

* See Appendix for a copy of Ref. [7].

where $T_{on} - T_{off} = (\Delta T_1 + \Delta T_2)$ represents the temperature hysteresis of the on/off controller.

In summary, it has been shown that the on/off controller used in the studies performed in Section III-D, is based on the optimal control policy obtained by solving the problem defined by Eqs. (3.31) - (3.34). The reason that this controller is optimal rather than suboptimal [see Eq. (3.36)] is that the parametric studies were performed for a clear day [see Eq.(3.7)], the case when only two switches occur per day. The switching due to the cycling phenomena (discussed in Sections III-C and III-D) are caused by the feedback structure of the controller which was not considered in solving the optimum control problem of Eqs. (3.31) - (3.34). This problem must be considered in the future work. In addition, work is needed to include the dynamics of the storage tank and the transport piping.

IV. CONCLUSION AND CONTINUATION

The work supported under this contract led to a number of important results as discussed below.

First of all a number of significant modifications of the existing TRNSYS program were implemented including a new numerical computation techniques. These modifications enable TRNSYS to be used as a tool for control studies.

Secondly a new dynamic collector model was developed. The collector loop is modeled as a distributed parameter system, represented by coupled partial differential equations which were solved analytically. The solution was used in the development of a simple computer code which was then utilized to evaluate the controller performance in terms of stability (cycling) and energy collection. A systematic variation of key parameters identified the most sensitive variables in terms of control.

The continuation work, presently being carried out, extends the work on the dynamic model to the entire loop to include the transport (piping) heat exchanges and storage.

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APPENDIX A

PUBLICATIONS:

1. Herczfeld, P.R.; Fischl, R.; Orbach, A.; "Optimizing Solar Energy Systems Using Continuous Flow-Control, "Published in the Proceeding of the I.S.E.S. Meeting, Delhi, India, 1977.
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OPTIMIZING SOLAR ENERGY SYSTEMS USING CONTINUOUS FLOW CONTROL

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The design and operation of solar heating and cooling systems involves two coupled, yet independently identifiable fundamental optimization problems. The first of these problems entertains the question: How should I design and build my system so that it will best satisfy my needs for the least cost? The second problem asks the question: How should I operate my system so that it will best satisfy my needs for the least cost?

This paper is concerned with the latter problem, namely the problem of designing control strategies in order to maximize the collection and utilization of solar energy. Specifically, the emphasis of this work is on the control of the heat transfer fluid flow in the solar energy system.

The heat collected by a flat plate liquid solar collector can be written as:

$$\dot{Q}(t) = c_p \dot{m} \Delta T_c = A \eta q_1(t)$$

where

- $\dot{m}$ = mass flow rate
- $\Delta T_c = T_o - T_i$ = rise temperature
- T_o = Collector output temperature
- T_i = Collector input temperature
- η = Instantaneous collector efficiency
- q_1 = Solar flux density

Presently, most existing solar energy systems use a constant flow rate with a binary (off/on) flow control:

$$\dot{m} = \begin{cases} 0 & \text{if } \Delta T_c < \Delta T_{c1} \\ \dot{m}_f & \text{if } \Delta T_c > \Delta T_{c2} \end{cases}$$

where $\Delta T_{c1} < \Delta T_{c2}$ are on and off set points, respectively, and $\dot{m}_f$ is a fixed flow rate. The time variation of the collected energy, $\dot{Q}(t)$, is reflected in the time variation of the temperature rise across the collectors $\Delta T_c(t)$. The control strategy requires the incorporation of the hysteresis algorithm for stability. The off/on control device is, for most cases, a simple thermostatic switch that turns the pump on and off.

The continuous flow control system is characterized by:

$$\dot{Q}(t) = c_p \dot{m}(t) \Delta T_c(t)$$

where the flow rate $\dot{m}(t)$, and the rise temperature, $\Delta T_c(t)$ are functions of time. The flow control strategy depends on the state of the system. The controller is either a modulating valve (as used in most process controlled industries) or a variable speed pump. A special case of the continuous flow control system is the proportional flow control system, where the flow rate, $\dot{m}(t)$, is controlled to give a constant temperature rise, $\Delta T_c = \Delta T_f$, so that $\dot{Q} = c_p \dot{m}(t) \Delta T_f$. This controller is a simple feedback controller using ΔT_f as a reference signal.

The performance of typical solar energy systems using off/on and continuous flow control strategies were simulated on a digital computer. The continuous flow control system showed a significantly improved performance over the off/on control system under identical conditions.

In heating applications the continuous flow control increases the time interval for . . . useful energy can be collected. The most significant

improvements in system performance due to flow control are in cooling applications. In the cooling mode, in addition to the quantity of collected thermal energy, one must also consider the quality of the energy, that is its temperature. To operate an absorption type air conditioner, a minimum generator input temperature is required, which in turn requires that the collector output temperature be high. In the continuous flow control mode the range of solar flux , q_1 , for which high grade energy can be collected and hence the absorption chiller can be operated is extended.

The continuous flow control device considerably reduces the hysteresis effects which tend to degrade the performance of the off/on system.

The design and operation of a solar heated and cooled manufacturing plant which utilizes real time computer control (continuous flow control) for the maximization of the collection and utilization of solar energy will be discussed.

CONTROL MODELING USING THE TRISYS PROGRAM

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Drexel University

Abstract

Introduction

```

graph TD
    FGL_SYSTEM[FGL SYSTEM] --- DATA_INTERFACE[DATA INTERFACE]
    FGL_SYSTEM --- DATA_STORAGE[DATA STORAGE]
    DATA_INTERFACE --- READER_TAPE[READER TAPE]
    DATA_INTERFACE --- TRUSSYS[TRUSSYS]
    TRUSSYS --- TRANSDUCER_EVALUATION[TRANSDUCER EVALUATION]
    DATA_STORAGE --- EVALUATION_EVALUATION[EVALUATION EVALUATION]
    TRANSDUCER_EVALUATION --- Q1_Q2_ETC1["Q1, Q2, etc"]
    EVALUATION_EVALUATION --- Q1_Q2_ETC2["Q1, Q2, etc"]
  
```

comparison (between the proportional and on/off controller) is to be made using real life operating data, one aspect of this project is the validation of the model as shown in Fig. 1. However, even though the various components of the system are valid, a major problem still exists; that is, to obtain accurate simulations of the system performance under various control strategies. This is the subject of this paper, namely, the inability of the TRNSYS program to simulate accurately the performance of the solar system under real time control situation. This problem was manifested in the inaccuracies introduced by the numerical integration routine, (i.e. inaccurate updating of the temperatures, flows, etc.), although the relative errors on these quantities were within the tolerance limits.

The numerical integration method used in the TENSYS program is depicted in Fig. 2. The

Figure 2: TINSYS CONFIGURATION FLOW CHART

method is of the predictor-corrector type, using a forward Euler predictor and a trapezoidal corrector described by the following equations:

$$\begin{aligned} \text{Predictor: } T_n^{(0)} &= T_{n-1} + \Delta t \left. \frac{dT}{dt} \right|_{n-1} \\ \text{Corrector: } T_n^{(i)} &= T_{n-1} + \frac{\Delta t}{2} \left[\left. \frac{dT}{dt} \right|_{n-1} + \left. \frac{dT}{dt} \right|_n^{(i-1)} \right] \end{aligned} \quad (1)$$

where T is the temperature; Δt is the integration step; the subscript n denotes the current time step, t_n ; and the superscript i is the corrector iteration index. One of the difficulties with this integration method is that at the point when the pump is turned on or off (i.e. the switching point) an inherent delay of Δt is introduced as shown in Fig. 3. This

Figure 3: EXAMPLE OF SOLAR SYSTEM EQUATION SIMULATION VIA TINSYS AND BACKWARD EULER METHOD.

figure depicts the results of using Eq. (1) to solve the differential equation which simulates the operation of a solar tank to load loop, namely

$$\frac{dT}{dt} = \begin{cases} -10T + 2500 & 0 \leq t \leq 0.05 \text{ hrs.} \\ -30T + 2500 & 0.05 \text{ hrs.} \leq t \end{cases} \quad (2)$$

Two time steps $\Delta t = 0.01$ hrs. and $\Delta t = 0.05$ hrs. are considered. It should be noted that at the switching point (i.e. when a load is connected to the tank) the exact solution indicates that the temperature $T(t)$ decays. On the other hand the TINSYS solution continues to rise to the next time step (although the rate of rise is slower). Clearly, this yields erroneous temperature profiles and also fails to maintain the energy balance at each time step. Furthermore, in terms of control, it gives the wrong switching times as to when the pumps are turned on or off (if the pumps are controlled by the various temperatures in the system). Similar effects are observed in the collector loop.

The system of differential equations encountered in solar system can be generally classified as stiff equations (i.e. equations have both "fast" and "slow" time constants). In general, the desired properties of the integration algorithm for such a system are:

- Algorithm should be A-stable in the sense of Dahlquist [3], i.e. the solution should converge to the steady-state value independent of the step size, Δt .
- An economical fixed step size should produce a stable output with reasonable errors.
- Fast modes should be simulated without oscillations as well as with stability.
- The algorithm should allow automatic integration with variable step size as a function (1) non-linearities, (2) discontinuities, (3) hard limits, (4) rate of change of forcing functions, (5) estimates of linear error.
- The algorithm should not require historical data.

The first two requirements eliminate most integration methods from consideration. Table I gives a number of numerical integration methods which are A-stable. Note that the forward Euler predictor of Eq. (1) is not A-stable.

All the methods shown are stable for any step size, provided that the real parts of the characteristic equation roots are negative, and the choice of step size, Δt , determines the accuracy of the solution, i.e. the maximum allowable truncation error. Dahlquist [3] shows that the trapezoidal method gives the best results in terms of accuracy. However, it encounters difficulties with stiff equations and when the derivatives are discontinuous as shown in Fig. 3 at the point of switching. On the otherhand, some methods (such as backward Euler's method) improve the solution at the discontinuities but reduce the accuracy of the solution for the same time step as shown in Fig. 3.

The evaluation of the numerical integration methods given in Table I considers the merits of these methods not only in terms of their A-stability and accuracy but also in terms of

Table 1. Evaluation of the Various Numerical Integration Methods Considered

METHOD	STABILITY	NATURE OF DIFF. EQUATIONS AND DISCONTINUITIES	ACCURACY	CONVERGENCE	COMPUTATION EFFORT	IMPLEMENTATION IN TRISYS
TRAPEZOIDAL RULE (4)	STABLE	POOR	VERY GOOD	FAST	RELATIVELY SMALL	EASY
CALAHAN'S METHOD (5)	STABLE	GOOD	FAIR	FAST	LARGE	DIFFICULT
BRANDEN'S METHOD (6)	STABLE	GOOD	VERY GOOD	RELATIVELY FAST	LARGE	DIFFICULT
WEIGHTING-FACTORS METHOD	STABLE	GOOD	VERY GOOD	RELATIVELY FAST	LARGE	RELATIVELY EASY
BACKWARD EULER METHOD	STABLE	GOOD	FAIR	SLOW	VERY LARGE	EASY

* - Modified Branden's method.

the computational effort, convergence and compatibility with the TRISYS computational algorithm. For example, both Calahan's semi-implicit method [5] and Branden's method [6] have the desirable properties discussed above and fast convergence rates, however, they are difficult to implement in the TRISYS computational algorithm.

This paper considers the Backward Euler and Weighting - Factors (W.F.) methods because they can be easily implemented in the TRISYS algorithm. The predictor corrector method, which is compatible with TRISYS, for each of these methods is as follows:

Backward Euler (Single-Step) integration method:

$$\text{Predictor: } T_m^{(0)}(k) = T_{m-1}(k) \quad (3)$$

$$\text{Corrector: } T_m^{(i)}(k) = T_{m-1}(k) + \Delta t \left. \frac{df(k)}{dt} \right|_{m-1}^{i-1}$$

Weighting - Factor (W.F.) integration method:

$$\text{Predictor: } T_m^{(0)}(k) = T_{m-1}(k) \quad (4)$$

$$\text{Corrector: } T_m^{(i)}(k) = T_{m-1}(k) + \Delta t \left\{ (1-W(k)) \left. \frac{df(k)}{dt} \right|_{m-1}^{i-1} + W(k) \left. \frac{df(k)}{dt} \right|_{m-1} \right\}$$

Where $W(k)$ is a weighting factor:

$$W(k) = \begin{cases} 0, & \text{when a discontinuous derivative is encountered} \\ 1/2, & \text{otherwise} \end{cases}$$

Note that the W.F. (which is a modified Branden's method) represents a combination of the trapezoidal method and backward Euler's method. That is, when $W(k) = 0$ then the corrector of Eq.(4) is identical to that of Eq.(3) and when $W(k) = 1/2$, then the corrector is identical to that of Eq.(1). Hence, the W.F. method is attractive because of its accuracy (which is similar to that of trapezoidal method) and its ability to handle the discontinuous derivatives (which is the feature of the backward Euler method). The method is relatively easy to implement in the TRISYS program.

Results and Discussions:

The results of using these integration rules are shown in Figs. 4-6. Figure 4 compares the performance of the three rules given by Eqs. (1), (3) and (4).

Note that the W.F. method is the "best" in terms of tracking the "exact" solution (by "exact" solution, we mean the analytic solution, evaluated at the two steps, of the differential equation given by Eq.(2)). A comparison table of the results is given in Table II, which shows the number of iterations for convergence

per time step and the percent of relative error defined by:

$$\text{relative error} \% = \frac{|T_{in}(k) - T_{in}^{\text{exact}}|}{|T_{in}^{\text{exact}}|} \cdot 100\%$$

Note that the W.F. method yields an error of less than 1%.

Figure 4: EXAMPLE OF SOLAR SYSTEM EQUATION SIMULATION VIA TRNSYS, BACKWARD-EULER METHOD AND WEIGHTING-FACTOR METHOD.

Fig. 5 gives an other example in which two switching conditions are encountered.

Figure 5: EXAMPLE OF SOLAR SYSTEM EQUATION UNDER TWO SWITCHING CONDITIONS:- SIMULATION VIA TRNSYS, BACKWARD EULER AND WEIGHTING-FACTOR METHOD.

Again, from Table III, the relative error of the W.F. method is less than 1% as compared to the other methods whose errors are only within 10%.

Table II. Comparison of the Numerical Integration Methods for the Example of Fig. 4.

TDL	EXACT SOLUTION	TRAPEZOIDAL METHOD			BACKWARD EULER			WEIGHTING-FACTOR METHOD		
		SOLUTION	REL. ERR. (%)	# OF ITERATIONS	SOLUTION	REL. ERR. (%)	# OF ITERATIONS	SOLUTION	REL. ERR. (%)	# OF ITERATIONS
0	0	0	0	5	0	0	5	0	0	5
0.01	23.79	23.81	.004	5	22.73	4.456	7	23.81	.004	6
0.02	45.31	45.31	.002	5	43.32	4.24	7	45.35	.005	6
0.03	64.79	64.84	.007	5	62.17	4.04	7	64.84	.007	6
0.04	82.02	82.08	.007	5	79.25	3.01	7	82.08	.007	6
0.05	98.37	98.43	.006	7	94.77	3.65	9	98.43	.006	9
0.06	94.47	103.2	9.17%	6	92.13	2.78	9	94.94	.5	7
0.07	91.51	97.91	6.91	6	92.10	1.61	9	91.97	.37	7
0.08	79.41	91.33	5.22	6	89.34	1.	9	89.68	.369	6
0.09	67.46	81.30	3.925	6	87.34	.39	6	88.67	.382	6
0.10	46.83	69.22	2.918	5	86.01	.325	6	86.80	.377	6
0.11	35.12	57.88	1.107	5	85.70	.14	6	85.80	.09	6
0.12	25.13	46.55	1.62	5	85.16	.012	6	85.25	.07	6
0.13	11.64	35.31	1.2	5	84.74	.059	6	84.32	.047	6
0.14	21.34	25.03	.659	5	84.01	.013	7	84.37	.035	6
0.15	44.85	81.73	.174	5	84.16	.015	7	84.10	.024	6

Table III. Comparison of the Numerical Integration Methods for the Example of Fig. 5.

TIME	TEMPERATURE	TRAPEZOIDAL RULE			BACKWARD EULER METHOD			WEIGHTING FACTOR METHOD		
		LOCATION	% OF TEMPERATURE ERROR	# OF ITERATIONS	LOCATION	% OF TEMPERATURE ERROR	# OF ITERATIONS	LOCATION	% OF TEMPERATURE ERROR	# OF ITERATIONS
0	0	0	0	1	0	0	1	0	0	1
0.01	33.79	33.81	.004	1	33.73	0.005	1	33.81	.004	1
0.02	45.31	45.35	.008	1	45.23	0.015	1	45.35	.008	1
0.03	61.79	61.84	.007	1	61.72	0.011	1	61.84	.007	1
0.04	82.47	82.48	.001	1	82.35	0.014	1	82.48	.001	1
0.05	98.37	98.43	.006	1	98.27	0.010	1	98.43	.006	1
0.06	94.47	100.1	5.725	6	93.33	1.222	3	94.95	.508	2
0.07	91.36	97.89	6.512	6	90.30	1.62	3	91.92	.571	2
0.08	89.41	91.33	2.12	4	88.54	1	3	89.63	.264	2
0.09	87.64	91.30	3.915	4	87.34	.592	3	87.87	.302	2
0.10	86.60	89.27	2.915	4	86.01	1.137	3	86.83	.328	2
0.11	102.23	96.05	6.05	5	101.30	.91	2	101.60	.626	2
0.12	116.27	110.79	4.8	5	114.10	1.26	2	115.67	.42	2
0.13	132.07	126.00	3.89	5	127.10	1.458	2	128.59	.403	2
0.14	148.33	136.00	3.27	5	135.30	1.557	2	140.10	.506	2
0.15	159.95	145.00	2.75	5	143.10	1.89	2	150.60	.732	2

Another important observation is the switching time. The examples of Figs. 4 and 5 consider the case when the switching times are given a priori (i.e. $t = .05$ hr. or $t = .1$ hr.). Note that in both the backward Euler and W.F. methods the time of switching is exactly as it is specified in contrast to the results obtained using the integration method of Eq. (1) which introduces a time delay equal to the time step, Δt , selected as shown in Fig. 3. This time delay is inherent in the method and can not be avoided. Furthermore, it introduces errors in the energy balance per each step following a switching condition. When using the methods of Eqs. (3) and (4) the energy balance is guaranteed at each time step. The only disadvantage of these methods is that they require more corrector integration steps for convergence.

When the on/off switching of the pump is controlled by the temperature (via a pump controller), then additional errors may be introduced. This is depicted in Fig. 6, which considers the case of the room load being supplied from a storage tank.

The room thermostat, which controls the load-loop pump, is set to turn the pump when $T_R \leq 68^\circ\text{F}$ and turn it off when $T_R \leq 70^\circ\text{F}$. It is noted from Fig. 6 and Table IV that the W.F. method is the only one which tracks the thermostat limits the best.

The method of Eq. (1) has a tendency to result in temperatures above the lower limit (in addition to not satisfying the energy balance). The errors in tracking by the W.F. methods are

due to the choice of the integration time step, since the time in which the temperature crosses the limits is not on integral value of the time step but some other value. This problem is also observed in the "exact" solution shown in fig. 6. This can only be rectified by introducing a variable time step feature.

Figure 6: EXAMPLE OF ROOM CONTROLLED TEMPERATURE; SIMULATION VIA TENSYS, BACKWARD EULER METHOD AND WEIGHTING-FACTOR METHOD.

Table IV. Comparison of the Numerical Integration Methods for the example of Fig. 6.

TIME	1/FCT METHOD	BACKWARD EULER	IMPLICIT EULER	WEIGHTING-FACTOR METHOD
.0	66.19	66.19	66.69	66.66
.01	61.22	61.31	65.09	61.33
.02	59.55	59.66	62.69	59.66
.03	57.32	57.44	63.61	57.44
.04	56.28	56.12	61.36	56.40
.05	55.16	55.41	59.16	55.29
.06	54.29	54.44	57.55	54.01
.07	53.36	54.37	55.35	53.32
.08	52.53	53.16	53.15	52.51
.09	51.43	52.37	51.17	51.36
.10	50.91	51.64	51.12	50.55
.11	50.29	50.79	47.51	49.44
.12	49.51	50.10	51.16	49.16
.13	48.81	51.17	50.46	48.47
.14	48.13	50.15	47.76	47.79
.15	47.45	49.76	49.67	47.30

Conclusion

Both the Weighting-Factor method and the Backward Euler method were tried in the TRISYS computation algorithm. Although the Backward Euler method is easier to implement it was found to be less accurate and requiring more computation time (i.e., iterations) to converge at each time step. The W.F. method has been implemented in our TRISYS program (Version 8.2) and has been used to simulate various solar systems. The result gives a significant improvement in the performance of the program (in terms of convergence during control switching actions)

and the accuracy of the computed values (i.e., excellent temperature tracking and energy balance at each time step). The future work is devoted to incorporate a variable time step scheme into the W.F. method so as to improve the temperature tracking encountered where control switching is activated by the states of the system such as ΔT_c .

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STUDY OF PUMP CYCLING IN THE CONTROL
OF SOLAR HEATING & COOLING SYSTEMS

CONTRACT # E-8-77-5-02-4512

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One of the more serious problems in the control of solar heating and cooling systems is cycling which reduces the collection efficiency and the lifetime of pumps, valves, etc. [1]. The purpose of this paper is to present the results of an analytic study that relates cycling to various system parameters such as flow rate, sensor position, collector capacitance, length of transport system, etc.

The dynamic model of the collector loop, shown in fig. 1, consists of a collector subsystem with capacitance, two transport subsystems to and from the storage, and a stratified storage. The model is described in terms of the four coupled, inhomogeneous partial differential equations given below:

1. collector (distributed parameter model)

$$\begin{aligned} W_c [C_{co} (1 - \gamma_1) + C_c \gamma_1] \frac{\partial T_{fc}(x,t)}{\partial t} = \\ W_c [F'_{co} (1 - \gamma_1) + F'_c \gamma_1] [(\alpha)_c I(t) - \\ - U_{lc} (T_{fc}(x,t) - T_a)] - \gamma_1 A_c c_p \frac{\partial T_{fc}(x,t)}{\partial x} \end{aligned} \quad (1)$$

2. transport 1 (from collector to storage)

$$\begin{aligned} W_{t1} [C_{to1} (1 - \gamma_1) + C_{t1} \gamma_1] \frac{\partial T_{ft1}(y_1,t)}{\partial t} = \\ W_{t1} [F'_{to1} (1 - \gamma_1) + F'_{t1} \gamma_1] [(\alpha)_{t1} I(t) \end{aligned}$$

(2)

3. transport 2 (from storage to collector)

$$\begin{aligned} W_{t2} [C_{to2} (1 - \gamma_1) + C_{t2} \gamma_1] \frac{\partial T_{ft2}(y_2,t)}{\partial t} = \\ W_{t2} [F'_{to2} (1 - \gamma_1) + F'_{t2} \gamma_1] [(\alpha)_{t2} I(t) \\ - U_{lt2} (T_{ft2} - T_a)] - \gamma_1 A_c c_p \frac{\partial T_{ft2}(y_2,t)}{\partial y_2} \end{aligned} \quad (3)$$

4. storage (stratified)

$$\begin{aligned} W_s c_p \frac{\partial T_s}{\partial t} = \gamma_1 A_c c_p (T_{ft1}(L_1,t) - T_{sl}) \\ - \gamma_2 A_L c_p (T_{su} - T_{sl}) - U_{LS} A_s (T_s - T_a) \end{aligned} \quad (4)$$

Figure 1: Solar Collector Loop with Transport.

In equations (1) - (4), y_i is the pump control indicator (i.e. $y_1 = 1$ - pump on; $y_1 = 0$ - pump off). It is convenient to normalize the coordinates along the fluid flow by letting

$$\xi = \frac{x}{L}, \quad \eta_1 = \frac{y_1}{L_1} \quad \text{and} \quad \eta_2 = \frac{y_2}{L_2}$$

Equations (1) - (4) can now be written in the following form:

$$\begin{aligned} \frac{\partial T_c(\xi, t)}{\partial t} &= (1 - \gamma_1) \frac{1}{\tau_{fc}} [a_c f(t) - (T_{fc} - T_a)] \\ &+ \gamma_1 \frac{1}{\tau_{fc}} [a_c f(t) - (T_{fc} - T_a)] - \gamma_1 \frac{1}{\tau_{tc}} \frac{\partial T_c}{\partial \xi} \end{aligned} \quad (5)$$

$$\begin{aligned} \frac{\partial T_{t1}(\eta_1, t)}{\partial t} &= (1 - \gamma_1) \frac{1}{\tau_{t1}} [a_{t1} f(t) - (T_{t1} - T_a)] \\ &+ \gamma_1 \frac{1}{\tau_{t1}} [a_{t1} f(t) - (T_{t1} - T_a)] - \gamma_1 \frac{1}{\tau_{t1}} \frac{\partial T_{t1}}{\partial \eta_1} \end{aligned} \quad (6)$$

$$\begin{aligned} \frac{\partial T_{t2}(\eta_2, t)}{\partial t} &= (1 - \gamma_1) \frac{1}{\tau_{t2}} [a_{t2} f(t) - (T_{t2} - T_a)] \\ &+ \gamma_1 \frac{1}{\tau_{t2}} [a_{t2} f(t) - (T_{t2} - T_a)] - \gamma_1 \frac{1}{\tau_{t2}} \frac{\partial T_{t2}}{\partial \eta_2} \end{aligned} \quad (7)$$

$$\begin{aligned} \frac{\partial T_s}{\partial t} &= \frac{\gamma_1}{\tau_{s1}} (T_{t1}(1, t) - T_{s1}) + \gamma_2 \frac{1}{\tau_{s2}} (T_{t2} - T_{s2}) \\ &- \frac{1}{\tau_{s1}} (T_s - T_a) \end{aligned} \quad (8)$$

The various time constants (τ 's) are defined in Table I and can be either calculated or measured for a particular system. The form of the partial differential equations describing the collector and the transport is similar, which is helpful in obtaining a solution. It is to be noted, however, that the magnitudes of the corresponding coefficients are vastly different.

The boundary and initial conditions are defined such that they ensure that the solution will be continuous at every point in the collector loop at all times under both stagnant ($y_i = 0$) and pumped conditions. Because the partial differential equations are coupled through the boundary conditions they have to be treated with extreme care, especially under stagnant condition.

Equations (5)-(8) and the associated boundary and initial conditions represent the dynamic model of the collector loop. The task is to obtain an expression for the fluid temperature in the collector loop as a function of time and space. To this end these partial differential equations were solved analytically using standard Green's function or similar techniques with the solar radiation and ambient temperature as forcing functions. The solution, in general, is quite elaborate. However, a relatively easy closed form solution exists for the case of large, mixed storage subsystem. In principle this solution could be incorporated into existing simulation models such as TRNSYS.

Table 1. Characteristic Time Constants of the Dynamic Collector Loop Model.

UNIT	TIME CONSTANTS
COLLECTOR	$\tau_{fc} = \frac{C_{co}}{U_{LC} F_{co}} ; \quad \tau_{tc} = \frac{C_{co}}{U_{LC} F_{tc}} ; \quad \tau_{sc} = \frac{C_{co} A_c}{h_c c_p}$
TRANSPORT	$\tau_{t1} = \frac{C_{t1}}{U_{L1} F_{t1}} ; \quad \tau_{t2} = \frac{C_{t2}}{U_{L2} F_{t2}} ; \quad \tau_{st} = \frac{C_{t1} A_{t1}}{h_c c_p}$ $i=1,2$
STORAGE	$\tau_{s1} = \frac{M_s}{h_c} ; \quad \tau_{s2} = \frac{M_s}{h_s} ; \quad \tau_{st} = \frac{M_s c_p}{U_{LS} A_s}$

is an example for the limiting case of a very short transport system, the variation of the fluid temperature in the collector loop with space and time is given by eq. (9).

$$T_{fc}(t, z) = T_1(F(t) - \frac{\tau_{fc}}{t} F(t - \tau_{fc}) U(t - \tau_{fc})) + \frac{\tau_{fc}}{t} A_1(t - \tau_{fc}) U(t - \tau_{fc}) - \frac{\tau_{fc}}{t} A_2(t - \tau_{fc}) U(t - \tau_{fc}) + (1 - \tau_{fc})(F(t) + \frac{\tau_{fc}}{t} A_1(t)) \quad (9)$$

where

$$F(t) = \frac{1}{\tau_{fc}} \int_0^t \{a_c F(\lambda) + T_a(\lambda)\} e^{-\frac{(t-\lambda)}{\tau_{fc}}} d\lambda$$

In the above equation $F^*(t)$ is the same as $F(t)$ with τ_{fc} replaced by τ_{fc}^* , $A_1(t, 0)$ is the initial condition, $A_2(t) = T_{fc}(0, t)$ is the boundary condition, and $U(\cdot)$ is the unit step function.

A preliminary parametric study of this equation as a function of the various time constants was carried out on a digital computer. The results of this study properly reflect cycling as it is observed experimentally [2].

Since the complete solution is a function of both time and space, the control can be related to sensor location. In fact, it was found that cycling depends critically on sensor location. If, for example, the temperature sensors used in the control are located at the bottom of the storage tank and at the output of the collector, then the following three characteristic time periods can be distinguished during cycling: i) During the first time period when the sun is rising, the pump is off and the capacity of the collector loop (particularly the collector) is "charged," i.e., the fluid temperature in the collector rises towards the upper control set-point T_1 (i.e., the pump turn-on temperature). ii) During the second period the pump is on and the collector output temperature continues to rise above T_1 . The time duration of this period is equal to the delay time of the system, τ_{tc} . iii) During the third time period, the collector output temperature rapidly decays and capacity is "discharged." When the temperature drops below the lower control set-point T_2 (i.e., the pump turn-off temperature), the pump turns off and the cycle repeats. If the temperature does not drop below T_2 the pump remains on and the "steady state" is reached.

Cycling, it was found, depends on the time delay in the response of the system, τ_{tc} . The delay in turn is a function of flow rate. Cycling phenomena at two different flow rates, i.e. at two different time delays are shown in Fig. 2.

Fig. 1a

$T_1 = 38^\circ\text{C}$ $T_2 = 25^\circ\text{C}$ $T_{cl} = 32^\circ\text{C}$ $\tau_{fc} = 2.5$ hr

$\tau_{tc} = 0.075$ hr, steady state (s.s) reached at 9.25; (b) $\tau_{tc} = 0.091$ hr, steady state reached at 9.15.

Fig. 1b

Fig. 2: Cycling During Warm-up For a Clear Day At Two Different Flow Rates.

The analytic study provides a basis for a sensitivity study of the cycling process which is presently in progress. This study relates cycling to:

- i. System parameters (capacitance of collector, length of transport, etc.)
- ii. System time constant and delays
- iii. Sensor location
- iv. Climatic variations (solar flux, etc.)
- v. Control strategy (set points, flow rates, etc.)

The results of this on-going work will be published in the near future.

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NOMENCLATURE

T_{fc}	Temperature of fluid in the collector
T_{ft_1}	Temperature of fluid in transport
T_{su}	Temperature of fluid in the upper section of stratified storage
T_{sm}	Temperature of fluid in the middle section of stratified storage
T_{sl}	Temperature of fluid in the lower section of stratified storage
T_s	Temperature of mixed storage, (average storage temperature)
T_1	Upper control set-point (when pump turns on) $T_1 = T_1(T_{sl})$
T_2	Lower control set-point (when pump turns off) $T_2 = T_2(T_{sl})$
T_a	Ambient temperature
T_{slo}	Temperature of fluid from load to bottom of stratified storage
$I(t)$	Solar flux on collector surface
I_0	Maximum solar flux on collector surface
$f(t) = I(t)/I_0$	Normalized solar flux
x	Distance along collector tubing
y_i	Distance along transport piping
L	Length of tubing in collector
L_i	Length of piping in transports
C_c, C_{t_i}	lumped capacitances per unit area of collector, transports--flow condition
C_{co}, C_{to_i}	lumped capacitances per unit area of collector, transports--stagnant conditions

A_c, A_{t_1}, A_s	Surface areas of collectors, transports and storage
U_{lc}, U_{lt_1}, U_{ls}	Heat loss coefficients of collector, transports and storage per unit area
M_s	Mass of storage
$\dot{m}_c, \dot{m}_L$	Mass flow rates in collector and load loops
$(\tau\alpha)_c, (\tau\alpha)_t$	Transmittance-absorptance product of collector and transport
a_i	Fraction of A_{t_1} that is illuminated by the solar flux
c_p	Specific heat of fluid
W_c, W_{t_1}	Width of collector and transports
F_{co}^i, F_c^i	Collector geometry efficiency factors (pump off and on)
F_{to1}^i, F_{t1}^i	Transport geometry efficiency factors (pump off and on)
γ_1, γ_2	Control indicator for collector and load loops
t	time

$$\eta_c = \frac{I_o(\tau\alpha)_c}{U_{lc}} \quad ; \quad \eta_{t_1} = \frac{I_o(\tau\alpha)t_1 a_i}{U_{lt_1}}$$

FLOW CONTROL IN SOLAR HEATING AND COOLING APPLICATIONS

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ABSTRACT

This paper concerns itself with flow control in solar heating and cooling applications. A steady state and dynamic distributed parameter model is defined for the collector loop consisting of storage, collector and transport (piping) subsystems. It is shown that the steady state model of the collector does not reflect the true performance of the solar energy system, in particular it does not explain pump cycling. The analytic solution that was obtained for the dynamic model of the collector loop does predict cycling and in general corresponds to the true behavior of the collector loop dynamics. The sensitivity of cycling to system parameters such as flow rate, collector capacitance and sensor position is discussed.

1. INTRODUCTION

The control systems in solar heating and cooling applications perform multiple tasks. The control of the flow being one of the most important assignments of the control system. In solar applications the expression "flow control" usually refers to the control of the liquid flow in the collector loop. In terms of the flow control problem, the solar energy system can be represented by the control system shown in Fig. 1, where the controlled input is the mass flow rate, $\dot{m}_c(t)$, and the measurable outputs are the various temperatures T_a , T_{co} , ΔT_c . The other inputs which affect the system performance are functions of climate, load and auxiliary inputs. The solar system flow control problem is the problem of synthesizing an optimal controller; i.e., the problem of finding the "best" flow control strategy for the system which maximizes the collection of usable solar energy. If the structure of the controller is not specified, then this problem can be viewed as a classical optimal control problem in which the optimal control strategy minimizes some performance index. If the controller structure is specified (such as the feedback controller), then the problem is concerned with selecting the "best" set points. In either case, the effectiveness of the resulting control strategy depends on how well the collector loop dynamics have been modeled in developing the control strategy.

Fig. 1: Block Diagram of Flow Control System.

When considering various control strategies, it is imperative to keep in sight the practical aspect of the problem, namely, the control strategy has to be implementable, cost-effective and reliable. It is significant to observe that a recent study [1] of the control system performance of commercial demonstration projects have shown that the single most important problem with on/off controllers is pump cycling during start up or low solar insolation, yet this important problem has been ignored by most control studies to date. The purpose of this paper is to reexamine the general control problem for solar heating and cooling applications (such as pump cycling) in terms of the collector loop modeling.

2. CONTROL MODELING

Control models are usually developed and evaluated by analytic and/or computer simulation techniques. In order to study the flow control problem, it is important to recognize that any control strategy must depend on the following four interrelated but separate items:

- The model of the system;
- The disturbance functions;
- The measured states of the system; and
- The control objective.

Each of these four items are discussed below.

a. Model of the System

by the model of the system is meant the characterization and mathematical description of the components of the system and their interconnection. In general, one has to consider the entire system, from energy inputs to load, however, in this paper we shall limit ourselves to the collector loop as shown in Fig. 2.

Fig. 2: Solar Collector Loop with Transport.

The collector loop consists of the storage, collector and mass transport subsystems.

(1) Storage. There are a number of different ways to model the storage subsystem, such as the distributed parameter [2], finite element or stratified [3] and mixed [3] models. In this paper the stratified model will be used:

$$\begin{aligned} \frac{H}{N} c_p \frac{dT_i}{dt} = & \alpha_i \dot{m}_c c_p (T_{co} - T_i) + \delta_i \dot{m}_L c_p (T_L - T_i) \\ & + \gamma_i \dot{m}_c c_p (T_{i-1} - T_i) - \delta_i \dot{m}_L c_p (T_i - T_{i+1}) \\ & + \frac{U_L P}{N} (T_{env} - T_i) \end{aligned} \quad (1)$$

where

$$\alpha_i = \begin{cases} 1 & \text{if } T_{i-1} > T_c > T_i \\ 0 & \text{otherwise} \end{cases}; \quad \delta_i = \begin{cases} 1 & \text{if } T_i > T_L > T_{i+1} \\ 0 & \text{otherwise} \end{cases}$$

$$\gamma_i = \begin{cases} 1 & \text{if } T_{i-1} > T_c > T_i \\ 0 & \text{otherwise} \end{cases}; \quad \delta_i = \begin{cases} 1 & \text{if } T_i > T_L > T_{i+1} \\ 0 & \text{otherwise} \end{cases}$$

(2) Collector. The liquid flat-plate collector can be described by distributed parameter [4], lumped (uniform-temperature) [4,5] and steady state (zero-capacitance) [6-7] models. In this paper both the distributed parameter and steady state models will be considered.

(i) distributed parameter model:

$$W c_A \frac{\partial T_f}{\partial t} = F_c' W [I(t) - U_L (T_f - T_a)] - \dot{m}_c c_p \frac{\partial T_f}{\partial x} \quad (2)$$

(ii) steady state model:

$$\begin{aligned} \dot{Q}_a &= \dot{m}_c c_p (T_{co} - T_{ci}) = F_c' A_c [I(t) - U_L (T_m - T_a)] \\ &= F_R A_c [I(t) - U_L (T_{ci} - T_a)] \end{aligned} \quad (3)$$

(3) Transport. The piping between the collector and the storage can be thought of as a very poor collector and can be modeled accordingly.*

(i) distributed parameter model:

$$W_p c_p \frac{\partial T_p}{\partial t} = F_p' W_p [I(t) - U_L (T_p - T_a)] - \dot{m}_c c_p \frac{\partial T_p}{\partial x} \quad (4)$$

(ii) steady state model

$$\dot{m}_c c_p (T_{po} - T_{pi}) = U_L A_p (T_{pi} - T_a) \quad (5)$$

b. The Disturbance (or Forcing) Functions

The disturbance functions drive the system; they can be identified in this model as the solar flux, $I(t)$, the ambient temperature, $T_a(t)$ and the load, $\dot{Q}_L(t)$. All three of these functions are stochastic in nature and their prediction in the short-term scale (0.1 hr or less) is difficult. A useful, practical control strategy must take into consideration the stochastic nature of these forcing functions but must depend on the determination of the state of the system for the implementation of the control strategy.

c. State of the System

The state of the system is usually measured by temperature sensors placed at various key locations throughout the system. Since the controllers are actuated by the sensors their accuracy in determining the state of the system is crucial.

d. Control Objectives

The control strategy is based on an optimization problem which determines the set-points and flow control.

(1) Optimization. The system performance is optimized using a performance index which is defined in terms of energy collection and/or economic considerations, i.e.,

*Note there are two transport subsystems to and from the collector.

(2) Control set-points. For implementation of the control strategy one has to define operating set-points which activate the controllers. For example, the set-points T_1 and T_2 turn on and off the pump in the collector loop for the on/off controller.

(3) Flow control. The mass flow-rate in the collector loop is controlled as a function of sensor inputs. If, for example, ΔT_c is measured then one can talk of:

(i) On/off controllers where the flow-rate is binary, having a fixed value $\dot{m}_{c,max}$ or zero;

(ii) Proportional controllers where $\dot{m}_c = k \Delta T_c$; and

(iii) Continuous flow controllers where $\dot{m}_c$ may be a more complex function of ΔT_c .

In the following two sections a steady state and a dynamic control model will be discussed based on the concepts defined above.

3. STEADY STATE CONTROL MODEL

The various elements of the model are defined below:

a. System Model

stratified storage model [Eq. (2)];
steady state collector model [Eq. (3)];
steady state transport model [Eq. (5)]; and
in addition, it is assumed that the transport is short so that $T_{so} = T_{ci}$ and $\Delta T_c = T_{co} - T_{ci} = T_{co} - T_{so}$.

b. Disturbance Functions

Solar flux, ambient temperature, load vary stochastically.

c. State of the System

$T_{so} (= T_{ci})$ and T_{co} are measured.

d. Control Objective

Performance index: heat gain [Eq. (3)] maximized;
set-points: $0 < \Delta T_{c,min} < \Delta T_c$;
flow control: the mass flow-rate can be controlled either by a variable speed pump or by a pinch valve between an upper and lower limit -
 $\dot{m}_{c,min} < \dot{m}_c < \dot{m}_{c,max}$.

Using the above specifications of the system and constraints, the useful heat gain can be optimized by calculus of variations or by other similar techniques [8]. The resultant continuous flow control strategy is shown in Fig. 3. The continuous flow controller operates at lower solar fluxes; i.e., during early morning and late afternoon hours and during partially overcast periods. The minimum solar fluxes at which the system turns on as a function of flow-rate at various minimum rise temperatures, $\Delta T_{c,min}$, is shown in Fig. 4. In

general, the performance of the continuous flow controller is better than the on/off controller and is about equivalent to the performance of the proportional flow controller [10-11] (which, incidentally, is not based on optimization). It must be realized that the effectiveness of various other elements of the collector loop (i.e., heat exchangers, pumps, etc.), is also a function of the flow-rate. For example, the energy required to operate the system can be incorporated into the optimization by redefining the useful heat gain as:

$$\dot{Q}_u^* = \dot{Q}_u - P(\dot{m}_c) = c_p \dot{m}_c (T_{co} - T_{ci}) - P(\dot{m}_c) \quad (6)$$

where $P(\dot{m}_c)$ is the pumping power, a function of the flow-rate. Equation (6) was optimized for various pumping power functions and it was found that it affects the control strategy in two ways:

(1) the optimal path in the $\dot{m}_c - \Delta T_c$ plane is slightly altered; and

(2) more significantly, a minimum value of $\dot{m}_c$ is established below in which $\dot{Q}_u^*$ becomes negative.

Fig. 3: Continuous Flow Control.

Fig. 4: Minimum Solar Flux for which System is "on" vs Flow-Rate.

During these investigations, it became clear that the steady state model of the collector does not (and, in fact, can not) predict cycling. Cycling is related to the capacitance of the collector which is being "charged" under stagnant conditions (no flow) and "discharged" into the storage tank during transient periods before steady state is

reached. In other words, the collector in fact collects useful energy during no flow conditions which is transferred toward the load during transient. When comparing various flow controls one has to account for this energy too. To derive an optimal control strategy one must consider a dynamic model of the collector.

4. DYNAMIC CONTROL MODEL

The control model is specified below:

a. System Model

stratified storage model [Eq. (1)];
distributed parameter collector model as given by Eq. (2) which can be normalized:

$$\frac{\partial T_f(\xi, t)}{\partial t} = \frac{1}{\tau_{fc}} \left[\alpha_c f(t) - (T_f(\xi, t) - T_a) \right] \times \left[1 + \gamma_1 \left(\frac{\tau_{fc}}{\tau_{fc}} - 1 \right) \right] - \gamma_1 \frac{1}{\tau_{tc}} \frac{\partial T_f(\xi, t)}{\partial \xi} \quad (7)$$

where

$$\tau_c = \frac{I_a(\tau_0) c}{U_L}; \quad \tau_{fc} = \frac{C_A}{U_L F}; \quad \tau_{tc} = \frac{C_A A_C}{U_c S_p}$$

and the primed time constants (e.g., τ'_{fc}) are defined for the flow condition, γ_1 is the pump control indicator.

Distributed parameter transport which when normalized is in the same form as Eq. (7).

b. Disturbance Functions

solar flux, ambient temperature.

c. State of the System

T_{so} and T_{co} are measured.

d. Control Objective

For the present, we assume an on/off controller with turn on and turn off set-points T_1 and T_2 , respectively.

e. Analytic Solution of the Dynamic Control Model

The dynamic control model is described in terms of a set of coupled, inhomogeneous partial differential equations as defined above [i.e., Eqs. (1), (7)]. We seek a solution that would give the fluid temperature in the collector loop as a function of position and time.

Boundary and initial conditions have to be specified and ensure that the solution is continuous at every point of the collector loop at all times under both stagnant and pumped conditions. Because the partial differential equations are coupled through the boundary conditions they have to be treated with extreme care, especially under stagnant conditions when large temperature gradients

can exist at the component interfaces. These partial differential equations can be solved analytically using standard Green's function or similar techniques [9] with the solar radiation and ambient temperatures as forcing functions. The solution, in general, is quite elaborate. However, a relatively easy closed form solution exists for the case of large storage and short transport subsystems. The variation of the fluid temperature in the collector loop with space and time for this case is given below:

$$T_f(\xi, t) = \gamma_1 F'(t) - e^{-t/\tau'_{fc}} F'(t - \tau_{tc}) U(t - \tau_{tc}) + e^{-t/\tau'_{fc}} A_1(\xi - t/\tau_{tc}) U(\xi - t/\tau_{tc}) + e^{-t/\tau_{tc}/\tau'_{fc}} A_2(t - \tau_{tc}) U(t - \tau_{tc}) + (1 - \gamma_1) [F(t) + e^{-t/\tau_{fc}} A_1(\xi)], \quad (8)$$

$$F(t) = \frac{1}{\tau_{fc}} \int_0^t [\alpha_c f(\lambda) + T_a(\lambda)] e^{-(t-\lambda)/\tau_{fc}} d\lambda$$

In the above equation $F'(t)$ is the same as $F(t)$ with τ_{fc} replaced by τ'_{fc} . $A_1(\xi/0)$ is the initial condition, $A_2(t) = T_{fc}(0, t)$ is the boundary condition, and $U(\cdot)$ is the unit step function.

5. DISCUSSION

A preliminary parametric study of Eq. (8) was carried out. The results of this study properly reflect cycling as it is observed experimentally. Figure 5 shows typical cycling during the morning warm up period. The following three characteristic time periods can be distinguished during cycling:

(i) During the first time period when the sun is rising, the pump is off and the capacity of the collector loop is "charged"; i.e., the fluid temperature in the collector rises towards the upper control set-point T_1 . The rate of the charging is a function of τ_{fc} which depends on the collector efficiency and capacitance.

(ii) During the second period the pump is on and the collector output temperature continues to rise above T_1 . The time duration of this period is equal to the delay time of the system, τ_{tc} , which varies directly with the collector capacitance and inversely with the flow rate.

(iii) During the third time period, the collector output temperature rapidly decays and capacitance is "discharged". When the temperature drops below the lower control set-point T_2 the pump turns off and the cycle repeats. If $T_{fc} > T_2$ the pump remains on and the "steady state" is reached.

During the second and third time periods energy is being transferred from the collector to the storage tank. The steady state model does not account for this useful energy gain.

One can reduce cycling by continuous flow control. This is shown in Fig. 5b. All the system parameters are identical for the cycling process shown in Figs. 5a and 5b except for the latter one where the flow rate was reduced by 20%, which reduced cycling.

The analytic study has shown that the control performance depends crucially on sensor location. For most practical systems the temperature sensors are located at the collector-transport subsystem interfaces. In these regions great temperature gradients can exist in stagnant condition, particularly if the pipes are poorly insulated. As a result of this the temperature sensor does not accurately measure the temperature of the collector. This in turn can cause excess cycling and reduced collection efficiency.

Fig. 5a

$T_1=38^\circ\text{C}$ $T_2=35^\circ\text{C}$ $T_{ci}=32^\circ\text{C}$ $\tau_{fc}=2.5$ hr

For (a) $\tau_{tc}=0.075$ hr, steady state (s.s.) reached at 9.75; (b) $\tau_{tc}=0.091$ hr, steady state reached at 9.15.

Fig. 5b

Fig. 5: Cycling During Warm-up For a Clear Day At Two Different Flow Rates.

NOMENCLATURE

- C_A - lumped value of collector capacitance
- η_R - collector efficiency factor
- M - mass of liquid in storage tank
- $\dot{m}_c$ - mass flow-rate in collector loop
- $\dot{m}_L$ - mass flow-rate to load
- T_a - ambient temperature
- T_{ci} - inlet collector fluid temperature
- T_{co} - outlet collector fluid temperature
- T_f - local collector fluid temperature
- T_L - load temperature
- T_s - storage tank temperature
- T_{so} - storage outlet temperature
- U - overall loss coefficient
- W - width of collector
- x - direction of mass flow-rate
- ΔT_c - temperature drop across collector

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Presently, a detailed parametric study and sensitivity analysis of the dynamic control model is being carried out.

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OPTIMAL AND SUB-OPTIMAL CONTROL STRATEGIES AND SENSITIVITY STUDY FOR SOLAR LIQUID COLLECTOR SYSTEMS

BY

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ABSTRACT

This paper is concerned with the control of liquid flow in the collector loop for solar heating application. The purpose of the paper is three fold: First a dynamic model which accurately reflects the dynamic behavior of the solar collector is given. Second, an optimal and suboptimal control strategy which maximizes the net usable energy is obtained using this dynamic model. Third, the implementation of the suboptimal policy via a thermostat on/off controller is investigated. Specifically, criteria are given for the selection of the control set points.

1. INTRODUCTION

Much attention has been recently devoted to the control of solar heating and cooling system [1]. Most of this work has concentrated on the optimal or adaptive control of the solar system [2-5] in which the dominant system dynamics are dictated by the storage tank while the collector loop dynamics are either neglected (e.g. using the steady-state H&B model [7]) or are represented by ordinary differential equation namely a uniform temperature or a "one-node" model [3]. Although these assumptions may be valid when considering the long term performance of the system (i.e. for a week or longer); for a short period of time when the controller action is significant (such as during start-up and shut-down periods) the collector loop dynamics cannot be neglected and in fact become of primary importance. Recent work [9] has shown that the dynamic behavior of the components in the solar collector loop (i.e. collectors, transport and storage) are best described by distributed parameter models, namely a set of partial differential equations, since they reflect the pump cycling phenomena experienced in the field when implementing on/off control strategies [10].

This paper is concerned with further studies of the distributed parameter model of the collector loop dynamics presented in [9] in order to determine the optimal control strategy and its implementation. Of particular interest is the performance of the controller in terms of the sensitivity of the control

strategy with respect to the various set points and system parameters in order to reduce the collector loop instabilities such as pump cycling.

2. SYSTEM MODEL

This paper is concerned with the control of the collector loop for solar heating application. The collector loop consists of solar collectors, transport subsystem and the storage as shown in Fig. 1. The control problem is concerned with the control of liquid flow in the collector loop via a controller which senses the temperature at various points in the loop and controls the operation of the pump.

Fig. 1. Collector loop with transport lines.

The simplest model which best describes the dynamics of the liquid flat-plate collector for control purposes is Klein's Plug-Flow Model (PFM), which gives the rate of accumulation of internal energy [8,9]

$$\rho c_p \frac{\partial T_f(x,t)}{\partial t} = \left\{ \begin{array}{l} (\tau a) F' W I(t) - \\ c_p \dot{m}_c(t) \frac{\partial T_f(x,t)}{\partial x} - \\ F' W U_L [T_f(x,t) - T_a(t)] \end{array} \right\} \quad (1)$$

in terms of the rates of absorbed energy, useful energy gained by the fluid, and energy

losses which are given by the first, second and third terms on the right-hand side, respectively. A similar distributed parameter model can be stated for the piping transport system between the collector and the storage [9] and the storage subsystem [11].

In this paper we shall assume that the transport system and storage dynamics can be neglected over the time period of interest. Therefore, we shall concentrate on the control of the solar collector loop described by the PFM model of (1) which can be rewritten as

$$\frac{\partial T_f(x,t)}{\partial t} = -u(t) \frac{\partial T_f(x,t)}{\partial x} - \alpha T_f(x,t) + v(t) \quad (2)$$

where $u(t)$ is the effective fluid velocity which is the control variable; λ is the collector time constant; and $v(t)$ represents the disturbance function due to the solar insolation, $I(t)$, and the ambient temperature, $T_a(t)$. Note that Eq. (2) represents a bilinear differential equation which is linear in state, linear in control but not jointly linear. For the special case when the control is constant, i.e., $u(t) = v$, then Eq. (2) becomes a linear hyperbolic differential equation, namely

$$\frac{\partial T_f(x,t)}{\partial t} + v \frac{\partial T_f(x,t)}{\partial x} + \alpha T_f(x,t) = v(t) \quad (3)$$

which can be solved analytically to give the fluid temperature profile across the collector, $T_f(x,t)$, as a function of time and space $0 \leq x \leq L$. Such a solution for the following boundary conditions:

$$\begin{aligned} \text{At } x = 0: & \quad T_f(0,t) = T_{fi}(t) \\ \text{At } t = 0: & \quad T_f(x,0) = T_{fx}(x) \end{aligned} \quad (4)$$

is given by

$$T_f(x,t) = \left\{ \begin{aligned} & G(t) - e^{-\frac{\alpha x}{v}} G(t - \frac{x}{v}) U(t - \frac{x}{v}) \\ & + T_{fx}(x - vt) U(x - vt) e^{-\alpha t} \\ & + T_{fi}(t - \frac{x}{v}) U(t - \frac{x}{v}) e^{-\frac{\alpha x}{v}} \end{aligned} \right\} \quad (5)$$

where $G(t) = e^{-\alpha t} * v(t)$ is the convolution of the system impulse response $e^{-\alpha t}$ with the input $v(t)$. Note that the first two terms of (5) represent the effect of the climatic forcing function while the last two terms give the effect of the initial and boundary conditions, respectively, on the fluid temperature, T_f . Furthermore, the term x/v represents the delay time, namely transit time for a slug of fluid to travel from the collector inlet to a point x with velocity v .

The importance of the explicit relation of (5) is that it allows one to obtain the fluid

temperature as a function of time at any point $0 \leq x \leq L$ for a given climatic condition, $v(t)$; the collector time constant, α^{-1} ; the effective fluid velocity v ; the collector inlet temperature $T_{fi}(t)$; and the initial temperature profile across the collector $T_{fx}(x)$ for $0 \leq x \leq L$. For example, at the collector outlet the fluid temperature, $T_f(L,t)$, can be evaluated as a function of time using (5) when $x = L$, as shown in Fig. 2. The data for this example are given in the Appendix. Note that this case represents the situation when the collector inlet temperature, $T_f(0,t) = 15^\circ\text{C}$ and ambient temperature $T_a(t) = 5^\circ\text{C}$ are constant over the time period shown. Referring to Fig. 2, the pump is turned on at $t = 7.3$ hrs when $T_f(L) = 15^\circ\text{C}$ as indicated by point A on the figure. The temperature rises from point A to B, where the time interval represents the transit time of the cold fluid between inlet and outlet. The discontinuity (depicted by B-C) represents the drop in outlet temperature when the collector inlet fluid starts affecting the outlet temperature. For all time following point C, the outlet temperature rises in accordance with the solar insolation.

Note that if this collector system was controlled by an on/off controller whose turn-off temperature $T_{off} = 12^\circ\text{C}$, then the pump would turn-off. Such a turn-on/turn-off operation of the pump is referred to as "pump-cycling" and has been observed during solar system operation [10] as shown in Fig. 3. In Ref. [9], a PFM collector model similar to that given by (3) has been used to simulate the pump-cycling phenomena. Based on these results, it is felt that the collector model of Eq. (2) accurately represents the collector dynamics and therefore is used to obtain the optimal control strategy.

3. OPTIMAL CONTROL OF SOLAR COLLECTORS

The optimization considered in this paper uses the model of Eq. (2) to obtain the maximum net useful energy gain (including pump losses) over each day by controlling the fluid flow rate in the collector loop. The net energy to be maximized during the specified time interval $(0, t_f)$ is given by

$$\int_0^{t_f} \dot{W}_c u(t) [AT_c(t) - c] dt$$

where $AT_c = T_f(L,t) - T_{fi}(t)$, the temperature rise across the collector. Note that the net energy consists of the gross heat energy collected minus the energy required to pump the fluid, which we assume to be proportional to the total fluid mass pumped [17]. Thus c is a measure of the efficiency of the pumping mechanism.

The optimal control problem considered can

Fig. 2. Collector outlet temperature profile vs. time.

be stated as follows: Given $v(t)$, $T_{in}(t)$, and T_0 , find the effective fluid velocity $u(t)$ which minimizes the cost functional

$$J(u) = - \int_0^{t_f} W_C u(t) [\Delta T_C(t) - c] dt \quad (6)$$

subject to the state equation of Eq. (2), and the constraints:

$$T_f(0, t) = T_{in}(t), \quad 0 \leq t \leq t_f \quad (7)$$

$$T_f(x, 0) = T_0, \quad 0 \leq x \leq L \quad (8)$$

$$0 \leq u(t) \leq M, \quad 0 \leq t \leq t_f \quad (9)$$

Note that constraint (9) bounds the fluid velocity to a specified maximum M . Furthermore the constraint (8) assures that initially (say before sunrise) the temperature distribution across the collector is constant. Using the necessary conditions for optimality derived in [13], the optimal control policy is a bang-bang policy, namely the optimal values are determined by

$$u(t) = \begin{cases} 0 & \text{if } S(t) < 0 \\ M & \text{if } S(t) > 0 \end{cases} \quad (10)$$

Fig. 3. Flat-plate collector outlet temperature during cycling (experimental data)

where $S(t)$ is the switching function given by

$$S(t) = W_C [\Delta T_C - c] - D(t) \quad (11)$$

where

$$D(t) = \int_0^L p(x, t) \frac{\partial T_f(x, t)}{\partial x} dx \quad (12)$$

The costate variable $p(x, t)$ is determined by following equations [13]:

$$\frac{\partial p(x, t)}{\partial t} + u(t) \frac{\partial p(x, t)}{\partial x} = \epsilon p(x, t) \quad (13)$$

subject to $p(x, t_f) = 0, \quad 0 \leq x \leq L$

$$p(L, t) = W_C, \quad 0 \leq t \leq t_f$$

The state equation (2), costate equation (13), and switching criterion (10) form an inter-related system from which the switching times of the optimal policy can be determined.

In general the optimal policy of (11) cannot be implemented using a feedback structure since the term $D(t)$ in the switching function requires future knowledge of the input functions $I(t)$, $T_a(t)$ and $T_{in}(t)$. However, if $D(t) = 0$ for all t in $[0, t_f]$, then the optimal policy can be implemented using the feedback structure where the controller implements (10), namely it becomes an on/off controller. Since in general $D(t) \neq 0$, then such a controller gives a suboptimal policy. Therefore, it is interesting to find the conditions under which the suboptimal policy approaches the optimal control policy.

It can be shown [13] that if the optimal control policy results in a two-switch policy (i.e. the pump is turned on only once at the beginning of the day and then shut off at the end of the day) then the suboptimal and optimal policies are identical. This is the case which occurs on a clear solar day.

During other days when many switches occur then the suboptimal policy is approximately equal to the optimal policy if the switch-off times (i.e. pump-off times) are greater than $3/\alpha$ (i.e. three times the collector time constant). Similar results have been obtained when the transport system is included (see [13]).

It should be noted that these results have been obtained by neglecting the storage subsystem dynamics, namely a large storage tank. Finally, since the actual thermostat on/off controller differs from the ideal one given by (11) in that a hysteresis is included to guarantee system stability, we shall next investigate the selection of the set points of the thermostat on/off controller, namely T_{on} and T_{off} , the turn-on and turn-off temperatures, respectively.

SENSITIVITY ANALYSIS

The sensitivity studies were made on the performance of the solar control system when the collector loop is modeled by (2) and the controller is a thermostat on/off controller. These studies were made with respect to the collector parameters and the set-points. Fig. 4. shows a typical result of the collector outlet temperature and collected total energy for system parameters given in the Appendix and set-points indicated. The pump first turns on at the time 8.51 hrs in the morning, it cycles until 9.17 hrs or until the outlet fluid temperature, $T_o(L,t)$ remains above the off set point, T_{off} . It should be noted that energy is collected during the cycling process although at a somewhat lower efficiency.

A number of similar computer runs were made, systematically varying the system and control parameters. Table I summarizes the results in terms of normalized sensitivities ($\partial y/y$) ($\partial p/p$) where y is either the energy collected or number of cycles and p denotes the parameters varied.

The most sensitive parameter, in terms of both energy collected and cycling, is the turn-off set point T_{off} . This should be set as low as

possible. The effect of the turn-on set point, T_{on} , is less dramatic. Table II provides numerical values for this sensitivity analysis, where $\Delta T_{off} = T_{off} - T_s$ is the turn-off temperature relative to the storage temperature and $\Delta T_h = T_{on} - T_{off}$ is the hysteresis setting.

From the closed-form solution of the PFM (9) one can obtain conditions on ΔT_{off} and ΔT_h such that no cycling occurs, namely:

- (a) $\Delta T_{off} = 0$.
- (b) ΔT_h is set such that
 - (i) $\Delta T_o(t_0) \geq \Delta T_{off}$; and
 - (ii) $\Delta T_o(t_0 + L/\mu) \geq \Delta T_{off}$,

where t_0 is the first pump turn-on time. Note that although there may be many t_0 which satisfy (i) they do not necessarily satisfy (ii). Thus, for no cycling situation (i) and (ii) must be satisfied simultaneously.

Table I. Results for parameter variations.

SYSTEM CONTROL VARIABLES	SYSTEM	ENERGY COLLECTED	NUMBER OF CYCLES
	T_{off}	-1.5	260
	FLUX RATE	0.1	3
	T_{on}	-0.1	-5
SYSTEM PARAMETERS	$\frac{1}{\alpha}$	2.0	-2.5
	(m)	-0.1	-2.5

Table II. Numerical example for set-point changes

$\Delta T_{off} [^{\circ}\text{C}]$ ($T_{off} - T_s$)	$\Delta T_h [^{\circ}\text{C}]$ ($T_{on} - T_{off}$)	ENERGY COLLECTED [KJ]	NUMBER OF CYCLES
0	0	9425	0
	5	9247	0
2	0	8334	4
	5	8793	4

Fig. 4. Outlet fluid temperature and energy vs. time.

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NOMENCLATURE

- C_c - lumped collector thermal capacitance per unit area.
 c_p - specific heat capacitance of fluid.
 F' - collector geometry efficiency factor.
 I_0 - amplitude of solar intensity.
 L - collector length.
 U_L - collector's heat loss coefficient.
 W - collector width.
 $\tau\alpha$ - transmittance-absorptance product.

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APPENDIX

Initial and boundary conditions	nominal values of parameters		weather conditions
$T_f(x,0) = 15^\circ\text{C}$ $T_f(0,t) = 10^\circ\text{C}$	$C_c = 10.22 \frac{\text{kJ}}{\text{m}^2\text{-}^\circ\text{C}}$ $F' = .95$ $(\tau\alpha) = .8281$ $R_c = 227.19 \frac{\text{kJ}}{\text{hr}}$ $A_c = 2. \text{m}^2$	$U_L = 18.65 \frac{\text{kJ}}{\text{m}^2\text{-}^\circ\text{C-hr}}$ $W = .87 \text{m}$ $v = 106.97 \frac{\text{m}}{\text{hr}}$ $L = 2.3 \text{m}$ $c_p = 4.19 \frac{\text{kJ}}{\text{kg-}^\circ\text{C}}$	$T_a(t) = 5^\circ\text{C}$ $I(t) = I_0 \cos(\omega(t-6))$ $\omega = .2618 \text{rad}$ $I_0 = 3000. \frac{\text{kJ}}{\text{m}^2\text{-hr}}$

APPENDIX B

TRNSYS COMPUTER CODE VERSION 9.2

FLOW CHART

IDENTIFICATION
POINT FIVE-FOUR
TYPE CHARACTERS

31 32 33 34 35 40 50 52 54 56 58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 100

31 32 33 34 35 40 50 52 54 56 58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 100

31 32 33 34 35 40 50 52 54 56 58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 100

31 32 33 34 35 40 50 52 54 56 58 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 100

B-6

GET UNIDENTIFIED NEXT SLAVE

GET NEXT OF ARRAY

SLAVE NOT ARMED IF BOTH ARMED

A DECIMAL POINT
HAS BEEN DETECTED

A CHANGE IN SLAVE SPACE HAS
BEEN DETECTED

ANALYZE SHIP FOR
SHIP DETECTED

EXEC

21. IS THE PAY INCREASE (BY THE SUPPLY) OF THE
Tth UNIT TO BE TAKEN

NOTE is THE TYPE SOURCE

1. THE FIRST OF THESE IS THE
 

[illegible]

 

SIMUL

SIMUL will control the operation. After printing headings and checking for errors it will start incrementing time in a loop. The program exit the loop if time $\geq$ TFINAL, or if an error in convergence of diff. eq. (if there are any) is detected. If there are differential eqs. SIMUL is trying to predict values of temperatures and then correct them (according to method discussed in Chapter 1.10 in the manual). If convergence fails within max allowed iterations per time-step a warning is issued. After the max number of allowed warnings occurs an error statement is issued and the simulation terminates.

(Calling routines: TYPECK, PRINT,
EXEC, MAP (optional))

```

graph TD
    Start(( )) --> Cond1{if (L1) == 0?}
    Cond1 -- YES --> Box1[L1 = L1 - 1]
    Cond1 -- NO --> Cond2{if (L1 == 0) ?}
    Cond2 -- YES --> Box2[L1 = 0]
    Cond2 -- NO --> Box3[L1 = 1]
    Box1 --> Box3
    Box2 --> Box3
    Box3 --> End(( ))
  
```

$\nabla R = 1, \forall v$
 $\text{PUT}(v, d) = \text{PUT}(v, u) =$
 $\text{PUT}(v, d) = \text{PUT}(v, u) = 0 \text{ if}$

INTEGRATION IS FORGOTTEN WHEN

```

graph TD
    START([START]) --> FOR((FOR))
    FOR --> IF{if A < B then}
    IF -- YES --> A1[A := A + 1]
    IF -- NO --> A2[A := A + 2]
    A1 --> A3[A := A + 1]
    A2 --> A3
    A3 --> END([END])
  
```

```

graph TD
    Start(( )) --> Decision{if (A < B)}
    Decision -- Yes --> PrintA[PRINT A - B]
    PrintA --> GoTo100[GO TO 100]
    Decision -- No --> GoTo100
    GoTo100 --> Connector100((100))
    Connector100 --> CallTrace[CALL TRACE]
    CallTrace --> End((END))
  
```

```

graph TD
    Start([START]) --> Init[SE = 1; ER]
    Init --> Calc[ $MIN(3H_2) + MIN(2H_2)$ ]
    Calc --> Print[PRINT SE, ER]
    Print --> End([END])
  
```

MIN() is the min of MIN(3H₂)
 while ALL inputs has changed

```

graph TD
    Start([START]) --> Init["SE = 1; ER"]
    Init --> Calc["MIN(3H2) + MIN(2H2)"]
    Calc --> Print["PRINT SE, ER"]
    Print --> End([END])
  
```

NO → END OF WHILE LOOP

YES →

RETURN

$LL \leftarrow \text{NDCP}(N, Z)$
 $NW \leftarrow \text{NDCP}(N, I)$
 $\text{NDCP}(N, Z) \leftarrow \text{NDCP}(N, Z)$
 $\text{NDCP}(N, Z) \leftarrow \text{NDCP}(N, Z) + 1$

```

graph TD
    Start([Start]) --> Decision{Is the project completed?}
    Decision -- Yes --> End1([End])
    Decision -- No --> AddDay1[Add 1 day to the project duration]
    AddDay1 --> Decision2{Is the project duration greater than 30 days?}
    Decision2 -- Yes --> AddDay2[Add 1 day to the project duration]
    Decision2 -- No --> End2([End])
  
```

$$A_{\text{H}_2\text{O}} = \frac{1}{1 + \frac{1}{K_{\text{H}_2\text{O}}}} = \frac{1}{1 + \frac{1}{1.5 \times 10^{-3}}} = 0.0015$$

WFOV-14-1

$\frac{1}{2} \log \frac{1}{2}$
 $\frac{1}{2} \log \frac{1}{2}$
 $\frac{1}{2} \log \frac{1}{2}$
 $\frac{1}{2} \log \frac{1}{2}$

$$\frac{\partial \mathcal{L}}{\partial \mathbf{W}_1} = \frac{\partial \mathcal{L}}{\partial \mathbf{W}_2} \mathbf{W}_2^T \mathbf{W}_1^T + \frac{\partial \mathcal{L}}{\partial \mathbf{W}_2} \mathbf{W}_2^T \mathbf{W}_1^T \mathbf{W}_1^T \mathbf{W}_1^T$$

100

$$\begin{aligned} \text{Aufgabe 1, 10} \\ \text{Okt (19.10.19)} - \text{L. 10.10.19} \\ \text{F}_2(19.10.19) - \text{T (10.10.19)} \\ \text{D. 10.10.19 (19.10.19)} \\ \text{D. 10.10.19 (19.10.19)} \end{aligned}$$

$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{x}} \right) = \frac{\partial L}{\partial x}$

TRACE

INITIALIZE AT 100

PRINTS SPACE, UNIT, TYPE, BY NAME, ADDRESS, COUNT (CASE)

ADDRESS: (10000-10000)

DO FOR 2, 3, 4

DO FOR 2

DO FOR 2, 3, 4

IF THE UNIT HAS NO
A) INPUTS B) INPUTS C) INPUTS
D) OUTPUTS, CONTINUE TO 100

IF (UNIT) < 0

YES

NO

CONTINUE TO 100

UNIT = 0

UNIT = 0

UNIT = 0

UNIT = 0

UNIT = 0

UNIT = 0

UNIT = 0

UNIT = 0

UNIT = 0

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UNIT = 0

UNIT = 0

UNIT = 0

UNIT = 0

UNIT = 0

UNIT = 0

IF WE CHANGE 10000, OUR EXAMPLE
TO 72, THEN IF WE HAVE UNIT ADDRESS
WE WILL TO PRINT THE UNIT, SO THIS UNIT
PRINTS CASE 21 UNIT

RETURN

PRINT LAST PAGE

IF THE FILE DATA AND INFORMATION IS AVAILABLE "PRINT" COMMAND IS USED TO PRINT THE INFORMATION IN A MANNER TO "CLEAR"

PRINT LAST PAGE

PRINT

TYPE 2

THIS ROUTINE SIMULATES A STRATIFIED STORAGE TANK CONSISTING OF NEQ FULLY MIXED SECTIONS, THE VALUE OF NEQ BEING CHOSEN BY THE USER. REFERENCE "EXPERIMENTAL AND SIMULATED PERFORMANCE OF A CLOSED LOOP SOLAR WATER HEATING SYSTEM", BY P.J.COOPER, S.A.KLEIN, AND C.W.S.DIXON PRESENTED AT THE ISES MEETING IN AUGUST, 1975.

VOL-TOTAL VOLUME OF TANK, NEQ-NO. OF EQUAL VOLUME TANK SECTIONS
CPH-SPECIFIC HEAT OF FLUID IN TANK, RHOH- DENSITY OF TANK FLUID
HIGH - TANK HEIGHT -
U - HEAT LOSS COEFFICIENT PER UNIT AREA OF TANK
FLWS- FLOW RATE FROM HEAT SOURCE, TIN-TEMP. FROM HEAT SOURCE.
FLWL- FLOW RATE TO LOAD (MAKEUP FLUID FLOW RATE)
TL-TEMP. OF FLUID REPLACING THAT EXTRACTED TO SUPPLY THE LOAD
UA - TANK HEAT LOSS COEFFICIENT MULTIPLIED BY SURFACE AREA

உள்ளுறை: பத்திரிகைகளுக்காக

የኢትዮጵያ ፌዴራላዊ ዲሞክራሲያዊ ሪፐብሊክ
የፍትሕና የሕዝብ አገልግሎት ሚኒስቴር

ONE NONE TASK EQUATIONS

$$\langle \bar{\psi} \psi \rangle = 1$$

संज्ञा

$$\begin{aligned} \frac{d}{dt} \left(\frac{1}{2} m \dot{x}^2 + \frac{1}{2} m \dot{y}^2 + \frac{1}{2} m \dot{z}^2 \right) &= \frac{d}{dt} \left(\frac{1}{2} m \dot{x}^2 + \frac{1}{2} m \dot{y}^2 + \frac{1}{2} m \dot{z}^2 \right) \\ &= m \dot{x} \ddot{x} + m \dot{y} \ddot{y} + m \dot{z} \ddot{z} \\ &= m \dot{x} \ddot{x} + m \dot{y} \ddot{y} + m \dot{z} \ddot{z} \end{aligned}$$

04777 (6479 179)

$\frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$
 $\frac{1}{4} \times \frac{1}{4} = \frac{1}{16}$
 $\frac{1}{16} \times \frac{1}{16} = \frac{1}{256}$
 $\frac{1}{256} \times \frac{1}{256} = \frac{1}{65536}$
 $\frac{1}{65536} \times \frac{1}{65536} = \frac{1}{4294967296}$
 $\frac{1}{4294967296} \times \frac{1}{4294967296} = \frac{1}{18446744073709551616}$

$\frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$
 $\frac{1}{4} \times \frac{1}{4} = \frac{1}{16}$
 $\frac{1}{16} \times \frac{1}{16} = \frac{1}{256}$

॥१॥

11-100-100

$$\log(100 - r_2) > 0.2$$
$$P_2 = \text{MSB}(T0) - r_c$$

1

76J

1

7

1

```

graph TD
    Start(( )) --> Init[ $t = 0, j = 1, UA = 0$   
 $UA_{max} = 0, UA_{min} = 0$   
 $UA_{opt} = 0$ ]
    Init --> LoopStart[ $for j = 1, N$   
 $UA = UA_{max}$ ]
    LoopStart --> Cond1{ $j > N$ }
    Cond1 -- YES --> Cond2{ $UA > UA_{max}$ }
    Cond1 -- NO --> Cond2
    Cond2 -- YES --> UAUpdate[ $UA = UA - UA_{max}$ ]
    Cond2 -- NO --> Calc[ $UA_{opt} = UA_{opt} + (UA - UA_{opt})$   
 $UA_{opt} = UA_{opt} + (UA - UA_{opt})$ ]
    UAUpdate --> Cond1
    Calc --> Cond3{ $UA_{opt} > 0$ }
    Cond3 -- YES --> UAUpdate
    Cond3 -- NO --> Cond4{ $UA > UA_{max}$ }
    Cond4 -- YES --> UAUpdate
    Cond4 -- NO --> Cond5{ $UA > 0$ }
    Cond5 -- YES --> UAUpdate
    Cond5 -- NO --> End(( ))
    
```

```

SUBROUTINE TYPESTIME,XIN,OUT,T,DTOT,PAR,INFO)
  DIMENSION XIN(10),PAR(15),OUT(20),INFO(5)
  THIS ROUTINE SIMULATES THE PERFORMANCE OF A SENSIBLE HEAT
  EXCHANGER GIVING OUTLET TEMPS OF HOT AND COLD STREAMS.
  MODE=1,2,3,4 SIGNIFY PARALLEL, COUNTERFLOW, CROSS FLOW AND CONSTANT
  EFFECTIVENESS MODES.
  IF MODE=4, THE HEAT EXCHANGER IS MODELED USING A CONSTANT
  VALUE OF ITS EFFECTIVENESS, EFF, PROVIDED AS PART(2) BASED UPON
  THE HOT CAPACITANCE RATE, CH.
  UA=OVERALL TRANSFER COEFF PER UNIT TEMP DIFFERENCE; CPH=SPECIFIC
  HEAT OF HOT SIDE FLUID, CPC=SPECIFIC HEAT OF COLD SIDE FLUID
  FWH=HOT SIDE FLOW RATE, FCI=COLD SIDE INLET TEMP, FLWC=COLD SIDE
  FLOW RATE

```

TYPE 6

THIS ROUTINE MODELS AN AUXILIARY HEATER WHICH ADDS HEAT TO A FLOWSTREAM OF TEMP TIN AND FLOWRATE FLOW AT A RATE EQUAL TO QMAX WHENEVER IGAM IS UNITY AND FLOW IS NON-ZERO AND TOUT IS LESS THAN TSET

MODIFIED TYPE 6

TYPE 2

```
THIS SUBROUTINE SIMULATES A HOUSE-HEATING THERMAL LOAD
IT USES THE ENERGY PER DEGREE-DAY CONCEPT
IF ICT=1, AUXILIARY ENERGY IS ADDED IN PARALLEL WITH SOLAR HEAT
IF ICT=2, AUXILIARY ENERGY IS ADDED IN SERIES WITH THE SOLAR HEAT
IF ICT=3, THE SUBROUTINE IS A FORCING FUNCTION TO OUTPUT THE
HEATING LOAD REQUIRED BY THE ENERGY PER DEGREE-DAY CONCEPT
IF ICT=4, THE SUBROUTINE MODELS A ONE NODE HOUSE
WITH FLOATING ROOM TEMPERATURE AND NO BUILT IN AUXILIARY.
UA IS THE OVERALL LOSS COEFFICIENT FOR THE HOUSE
TA IS THE TEMPERATURE OF THE INTERIOR OF THE HOUSE
TR IS THE HOUSE CAPACITANCE IF ICT=4
FLOW IS THE MAXIMUM FLOW RATE OF THE HEATING FLUID
CP IS THE SPECIFIC HEAT OF THE HEATING FLUID
ETA IS THE EFFECTIVENESS OF THE HEAT EXCHANGER
CMIN IS THE MINIMUM FLOW CAPACITY OF THE HEAT EXCHANGER

TAMB IS THE AMBIENT OUTSIDE AIR TEMPERATURE
THOT IS THE INLET HEATING FLUID TEMPERATURE
FLOW IS AN INPUT ONLY IF ICT=3 OR 4
```

TYPE 21

Q-10. How many people are there in the family?

MATHEMATICAL DESCRIPTION

If $\gamma_1=0$ and $\gamma_2=0$: Then $T_o=T_i$; $\dot{Q}_{aux}=0$

If $\gamma_1=1$ and $\gamma_2=0$: Then for $T \leq T_{max1}$, $T_o=T$, $\dot{Q}_{aux}=\dot{Q}_{max}$
 $T > T_{max1}$, $T_o=T_{max1}$, $\dot{Q}_{aux}=\dot{Q}$

If $\gamma_1=0$ and $\gamma_2=1$: Then for $T \leq T_{max2}$, $T_o=T$, $\dot{Q}_{aux}=\dot{Q}_{max}$
 $T > T_{max2}$, $T_o=T_{max2}$, $\dot{Q}_{aux}=\dot{Q}$

where $T = T_i + \dot{Q}_{max} / \dot{M}_i c_p$
 $\dot{Q} = \dot{M}_i c_p (T_o - T_i)$

Note that γ_1 and γ_2 are mutually exclusive,
and $\dot{M}_o = \dot{M}_i$.

TRNSYS COMPONENT CONFIGURATION

PARAMETER NO.

1	$\dot{Q}_{max}$ - maximum heating rate.
2	T_{max1} - set temperature for off-peak hours
3	T_{max2} - set temperature for peak hours.
4	c_p - specific heat of fluid.

INPUT NO.

1	T_i - inlet temperature
2	$\dot{M}_i$ - fluid mass flow-rate.
3	γ_1 - on/off control function for off-peak hours.
4	γ_2 - on/off control function for peak hours.

OUTPUT NO.

1	T_o - outlet temperature.
2	$\dot{M}_o$ - fluid mass flow-rate.
3	$\dot{Q}_{aux}$ - required heating rate.

INFORMATION FLOW DIAGRAM

INPUTS 4
OUTPUTS 3
PARAMETERS 4
DERIVATIVE 0

PARAMETERS

1. $\dot{Q}_{max}$
2. T_{max1}
3. T_{max2}
4. c_p

TYPE 6*: MODIFIED AUXILIARY HEATER

GENERAL DESCRIPTION

This auxiliary heater is modeled to elevate the outlet temperature of the fluid using an external control function generated by the controller type 33. The heater is designed to add heat to the fluid at a user determined rate, $\dot{Q}_{\max}$, whenever one of the two control functions γ_1 or γ_2 is unity. The two control functions are designed to heat the fluid to a set temperature, $T_{\max_1}$ during off-peak hours, and $T_{\max_2}$ during peak hours. Usually, $T_{\max_1} \geq T_{\max_2}$ in order to charge the auxiliary tank using energy when off-peak utility rates are in effect. It should be noted that if $\dot{Q}_{\max}$ is not enough to elevate the fluid temperature to the set temperature, then the heater output temperature is given by

$$T_o = T_i + \dot{Q}_{\max} / (c_p \dot{M}).$$

On the other hand, if $\dot{Q}_{\max}$ is large enough to reach the set temperature, then the required heater used is

$$\dot{Q}_{\text{aux}} = \dot{M} \cdot c_p (T_o - T_i).$$

NOMENCLATURE

- c_p - fluid specific heat.
- $\dot{M}_i$ - inlet fluid mass flow-rate.
- $\dot{M}_o$ - outlet fluid mass flow-rate.
- $\dot{Q}_{\max}$ - maximum heating rate of heater.
- $\dot{Q}_{\text{aux}}$ - required heating rate.
- T_i - fluid inlet temperature.
- T_o - fluid outlet temperature.
- $T_{\max_1}$ - set temperature for off-peak hours.
- $T_{\max_2}$ - set temperature for peak hours.
- γ_1 - external control function for off-peak hours which has values of 0 or 1.
- γ_2 - external control function for peak hours which has values of 0 or 1.

TYPE 30: PROPORTIONAL CONTROLLER (Flow proportional to collected energy)

General Description

This controller generates a control function γ which has values $0 \leq \gamma \leq 1$. The value of γ is chosen to be a linear function of the rate of collected energy, $\dot{Q}_u$, when this energy is in the range $\dot{Q}_1 \leq \dot{Q}_u \leq \dot{Q}_2$, where the limits $\dot{Q}_1$ and $\dot{Q}_2$ are determined by $\dot{Q}_1 = c_p \dot{m}_{\min} \Delta T_d$, $\dot{Q}_2 = c_p \dot{m}_{\max} \Delta T_d$ and ΔT_d is a desired constant temperature difference. The controller turns on the pump when the temperature difference $\Delta T = T_1 - T_2$ is above a specified minimum $\Delta T_{\min}$ and maintains the minimum flow-rate of $\dot{m}_{\min}$ until the collected energy enters the region $\dot{Q}_1 \leq \dot{Q}_u \leq \dot{Q}_2$. For large values of $\dot{Q}_u$, the flow rate is at its maximum, $\dot{m}_{\max}$, and therefore the temperature difference ΔT will exceed the desired value ΔT_d . Note that this controller utilizes both the collected energy and the temperature difference to determine the control function γ . The outputs of this controller are: (i) the control function γ ; and (ii) the temperature difference ΔT which is used for printout purposes only.

NONECLATURE

- $\dot{Q}_u$ - rate of usable collected energy (KJ/hr)
- ΔT_d - desired temperature rise across the collectors ($^{\circ}\text{C}$)
- $\Delta T_{\min}$ - temperature rise across the collector at which the pump is turned on ($\Delta T_{\min} < \Delta T_d$), ($^{\circ}\text{C}$)
- T_1 - upper input temperature ($^{\circ}\text{C}$)
- T_2 - lower input temperature ($^{\circ}\text{C}$)
- $\Delta T = (T_1 - T_2)$ - input temperature difference ($^{\circ}\text{C}$)
- $\dot{m}$ - mass flow rate (Kg/hr)
- $\dot{m}_{\min}$ - minimum flow rate (Kg/hr)
- $\dot{m}_{\max}$ - maximum flow rate (Kg/hr)
- γ - output pump control function
- c_p - specific heat of fluid (KJ/Kg - $^{\circ}\text{C}$)

MATHEMATICAL DESCRIPTION

The controller function is shown graphically as follows:

mathematically this is expressed

$$Y = \begin{cases} 0 & \Delta T < \Delta T_{\min} \\ Y_{\min} & \Delta T \geq \Delta T_{\min} \text{ and } \dot{Q}_u \leq \dot{Q}_1 \\ \frac{\dot{Q}_u - \dot{Q}_1}{\dot{Q}_2 - \dot{Q}_1} & \dot{Q}_1 \leq \dot{Q}_u \leq \dot{Q}_2 \\ 1 & \dot{Q}_u > \dot{Q}_2 \end{cases}$$

where

$$\Delta T = T_2 - T_1$$

$$Y_{\min} = \frac{\dot{m}_{\min}}{\dot{m}_{\max}}$$

$$\dot{Q}_1 = c_p \dot{m}_{\min} \Delta T_d$$

$$\dot{Q}_2 = c_p \dot{m}_{\max} \Delta T_d$$

When the useful energy collected $\dot{Q}_u$ is in the interval $\dot{Q}_1 \leq \dot{Q}_u \leq \dot{Q}_2$, then the temperature difference $\Delta T_d = T_1 - T_2$ is kept constant. For $\dot{Q}_u > \dot{Q}_2$, the flow-rate is at maximum so that ΔT is greater than ΔT_d . Note that energy collection starts when $\Delta T > \Delta T_{min}$, where ΔT_{min} is specified. This implies that the minimum energy at which collection starts is $\dot{Q}_{min} = c_p \dot{m}_{min} \Delta T_{min}$. Thus, ΔT_{min} is selected to guarantee that $\dot{Q}_u \geq \dot{Q}_{min}$, where $\dot{Q}_{min}$ can represent pump losses.

TRNSYS Component Configuration

<u>PARAMETER NO.</u>	<u>DESCRIPTION</u>
1	c_p - specific heat of fluid
2	$\dot{m}_{min}$ - minimum mass flow rate
3	$\dot{m}_{max}$ - maximum mass flow rate
4	ΔT_{min} - temperature difference at which collection starts
5	ΔT_d - desired temperature rise across the collector

<u>INPUT NO.</u>	<u>DESCRIPTION</u>
1	$\dot{Q}_u$ - rate of collected energy
2	T_1 - upper input temperature
3	T_2 - lower input temperature

<u>OUTPUT NO.</u>	<u>DESCRIPTION</u>
1	γ - output control function
2	$\Delta T = (T_1 - T_2)$ - input temperature difference (only for printout use)

INFORMATION FLOW DIAGRAM

INPUTS 3
 OUTPUTS 2
 PARAMETERS 5
 DERIVATIVES 0

PARAMETERS

1. c_p
2. $\dot{m}_{min}$
3. $\dot{m}_{max}$
4. ΔT_{min}
5. ΔT_d

TYPE 33: CONTROLLER FOR SUPPLYING LOAD FROM TWO STORAGE TANKS AND OFF-PEAK ENERGY UTILIZATION

GENERAL DESCRIPTION

This controller generates five control functions which are designed to supply the heating load from two separate storage tanks: (i) Solar storage tank which stores solar energy (i.e. part of the solar collector loop); and (ii) auxiliary storage tank which stores the backup energy. The system operates so that energy is first taken out of the solar tank whenever its fluid temperature is above a T_{set} temperature otherwise energy is taken from the auxiliary tank. The auxiliary tank temperature is kept at certain set temperature T_{sa} during peak-hours and T_{sb} during off-peak-hours. This controller assumes that the heating load is constant during the day, at level $\dot{Q}_{day}$ and during the night at level $\dot{Q}_{nite}$. These loads are used as parameters to estimate the amount of energy which will be supplied from storage. In addition the utility's peak period must be identified. The five control functions generated by this controller are:

- (1) γ_1 - energy to be taken out of the solar tank at a rate of zero or $\dot{Q}_L$ (which can have one of two values, $\dot{Q}_{day}$ or $\dot{Q}_{night}$, for a day or night time load, respectively).
- (2) γ_2 - energy to be taken out of the auxiliary tank at a rate of zero or $\dot{Q}_L$ (which is equal to $\dot{Q}_{day}$ or $\dot{Q}_{night}$).
- (3) γ_3 - control function for the auxiliary heater during utility's peak period. (Note that the heater module Type 06 must be modified.)
- (4) γ_4 - control function for auxiliary heater during off-peak period.
- (5) γ_5 - control function for the pump in the auxiliary tank to load loop. It is always zero unless either γ_3 or γ_4 is one.

Note that γ_1 and γ_2 cannot be zero simultaneously since we assume that the load is fully supplied by either the solar or the auxiliary tank. Also

γ_3 and γ_4 cannot be zero or one simultaneously.

Based on the time of day and the day of the week (Saturday and Sunday are off-peak hours) the controller selects which one of the two tanks supplies the load, and decides whether or not the auxiliary tank should be "charged" to the set temperature. The controller strategy is designed to use the solar tank whenever possible. In addition, it must ensure that sufficient energy is stored in the auxiliary system for cloudy days.

NOMENCLATURE

γ_1 - on/off control function for supplying load from solar tank.

γ_2 - on/off control function for supplying load from auxiliary tank.

γ_3 - control function for the auxiliary heater during utility's peak period.

γ_4 - control function for the auxiliary heater during utility's off-peak period.

γ_5 - on/off control function for the pump in auxiliary loop.

Q_{day} - estimated average load during the day.

Q_{nite} - estimated average load during the night.

T_{set} - minimum set temperature for solar tank below which it cannot supply the load.

T_{sa} - desired set temperature for auxiliary storage during peak period.

T_{sb} - desired set temperature for auxiliary storage during off-peak period.

T_{s_1} - solar tank fluid temperature.

T_{s_2} - auxiliary tank fluid temperature.

P_{on} - start time of utility's peak period (in hours).

P_{off} - final time of utility's peak period (more than 0. p.m.).

t_{start} - starting time of simulation run.

t_{stop} - stopping time of simulation run.

day - day in which the simulation starts.

TRNSYS Component Configuration

<u>PARAMETER NO.</u>	<u>DESCRIPTION</u>
1	Q_{day} - estimated average load during the day
2	Q_{nite} - estimated average load during the night
3	T_{set} - set temperature for solar tank
4	T_{sa} - set temperature for auxiliary tank (peak-period)
5	T_{sb} - set temperature for auxiliary tank (off-peak period)
6	P_{on} - start time for peak- period
7	P_{off} - final time for peak-period
8	t_{start} - start time of the simulation
9	t_{stop} - final time of the simulation
10	day - the day in which the simulation starts (the day of the week)

INPUT NO.

1	T_{s1} - solar tank fluid temperature
2	T_{s2} - auxiliary tank fluid temperature

OUTPUT NO.

1	γ_1 - on/off control to supply load from solar tank
2	γ_2 - on/off control to supply load from auxiliary tank
3	γ_3 - control function for heater (peak-period)
4	γ_4 - control function for heater (off-peak-period)
5	γ_5 - on/off control function for auxiliary pump

INFORMATION FLOW DIAGRAM

INPUTS	2
OUTPUTS	5
PARAMETERS	10
DERIVATIVES	0

PARAMETERS

- (1) Q_{day}
- (2) Q_{nite}
- (3) i_{set}
- (4) T_{sa}
- (5) T_{sb}
- (6) p_{on}
- (7) p_{off}
- (8) t_{start}
- (9) t_{stop}
- (10) day

APPENDIX D

DETAILED DESCRIPTION OF PROGRAM

1. Introduction

The appendix gives an explanation of the parameters inputted to the program, the calculated quantities outputted, how the state of the system is determined.

2. Input/Output

The program accepts a total of twenty-two parameters and constants which are inputted from a stored data file or manually from a keyboard.

The parameters and constants are divided into five groups which are:

- i. System parameters. Characterize a flat plate collector loop with a large fluid storage.

τ_{fc} - static time constant (hrs)

A_c - collector area m^2

$\tau\alpha$ - collector transmittance-absorptance product

F' - collector geometric efficiency factor

C_{pf} - fluid specific heat (kJ/kg-°C)

- ii. Climatic Parameters. This data is obtained via direct measurement or from available weather data.

T_a - ambient temperature (°C)

I_o - peak insulation (kJ/m²-hr)

ω - frequency of climatic variation = $\frac{2\pi}{24 \text{ hrs}}$ (rad)

- iii. Control Parameters. These are set for the particular operating configuration to be evaluated.

T_{on} - pump turn on temperature (°C)

T_{off} - pump turn off temperature (°C)

$\dot{m}$ - fluid flow rate (kg/hr)

- iv. Initial Conditions. These describe the state of the system when observation commences (i.e. initial temperature of components).
- T_i - initial temperature of the collector ($^{\circ}\text{C}$)
- T_s - temperature of the storage ($^{\circ}\text{C}$)
- v. Computation parameters. The grouping consists of seven parameters which specify convergence tolerances, time steps and frequency of temperature printouts.

From this input data the following quantities are computed as a function of time and are available as output data:

- a) Collector output temperature
- b) Summary of energy collected
- c) Solar insolation
- d) Instantaneous and daily efficiency
- e) Collector temperature maxima and minima, with time of occurrence
- f) Pump turn-on and turn-off times
- g) Time and temperature when steady state is reached

3. Determination of System State

The solar thermal system has four possible states [see Fig. (3.5)]

- i. Initial warm-up period ($\gamma=0$).
- ii. Initial time delay period ($\gamma=1$)
- iii. Cool off period ($\gamma=1$)
- iv. Continuous flow period ($\gamma=1$)

These were discussed in detail in Section (III C-1).

For each system state the collector outlet fluid temperature is computed from one of four subroutines as follows:

- i. Subroutine A: $T_{co}(t) = T_c^a$ (static temperature prior to first pump turn-on)
- ii. Subroutine B: $T_{co}(t) = T_c^b$ (used during each initial time delay period).
- iii. Subroutine C: $T_{co}(t) = T_c^c$ (used during each cool-off period and for continuous flow)
- iv. Subroutine D: $T_{co}(t) = T_c^d$ (static temperature after first pump turn-on)

Where the initial conditions of the equations in the subroutines are taken from the previous state (period).

A flowchart of the portion of the program which keeps track of the system state is shown in Fig. (D-1). Initially time, t , is set to the hour of sunrise (Block A). Next (Block B) Subroutine A computes the collector outlet temperature based upon the initial conditions and solar insolation at sunrise. This continues until the collector outlet temperature rises to the pump turn-on temperature (Block C). At this point Subroutine B is used to compute $T_{co}(t)$. Subroutine B is used for a time of τ_{tc} hrs after the time the pump turns-on. After this time (τ_{tc} hrs) Block E transfers to the next subroutine, C. At this point the collector outlet temperature may drop below the turn-off temperature (tested for in Block H) or if there is sufficient insolation intensity the pump will remain on for the rest of the day (tested for in Block G). If the temperature falls below the turn-off temperature the initial conditions of the system are transferred to Subroutine D (Block I) and collector outlet temperature is computed by this subroutine until the pump turns on again (Block J). At this point Blocks D through I are sequentially executed until cycling stops. When cycling stops (i.e., Block G is satisfied) the pump remains on and Subroutine C is used to compute the outlet temperature till the selected time to end the simulation, t_{max} , is attained (Blocks K and L). At this time the simulation is completed.

Fig. D.1: SYSTEM STATE AND COLLECTOR
OUTLET TEMPERATURE FLOWCHART

RUN T3

COLLECTOR-CYCLING MODEL

DO YOU WISH TO INPUT DATA FILE, Y OR N? Y

#C4DEMO.DAT

OMEGA.....	0.26180
TAU FC.....	1.42500
START TIME.....	6.00000
INITIAL TEMP.....	0.00000
AMBIENT TEMP.....	0.00000
COLLECTOR AREA.....	2.00000
PEAK SOLAR INSOLATION.....	3000.00000
T1, PUMP TURN ON TEMP.....	46.00000
T1 SEARCH TERM VAL.....	0.00100
TIME STEP INCR.....	0.50000
T2, PUMP TURN OFF TEMP....	42.50000
MIXED STORAGE TEMP.....	40.00000
PT.C TIME STEP.....	0.00500
PT.D TIME STEP.....	0.20000
PT.D NO. OF TIME STEPS....	5.00000
COLL TAU ALPHA PRODUCT....	0.82610
COLL GEOM EFF COEFF.....	0.95000
COLLECTOR FLOW RATE.....	170.00000
FLUID SPECIFIC HEAT.....	4.19000
COLL LOSS COEFF.....	18.65000
COLL CAPACITANCE.....	10.22000
Z.BNDRY MATCH PARAMETER...	0.00200

B-1

APPENDIX B

INITIALIZATION VERIFIED Y OR N? Y

DO YOU WISH AUTOPERTURBATION OF PARAMETERS, Y OR N ? Y

DELTA OMEGA..... 0.00000
DELTA TAU FC..... 0.00000
DELTA START TIME..... 0.00000
DELTA INITIAL TEMP..... 0.00000
DELTA AMBIENT TEMP..... 0.00000
DELTA COLLECTOR AREA..... 0.00000
DELTA PEAK SOLAR INSOLATION... 0.00000
DELTA PUMP TURN ON TEMP..... 0.00000
DELTA SEARCH TERM VAL..... 0.00000
DELTA TIME STEP INCR..... 0.00000
DELTA PUMP TURN OFF TEMP..... 0.00000 -1.
DELTA MIXED STORAGE TEMP..... 0.00000
DELTA PT. C TIME STEP..... 0.00000
DELTA PT. D TIME STEP..... 0.00000
DELTA PT. B NO. OF TIME STEPS. 0.00000
DELTA COLL TAU ALPHA PRODUCT.. 0.00000
DELTA COLL GEOM EFF COEFF..... 0.00000
DELTA COLLECTOR FLOW RATE..... 0.00000
DELTA FLUID SPECIFIC HEAT..... 0.00000
DELTA COLL LOSS COEFF..... 0.00000
DELTA COLL CAPACITANCE..... 0.00000
DELTA Z-BNDRY MATCH PARAMETER. 0.00000

PERTURBATIONS VERIFIED, Y OR N ? Y

DO YOU WISH TO CALCULATE TEMPERATURE AFTER STEADY STATE? Y OR N? Y

TYPE THE DESIRED TIME INCREMENT IN HRS .1

TYPE THE TIME WHEN THE CALCULATIONS SHOULD STOP. (NOTE: 0. TO 24. HRS) 12.

TYPE NUMBER OF ITERATIONS (00 TO 99 INTEGER FORMAT) 02

DO YOU WISH ALL INTERMEDIATE VALUES OF TC? Y OR N? Y

BASE STEADY STATE TIME = 8.89252

TA =	6.00000	TFCA(T) =	0.00000
TA =	6.50000	TFCA(T) =	2.72652
TA =	7.00000	TFCA(T) =	9.75219
TA =	7.50000	TFCA(T) =	19.67076
TA =	8.00000	TFCA(T) =	31.40703
TA =	8.50000	TFCA(T) =	44.12269
TA =	8.57246	TFCA(T) =	46.00535
TB =	8.57820	TFCB(T) =	46.36788
TB =	8.58394	TFCB(T) =	46.73368
TB =	8.58968	TFCB(T) =	47.09740
TB =	8.59542	TFCB(T) =	47.45903
TB =	8.60116	TFCB(T) =	47.81868
TC =	8.60312	TFCC(T) =	43.18412

PART C MIN TIME = 8.60812

PART C MIN TC = 42.11902

ENERGY COLLECTED FROM ABOVE CYCLE = 148.94167

AVAILABLE SOLAR ENERGY = 5119.25000

CYCLE EFFICIENCY = 2.90944

COLLECTED ENERGY SUMMARY

TIME=	8.57246	DELTA ENGY=	4.90565	TOTAL ENGY=	4.90565
TIME=	8.57361	DELTA ENGY=	4.96596	TOTAL ENGY=	9.87161
TIME=	8.57476	DELTA ENGY=	5.02622	TOTAL ENGY=	14.89783
TIME=	8.57590	DELTA ENGY=	5.08638	TOTAL ENGY=	19.98421
TIME=	8.57705	DELTA ENGY=	5.14650	TOTAL ENGY=	25.13071
TIME=	8.57820	DELTA ENGY=	5.20653	TOTAL ENGY=	30.33725
TIME=	8.57935	DELTA ENGY=	5.26651	TOTAL ENGY=	35.60375
TIME=	8.58050	DELTA ENGY=	5.32642	TOTAL ENGY=	40.93017
TIME=	8.58165	DELTA ENGY=	5.38624	TOTAL ENGY=	46.31642
TIME=	8.58279	DELTA ENGY=	5.44601	TOTAL ENGY=	51.76243
TIME=	8.58394	DELTA ENGY=	5.50571	TOTAL ENGY=	57.26814
TIME=	8.58509	DELTA ENGY=	5.56534	TOTAL ENGY=	62.83347
TIME=	8.58624	DELTA ENGY=	5.62490	TOTAL ENGY=	68.45837
TIME=	8.58739	DELTA ENGY=	5.68440	TOTAL ENGY=	74.14277
TIME=	8.58853	DELTA ENGY=	5.74383	TOTAL ENGY=	79.88660
TIME=	8.58968	DELTA ENGY=	5.80318	TOTAL ENGY=	85.68977
TIME=	8.59083	DELTA ENGY=	5.86248	TOTAL ENGY=	91.55225
TIME=	8.59198	DELTA ENGY=	5.92170	TOTAL ENGY=	97.47396
TIME=	8.59313	DELTA ENGY=	5.98086	TOTAL ENGY=	103.45482
TIME=	8.59428	DELTA ENGY=	6.03995	TOTAL ENGY=	109.49477
TIME=	8.59542	DELTA ENGY=	6.09898	TOTAL ENGY=	115.59375
TIME=	8.59657	DELTA ENGY=	6.15793	TOTAL ENGY=	121.75168
TIME=	8.59772	DELTA ENGY=	6.21682	TOTAL ENGY=	127.96850
TIME=	8.59887	DELTA ENGY=	6.27565	TOTAL ENGY=	134.24416
TIME=	8.60002	DELTA ENGY=	6.33440	TOTAL ENGY=	140.57855
TIME=	8.60116	DELTA ENGY=	1.09624	TOTAL ENGY=	141.67479
TIME=	8.60135	DELTA ENGY=	1.10250	TOTAL ENGY=	142.77728
TIME=	8.60155	DELTA ENGY=	1.11308	TOTAL ENGY=	143.89236
TIME=	8.60174	DELTA ENGY=	1.12490	TOTAL ENGY=	145.01726
TIME=	8.60194	DELTA ENGY=	1.12893	TOTAL ENGY=	146.14609
TIME=	8.60214	DELTA ENGY=	1.09979	TOTAL ENGY=	147.23988
TIME=	8.60233	DELTA ENGY=	1.04666	TOTAL ENGY=	148.28654
TIME=	8.60253	DELTA ENGY=	0.95434	TOTAL ENGY=	149.24088
TIME=	8.60273	DELTA ENGY=	0.81373	TOTAL ENGY=	150.05460
TIME=	8.60292	DELTA ENGY=	0.61572	TOTAL ENGY=	150.67032
TIME=	8.60312	DELTA ENGY=	0.35121	TOTAL ENGY=	151.02153

TD =	8.72422	IFCD(T) =	46.00820		
TB =	8.72996	TFCB(T) =	46.40816		
TC =	8.73569	TFCB(T) =	46.81377		
TD =	8.74143	TFCB(T) =	47.21685		
TB =	8.74717	TFCB(T) =	47.61746		
TC =	8.75291	TFCB(T) =	48.01558		
TD =	8.75490	TFCB(T) =	43.16749		
PART C MIN TIME =	8.75990	PART C MIN TC =	42.31564		
ENERGY COLLECTED FROM ABOVE CYCLE =	151.14497	AVAILABLE SOLAR ENERGY =	587.56018	CYCLE EFFICIENCY =	25.72417

COLLECTED ENERGY SUMMARY

TIME=	8.72422	DELTA ENGY=	4.90565	TOTAL ENGY=	155.92719
TIME=	8.72536	DELTA ENGY=	4.97258	TOTAL ENGY=	160.89977
TIME=	8.72651	DELTA ENGY=	5.03944	TOTAL ENGY=	165.93921
TIME=	8.72766	DELTA ENGY=	5.10620	TOTAL ENGY=	171.04541
TIME=	8.72881	DELTA ENGY=	5.17288	TOTAL ENGY=	176.21829
TIME=	8.72996	DELTA ENGY=	5.23948	TOTAL ENGY=	181.45776
TIME=	8.73111	DELTA ENGY=	5.30599	TOTAL ENGY=	186.76375
TIME=	8.73225	DELTA ENGY=	5.37242	TOTAL ENGY=	192.13617
TIME=	8.73340	DELTA ENGY=	5.43877	TOTAL ENGY=	197.57494
TIME=	8.73455	DELTA ENGY=	5.50503	TOTAL ENGY=	203.07997
TIME=	8.73570	DELTA ENGY=	5.57122	TOTAL ENGY=	208.65118
TIME=	8.73685	DELTA ENGY=	5.63731	TOTAL ENGY=	214.28850
TIME=	8.73800	DELTA ENGY=	5.70334	TOTAL ENGY=	219.99184
TIME=	8.73914	DELTA ENGY=	5.76924	TOTAL ENGY=	225.76111
TIME=	8.74029	DELTA ENGY=	5.83512	TOTAL ENGY=	231.59622
TIME=	8.74144	DELTA ENGY=	5.90090	TOTAL ENGY=	237.49712
TIME=	8.74259	DELTA ENGY=	5.96659	TOTAL ENGY=	243.46370
TIME=	8.74374	DELTA ENGY=	6.03220	TOTAL ENGY=	249.49590
TIME=	8.74488	DELTA ENGY=	6.09772	TOTAL ENGY=	255.59361
TIME=	8.74603	DELTA ENGY=	6.16317	TOTAL ENGY=	261.75677
TIME=	8.74718	DELTA ENGY=	6.22853	TOTAL ENGY=	267.98529
TIME=	8.74833	DELTA ENGY=	6.29381	TOTAL ENGY=	274.27911
TIME=	8.74948	DELTA ENGY=	6.35902	TOTAL ENGY=	280.63812
TIME=	8.75063	DELTA ENGY=	6.42414	TOTAL ENGY=	287.06226
TIME=	8.75177	DELTA ENGY=	6.48918	TOTAL ENGY=	293.55142
TIME=	8.75291	DELTA ENGY=	1.13310	TOTAL ENGY=	294.68451
TIME=	8.75311	DELTA ENGY=	1.13952	TOTAL ENGY=	295.82404
TIME=	8.75331	DELTA ENGY=	1.15235	TOTAL ENGY=	296.97638
TIME=	8.75351	DELTA ENGY=	1.16215	TOTAL ENGY=	298.13852
TIME=	8.75371	DELTA ENGY=	1.15946	TOTAL ENGY=	299.29797
TIME=	8.75390	DELTA ENGY=	1.13485	TOTAL ENGY=	300.43283
TIME=	8.75410	DELTA ENGY=	1.07885	TOTAL ENGY=	301.51169
TIME=	8.75430	DELTA ENGY=	0.98204	TOTAL ENGY=	302.49371
TIME=	8.75450	DELTA ENGY=	0.83494	TOTAL ENGY=	303.32864
TIME=	8.75470	DELTA ENGY=	0.62812	TOTAL ENGY=	303.95676
TIME=	8.75490	DELTA ENGY=	0.35717	TOTAL ENGY=	304.31393

TD = 0.86604 IFLU(T) = 46.02055
 TB = 0.87178 TFCB(T) = 46.44456
 TC = 0.87752 TFCB(T) = 46.88617
 TD = 0.88326 TFCB(T) = 47.32485
 TE = 0.88900 TFCB(T) = 47.76063
 TF = 0.89474 TFCB(T) = 48.19354
 TG = 0.89704 TFCB(T) = 47.37392

PART C MIN TIME = 0.90204 PART C MIN TC = 42.49369
 ENERGY COLLECTED FROM ABOVE CYCLE = 157.78445 AVAILABLE SOLAR ENERGY = 574.92297 CYCLE EFFICIENCY = 27.44480

COLLECTED ENERGY SUMMARY

TIME= 0.86604 DELTA ENGY= 4.90565 TOTAL ENGY= 309.21451
 TIME= 0.86719 DELTA ENGY= 4.97856 TOTAL ENGY= 314.19305
 TIME= 0.86834 DELTA ENGY= 5.05137 TOTAL ENGY= 319.24442
 TIME= 0.86949 DELTA ENGY= 5.12410 TOTAL ENGY= 324.36853
 TIME= 0.87064 DELTA ENGY= 5.19672 TOTAL ENGY= 329.56525
 TIME= 0.87179 DELTA ENGY= 5.26924 TOTAL ENGY= 334.83450
 TIME= 0.87293 DELTA ENGY= 5.34168 TOTAL ENGY= 340.17618
 TIME= 0.87408 DELTA ENGY= 5.41400 TOTAL ENGY= 345.59018
 TIME= 0.87523 DELTA ENGY= 5.48624 TOTAL ENGY= 351.07642
 TIME= 0.87638 DELTA ENGY= 5.55838 TOTAL ENGY= 356.63480
 TIME= 0.87753 DELTA ENGY= 5.63043 TOTAL ENGY= 362.26523
 TIME= 0.87868 DELTA ENGY= 5.70237 TOTAL ENGY= 367.96759
 TIME= 0.87982 DELTA ENGY= 5.77423 TOTAL ENGY= 373.74182
 TIME= 0.88097 DELTA ENGY= 5.84598 TOTAL ENGY= 379.58780
 TIME= 0.88212 DELTA ENGY= 5.91764 TOTAL ENGY= 385.50543
 TIME= 0.88327 DELTA ENGY= 5.98921 TOTAL ENGY= 391.49463
 TIME= 0.88442 DELTA ENGY= 6.06069 TOTAL ENGY= 397.55533
 TIME= 0.88556 DELTA ENGY= 6.13206 TOTAL ENGY= 403.68738
 TIME= 0.88671 DELTA ENGY= 6.20334 TOTAL ENGY= 409.89072
 TIME= 0.88786 DELTA ENGY= 6.27453 TOTAL ENGY= 416.16525
 TIME= 0.88901 DELTA ENGY= 6.34562 TOTAL ENGY= 422.51086
 TIME= 0.89016 DELTA ENGY= 6.41663 TOTAL ENGY= 428.92749
 TIME= 0.89131 DELTA ENGY= 6.48753 TOTAL ENGY= 435.41504
 TIME= 0.89245 DELTA ENGY= 6.55835 TOTAL ENGY= 441.97339
 TIME= 0.89360 DELTA ENGY= 6.62907 TOTAL ENGY= 448.60245
 TIME= 0.89474 DELTA ENGY= 1.33971 TOTAL ENGY= 449.94214
 TIME= 0.89497 DELTA ENGY= 1.34927 TOTAL ENGY= 451.29141
 TIME= 0.89520 DELTA ENGY= 1.36646 TOTAL ENGY= 452.65787
 TIME= 0.89543 DELTA ENGY= 1.37429 TOTAL ENGY= 454.03217
 TIME= 0.89566 DELTA ENGY= 1.35575 TOTAL ENGY= 455.38791
 TIME= 0.89589 DELTA ENGY= 1.29385 TOTAL ENGY= 456.68176
 TIME= 0.89612 DELTA ENGY= 1.17139 TOTAL ENGY= 457.85336
 TIME= 0.89635 DELTA ENGY= 0.97197 TOTAL ENGY= 458.82532
 TIME= 0.89658 DELTA ENGY= 0.67798 TOTAL ENGY= 459.50330
 TIME= 0.89681 DELTA ENGY= 0.40668 TOTAL ENGY= 459.90997

TD = 8.99960 TFCB(T) = 46.00144
 TB = 9.00534 TFCB(T) = 46.47771
 TB = 9.01108 TFCB(T) = 46.95210
 TB = 9.01682 TFCB(T) = 47.42316
 TB = 9.02256 TFCB(T) = 47.89098
 TB = 9.02829 TFCB(T) = 48.35555
 TC = 9.03329 TFCB(T) = 42.65266
 STEADY STATE TIME = 9.03829 STEADY STATE TFC = 42.65862
 ENERGY COLLECTED FROM ABOVE CYCLE = 185.94293 AVAILABLE SOLAR ENERGY = 594.18134 CYCLE EFFICIENCY = 31.29397

COLLECTED ENERGY SUMMARY

TIME	DELTA ENGY	TOTAL ENGY
8.99960	4.90565	464.81561
9.00073	4.98402	469.79962
9.00189	5.06226	474.86188
9.00304	5.14041	480.00229
9.00419	5.21844	485.22073
9.00534	5.29636	490.51709
9.00649	5.37417	495.89127
9.00764	5.45188	501.34314
9.00878	5.52947	506.87262
9.00993	5.60697	512.47961
9.01108	5.68435	518.16394
9.01223	5.76162	523.92554
9.01338	5.83878	529.76434
9.01453	5.91583	535.68018
9.01567	5.99279	541.67297
9.01682	6.06962	547.74261
9.01797	6.14636	553.88898
9.01912	6.22300	560.11200
9.02027	6.29951	566.41150
9.02141	6.37592	572.78741
9.02256	6.45224	579.23969
9.02371	6.52844	585.76813
9.02486	6.60453	592.37268
9.02601	6.68053	599.05322
9.02716	6.75641	605.80963
9.02829	6.83217	611.76141
9.02942	6.90785	617.71332
9.03056	6.98341	619.60028
9.03170	7.05885	621.48810
9.03284	7.13417	623.37677
9.03398	7.20945	625.26630
9.03512	7.28460	627.15668
9.03626	7.35962	629.04791
9.03740	7.43451	630.94000
9.03854	7.50929	632.83295
9.03968	7.58395	634.72680
9.04082	7.65849	636.62150
9.04196	7.73291	638.51705
9.04310	7.80721	640.41346
9.04424	7.88139	642.31072
9.04538	7.95545	644.20883
9.04652	8.02939	646.10780
9.04766	8.10321	648.00762
9.04880	8.17691	649.90830
9.04994	8.25049	651.80983
9.05108	8.32395	653.71222
9.05222	8.39729	655.61547
9.05336	8.47051	657.51958
9.05450	8.54361	659.42455
9.05564	8.61659	661.33038
9.05678	8.68945	663.23707
9.05792	8.76219	665.14462
9.05906	8.83481	667.05303
9.06020	8.90731	668.96230
9.06134	8.97969	670.87243
9.06248	9.05195	672.78342
9.06362	9.12409	674.69527
9.06476	9.19611	676.60798
9.06590	9.26801	678.52155
9.06704	9.33979	680.43598
 	

TC =	9.13830	TFCC(T) =	42.77594
TC =	9.23830	TFCC(T) =	42.89003
TC =	9.33830	TFCC(T) =	43.00081
TC =	9.43830	TFCC(T) =	43.10821
TC =	9.53830	TFCC(T) =	43.21214
TC =	9.63830	TFCC(T) =	43.31255
TC =	9.73830	TFCC(T) =	43.40934
TC =	9.83830	TFCC(T) =	43.50248
TC =	9.93830	TFCC(T) =	43.59187
TC =	10.03830	TFCC(T) =	43.67746
TC =	10.13830	TFCC(T) =	43.75925
TC =	10.23830	TFCC(T) =	43.83710
TC =	10.33830	TFCC(T) =	43.91100
TC =	10.43830	TFCC(T) =	43.98087
TC =	10.53830	TFCC(T) =	44.04670
TC =	10.63830	TFCC(T) =	44.10842
TC =	10.73830	TFCC(T) =	44.16600
TC =	10.83830	TFCC(T) =	44.21937
TC =	10.93830	TFCC(T) =	44.26854
TC =	11.03830	TFCC(T) =	44.31347
TC =	11.13830	TFCC(T) =	44.35408
TC =	11.23830	TFCC(T) =	44.39039
TC =	11.33830	TFCC(T) =	44.42235
TC =	11.43830	TFCC(T) =	44.44995
TC =	11.53830	TFCC(T) =	44.47319
TC =	11.63830	TFCC(T) =	44.49202
TC =	11.73831	TFCC(T) =	44.50644
TC =	11.83831	TFCC(T) =	44.51645
TC =	11.93831	TFCC(T) =	44.52201
TC =	12.03831	TFCC(T) =	44.52316
TIME =	9.03829	DELTA ENBY =	189.37343
TIME =	9.13830	DELTA ENBY =	197.73021
TIME =	9.23830	DELTA ENBY =	205.85655
TIME =	9.33830	DELTA ENBY =	213.74760
TIME =	9.43830	DELTA ENBY =	221.39763
TIME =	9.53830	DELTA ENBY =	228.80093
TIME =	9.63830	DELTA ENBY =	235.95264
TIME =	9.73830	DELTA ENBY =	242.84700
TIME =	9.83830	DELTA ENBY =	249.48135
TIME =	9.93830	DELTA ENBY =	255.84912
TIME =	10.03830	DELTA ENBY =	261.94681
TIME =	10.13830	DELTA ENBY =	267.77142
TIME =	10.23830	DELTA ENBY =	273.31644
TIME =	10.33830	DELTA ENBY =	278.58075
TIME =	10.43830	DELTA ENBY =	283.55734
TIME =	10.53830	DELTA ENBY =	288.24612
TIME =	10.63830	DELTA ENBY =	292.64258
TIME =	10.73830	DELTA ENBY =	296.74393
TIME =	10.83830	DELTA ENBY =	300.54587
TIME =	10.93830	DELTA ENBY =	304.04834
TIME =	11.03830	DELTA ENBY =	307.24814
TIME =	11.13830	DELTA ENBY =	310.14142
TIME =	11.23830	DELTA ENBY =	312.72743
TIME =	11.33830	DELTA ENBY =	315.00412
TIME =	11.43830	DELTA ENBY =	316.96974
TIME =	11.53830	DELTA ENBY =	318.62509
TIME =	11.63830	DELTA ENBY =	319.96655
TIME =	11.73831	DELTA ENBY =	320.99393
TIME =	11.83831	DELTA ENBY =	321.70694
TIME =	11.93831	DELTA ENBY =	322.10284

TOTAL ENBY =	822.20636
TOTAL ENBY =	1019.93459
TOTAL ENBY =	1223.79309
TOTAL ENBY =	1439.54065
TOTAL ENBY =	1660.93823
TOTAL ENBY =	1889.73914
TOTAL ENBY =	2125.69189
TOTAL ENBY =	2368.53882
TOTAL ENBY =	2618.92026
TOTAL ENBY =	2873.86938
TOTAL ENBY =	3135.81616
TOTAL ENBY =	3403.58765
TOTAL ENBY =	3676.90405
TOTAL ENBY =	3955.48484
TOTAL ENBY =	4239.04199
TOTAL ENBY =	4527.28809
TOTAL ENBY =	4819.93066
TOTAL ENBY =	5116.67480
TOTAL ENBY =	5417.22070
TOTAL ENBY =	5721.26904
TOTAL ENBY =	6028.51709
TOTAL ENBY =	6338.65849
TOTAL ENBY =	6651.38623
TOTAL ENBY =	6964.39014
TOTAL ENBY =	7283.35986
TOTAL ENBY =	7601.98486
TOTAL ENBY =	7921.95166
TOTAL ENBY =	8242.94531
TOTAL ENBY =	8564.65234
TOTAL ENBY =	8884.75488

ENERGY COLLECTED AFTER STEADY STATE = 8262.76270 AVAILABLE SOLAR ENERGY AFTER STEADY STATE = 16042.42671

EFFICIENCY AFTER STEADY STATE = 51.50348

TOTAL DAILY ENERGY COLLECTED = 8906.57910

AVAILABLE DAILY SOLAR ENERGY = 22918.34375

DAILY EFFICIENCY = 38.84223

OMEGA.....	0.24180
TAU FC.....	1.42500
START TIME.....	6.00000
INITIAL TEMP.....	0.00000
AMBIENT TEMP.....	0.00000
COLLECTOR AREA.....	2.00000
PEAK SOLAR INSOLATION.....	3000.00000
T1, PUMP TURN ON TEMP.....	46.00000
T1 SEARCH TERM VAL.....	0.00100
TIME STEP INCR.....	0.30000
T2, PUMP TURN OFF TEMP.....	41.50000
MIXED STORAGE TEMP.....	40.00000
PT.C TIME STEP.....	0.00500
PT.D TIME STEP.....	0.20000
PT.D NO. OF TIME STEPS....	5.00000
COLL TAU ALPHA PRODUCT....	0.82810
COLL GEOM EFF COEFF.....	0.95000
COLLECTOR FLOW RATE.....	170.00000
FLUID SPECIFIC HEAT.....	4.19000
COLL LOSS COEFF.....	18.65000
COLL CAPACITANCE.....	10.22000
Z.BNDRY MATCH PARAMETER...	0.00200

BASE STEADY STATE TIME = 8.14395

TA =	4.00000	TFCA(T) =	0.00000
TA =	4.50000	TFCA(T) =	2.72652
TA =	7.00000	TFCA(T) =	9.75219
TA =	7.50000	TFCA(T) =	19.67076
TA =	8.00000	TFCA(T) =	31.40703
TA =	8.50000	TFCA(T) =	44.12269
TA =	8.57244	TFCA(T) =	46.00535
TB =	8.57820	TFCB(T) =	46.36788
TB =	8.58394	TFCB(T) =	46.73368
TB =	8.58968	TFCB(T) =	47.09740
TB =	8.59542	TFCB(T) =	47.45905
TB =	8.60116	TFCB(T) =	47.81868
TC =	8.60616	TFCB(T) =	42.11642

STEADY STATE TIME = 8.61116 STEADY STATE TFC = 42.12300

ENERGY COLLECTED FROM ABOVE CYCLE = 176.63632

AVAILABLE SOLAR ENERGY = 5149.64844

CYCLE EFFICIENCY = 3.43007

COLLECTED ENERGY SUMMARY

TIME=	8.57246	DELTA ENGY=	4.90565	TOTAL ENGY=	4.90565
TIME=	8.57361	DELTA ENGY=	4.96596	TOTAL ENGY=	9.87161
TIME=	8.57476	DELTA ENGY=	5.02622	TOTAL ENGY=	14.89783
TIME=	8.57590	DELTA ENGY=	5.08638	TOTAL ENGY=	19.98421
TIME=	8.57705	DELTA ENGY=	5.14650	TOTAL ENGY=	25.13071
TIME=	8.57820	DELTA ENGY=	5.20653	TOTAL ENGY=	30.33725
TIME=	8.57935	DELTA ENGY=	5.26651	TOTAL ENGY=	35.60375
TIME=	8.58050	DELTA ENGY=	5.32642	TOTAL ENGY=	40.93017
TIME=	8.58165	DELTA ENGY=	5.38624	TOTAL ENGY=	46.31642
TIME=	8.58279	DELTA ENGY=	5.44601	TOTAL ENGY=	51.76243
TIME=	8.58394	DELTA ENGY=	5.50571	TOTAL ENGY=	57.26814
TIME=	8.58509	DELTA ENGY=	5.56534	TOTAL ENGY=	62.83347
TIME=	8.58624	DELTA ENGY=	5.62496	TOTAL ENGY=	68.45843
TIME=	8.58739	DELTA ENGY=	5.68440	TOTAL ENGY=	74.14277
TIME=	8.58853	DELTA ENGY=	5.74383	TOTAL ENGY=	79.88660
TIME=	8.58968	DELTA ENGY=	5.80318	TOTAL ENGY=	85.68977
TIME=	8.59083	DELTA ENGY=	5.86248	TOTAL ENGY=	91.55225
TIME=	8.59198	DELTA ENGY=	5.92170	TOTAL ENGY=	97.47396
TIME=	8.59313	DELTA ENGY=	5.98086	TOTAL ENGY=	103.45482
TIME=	8.59428	DELTA ENGY=	6.03995	TOTAL ENGY=	109.49477
TIME=	8.59542	DELTA ENGY=	6.09898	TOTAL ENGY=	115.59375
TIME=	8.59657	DELTA ENGY=	6.15793	TOTAL ENGY=	121.75168
TIME=	8.59772	DELTA ENGY=	6.21682	TOTAL ENGY=	127.96850
TIME=	8.59887	DELTA ENGY=	6.27565	TOTAL ENGY=	134.24416
TIME=	8.60002	DELTA ENGY=	6.33440	TOTAL ENGY=	140.57855
TIME=	8.60116	DELTA ENGY=	5.56936	TOTAL ENGY=	146.14792
TIME=	8.60216	DELTA ENGY=	5.56960	TOTAL ENGY=	151.71751
TIME=	8.60316	DELTA ENGY=	1.50475	TOTAL ENGY=	153.22226
TIME=	8.60416	DELTA ENGY=	1.50568	TOTAL ENGY=	154.72794
TIME=	8.60516	DELTA ENGY=	1.50662	TOTAL ENGY=	156.23456
TIME=	8.60616	DELTA ENGY=	1.50757	TOTAL ENGY=	157.74213
TIME=	8.60716	DELTA ENGY=	1.50850	TOTAL ENGY=	159.25063
TIME=	8.60816	DELTA ENGY=	1.50944	TOTAL ENGY=	160.76007
TIME=	8.60916	DELTA ENGY=	1.51039	TOTAL ENGY=	162.27046
TIME=	8.61016	DELTA ENGY=	1.51132	TOTAL ENGY=	163.78178

TOTAL ENERGY COLLECTED TO STEADY STATE = 176.63632

TOTAL SOLAR ENERGY TO STEADY STATE = 5149.64844

STEADY STATE EFFICIENCY = 3.43007

TC =	8.71116	TFCC(T) =	42.23321
TE =	8.81116	TFCC(T) =	42.38054
TC =	8.91116	TFCC(T) =	42.50490
TC =	9.01116	TFCC(T) =	42.62623
TC =	9.11116	TFCC(T) =	42.74442
TC =	9.21116	TFCC(T) =	42.85939
TC =	9.31116	TFCC(T) =	42.97108
TC =	9.41116	TFCC(T) =	43.07939
TC =	9.51116	TFCC(T) =	43.18428
TC =	9.61116	TFCC(T) =	43.28565
TC =	9.71116	TFCC(T) =	43.38344
TC =	9.81116	TFCC(T) =	43.47757
TC =	9.91116	TFCC(T) =	43.56800
TC =	10.01116	TFCC(T) =	43.65463
TC =	10.11116	TFCC(T) =	43.73743
TC =	10.21116	TFCC(T) =	43.81636
TC =	10.31116	TFCC(T) =	43.89134
TC =	10.41116	TFCC(T) =	43.96231
TC =	10.51116	TFCC(T) =	44.02924
TC =	10.61116	TFCC(T) =	44.09208
TC =	10.71116	TFCC(T) =	44.15078
TC =	10.81116	TFCC(T) =	44.20530
TC =	10.91116	TFCC(T) =	44.25561
TC =	11.01116	TFCC(T) =	44.30169
TC =	11.11117	TFCC(T) =	44.34348
TC =	11.21117	TFCC(T) =	44.38097
TC =	11.31117	TFCC(T) =	44.41412
TC =	11.41117	TFCC(T) =	44.44291
TC =	11.51117	TFCC(T) =	44.46731
TC =	11.61117	TFCC(T) =	44.48735
TC =	11.71117	TFCC(T) =	44.50297
TC =	11.81117	TFCC(T) =	44.51416
TC =	11.91117	TFCC(T) =	44.52095
TC =	12.01117	TFCC(T) =	44.52330

TIME=	8.61116	DELTA ENGY=	151.22165	TOTAL ENGY=	315.00345
TIME=	8.71116	DELTA ENGY=	160.49602	TOTAL ENGY=	475.49948
TIME=	8.81116	DELTA ENGY=	169.36578	TOTAL ENGY=	645.06525
TIME=	8.91116	DELTA ENGY=	178.42416	TOTAL ENGY=	823.48944
TIME=	9.01116	DELTA ENGY=	187.06624	TOTAL ENGY=	1010.55566
TIME=	9.11116	DELTA ENGY=	195.48497	TOTAL ENGY=	1206.04063
TIME=	9.21116	DELTA ENGY=	203.67464	TOTAL ENGY=	1409.71533
TIME=	9.31116	DELTA ENGY=	211.62981	TOTAL ENGY=	1621.34509
TIME=	9.41116	DELTA ENGY=	219.34477	TOTAL ENGY=	1840.68982
TIME=	9.51116	DELTA ENGY=	226.81628	TOTAL ENGY=	2067.50610
TIME=	9.61116	DELTA ENGY=	234.03673	TOTAL ENGY=	2301.54272
TIME=	9.71116	DELTA ENGY=	241.00230	TOTAL ENGY=	2542.54492
TIME=	9.81116	DELTA ENGY=	247.70702	TOTAL ENGY=	2790.25195
TIME=	9.91116	DELTA ENGY=	254.14868	TOTAL ENGY=	3044.40063
TIME=	10.01116	DELTA ENGY=	260.31949	TOTAL ENGY=	3304.72021
TIME=	10.11116	DELTA ENGY=	266.21747	TOTAL ENGY=	3570.93774
TIME=	10.21116	DELTA ENGY=	271.83963	TOTAL ENGY=	3842.77734
TIME=	10.31116	DELTA ENGY=	277.18002	TOTAL ENGY=	4119.95732
TIME=	10.41116	DELTA ENGY=	282.23541	TOTAL ENGY=	4402.19287
TIME=	10.51116	DELTA ENGY=	287.00247	TOTAL ENGY=	4689.19531
TIME=	10.61116	DELTA ENGY=	291.47906	TOTAL ENGY=	4980.67432
TIME=	10.71116	DELTA ENGY=	295.66003	TOTAL ENGY=	5276.33447
TIME=	10.81116	DELTA ENGY=	299.54376	TOTAL ENGY=	5575.87842
TIME=	10.91116	DELTA ENGY=	303.12720	TOTAL ENGY=	5879.00584
TIME=	11.01116	DELTA ENGY=	306.40903	TOTAL ENGY=	6185.41504
TIME=	11.11117	DELTA ENGY=	309.38574	TOTAL ENGY=	6494.80078
TIME=	11.21117	DELTA ENGY=	312.05649	TOTAL ENGY=	6806.85742
TIME=	11.31117	DELTA ENGY=	314.41748	TOTAL ENGY=	7121.27490
TIME=	11.41117	DELTA ENGY=	316.46814	TOTAL ENGY=	7437.74316
TIME=	11.51117	DELTA ENGY=	318.20663	TOTAL ENGY=	7753.94971
TIME=	11.61117	DELTA ENGY=	319.63397	TOTAL ENGY=	8075.58350
TIME=	11.71117	DELTA ENGY=	320.74667	TOTAL ENGY=	8396.33008
TIME=	11.81117	DELTA ENGY=	321.54364	TOTAL ENGY=	8717.87402
TIME=	11.91117	DELTA ENGY=	322.02731	TOTAL ENGY=	9039.90137

ENERGY COLLECTED AFTER STEADY STATE = 8965.69043

AVAILABLE SOLAR ENERGY AFTER STEADY STATE = 17768.69531

EFFICIENCY AFTER STEADY STATE = 50.45779

TOTAL DAILY ENERGY COLLECTED = 9142.32715

AVAILABLE DAILY SOLAR ENERGY = 22918.34375

DAILY EFFICIENCY = 39.89087

APPENDIX F

RT-11 FORTRAN IV

V01B-08

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PAGE 001

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DREXEL UNIVERSITYA SOLAR COLLECTOR MODEL
INCORPORATING PUMP CYCLINGAPRIL 6, 1979

-SKJ-

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0001 LOGICAL*1 STRING(32)
0002 LOGICAL*1 IY(4)
0003 COMMON /DICK/W,TAU0,TOS,TO,TA,AC,TFCA1,T2,Z,TS,T1
0004 COMMON/DICK1/STPB,TAU2,TAU1,TRNON,TFCC1,TFCB1,
1TRNOFF,TFCD1
0005 DATA STOW1,STOW2,STOW3,STOW4,STOW5,STOW6,STOW7,STOW8,STOW9,
CSTOW10,STOW11,STOW12,STOW13,STOW14,STOW15,STOW16,STOW17,STOW18,
CSTOW19,STOW20,STOW21,STOW22 /22*0.0/
0006 DATA XXD1,XXD2,XXD3,XXD4,XXD5,XXD6,XXD7,XXD8,XXD9,XXD10,XXD11,
CXXD12,XXD13,XXD14,XXD15,XXD16,XXD17,XXD18,XXD19,XXD20,
CXXD21,XXD22 /22*0.0/
0007 DATA AREA,TAUAL,EGEON,COLLOS,COLCAP /5*0.0/
0008 DATA COLK,FLOW/0.0,1.0/
0009 DATA IY/' ',' ','Y','N'/
0010 DATA W,TAU0,TOS,TO,TA,AC,T1,DIFF,DELTA,
1T2,TS,BELC,DELD,STPB,TAU1,TAU2,Z
1/0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,
10.,0.,0.,0./
0011 TENGY=0.0
0012 SOLIN=0.0
0013 CPF=0.0
0014 WRITE(5,10000)
0015 10000 FORMAT(/,30X,'COLLECTOR-CYCLING MODEL',/,/,/,/,/)
0016 LUN=5
0017 11006 CONTINUE
0018 WRITE(5,11002)
0019 11002 FORMAT('DO YOU WISH TO INPUT DATA FILE, Y OR N?',4X)
0020 CALL IPOKE('44','10000.OR.IPEEK('44))
0021 11009 IFILE=ITTRN()
0022 IF(IFILE.LT.0) GO TO 11009
0024 CALL IPOKE('44','07777.AND.IPEEK('44))
0025 11010 IF(ITTOUR(IFILE).NE.0) GO TO 11010
0027 WRITE(5,1818)
0028 IF(IFILE.EQ.IY(4)) IJK=0
0030 IF(IFILE.EQ.IY(4)) GO TO 1301

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```
0032      IF(IFILE.NE.IY(3).AND.IFILE.NE.IY(4)) GO TO 11006
0034      WRITE(5,11000)
0035 11000 FORMAT('**')
0036      ACCEPT 11001,KNT,STRING
0037 11001 FORMAT(Q,32A1)
0038      CALL ASSIGN(1,STRING,KNT)
0039      READ(1,11008) W,TAUO,TOS,TO,TA,AREA,SOLIN,T1,DIFF,DELTA,
      CT2,TS,DELC,DELD,STPB,TAUAL,EGEOM,FLOW,CPF,COLLOS,
      C COLCAP,Z
0040 11008 FORMAT(22(G11.5))
0041      IJK=1
0042      GO TO 11020
0043 78      CONTINUE
0044      WRITE(5,10032)
0045      IF(ISK.EQ.0) GO TO 10031
0047      ITMAX=ITMAX-1
0048      IF(ITMAX.LE.0) GO TO 10082
0050      GO TO 10084
0051      GO TO 10082
0052 11111 WRITE(5,10091)
0053 10091 FORMAT(' *****
      CTERMINATED *****',66(/))
0054 10082 CONTINUE
0055      ISK=0
      C
      C RETURN PERTURBED PARAMETERS TO INITIAL OPERATING POINT VALUES
      C
0056      W=STOW1
0057      TAUO=STOW2
0058      TOS=STOW3
0059      TO=STOW4
0060      TA=STOW5
0061      AREA=STOW6
0062      SOLIN=STOW7
0063      T1=STOW8
0064      DIFF=STOW9
0065      DELTA=STOW10
0066      T2=STOW11
0067      TS=STOW12
0068      DELC=STOW13
0069      DELD=STOW14
0070      STPB=STOW15
0071      TAUAL=STOW16
0072      EGEOM=STOW17
0073      FLOW=STOW18
0074      CPF=STOW19
0075      COLLOS=STOW20
0076      COLCAP=STOW21
0077      Z=STOW22
0078      GO TO 1301
0079 10084 CONTINUE
      C
      C UPDATE PARAMETERS
      C
0080 10032 FORMAT(66(/))
0081      T1=T1+TA
0082      T2=T2+TA
```

```
0083      TS=TS+TA
0084      W=W+XXD1
0085      TAU0=TAU0+XXD2
0086      TOS=TOS+XXD3
0087      TO=TO+XXD4
0088      TA=TA+XXD5
0089      AREA=AREA+XXD6
0090      SOLIN=SOLIN+XXD7
0091      T1=T1+XXD8
0092      DIFF=DIFF+XXD9
0093      DELTA=DELTA+XXD10
0094      T2=T2+XXD11
0095      TS=TS+XXD12
0096      DELC=DELC+XXD13
0097      DELD=DELD+XXD14
0098      STPB=STPB+XXD15
0099      TAUAL=TAUAL+XXD16
0100      EGEOM=EGEOM+XXD17
0101      FLOW=FLOW+XXD18
0102      CPF=CPF+XXD19
0103      COLLOS=COLLOS+XXD20
0104      COLCAP=COLCAP+XXD21
0105      Z=Z+XXD22
```

C

C WRITE UPDATED PARAMETERS

C

```
0106 11020 CONTINUE
0107      WRITE(5,1302) W
0108      WRITE(5,1818)
0109      WRITE(5,1012) TAU0
0110      WRITE(5,1818)
0111      WRITE(5,1022) TOS
0112      WRITE(5,1818)
0113      WRITE(5,1032) TO
0114      WRITE(5,1818)
0115      WRITE(5,1042) TA
0116      WRITE(5,1818)
0117      WRITE(5,1052) AREA
0118      WRITE(5,1818)
0119      WRITE(5,1054) SOLIN
0120      WRITE(5,1818)
0121      WRITE(5,1062) T1
0122      WRITE(5,1818)
0123      WRITE(5,1072) DIFF
0124      WRITE(5,1818)
0125      WRITE(5,1082) DELTA
0126      WRITE(5,1818)
0127      WRITE(5,1092) T2
0128      WRITE(5,1818)
0129      WRITE(5,1102) TS
0130      WRITE(5,1818)
0131      WRITE(5,1112) DELC
0132      WRITE(5,1818)
0133      WRITE(5,1122) DELD
0134      WRITE(5,1818)
0135      WRITE(5,1132) STPB
0136      WRITE(5,1818)
```

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0137      WRITE(S,1142) TAUAL
0138      WRITE(S,1818)
0139      WRITE(S,1152) EGEOM
0140      WRITE(S,1818)
0141      WRITE(S,1154) FLOW
0142      WRITE(S,1818)
0143      WRITE(S,1251) CPF
0144      WRITE(S,1818)
0145      WRITE(S,1252) COLLOS
0146      WRITE(S,1818)
0147      WRITE(S,1253) COLCAP
0148      WRITE(S,1818)
0149      WRITE(S,1162) Z
0150      WRITE(S,10033)
0151 10033 FORMAT(1X,/,1X,/)
0152      IF(IJK.EQ.1) GO TO 1912
0154      GO TO 10046
0155 10031 CONTINUE
0156      LUR=1
0157 88      FORMAT(0,F11.5)
0158      T1=T1+TA
0159      T2=T2+TA
0160      TS=TS+TA
0161 1301 WRITE(S,1302) W
0162 1302 FORMAT('$OMEGA.....',F11.5,4X)
0163      ACCEPT 88,NC,AI
0164      IF(NC.EQ.0) GO TO 1011
0166      W=AI
0167 1011 WRITE(S,1012)TAUD
0168 1012 FORMAT('$TAU FC.....',F11.5,4X)
0169      ACCEPT 88,NC,BI
0170      IF(NC.EQ.0) GO TO 1021
0172      TAUO=BI
0173 1021      WRITE(S,1022) TOS
0174 1022 FORMAT('$START TIME.....',F11.5,4X)
0175      ACCEPT 88,NC,CI
0176      IF(NC.EQ.0) GO TO 1031
0178      TOS = CI
0179 1031 WRITE(S,1032)TO
0180 1032 FORMAT('$INITIAL TEMP.....',F11.5,4X)
0181      ACCEPT 88,NC,DI
0182      IF(NC.EQ.0)GO TO 1041
0184      TO=DI
0185 1041 WRITE(S,1042) TA
0186 1042 FORMAT('$AMBIENT TEMP.....',F11.5,4X)
0187      ACCEPT 88,NC,EI
0188      IF(NC.EQ.0) GO TO 1051
0190      TA=EI
0191 1051 WRITE(S,1052) AREA
0192 1052 FORMAT('$COLLECTOR AREA.....',F11.5,4X)
0193      ACCEPT 88,NC,FI
0194      IF(NC.EQ.0) GO TO 1053
0196      AREA=FI
0197 1053 WRITE(S,1054)SOLIN
0198 1054 FORMAT('$PEAK SOLAR INSOLATION.....',F11.5,4X)
0199      ACCEPT 88,NC,SOLINI
0200      IF(NC.EQ.0) SOLIN=SOLINI

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```
0202 1061 WRITE(5,1062) T1
0203 1062 FORMAT('T1, PUMP TURN ON TEMP.....',F11.5,4X)
0204 ACCEPT 88,NC,PI
0205 IF(NC.EQ.0) GO TO 1071
0207 T1=PI
0208 1071 WRITE(5,1072) DIFF
0209 1072 FORMAT('T1 SEARCH TERM VAL.....',F11.5,4X)
0210 ACCEPT 88,NC,TAI
0211 IF(NC.EQ.0) GO TO 1081
0213 DIFF=TAI
0214 1081 WRITE(5,1082) DELTA
0215 1082 FORMAT('TIME STEP INCR.....',F11.5,4X)
0216 ACCEPT 88,NC,TBI
0217 IF(NC.EQ.0) GO TO 1091
0219 DELTA=TBI
0220 1091 WRITE(5,1092) T2
0221 1092 FORMAT('T2, PUMP TURN OFF TEMP.....',F11.5,4X)
0222 ACCEPT 88,NC,TCI
0223 IF(NC.EQ.0) GO TO 1101
0225 T2=TCI
0226 1101 WRITE(5,1102) TS
0227 1102 FORMAT('MIXED STORAGE TEMP.....',F11.5,4X)
0228 ACCEPT 88,NC,TDI
0229 IF(NC.EQ.0) GO TO 1111
0231 TS=TDI
0232 1111 WRITE(5,1112) DELC
0233 1112 FORMAT('PT.C TIME STEP.....',F11.5,4X)
0234 ACCEPT 88,NC,TEI
0235 IF(NC.EQ.0) GO TO 1121
0237 DELC=TEI
0238 1121 WRITE(5,1122) DELD
0239 1122 FORMAT('PT.D TIME STEP.....',F11.5,4X)
0240 ACCEPT 88,NC,TFI
0241 IF(NC.EQ.0) GO TO 1131
0243 DELD=TFI
0244 1131 WRITE(5,1132) STPB
0245 1132 FORMAT('PT.B NO. OF TIME STEPS.....',F11.5,4X)
0246 ACCEPT 88,NC,TGI
0247 IF(NC.EQ.0) GO TO 1141
0249 STPB=TGI
0250 1141 WRITE(5,1142) TAUAL
0251 1142 FORMAT('COLL TAU ALPHA PRODUCT.....',F11.5,4X)
0252 ACCEPT 88,NC,THI
0253 IF(NC.EQ.0) GO TO 1151
0255 TAUAL=THI
0256 1151 WRITE(5,1152) EGEOH
0257 1152 FORMAT('COLL GEOM EFF COEFF.....',F11.5,4X)
0258 ACCEPT 88,NC,CIK
0259 IF(NC.NE.0) EGEOH=CIK
0261 1153 WRITE(5,1154) FLOW
0262 1154 FORMAT('COLLECTOR FLOW RATE.....',F11.5,4X)
0263 ACCEPT 88,NC,FLOWI
0264 IF(FLOWI.EQ.0.0.AND.NC.NE.0) GO TO 1153
0266 GO TO 1159
0267 1158 FORMAT(' ***ERROR COLLECTOR FLOW IS ZERO***')
0268 1155 WRITE(5,1158)
0269 GO TO 1153
```



```
0270 1159 IF(NC.NE.0) FLOW=FLOWI
0272 WRITE(5,1251) CPF
0273 1251 FORMAT('FLUID SPECIFIC HEAT.....',F11.5,4X)
0274 ACCEPT 88,NC,CPFI
0275 IF(NC.NE.0) CPF=CPFI
0277 WRITE(5,1252) COLLOS
0278 1252 FORMAT('COLL LOSS COEFF.....',F11.5,4X)
0279 ACCEPT 88,NC,COLLOI
0280 IF(NC.NE.0) COLLOS=COLLOI
0282 WRITE(5,1253) COLCAP
0283 1253 FORMAT('COLL CAPACITANCE.....',F11.5,4X)
0284 ACCEPT 88,NC,COLCAI
0285 IF(NC.NE.0) COLCAP=COLCAI
0287 1161 WRITE(5,1162) Z
0288 1162 FORMAT('Z,BNDRY MATCH PARAMETER...',F11.5,4X)
0289 ACCEPT 88,NC,TJI
0290 IF(NC.NE.0) Z=TJI
```

C

C STORE OPERATING POINT PARAMETER VALUES IN STOWXX FOR EOC REFERENCE

C

```
0292 1912 CONTINUE
0293 STOW1=W
0294 STOW2=TAUQ
0295 STOW3=TOS
0296 STOW4=TQ
0297 STOW5=TA
0298 STOW6=AREA
0299 STOW7=SOLIN
0300 STOW8=T1
0301 STOW9=DIFF
0302 STOW10=DELTA
0303 STOW11=T2
0304 STOW12=TS
0305 STOW13=DELC
0306 STOW14=DELD
0307 STOW15=STPB
0308 STOW16=TAUAL
0309 STOW17=EGEOM
0310 STOW18=FLOW
0311 STOW19=CPF
0312 STOW20=COLLOS
0313 STOW21=COLCAP
0314 STOW22=Z
0315 IJK=0
0316 1812 WRITE(5,98)
0317 98 FORMAT(' $ INITIALIZATION VERIFIED Y OR N? ')
0318 CALL IPOKE('44','10000,OR,IPEEK('44))
0319 168 I=ITINR()
0320 IF(I.LT.0) GO TO 168
0322 CALL IPOKE('44','07777.AND,IPEEK('44))
0323 IF(I.EQ.IY(4)) GO TO 8
0325 878 IF(ITTOUR(I).NE.0) GO TO 878
0327 WRITE(5,1818)
0328 GO TO 1234
0329 8 IF(ITTOUR(I).NE.0) GO TO 8
0331 WRITE(5,1818)
0332 1818 FORMAT('') F-6
```

```
0333      GO TO 1301
0334      1234 CONTINUE
      C
      C REQUEST FOR PERTURBATION OF PARAMETERS MODE
      C
0335      10003 WRITE(5,10001)
0336      10001 FORMAT(' DO YOU WISH AUTOPERTURBATION OF PARAMETERS, Y OR N ?')
0337      CALL IPOKE('44','10000.OR.IPEEK('44'))
0338      10002 I=ITFINR()
0339      IF(I.LT.0)GO TO 10002
0341      CALL IPOKE('44','07777.AND.IPEEK('44'))
0342      IF(I.EQ.IY(3)) ISK=1
0344      IF(I.EQ.IY(4)) ISK=0
0346      IF(I.NE.IY(3).AND.I.NE.IY(4)) GO TO 10003
0348      10004 IF(ITTOUR(I).NE.0) GO TO 10004
0350      WRITE(5,1818)
0351      IF(ISK.EQ.0) GO TO 10030
      C
      C INPUT ROUTINE FOR PETURBATION CHANGES
      C
0353      10124 CONTINUE
0354      WRITE(5,10005) XXD1
0355      10005 FORMAT(' $DELTA OMEGA.....',F11.5,4X)
0356      ACCEPT 88,NC,XX
0357      IF(NC.NE.0) XXD1=XX
0359      WRITE(5,10006) XXD2
0360      10006 FORMAT(' $DELTA TAU FC.....',F11.5,4X)
0361      ACCEPT 88,NC,XX
0362      IF(NC.NE.0) XXD2=XX
0364      WRITE(5,10007) XXD3
0365      10007 FORMAT(' $DELTA START TIME.....',F11.5,4X)
0366      ACCEPT 88,NC,XX
0367      IF(NC.NE.0) XXD3=XX
0369      WRITE(5,10008) XXD4
0370      10008 FORMAT(' $DELTA INITIAL TEMP.....',F11.5,4X)
0371      ACCEPT 88,NC,XX
0372      IF(NC.NE.0) XXD4=XX
0374      WRITE(5,10009) XXD5
0375      10009 FORMAT(' $DELTA AMBIENT TEMP.....',F11.5,4X)
0376      ACCEPT 88,NC,XX
0377      IF(NC.NE.0) XXD5=XX
0379      WRITE(5,10010) XXD6
0380      10010 FORMAT(' $DELTA COLLECTOR AREA.....',F11.5,4X)
0381      ACCEPT 88,NC,XX
0382      IF(NC.NE.0) XXD6=XX
0384      WRITE(5,10011) XXD7
0385      10011 FORMAT(' $DELTA PEAK SOLAR INSOLATION...',F11.5,4X)
0386      ACCEPT 88,NC,XX
0387      IF(NC.NE.0) XXD7=XX
0389      WRITE(5,10012) XXD8
0390      10012 FORMAT(' $DELTA PUMP TURN ON TEMP.....',F11.5,4X)
0391      ACCEPT 88,NC,XX
0392      IF(NC.NE.0) XXD8=XX
0394      WRITE(5,10013) XXD9
0395      10013 FORMAT(' $DELTA SEARCH TERM VAL.....',F11.5,4X)
0396      ACCEPT 88,NC,XX
0397      IF(NC.NE.0) XXD9=XX
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0399      WRITE(5,10014) XXD10
0400 10014 FORMAT('$DELTA TIME STEP INCR.....',F11.5,4X)
0401      ACCEPT 88,NC,XX
0402      IF(NC.NE.0) XXD10=XX
0404      WRITE(5,10015) XXD11
0405 10015 FORMAT('$DELTA PUMP TURN OFF TEMP.....',F11.5,4X)
0406      ACCEPT 88,NC,XX
0407      IF(NC.NE.0) XXD11=XX
0409      WRITE(5,10016) XXD12
0410 10016 FORMAT('$DELTA MIXED STORAGE TEMP.....',F11.5,4X)
0411      ACCEPT 88,NC,XX
0412      IF(NC.NE.0) XXD12=XX
0414      WRITE(5,10017) XXD13
0415 10017 FORMAT('$DELTA PT. C TIME STEP.....',F11.5,4X)
0416      ACCEPT 88,NC,XX
0417      IF(NC.NE.0) XXD13=XX
0419      WRITE(5,10018) XXD14
0420 10018 FORMAT('$DELTA PT. D TIME STEP.....',F11.5,4X)
0421      ACCEPT 88,NC,XX
0422      IF(NC.NE.0) XXD14=XX
0424      WRITE(5,10019) XXD15
0425 10019 FORMAT('$DELTA PT. B NO. OF TIME STEPS.',F11.5,4X)
0426      ACCEPT 88,NC,XX
0427      IF(NC.NE.0) XXD15=XX
0429      WRITE(5,10020) XXD16
0430 10020 FORMAT('$DELTA COLL TAU ALPHA PRODUCT..',F11.5,4X)
0431      ACCEPT 88,NC,XX
0432      IF(NC.NE.0) XXD16=XX
0434      WRITE(5,10021) XXD17
0435 10021 FORMAT('$DELTA COLL GEOM EFF COEFF.....',F11.5,4X)
0436      ACCEPT 88,NC,XX
0437      IF(NC.NE.0) XXD17=XX
0439      WRITE(5,10022) XXD18
0440 10022 FORMAT('$DELTA COLLECTOR FLOW RATE.....',F11.5,4X)
0441      ACCEPT 88,NC,XX
0442      IF(NC.NE.0) XXD18=XX
0444      WRITE(5,10023) XXD19
0445 10023 FORMAT('$DELTA FLUID SPECIFIC HEAT.....',F11.5,4X)
0446      ACCEPT 88,NC,XX
0447      IF(NC.NE.0) XXD19=XX
0449      WRITE(5,10024) XXD20
0450 10024 FORMAT('$DELTA COLL LOSS COEFF.....',F11.5,4X)
0451      ACCEPT 88,NC,XX
0452      IF(NC.NE.0) XXD20=XX
0454      WRITE(5,10025) XXD21
0455 10025 FORMAT('$DELTA COLL CAPACITANCE.....',F11.5,4X)
0456      ACCEPT 88,NC,XX
0457      IF(NC.NE.0) XXD21=XX
0459      WRITE(5,10026) XXD22
0460 10026 FORMAT('$DELTA Z,BNDRY MATCH PARAMETER.',F11.5,4X)
0461      ACCEPT 88,NC,XX
0462      IF(NC.NE.0) XXD22=XX
      C
      C
      C
0464      WRITE(5,10121)
0465 10121 FORMAT('$ PERTURBATIONS VERIFIED, Y OR N ?',4X)
```

```

0466      CALL IPOKE('44','10000.0R,IPEEK('44'))
0467 10122 I=ITTINR()
0468      IF(I.LT.0) GO TO 10122
0470      CALL IPOKE('44','07777.AND,IPEEK('44'))
0471      IF(I.EQ.IY(4)) IV=1
0473      IF(I.EQ.IY(3)) IV=0
0475 10123 IF(ITTOUT(I).NE.0) GO TO 10123
0477      WRITE(5,1818)
0478      IF(IV.EQ.1) GO TO 10124
C
C  TEMPERATURES AFTER STEADY STATE REQUEST
C
0480      WRITE(5,1004)
0481      CALL IPOKE('44','10000.0R,IPEEK('44'))
0482 10125 I=ITTINR()
0483      IF(I.LT.0) GO TO 10125
0485      CALL IPOKE('44','07777.AND,IPEEK('44'))
0486      IF(I.EQ.IY(3)) ISKJ=1
0488      IF(I.EQ.IY(4)) ISKJ=0
0490 10126 IF(ITTOUT(I).NE.0) GO TO 10126
0492      IF(ISKJ.NE.1) GO TO 10128
0494      WRITE(5,1818)
0495      WRITE(5,1006)
0496      ACCEPT 1007,DELC1
0497      WRITE(5,1008)
0498      ACCEPT 1009,TMAX
0499 10128 WRITE(5,1818)
C
C  INPUT DESIRED NUMBER OF ITERATIONS
C
0500      WRITE(5,10028)
0501 10028 FORMAT('TYPE NUMBER OF ITERATIONS (00 TO 99 INTEGER FORMAT)',4X)
0502      ACCEPT 10029,ITMAX
0503 10029 FORMAT(I2)
0504 10030 CONTINUE
0505      WRITE(LUM,111)
0506 111      FORMAT('DO YOU WISH ALL INTERMEDIATE VALUES OF TC?
1 Y OR N? ')
0507      CALL IPOKE('44','10000.0R,IPEEK('44'))
0508 169 I=ITTINR()
0509      IF(I.LT.0) GO TO 169
0511      CALL IPOKE('44','07777.AND,IPEEK('44'))
0512      IF(I.EQ.IY(3)) SW1=0.
0514      IF(I.EQ.IY(4)) SW1=1.
0516 7891 IF(ITTOUT(I).NE.0) GO TO 7891
0518      WRITE(5,1818)
0519 10046 CONTINUE
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C COMPUTATION OF CONSTANTS FROM INPUT DATA XXXXXXXXXXXXXXXXXXXX
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0520      TAU2=COLCAP*AREA*(1./FLOW)*(1./CPF)
0521      TAU1=COLCAP/(COLLOS*EGEOM)
0522      AC=(SOLIN*TAUAL)/COLLOS
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
C DAILY PARAMETER INITIALIZATION XXXXXXXXXXXXXXXXXXXXXXXX
CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0523      STIMED=0.0

```

[illegible]

```

0566      IF ((FNEG*FPOS) .GT. 0.) GO TO 200
0568 30      TX=(TPOS*FNEG-T*FPOS)/(FNEG-FPOS)
0569      CALL TFCA(TX)
0570      FX=TFCA1
0571      IF (FPOS*FX) 301,400,300
0572 301      T=TX
0573      FPOS=FPOS/2.
0574 20      TEST= ABS(T-TPOS)
0575      IF (TEST .LE. DIFF) GO TO 400
0577      GO TO 30
0578 300      TPOS=TX
0579      FPOS=FX
0580      FNEG=FNEG/2.
0581      GO TO 20
0582 200      FPOS=FNEG
0583      TPOS=T
0584      IF (SW1 .EQ. 1.) GO TO 10
0586      FPOS1=FPOS +T1
0587      FPOS10=FPOS1+TA
0588      CALL IPOKE('44','10000.OR.IPEEK('44))
0589      WRITE(LUN,1000)TPOS,FPOS10
0590      I=ITTIMR()
0591      CALL IPOKE ('44','07777.AND.IPEEK('44))
0592      IF(I.EQ.IY(1)) GO TO 11111
0594      GO TO 10
0595 400      CALL TFCA(T)
0596      TFCA1=TFCA1+T1
0597      TFCA10=TFCA1+TA
0598      CALL IPOKE('44','10000.OR.IPEEK('44))
0599      WRITE(LUN,1000)T,TFCA10
0600      I=ITTIMR()
0601      CALL IPOKE ('44','07777.AND.IPEEK('44))
0602      IF(I.EQ.IY(1)) GO TO 11111
0604 1000      .FORMAT(IX, 'TA = ',F11.5,5X,'TFCA(T) = ',F11.5)
C
C  INITIALIZATION OF ENERGY VARIABLES XXXXXXXXXXXXXXXXXXXXXXXX
C
0605      FTIMEA=T
0606      FTEMPA=TFCA10
0607 7      TRNON=T
0608      CALL TFCB(TRNON)
0609      STENPB=TFEB1+TA
0610      STINEB=TRNON
0611      IF (SW1 .EQ. 1.) GO TO 11
0613      DELB=TAU2/STPB
0614      NSTPB=STPB
0615      DO 469 1JE=1,NSTPB
0616 12      T=T+DELB
0617      CALL TFCB(T)
0618      TFCB10=TFCB1+TA
0619      CALL IPOKE('44','10000.OR.IPEEK('44))
0620      WRITE(LUN,1001) T,TFCB10
0621      I=ITTIMR()
0622      CALL IPOKE('44','07777.AND.IPEEK('44))
0623      IF(I.EQ.IY(1)) GO TO 11111
C
C  INITIALIZATION OF ENERGY VARIABLES XXXXXXXXXXXXXXXXXXXXXXXX

```

```

      C
0625      FTIMEB=TRNON+TAU2
0626      CALL TFCB(FTIMEB)
0627      FTEMPB=TFCB1+TA
0628      STIMEC=TRNON+TAU2
0629      CALL TFCC(STIMEC)
0630      STEHPC=TFCC1+T2+TA
0631 469    CONTINUE
0632      GO TO 401
0633 11      T=TRNON+TAU2
0634      CALL TFCB(T)
      C
      C  INITIALIZATION OF ENERGY VARIABLES  XXXXXXXXXXXXXXXXXXXXXXXX
      C
0635      TFCB10=TFCB1+TA
0636      FTIMEB=TRNON+TAU2
0637      CALL TFCB(FTIMEB)
0638      FTEMPB=TFCB1+TA
0639      STIMEC=TRNON+TAU2
0640      CALL TFCC(STIMEC)
0641      STEHPC=TFCC1+T2+TA
0642      CALL IPOKE('44','10000.0R,IPEEK('44))
0643      WRITE(LUN,1001) T,TFCB10
0644      I=ITTIMR()
0645      CALL IPOKE('44','07777.AND,IPEEK('44))
0646      IF(I.EQ.IY(1)) GO TO 11111
0648      GO TO 401
0649 401    CONTINUE
0650 1001    FORMAT(1X,'TB = ',F11.5,5X,'TFCB(T) = ',F11.5)
0651      TPOS=T
0652      CALL TFCC(T)
0653      FPOS=TFCC1
0654      FPOS1=FPOS
0655 15      T=T+DELC
0656      CALL TFCC(T)
0657      FNEG=TFCC1
0658      FNEG1=FNEG
0659      IF ((FNEG*FPOS) .GT. 0.) GO TO 205
0661 35      TX=(TPOS*FNEG-T*FPOS)/(FNEG-FPOS)
0662      CALL TFCC(TX)
0663      FX=TFCC1
0664      IF (FPOS*FX) 306,405,305
0665 306      T=TX
0666      FPOS=FPOS/2.
0667 25      IF (ABS(T-TPOS) .LE. DIFF) GO TO 405
0669      GO TO 35
0670 305      TPOS=TX
0671      FPOS=FX
0672      FNEG=FNEG/2.
0673      GO TO 25
0674 205      IF (((T-TRNON-TAU2)/Z) .LE. 1.) GO TO 105
      C
      C  STEADY STATE EXIT-FINAL CYCLE  EXIT TO 77  XXXXXXXXXXXXXXXXXXXXXXXX
      C
0676      IF ((FPOS-FNEG) .LE. 0.) GO TO 77
0678 105      TPOS=T
0679      FPOS=TFCC1

```

```

0680          IF (SW1.EQ. 1.) GO TO 15
0682          FPOS1=FPOS+T2
0683          FPOS10=FPOS1+TA
0684          CALL IPOKE('44','10000,OR,IPEEK('44))
0685          WRITE(LUM,1002) TPOS,FPOS10
0686          I=ITTINR()
0687          CALL IPOKE('44','07777,AND,IPEEK('44))
0688          IF(I.EQ.IY(1)) GO TO 11111
0690          GO TO 15
0691 405        CALL TFCC(TPOS)
0692          TFCC1=TFCC1+T2
0693          TFCC10=TFCC1+TA
0694          CALL IPOKE('44','10000,OR,IPEEK('44))
0695          WRITE(LUM,1002) T,TFCC10
0696          I=ITTINR()
0697          CALL IPOKE('44','07777,AND,IPEEK('44))
0698          IF(I.EQ.IY(1)) GO TO 11111
C
C  INITIALIZATION OF ENERGY VARIABLES  XXXXXXXXXXXXXXXXXXXXXXXX
C
0700          FTIMEC=T
0701          FTEMPC=TFCC10
C
C  ENERGY COMPUTATION FOR CYCLES  XXXXXXXXXXXXXXXXXXXXXXXX
C
0702          XB=FLOW*CPF*((STEMPB-(TS+TA))+(.5*(FTEMPB-STEMPB)))*(FTIMEB
1-STIMEB)
0703          XC=FLOW*CPF*((FTEMPC-(TS+TA))+(.5*(STEMPC-FTEMPC)))*(FTIMEC
1-STIMEC)
0704          TCE=XB+XC
0705 3412      FORMAT(' ENERGY COLLECTED FROM ABOVE CYCLE = ',F11.5,
16X,' AVAILABLE SOLAR ENERGY = ',F11.5,6X,
2' CYCLE EFFICIENCY = ',F11.5,/)
0706 1002      FORMAT(1X,' TC = ',F11.5,5X,' TFCC(T) = ',F11.5)
C  CYCLE EXIT TO 46  XXXXXXXXXXXXXXXXXXXXXXXX
C
0707          GO TO 46
0708 77        TFCC1=TFCC1+T2
0709          TFCC10=TFCC1+TA
C
C  STEADY STATE TIME & TEMP WRITE  XXXXXXXXXXXXXXXXXXXXXXXX
C
0710          WRITE(LUM,1003) T,TFCC10
C
C  INITIALIZATION OF ENERGY VARIABLES  XXXXXXXXXXXXXXXXXXXXXXXX
C
0711          FTIMEC=T
0712          FTEMPC=TFCC10
C
C  FINAL CYCLE ENERGY COMPUTATIONS  XXXXXXXXXXXXXXXXXXXXXXXX
C
0713          XB=FLOW*CPF*((STEMPB-(TS+TA))+(.5*(FTEMPB-STEMPB)))*(FTIMEB
1-STIMEB)
0714          XC=FLOW*CPF*((FTEMPC-(TS+TA))+(.5*(STEMPC-FTEMPC)))*(FTIMEC
1-STIMEC)
0715          TCE=XB+XC

```


C FINAL CYCLE SOLAR ENERGY COMPUTATIONS XXXXXXXXXXXXXXXXXXXXXXXX
C

[illegible]

```

      1      ' TOS=',F11.5,4X,' DTSUN=',F11.5,/,
      2      ' DAYEFF=',F11.5,4X,' W=',F11.5,/,
      3      ' STIMEA=',F11.5,4X,'STEMPA=',F11.5,/,
      4      ' FTIMEA=',F11.5,4X,'FTEMPA=',F11.5,/,
      5      ' STIMED=',F11.5,4X,'STEMPD=',F11.5,/,
      6      ' FTIMED=',F11.5,4X,'FTEMPD=',F11.5,/,
      7      ' SOLIN=',F11.5,4X,' TMAX=',F11.5,/,
      8      ' CTEMPF=',F11.5,4X,' T2=',F11.5,/)
0753      TDE=(TENGY/ESUN)*(100.0)
0754      WRITE(5,1235) TENGY,ESUN,TDE
0755 1235  FORMAT(7X,'TOTAL ENERGY COLLECTED TO STEADY STATE = ',F11.5,/,
      C      ' TOTAL SOLAR ENERGY TO STEADY STATE = ',F11.5,/,
      C      ' STEADY STATE EFFICIENCY = ',F11.5,/)
0756 1003 FORMAT(1X,'STEADY STATE TIME = ',F11.5,5X,
      1'STEADY STATE TFC = ',F11.5)
      C
      C REQUEST FOR TEMPERATURE CALCULATION AFTER STEADY STATE XXXXX
      C
0757      IF(ISK.EQ.1) GO TO 10027
0759      WRITE(LUM,1004)
0760      CALL IPOKE('44','10000.OR.IPEEK('44'))
0761 1693  I=ITTINR()
0762      IF(I.LT.0) GO TO 1693
0764      CALL IPOKE('44','07777.AND.IPEEK('44'))
0765      IF(I.EQ.IY(3)) SM2=0.
0767      IF(I.EQ.IY(4)) SM2=1.
0769 7892  IF(ITTOUT(I).NE.0) GO TO 7892
0771      WRITE(5,1818)
0772      GO TO 65
      CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      C EXIT TO 65 XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      C
      CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      C PART C MINIMUM TIME ROUTINE XXXXXXXXXXXXXXXXXXXXXXXX
      C COMPUTATION OF STEADY STATE TIME XXXXXXXXXXXXXXXXXXXXXXXX
      CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0773 66      A=TFCC1
0774      TCA=T
0775 68      TCB=TCA+DELC
0776      CALL TFCC(TCB)
0777      B=TFCC1+T2
0778      IF ((A-B) .LE. 0.) GO TO 69
0780      TCA=TCB
0781      A=B
0782      GO TO 68
0783 69      AD=A+TA
0784      WRITE(LUM,67) TCA,AD
      CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      C SOLAR ENERGY CALCULATIONS FROM STEADY XXXXXXXXXXXXXXXXXXXXXXXX
      C STATE TIME TO END OF LAST CYCLE XXXXXXXXXXXXXXXXXXXXXXXX
      CXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0785      CESUN=0.0
0786      TSUN=STIMED
0787      CESUN=SOLIN*AREA*(1/W)*(COS(W*(STIMEA-TOS))-COS(W*(FTIMEC-TOS)))
0788      IF(STIMED.NE.0.0)
      1CESUN=SOLIN*AREA*(1/W)*(COS(W*(STIMED-TOS))-COS(W*(FTIMEC-TOS)))

```

[illegible]


```

      4' AVAILABLE DAILY SOLAR ENERGY = ',F11.5,6X,
      5' DAILY EFFICIENCY = ',F11.5,/)
      D      WRITE(5,8282) STIMED,STEMPD,FTIMED,FTEMPD,STIMEC,STEMPC,FTIMEC,
      1FTEMPC,XB,XC,TCE,TENGY,FLOW,CPF,TS,TA,CESUN,TSUN,CEFF,ESUN,
**** C
      2TOS,DTSUN,DAYEFF,W,STIMEA,STEMPA,FTIMEA,FTEMPA,STIMED,
**** C
      3STEMPD,FTIMED,FTEMPD,SOLIN,TMAX,CTEMP,T2
**** C
0874      WRITE(5,8818)
0875 8818  FORMAT(4(/))
0876      GO TO 78
      C
      C COMPUTATIONS COMPLETE EXIT TO BEGINNING 78 XXXXXXXXXXXXXXXX
      C
0877 567      CALL TFCC(T)
0878      TFCASS=TFCC1+T2
0879      TFCASO=TFCASS+TA
0880      CALL IPOKE('44','10000.OR.IPEEK('44))
0881      WRITE(LUM,1002) T,TFCASO
0882      I=ITTINR()
0883      CALL IPOKE('44','07777.AND.IPEEK('44))
0884      IF(I.EQ.IY(1)) GO TO 11111
      C
      C PART D CALCULATIONS XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      C
      C START OF 2ND AND ABOVE CYCLES XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
      C
0886      GO TO 79
0887 6      TRNOFF=T
0888      TPOS=T
0889      CALL TFCD(T)
      C
      C INITIALIZATION OF ENERGY VARIABLES XXXXXXXXXXXXXXXXXXXXXXXX
      C
0890      STIMED=T
0891      STEMPD=TFCD1+T1+TA
0892      FPOS=TFCD1
0893 16      T=T+DELD
0894      CALL TFCD(T)
0895      FNEG=TFCD1
0896      IF ((FNEG*FPOS) .GT. 0.) GO TO 206
0898 36      TX=(TPOS*FNEG-T*FPOS)/(FNEG-FPOS)
0899      CALL TFCD(TX)
0900      FX=TFCD1
0901      IF (FPOS*FX) 307,406,308
0902 307      T=TX
0903      FPOS=FPOS/2.
0904 26      IF (ABS(T-TPOS) .LE. DIFF) GO TO 406
0906      GO TO 36
0907 308      TPOS=TX
0908      FPOS=FX
0909      FNEG=FNEG/2.
0910      GO TO 26
0911 206      FPOS=FNEG
0912      TPOS=T
0913      IF (SW1 .EQ. 1.) GO TO 16

```

```

0915          FPOS1=FPOS+T1
0916          FPOS10=FPOS1+TA
0917          CALL IPOKE('44','10000,OR,IPEEK('44))
0918          WRITE(LUM,1010) TPOS,FPOS10
0919          I=ITTIMR()
0920          CALL IPOKE('44','07777,AND,IPEEK('44))
0921          IF(I.EQ.IY(1)) GO TO 11111
0923          GO TO 16
0924 406        CALL TFCD(T)
0925          TFCD1=TFCD1+T1
0926          TFCD10=TFCD1+TA
0927          CALL IPOKE('44','10000,OR,IPEEK('44))
0928          WRITE(LUM,1010) T,TFCD10
0929          I=ITTIMR()
0930          CALL IPOKE('44','07777,AND,IPEEK('44))
0931          IF(I.EQ.IY(1)) GO TO 11111
      C
      C  INITIALIZATION OF ENERGY VARIABLES  XXXXXXXXXXXXXXXXXXXXXXXX
      C
0933          FTIMED=T
0934          FTEMPD=TFCD10
0935          GO TO 7
      C
      CPART D COMPUTATIONS COMPLETE EXIT TO 7 PART B  XXXXXXXXXXXXXXXXXXXX
      C
0936 1010      FORMAT(1X,'TD = ',F11.5,5X,'TFCD(T) = ',F11.5)
0937          STOP
0938          END
C.MAIN.] ERRORS: 000,

```

RT-11 FORTRAN IV

STORAGE MAP

NAME	OFFSET	ATTRIBUTES
STRING	000006	LOGICAL*1 ARRAY (32)
IY	000046	LOGICAL*1 ARRAY (4)
STOW1	000052	REAL*4 VARIABLE
STOW2	000056	REAL*4 VARIABLE
STOW3	000062	REAL*4 VARIABLE
STOW4	000066	REAL*4 VARIABLE
STOW5	000072	REAL*4 VARIABLE
STOW6	000076	REAL*4 VARIABLE
STOW7	000102	REAL*4 VARIABLE
STOW8	000106	REAL*4 VARIABLE
STOW9	000112	REAL*4 VARIABLE
STOW10	000116	REAL*4 VARIABLE
STOW11	000122	REAL*4 VARIABLE
STOW12	000126	REAL*4 VARIABLE
STOW13	000132	REAL*4 VARIABLE
STOW14	000136	REAL*4 VARIABLE
STOW15	000142	REAL*4 VARIABLE
STOW16	000146	REAL*4 VARIABLE
STOW17	000152	REAL*4 VARIABLE
STOW18	000156	REAL*4 VARIABLE
STOW19	000162	REAL*4 VARIABLE
STOW20	000166	REAL*4 VARIABLE
STOW21	000172	REAL*4 VARIABLE
STOW22	000176	REAL*4 VARIABLE
XXD1	000202	REAL*4 VARIABLE
XXD2	000206	REAL*4 VARIABLE
XXD3	000212	REAL*4 VARIABLE
XXD4	000216	REAL*4 VARIABLE
XXD5	000222	REAL*4 VARIABLE
XXD6	000226	REAL*4 VARIABLE
XXD7	000232	REAL*4 VARIABLE
XXD8	000236	REAL*4 VARIABLE
XXD9	000242	REAL*4 VARIABLE
XXD10	000246	REAL*4 VARIABLE
XXD11	000252	REAL*4 VARIABLE
XXD12	000256	REAL*4 VARIABLE
XXD13	000262	REAL*4 VARIABLE
XXD14	000266	REAL*4 VARIABLE
XXD15	000272	REAL*4 VARIABLE
XXD16	000276	REAL*4 VARIABLE
XXD17	000302	REAL*4 VARIABLE
XXD18	000306	REAL*4 VARIABLE
XXD19	000312	REAL*4 VARIABLE
XXD20	000316	REAL*4 VARIABLE
XXD21	000322	REAL*4 VARIABLE
XXD22	000326	REAL*4 VARIABLE
AREA	000332	REAL*4 VARIABLE
TAUAL	000336	REAL*4 VARIABLE
EGEOM	000342	REAL*4 VARIABLE
COLLOS	000346	REAL*4 VARIABLE
COLCAP	000352	REAL*4 VARIABLE
COLK	000356	REAL*4 VARIABLE
FLOW	000362	REAL*4 VARIABLE
DIFF	000366	REAL*4 VARIABLE
DELTA	000372	REAL*4 VARIABLE
DELC	000376	REAL*4 VARIABLE
DELD	000402	REAL*4 VARIABLE

RT-11 FORTRAN IV

STORAGE MAP

NAME	OFFSET	ATTRIBUTES	
TENGY	007576	REAL*4	VARIABLE
BOLIN	007602	REAL*4	VARIABLE
CPF	007606	REAL*4	VARIABLE
LUM	007612	INTEGER*2	VARIABLE
IPOKE	000000	INTEGER*2	PROCEDURE
IPEEK	000000	INTEGER*2	PROCEDURE
IFILE	007614	INTEGER*2	VARIABLE
ITTINR	000000	INTEGER*2	PROCEDURE
ITTOUR	000000	INTEGER*2	PROCEDURE
IJK	007616	INTEGER*2	VARIABLE
KNT	007620	INTEGER*2	VARIABLE
ASSION	000000	REAL*4	PROCEDURE
ISK	007622	INTEGER*2	VARIABLE
ITMAX	007624	INTEGER*2	VARIABLE
STON3	007626	REAL*4	VARIABLE
LUR	007632	INTEGER*2	VARIABLE
NC	007634	INTEGER*2	VARIABLE
AI	007636	REAL*4	VARIABLE
BI	007642	REAL*4	VARIABLE
CI	007646	REAL*4	VARIABLE
DI	007652	REAL*4	VARIABLE
EI	007656	REAL*4	VARIABLE
FI	007662	REAL*4	VARIABLE
BOLINI	007666	REAL*4	VARIABLE
PI	007672	REAL*4	VARIABLE
TAI	007676	REAL*4	VARIABLE
TBI	007702	REAL*4	VARIABLE
TCI	007706	REAL*4	VARIABLE
TBI	007712	REAL*4	VARIABLE
TEI	007716	REAL*4	VARIABLE
TFI	007722	REAL*4	VARIABLE
TGI	007726	REAL*4	VARIABLE
THI	007732	REAL*4	VARIABLE
CIK	007736	REAL*4	VARIABLE
FLQNI	007742	REAL*4	VARIABLE
CPFI	007746	REAL*4	VARIABLE
COLLOI	007752	REAL*4	VARIABLE
COLCAI	007756	REAL*4	VARIABLE
TJI	007762	REAL*4	VARIABLE
I	007766	INTEGER*2	VARIABLE
XX	007770	REAL*4	VARIABLE
IV	007774	INTEGER*2	VARIABLE
ISKJ	007776	INTEGER*2	VARIABLE
DELC1	010000	REAL*4	VARIABLE
THAX	010004	REAL*4	VARIABLE
SW1	010010	REAL*4	VARIABLE
STIMED	010014	REAL*4	VARIABLE
STEMPD	010020	REAL*4	VARIABLE
FTIMED	010024	REAL*4	VARIABLE
FTEMPD	010030	REAL*4	VARIABLE
DAYEFF	010034	REAL*4	VARIABLE
ESUN	010040	REAL*4	VARIABLE
TNGYN1	010044	REAL*4	VARIABLE
SAX	010050	REAL*4	VARIABLE
CAX	010054	REAL*4	VARIABLE
SQRT	000000	REAL*4	PROCEDURE
ABS	000000	REAL*4	PROCEDURE

NAME	OFFSET	ATTRIBUTES
TAX	010060	REAL*4 VARIABLE
OMGA	010064	REAL*4 VARIABLE
ATAN	000000	REAL*4 PROCEDURE
PRMTN	010070	REAL*4 VARIABLE
T	010074	REAL*4 VARIABLE
TPDS	010100	REAL*4 VARIABLE
TFCA	000000	REAL*4 PROCEDURE
STIMEA	010104	REAL*4 VARIABLE
STEMPA	010110	REAL*4 VARIABLE
FPOS	010114	REAL*4 VARIABLE
FPOS1	010120	REAL*4 VARIABLE
FPOS10	010124	REAL*4 VARIABLE
FNEG	010130	REAL*4 VARIABLE
TX	010134	REAL*4 VARIABLE
FX	010140	REAL*4 VARIABLE
TEST	010144	REAL*4 VARIABLE
TFCA10	010150	REAL*4 VARIABLE
FTIMEA	010154	REAL*4 VARIABLE
FTEMPA	010160	REAL*4 VARIABLE
TFCD	000000	REAL*4 PROCEDURE
STEMPB	010164	REAL*4 VARIABLE
STIMEB	010170	REAL*4 VARIABLE
DELB	010174	REAL*4 VARIABLE
NSTPB	010200	INTEGER*2 VARIABLE
IJE	010202	INTEGER*2 VARIABLE
TFCB10	010204	REAL*4 VARIABLE
FTIMEB	010210	REAL*4 VARIABLE
FTEMPB	010214	REAL*4 VARIABLE
STIMEC	010220	REAL*4 VARIABLE
TFCC	000000	REAL*4 PROCEDURE
STEMPC	010224	REAL*4 VARIABLE
FNEG1	010230	REAL*4 VARIABLE
TFCC10	010234	REAL*4 VARIABLE
FTIMEC	010240	REAL*4 VARIABLE
FTEMPC	010244	REAL*4 VARIABLE
XB	010250	REAL*4 VARIABLE
XC	010254	REAL*4 VARIABLE
TCE	010260	REAL*4 VARIABLE
CESUN	010264	REAL*4 VARIABLE
COS	000000	REAL*4 PROCEDURE
CEFF	010270	REAL*4 VARIABLE
EINT	010274	REAL*4 VARIABLE
TINEN1	010300	REAL*4 VARIABLE
TEMPN1	010304	REAL*4 VARIABLE
ENGYN1	010310	REAL*4 VARIABLE
TINEN2	010314	REAL*4 VARIABLE
TEMPN2	010320	REAL*4 VARIABLE
TDE	010324	REAL*4 VARIABLE
SM2	010330	REAL*4 VARIABLE
A	010334	REAL*4 VARIABLE
TCA	010340	REAL*4 VARIABLE
TCB	010344	REAL*4 VARIABLE
B	010350	REAL*4 VARIABLE
AO	010354	REAL*4 VARIABLE
TSUN	010360	REAL*4 VARIABLE
ENGIN2	010364	REAL*4 VARIABLE
DTSUM	010370	REAL*4 VARIABLE

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STORAGE MAP

NAME	OFFSET	ATTRIBUTES	
CTEMP	010374	REAL*4	VARIABLE
TIMEN3	010400	REAL*4	VARIABLE
DELSS	010404	REAL*4	VARIABLE
TEMPN3	010410	REAL*4	VARIABLE
ENGYN3	010414	REAL*4	VARIABLE
TFCAS	010420	REAL*4	VARIABLE
TFCAS0	010424	REAL*4	VARIABLE
TFC	000000	REAL*4	PROCEDURE
TFC010	010430	REAL*4	VARIABLE
COMMON BLOCK /DICK/			LENGTH 000054
W	000000	REAL*4	VARIABLE
TAU0	000004	REAL*4	VARIABLE
TDS	000010	REAL*4	VARIABLE
T0	000014	REAL*4	VARIABLE
TA	000020	REAL*4	VARIABLE
AC	000024	REAL*4	VARIABLE
TFCA1	000030	REAL*4	VARIABLE
T2	000034	REAL*4	VARIABLE
Z	000040	REAL*4	VARIABLE
TS	000044	REAL*4	VARIABLE
T1	000050	REAL*4	VARIABLE
COMMON BLOCK /DICK1/			LENGTH 000040
STPB	000000	REAL*4	VARIABLE
TAU2	000004	REAL*4	VARIABLE
TAU1	000010	REAL*4	VARIABLE
TRNDN	000014	REAL*4	VARIABLE
TFCC1	000020	REAL*4	VARIABLE
TFCB1	000024	REAL*4	VARIABLE
TRNOFF	000030	REAL*4	VARIABLE
TFCD1	000034	REAL*4	VARIABLE

```

0001      SUBROUTINE TFCA(T)
0002      COMMON /DICK/ W,TAU0,T0S,TO,TA,AC,TFCA1,T2,Z,TS,T1
0003      WT=W*TAU0
0004      TIME=T-T0S
0005      F=1.+(WT)**2.
0006      TFCA1=((TO-TA)+((AC*WT)/F))*EXP(-TIME/TAU0)+
1      (AC/SQRT(F))*SIN(W*TIME-ATAN(WT))-T1
0007      RETURN
0008      END

```

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STORAGE MAP

NAME	OFFSET	ATTRIBUTES
T	000014	REAL*4 PARAMETER VARIABLE
WT	000016	REAL*4 VARIABLE
TIME	000022	REAL*4 VARIABLE
F	000026	REAL*4 VARIABLE
EXP	000000	REAL*4 PROCEDURE
SQRT	000000	REAL*4 PROCEDURE
SIN	000000	REAL*4 PROCEDURE
ATAN	000000	REAL*4 PROCEDURE

COMMON BLOCK /DICK/ LENGTH 000054

W	000000	REAL*4 VARIABLE
TAU0	000004	REAL*4 VARIABLE
T0S	000010	REAL*4 VARIABLE
TO	000014	REAL*4 VARIABLE
TA	000020	REAL*4 VARIABLE
AC	000024	REAL*4 VARIABLE
TFCA1	000030	REAL*4 VARIABLE
T2	000034	REAL*4 VARIABLE
Z	000040	REAL*4 VARIABLE
TS	000044	REAL*4 VARIABLE
T1	000050	REAL*4 VARIABLE

```

0001      SUBROUTINE TFCB(T)
0002      COMMON/DICK/W,TAU0,T0S,TD,TA,AC,TFCA1,T2,Z,TS,T1
0003      COMMON/DICK1/STPB,TAU2,TAU1,TRNON,TFCC1,TFCB1,
           1      TRNOFF,TFCD1
0004      A=W*TAU1
0005      B=AC/SQRT(1.+(A)**2)
0006      C=T-TRNON
0007      D=ATAN(A)
0008      TFCB1=(T1-B*SIN(W*(TRNON-T0S)-D))*EXP(-C/TAU1)+
           1      B*SIN(W*(T-T0S)-D)
0009      RETURN
0010      END

```

RT-11 FORTRAN IV

STORAGE MAP

NAME	OFFSET	ATTRIBUTES
T	000014	REAL*4 PARAMETER VARIABLE
A	000016	REAL*4 VARIABLE
B	000022	REAL*4 VARIABLE
SQRT	000000	REAL*4 PROCEDURE
C	000026	REAL*4 VARIABLE
D	000032	REAL*4 VARIABLE
ATAN	000000	REAL*4 PROCEDURE
SIN	000000	REAL*4 PROCEDURE
EXP	000000	REAL*4 PROCEDURE

COMMON BLOCK /DICK/ LENGTH 000054

W	000000	REAL*4 VARIABLE
TAU0	000004	REAL*4 VARIABLE
T0S	000010	REAL*4 VARIABLE
TD	000014	REAL*4 VARIABLE
TA	000020	REAL*4 VARIABLE
AC	000024	REAL*4 VARIABLE
TFCA1	000030	REAL*4 VARIABLE
T2	000034	REAL*4 VARIABLE
Z	000040	REAL*4 VARIABLE
TS	000044	REAL*4 VARIABLE
T1	000050	REAL*4 VARIABLE

COMMON BLOCK /DICK1/ LENGTH 000040

STPB	000000	REAL*4 VARIABLE
TAU2	000004	REAL*4 VARIABLE
TAU1	000010	REAL*4 VARIABLE
TRNON	000014	REAL*4 VARIABLE
TFCC1	000020	REAL*4 VARIABLE
TFCB1	000024	REAL*4 VARIABLE
TRNOFF	000030	REAL*4 VARIABLE
TFCD1	000034	REAL*4 VARIABLE

```

0001      SUBROUTINE TFCC(T)
0002      COMMON/DICK/W,TAU0,TOS,TO,TA,AC,TFCA1,T2,
          1      Z,TS,T1
0003      COMMON/DICK1/STPB,TAU2,TAU1,TRNON,TFCC1,TFCB1,
          1      TRNOFF,TFCD1
0004      A=(T-TRNON-TAU2)/Z
0005      B=W*TAU1
0006      C=ATAN(B)
0007      D=AC/SQRT(1.+(B)**2)
0008      E=EXP(-TAU2/TAU1)
0009      F=TS*E
0010      G=(T1-TS)*E
0011      IF (A .GT. 1.) GO TO 13
0012      P=B*((A)**2)*(1.-2.*A)+1.)
0013      GO TO 14
0014      P=0.
0015      13      TFCC1=P+F+D*(SIN(W*(T-TOS)-C)-E*SIN(W*(T-TOS-TAU2)-C))-T2
0016      14
0017      RETURN
0018      END

```

RT-11 FORTRAN IV

STORAGE MAP

NAME	OFFSET	ATTRIBUTES
T	000014	REAL*4 PARAMETER VARIABLE
A	000016	REAL*4 VARIABLE
B	000022	REAL*4 VARIABLE
C	000026	REAL*4 VARIABLE
ATAN	000000	REAL*4 PROCEDURE
D	000032	REAL*4 VARIABLE
SQRT	000000	REAL*4 PROCEDURE
E	000036	REAL*4 VARIABLE
EXP	000000	REAL*4 PROCEDURE
F	000042	REAL*4 VARIABLE
G	000046	REAL*4 VARIABLE
P	000052	REAL*4 VARIABLE
SIN	000000	REAL*4 PROCEDURE

COMMON BLOCK /DICK/ LENGTH 000054

W	000000	REAL*4 VARIABLE
TAU0	000004	REAL*4 VARIABLE
TOS	000010	REAL*4 VARIABLE
TO	000014	REAL*4 VARIABLE
TA	000020	REAL*4 VARIABLE
AC	000024	REAL*4 VARIABLE
TFCA1	000030	REAL*4 VARIABLE
T2	000034	REAL*4 VARIABLE
Z	000040	REAL*4 VARIABLE
TS	000044	REAL*4 VARIABLE
T1	000050	REAL*4 VARIABLE

COMMON BLOCK /DICK1/ LENGTH 000040

STPB	000000	REAL*4 VARIABLE
TAU2	000004	REAL*4 VARIABLE
TAU1	000010	REAL*4 VARIABLE
TRNON	000014	REAL*4 VARIABLE
TFCC1	000020	REAL*4 VARIABLE
TFCB1	000024	REAL*4 VARIABLE
TRNOFF	000030	REAL*4 VARIABLE
TFCD1	000034	REAL*4 VARIABLE

```

0001      SUBROUTINE TFCD(T)
0002      COMMON/DICK/W,TAU0,T0S,T0,TA,AC,TFCA1,T2,Z,TS,T1
0003      COMMON/DICK1/STPB,TAU2,TAU1,TRNON,TFCC1,TFCB1,TRNOFF,TFCD1
0004      A=W*TAU0
0005      B=AC/SQRT(1.+(A)**2)
0006      C=ATAN(A)
0007      TFCD1=EXP(-(T-TRNOFF)/TAU0)*(T2-B*SIN(W*(TRNOFF-T0S)
1          -C))+B*SIN(W*(T-T0S)-C)-T1
0008      RETURN
0009      END

```

RT-11 FORTRAN IV

STORAGE MAP

NAME	OFFSET	ATTRIBUTES
T	000014	REAL*4 PARAMETER VARIABLE
A	000016	REAL*4 VARIABLE
B	000022	REAL*4 VARIABLE
SQRT	000000	REAL*4 PROCEDURE
C	000026	REAL*4 VARIABLE
ATAN	000000	REAL*4 PROCEDURE
EXP	000000	REAL*4 PROCEDURE
SIN	000000	REAL*4 PROCEDURE

COMMON BLOCK /DICK/ LENGTH 000054

W	000000	REAL*4 VARIABLE
TAU0	000004	REAL*4 VARIABLE
T0S	000010	REAL*4 VARIABLE
T0	000014	REAL*4 VARIABLE
TA	000020	REAL*4 VARIABLE
AC	000024	REAL*4 VARIABLE
TFCA1	000030	REAL*4 VARIABLE
T2	000034	REAL*4 VARIABLE
Z	000040	REAL*4 VARIABLE
TS	000044	REAL*4 VARIABLE
T1	000050	REAL*4 VARIABLE

COMMON BLOCK /DICK1/ LENGTH 000040

STPB	000000	REAL*4 VARIABLE
TAU2	000004	REAL*4 VARIABLE
TAU1	000010	REAL*4 VARIABLE
TRNON	000014	REAL*4 VARIABLE
TFCC1	000020	REAL*4 VARIABLE
TFCB1	000024	REAL*4 VARIABLE
TRNOFF	000030	REAL*4 VARIABLE
TFCD1	000034	REAL*4 VARIABLE

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