SYSTEMS APPROACH TO DETERMINE OPTIMAL SYSTEM

PARAMETERS FOR SUPPLYING INDUSTRIAL PROCESS

HOT WATER USING SOLAR ENERGY

by

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ABSTRACT

SYSTEMS APPROACH TO DETERMINE OPTIMAL SYSTEM PARAMETERS FOR SUPPLYING INDUSTRIAL PROCESS HOT WATER USING SOLAR ENERGY

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This thesis studies a system which is to provide process hot water for industrial use. The system attempts to provide part of the energy needed by using solar energy. A particular system configuration is chosen after system elements have been modeled in the form of computer programs and simulations are run to evaluate system performance. A control philosophy is developed from the results of the system simulation and this is used to optimize system performance with respect to cost. The results of the optimization are discussed and also the cost projections of the solar system versus a conventional fuel system are compared. Lastly, recommendations concerning implementation of the solar system are given.

TABLE OF CONTENTS

LIST OF SYMBOLS

SYMBOL	DEFINITION	UNITS OR REFERENCE
COP	Heat pump's coefficient of performance	none
C_p	Specific Heat of the fluid in the tanks and collectors	j/kg^oC
CURVE	Curve fitting subroutine to find coefficients for cubic	See pg. 30
DEL	Buffer temperature for the heat pump-heat exchanger use decision	^oC
DMDT	Fluid flow rate in the system	kg/sec
FRAC	Time spent feeding energy to a particular tank	min
H_r	Hour of the day	hours
KW	Power used by the heat pump in the form of electricity	watts
Nser	Number of collectors in series	none
PAR	Number of series collector sections in parallel	none
PF	Value of the heat pump load constant	none
S	Solar power absorbed by the collector	w/m^2
T_a	Ambient temperature	^oC
T_c	Temperature of the collector cover	^oK
$T_{f,i}$	Fluid input temperature to the collector	^oC
$T_{f,o}$	Fluid output temperature of the collector	^oC
TLOSS	Heat pump load from tanks	watts
T_p	Plate temperature of the collector	^oK

LIST OF FIGURES

LIST OF FIGURES (CONT.)

LIST OF TABLES

CHAPTER I

INTRODUCTION

The objective of this thesis is to design an economical (cost optimal) process hot water system utilizing solar energy. A cost comparison can then be made with the present natural gas system used. This will allow economic projections to be made. The long range goal is to replace valuable and depletable conventional energy sources with solar energy. In this case, the conventional energy referred to will be natural gas used in burners whose purpose is to raise water temperature.

Solar energy is being considered here mainly because of the recent energy crisis. The method presently in use to heat water is the conventional gas fired burner. Because of the energy crisis, attention has been focused on the escalating price of natural gas and also its ever decreasing availability. At some point in the near future, natural gas sources will be depleted. This event will cause a major conversion by industry to another energy source. One of these possible energy sources is the sun. Enough energy falls in the United States in the form of solar radiation each year to provide significantly more than our present total energy usage. This energy is provided at no charge by the sun and is a pollution free source as well. The source will last as long as the sun, so that there is no concern of depleting the supply. Since this energy is available now, why should industry wait for natural gas supplies to dwindle before turning to solar energy? There are several possible reasons for waiting. One reason is cost. Although the solar radiation comes to us free, the collecting devices used to turn this energy into a form directly usable by industry come at a cost. Also, we have no control over the weather. If clouds cover the sky for days on end, only a minimum amount of energy may filter through. This calls for a storage ability in the solar energy system. Another reason is the cheap price of natural gas. Until recently, natural gas has been priced so low that solar energy was not even considered to be close to competing with it. Rising natural gas prices have made this reason loose validity. The main reason behind choosing solar energy over natural gas in the final analysis is cost. Cost is the driving force which plays the greatest part in deciding which alternatives industry turns to. Thus, it is the purpose of this thesis to determine the feasibility of solar energy cost wise as opposed to natural gas in a particular application.

The actual process hot water system studied in this thesis is a model of a unit for an aluminum extrusion company. The process hot water system is designed for use in the aluminum anodizing line. Anodizing is an electrochemical reaction that builds a hard transparent oxide film on the surface of the aluminum. By making the aluminum part an anode in an electrolyte solution, a dense anodic coating is formed. This coating is clear, transparent, and colorless, with about the hardness of a diamond. This gives the aluminum a coating which makes it corrosion resistant, wear resistant, and gives it extra hardness. Also, because the anodizing coating is porous, it will allow dye to permeate the metal. This makes it possible to dye the aluminum a desired color.

The anodizing and dyeing process requires hot water based solutions in which the aluminum is dipped. It is this hot water which requires energy to maintain it at specific temperatures. The water based solutions are kept in tanks of 13.84 cubic meters each. Each tank has a specific job to perform. These range from etching and rinsing to anodizing and coloring. Accordingly, their temperatures must be maintained at a temperature suited to the specific task each is performing. This ranges from ambient tmeperature, for rinse tanks, to 93.3 degrees Centigrade, for hot water seal tanks. Since the tanks are located inside a building, the ambient temperature tanks require no energy input. All other tanks require energy to raise and maintain their temperatures above ambient at their specific duty temperatures.

The energy requirements for the tanks vary from tank to tank, but an average power requirement for each tank has been estimated. These power requirements are shown in Table 1. Since the system is to run 24 hours per day, this allows a calculation to be made on daily energy requirements. This energy is presently supplied by natural gas fired immersion

TABLE 1

POWER REQUIRED BY TANKS IN PROCESS HOT WATER SYSTEM

Tank	Tank Temperature (Degrees Centigrade)	Power Required (Watts)
1	71.1	66,777
2	76.7	78,638
3	60.0	45,583
4	93.3	132,773
5	65.6	40,993
6	62.8	38,551
7	65.6	40,993
8	60.0	33,624
9	65.6	40,993
10	57.2	32,639
11	65.6	40,993
12	71.1	66,777
13	93.3	132,773
14	93.3	132,773

burners in each tank.

The proposal of this thesis is to offset this natural gas usage, either partially or wholly, by using solar energy. This may result in a savings on energy costs since solar energy is supplied by the sun at no charge. To do this, a standard flat plate collector system will be used. This consists of a collecting array, piping and pumps to move the working fluid, and heat exchangers or heat pumps to transfer the energy collected by the working fluid to the tanks requiring it. Figure 1 depicts this basic system.

An analysis of this solar energy system, its cost and performance, is what must be performed in order to decide whether or not its addition will be cost effective. There are many system variants which must be examined and finally adjusted for an optimum cost effective system. These variants include array size, flow rates of working fluids, and whether to use heat pumps or heat exchangers or a combination of the two. These decisions will be made after examining and analysing results obtained from system simulations on a digital computer. This introduces the method by which this problem is to be solved. The Systems Approach will be used. A block diagram of this method is shown in Figure 2. The Systems Approach consists of determining an objective, then setting down requirements and alternatives. Controls are applied and test output is generated. This output is then compared to the objective and controls are continually adjusted until objective and output

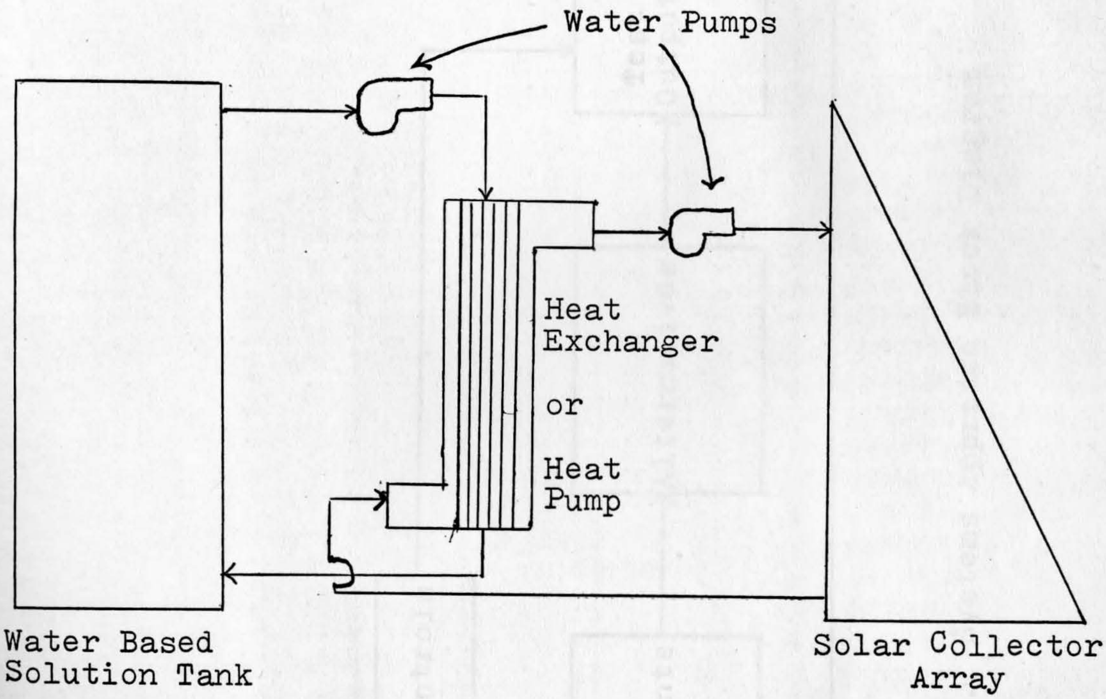


Fig. 1. Basic Solar System Design

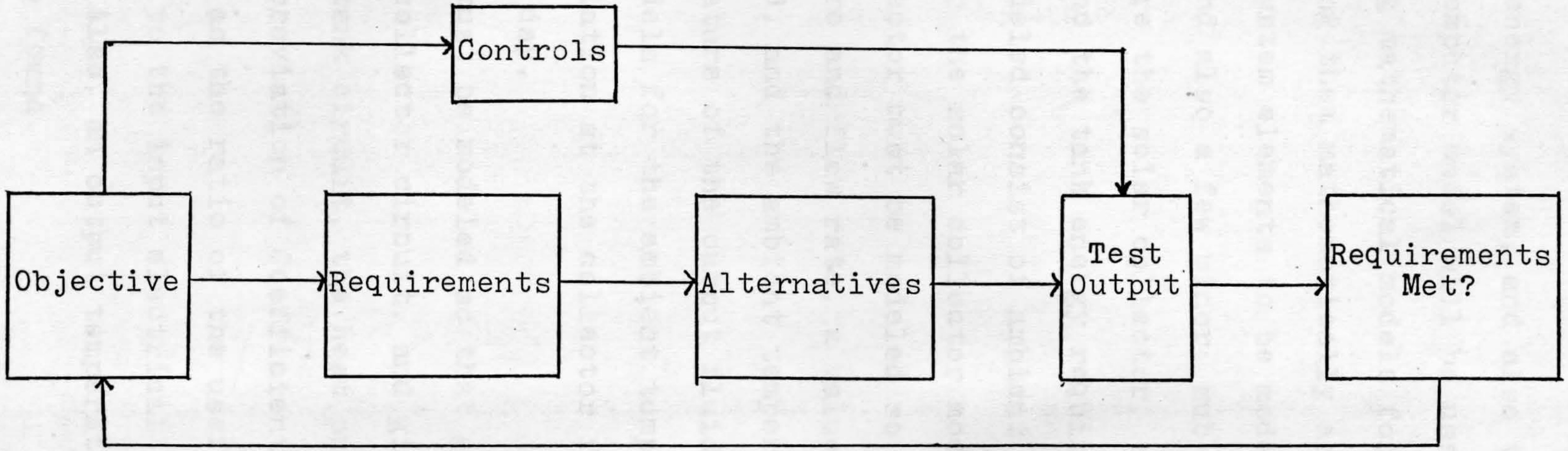


Fig. 2. Systems Approach Block Diagram

are acceptable.

For the solar energy system, and also the process hot water system, a computer model will be used. This will consist of determining mathematical models for all system elements and connecting them mathematically as they are connected physically. System elements to be modeled consist of four major elements and also a few minor sub-elements. The four major elements are the solar collector, the heat pump, the heat exchanger, and the tank energy requirements. The sub-elements to be modeled consist of ambient conditions necessary for input to the solar collector model.

The solar collector must be modeled so that given an input fluid temperature and flow rate, a value of solar insolation, a wind speed, and the ambient temperature at the collector, the temperature of the output fluid may be found. This also involves models for the ambient temperature, wind speed, and solar insolation at the collector for specific days and hours of the day.

The heat pump must be modeled so that given an input temperature from the collector circuit, and given an input temperature from the tank circuit, the heat pump COP can be found. COP is the abbreviation of Coefficient Of Performance which is defined as the ratio of the useful output energy of the heat pump to the input electrical energy used to power the heat pump. Also, an output temperature to the collector side must be found.

The heat exchanger must be modeled so that given an input temperature from the collector circuit and an input temperature from the tank circuit, an output temperature at the collector circuit can be found, and also the energy transfer rate to the tanks can be found.

Lastly, the tank circuit must be modeled so that the energy requirements are known and temperature requirements are known given any time of day. Once this is done, energy loads are known.

When the system element models have been found, they will be reduced to computer subroutines. This will allow a major program to be written which will be able to connect system elements mathematically in the computer and arrange to run computer simulations of the various configurations. From these simulations, the optimal system parameters will be chosen and an appropriate control philosophy will be developed. The system will then be evaluated using this controller. The resulting energy displacement by the solar energy system will then be used along with element costs to determine the cost of energy using this optimal system. The energy cost will then be compared to conventional energy costs to determine the advisability of implementing such a system.

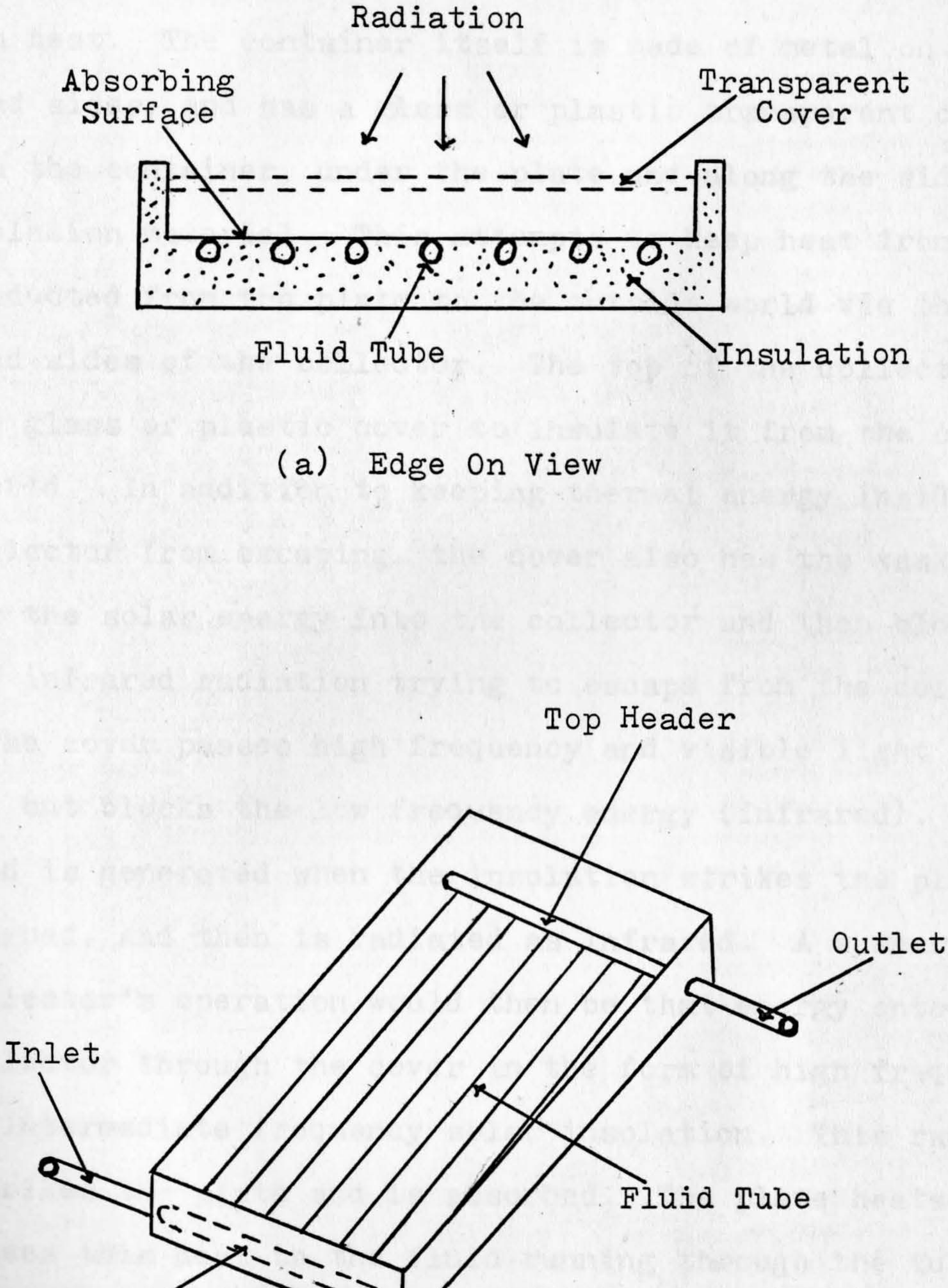
CHAPTER II

SYSTEM ELEMENT MODELS

The Solar Collector Model

The first element to be considered in approaching the problem is the solar collector. There are a wide variety of collectors available today. Most use the same basic idea, although there are many variants between collectors. These variants consist of such things as multiple covers, dimensions of the collector, piping geometry used, and selective coatings. In order to understand these differences and model a collector in the simplest fashion, the simplest design of the basic flat plate collector will be considered.

A drawing of the basic flat plate collector appears in Figure 3. As seen in the figure, the collector consists of a flat plate made of metal which is fairly thin. This plate is the absorber of the solar energy. Either running through the plate itself, or bonded below or above the plate, are the tubes which pass the working fluid into thermal contact with the plate. This is accomplished by bringing the incoming fluid into a header which then routes the fluid through the tubes in contact with the plate. The top header then receives the heated fluid and lets it out of the outlet tube to the rest of the system.



(b) Tilted View

Fig. 3. Basic Flat Plate Collector

The plate and its associated tubing are located inside of an appropriate container made in such a manner as to keep in heat. The container itself is made of metal on the back and sides, and has a glass or plastic transparent cover. In the container, under the plate and along the sides, is insulation material. This attempts to keep heat from being conducted from the plate to the outside world via the back and sides of the collector. The top of the collector has the glass or plastic cover to insulate it from the outside world. In addition to keeping thermal energy inside the collector from escaping, the cover also has the task of passing the solar energy into the collector and then blocking any infrared radiation trying to escape from the collector. The cover passes high frequency and visible light energy, but blocks the low frequency energy (infrared). The infrared is generated when the insolation strikes the plate, is absorbed, and then is radiated as infrared. A summary of the collector's operation would then be that energy enters the collector through the cover in the form of high frequency and intermediate frequency solar insolation. This radiation strikes the plate and is absorbed. The plate heats up and passes this heat to the fluid running through the tubes. Thus there is a rise in temperature in the water from inlet to outlet and so energy is gained in the form of hot water.

Now that a general description has been given of the collector, its thermal performance may be considered. Because this collector is to be used in a system, it is desired to know its response to various conditions. In particular, given solar insolation, input fluid temperature, wind speed, and ambient temperature, what will be the output fluid temperature? The following discussion is in no way an attempt at an in depth theoretical analysis of the collector performance. Rather, it is an attempt to provide a basic insight into the manner in which the collector was modeled in this study. Equations (1) through (18) and the particular method utilizing these equations were found in a text dealing with solar energy and related thermal processes, [1].

To begin with, there are three basic means of energy transfer possible in this collector. These are conduction, convection, and radiation. These three methods of energy transfer are applied to the back, cover, and sides of the collector to derive an equation for the loss coefficient, U_l. The back loss coefficient, U_b, is considered first.

The back loss coefficient, U_b, is given by Equation (1). K_i is the insulation's thermal conductivity and L_{bi} is

$$U_b = \frac{K_i}{L_{bi}} \qquad (1)$$

the thickness of the back insulation. The radiation losses and the convection losses of the back are usually so small, compared to conduction, that they are neglected. This reduces U_b to the simple conduction law of heat transfer. The edge losses are also computed in the same way. Equation (2) gives the value of U_e, the edge losses. Again, K_i is the thermal conductivity of the insulation and L_{ei} is its

$$U_e = \frac{K_i * A_e}{L_{ei} * A_{coll}} \qquad (2)$$

thickness. The terms A_e and A_{coll}, the area of the edge and the area of the active frontal collecting surface, respectively, are used so that the coefficient may be normalized to the active frontal collector area. By doing this, when U_e is multiplied by frontal collector area, the correct coefficient will be computed. U_b was also computed in this manner, however, since the area of the back and front of the particular collector being used is equal, the area terms produce an unnoticed 1 in the equation.

Next, consider the top losses. This can be due to all three ways of energy transfer. The first is convection between the plate and the cover. The convection coefficient between two parallel planes tilted at an angle of 45 degrees to the horizontal has been found to be as given in Equation (3). T_{av} is the average temperature between the cover and

$$H_{p-c} = \left[1 - .0018*(T_{av} - 10)\right] * (1.14) * \left[\frac{DT^{.31}}{Z^{.07}}\right] \qquad (3)$$

plate, and DT is the temperature difference. Z is the distance between cover and plate. The wind convection coefficient from the cover to the air, H_w, has been found to be as given in Equation (4). WV is wind velocity. The radiation

$$H_w = 5.7 + 3.8*WV \qquad (4)$$

coefficient from the plate to the cover, $H_{r,p-c}$, has been found to be as given in Equation (5). T_p and T_c are the temperatures of the plate and cover, respectively. ϵ_p and ϵ_c are the emittance of the plate and cover, respectively. Also, σ is Boltzman's constant. The radiation coefficient

$$H_{r,p-c} = \frac{\sigma*(T_p^2 + T_c^2)*(T_p + T_c)}{\frac{1}{\epsilon_p} + \frac{1}{\epsilon_c} - 1} \tag{5}$$

from cover to sky has been found to be as given in Equation (6). T_s is sky temperature, T_c is cover temperature, σ is Boltzman's constant, ϵ_c is the emittance of the cover, and $H_{r,c-s}$ is the constant's name. Using these relations, the

$$H_{r,c-s} = \epsilon_c*\sigma*(T_c^2 + T_s^2)*(T_c + T_s) \tag{6}$$

total top loss can be written as given in Equation (7).

$$U_t = \left[\frac{1}{H_{p-c} + H_{r,p-c}} + \frac{1}{H_w + H_{r,c-s}}\right]^{-1} \tag{7}$$

To use these formulas, however, it is noted that T_c be known. However, by using the fact that heat loss from plate to cover is the same as plate to surroundings, Equation (8) is arrived at. The procedure is to guess a cover

$$T_c = T_p - \left[\frac{U_t*(T_p - T_a)}{H_{p-c} + H_{r,p-c}}\right] \tag{8}$$

temperature from which H_{p-c}, $H_{r,p-c}$, $H_{r,c-s}$, and H_w are calculated using Equations (3) through (6). U_t is then found by Equation (7) and T_c is calculated from Equation (8). If T_c is close to the guess, is is correct. If not, the new value for T_c is used to perform the loss coefficient calculations again and to calculate another T_c. The procedure is repeated until a T_c is reached which is unchanging. This is the correct T_c for the given T_p. So given T_p, the losses due to convection, conduction, and radiation are known. The loss coefficient for the total losses, U_l, is given by Equation (9).

$$U_l = U_t + U_b + U_e \tag{9}$$

The next item to consider is T_p, the plate temperature. This is dependant on three things: the incoming solar energy; the energy losses due to U_l; and the energy being removed by the working fluid. First, a look at the energy removal system used is in order. Figure 4 shows the plate and tube arrangement used to remove heat from the plate. By considering this as a classical fin problem, a fin efficiency, F, is determined and is given in Equation (10). New terms appearing in this equation are W, the distance between tubes; K_p, the thermal conductivity of the

$$F = \frac{\tanh\left[\dfrac{U_l*(W - D)}{2*K_p*\delta}\right]}{\dfrac{U_l*(W - D)}{2*K_p*\delta}} \tag{10}$$

plate; D, the outside diameter of the tubes; and δ, the plate thickness. Next, the bond resistance is considered and the analysis leads to Equation (11). C_b is the bond thermal conductivity of the plate to tube bond. $H_{f,i}$ is the heat transfer coefficient inside the tubes, corresponding to either forced or natural circulation. D_i is the inside diameter of the tubes. Next, a formula for useful gain

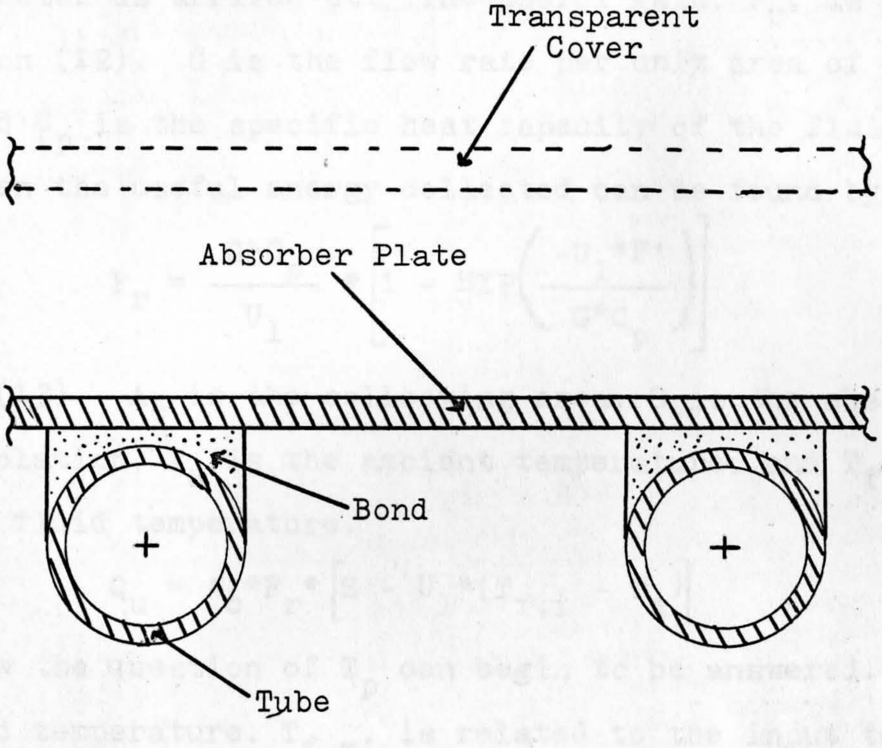


Fig. 4. Plate And Tube Arrangement

$$F' = \frac{\frac{1}{U_l}}{\frac{W}{U_l * D + (W - D)*F} + \frac{W}{C_b} + \frac{W}{\pi * D_i * H_{f,i}}} \quad (11)$$

of a collector is arrived at. The useful gain, F_r, is given in Equation (12). G is the flow rate per unit area of collector and C_p is the specific heat capacity of the fluid used. Then the useful energy collected can be found by

$$F_r = \frac{G*C_p}{U_l} * \left[1 - EXP\left(\frac{-U_l*F'}{G*C_p}\right)\right] \quad (12)$$

Equation (13). A_c is the collecting area, S is the absorbed solar insolation, T_a is the ambient temperature, and $T_{f,i}$ is the input fluid temperature.

$$Q_u = A_c*F_r*\left[S - U_l*(T_{f,i} - T_a)\right] \quad (13)$$

Now the question of T_p can begin to be answered. The mean fluid temperature, $T_{f,m}$, is related to the input temperature and Q_u, U_l, F_r, F', and A_c by Equation (14). Equation (15) and Equation (16) relate the mean fluid temperature and useful gain to the mean plate temperature, $T_{p,m}$.

$$T_{f,m} = T_{f,i} + \frac{Q_u}{U_l*F_r*A_c} * \left[1 - \frac{F_r}{F'}\right] \quad (14)$$

$$T_{p,m} = Q_u*R_{p-f} + T_{f,m} \quad (15)$$

$$R_{p-f} = \frac{1}{H_{f,i}*\pi*D_i*N*L} \quad (16)$$

N is the number of tubes and L is the length of a tube.

Having all of these equations now permits the writing of a computer program which will calculate the fluid output temperature given an input temperature and solar insolation. The flow diagram is shown in Figure 5. Equation (17) referred to in the flow chart is given below and relates the useful energy gained to a rise in fluid temperature. $T_{f,o}$ is the output fluid temperature and DMDT is the rate of mass flow of the fluid. The procedure is to guess a value of T_p,

$$T_{f,o} = \frac{Q_u}{DMDT*C_p} + T_{f,i} \qquad (17)$$

then guess T_c. Now use T_p guessed to perform the iterative calculations described earlier to find a correct T_c for the guessed T_p. Now with this T_c and T_p use Equations (1) through (9) to find U_l. Next, use Equations (10) through (16) to find a new T_p. Use this new value of T_p to repeat all calculations until the value for T_p stabilizes. This is then the correct value for T_p.

Knowing T_p, it is now possible to find the value of the fluid output temperature using Equation (17). This completes the procedure for obtaining an output fluid temperature from the collector given input fluid temperature, solar insolation absorbed, wind velocity, and ambient temperature. It should be noted that the method used to do this was essentially energy balancing. That is, writing equations for the various energy flows in the collector and using conservation of energy to interrelate the equations. This necessarily used steady state analysis because of the extreme complexity of the situation. Thus, the method gives the steady state value of $T_{f,o}$, and variations with time are not

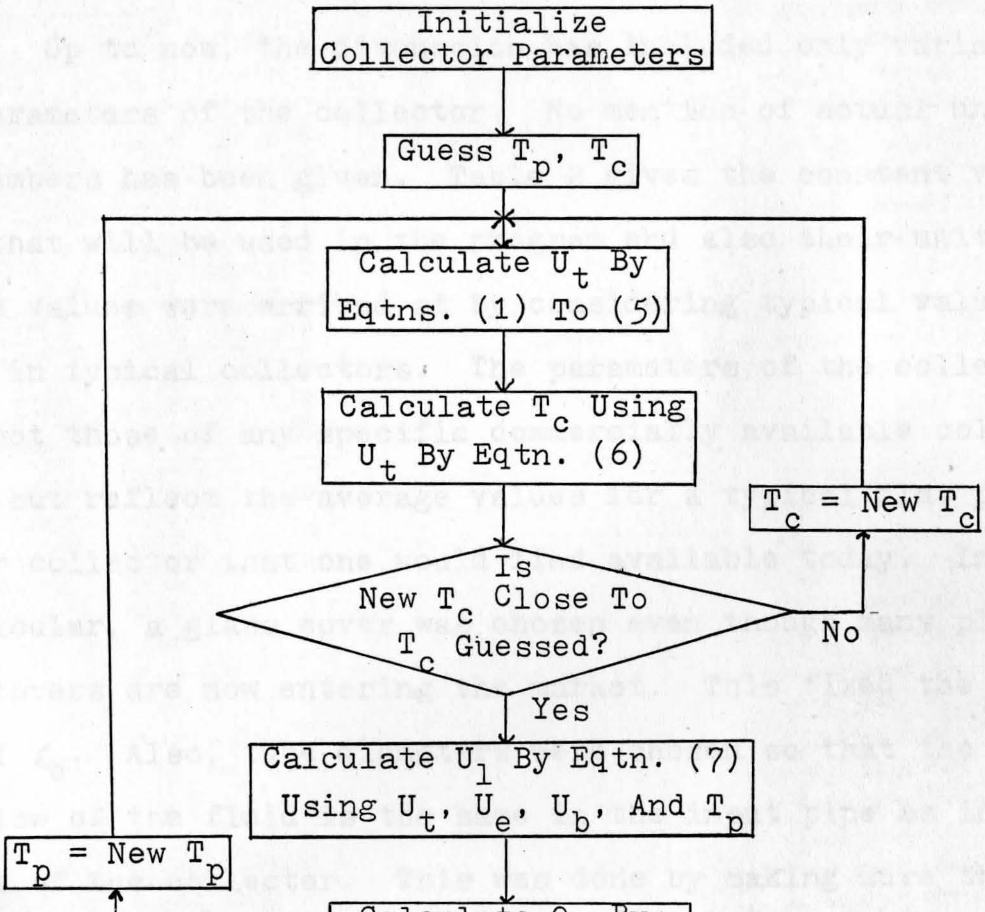


Fig. 5. TOUTC Flow Chart

dealt with.

Up to now, the discussion has included only variables as parameters of the collector. No mention of actual units or numbers has been given. Table 2 gives the constant values that will be used in the program and also their units. These values were arrived at by considering typical values used in typical collectors. The parameters of the collector are not those of any specific commercially available collector, but reflect the average values for a typical flat plate solar collector that one would find available today. In particular, a glass cover was chosen even though many plastic covers are now entering the market. This fixed the value of ε_c. Also, tube diameters were chosen so that the rate of flow of the fluid is the same in the input pipe as in the tubes of the collector. This was done by making sure the cross-sectional areas of all tubes in the collector added to equal the cross-sectional area of the input pipe and also the output pipe. The specific heat used is that of water, even though an additive will be used with the water so as to insure that the fluid does not freeze in the cold months. The plate emittance used was for a selective coating. The remainder of the parameters were chosen by examining values used in Reference [1].

Even with all of these parameter values given, it is still noticed that values for T_s, T_a, $T_{f,i}$, S, WV, and DMDT are not given. The value for T_s was chosen as given in Equation (18). T_s and T_a are in degrees Kelvin. The other

TABLE 2

COLLECTOR PARAMETERS ADOPTED

Constant Name	Constant Description	Value Adopted And Units
T_p	Plate Temperature	°K
T_c	Cover Temperature	°K
ϵ_p	Plate Emittance	.1
ϵ_c	Cover Emittance	.88
T_s	Sky Temperature	°K
Z	Plate To Cover Distance	5 cm
WV	Wind Velocity	m/sec
T1	Test 1	.1 °C
T2	Test 2	.1 °C
K_i	Thermal Insulation Constant	.0245 w/m^2°C
C_b	Bond Conduction Constant	50 w/m°C
L_{ei}	Thickness Of Edge Insulation	.02 m
A_e	Area Of Collector Edge	.9 m
W	Distance Between Tubes	.1 m
D	Outside Diameter Of Tubes	.015875 m
L_{bi}	Thickness Of Back Insulation	.05 m
δ	Plate Thickness	.001 m
K_p	Plate Thermal Conductivity	400 w/m°C
D_i	Inside Diameter Of Tubes	.0127 m
$H_{f,i}$	Fluid To Tube Heat Transfer Coeff.	1500 w/m^2°C
G	Flow Rate Per Unit Area Collector	kg/sec-m^2
C_p	Specific Heat Of Fluid	4190 j/kg°C
A_{coll}	Area Of Collector Plate	2 m^2

TABLE 2 CONTINUED

Constant Name	Constant Description	Value Adopted And Units
S	Solar Insolation Absorbed	w/m^2
$T_{f,i}$	Input Fluid Temperature	°K
$T_{f,o}$	Output Fluid Temperature	°K
T_a	Ambient Temperature	°K
N	Number Of Fluid Tubes	7
L_t	Length Of Fluid tubes	2 m
DMDT	Mass Flow Rate Of Fluid	kg/sec

values are variables which depend on hour of the day and day of the year (except for DMDT). They will be dealt with in

$$T_s = .0552*T_a^{1.5} \tag{18}$$

the following sections. DMDT is a variable which will be chosen as seen fit by running simulations.

This completes the formulation of the model used for the solar collector. The computer subroutine used for this model can be found in Appendix A. The subroutine, which returns a value of $T_{f,o}$ for given input fluid temperature and ambient conditions, is named TOUTC. The subroutine which provides collector parameters for TOUTC is named COLPAR.

The Solar Radiation Model

Since one of the inputs to the solar collector model is S, radiation absorbed, a model is needed to provide this variable given hour of the day and day of the year. The amount of solar energy reaching the Earth needs to be computed and also the amount of this energy which is being absorbed by the solar collector itself.

The amount of solar radiation reaching the ground depends on a host of variables. They include time of day, day of the year, dust content of the atmosphere, water vapor content (humidity) of the atmosphere, cloud coverage, and also the particular location on Earth. Also, the solar radiation reaching the ground consists of two basic forms, direct or beam radiation, and diffuse radiation. Beam radiation is defined as the radiation arising from the sun and following a straight path directly to the ground. This radiation is at a peak when measured by an instrument whose collecting or measuring surface is aimed directly at the sun. Diffuse radiation arises from the scattering effects of the Earth's atmosphere and its contents. This radiation usually has no preferred direction and is measured at approximately the same value in any direction in the sky when there is appreciable cloud cover. Otherwise, 80% of the diffuse radiation is concentrated near the sun's position in the sky when the sky is clear. In addition to the two basic forms of radiation, the radiation is also broken up into a number of different frequencies. A plot of power versus frequency is shown in Figure 6, [1]. The following discussion will concern itself only with the frequencies capable of being passed through the glass cover of the solar collector with little or no attenuation.

Clearly, the best possible way to obtain values for solar radiation at a particular site would be to go out and take measurements at the site. In the absence of such data, an estimation method must be developed. In searching for a method to use, a paper by J.W. Spencer, [2], was found which provided a value of solar energy reaching the ground at sea level. This value was good for clear days and represented beam radiation. The value of solar radiation is given in Equation (19). The H in the equation represents the solar altitude and A_n is as given in Equation (20). W_p is the

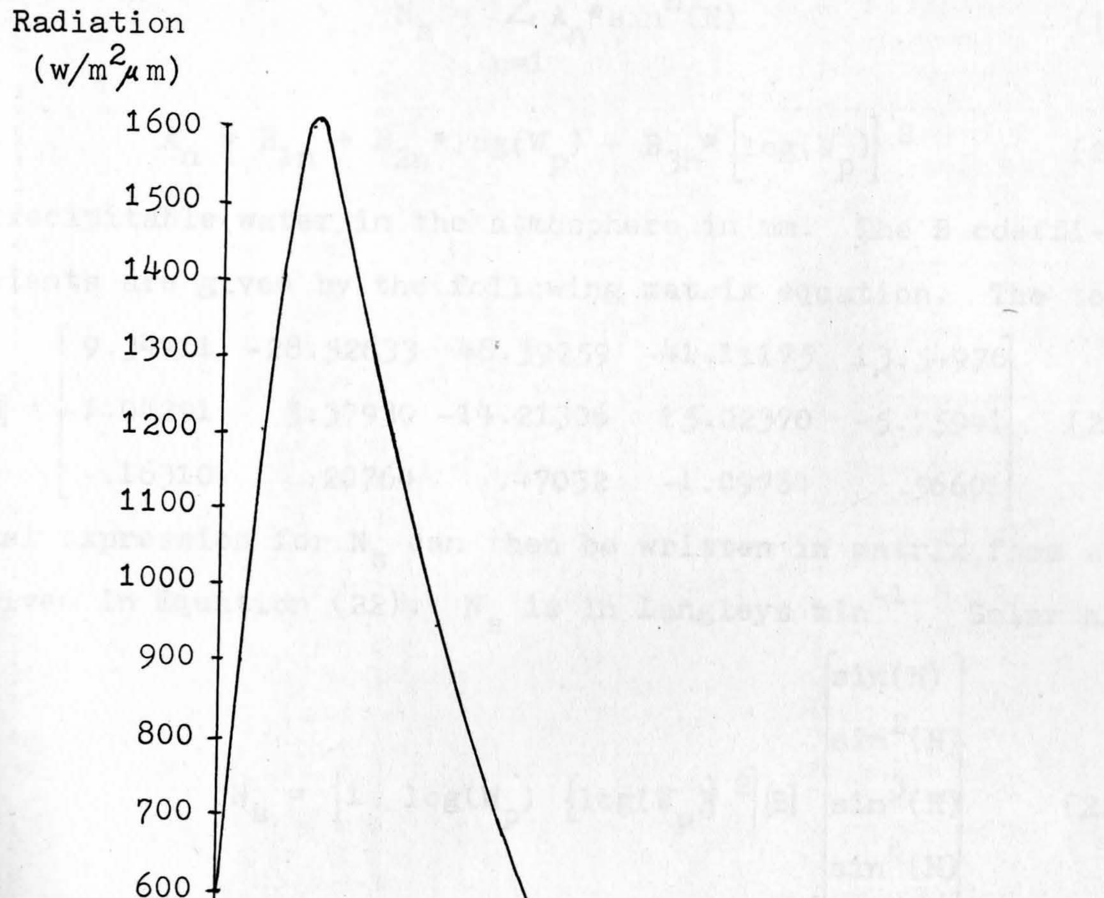


Fig. 6. Spectral Beam Radiation Versus Wavelength

$$N_s = \sum_{n=1}^{5} A_n * \sin^n(H) \qquad (19)$$

$$A_n = B_{1n} + B_{2n} * \log(W_p) + B_{3n} * \left[\log(W_p)\right]^2 \qquad (20)$$

precipitable water in the atmosphere in mm. The B coefficients are given by the following matrix equation. The total expression for N_s can then be written in matrix form as given in Equation (22). N_s is in Langleys $\min^{-1}$. Solar altitude, H, can be found for any time of day and day of year by Equation (23) and (24), [1]. L_a is the lattitude of the location on Earth and H_r is the hour of the day. D_c is the day of the year.

$$[B] = \begin{bmatrix} 9.34711 & -28.52633 & 48.39759 & -41.11175 & 13.54976 \\ -1.04291 & 5.37930 & -14.21306 & 15.02370 & -5.75941 \\ -.16310 & .20764 & .47032 & -1.09764 & .56601 \end{bmatrix} \qquad (21)$$

$$N_s = \begin{bmatrix} 1 & \log(W_p) & \{\log(W_p)\}^2 \end{bmatrix} [B] \begin{bmatrix} \sin(H) \\ \sin^2(H) \\ \sin^3(H) \\ \sin^4(H) \\ \sin^5(H) \end{bmatrix} \qquad (22)$$

$$\sin(H) = \cos(L_a)*\cos(D_l)*\cos\left[15*(H_r - 12)\right] + \sin(L_a)*\sin(D_l) \qquad (23)$$

$$D_l = 23.5*\sin\left[\frac{360}{365}*(D_c - 80)\right] \qquad (24)$$

The only apparent unknown in Equation (22) is the variable W_p. A value for W_p may be found by using Local Climatological Data supplied by the U.S. Department of

Commerce. The values shown in Table 3, [3], are relative humidity versus time of the day and month of the year. Relative humidity is defined as shown in Equation (25), [4]. W_p is partial pressure in mm of precipitable water and E is saturation pressure in mm of precipitable water. Values for

$$R = 100*\frac{W_p}{E} \tag{25}$$

E are given in Table 4, [4], for various temperatures. An interpolation formula which matches the table almost exactly is given by Equation (26), [4]. T is temperature in degrees Centigrade. The constants A, B, and C are found by using

$$\log(E) = A + \frac{B}{T} + C*\log(T) \tag{26}$$

three sets of values of T and E from the table in Equation (26) to get three equations in three unknowns. The equations in matrix form are shown in Equation (27) and the values used for T and C are the three sets of values asterisked in Table 4. The solution of Equation (27) yields Equation

$$\begin{bmatrix} 1 & T_1^{-1} & \log(T_1) \\ 1 & T_2^{-1} & \log(T_2) \\ 1 & T_3^{-1} & \log(T_3) \end{bmatrix} \begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} \log(E_1) \\ \log(E_2) \\ \log(E_3) \end{bmatrix} \tag{27}$$

(28) when the values of A, B, and C are substituted into Equation (26). T must be in degrees Centigrade. So given a

$$\log(E) = 26.99488 - 3090.45310*T^{-1} - 6.16463*\log(T) \tag{28}$$

value of T, a value of E may be found from Equation (28). This value may then be used in Equation (25). Equation (25)

TABLE 3

RELATIVE HUMIDITY, R, VERSUS TIME OF DAY FOR MONTHS OF THE YEAR

Month	Hour 1	7	13	19
	R(%)			
Jan	80	82	73	77
Feb	80	82	69	74
Mar	79	81	65	70
Apr	76	79	56	63
May	78	78	53	61
Jun	83	81	55	63
Jul	84	84	54	64
Aug	86	87	54	67
Sept	85	88	57	72
Oct	81	85	57	70
Nov	79	82	67	73
Dec	82	83	74	78

TABLE 4

SATURATION PRESSURE, E, FOR VARIOUS TEMPERATURES

T(°C)	0	5	10	15	20	25	30
E(mm)	4.58*	6.54	9.21	12.78*	17.51	23.69	31.71*

is rewritten as Equation (29). The value for R may be found by now using the values of R given in Table 3. These val-

$$W_p = \frac{R*E}{100} \tag{29}$$

are given for 1 AM, 7 AM, 1 PM, and 7 PM for the various months of the year. They have been found by taking measurements over forty years and averaging them. A method of interpolating on an hour to hour basis is needed. Month by month values change slowly enough, however, so as to use the table as is.

The method chosen for interpolating hourly values is the method of differences. A brief description of the mechanics of the method is in order. First, a table is set up as shown in Figure 7. Next, differences are calculated. The differences are then used in the following equation, [5].

$$Y_k = Y_o + K*\Delta*Y_o + \frac{K*(K-1)}{2!}*\Delta^2*Y_o + \frac{K*(K-1)*(K-2)}{3!}*\Delta^3*Y_o + \ldots \tag{30}$$

The value of K in the above equation is given by Equation (31), [5]. In general, n + 1 data points give an n^{th} order fit to the data. For the purposes of the problems in this

$$K = \frac{X_k - X_o}{X_{k+1} - X_k} \tag{31}$$

thesis, a program called CURVE was developed to curve fit four data points as a cubic. The standard cubic is shown as Equation (32). The coefficients for this cubic were solved for from Equations (30) and (31) by expanding and were found to be as given in Equations (33) through (36).

X	Y	Δ	Δ^2	Δ^3
X_0	Y_0			
		$Y_1 - Y_0$		
X_1	Y_1		$Y_2 - 2*Y_1 + Y_0$	
		$Y_2 - Y_1$		$Y_3 - 3*Y_2 + 3*Y_1 - Y_0$
X_2	Y_2		$Y_3 - 2*Y_2 + Y_1$	
		$Y_3 - Y_2$		
X_3	Y_3			

Fig. 7. Method Of Differences

$$Y = A_0 + A_1*X + A_2*X^2 + A_3*X^3 \qquad (32)$$

$$A_0 = \frac{\Delta^3}{6*V^3} \qquad (33)$$

$$A_1 = \frac{\Delta^2 - \Delta^3}{2*V^2} - \frac{\Delta^3*X_0}{2*V^3} \qquad (34)$$

$$A_2 = \frac{3*\Delta + \Delta^3}{3*V} + \frac{2*\Delta^3*X_0 - \Delta^2*(2*X_0 + V)}{2*V^2} + \frac{\Delta^3*X_0^2}{2*V^3} \qquad (35)$$

$$A_3 = Y_0 - \frac{3*\Delta*X_0 + \Delta^3*X_0}{3*V} + \frac{2*\Delta^2*(X_0^2 + V*X_0) - \Delta^3*X_0^3}{2*V^2} - \frac{\Delta^3*X_0^3}{6*V^3} \qquad (36)$$

The value of V in the above equations is equal to the difference between successive values of X. Using this method, the values of X must be equally spaced by this constant, V. Table 3 and CURVE were used to find A_0 through A_3 for each month of the year. This was then entered into a subroutine called HUMID which uses these cubics to obtain a value of W_p by using Equations (28) and (29). Now given a value of the ambient temperature, the hour of the day, and the day of the year, a value of beam radiation on a clear day can be found using Equation (22) and subroutine HUMID.

Next, a method of estimating diffuse radiation is desired. The diffuse radiation depends heavily on cloud cover. Since cloud cover data is not available on an hourly basis or even a daily basis, a very accurate hourly model cannot be obtained. Since there is total radiation data available on a monthly basis in the form of mean percentage of possible sunshine and mean daily solar radiation, an average radiation figure may be obtained which would represent conditions averaged over many years. This value of radiation would include both diffuse and beam radiation components. The reasoning for this model is as follows. Since data on total radiation falling on a horizontal surface on a daily basis (averaged for each month) is known (see Table 5, [6]), an estimate of total yearly radiation may be computed. Next, the subroutine developed earlier to estimate hourly beam radiation may be modified by using the mean percentage of possible sunshine data. Since, in essence, the subroutine provides the maximum possible beam sunshine value for a clear day, and on a clear day 80% of the diffuse radiation originates near the sun, this value could be taken to be the total maximum possible radiation value. Doing this then, the actual value of radiation is this value multiplied by the mean percentage of possible sunshine, for which data is known. This would then model the system as all radiation being considered as beam, but the total radiation would still add up to the actual beam plus diffuse radiation. One way to check this is to compare the previously computed yearly estimate of total radiation with the value obtained by integrating the hourly values provided by the modified subroutine. This has been done on a digital computer and the results have been satisfactorily close. Another

TABLE 5

MEAN DAILY SOLAR RADIATION FOR MONTHS OF THE YEAR

Month	Radiation (Langleys)
Jan	125
Feb	183
Mar	303
Apr	286
May	502
Jun	562
Jul	562
Aug	494
Sept	278
Oct	289
Nov	141
Dec	115

justification of this method is that this thesis is concerned with long run averages rather than short term events and performances. While it is true that on an hourly basis solar radiation absorbed may vary drastically, the results that are being looked for are average system performances over many years. Having settled upon this model, CURVE was used to reduce the mean percentage data in Table 6, [6], to cubic equations as functions of day of the year.

The subroutine now provides a value of total radiation available at the ground at any time of day and day of the year for a flat collector surface one meter square whose normal points directly at the sun. However, since tracking collectors are not going to be used, a correction for the sun's position in the sky must be made. This is taken care of by Equation (37), [1], which relates the angle of incidence of the beam to the surface normal, I, to the lattitude, L_a, where the collector is located; the hour of day, H_r; the declination, D_l; the angle at which the collector is inclined from the horizontal, T_{ip}; and the number of degrees west of south the collector is pointed, A_z. By adding this to

$$\cos(I) = \left[\cos(A_z)*\sin(L_a)*\sin(T_{ip}) + \cos(L_a)*\cos(T_{ip})\right] *\cos(D_l)*\cos\{15*(H_r - 12)\} + \sin(A_z)*\sin(T_{ip}) *\cos(D_l)*\sin\{15*(H_r - 12)\} + \left[\sin(L_a) *\cos(T_{ip}) - \cos(A_z)*\cos(L_a)*\sin(T_{ip})\right] *\sin(D_l) \quad (37)$$

TABLE 6

MEAN PERCENTAGE OF POSSIBLE SUNSHINE FOR MONTHS OF THE YEAR

Month	Mean Percentage (%)
Jan	29
Feb	36
Mar	45
Apr	52
May	61
Jun	67
Jul	71
Aug	68
Sept	62
Oct	54
Nov	32
Dec	25

the subroutine as a multiplier of the value of radiation, the angle of incidence of the beam of radiation to the stationary collecting surface is taken care of.

One last item is needed to determine the actual solar energy absorbed by the collector. This is how much radiation penetrates through the glass cover, and how much of this radiation is absorbed by the collector plate. Some radiation is reflected by the cover and some is absorbed by it. The remainder travels through. For glass, this is about .9 of the radiation normal to the surface. The plate also reflects a small amount of radiation. But the value of radiation transmitted through the cover and absorbed is about .9 of the total transmitted through the cover. So in conclusion, to find the solar energy absorbed by the collector, Equation (38) is used, [1]. T_{au} is the transmittance of the glass and A_{1p} is the absorbtivity of the plate. Cos(I) is as given by Equation (37). R_{ad} is the total available represented as discussed earlier as the total amount of radiation in the form of beam.

$$S = T_{au}*A_{1p}*\cos(I)*R_{ad} \qquad (38)$$

The subroutines for the solar radiation absorbed may be found in Appendix A under the names SOLIN and HUMID. Also, a flow chart of the procedure to find the solar energy absorbed is shown in Figure 8.

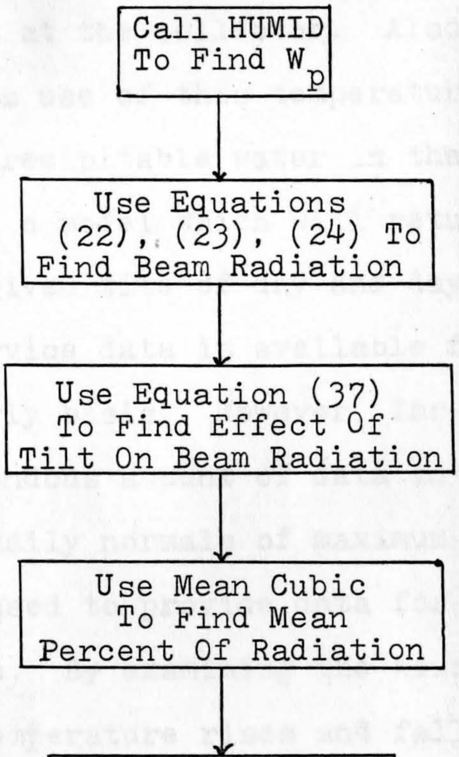


Fig. 8. SOLIN Flow Chart

The Ambient Temperature Model

Another input to the solar collector model is the ambient temperature at the collector. Also, the solar insolation model makes use of this temperature in determining W_p, the amount of precipitable water in the air. A need is then seen to derive a model which will return a value of ambient temperature given time of day and day of the year.

Weather Service data is available for the area in question on an hourly basis. However, for the purpose of reducing this tremendous amount of data into a fairly compact program, the daily normals of maximum and minimum temperatures will be used to provide data for a sinusoidally varying temperature. By examining the hourly record, it is evident that the temperature rises and falls during the average day closely approximate a sine wave with a certain amount of phase shift. Figure 9 shows the general model that will be used. By using daily extremes of temperatures, the representation of temperature mathematically is shown in Equation (39). H_r is the hour of the day with midnight being zero, and P_h is the proper phase shift to ensure that daily max and min temperatures occur at the proper time. T_{max} and T_{min} are the maximum daily temperature and the minimum daily temperature, respectively, which are provided by the U.S. Weather Service, [3]. The records suggest approximately 1600 hours (4 PM) for the maximum temperture to occur during the day. This makes P_h equal to -2.618 radians.

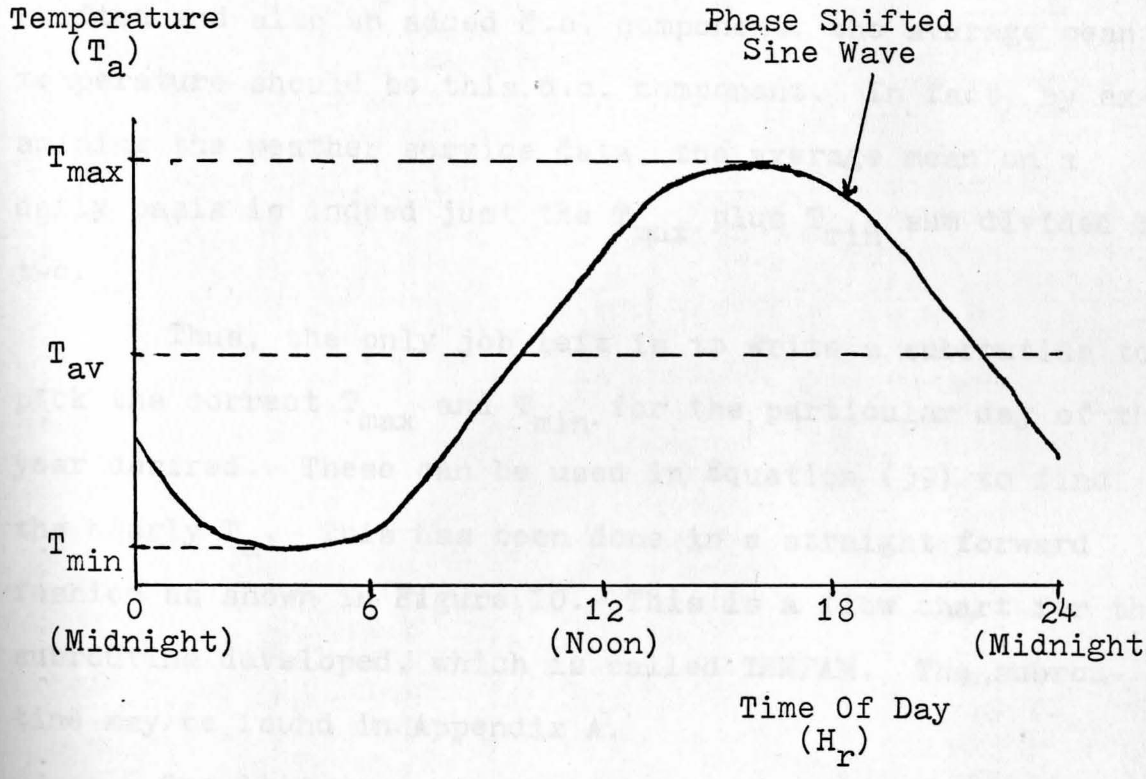


Fig. 9. Daily Temperature Model

$$T_a = \left[\frac{T_{max} - T_{min}}{2}\right] * \sin\left\{\frac{\pi * H_r}{12} + P_h\right\} + \left[\frac{T_{max} + T_{min}}{2}\right] \qquad (39)$$

Since the temperature is represented by a sine wave phase shifted and also an added d.c. component, the average mean temperature should be this d.c. component. In fact, by examining the weather service data, the average mean on a daily basis is indeed just the T_{max} plus T_{min} sum divided by two.

Thus, the only job left is to write a subroutine to pick the correct T_{max} and T_{min} for the particular day of the year desired. These can be used in Equation (39) to find the hourly T_a. This has been done in a straight forward fashion as shown in Figure 10. This is a flow chart for the subroutine developed, which is called TEMPAM. The subroutine may be found in Appendix A.

One last comment should be made on this model. It is to be emphasized that this model will not provide the temperature for any given day, past or future, but will provide a temperature which is an average value for a particular hour of the day and day of the year. This has been arrived at by averaging values over a large number of years, It is also in the interest of this thesis, since an average performance is sought, not the extreme variations which might occur in the physical system.

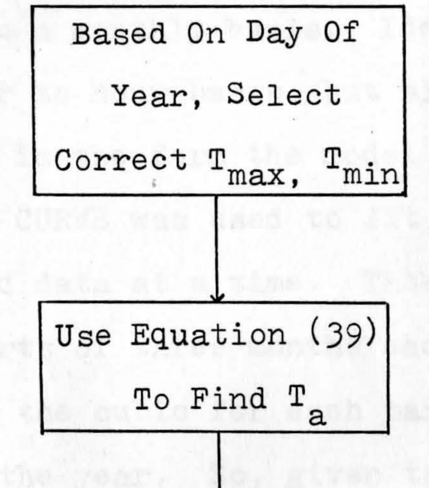


Fig. 10. Flow Chart For TEMPAM

The Wind Model

Another input to the solar collector model is the wind velocity at the collector. Again, weather service data is available only on a monthly basis. Ideally, one would like to have an hour to hour basis, but since data is provided monthly, this is the form the model will use.

Once again, CURVE was used to fit a cubic to three months of wind speed data at a time. Thus, the year is broken into four parts of three months each, and the resulting coefficients of the cubic for each part are used at that particular part of the year. So, given the day of the year, this subroutine will return an average wind speed for that day. The table of wind speeds used in finding the appropriate cubics is shown in Table 7, [3]. The subroutine name is WIND and it may be found in Appendix A.

One last comment on WIND is in order. The data for WIND is taken at the local airport and as such, actual site wind velocity may be different. In all probability it is lower, since the site is in the city where wind shields exist. On the absence of the actual site data, however, this available data will be used.

The Heat Exchanger Model

Now that the solar collector and its various inputs have been modeled, attention can be turned to the modeling of another main element of the system. This element is the

TABLE 7

WIND SPEEDS FOR MONTHS OF THE YEAR

Month	Wind Speed WV (m/sec)
Jan	5.28
Feb	5.23
Mar	5.23
Apr	5.01
May	4.38
Jun	3.89
Jul	3.53
Aug	3.40
Sept	3.71
Oct	4.16
Nov	5.05
Dec	5.19

heat exchanger whose job is to extract heat energy from the collector circuit fluid and to inject this energy into the tank circuit fluid.

There are many types of heat exchangers available today. The type considered here is the tube and shell heat exchanger which is very common. This is shown in Figure 11. This exchanger operates by taking in a hot fluid in port 1a and passing it into thermal contact with a fluid entering port 2a. The surface separating the two fluids has a conduction or heat transfer coefficient associated with it. This coefficient, U, ranges from 850 to 4000 $w/m^{2\circ}C$ in the many available exchangers considered. It is this surface area, A, which enters into the calculation of the energy flow in the exchanger. When the flow pattern is as described above, it is known as parallel flow. However, a larger temperature gradient may be induced in the exchanger if instead of letting the fluid on side 2 of the exchanger enter at 2a, it is allowed to leave at 2a and enter at 2b. This type of flow pattern is known as counter flow. Counter flow allows a more efficient use of the exchanger than parallel flow, and so it will be the flow pattern used.

An expression is now needed for determining the energy flow in the exchanger given the two input fluid temperatures, T_{1a} and T_{2b}. Equation (40) is the desired equation

$$Q = U*A*\Delta T_m \tag{40}$$

for determining Q, the energy flow, [7]. U and A are as previously defined. The term ΔT_m is the mean temperature

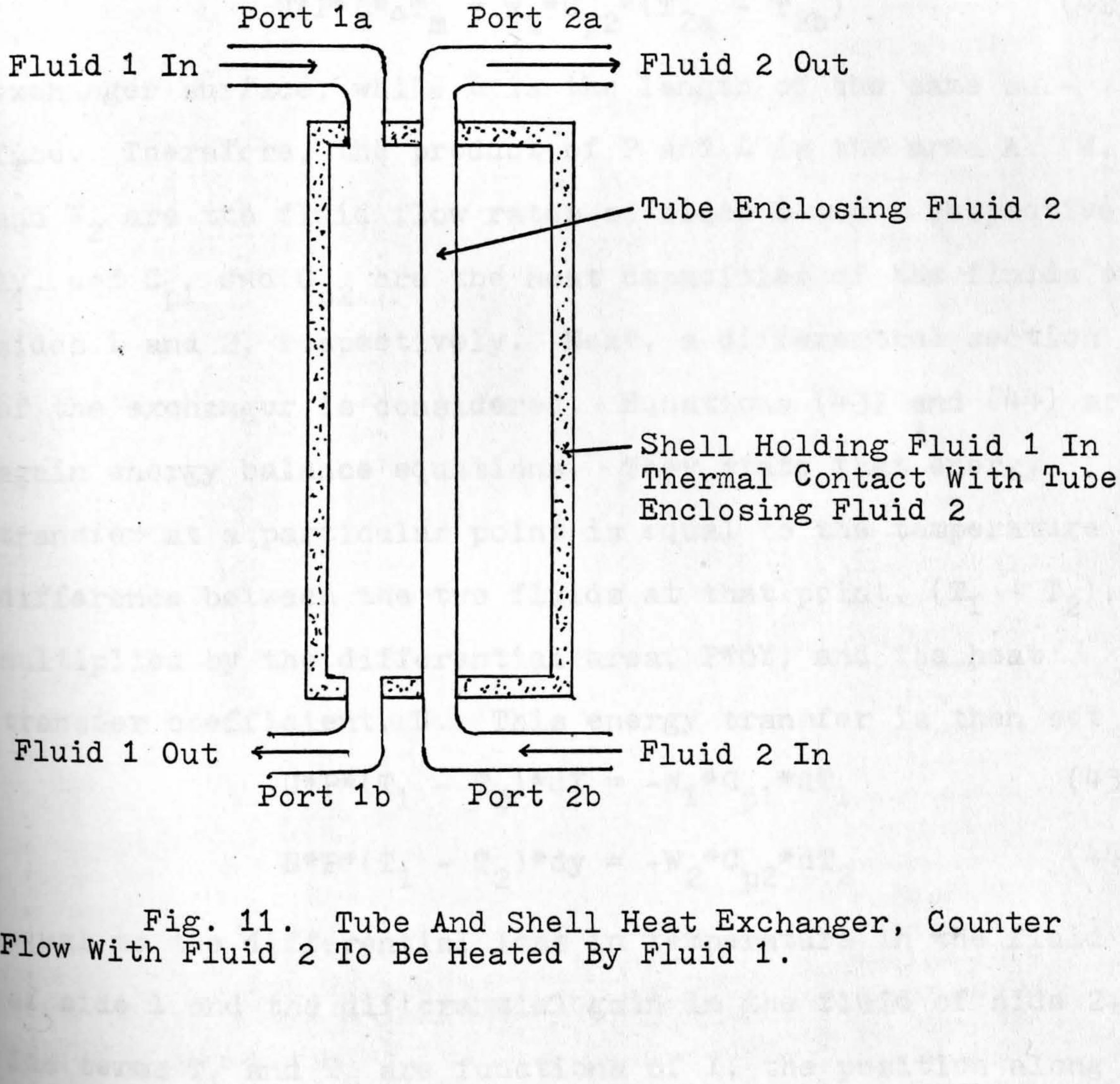


Fig. 11. Tube And Shell Heat Exchanger, Counter Flow With Fluid 2 To Be Heated By Fluid 1.

difference between the two fluids in the exchanger. This term must be solved for. Equations (41) and (42) are energy balance equations which state that the energy transferred is equal to the energy lost by the fluid on side 1 and gained by the fluid on side 2. P is defined as the depth of the

$$U*P*L*\Delta T_m = W_1*C_{p1}*(T_{1a} - T_{1b}) \quad (41)$$

$$U*P*L*\Delta T_m = W_2*C_{p2}*(T_{2a} - T_{2b}) \quad (42)$$

exchanger surface, while L is the length of the same surface. Therefore, the product of P and L is the area A. W_1 and W_2 are the fluid flow rates of sides 1 and 2, respectively, and C_{p1} and C_{p2} are the heat capacities of the fluids of sides 1 and 2, respectively. Next, a differential section of the exchanger is considered. Equations (43) and (44) are again energy balance equations. They state that energy transfer at a particular point is equal to the temperature difference between the two fluids at that point, $(T_1 - T_2)$, multiplied by the differential area, P*dY, and the heat transfer coefficient, U. This energy transfer is then set

$$U*P*(T_1 - T_2)*dY = -W_1*C_{p1}*dT_1 \quad (43)$$

$$U*P*(T_1 - T_2)*dy = -W_2*C_{p2}*dT_2 \quad (44)$$

equal to the differential loss in temperature in the fluid of side 1 and the differential gain in the fluid of side 2. The terms T_1 and T_2 are functions of Y, the position along the length dimension of the exchanger. Now Equations (40) and (41) are rewritten as (45) and (46) and Equations (42) and (43) are rewritten as (47) and (48). Equation (46) is

$$\frac{1}{W_1*C_{p1}} = \frac{T_{1a} - T_{1b}}{U*P*L*\Delta T_m} \quad (45)$$

$$\frac{1}{W_2*C_{p2}} = \frac{T_{2a} - T_{2b}}{U*P*L*\Delta T_m} \quad (46)$$

$$\frac{1}{W_1*C_{p1}} = \frac{-dT_1}{U*P*(T_1 - T_2)*dY} \quad (47)$$

$$\frac{1}{W_2*C_{p2}} = \frac{-dT_2}{U*P*(T_1 - T_2)*dY} \quad (48)$$

is then subtracted from (45) and Equation (48) is subtracted from (47) to give Equations (49) and (50). Equation (50) is

$$\frac{1}{W_1*C_{p1}} - \frac{1}{W_2*C_{p2}} = \frac{(T_{1a} - T_{2a}) + (T_{2b} - T_{1b})}{U*P*L*\Delta T_m} \quad (49)$$

$$\frac{1}{W_1*C_{p1}} - \frac{1}{W_2*C_{p2}} = \frac{-d(T_1 - T_2)}{U*P*(T_1 - T_2)*dY} \quad (50)$$

is subtracted from (49) to give Equation (51). Integration of Equation (51) is carried out as indicated in Equation (52) and results in Equation (53).

$$\frac{-d(T_1 - T_2)}{U*P*(T_1 - T_2)*dY} = \frac{(T_{1a} - T_{2a}) + (T_{2b} - T_{1b})}{U*P*L*\Delta T_m} \quad (51)$$

$$-\int_{T_{1a} - T_{2a}}^{T_{1b} - T_{2b}} \frac{d(T_1 - T_2)}{(T_1 - T_2)} = \frac{(T_{1a} - T_{2a}) + (T_{2b} - T_{1b})}{\Delta T_m} * \int_0^L \frac{dY}{L} \quad (52)$$

$$\Delta T_m = \frac{(T_{1b} - T_{2b}) - (T_{1a} - T_{2a})}{\ln\left[\dfrac{T_{1b} - T_{2b}}{T_{1a} - T_{2a}}\right]} \qquad (53)$$

The above result may now be used in Equation (40) to solve for Q. However, the quantities T_{1b} and T_{2a} are still unknown. Equations (54) and (55) are again energy balance equations. They account for changes in temperatures due to energy transfer. Using Equations (54) and (55) to substitute

$$T_{1b} = T_{1a} - \frac{Q}{C_{p1}*W_1} \qquad (54)$$

$$T_{2a} = T_{2b} + \frac{Q}{C_{p2}*W_2} \qquad (55)$$

for the unknowns T_{1b} and T_{2a} in Equation (53), and then using Equation (53) in Equation (40), the following result is obtained. Equation (56) is the equation for a counterflow,

$$Q = \frac{(T_{1a} - T_{2b})*EXP(U*A*\alpha) + T_{2b} - T_{1a}}{\dfrac{EXP(U*A*\alpha)}{C_{p2}*W_2} - \dfrac{1}{C_{p1}*W_1}} \qquad (56)$$

$$\alpha = \frac{1}{C_{p2}*W_2} - \frac{1}{C_{p1}*W_1} \qquad (57)$$

single pass, heat exchanger. All variables are known in this equation. Equations (54) and (55) may use Q obtained from Equation (56) to solve for T_{1b} and T_{2a}, the temperatures of the fluids returning to the tanks and solar collectors, respectively. Values for U and A will be chosen during the simulation runs to make use of the information gathered then.

The subroutine name for this model is HEXC and it may be found in Appendix A. Given the input fluid temperatures, it returns values of the outlet fluid temperatures. A flow diagram of the program is given in Figure 12. Another feature was added to this subroutine. It has the ability to calculate the outlet temperatures for either the parallel or counter flow mode. The equation for Q of a parallel flow exchanger is given below and was obtained in a manner similar to the counter flow equation, [7]. The main reason for including this in the subroutine was to be able to compare the effects of parallel flow and counter flow with ease.

The counter flow, single pass exchanger was chosen because of its simplicity and its common use and availability.

$$Q = \left[1 - EXP(-U*A*\acute{\alpha})\right] * \frac{(T_{1a} - T_{2a})}{\acute{\alpha}} \qquad (58)$$

$$\acute{\alpha} = \frac{1}{C_{p1}*W_1} + \frac{1}{C_{p2}*W_2} \qquad (59)$$

The Heat Pump Model

Another major system element to model is the heat pump. A heat pump is in essence a temperature amplifier. It uses the available heat energy of some common heat source, such as hot waste water, and also electrical energy to power a compressor. Figure 13 shows a schematic diagram of a heat pump. The cycle begins by passing hot waste water

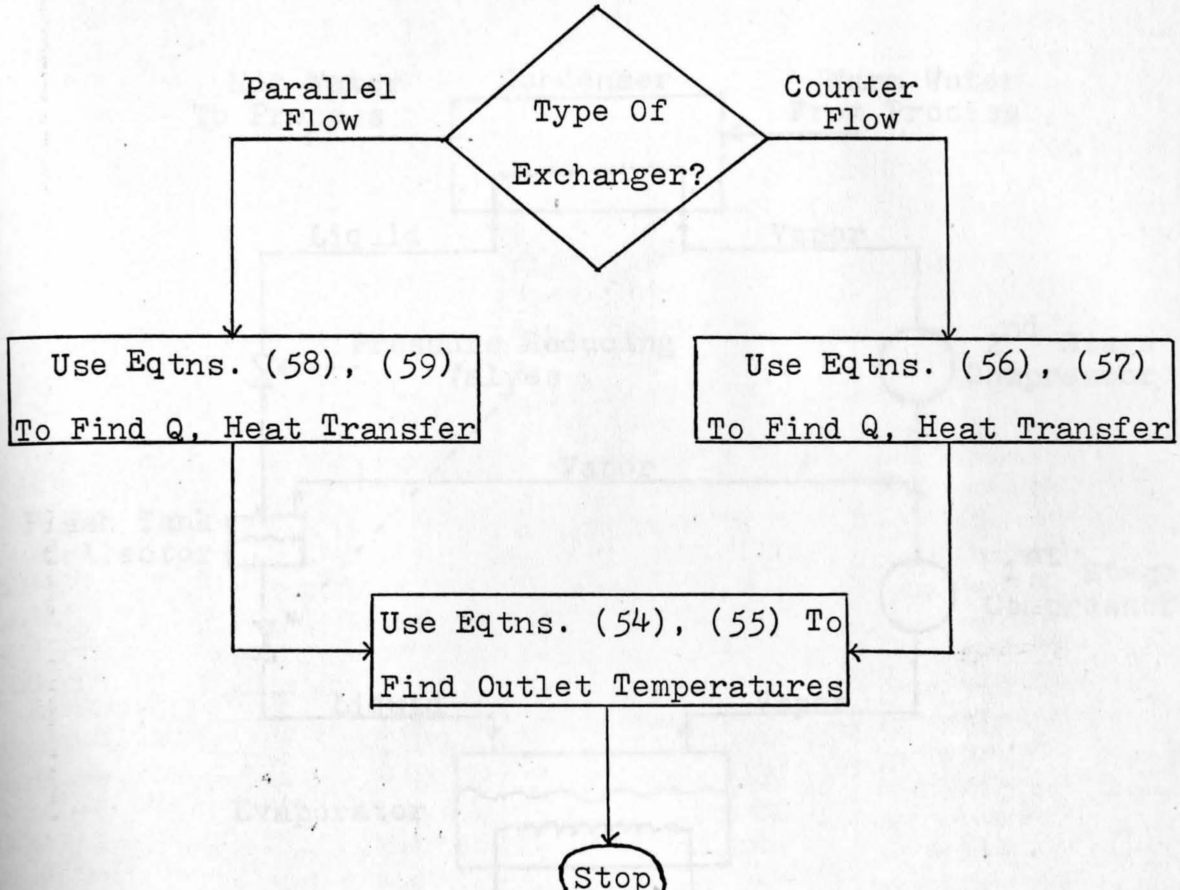


Fig. 12. Flow Diagram For HEXC

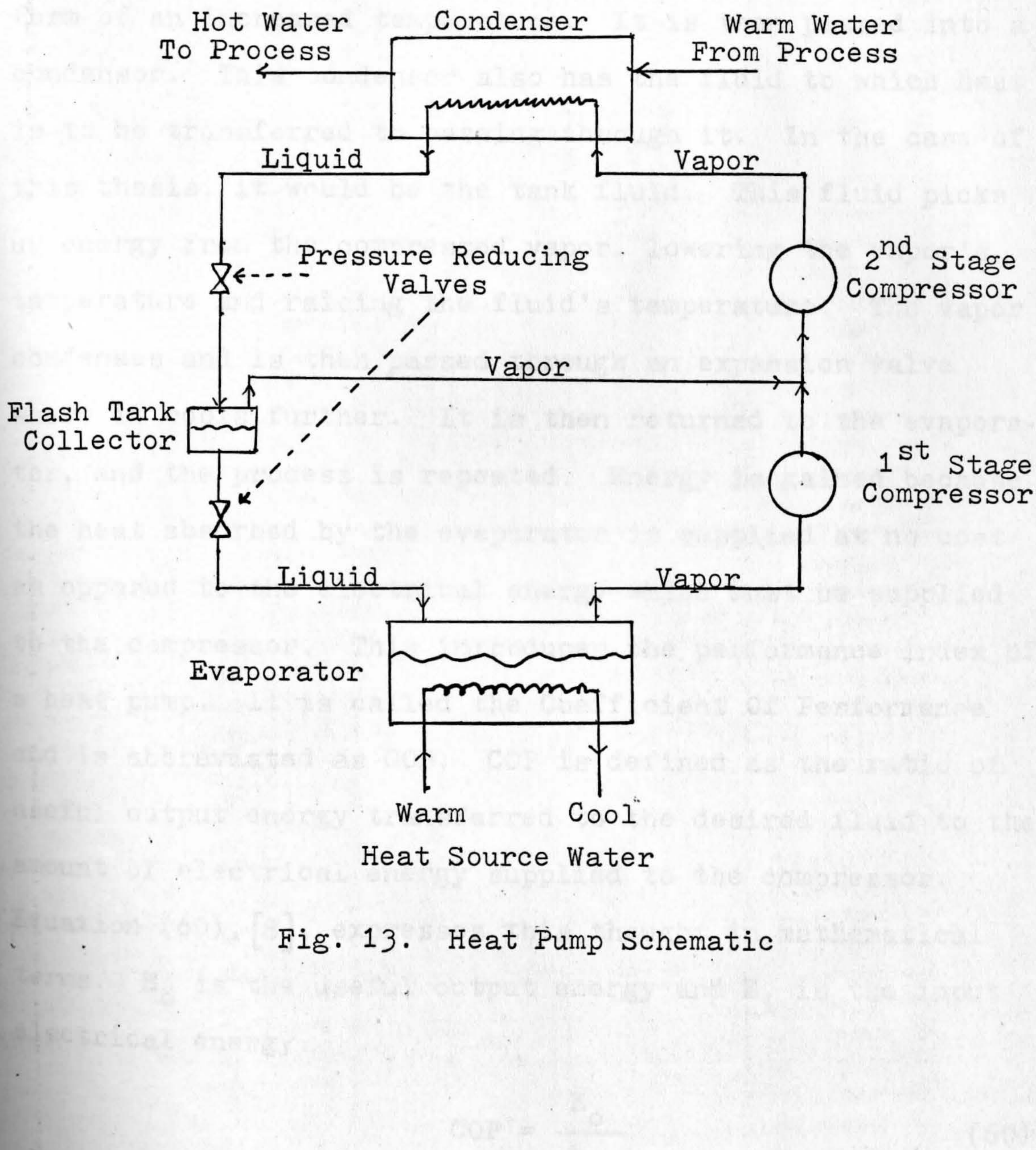


Fig. 13. Heat Pump Schematic

(or in the case of this thesis, the solar collector fluid) into the evaporator. Heat is absorbed into the working fluid of the heat pump. This causes the production of vapor. This vapor is then compressed and thus gains energy in the form of an increased temperature. It is then passed into a condensor. This condensor also has the fluid to which heat is to be transferred to passing through it. In the case of this thesis, it would be the tank fluid. This fluid picks up energy from the compressed vapor, lowering the vapor's temperature and raising the fluid's temperature. The vapor condenses and is then passed through an expansion valve where it cools further. It is then returned to the evaporator, and the process is repeated. Energy is gained because the heat absorbed by the evaporator is supplied at no cost as opposed to the electrical energy which must be supplied to the compressor. This introduces the performance index of a heat pump. It is called the Coefficient Of Performance and is abbreviated as COP. COP is defined as the ratio of useful output energy transferred to the desired fluid to the amount of electrical energy supplied to the compressor. Equation (60), [8], expresses this thought in mathematical terms. E_o is the useful output energy and E_i is the input electrical energy.

$$COP = \frac{E_o}{E_i} \tag{60}$$

The difference between E_o and E_i is the energy supplied by the heat source. Again, this is where a gain is made since the heat source is a free supply, usually waste hot water in industry. In an ideal heat pump, Equation (61) gives the value of COP,[8]. T_h is the temperature of the output fluid and T_c is the temperature of the heat source, both in absolute temperatures. In practice, however, Equa-

$$COP = \frac{T_h}{T_h - T_c} \qquad (61)$$

tion (61) fails because of fluid friction, compressor friction, heat transfer to the walls of the compressor, and other real world loss processes. In place of Equation (61), manufacturers supply a set of curves which relate COP to delivery temperature and source temperature.

The curves for the particular heat pump to be used in this thesis are shown in Figure 14,[8]. It can be seen that it is desired to have the heat source and the delivery fluid temperatures as close as possible for a high COP. For the purpose of this thesis, the heat source is the collector fluid and the delivery temperatures are the tank water temperatures.

It is desired to know the temperature of the collector circuit fluid as it comes out of the heat pump. The temperature of the fluid going into the heat pump is known and also the delivery or tank temperatures are known. Thus, a COP can be found. The energy being delivered to the tanks is unknown. This will depend on a number of things. First, the heat pump chosen is sized so that it can supply the maximum amount of power required by the job. How much power is

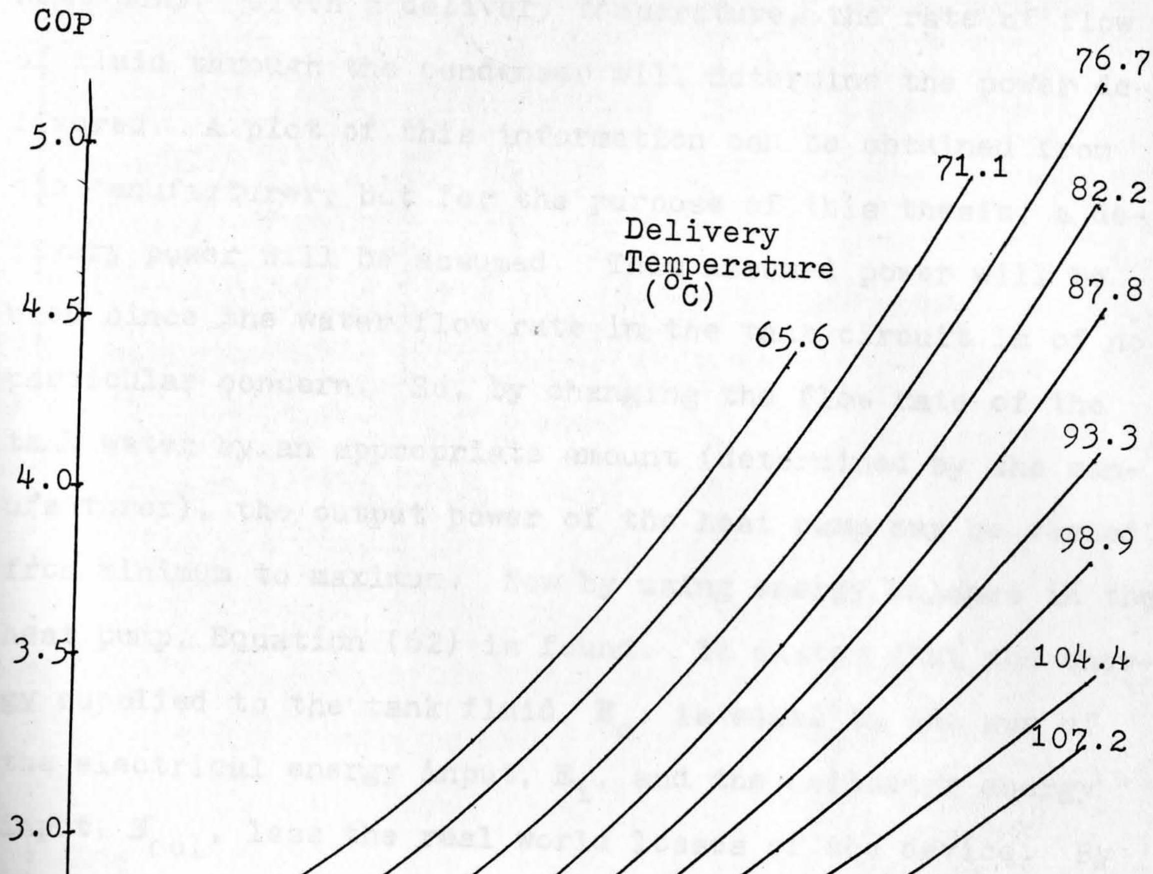


Fig. 14. Heat Pump COP Curves

drawn from the heat pump is a function of the particular heat pump. Given a delivery temperature, the rate of flow of fluid through the condenser will determine the power delivered. A plot of this information can be obtained from the manufacturer, but for the purpose of this thesis, a delivery power will be assumed. This assumed power will be used since the water flow rate in the tank circuit is of no particular concern. So, by changing the flow rate of the tank water by an appropriate amount (determined by the manufacturer), the output power of the heat pump may be varied from minimum to maximum. Now by using energy balance in the heat pump, Equation (62) is found. It states that the energy supplied to the tank fluid, E_o, is equal to the sum of the electrical energy input, E_i, and the collector energy input, E_{col}, less the real world losses of the device. By

$$E_o = E_i + E_{col} - \text{LOSSES} \qquad (62)$$

rewriting Equation (62) in power form, and by including the losses in the E_i term, Equation (63) results. TLOSS is the power supplied to the tanks. KW is the combined input electrical power and loss power. T_{pic} is the input fluid temperature to the heat pump from the collectors and T_{poc} is the output fluid temperature returning to the collectors.

$$\text{TLOSS} = \text{KW} + (T_{pic} - T_{poc})*\text{DMDT}*C_p \qquad (63)$$

DMDT and C_p are the collector fluid flow rate and heat capacity, respectively. Now using Equation (60) in power form, Equations (63) and (60) are combined to give Equation (64).

$$T_{poc} = T_{pic} - \frac{TLOSS*(COP - 1)}{COP*C_p*DMDT} \qquad (64)$$

All quantities can be found or are known in this equation. TLOSS is just the desired power output of the heat pump, or the desired load. So now the unknown return temperature of the fluid to the collector may be found. The procedure is as follows. Use the tank required delivery temperature and the heat source fluid temperature, T_{pic}, to determine COP from the curves given. Then use this COP in Equation (64) along with the desired power output, TLOSS, to find T_{poc}. A subroutine has been developed for this purpose. The given curves have been put into cubic form using CURVE and stored in the program. Thus, given a particular delivery temperature of a tank, the program selects the correct coefficients for the cubic which is a function of T_{pic}. This cubic then gives the value of COP. Thus a value can be returned for T_{poc}. This program is called HPUMP and can be found in Appendix A. The flow chart is shown in Figure 15.

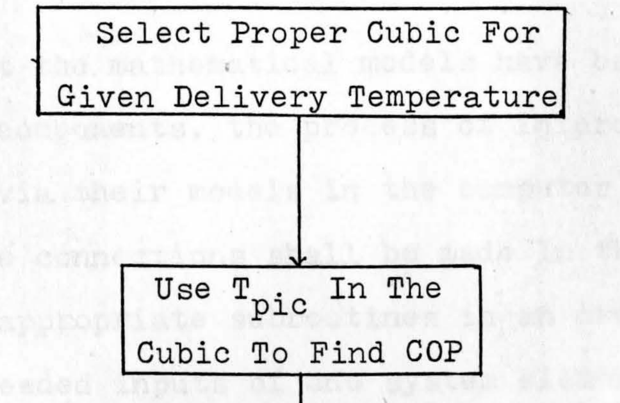


Fig. 15. Subroutine HPUMP Flow Chart

CHAPTER III

SYSTEM SIMULATION, CONTROL PHILOSOPHY, AND OPTIMIZATION

Simulation Approach

Now that the mathematical models have been defined for all system components, the process of interconnecting the components via their models in the computer may be accomplished. The connections shall be made in the computer by calling the appropriate subroutines in an order which will feed the needed inputs of one system element with the outputs of the previous element in the system.

A decision on the basic system configuration needs to be made at this point. Since the system, as described earlier, consists of fourteen different tanks with a variety of water based solutions at various desired temperatures, mixing of these solutions is not permitted. Therefore, an interface between the collectors and the tanks must be used which allows no mixing of the collector water with the tank solutions, and also allows no mixing of the tank solutions with each other. Also involved in this decision is the anticipated performance of the system. It is known that since the collector system fluid output temperature varies with the time of day and day of the year due to ambient temperature and solar insolation changes, that at times the fluid temperature will be lower than any desired tank temperature.

Since a heat exchanger depends on a temperature gradient to transfer energy, if the gradient is not negative from collector to tank, that is, if the collector temperature is lower than the tank temperature, then energy will be transferred to the collectors from the tank only to radiate out of the collector system and into the atmosphere. Yet, even when a lower temperature than the desired tank temperature exists at the collector output, energy collection is sometimes possible. This is where the heat pump can be used. Since the heat pump uses a heat source to lower its energy consumption per delivered unit of energy, these lower than tank temperatures may be used to provide energy.

With all of these considerations in mind, the proposed system configuration which was chosen is shown in Figure 16. As can be seen, a heat exchanger is provided for each tank in the line. Each exchanger has the option of being either connected directly to the solar collector array or to the heat pump, depending on the output temperature of the collector array and the desired tank temperature. Also, it is noted here that the tanks are not all fed energy at once, but that a sequenced switching is performed by valves whereby one tank at a time is connected to receive energy. This is done so that precise control of each tank temperature may be maintained. This configuration was chosen because it meets the requirements of the system as discussed earlier and also because of its simple form. Obviously, this is but one of many possible system configurations.

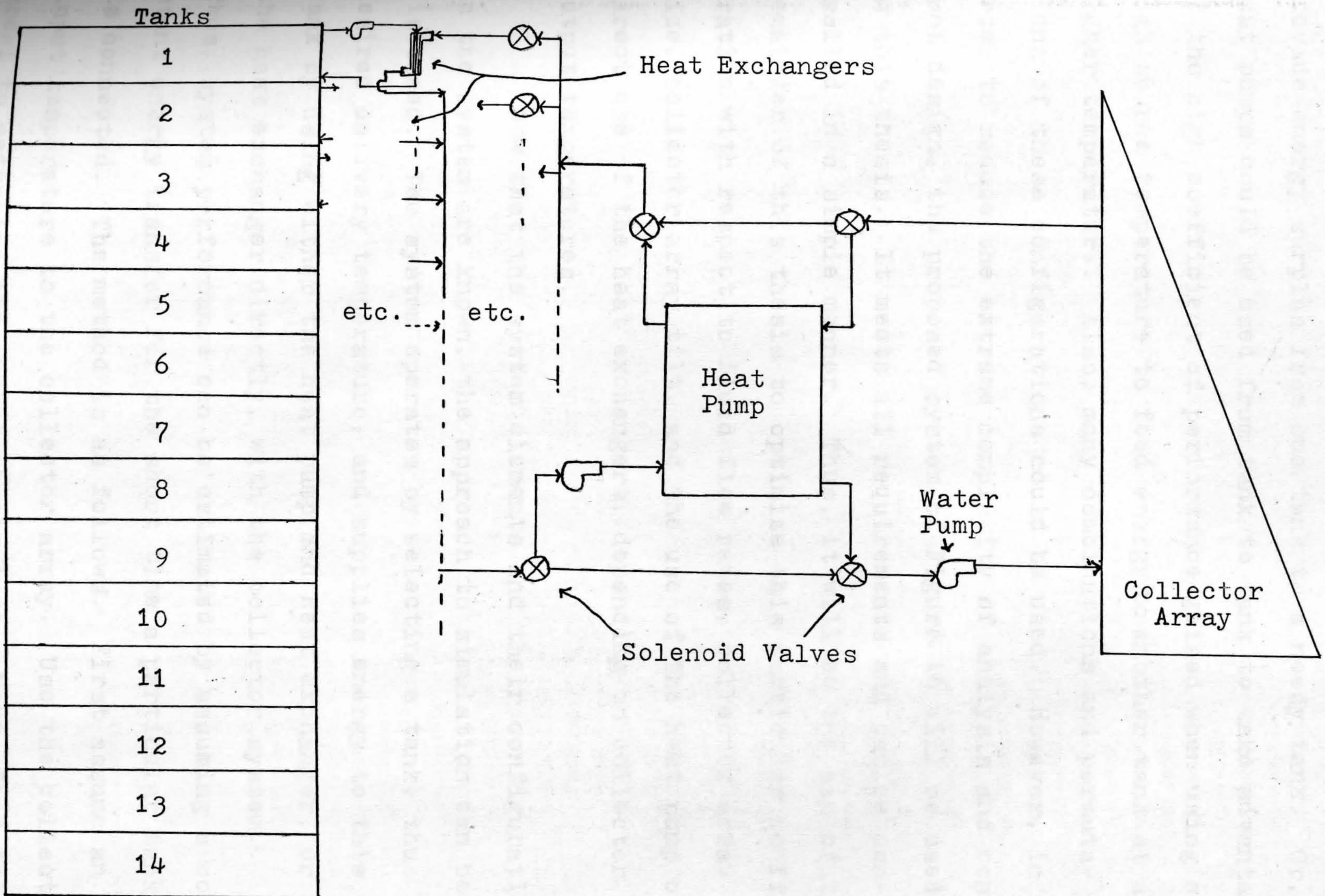


Fig. 16. Proposed System Configuration

Others could include heat exchangers from tank to tank to provide energy surplus from one tank to a needy tank. Or, heat pumps could be used from tank to tank to take advantage of the high coefficient of performance gained when using a high source temperature to feed energy to another tank at a higher temperature. Also, many combinations and permutations of these configurations could be used. However, in order to reduce the extreme complexity of analysis and control design, the proposed system of Figure 16 will be used in this thesis. It meets all requirements and can be controlled in a simple manner. Thus, it will be the aim of the remainder of this thesis to optimize this particular configuration with respect to fluid flow rates, collector array size, collector array tilt, and the use of the heat pump or direct use of the heat exchangers, depending on collector output temperatures.

Now that the system elements and their configuration in the system are known, the approach to simulation can be discussed. The system operates by selecting a tank, thus a desired delivery temperature, and supplies energy to this tank by using either the heat pump and heat exchanger, or the heat exchanger directly, with the collector system. Thus, system performance can be estimated by assuming a constant energy transfer for the short time a particular tank is connected. The method is as follows. First assume an input temperature to the collector array. Use the collector model to determine the output temperature. Next, feed this output temperature to either the heat pump or heat exchanger model, depending on how hot the temperature of the fluid is. Use the model to determine the temperature of the output fluid from the heat pump or heat exchanger. This fluid is now the input fluid to the collector array. If its temperature agrees with the original guess temperature, the process is stopped. Otherwise, the circuit around the system is calculated again until the starting input temperature to the collector matches the finishing output temperature of the heat exchanger or the heat pump. When this occurs, the steady-state temperatures around the system are known, and so the steady-state energy transfers can be calculated. By calculating the steady-state energy transfer for each tank as it is switched in during the day, the system performance can be estimated for the entire system. The method described above is used in the computer as a subroutine called LINK. This subroutine links the components and determines the steady-state conditions through iterations. A flow diagram for LINK is seen in Figure 17.

In LINK, there are subroutines called which have not been previously discussed. The first is ARRAY. This subroutine connects the collectors in parallel and series combinations and calls the collector model subroutine TOUTC to determine the appropriate output temperature of each collector in series. The parallel sections, of course, have the same output temperatures since they have common input fluid temperatures and the same number of series collectors.

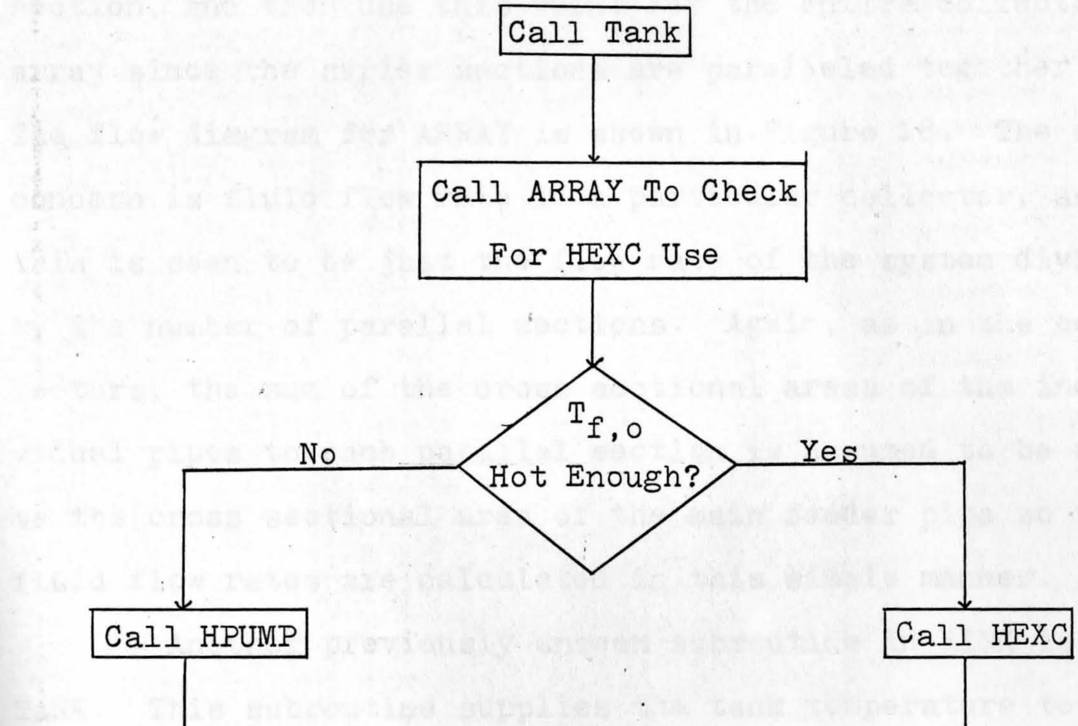


Fig. 17. Subroutine LINK Flow Chart

Thus, all that is really needed is to figure out one series section, and then use this value for the entire collector array since the series sections are paralleled together. The flow diagram for ARRAY is shown in Figure 18. The major concern is fluid flow rate in a particular collector, and this is seen to be just the flow rate of the system divided by the number of parallel sections. Again, as in the collectors, the sum of the cross sectional areas of the individual pipes to each parallel section is assumed to be equal to the cross sectional area of the main feeder pipe so that fluid flow rates are calculated in this simple manner.

Another previously unseen subroutine in LINK is TANK. This subroutine supplies the tank temperature to LINK. As explained earlier, the tanks are fed energy one at a time. There is a sequenced switching which takes place. The actual switching is done in the main program by a simple indexer. When LINK is called, the value of this indexer, from one to fourteen, is passed on to LINK and thus to TANK. The indexer determines what particular tank is being fed energy at that particular time, the numbers one through fourteen representing tanks one through fourteen. However, because the different tanks lose energy at different rates, the time spent on a particular tank is not necessarily equal to the time spent on another tank. It was decided that at any particular time period, the heat pump should have a constant load on it. This means it is delivering a constant amount of energy to the tanks at any time. But referring to

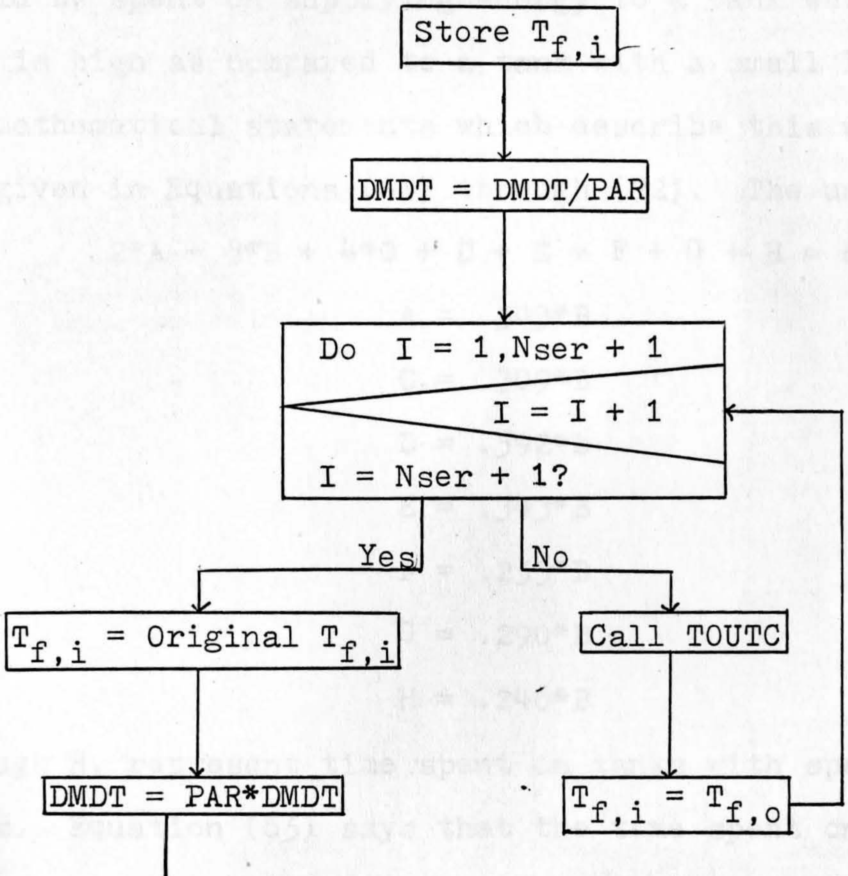


Fig. 18. Flow Chart For ARRAY

Table 1, it is seen that some tanks lose energy more quickly than others. Because of this, a larger amount of time should be spent on supplying energy to a tank whose loss rate is high as compared to a tank with a small loss rate. The mathematical statements which describe this weighting are given in Equations (65) through (72). The unknowns, A

$$2*A + 3*B + 4*C + D + E + F + G + H = 60 \quad (65)$$

$$A = .503*B \quad (66)$$

$$C = .309*B \quad (67)$$

$$D = .592*B \quad (68)$$

$$E = .343*B \quad (69)$$

$$F = .253*B \quad (70)$$

$$G = .290*B \quad (71)$$

$$H = .246*B \quad (72)$$

through H, represent time spent on tanks with specific loss rates. Equation (65) says that the time spent on all fourteen tanks whould add up to sixty minutes or one hour. Equations (66) through (72) are merely ratios of the time spent on the different tanks with respect to B type tanks obtained by taking tank loss ratios. Solution of these equations for times A through H result in the values of Table 8. These are the values in minutes that the sequencer should allow a particular type tank to be fed energy during the hour. Since the sequencer moves down the tanks in order, the first tank, an A type, 71.1 °C, 66,777 w loss tank, is given energy first. It is fed for 4.33 minutes and then the next tank, a D type, 76.7 °C, 78,638 w loss tank, is

TABLE 8

TIME ALLOTTED EACH TANK PER HOUR

Tank Type	Tanks Of This Type From Table 1	Minutes Spent On This Tank Type
A	#1, #12	4.33
B	#4, #13, #14	8.61
C	#5, #7, #9, #11	2.66
D	#2	5.10
E	#3	2.95
F	#8	2.18
G	#6	2.50
H	#10	2.12

switched in for 5.10 minutes. The remaining twelve tanks follow with their appropriate time intervals. Thus, the value of the sequencer determines which tank is in use, what the tank temperature is, and how much time is spent on that tank. Naturally, once the sequencer reaches fourteen, it returns to one and the process repeats. By this system, no one tank is favored over another, since each tank's energy loss is taken into account in deciding how much energy to allot it.

Since the heat pump must feed a heat exchanger, a complex thermal process would normally need to be solved by iterations in order to provide the value of the delivery temperature to the heat pump. In order to greatly simplify the modeling, the following reasoning is used to eliminate the tank-heat exchanger-heat pump interface mathematically. If the tank fluid entering the exchanger has the same flow rate as the heat pump fluid entering the exchanger, and if the exchanger is capable of transferring an adequate amount of heat, then the output temperature of the heat pump side will be equal to or slightly greater than the input temperature of the tank. Thus, the input temperature (the delivery temperature) to the heat pump will be approximately the tank temperature if the heat exchanger is efficient enough. This assumption will be made. Justification of this assumption is further obtained by realizing that since a counter flow exchanger is being used, the end temperatures even more closely approach each other than a parallel flow exchanger.

One last word about subroutine LINK is in order. This concerns how the decision is made on whether to use the heat pump and exchangers or just the exchangers. As noted earlier, there are times when the fluid output temperature of the collectors will not be large enough to use the heat exchangers alone. The way this is determined is to run a test before deciding upon the heat pump or heat exchanger. It goes as follows. Subroutine TANK is called to determine the particular tank temperature being worked with. This temperature is then used as the guess input temperature to ARRAY and a value of the output fluid temperature is calculated. If this output fluid temperature is larger than the input fluid temperature, energy can be supplied to the tank and so the heat exchangers are used directly. However, if this temperature is lower than the input temperature, it is then realized that the output fluid of the collector is not hot enough to use the heat exchanger alone and thus the heat pump is used. Also, there is a buffer temperature defined, DEL, which is used to make sure that at least a difference of DEL degrees exists between the tank and collector fluids so that a sufficient amount of heat will flow.

One last word on TANK is also in order. In as much as the tank temperatures are assumed to be constant, it is realized that in reality they are not. If the solar energy was unable to supply the correct amount of energy, the temperatures might fall below their nominal values. That is why it is assumed that the gas burners are still in each tank supplying energy when the solar system can not. The burners are switched in to prevent the tanks from dropping below their nominal temperature values. This completes the discussion on LINK and its associated subprograms. LINK may be found in Appendix A.

As the program now stands, simulation would be possible. A main program which would call LINK and provide a sequencer could be written. This program could state the hour of the day and day of the year, call LINK, and receive the steady-state energy transfer which is taking place. Although in theory this could be done, a great deal needs to be known yet. What if the sun has not risen yet? The results would be meaningless if results occured at all. The program might not iterate to stability because of the nature of the situation. Or, what size load should be given to the heat pump? Too large a load might freeze the fluid in the collector pipes by drawing too much energy from it. Also, at what rate should water be run through the collector array? Too fast a flow might not pick up enough energy to raise the water to a temperature which will ever be acceptable to use the heat exchangers alone. Clearly these questions must be considered and at least approximate answers must be arrived at before optimization simulations can begin.

Control Philosophy

In considering the question of how large a load should be placed on the heat pump, a reasonable answer appears to be as much as it will take to use nearly all of the solar energy being collected. This can be put into a mathematical statement as Equation (73). This equation says the

$$SE = (T_{f,o} - T_{f,i})*DMDT*C_p \qquad (73)$$

solar energy collected per unit of time, SE, is equal to the rate of energy gained by the working fluid, where $T_{f,o}$ is the output fluid temperature and $T_{f,i}$ is the input fluid temperature to the collectors. DMDT and C_p are the rate of mass flow and heat capacity of the fluid, respectively. In the actual system, temperature sensors could supply values for $T_{f,o}$ and $T_{f,i}$. TLOSS, the load on the heat pump, can now be sized using the value of SE. Since it is possible for the heat pump to draw more energy from the collector fluid than is being supplied by the collectors, the value of TLOSS must be kept low enough so that this does not occur. Otherwise, the temperature of the fluid would spiral downward until it froze. Equation (74) states this mathematically. This equation states that no greater of a load than

$$TLOSS \leq SE + KW \qquad (74)$$

the sum of the available solar energy being transferred into the collector fluid and the electrical power being used by the heat pump may be used. Using Equations (73) and (60), Equation (75) is obtained.

$$TLOSS < \frac{(T_{f,o} - T_{f,i})*C_p*DMDT*COP}{(COP - 1)} \qquad (75)$$

It would appear that the value of COP would be needed in order for this equation to be used. This is no problem in the simulation runs because the value of COP is found before the value of TLOSS is used in the calculations. In the actual physical system, however, a way will have to be provided for the value of COP to be found in order that the load, TLOSS, may be sized properly. In Equation (75), the replacement of the less than sign with an equal sign and the addition of a factor, PF, which may take on a value between zero and one, results in Equation (76).

$$TLOSS = \frac{(T_{f,o} - T_{f,i})*C_p*DMDT*COP*PF}{(COP - 1)} \qquad (76)$$

When PF has the value of one, all collected energy will be used by the heat pump. When PF has the value zero, none of the collected energy will be used by the heat pump. In addition to this, an effect on the behavior of the system comes into play for a PF equal to one. Since all energy is used, the fluid returns to the collectors with its original input temperature. Therefore, the iterations around the system stabilize instantly. However, if PF is slightly less than one, the input fluid will return slightly warmer than its original value, and the new output temperature is thus changed. Iterations will occur until the proper operating temperatures result at which the system stabilizes. This, however, would not be the desired result. Since the value of PF is less than one, the value of TLOSS would allow each successive iteration to raise the value of $T_{f,i}$, regardless of $T_{f,o}$. Because a limit is reached with regards to maximum fluid output temperature of the collector, the $(T_{f,o} - T_{f,i})$ factor gets smaller and thus, so does TLOSS for each iteration when $T_{f,o}$ maximum is reached. In order to avoid this condition, the value of $T_{f,o}$ will be checked at each iteration. Once it has stabilized at its maximum value, PF will be set to one. This will allow the system to stabilize. Using this scheme, a high final $T_{f,o}$ will be reached, and also $T_{f,i}$ will remain small enough to cause a large TLOSS. This operating point is the desired result, since the stabilized temperatures will be the highest values possible. The higher the fluid temperature going into the heat pump, the higher its COP. The value of PF will have to be adjusted in the simulations to optimize the system. It may turn out that a PF of .5 results in a greater overall system performance than a PF of .9. This may at first seem contradictory, since for the larger PF, more of the input solar energy is used. But the operating point of the system, that is the stabilized temperatures, may be such as to cause greater efficiency at the lower value of PF.

Next, the problem of when to start and stop the system is considered. Fortunately, for the simulation runs this information is provided by SOLIN, the solar insolation model subroutine. When a value of S, solar insolation absorbed, is negative, this means the sun has not risen or has set. Thus, a negative value of S can be used to stop the simulation runs at sundown, and also detect when to begin the runs in the morning. In the actual physical system, some sort of sensor will have to be provided to perform this function.

Another decision to make is the rate of fluid flow in the system. To make an initial intelligent guess at a proper flow rate, simulations were run using only the collector subroutine and its associated input subroutines. Arbitrary values of input fluid temperatures were used and various flow rates were used to generate a family of curves. These curves were plots of fluid output temperature versus flow rate of the fluid. A set of these curves was obtained for the hours of 8 AM to 4 PM on the 15^{th} day of each month of the year. The results seemed to indicate that a flow rate of about .002 kg/sec per collector unit was necessary to raise the input fluid temperature an appreciable amount. A faster flow rate just did not raise the temperatures enough, and a slower rate did not really effect the final temperature values very much. An example family of curves is shown in Figure 19. For the particular collector being used, then, a flow rate of .002 kg/sec was chosen as a first guess. This will be varied slightly in the optimization simulations to obtain the best flow rate.

One last subroutine is needed before trial simulation runs can be made. This subroutine is the time incrementer. In order to keep in synchronization with tanks,

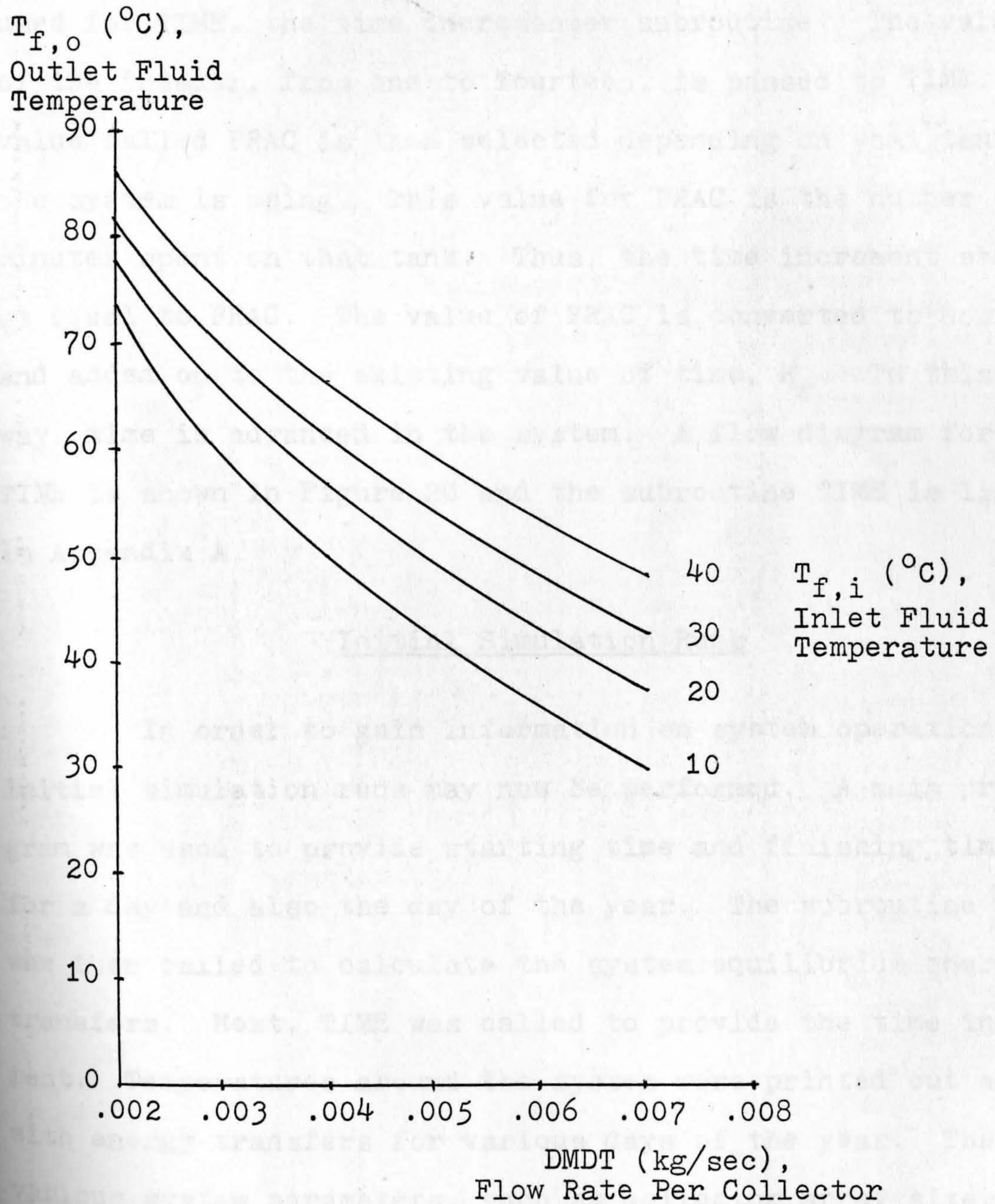


Fig. 19. Collector Performance For March 15, 10 AM, For Various Input Fluid Temperatures And Fluid Flow Rates.

time increments equal to the time duration per tank are needed. This means the simple indexer used for TANK can be used for TIME, the time incrementer subroutine. The value of the indexer, from one to fourteen, is passed to TIME. A value called FRAC is then selected depending on what tank the system is using. This value for FRAC is the number of minutes spent on that tank. Thus, the time increment should be equal to FRAC. The value of FRAC is converted to hours and added on to the existing value of time, H_r. In this way, time is advanced in the system. A flow diagram for TIME is shown in Figure 20 and the subroutine TIME is listed in Appendix A.

Initial Simulation Runs

In order to gain information on system operation, initial simulation runs may now be performed. A main program was used to provide starting time and finishing time for a day and also the day of the year. The subroutine LINK was then called to calculate the system equilibrium energy transfers. Next, TIME was called to provide the time increment. Temperatures around the system were printed out along with energy transfers for various days of the year. The various system parameters, such as collector array size, fluid flow rate, the heat exchanger's heat transfer coefficient and area, the value of PF for the heat pump, the value of DEL for the heat exchanger-heat pump decision, and collector array tilt were all adjusted until reasonable results

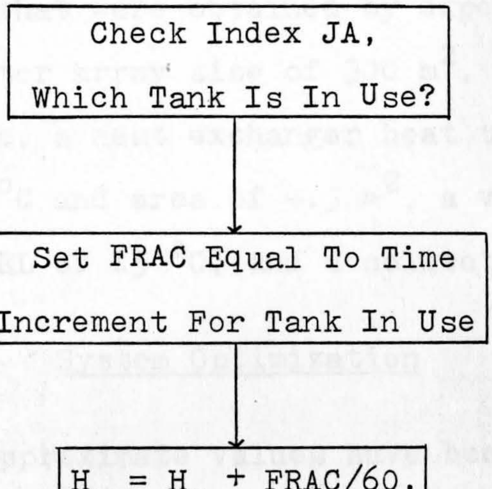


Fig. 20. Flow Chart For TIME

for system performance were obtained. Typical system performance is shown for the day of March 15 in Figures 21 and 22. These figures show plots of fluid temperatures around the system and energy being transferred. The particular results obtained in these plots are for values of the various system parameters that were obtained by experimentation. These are a collector array size of 300 m^2, a fluid flow rate of .002 kg/sec, a heat exchanger heat transfer coefficient of 1700 $w/m^{2\,o}C$ and area of 4.5 m^2, a value for PF of .95, a value for DEL of 15 ^oC, and a collector tilt of 45^o.

System Optimization

Now that approximate values have been found for the various system parameters, these values may be varied one at a time to determine the effect on the system and to find the optimum value of each parameter. In this case, optimum refers to the lowest cost paid for energy. Since cost is to be the parameter which will be of most interest, a method must be found to calculate it.

In order to calculate cost, three main items need to to be known. These three items are cost of the system components, cost of energy used by the system to operate, and amount of energy provided by the system. The amount of energy provided by the system can be calculated using the results of simulation runs. Since the simulation calculates the stabilized system energy transfers each time LINK is called, this information can be used to determine total

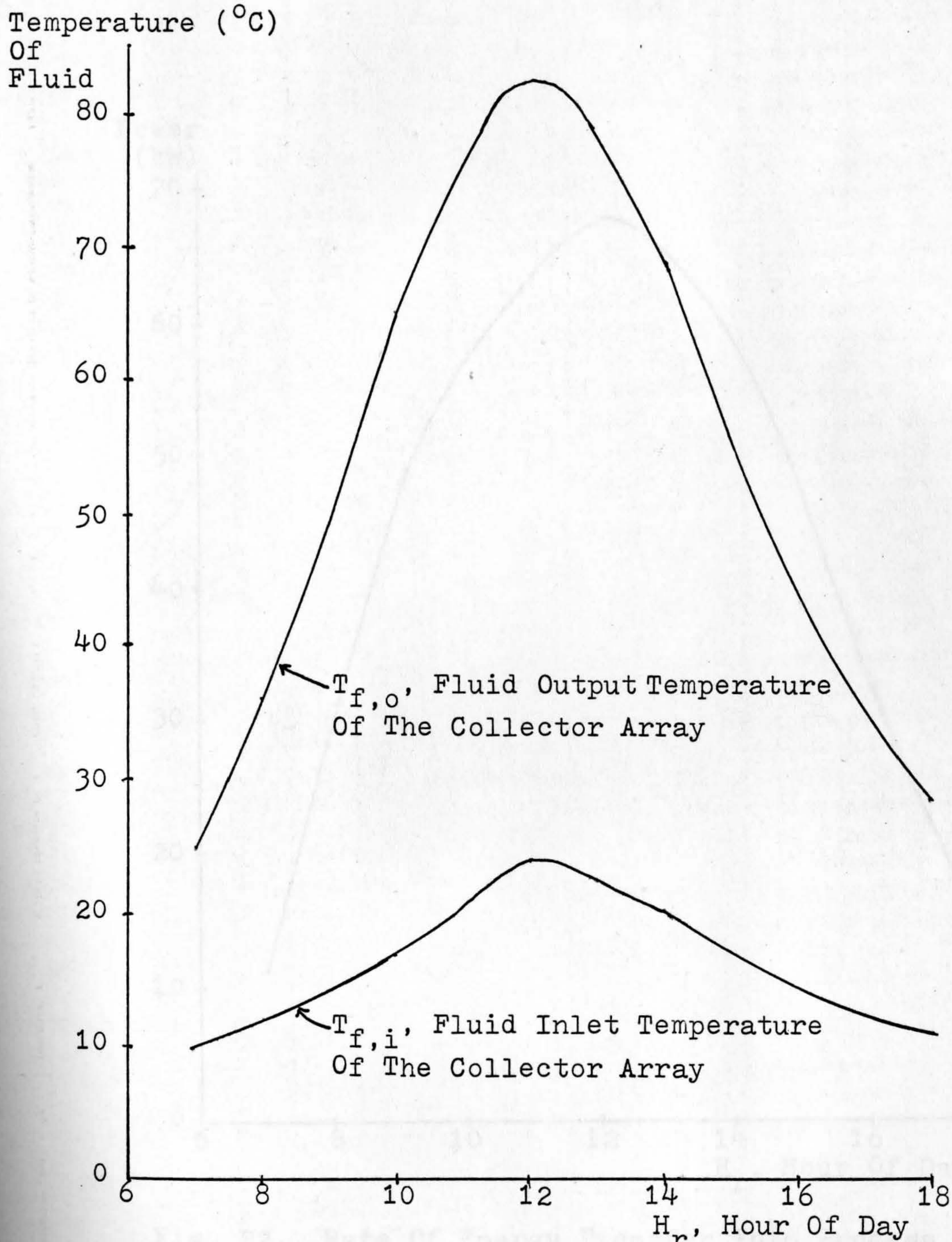


Fig. 21. Fluid Temperatures Of Solar System (300 m^2 Array) For March 15.

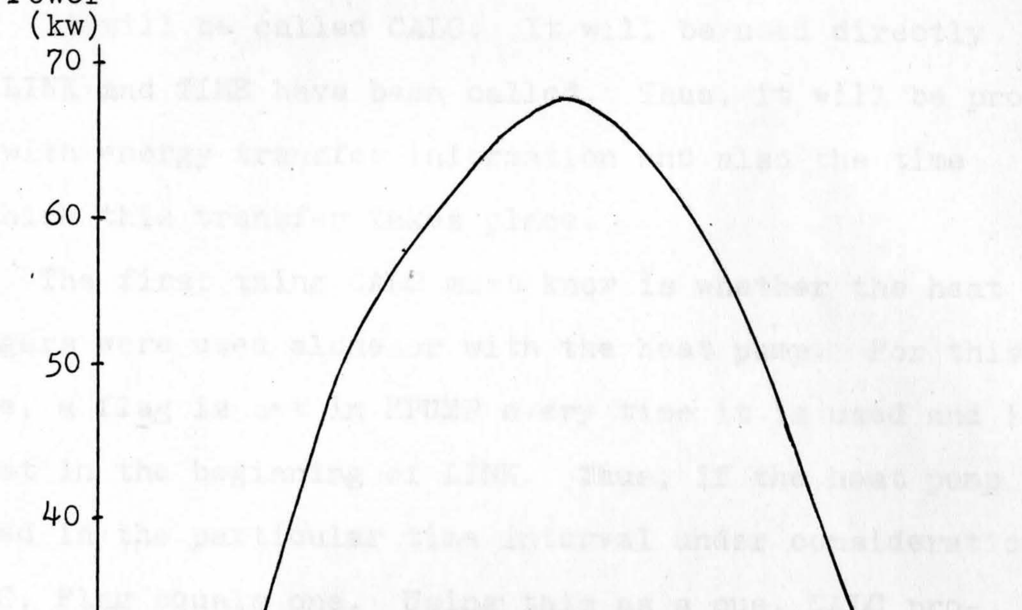


Fig. 22. Rate Of Energy Transfer Into Process Hot Water System By Solar System (300 m^2 Array) For March 15.

energy provided and used by the system. In order to do this using the present subroutines, a new subroutine must be devised. It will be called CALC. It will be used directly after LINK and TIME have been called. Thus, it will be provided with energy transfer information and also the time over which this transfer takes place.

The first thing CALC must know is whether the heat exchangers were used alone or with the heat pump. For this purpose, a flag is set in HPUMP every time it is used and it is reset in the beginning of LINK. Thus, if the heat pump was used in the particular time interval under consideration by CALC, Flag equals one. Using this as a cue, CALC proceeds to find the energy provided by the collector array. Equation (77) gives the incremental energy transferred, by the collector array into the fluid, over the time period in question. It states that the incremental energy transferred

$$DS = (T_{f,o} - T_{f,i})*DMDT*C_p*FRAC*60. \quad (77)$$

equals the power lost by the fluid multiplied by the time, FRAC*60., over which the transfer takes place. The 60. factor changes FRAC from minutes to seconds so that DS is in joules. If FLAG equals zero, then only the heat exchangers are being used. Thus, only two water pumps are working in the system, the tank to exchanger pump, and the exchanger to collector pump. The energy being used by them must be accounted for. This is done by Equation (78). This equation

$$DPEL = PEL2*FRAC*60. \quad (78)$$

states that the incremental energy used by the pumps, DPEL, is equal to the power rating of the two pumps, PEL2, multiplied by the time they are used, again, in seconds. Their power rating will be discussed later. If, however, FLAG was equal to one, then the heat pump was also used. In that case, three water pumps are being used. One is used from tank to exchanger, one is used from exchanger to heat pump, and one is used from heat pump to collector array. In this case, Equation (79) is used where PEL3 is the power rating of the three pumps. Also, Equation (80) is used to find the incremental electrical energy used by the heat pump. This is obtained by using Equation (40).

$$DPEL = PEL3*FRAC*60. \tag{79}$$

$$DHPEL = \frac{TLOSS*FRAC*60.}{COP} \tag{80}$$

Now that all energy transfers have been calculated, the total delivered energy to the tanks, TOT, is calculated by Equation (81). Since the subroutine CALC is used over a

$$TOT = TOT + DS + DHPEL \tag{81}$$

year's time, the appropriate initializations are made when it is called for the first time. Also, each time it is called, all incremental quantities are initialized to zero before calculations begin. In this way, at the end of the year a value is available for the total energy gained during the year by the system, and also the total electrical energy used during the year by the system. A flow chart for CALC is shown in Figure 23 and the subroutine may be found in Appendix A.

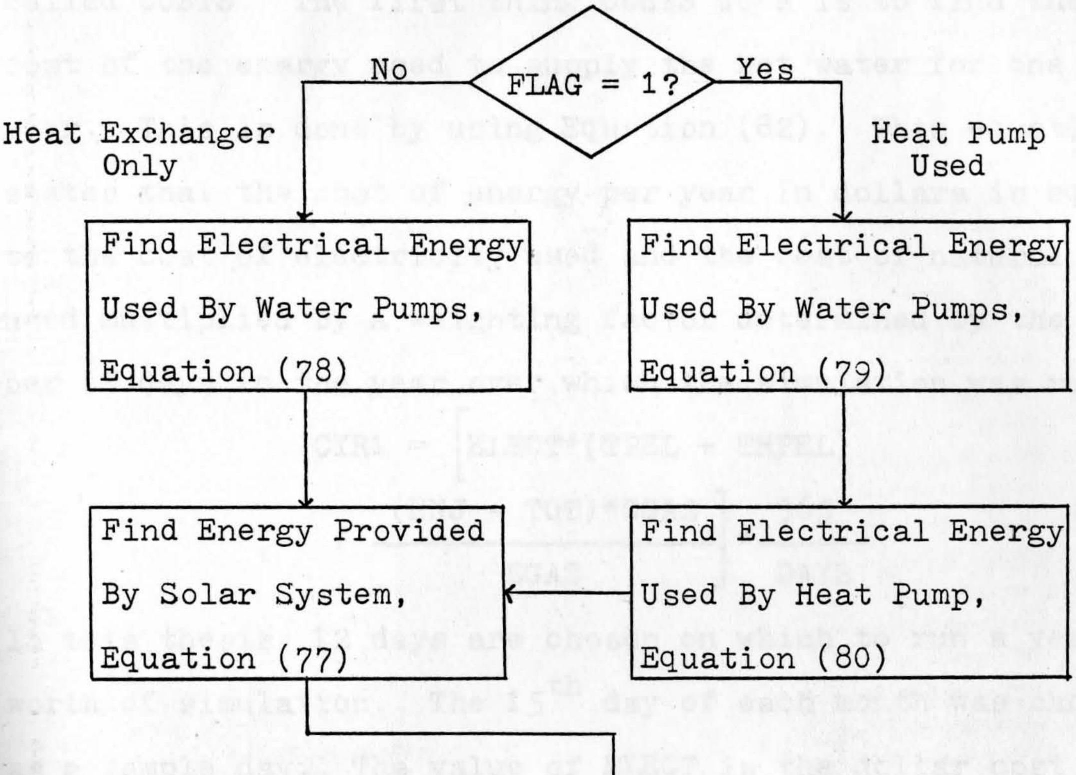


Fig. 23. Flow Chart For Subroutine CALC

After the year's simulation has been run, the actual costs may be calculated. This is done by the subroutine called COSTS. The first thing COSTS does is to find the cost of the energy used to supply the hot water for one year. This is done by using Equation (82). This equation states that the cost of energy per year in dollars is equal to the cost of electricity used and the cost of natural gas used multiplied by a weighting factor determined by the number of days in the year over which the simulation was run.

$$CYR1 = \left[ELECT*(TPEL + THPEL) + \frac{(ENJ - TOT)*CGAS}{EGAS} \right] * \frac{365}{DAYS} \tag{82}$$

In this thesis, 12 days are chosen on which to run a year's worth of simulation. The 15^{th} day of each month was chosen as a sample day. The value of ELECT is the dollar cost per joule of electricity and TPEL and THPEL are the total water pump and heat pump electrical joules used for the days considered, respectively. The value for ENJ is the total energy needed by the process hot water system to operate for the number of days the simulation was run. The value of TOT, the energy supplied to the tanks, is thus subtracted from this to give the energy needed by the tanks in the form of natural gas. The factor CGAS is the cost of gas per cubic foot, and EGAS is the energy provided per cubic foot of gas by assuming an 80% efficiency rate of the gas burners.

Equation (82) provides a means of calculating energy cost for the energy used for one year. Now an equation is needed to find capital costs for one year. It will be assumed that financing will be handled by a loan over a number of years. Ten years is the nominal choice made and an interest rate on the unpaid balance of 8% compounded annually is assumed. The equation providing the yearly payment is found by calculating the payments due at the end of year 1, year 2, year 3, etc. A pattern is noticed and this permits the writing of an equation for finding the yearly payment for X years. If P is the borrowed principle, X is the number of years the payment is over, I is the interest rate on the unpaid balance compounded annually, and YR is the yearly payment, then Equation (83) is the general equation. Solving for YR and replacing the summation in Equation (83) with an equivalent expression found in infinite series work, [5], Equation (84) results. Now Equation (84) may be used in COSTS to find the annual payment on the capital equipment.

$$(I + 1)^{X} * P - YR * \sum_{i=1}^{X-1} (I + 1)^{i} = YR \qquad (83)$$

$$YR = \frac{P * I * (I + 1)^{X}}{(I + 1)^{X} - 1} \qquad (84)$$

This includes the cost of the water pumps, the heat pump, the collector array, the heat exchangers, the control system, and other miscellaneous costs such as piping and installation. The value CYR2 is the sum of these costs. Equation (85) is then used to find the annual payment, where X is ten years and AI is 8% interest. Thus, the total cost

$$YR = \frac{CYR2*AI*(AI + 1)^X}{(AI + 1)^X - 1} \quad (85)$$

for energy over a one year period is equal to YR plus the CYR1 energy cost supplied by Equation (83). The total yearly cost is given as COST in Equation (86).

$$COST = YR + CYR1 \quad (86)$$

A number of items need to be provided before this subroutine and subroutine CALC can be used. The first is a value for the power ratings of the water pumps. In order to make a reasonable estimation of the power required, the flow rates and pressure drops occurring in the system must be calculated. The collector circuit will require the most power since it consists of mostly tubing of .5 inch diameter. The smaller the diameter of the tubing, the greater the pressure losses due to friction. Since large tubing will be used to carry the fluid to and from the collectors, the pressure drop in it will not be as high as in the collectors. Also, a considerable pressure drop is experienced in the heat pump or the heat exchanger, whichever is being used. To estimate the size of the pump needed, a standard piping table was used which provided the pressure drop in pipes of a given diameter for a specific flow rate of water, [9]. These drops were in pounds of force per one hundred feet of pipe length. For the collector array, an array consisting of a section of two collectors in series, and 150 of these sections paralleled together is considered. This array was the type arrived at by the initial simulations.

Also, an assumption was made that the drop in the heat exchanger or heat pump is about one half of that experienced in the collector array. Since actual piping sizes in the heat pump and heat exchanger are unknown, this assumption was used. As a rough estimate, it was found that a one horsepower pump could supply the power for the collector circuit and also the exchanger to heat pump circuit, while a one half horsepower pump could supply the tank to exchanger circuit. Admittedly these values are largely guesses, but they are intelligent guesses. Also, because of the size of the other electrical power being used in the heat pump, at times the water pumps will have a negligible effect on electrical costs. Thus, it is not a critical assumption.

Other items needed in COSTS are the price of gas and electricity. A cost of $1.71 per million BTU of energy supplied is assumed for natural gas. This is a 1975 price. Also, 3¢ per kilowatt hour is the assumed price of electricity, which is a 1975 price. These are converted to dollars per joule in the COSTS subroutine. Other items are costs of the heat pump, water pumps, and other system plumbing. Using a value of $15,000 for the heat pump, $200 each for the large water pumps, and $100 each for the small water pumps, a value must be found for the plumbing and installation. Based on the cost of pipe and the amount of pipe needed, this comes to about $1000. Also, the heat exchangers cost about $500 each. Another major item to be accounted for is the collector array itself. Prices varying from $5 to $14 per square foot or \$50 to \$150 per square meter of collecting area will be used. The control system cost is estimated at \$10,000. Specific details of the control system will be discussed in Chapter IV.

The program may now be used for optimization. The general parameters found in the initial simulation runs will be used as starting guesses in the optimization runs. The plan for optimization is as follows, in order:

1. Vary the collector array tilt from 30 to 60 degrees to discover the optimum tilt.
2. Vary the value of PF for the heat pump to discover the optimum value.
3. Vary the value of DEL for the heat exchanger-heat pump decision to discover the optimum value.
4. Vary the collector fluid flow rate to find the optimum value.
5. Vary the collector array size to find the optimum value.

Since making a change in one system parameter has an interactive effect on system performance with any other changes made, the process of optimization will be repeated until a lowest cost condition exists. This will then be considered the optimum cost effective operating point of the system. The order of the changes decided upon was chosen with the idea that the changes least likely to be strongly interactive with other changes to be made later should be done first.

Upon running the optimization simulations, it was discovered that the solar energy system was never cheaper to operate than the straight natural gas system using 1975 prices. Because of this, the initial results obtained were of no use. For example, it would turn out that the best collector tilt would approach ridiculous values, indicating that no solar energy incident was the best value. This, of course, said that all natural gas was the cheapest way to operate. The other parameters behaved in a like manner. All converged to values which would indicate that little or no solar energy should be used. Not only did no condition ever exist that would make solar energy cheaper that natural gas, but also there were no relative minimums occuring. This indicates that any increase in the use of solar energy would produce an increase in cost for the system. The main reason for this behavior was found to be the high cost of electricity as compared to natural gas. In fact, the price of electricity per unit of energy is about five times that of natural gas. Thus, even when the solar system was displacing natural gas, if the heat pump was being used, electricity was used. This electricity and the water pump's electricity were costing more than the natural gas would have cost. By running simulations, it was seen that the COP of the heat pump was averaging about 4.8. This meant that for every four units of solar energy delivered, about one unit of electrical energy was used in the heat pump. Thus, one fifth of the energy supplied was electrical, and since electrical energy cost more than five times as much as natural gas, the solar system was actually costing more to use than just using natural gas. Also, the water pumps were using energy.

Since cost optimization was not possible, in order to present additional information on system performance, it was decided to approach the optimization problem in a different manner. Because an all natural gas system is the cheapest system, the solar energy system was not able to be optimized in a non-trivial manner. However, if the amount of natural gas displaced by solar energy is a fixed number, then an optimum system should be able to be found which would be able to be optimized with respect to cost. This cost would always be above that for natural gas alone, but there should be a relative minimum which occurs. This would be an optimum point of operation.

With this in mind, a new scheme for optimization of the system for a given required displacement of natural gas was devised. Since, on the average, the sun remains up about ten hours per day, if the solar system was to provide 100% of the energy requirements during this time, this would still represent only about ten-twentyfourths or less than half of the energy requirements of the hot water for one day. Thus, it was decided that total energy displacement of five to forty percent, at five percent intervals, be tried. For each required displacement, the system would be optimized with respect to cost. The same program could be used, only this time instead of just looking for the lowest cost, an energy delivered level would be first imposed on the system regardless of cost. Parameters would then be varied to hold this solar energy delivery level, but to attempt cost reduction. The procedure is as follows, in order:

1. Start with an array size guessed by assuming 300 watts per square meter for ten hours a day provided by the solar system. Use the known required energy for one year and the percent required solar system displacement value given to estimate needed area.

2. Use the initial simulation run values for tilt, PF, DEL, and flow rate to adjust array size to give desired solar system energy displacement.

3. While attempting to hold energy displacement constant, try to reduce yearly cost by varying the tilt, PF, DEL, and flow rate one at a time. Make reductions on array size when parameter adjustments increase the solar system energy displacement.

Using this method, the results shown in Figure 24 and Figure 25 were obtained.

Figure 24 shows a family of curves representing the optimal cost per year for a system providing from five to forty percent of the total yearly energy requirement. The different curves represent different costs per square meter of collector area. The results confirm the previous optimization results. It is seen that none of the optimized systems would present a lower cost per year than natural gas alone. It is also seen that as the 40% mark is reached, costs increase at a higher rate.

Figure 25 shows a plot of optimum array size versus energy displaced. The different curves are the result of various costs per square meter of collecting area. Again,

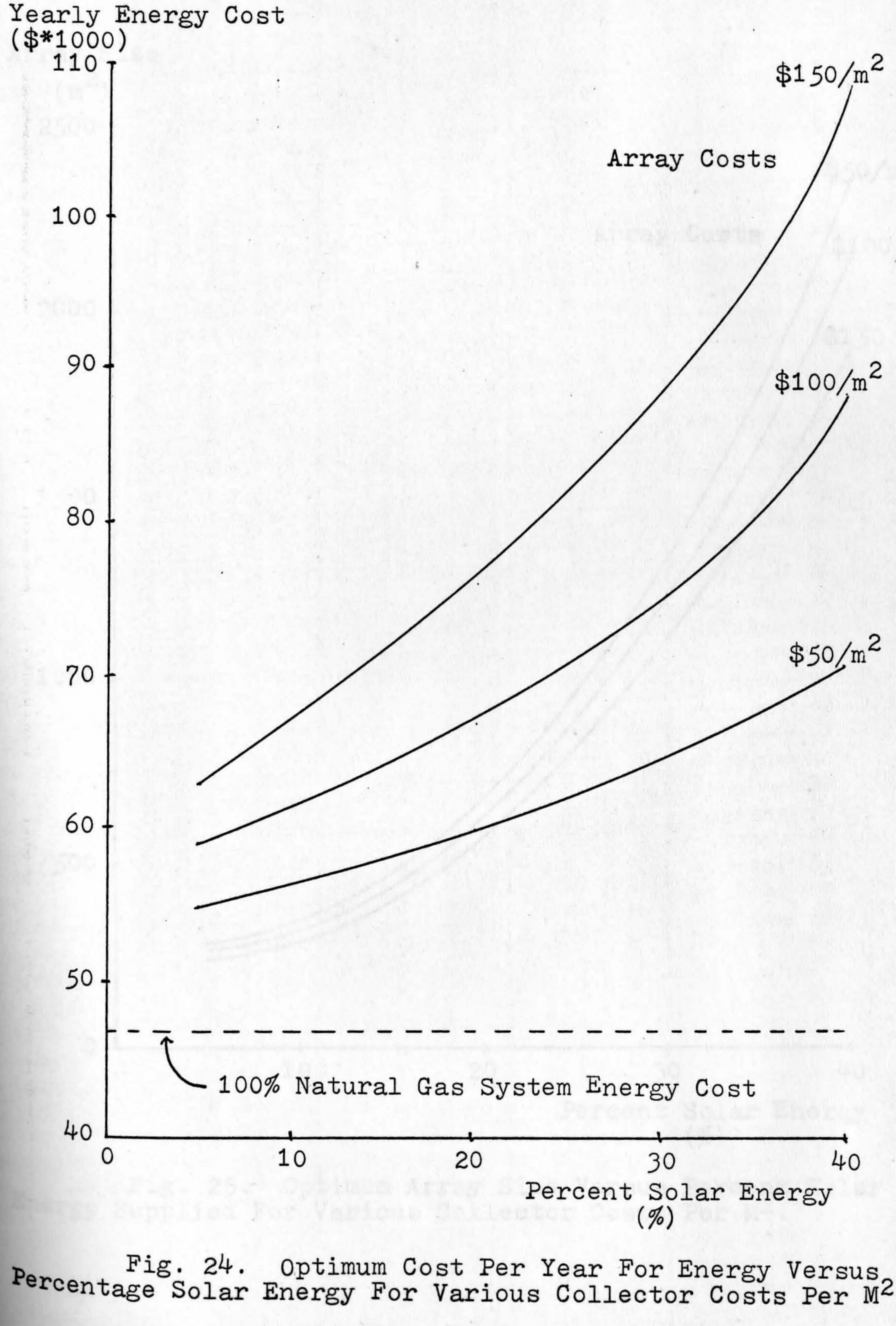


Fig. 24. Optimum Cost Per Year For Energy Versus Percentage Solar Energy For Various Collector Costs Per M^2.

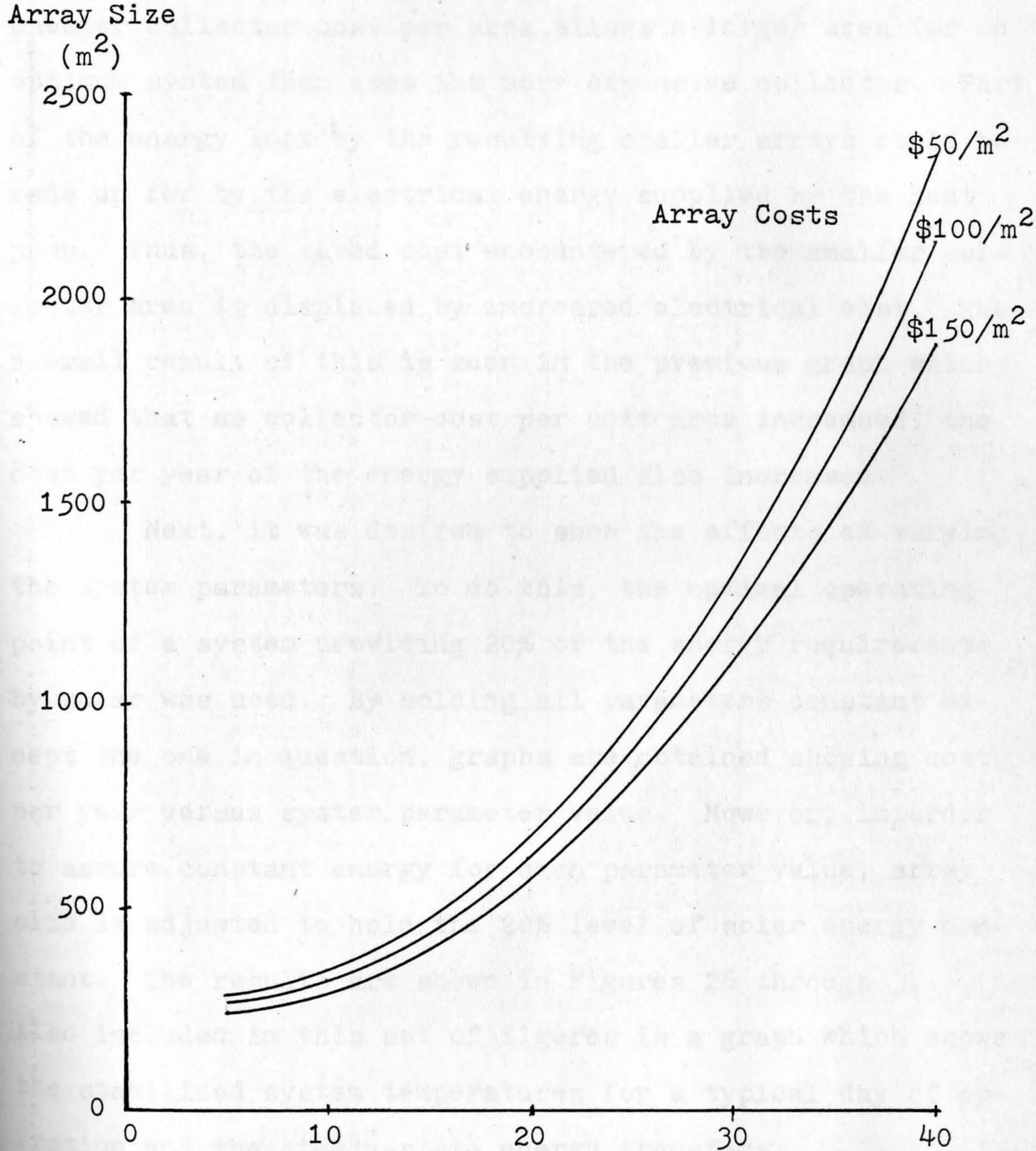


Fig. 25. Optimum Array Size Versus Percent Solar Energy Supplied For Various Collector Costs Per M^2.

as the energy requirement is raised, the yearly cost increases at a greater rate. Also, it is noted that the cheaper collector cost per area allows a larger area for an optimum system than does the more expensive collector. Part of the energy lost by the resulting smaller arrays could be made up for by the electrical energy supplied by the heat pump. Thus, the saved cost encountered by the smaller collector area is displaced by increased electrical cost. The overall result of this is seen in the previous graph which showed that as collector cost per unit area increased, the cost per year of the energy supplied also increased.

Next, it was desired to show the effects of varying the system parameters. To do this, the optimal operating point of a system providing 20% of the energy requirements by solar was used. By holding all parameters constant except the one in question, graphs are obtained showing cost per year versus system parameter value. However, in order to assure constant energy for each parameter value, array size is adjusted to hold the 20% level of solar energy constant. The results are shown in Figures 26 through 31. Also included in this set of figures is a graph which shows the stabilized system temperatures for a typical day of operation and the steady-state energy transfers.

Figure 26 shows a plot of yearly energy cost for a 20% solar supplied system. The tilt of the array is varied from 20° to 70° at 5° intervals. The effect of tilt on cost is thus shown. Naturally, to maintain 20% solar energy

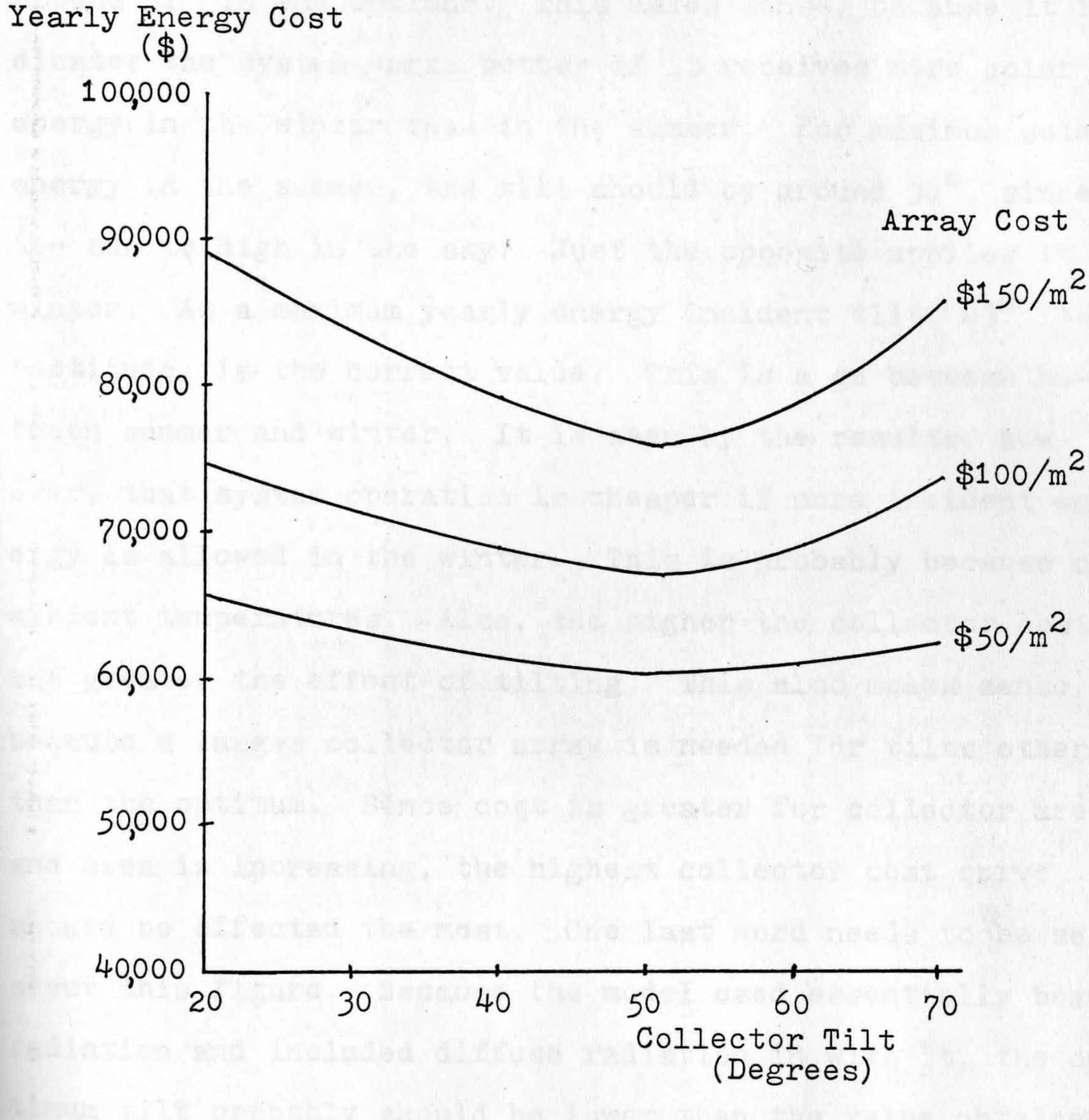


Fig. 26. Yearly Energy Cost Versus Collector Tilt For 20% Solar Energy Supplied System At Various Collector Costs Per Square Meter.

delivery, the array size is changed. Otherwise, all other parameters are held constant. It can be seen that a tilt of around 51^{o} is the optimum. This makes sense, because it indicates the system works better if it receives more solar energy in the winter than in the summer. For maximum solar energy in the summer, the tilt should be around 30^{o}, since the sun is high in the sky. Just the opposite applies in winter. As a maximum yearly energy incident tilt, 43^{o}, the lattitude, is the correct value. This is a go between between summer and winter. It is seen by the results, however, that system operation is cheaper if more incident energy is allowed in the winter. This is probably because of ambient temperatures. Also, the higher the collector cost, the greater the effect of tilting. This also makes sense, because a larger collector array is needed for tilts other than the optimum. Since cost is greater for collector area, and area is increasing, the highest collector cost curve should be effected the most. One last word needs to be said about this figure. Because the model used essentially beam radiation and included diffuse radiation in with it, the optimum tilt probably should be lower than the value obtained here. This is because diffuse radiation would provide a noticable contribution in the winter and the best angle for collecting diffuse radiation is 0^{o}, or a horizontal position on the ground. This would lower the optimum tilt angle.

The next figure to be discussed is Figure 27, the yearly energy cost versus PF plot. It turns out that the

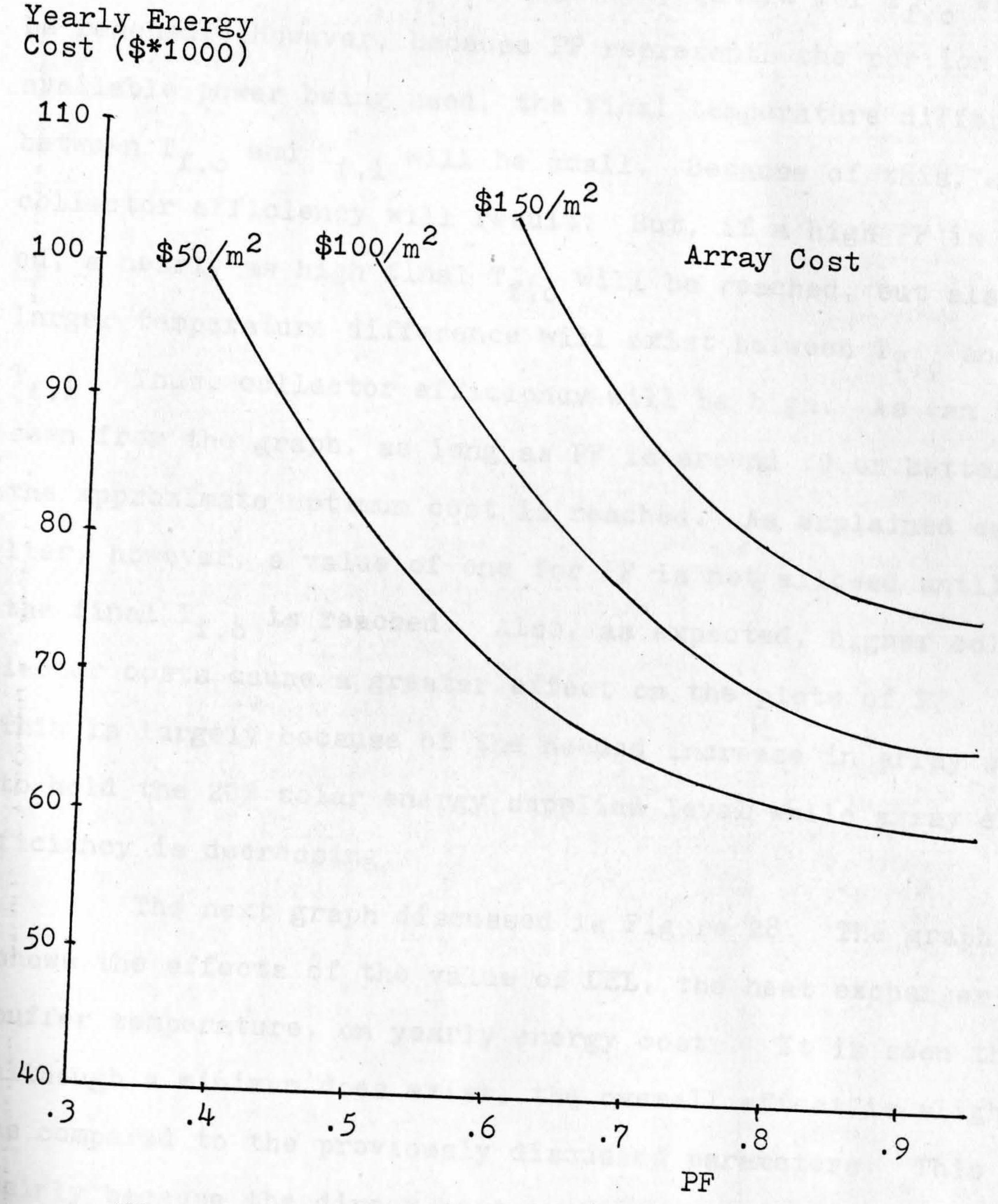


Fig. 27. Yearly Energy Cost Versus PF For 20% Solar Energy Supplied System At Various Collector Costs Per M^2.

optimum value of PF is about .95. This can be reasoned as follows. If PF is small, a high temperature for $T_{f,o}$ will be reached. However, because PF represents the portion of available power being used, the final temperature difference between $T_{f,o}$ and $T_{f,i}$ will be small. Because of this, a low collector efficiency will result. But, if a high PF is used, a nearly as high final $T_{f,o}$ will be reached, but also a larger temperature difference will exist between $T_{f,o}$ and $T_{f,i}$. Thus, collector efficiency will be high. As can be seen from the graph, as long as PF is around .9 or better, the approximate optimum cost is reached. As explained earlier, however, a value of one for PF is not allowed until the final $T_{f,o}$ is reached. Also, as expected, higher collector costs cause a greater effect on the plots of PF. This is largely because of the needed increase in array size to hold the 20% solar energy supplied level while array efficiency is decreasing.

The next graph discussed is Figure 28. The graph shows the effects of the value of DEL, the heat exchanger buffer temperature, on yearly energy costs. It is seen that although a minimum does exist, the overall effect is slight as compared to the previously discussed parameters. This is mainly because the direct heat exchanger-solar collector mode is used only about 20% of the time. Thus, it contributes a small amount of energy compared to the heat pump. The value that seemed to optimize the system for 20% solar energy supplied is about 17 °C. The various collector costs

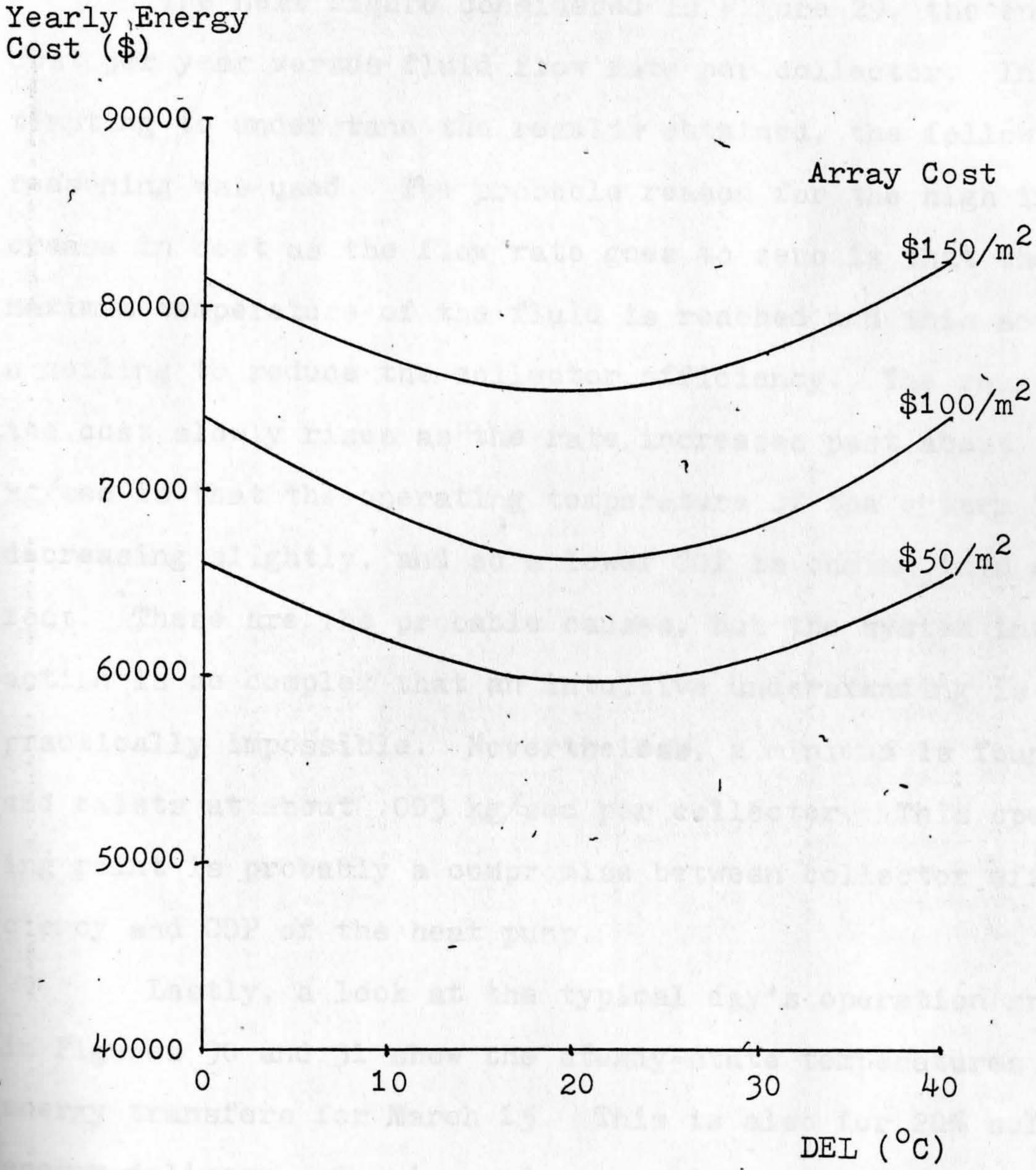


Fig. 28. Yearly Energy Cost Versus DEL For 20% Solar Energy Supplied System At Various Collector Costs Per Square Meter.

also did not seem to have much effect on the shape of the curves.

The next figure considered is Figure 29, the energy cost per year versus fluid flow rate per collector. In attempting to understand the results obtained, the following reasoning was used. The probable reason for the high increase in cost as the flow rate goes to zero is that the maximum temperature of the fluid is reached and this acts as a ceiling to reduce the collector efficiency. The reason the cost slowly rises as the rate increases past about .003 kg/sec is that the operating temperature of the system is decreasing slightly, and so a lower COP is coming into effect. These are the probable causes, but the system interaction is so complex that an intuitive understanding is practically impossible. Nevertheless, a minimum is found and exists at about .003 kg/sec per collector. This operating point is probably a compromise between collector efficiency and COP of the heat pump.

Lastly, a look at the typical day's operation graphs in Figures 30 and 31 show the steady-state temperatures and energy transfers for March 15. This is also for 20% solar energy delivery. Sunrise and sunset determine starting and stopping times.

This concludes the simulation, optimization, and control philosophy work of this chapter. However, further information may be found in the results obtained. The results so far have been strictly for a solar system versus a

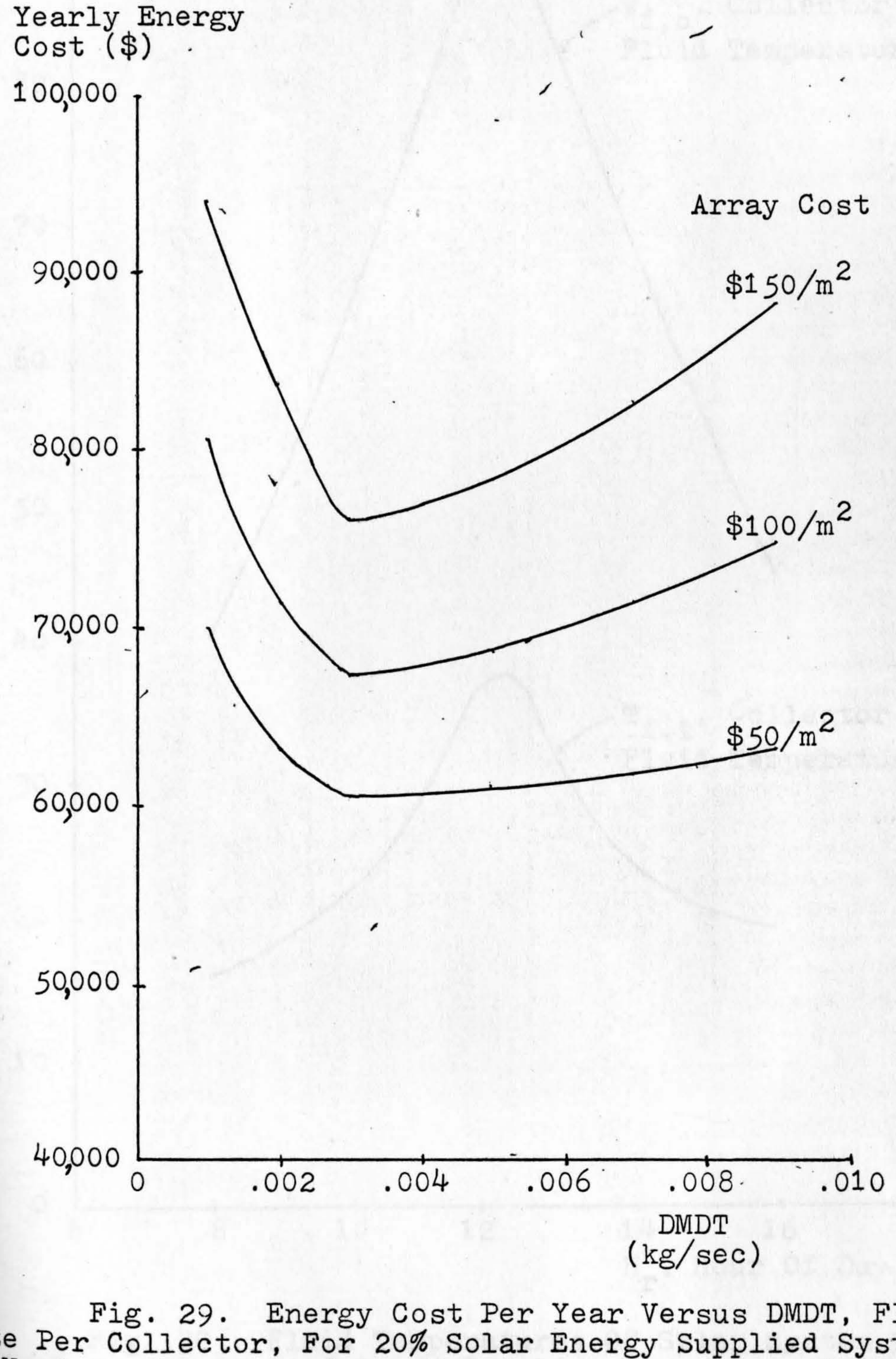


Fig. 29. Energy Cost Per Year Versus DMDT, Flow Rate Per Collector, For 20% Solar Energy Supplied System At Various Collector Costs Per Square Meter.

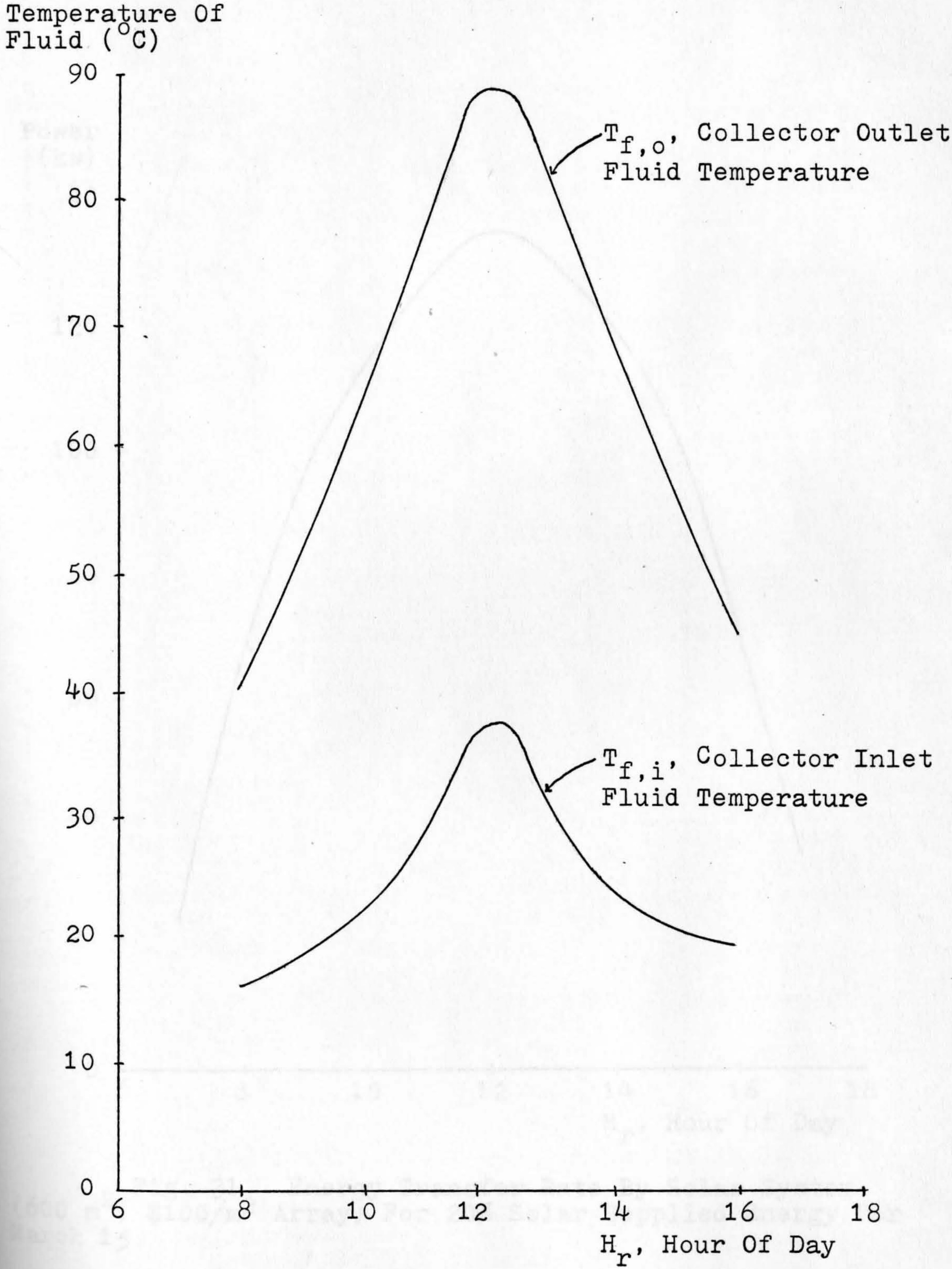


Fig. 30. Fluid Temperatures Of Solar System (600 m^2, \$100/m^2 Array) For 20% Solar Supplied Energy For March 15.

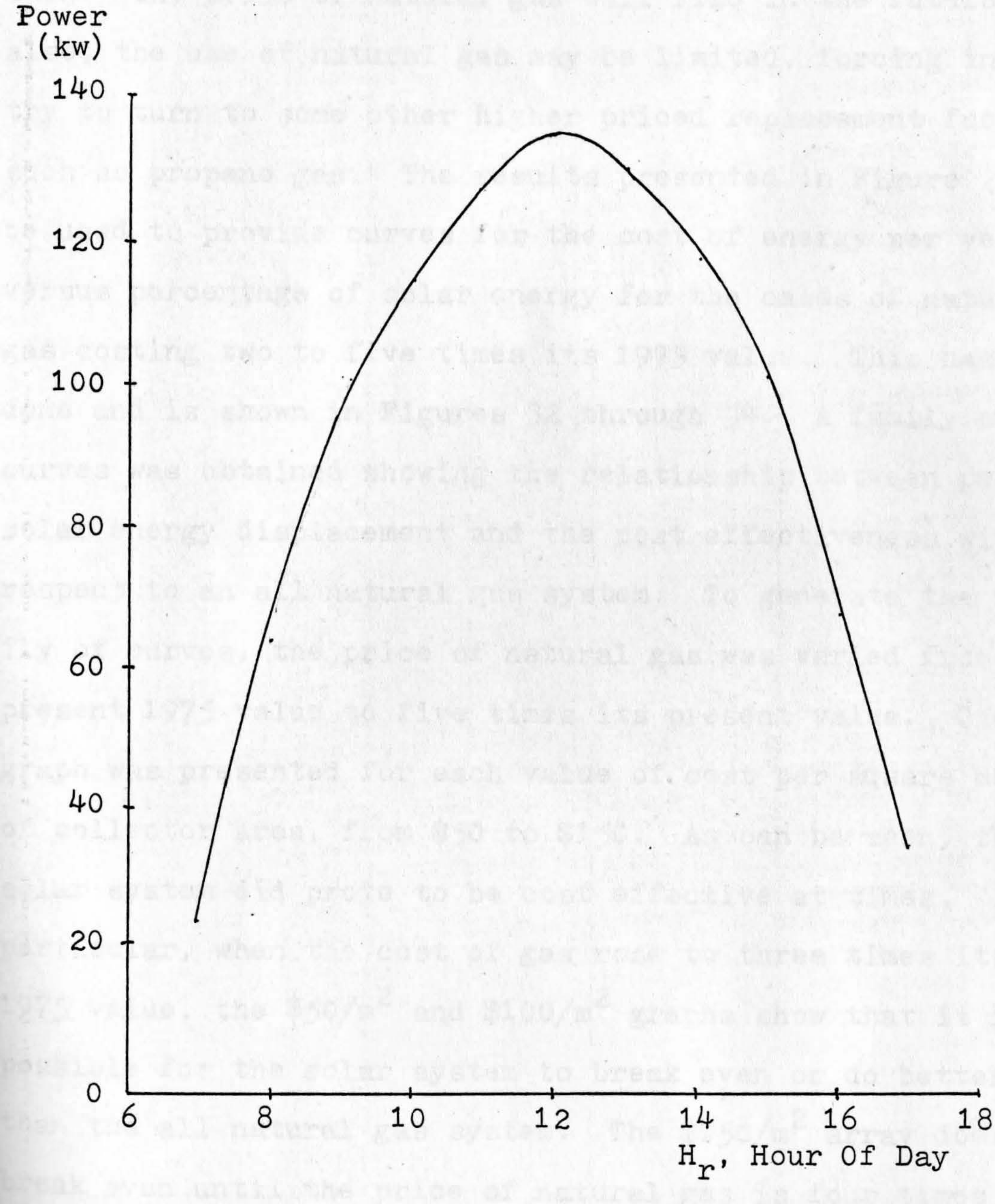


Fig. 31. Energy Transfer Rate By Solar System (600 m^2, \$100/m^2 Array) For 20% Solar Supplied Energy For March 15.

natural gas system using the price of the natural gas system as of 1975 at the particular location of the plant in question. The price of natural gas will rise in the future, and also, the use of natural gas may be limited, forcing industry to turn to some other higher priced replacement fuel such as propane gas. The results presented in Figure 24 may be used to provide curves for the cost of energy per year versus percentage of solar energy for the cases of natural gas costing two to five times its 1975 value. This has been done and is shown in Figures 32 through 34. A family of curves was obtained showing the relationship between percent solar energy displacement and the cost effectiveness with respect to an all natural gas system. To generate the family of curves, the price of natural gas was varied from its present 1975 value to five times its present value. One graph was presented for each value of cost per square meter of collector area, from $50 to $150. As can be seen, the solar system did prove to be cost effective at times. In particular, when the cost of gas rose to three times its 1975 value, the $\$50/m^2$ and $\$100/m^2$ graphs show that it is possible for the solar system to break even or do better than the all natural gas system. The $\$150/m^2$ array does not break even until the price of natural gas is four times its 1975 value. Also, relative minimums in cost are noted in some curves for a certain percentage of solar energy displacement. A system to be designed would use these minimums as the desired operating point for the lowest cost per year

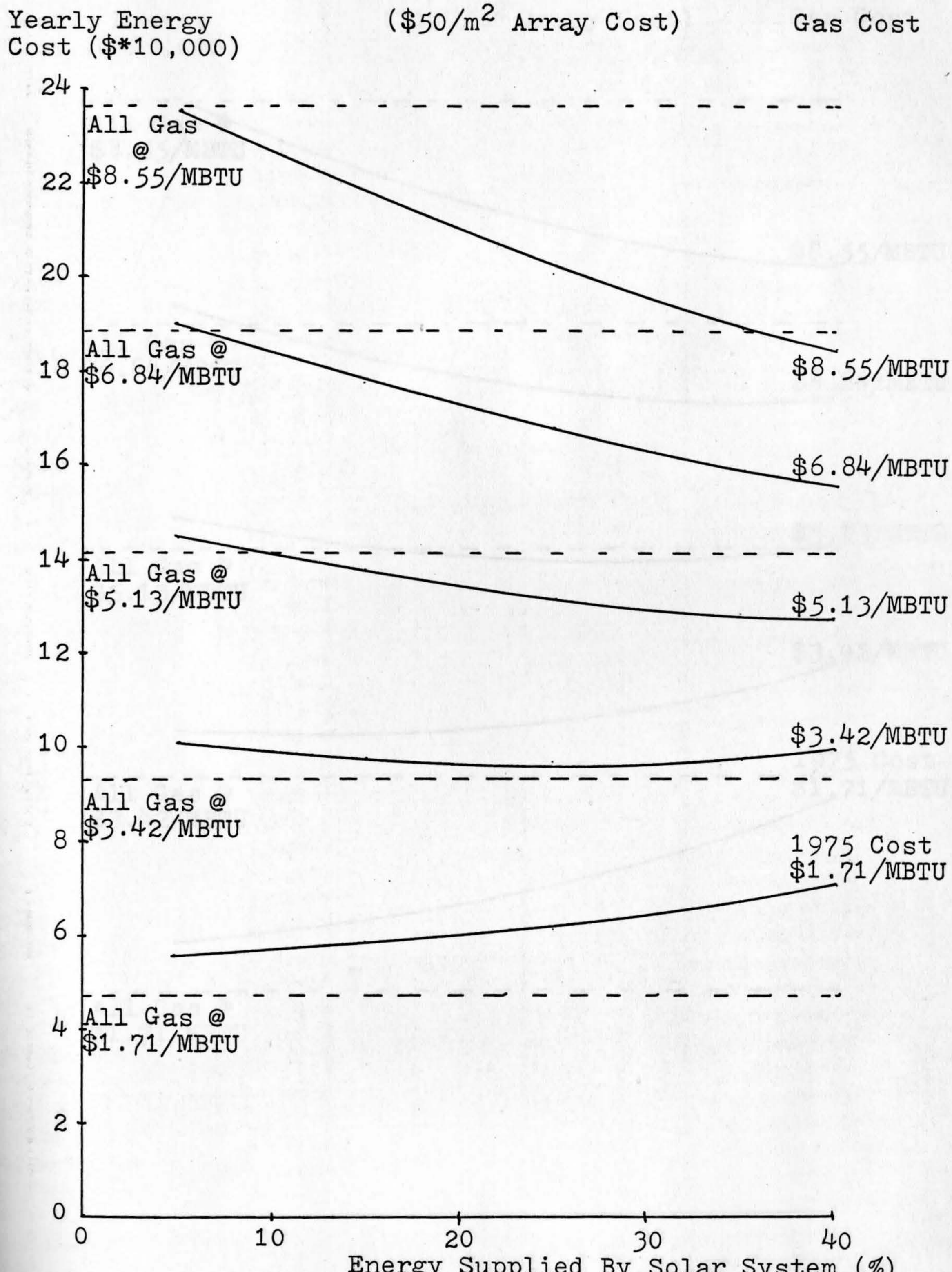


Fig. 32. Optimum Cost Per Year For Energy Versus Percent Energy Supplied By Solar System For Various Multiples Of 1975 Cost Of Natural Gas.

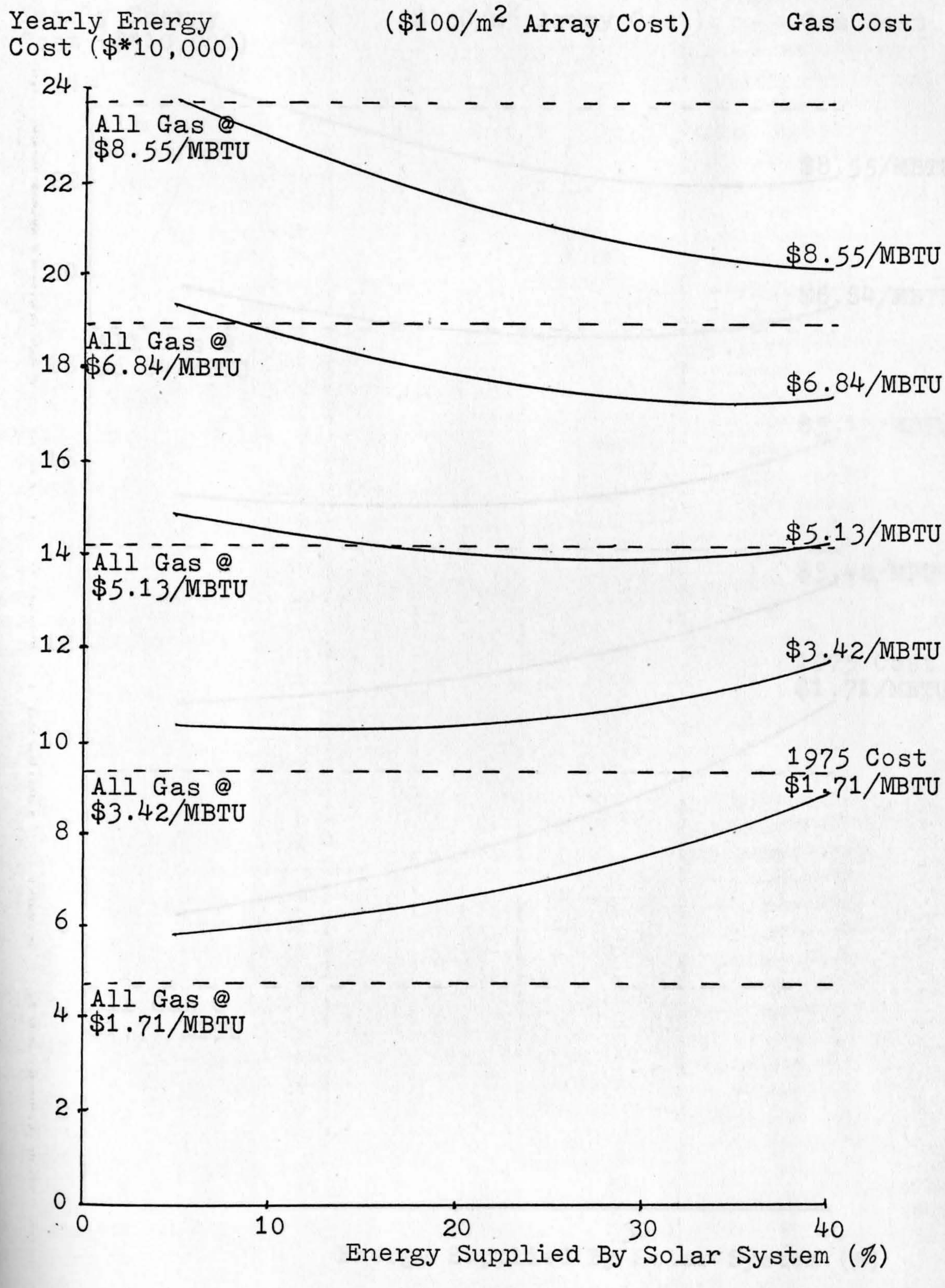


Fig. 33. Optimum Cost Per Year For Energy Versus Percent Energy Supplied By Solar System For Various Multiples Of 1975 Cost Of Natural Gas.

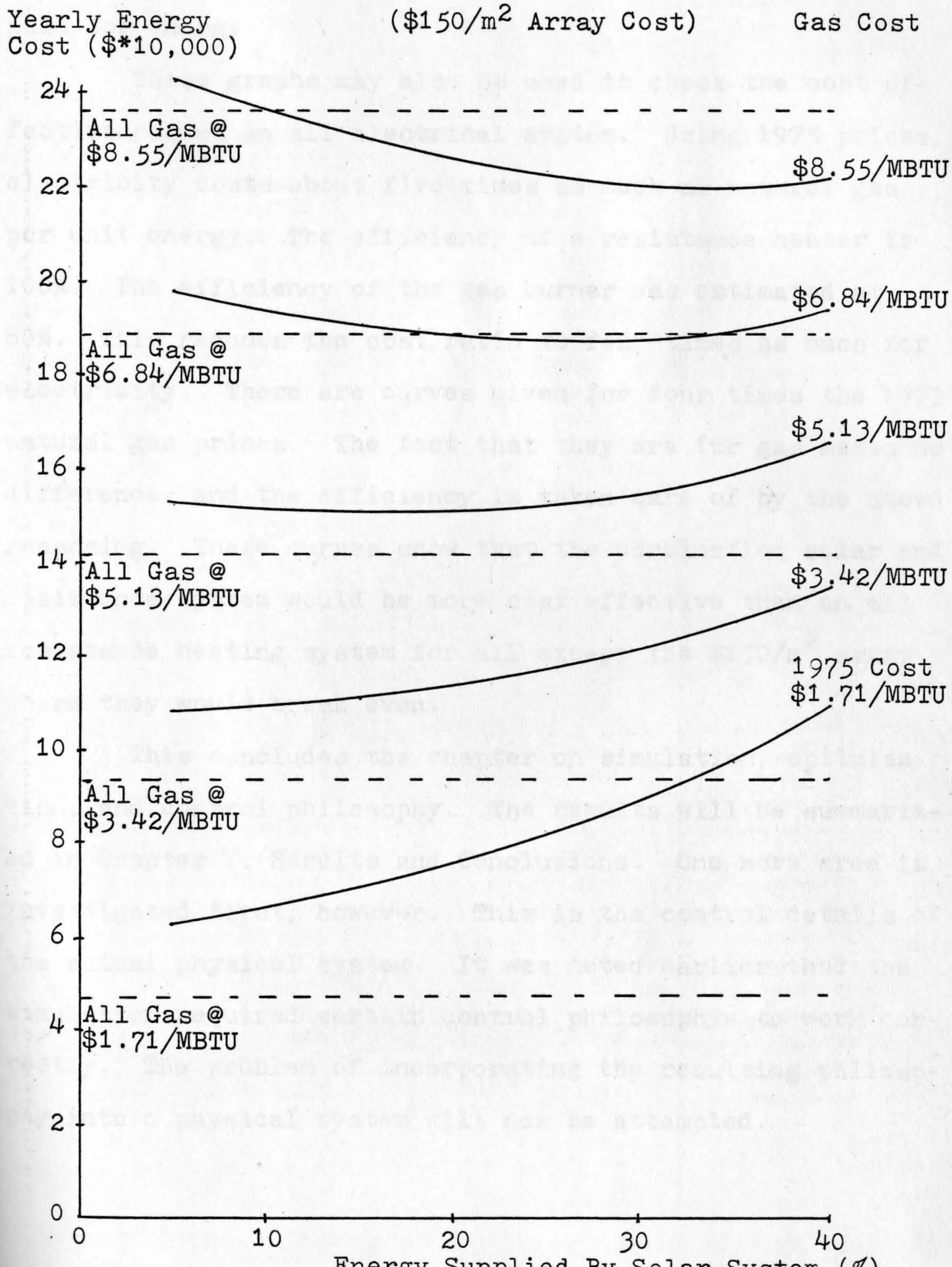


Fig. 34. Optimum Cost Per Year For Energy Versus Percent Energy Supplied By Solar System For Various Multiples Of 1975 Cost Of Natural Gas.

paid for energy.

These graphs may also be used to check the cost effectiveness of an all electrical system. Using 1975 prices, electricity costs about five times as much as natural gas per unit energy. The efficiency of a resistance heater is 100%. The efficiency of the gas burner was estimated at 80%. This reduces the cost ratio to four times as much for electricity. There are curves given for four times the 1975 natural gas prices. The fact that they are for gas makes no difference, and the efficiency is taken care of by the above reasoning. These curves show that the combination solar and resistance system would be more cost effective than an all resistance heating system for all except the $150/m^2 array where they would break even.

This concludes the chapter on simulation, optimization, and control philosophy. The results will be summarized in Chapter V, Results and Conclusions. One more area is investigated first, however. This is the control details of the actual physical system. It was noted earlier that the simulation required certain control philosophys to work correctly. The problem of incorporating the resulting philosophy into a physical system will now be attempted.

CHAPTER IV

SOLAR SYSTEM CONTROL DETAILS

It is the purpose of this chapter to suggest a method by which the control philosophy, developed while running simulations, can be physically implemented. The method presented here is not the exclusive or necessarily the best method, but one which will do the job while remaining fairly simple.

Since there are quite a few complex tasks to be performed, a mini or micro computer could be used. For this system, however, this would probably be overkill. A simpler and less costly controller could be a calculator chip with an added memory system and a timer. To determine the precise requirements of the controller, the items to be controlled are recalled. First, there was a need for switching by means of valves between load tanks. This required a certain amount of predetermined time spent on each tank. This task could be handled by a simple timing circuit and solenoid controlled valves. There are a number of timing integrated circuits on the market. One could be used for each tank, its time on preset, and then the off signal at the end of its cycle could be used to trigger the next tank timer to start. The timers could be arranged in a ring type circuit, where one tank timer would be on at a time and the process would repeat once the last timer was reached. The valve on each tank could be on when the particular timer for that tank is on. Thus, the switching problem is solved.

Next, a decision was needed to find out whether to use the heat exchangers by themselves or with the heat pump. This depended on the tank temperature and also the outlet fluid temperature of the collector array. For this purpose, temperature sensors would be used. They would detect the fluid temperature, change this analog signal to digital by using analog-to-digital, A/D, converters, and then use the calculator chip to compare the difference of tank temperature with fluid output temperature of the collector array. This is the value which must be greater than DEL for the heat exchangers alone to work. By using digital logic to preprogram the operation of the calculator chip, the value of DEL will be compared with this difference. The outcome will cause the switching of the appropriate solenoid controlled valves to either include or remove the heat pump from the circuit.

Another calculator aided decision to make is the value of TLOSS, the tank load, to give to the heat pump (via tank fluid flow rate to the heat pump). Again, temperature sensors with A/D converters could be used to sample temperatures. Then, the calculator could calculate the appropriate value of TLOSS using Equation (76). The value of COP could be found by temperature sensors and A/D converters monitoring the delivery temperature to the heat pump and the collector fluid input temperature to the heat pump. A calculation using these numbers and prestored constants could be made by the calculator chip which would provide the COP. Once TLOSS is found, the fluid rate of the delivery fluid to the heat pump could be set using the values provided by the manufacturer of the heat pump for fluid rate and power delivered. Also, a temperature comparison between intervals could be made to determine when to set PF to 1. This assured that the highest operating temperature of the outlet collector fluid would be reached while maintaining a high energy transfer rate.

The control details have now been taken care of. It was seen that a calculator chip, digital logic, read only memories, A/D converters, solenoid controlled valves, and integrated circuit timers were needed to provide a controller. Also, a method of fluid flow rate for the water pump supplying the tank side of the heat pump was needed. This equipment would have to be assembled and provided with power supplies. Also, since this controller is not being built by the writer of this thesis, the construction details will not be given here. However, an APL, [10], type program for the controller operation is given here to organize the controller functions into a neat package.

1. Tank Timer Starts

2. Test For Heat Pump Use
   ⟶(No Heat Pump, Go To 5)

3. Calculate TLOSS, Store $T_{f,o}$, Throw Valves

4. Set TLOSS Fluid Speed

5. Time For X Minutes
⟶(If Tank Time Through, Go To 8)

6. If Using Heat Pump, Check $T_{f,o}$
⟶(If $T_{f,o}$ Limit Reached, Go To 5)

7. ⟶(Go To 3)

8. Change Tanks, Set Timer
⟶(Go To 1)

Certain safeguards are needed in the real system. These include placing a sensor in each tank to turn on the natural gas if the solar energy is not enough to hold the desired tank temperature. Another would be a solar cell to detect if there was not enough sunshine to run the system, as in a rain storm. On site adjustment of parameters used for control would also be necessary to insure smooth and proper operation.

The estimate of $10,000 used for a controller is now seen to be high. Perhaps $3,000 would have been a better figure to use. This seems more realistic because the electronics needed for the control system could be provided for about $500, and the solenoid controlled valves and temperature and fluid flow rate sensors along with system design and installation costs would run about $2,500.

CHAPTER V

RESULTS AND CONCLUSIONS

What is needed now is an overview of what was done and what results were obtained. From this, conclusions can be drawn and recommendations can be made. To begin with, all system elements were mathematically modeled. These models were turned into programs for computer use. The models were connected in the computer by controlling subroutines. A subroutine was provided to calculate energy transfer and yearly energy costs. By following an orderly prescribed method, optimization was attempted. This first optimization attempt included a control philosophy which was obtained through running initial simulations. The results of this optimization attempt were negative. They indicated that, using the costs decided upon (current 1975 prices), the system using straight natural gas was always cheaper than the system using solar energy. The main reasons for this were seen to be that the cost of electricity used in the heat pump was too high and also, the yearly cost on the system's capital equipment was high.

In order to derive results that would lead to a better understanding of the system, a new optimization technique was used. This involved setting a predetermined amount of energy to be provided by the solar system. The cost was not considered at this point. Once parameters had been found to supply this energy, cost optimization was attempted while holding this energy level. The results indicated that the results of the previous optimization attempt were correct. They showed that even an optimized solar system could not cost less than a full natural gas system using 1975 prices, regardless of the percentage of energy the solar system contributed. This optimization, however, produced graphs which gave insight into the effect on system performance of the parameters used. Also, the results of the optimization were used to project cost effectiveness of the solar system for rising natural gas prices. The overall conclusion seems to be that if natural gas is available today in the needed quantities (which it is not in the location being considered), its present cost would make the attempt to use solar energy economically unwise at this time. This does not say that solar energy could not be used to lower the cost of energy used, but that the particular system studied in this thesis and its configuration would not be acceptable at current prices (1975). It may turn out that one of the alternate configurations discussed earlier would prove cost effective.

Another area that could have been investigated and might have helped lower cost is energy storage. The system studied included no storage facilities. There were available, however, large rinse tanks amoung the tanks which required heating. The tanks could have been used for energy storage. This energy could then have been used when the sun went down. A rough calculation was carried out for supplying 100% of the needed energy by using solar and storage. Average values were used for system parameters such as COP and collected solar energy per square meter of collector. The results indicated that the cost of this 100% solar system using storage was far too high to be considered economically feasible. Storage used with a less than 100% solar energy system might prove worthwhile, however.

The look into rising natural gas prices and its effect on solar system economics showed that if natural gas prices rose to 3 times their present value, the particular system studied would be able to break even or even save money over an all natural gas system. Presently, the company, used as the basis for system design, has been forced to use propane in place of natural gas. Propane's cost as of 1975 at their location is about $3.82/MBTU, or approximately 2¼ times the cost of natural gas. Thus, because of the shortage of natural gas, the use of propane could make the system studied economically feasible today, depending on collector costs. Also, if pure electrical energy, resistive heating, were used, the solar system would definitely become economical for use today since electricity is currently about 5 times the cost of natural gas supplied energy. As collector costs come down, the solar system will become even more attractive.

It was seen that a relatively simple controller could be used in the system studied. In fact, the cost of building such a controller is today economically within reason. The cost, however, was estimated too high, $10,000, in the optimization runs and this might make the solar system more competitive in price. Also, the capital costs used in the optimization runs were rough estimates, and as such, might have caused the solar system to cost more than it should have.

In conclusion, the system studied in this thesis can be cost effective today if the cost of natural gas or a relacement fuel were about 3 times the 1975 prices used for natural gas. If gas is heavily regulated, as it is beginning to be today, a higher priced replacement fuel is mandatory. Thus, the solar system would prove economical. Also, a more specialized solar system might reduce costs even more by using components specifically designed for the task of heating water to high temperatures. A focusing high temperature collector would be such a component. Solar energy is being put to use today and components are being made more readily available. It will prove to be the energy of the near future, as well as a major source for years beyond.

APPENDIX A

Computer Program Listing

```
$JOB
      COMMON HOUR,DAY,COP,TFC,TA,WV,S,TLOSS,FLAG,TFI,JA,TILT,PAR,NSER
      REAL CCST(5000),PARAM(500)
      NSER=2.
      PAR=80.
      TILT=40.
      DAYS=1.
      IK=4
      DO 1 IA=1,IK
      START=1.
      DAY=35.
      DAYF=35.
      QT=10.
    4 HOUR=9.
      DMDT=.002*PAR
      PF=.5
    3 DEL=20.
      DO 2 JA=1,14
      CALL LINK(DMDT,DEL,PF)
      CALL TIME(FRAC)
      CALL CALC(START,FRAC,DMDT,TPEL,THPEL,TOT)
      IF(HCUR.GE.QT)GC TC 6
    2 START=0.
      IF(HOUR.LT.QT)GO TC 3
    6 WRITE(6,100)DAY
  100 FORMAT(' ',F5.1)
      DAY=DAY+30.
      IF(DAY.GT.DAYF)GO TC 5
      GO TC 4
    5 CALL CCSTS(TPEL,THPEL,TOT,CYR1,YR,DAYS)
      COST(IA)=CYR1+YR
      PARAM(IA)=TILT
    1 TILT=TILT+5.
      CALL PLOT72(PARAM,CCST,IK,1)
      STOP
      END
C     SUBRCUTINE TO SUPPLY STANDARD CCLLECTOR PARAMETERS
      SUBROUTINE CCLPAR(SIG,TP,EP,EC,Z,PI,K,LB,LE,AE,AB,W,D,CB,DI,HFI,CP
     1,AC,A,N,LT,KP,DELP,TAU,ALPHA)
      REAL LB,LE,N,LT,K,KP
      TAU=.9
      ALPHA=.9
      SIG=5.6697E-08
      TP=45.
      EP=.1
      EC=.88
      Z=10.
      K=.0245
      LB=.05
      LE=.02
      AE=.9
      AB=2.
      D=.015875
      W=.15
      CB=50.
      KP=400.
      DELP=.001
      PI=3.141592654
      DI=.0127
```

```
      HFI=1500.
      CP=4190.
      AC=2.
      A=2.
      N=7.
      LT=2.
      RETURN
      END
C     THE COLLECTOR MODEL SUBROUTINE
      SUBROUTINE TOUTC(DMDT,ISAV)
      COMMON HOUR,DAY,COP,TFO,TA,WV,S,TLOSS,FLAG,TFI,JA,TILT,PAR,NSER
      REAL LB,LE,N,LT,K,KP
      CALL CCLPAR(SIG,TP,EP,EC,Z,PI,K,LB,LE,AE,AB,W,D,CB,DI,HFI,CP,AC,A,
     1N,LT,KP,DELP,TAU,ALPHA)
      CALL WIND
      PHASE=-5./6.*3.1415927
      CALL TEMPAM(PHASE)
      CALL SCLIN(TAU,ALPHA,RAC,1)
      C=273.15
      TP=TA+10.
      IF(TP.LT.TFI)TP=TFI+5.
      IF(ISAV.GT.1)TP=TPSAV
      ITC1=0
      ITC2=0
      T1=.1
      T2=.1
      TA=TA+C
      TP=TP+C
      TS=.0552*TA**1.5
      IF(TFI.GT.100..OR.TFI.LT.0.)WRITE(6,105)TFI
  105 FORMAT(' ','TFI=',E15.7)
      TFI=TFI+C
   50 TC=TA
      IF(ISAV.GT.1)TC=TCSAV
    1 HRPC=SIG*(TP**2+TC**2)*(TP+TC)/(1./EP+1./EC-1.)
      HRCS=EC*SIG*(TC**2+TS**2)*(TC+TS)
      IF(TP.LT.TC)HPC1=0.
      IF(TP.LT.TC)GO TO 6
      HPC1=1.14*(TP-TC)**.31/Z**.07
    6 HPC=HPC1*(1.-.0009*(TP-TC-20.))
      HW=5.7+3.8*WV
      UT=1./(1./(HPC+HRPC)+1./(HW+HRCS))
      TCT=TP-UT*(TP-TA)/(HPC+HRPC)
      AT1=TCT-TC
      TEST1=ABS(TC-TCT)
      ITC1=ITC1+1
      IF(ITC1.GT.4)WRITE(6,100)ITC1,TEST1,HOUR,ISAV
  200 FORMAT(' ','TC=',2X,E15.7,2X,'TCT=',E15.7,2X,'TP=',E15.7,2X,'TFI='
     1,E15.7)
      ATC=TC-C
      ATCT=TCT-C
      ATP=TP-C
      ATFI=TFI-C
      IF(ITC1.GT.4)WRITE(6,200)ATC,ATCT,ATP,ATFI
      IF(TEST1.LT.T1)GO TO 2
      TC=TCT+.01*AT1
      GO TO 1
    2 UB=K/LB
      UE=K/LE*AE/AB
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      UL=UT+UB+UE
      G=DMDT/AC
      F=2.*TANH((UL/(KP*DELP)*(W-D)/2.))/((W-D)*UL/(KP*DELP))
      FPR=(1./UL)/(W*(1./(UL*(D+(W-D)*F)))+1./CB+1./(PI*DI*HFI))
      IF(UL*FPR/(G*CP).GT.10.)GO TO 4
      FR=G*CP*(1.-EXP(-UL*FPR/(G*CP)))/UL
      GO TO 5
    4 FR=G*CP/UL
    5 QU=AC*FR*(S-UL*(TFI-TA))
      TFM=TFI+(QU/(UL*FR*A))*(1.-FR/FPR)
      TPM=QU/(HFI*PI*DI*N*LT)+TFM
      AT2=TPM-TP
      TEST2=ABS(TP-TPM)
      ITC2=ITC2+1
      IF(ITC2.GT.5)WRITE(6,101)ITC2,TEST2
      IF(TEST2.LT.T2)GO TO 3
      TP=TPM+.1*AT2
      IF(ITC2.GT.3)TP=TPM
      ITC1=0
      IF(ITC2.GT.4.AND.AT2.EQ.TEST2)GO TO 3
      GO TO 50
    3 TFO=QU/(DMDT*CP)+TFI
      TCSAV=TC
      TA=TA-C
      TC=TC-C
      TP=TP-C
      TS=TS-C
      TFO=TFO-C
      TFI=TFI-C
      TPSAV=TP
  100 FORMAT(' ','WARNING: ITC1 EQUALS',2X,I2,5X,E15.7,5X,E15.7,5X,I2)
  101 FORMAT(' ','WARNING: ITC2 EQUALS',2X,I2,5X,E15.7)
      RETURN
      END
C     SUBROUTINE TO DETERMINE SOLAR ENERGY ABSORBED BY COLLECTOR
      SUBROUTINE SOLIN(TAU,ALPHA,RAD,MEAN)
      COMMON HOUR,DAY,CCP,TFO,TA,WV,S,TLOSS,FLAG,TFI,JA,TILT,PAR,NSER
      DIMENSION A(3),B(3,5),C(5),D(5),E(16)
      DATA E/.2749998E+02,.3888886E-01,.4444443E-02,-.2469136E-04,-.1756
     1248E+02,.1031944E+01,-.4166663E-02,.6172839E-05,-.5168748E+02,.153
     11944E+01,-.5833331E-02,.6172839E-05,.1775875E+04,-.1306111E+02,.31
     166666E-01,-.2469136E-04/
      TIP=TILT
      AZIM=0.
      LAT=43.
      HAT=43.
      CONV=.017453
      CALL HUMID(W)
      DELTA=23.5*SIN((360./365.)*(DAY-80.)*CONV)
      SALPH=COS(LAT*CONV)*COS(DELTA*CONV)*COS(15.*(HOUR-12.)*CONV)+SIN(L
     1AT*CONV)*SIN(DELTA*CONV)
      A(1)=1.
      A(2)=ALOG10(W)
      A(3)=A(2)**2
      B(1,1)=9.3471106
      B(1,2)=-28.5263329
      B(1,3)=48.3975878
      B(1,4)=-41.1117492
      B(1,5)=13.5497572
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      B(2,1)=-1.0429129
      B(2,2)=5.9379309
      B(2,3)=-14.2130641
      B(2,4)=15.0237007
      B(2,5)=-5.7594145
      B(3,1)=-.1630977
      B(3,2)=.2076373
      B(3,3)=.4703185
      B(3,4)=-1.0976389
      B(3,5)=.5660107
      C(1)=SALPH
      C(2)=C(1)**2
      C(3)=C(1)**3
      C(4)=C(1)**4
      C(5)=C(1)**5
      DO 2 J=1,5
      SUM=0.
      DO 1 I=1,3
      BIT1=A(I)*B(I,J)
    1 SUM=SUM+BIT1
    2 D(J)=SUM
      RAD=0.
      DO 3 K=1,5
      BIT2=D(K)*C(K)
    3 RAD=RAD+BIT2
      IF(DAY.LT.15.)DAY=DAY+365.
      IF(DAY.GE.15..AND.DAY.LT.105.)K=1
      IF(DAY.GE.105..AND.DAY.LT.195.)K=5
      IF(DAY.GE.195..AND.DAY.LT.285.)K=9
      IF(DAY.GE.285..AND.DAY.LT.375.)K=13
      AVG=E(K)+E(K+1)*DAY+E(K+2)*DAY**2+E(K+3)*DAY**3
      IF(DAY.GT.365.)DAY=DAY-365.
      RAD=RAD*4.186*10000./60.
      IF(MEAN.EQ.1)RAD=RAD*AVG/100.
      CZI=(COS(AZIM*CONV)*SIN(HAT*CONV)*SIN(TIP*CONV)+COS(HAT*CONV)*COS(
     1TIP*CONV))*COS(DELTA*CONV)*COS(15.*(HOUR-12.)*CONV)+SIN(AZIM*CONV)
     1*SIN(TIP*CONV)*COS(DELTA*CONV)*SIN(15.*(HOUR-12.)*CONV)+(SIN(HAT*C
     1ONV)*COS(TIP*CONV)-COS(AZIM*CONV)*COS(HAT*CONV)*SIN(TIP*CONV))*SIN
     1(DELTA*CONV)
      S=TAU*ALPHA*CZI*RAD
      RETURN
      END
C     SUBROUTINE TO FIND HUMIDITY
      SUBROUTINE HUMID(W)
      COMMON HOUR,DAY,COP,TFO,TA,WV,S,TLOSS,FLAG,TFI,JA,TILT,PAR,NSER
      DIMENSION A(28),B(20)
      DATA         A/.7691199E+02,.3611109E+01,-.5416666E+00,.1851851
     1E-01,.7589116E+02,.4826386E+01,-.7430555E+00,.2546296E-01,.7417821
     1E+02,.5673610E+01,-.8819444E+00,.3009259E-01,.6904010E+02,.8185184
     1E+01,-.1268517E+01,.4320987E-01,.7149690E+02,.7745369E+01,-.128703
     17E+01,.4475309E-01,.7692744E+02,.7300923E+01,-.1273148E+01,.447530
     19E-01,.7616818E+02,.9328702E+01,-.1550925E+01,.5401234E-01/
      DATA B/.7691046E+02,.1079629E+02,-.1768517E+01,.6172839E-01,.75577
     113E+02,.1112963E+02,-.1768517E+01,.6172839E-01,.7209642E+02,.10474
     153E+02,-.1627313E+01,.5632716E-01,.7401155E+02,.5840277E+01,-.8819
     1444E+00,.3009259E-01,.7924611E+02,.3247683E+01,-.5115740E+00,.1774
     1691E-01/
      IF(DAY.GE.1..AND.DAY.LE.31.)I=1
      IF(DAY.GE.32..AND.DAY.LE.59.)I=5
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      IF(DAY.GE.60..AND.DAY.LE.90.)I=9
      IF(DAY.GE.91..AND.DAY.LE.120.)I=13
      IF(DAY.GE.121..AND.DAY.LE.151.)I=17
      IF(DAY.GE.152..AND.DAY.LE.181.)I=21
      IF(DAY.GE.182..AND.DAY.LE.212.)I=25
      IF(DAY.GE.213..AND.DAY.LE.243.)I=29
      IF(DAY.GE.244..AND.DAY.LE.273.)I=33
      IF(DAY.GE.274..AND.DAY.LE.304.)I=37
      IF(DAY.GE.305..AND.DAY.LE.334.)I=41
      IF(DAY.GE.335..AND.DAY.LE.365.)I=45
      HA=26.9948786
      HB=-3090.4530960
      HC=-6.1646341
      TA=TA+273.15
      E=10.**(HA+HB/TA+HC*ALOG10(TA))
      IF(I.GT.25)GO TO 99
      R=A(I)+A(I+1)*HOUR+A(I+2)*HOUR**2+A(I+3)*HOUR**3
      GO TO 55
   99 R=B(I-28)+B(I-27)*HOUR+B(I-26)*HOUR**2+B(I-25)*HOUR**3
   55 W=E*R/100.
      TA=TA-273.15
      RETURN
      END
C     SUBROUTINE TO DESCRIBE WIND CONDITIONS
      SUBROUTINE WIND
      COMMON HOUR,DAY,COP,TFO,TA,WV,S,TLOSS,FLAG,TFI,JA,TILT,PAR,NSER
      DIMENSION A(16)
      DATA               A/.1207500E+02,-.2583336E-01,.5555558E-03,-.37037
     105E-05,.1846243E+02,-.8666611E-01,.1666638E-03,.5886878E-11,.82568
     160E+02,-.895629E+00,.3472216E-02,-.4320980E-05,-.4003872E+03,.3564
     1442E+01,-.1027777E-01,.9876539E-05/
      IF(DAY.LT.15.)DAY=DAY+365.
      IF(DAY.GE.15..AND.DAY.LT.105.)I=1
      IF(DAY.GE.105..AND.DAY.LT.195.)I=5
      IF(DAY.GE.195..AND.DAY.LT.285.)I=9
      IF(DAY.GE.285..AND.DAY.LE.375.)I=13
      WV=A(I)+A(I+1)*DAY+A(I+2)*DAY**2+A(I+3)*DAY**3
      IF(DAY.GT.365.)DAY=DAY-365.
      RETURN
      END
C     SUBROUTINE TO DESCRIBE AMBIENT TEMPERATURE AT COLLECTOR
      SUBROUTINE TEMPAM(PHASE)
      COMMON HOUR,DAY,COP,TFO,TA,WV,S,TLOSS,FLAG,TFI,JA,TILT,PAR,NSER
      DIMENSION TMAX(91),TMIN(91)
      DATA              TMAX/33.,33.,34.,35.,36.,38.,39.,40.,41.,42.,43.,
     144.,45.,46.,48.,49.,51.,52.,53.,55.,56.,57.,59.,60.,61.,62.,63.,64
     1.,65.,67.,68.,69.,70.,71.,72.,73.,74.,75.,76.,77.,78.,79.,80.,81.,
     181.,82.,82.,82.,81.,80.,80.,79.,78.,77.,76.,75.,74.,72.,71.,70.,69
     1.,68.,67.,66.,65.,63.,62.,61.,60.,58.,57.,56.,55.,53.,51.,50.,48.,
     146.,45.,44.,43.,42.,41.,40.,39.,37.,36.,35.,35.,34.,33./
      DATA TMIN/19.,18.,18.,19.,20.,21.,22.,23.,24.,25.,25.,26.,27.,28.,
     129.,30.,31.,32.,33.,34.,35.,36.,37.,38.,39.,40.,41.,42.,43.,44.,45
     1.,46.,47.,48.,49.,50.,51.,52.,53.,54.,55.,56.,58.,58.,59.,59.,60.,
     159.,59.,58.,57.,56.,55.,54.,53.,52.,51.,50.,49.,48.,47.,46.,45.,44
     1.,43.,42.,41.,41.,40.,39.,39.,38.,38.,36.,35.,34.,33.,32.,31.,30.,
     129.,28.,27.,26.,25.,24.,23.,22.,21.,20.,19./
      IF(DAY.GE.10.)GO TO 1
      K=1
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      GO TO 100
    1 IF(DAY.GE.40.)GO TO 2
      K=2
      GO TO 100
    2 IF(DAY.GE.47.)GO TO 3
      K=3
      GO TO 100
    3 IF(DAY.GE.52.)GO TO 4
      K=4
      GO TO 100
    4 IF(DAY.GE.58.)GO TO 5
      K=5
      GO TO 100
    5 IF(DAY.GE.62.)GO TO 6
      K=6
      GO TO 100
    6 IF(DAY.GE.64.)GO TO 7
      K=7
      GO TO 100
    7 IF(DAY.GE.67.)GO TO 8
      K=8
      GO TO 100
    8 IF(DAY.GE.69.)GO TO 9
      K=9
      GO TO 100
    9 IF(DAY.GE.72.)GO TO 10
      K=10
      GO TO 100
   10 IF(DAY.GE.74.)GO TO 11
      K=11
      GO TO 100
   11 IF(DAY.GE.76.)GO TO 12
      K=12
      GO TO 100
   12 IF(DAY.GE.79.)GO TO 13
      K=13
      GO TO 100
   13 IF(DAY.GE.82.)GO TO 14
      K=14
      GO TO 100
   14 IF(DAY.GE.85.)GO TO 15
      K=15
      GO TO 100
   15 IF(DAY.GE.88.)GO TO 16
      K=16
      GO TO 100
   16 IF(DAY.GE.91.)GO TO 17
      K=17
      GO TO 100
   17 IF(DAY.GE.93.)GO TO 18
      K=18
      GO TO 100
   18 IF(DAY.GE.96.)GO TO 19
      K=19
      GO TO 100
   19 IF(DAY.GE.99.)GO TO 20
      K=20
      GO TO 100
   20 IF(DAY.GE.101.)GO TO 21
      K=21
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      GO TO 100
   21 IF(DAY.GE.104.)GO TO 22
      K=22
      GO TO 100
   22 IF(DAY.GE.108.)GO TO 23
      K=23
      GO TO 100
   23 IF(DAY.GE.111.)GO TO 24
      K=24
      GO TO 100
   24 IF(DAY.GE.114.)GO TO 25
      K=25
      GO TO 100
   25 IF(DAY.GE.117.)GO TO 26
      K=26
      GO TO 100
   26 IF(DAY.GE.121.)GO TO 27
      K=27
      GO TO 100
   27 IF(DAY.GE.124.)GO TO 28
      K=28
      GO TO 100
   28 IF(DAY.GE.128.)GO TO 29
      K=29
      GO TO 100
   29 IF(DAY.GE.132.)GO TO 30
      K=30
      GO TO 100
   30 IF(DAY.GE.136.)GO TO 31
      K=31
      GO TO 100
   31 IF(DAY.GE.139.)GO TO 32
      K=32
      GO TO 100
   32 IF(DAY.GE.142.)GO TO 33
      K=33
      GO TO 100
   33 IF(DAY.GE.144.)GO TO 34
      K=34
      GO TO 100
   34 IF(DAY.GE.147.)GO TO 35
      K=35
      GO TO 100
   35 IF(DAY.GE.150.)GO TO 36
      K=36
      GO TO 100
   36 IF(DAY.GE.153.)GO TO 37
      K=37
      GO TO 100
   37 IF(DAY.GE.156.)GO TO 38
      K=38
      GO TO 100
   38 IF(DAY.GE.159.)GO TO 39
      K=39
      GO TO 100
   39 IF(DAY.GE.163.)GO TO 40
      K=41
      GO TO 100
   40 IF(DAY.GE.166.)GO TO 41
      K=41
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      GO TO 100
   41 IF(DAY.GE.171.)GO TC 42
      K=42
      GO TO 100
   42 IF(DAY.GE.177.)GO TC 44
      K=43
      GO TC 100
   44 IF(DAY.GE.181.)GO TC 45
      K=44
      GO TO 100
   45 IF(DAY.GE.188.)GC TC 46
      K=45
      GO TC 100
   46 IF(DAY.GE.194.)GO TC 47
      K=46
      GO TO 100
   47 IF(DAY.GE.216.)GO TC 48
      K=47
      GO TO 100
   48 IF(DAY.GE.220.)GO TC 49
      K=48
      GO TO 100
   49 IF(DAY.GE.227.)GO TC 50
      K=49
      GO TO 100
   5C IF(DAY.GE.233.)GO TC 51
      K=50
      GO TC 100
   51 IF(CAY.GE.239.)GO TC 52
      K=51
      GO TO 100
   52 IF(DAY.GE.243.)GO TC 53
      K=52
      GO TC 100
   53 IF(DAY.GE.246.)GO TC 54
      K=53
      GO TC 100
   54 IF(DAY.GE.250.)GO TC 55
      K=54
      GO TC 100
   55 IF(DAY.GE.254.)GO TC 56
      K=55
      GO TO 100
   56 IF(DAY.GE.259.)GO TC 57
      K=56
      GO TO 100
   57 IF(DAY.GE.263.)GO TC 58
      K=57
      GO TO 100
   58 IF(DAY.GE.267.)GO TC 59
      K=58
      GO TC 1CO
   59 IF(DAY.GE.270.)GO TC 60
      K=59
      GO TC 100
   6C IF(DAY.GE.273.)GC TC 61
      K=60
      GO TO 100
   61 IF(DAY.GE.276.)GO TC 62
      K=61
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      GO TO 100
   62 IF(DAY.GE.279.)GO TO 63
      K=62
      GO TO 100
   63 IF(DAY.GE.282.)GO TO 64
      K=63
      GO TO 100
   64 IF(DAY.GE.285.)GO TO 65
      K=64
      GO TO 100
   65 IF(DAY.GE.288.)GO TO 66
      K=65
      GO TO 100
   66 IF(DAY.GE.291.)GO TO 67
      K=66
      GO TO 100
   67 IF(DAY.GE.293.)GO TO 68
      K=67
      GO TO 100
   68 IF(DAY.GE.295.)GO TO 69
      K=68
      GO TO 100
   69 IF(DAY.GE.298.)GO TO 70
      K=69
      GO TO 100
   70 IF(DAY.GE.301.)GO TO 71
      K=70
      GO TO 100
   71 IF(DAY.GE.303.)GO TO 72
      K=71
      GO TO 100
   72 IF(DAY.GE.305.)GO TO 73
      K=72
      GO TO 100
   73 IF(DAY.GE.309.)GO TO 74
      K=73
      GO TO 100
   74 IF(DAY.GE.312.)GO TO 75
      K=74
      GO TO 100
   75 IF(DAY.GE.315.)GO TO 76
      K=75
      GO TO 100
   76 IF(DAY.GE.318.)GO TO 77
      K=76
      GO TO 100
   77 IF(DAY.GE.321.)GO TO 78
      K=77
      GO TO 100
   78 IF(DAY.GE.325.)GO TO 79
      K=78
      GO TO 100
   79 IF(DAY.GE.327.)GO TO 80
      K=79
      GO TO 100
   80 IF(DAY.GE.329.)GO TO 81
      K=80
      GO TO 100
   81 IF(DAY.GE.331.)GO TO 82
      K=81
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      GO TO 100
   82 IF(DAY.GE.333.)GO TC 83
      K=82
      GO TC 100
   83 IF(DAY.GE.336.)GC TC 84
      K=83
      GO TC 100
   84 IF(DAY.GE.338.)GO TC 85
      K=84
      GO TO 100
   85 IF(DAY.GE.341.)GO TC 86
      K*85
      GO TO 100
   86 IF(DAY.GE.344.)GO TC 87
      K=86
      GO TO 100
   87 IF(DAY.GE.347.)GO TC 88
      K=87
      GO TC 100
   88 IF(DAY.GE.351.)GO TC 89
      K=88
      GO TO 100
   89 IF(DAY.GE.355.)GO TC 90
      K=89
      GO TO 100
   90 IF(DAY.GE.361.)GO TC 91
      K=90
      GO TC 100
   91 K=91
  100 TA=(TMAX(K)-TMIN(K))/2.*SIN(3.141597*HOUR/12.+PHASE)+(TMAX(K)+TMIN
     1(K))/2.
      TA=(TA-32.)*5./9.
      RETURN
      END
C     SUBROUTINE TO FIND HEAT PUMP COP
      SUBROUTINE HPUMP(TPIC,TPOC,DMDT,DELIV)
      COMMON HOUR,DAY,COP,TFO,TA,WV,S,TLOSS,FLAG,TFI,JA,TILT,PAR,NSER
      DIMENSICN A(28),B(8)
      DATA        A/.2054319E+01,.2175925E-01,-.2453702E-03,.262345
     17E-05,.1458021E+01,.3814818E-01,-.4259257E-03,.3086419E-05,.166419
     19E+01,.2629614E-01,-.2962940E-03,.2469127E-05,.2717288E+01,-.25740
     199E-01,.4074106E-03,-.6172980E-06,.2750616E+01,-.2907410E-01,.4074
     1075E-03,-.6172863E-06,.3449998E+01,-.6361103E-01,.8888883E-03,-.27
     177776E-05,.2476538E+01,.5148158E-01,-.9814824E-03,.6790126E-05/
      DATA B/.2445680E+01,.3018503E-01,-.5185166E-03,.432098E-05,.212962
     19E+01,.3111104E-01,-.4444432E-03,.3703700E-05/
      TPIC=1.8*TPIC+32.
      IF(DELIV.EQ.150.)I=1
      IF(DELIV.EC.160.)I=5
      IF(DELIV.EQ.170.)I=9
      IF(DELIV.EQ.180.)I=13
      IF(DELIV.EQ.190.)I=17
      IF(DELIV.EQ.200.)I=21
      IF(DELIV.EQ.135.)I=25
      IF(DELIV.EQ.140.)I=29
      IF(DELIV.EQ.145.)I=33
      IF(I.GT.25)GO TO 99
      COP=A(I)+A(I+1)*TPIC+A(I+2)*TPIC**2+A(I+3)*TPIC**3
      GO TC 55
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   99 COP=B(I-28)+B(I-27)*TPIC+B(I-26)*TPIC**2+B(I-25)*TPIC**3
   55 TPIC=(5./9.)*(TPIC-32.)
      CP=4190.
      TLOSS=TLOSS*COP*CP/(COP-1.)
      TPOC=TPIC-(TLOSS/CCP)*(COP-1.)/(CP*DMDT)
      FLAG=1.
      RETURN
      END
C     SUBROUTINE FOR HEAT EXCHANGER CALCULATIONS
      SUBROUTINE HEXC(TPIC,TPOC,TPIT,DMDT,IPAR)
      CP1=4190.
      CP2=4190.
      U=200.
      A=50.
      DMDT1=DMDT
      DMDT2=DMDT
      IF(IPAR.NE.1)GO TO 4
      ALPHA=1./(CP1*DMDT1)+1./(CP2*DMDT2)
      IF((U*A*ALPHA).GE.20.)GO TO 2
      GO TO 1
    2 Q=(TPIC-TPIT)/ALPHA
      GO TO 3
    1 Q=(TPIC-TPIT)*(1.-EXP(-U*A*ALPHA))/ALPHA
    4 ALPHA=1./(CP2*DMDT2)-1./(CP1*DMDT1)
      IF(ALPHA.EQ.0.)ALPHA=.0000001
      IF((U*A*ALPHA).GE.20.)Q=(TPIC-TPIT)*(CP2*DMDT2)
      IF((U*A*ALPHA).LE.-20.)Q=(TPIC-TPIT)*(CP1*DMDT1)
      IF((U*A*ALPHA).LT.20..AND.(U*A*ALPHA).GT.-20.)Q=(TPIC-TPIT)*(EXP(U
     1*A*ALPHA)-1.)/(EXP(U*A*ALPHA)/(CP2*DMDT2)-1./(CP1*DMDT1))
    3 TPOC=TPIC-Q/(CP1*DMDT1)
      TPOT=TPIT+Q/(CP2*DMDT2)
      RETURN
      END
C     SUBROUTINE TO PUT COLLECTORS IN  SERIES,PARALLEL
      SUBROUTINE ARRAY(DMDT)
      COMMON HOUR,DAY,COP,TFO,TA,WV,S,TLOSS,FLAG,TFI,JA,TILT,PAR,NSER
      TFI1=TFI
      DMDT=DMDT/PAR
      DO 1 I=1,NSER
      ISAV=I
      CALL TOUTC(DMDT,ISAV)
    1 TFI=TFO
      TFI=TFI1
      DMDT=DMDT*PAR
      RETURN
      END
C     SUBROUTINE TO CONNECT SYSTEM COMPONENTS
      SUBROUTINE LINK(DMDT,DEL,PF)
      COMMON HOUR,DAY,COP,TFO,TA,WV,S,TLOSS,FLAG,TFI,JA,TILT,PAR,NSER
      FLAG=0.
      ITL=0
      T=.1
      CALL TANK(DELIV)
      TFI=(DELIV-32.)/1.8
      CALL ARRAY(DMDT)
      TEST1=TFO-(DELIV-32.)/1.8-DEL
      IF(TEST1.LE.0.)GO TO 3
```

```
    2 CALL ARRAY(DMDT)
      TPIC=TFO
      CALL HEXC(TPIC,TPOC,DELIV,DMDT,0)
      ATEST=TPOC-TFI
      TEST=ABS(TPOC-TFI)
      ITL=ITL+1
      IF(ITL.GT.5)WRITE(6,100)ITL
      IF(ITL.GT.5)WRITE(6,200)HOUR,DAY,TPOC,TPIC
  200 FORMAT(' ','HOUR=',F5.2,5X,'DAY=',F7.2,5X,'TPOC=',F7.2,5X,'TPIC=',
     1F7.2)
      IF(TEST.LT.T)GO TO 4
      TFI=TPOC+4.*ATEST
      GO TO 2
    3 TFI=TA
    5 CALL ARRAY(DMDT)
      TPIC=TFO
      TLOSS=(TFO-TFI)*DMDT*PF
      CALL HPUMP(TPIC,TPOC,DMDT,DELIV)
      ATEST=TPOC-TFI
      SIGN=0.
      IF(ATEST.LT.0.)SIGN=-1.
      TEST=ABS(TPOC-TFI)
      ITL=ITL+1
      IF(ITL.GT.10)WRITE(6,101)ITL
      IF(ITL.GT.10)WRITE(6,200)HOUR,DAY,TPOC,TPIC
      IF(TEST.LT.T)GO TO 4
      TFI=TPOC+1.*ATEST
      GO TO 5
  100 FORMAT(' ','WARNING: HEXC ITL EQUALS',2X,I2)
  101 FORMAT(' ','WARNING: HPUMP ITL EQUALS',2X,I2)
  102 FORMAT(' ','DANGER: FREEZING FLUID',2X,'TFI=',F7.2,2X,'TFO='
     1,F7.2)
    4 IF(TFI.LT.0.)WRITE(6,102)TFI,TFO
      RETURN
      END
C     SUBROUTINE TO INCREMENT TIME SYNCRONIZED WITH TANK SWITCHING
      SUBROUTINE TIME(FRAC)
      COMMON HOUR,DAY,COP,TFO,TA,WV,S,TLOSS,FLAG,TFI,JA,TILT,PAR,NSER
      IF(JA.EQ.1)FRAC=4.33
      IF(JA.EQ.2)FRAC=5.10
      IF(JA.EQ.3)FRAC=2.95
      IF(JA.EQ.4)FRAC=8.61
      IF(JA.EQ.5)FRAC=2.66
      IF(JA.EQ.6)FRAC=2.50
      IF(JA.EQ.7)FRAC=2.66
      IF(JA.EQ.8)FRAC=2.18
      IF(JA.EQ.9)FRAC=2.66
      IF(JA.EQ.10)FRAC=2.12
      IF(JA.EQ.11)FRAC=2.66
      IF(JA.EQ.12)FRAC=4.33
      IF(JA.EQ.13)FRAC=8.61
      IF(JA.EQ.14)FRAC=8.61
      FRAC=2.*FRAC
      HOUR=HOUR+FRAC/60.
      RETURN
      END
C     SUBROUTINE TO DETERMINE DELIV TEMPERATURE OF TANKS
      SUBROUTINE TANK(DELIV)
```

```
      COMMON HOUR,DAY,COP,TFO,TA,WV,S,TLOSS,FLAG,TFI,JA,TILT,PAR,NSER
      IF(JA.EQ.1)DELIV=160.
      IF(JA.EQ.2)DELIV=170.
      IF(JA.EQ.3)DELIV=140.
      IF(JA.EQ.4)DELIV=200.
      IF(JA.EQ.5)DELIV=150.
      IF(JA.EQ.6)DELIV=145.
      IF(JA.EQ.7)DELIV=150.
      IF(JA.EQ.8)DELIV=140.
      IF(JA.EQ.9)DELIV=150.
      IF(JA.EQ.10)DELIV=135.
      IF(JA.EQ.11)DELIV=150.
      IF(JA.EQ.12)DELIV=160.
      IF(JA.EQ.13)DELIV=200.
      IF(JA.EQ.14)DELIV=200.
      RETURN
      END
C     SUBROUTINE TO CALCULATE ENERGY USED IN THE SYSTEM
      SUBROUTINE CALC(START,FRAC,DMDT,TPEL,THPEL,TOT)
      COMMON HOUR,DAY,COP,TFO,TA,WV,S,TLOSS,FLAG,TFI,JA,TILT,PAR,NSER
      IF(START.NE.1.)GO TO 3
      TOT=0.
      THPEL=0.
      TPEL=0.
      THP=0.
      TEX=0.
    3 DHPEL=0.
      DS=0.
      DPEL=0.
      DHP=0.
      IF(FLAG.EQ.1.)GO TO 1
      DS=(TFO-TFI)*DMDT*4190.*FRAC*60.
      DPEL=200.*FRAC*60.
      GO TO 2
    1 DHPEL=TLOSS/COP*FRAC*60.
      DHP=TLOSS*FRAC*60.
      DS=(TFO-TFI)*DMDT*4190.*FRAC*60.
      DPEL=300.*FRAC*60.
    2 TOT=TOT+DS+DHPEL
      THPEL=THPEL+DHPEL
      TPEL=TPEL+DPEL
      THP=THP+DHP
      IF(FLAG.EQ.1.)DS=0.
      TEX=TEX+DS
      RETURN
      END
C     SUBROUTINE TO CALCULATE ENERGY COSTS FOR ONE YEAR
      SUBROUTINE COSTS(TPEL,THPEL,TOT,CYR1,YR,DAYS)
      COMMON HOUR,DAY,COP,TFO,TA,WV,S,TLOSS,FLAG,TFI,JA,TILT,PAR,NSER
      ELECT=.8333333E-08
      BTU=3155830.
      HOURS=24.
      AJBTU=1055.06
      ENJ=HOURS*DAYS*AJBTU*BTU
      CGAS=.1283697E-02
      EGAS=750.7*AJBTU
      CP=4200.
      CHP=15000.
```

```
      CCM2=50.
      CEX=14.*500.
      CMIS=5000.
      CCON=10000.
      X=10.
      AI=.08
    5 CYR1=(ELECT*(TPEL+THPEL)+(ENJ-TCT)/EGAS*CGAS)*365./DAYS
      CYR2=CP+CHP+CCM2*NSER*PAR*2.+CEX+CMIS+CCON
      YR=(CYR2*AI*(AI+1.)**X)/((AI+1.)**X-1.)
      RETURN
      END
```

APPENDIX B

Subroutine Names And Descriptions

Subroutine Name	Description
COLPAR	Supplies collector parameters used
TOUTC	Collector model
SOLIN	Finds solar energy absorbed by collector
HUMID	Finds humidity at collector
WIND	Finds wind speed at collector
TEMPAM	Finds ambient temperature
HPUMP	Heat pump model
HEXC	Heat exchanger model
ARRAY	Puts collectors in series, parallel
LINK	Connects system components
TIME	Increments time
TANK	Finds temperature of tank being used
CALC	Calculates energy transfers in system
COSTS	Calculates energy costs for one year

REFERENCES

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

[2] J.W. Spencer, "Computer Estimation of Direct Solar Radiation on Clear Days", Solar Energy, Vol. 13, pp.437-438, 1972.

[3] Local Climatological Data, Youngstown, Ohio, U.S. Department of Commerce, 1972.

[4] O.G. Sutton, Micrometeorology. New York: McGraw-Hill, 1953.

[5] I.S. Sokolnikoff and R.M. Redheffer, Mathematics of Physics and Modern Engineering. New York: McGraw-Hill, 1966.

[6] The Monthly Weather Review and Climatological Data National Summary Through 1962, as presented in Harnessing the Sun by John Keys, 1974.

[7] A.I. Brown, Introduction to Heat Transfer. New York: McGraw-Hill, 1958.

[8] S.A. Trumbower, The Templifier--A New Heat Source For Industry, Westinghouse Electric Corporation, 1972.

[9] ASHRAE Handbook and Product Directory of 1975 Equipment. New York: American Society of Heating, Refrigerating, and Air Conditioning Engineers, 1975.

[10] Fredrick J. Hill and Gerald R. Peterson, Introduction to Switching Theory and Logical Design. New York: John Wiley and Sons, 1974.