Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

ENERGY & ENVIRONMENT DIVISION

Submitted to the Journal of Solar Energy

COMPARISON OF PROPORTIONAL AND ON/OFF SOLAR COLLECTOR LOOP CONTROL STRATEGIES USING A DYNAMIC COLLECTOR MODEL

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December 1979

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

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COMPARISON OF PROPORTIONAL AND ON/OFF SOLAR COLLECTOR LOOP CONTROL STRATEGIES USING A DYNAMIC COLLECTOR MODEL*

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ABSTRACT

Common control strategies used to regulate the flow of liquid through flat-plate solar collectors are discussed and evaluated using a dynamic collector model. Performance of all strategies is compared using different set points, flow rates, insolation levels and patterns (clear and cloudy days), and ambient temperature conditions.

The unique characteristic of the dynamic collector model is that it includes effects of collector capacitance. In general, capacitance has a minimal effect on long term collector performance; however, short term temperature response and the energy -storage capability of collector capacitance are shown to play significant roles in comparing on/off and proportional controllers. Inclusion of these effects has produced considerably more realistic simulations than any generated by steady-state models.

Simulations indicate relative advantages and disadvantages of both types of controllers, conditions under which each performs better, and the importance of pump cycling and controller set points on total energy collection.

Results show that the turn-on set point is not always a critical factor in energy collection since collectors store energy while they warm up and during cycling; and, that proportional flow controllers

[*] This work has been supported by the Systems Analysis and Design Branch, Systems Development Division, Office of Solar Applications, U.S. Department of Energy, under Contract No. W-7405-ENG-48.

provide improved energy collection only during periods of interrupted or very low insolation when the maximum possible energy collection is relatively low. Although proportional controllers initiate flow at lower insolation levels than on/off controllers, proportional controllers produce lower flow rates and higher average collector temperatures resulting in slightly lower instantaneous collection efficiencies.

1) INTRODUCTION

Active solar heating systems are generally capital intensive; therefore, improvements which increase system efficiency must do so with only a small incremental initial cost in order for them to help solar energy compete with other energy sources. Since improved control systems and strategies may satisfy thls criterion, researchers and manufacturers have sought to evaluate and improve system controllers.

Commercially available controllers for domestic heating systems include both on/off and proportional feedback control[41]. While some manufacturers have advertised microprocessor based control systems, none of these systems are applicable, as yet, for residential solar energy usage. On/off controllers have had the widest application due to their simplicity and generally reliable operation. However, demonstration projects [5,8,25,36] have shown that two problems can occur with these controllers: 1) they can cause the circulating pump to cycle on and off excessively and 2) improper selection of set points can cause low system efficiency. In response to these problems some controller manufacturers have marketed proportional flow controllers, claiming improved overall system efficiencies.

With the exemption of the work at Drexel University[29] computer simulations for control strategy development and evaluation have used only steady-state collector models. These zero capacitance models do not accurately predict collector performance during short time periods when conditions are rapidly changing. This limitation distorts evaluations of control schemes, particularly when cycling occurs. Also, most studies have evaluated only two or three test cases that are not representative of the span of operating conditions a controller might encounter.

In this study, a dynamic model which includes the effects of collector capacitance is used to evaluate on/off and proportional controllers. Conditions under which each will perform more effectively are determined. Control set points are varied to evaluate their importance and to provide upper and lower bounds for collection efficiency. Flow rates and meteorological conditions are also varied to evaluate the controllers under different situations. Methods for determining the proper control set points are also discussed.

2) DYNAMIC FLAT-PLATE SOLAR COLLECTOR MODEL

The Hottel-Whillier-Bliss (H.W.B.) collector model [7,12,16,17,37], as adapted by Klein [19,20] to include effects of capacitance, is used to describe the operation of a flat-plate solar collector. The model is based upon a heat balance on a tube and fluid element within a collector, where the entire capacitance of the collector is lumped within the tubes and circulating fluid. The heat balance is solved, using numerical methods on a digital computer, to describe the circulating fluid's temperature as a function of time and space.

Klein's major assumptions are:

1. The entire capacitance of the collector, per unit area, including fluid capacitance is represented as a single capacitance coefficient, C_A.
2. The tube and fluid are at the same temperature.
3. There is no thermal conduction along the tube.
4. The fluid flow is slug flow.
5. The ambient temperature, solar insolation, flow rate, loss factor, and fin efficiency do not vary along the flow direction.

The transient heat balance for a collector element of width W_c, for flow and no-flow conditions is:

$$\partial T_{f,x}/\partial t = \gamma\left[(F'/C_A)\left[S - U_L(T_{f,x} - T_a)\right] - (\dot{m}c_p/C_A W_c)(\partial T_{f,x}/\partial x)\right] + (1-\gamma)\left[(F'/C_A)\left[S - U_L(T_{f,x} - T_a)\right]\right] \quad (1)$$

Where: If $\gamma = 1$ pump is running

If $\gamma = 0$ pump is not running

and: W_c = collector width (normal to flow)

C_A = capacitance coefficient per unit area

$T_{f,x}$ = fluid temperature at position x

t = time

F′ = plate fin efficiency factor

S = rate of absorption of incident solar radiation on the collector plate per unit area and is equal to the product of the insolation rate (I) and the transmittance-absorptance coefficient ($\tau\alpha$).

U_L = the collector loss coefficient per unit area

T_a = ambient temperature

$\dot{m}$ = fluid mass flow rate

c_p = fluid thermal capacitance

x = displacement in flow direction

This equation is for a non-drain down collector; fluid stays within the collector even when the pump is off. For a drain down system the collector and fluid capacitance would have to be treated separately.

C_A is a weighted average of total collector capacitance. Using weighting factors for various collector components Klein[19] has made estimates of C_A that range from .35 to .85 BTU/ft^2-^{o}F (7.2 to 17.4 kJ/m^2-^{o}C).

<u>A Collector Model for Evaluating Control Strategies</u>. Equation 1 is solved numerically by breaking the collector into a number of nodes or perfectly stirred tanks, thus the time dependent temperature of the N^{th} node is written as:

$$dT_N/dt = \gamma\left[(F'/C_A)[S - U_L(T_{f_N} - T_a)] + (\dot{m}c_p/C_A W_c \Delta x)(T_{f_{N-1}} - T_{f_N})\right] + (1 - \gamma)\left[(F'/C_A)[S - U_L(T_{f_N} - T_a)]\right] \quad (2)$$

For the first node the equation is:

$$dT_1/dt = \gamma\left[(F'/C_A)[S - U_L(T_{f_1} - T_a)] + (\dot{m}c_p/C_A W_c \Delta x)(T_{in} - T_{f_1})\right] + (1 - \gamma)\left[(F'/C_A)[S - U_L(T_{f_1} - T_a)]\right] \quad (3)$$

For the last node the equation is:

$$dT_{out}/dt = \gamma\left[(F'/C_A)[S - U_L(T_{out} - T_a)] + (\dot{m}c_p/C_A W_c \Delta x)(T_{out-1} - T_{out})\right] + (1-\gamma)\left[(F'/C_A)[S - U_L(T_{out} - T_a)]\right] \quad (4)$$

These equations for N nodes were solved using the Parasol program developed by Auslander[3]. Parasol uses the fourth-order Runge-Kutta method to solve differential equations. The Parasol program's output is the fluid temperature at different positions along the flow path and for discrete time intervals.

The model described by equations 2, 3, and 4 is adopted for the following reasons:

1) It provides a simple and accurate description of the transient temperature distribution in a collector's circulating fluid.
2) It included the effects of collector capacitance.
3) It is derived from a well established and respected collector model.
4) Results it provides are usable and consistent with known collector operation.

3) COLLECTOR PARAMETERS

To compare various control strategies using a computer model, appropriate parameters must be used which represent a typical collector under the influence of common external conditions. Although a multi-node model is used for simulation, a single node model is used to define the appropriate parameters. These parameters are then scaled for use in a multi-node model.

In the limiting case of a single node model equation 2 reduces to [for flow conditions]:

$$C_A dT_{out}/dt = F'[S - U_L(T_{out} - T_a)] + (\dot{m}c_p/A_c)(T_{in} - T_{out}) \quad (5)$$

This equation can also be written to demonstrate the functional dependence of the collector temperature on 1) insolation and ambient temperature, 2) fluid flow rate and 3) collector characteristics:

$$C_A dT_{out}/dt = (K_{gain})f(t) + (K_{flow})T_{in} - (K'_{flow})T_{out} \quad (6)$$

Where: K_{gain} represents the collector's gain from insolation and losses to the environment

$$K_{gain} = F'[S_{max} + U_L T_{a,max}]$$

$f(t)$ represents the time variation of the normalized forcing function due to insolation and ambient temperature

K_{flow} represents the fluid flow rate per unit area of collector

$$K_{flow} = \dot{m}c_p/A_c$$

$$K'_{flow} = \dot{m}c_p/A_c + F'U_L$$

K_{flow} approximately equals K'_{flow} since $F'U_L << \dot{m}c_p/A_c$

C_A represents the collector/fluid capacitance per unit area

By allowing K_{gain} and K_{flow} (and K'_{flow}) to take on either HIGH or LOW values while keeping all other parameters constant, the control strategy comparisons are based on a limited but comprehensive set of meteorological and flow variations which are used to define limits of operation for a typical collector. The numerical values for the parameters used are described below and summarized in Table 1.

TABLE I: SUMMARY OF COLLECTOR PARAMETERS AND SIMULATION RUNS

CAPACITANCE

C_A = .7 BTU/ft^2-^oF
14.3 kJ/m^2-^oC

HIGH GAIN

I_{max} = 300 BTU/ft^2-hr
946 watts/m^2

$T_{a(max)}$ = 70^oF
21.1^oC

HIGH FLOW

$\dot{m}c_p/A_c$ (max) = 25 BTU/ft^2-hr-^oF
511 kJ/m^2-hr-^oC

COLLECTOR LOSS COEFFICIENT

U_L = .7 BTU/ft^2-hr-^oF
3.97 watts/m^2-^oC

LOW GAIN

I_{max} = 150 BTU/ft^2-hr
473 watts/m^2

$T_{a(max)}$ = 50^oF
10^oC

LOW FLOW

$\dot{m}c_p/A_c$ (max) = 15 BTU/ft^2-hr-^oF
306 kJ/m^2-hr-^oC

TRANSMITTANCE/ ABSORPTANCE

$\tau\alpha$ = 0.84

INLET FLUID TEMPERATURE

T_{in} = 115^oF
46.1^oC

FIN EFFICIENCY

F' = .95 (flow)
1.0 (no flow)

SUMMARY OF SIMULATION RUNS

Clear Day Runs $I = I_{max}(\sin \pi t/12)$

RUN #	1	2	3	4
GAIN:	HIGH	HIGH	LOW	LOW
FLOW:	HIGH	LOW	HIGH	LOW

Cloudy Day Runs $I = [I_{max}/2][\sin(\pi t/12)][\cos(40\pi t/12) + 1]$

RUN #	1	2	3	4
GAIN:	HIGH	HIGH	LOW	LOW
FLOW:	HIGH	LOW	HIGH	LOW

The collector loss coefficient (U_L), the transmittance/ absorptance coefficient($\tau\alpha$), and the collector fin efficiency (F') are kept constant for all simulation runs. Changing them would be equivalent to changing ambient temperature or insolation rate, which is done. The values chosen are typical for well made collectors [1,2,6,9,12,24,29,35,39,41].

The dynamics associated with the storage tank and piping to the collector are neglected and therefore the collector inlet temperature, T_{in}, is constant. The value chosen, $115^oF(46.1^oC)$, is a representative storage tank temperature [22]. For comparative results, storage tank dynamics are not critical. However, the effect of a 'cold slug' of inlet fluid was examined for a series of simulation runs (see Appendix II).

Preliminary simulation runs showed that changes in collector capacitance, within the range of suggested capacitances, has a minimal effect on comparisons of different control strategies; therefore, collector capacitance, C_A, is kept constant at 0.7 BTU/ft^2-^oF (14.3 kJ/m^2-^oC). This value was suggested by Klein[20] for a two-cover collector and is compatible with values used in other studies[9,29].

Collector insolation, heat loss, capacitance and flow rate are all scaled per unit area of collector which allows a majority of the results to be independent of collector area. K_{flow} is assigned either a HIGH FLOW or LOW FLOW value which represents either an approximate maximum or minimum value of flow rates used in the solar industry [2,6,24,28,29,35,39,41]. These two flow rates, 15 and 25 lbm/ft^2-hr (73.2 and 122 kg/m^2-hr) provide good comparisons for different collector controllers and help define operating ranges. The circulating fluid is modeled as water with a heat capacity, c_p, of 1 BTU/lbm-^oF (4.18 kJ/kg-^oC).

The solar day for all runs is 12 hours long with a peak insolation rate reached at hour 6. For a clear day (no interruptions of insolation) the insolation rate, I, is proportional to a sine wave with a 24 hour period:

$$I = I_{max} \sin(\pi t/12) \qquad t = \text{hours}$$

For a cloudy day the insolation is intermittently interrupted. Following Close[9], the insolation rate as a function of time is:

$$I = (I_{max}/2)[\sin\pi\ t/12)][\cos(40\pi\ t/12) + 1] \qquad t = \text{hours}$$

The ambient temperature, T_a, is proportional to a sine wave with a 24 hour period, the peak value is at the 9th hour of the solar day:

$$T_a = TO + TM \left[\sin(\pi t/12 - \pi/4)\right] \qquad t = \text{hours}$$

K_{gain}, like K_{flow}, is assigned either a HIGH GAIN or a LOW GAIN value which represents either a maximum or minimum net energy gain by the collector, independent of the insolation pattern simulated. Peak insolation values are 300 BTU/ft^2-hr(946 W/m^2) for the high gain cases and 150 BTU/ft^2 (473 W/m^2) for the low gain cases. These values are applicable for the United States[27] and are consistent with values used in other studies[15,23,29,31,35]. Low gain corresponds to low ambient temperatures and thus maximum collector losses, the opposite is true for high gain cases. The collector temperature is assumed to equal the ambient temperature at sunrise.

4) COLLECTOR FLOW CONTROLLERS

Collection of solar energy is controlled by the flow of fluid through the collector loop (see Figure 1). Collector outlet and storage tank temperatures are compared by a controller to determine the fluid flow rate. The difference between the collector outlet temperature and the storage tank temperature is known as ΔT and represents the temperature rise across the collector.

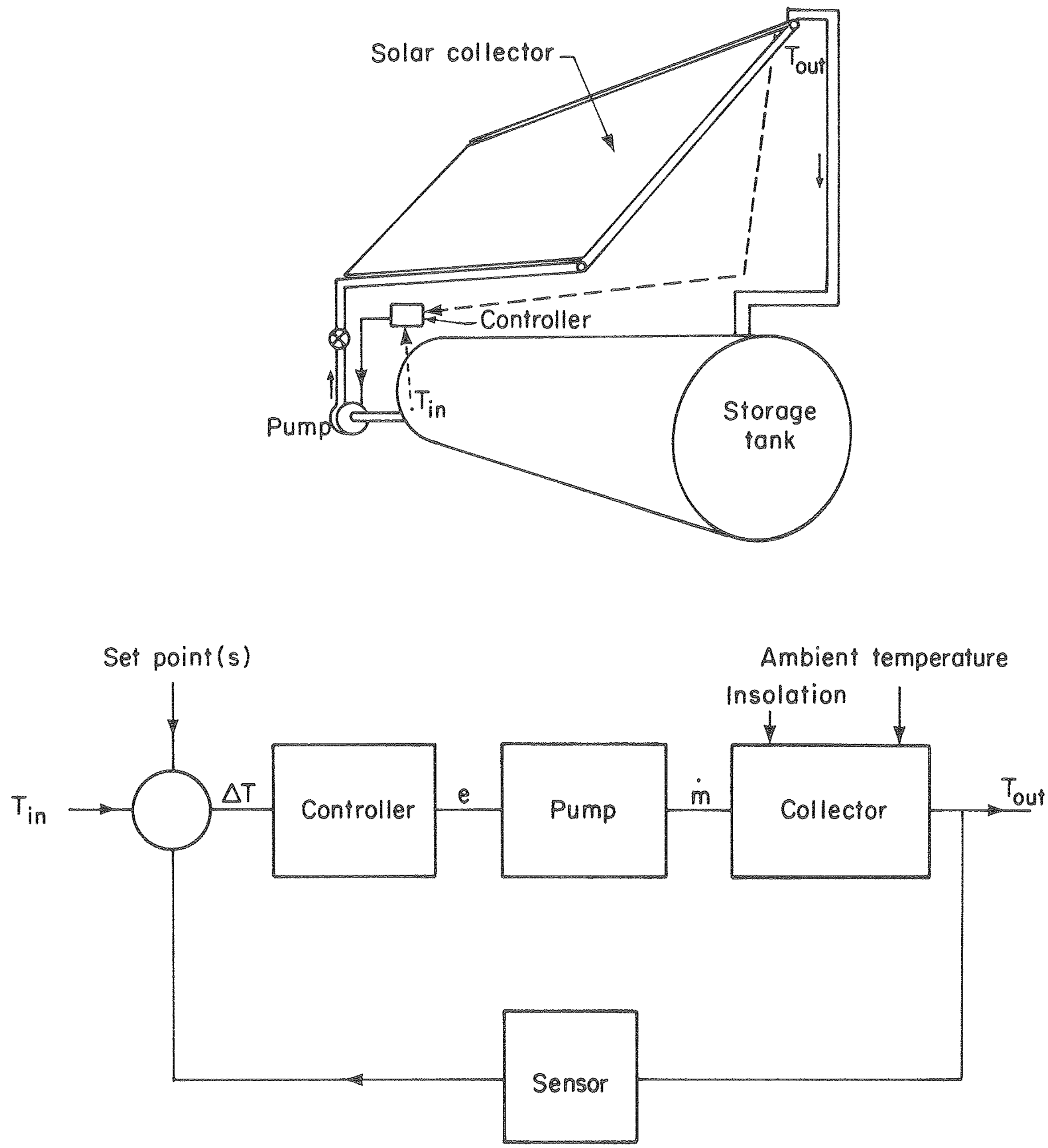
On/Off Control. The on/off controller is a thermostat which turns the fluid circulation pump either on or off based on the temperature rise across the collector, ΔT. Figure 2 illustrates the operation of the on/off controller and the following definitions apply to this type of controller:

ΔT_{off} = temperature difference between fluid outlet and inlet sufficient to turn pump off.

ΔT_{on} = temperature difference between fluid outlet and inlet sufficient to turn pump on.

The region between ΔT_{on} and ΔT_{off} is known as the hysteresis zone. Because of hysteresis on/off controllers have "memory" which limits pump cycling.

Flow rate ($\dot{m}$) through the collector can be defined as:



TYPICAL SOLAR ENERGY COLLECTION SYSTEM AND CONTROL BLOCK DIAGRAM

FIGURE 1

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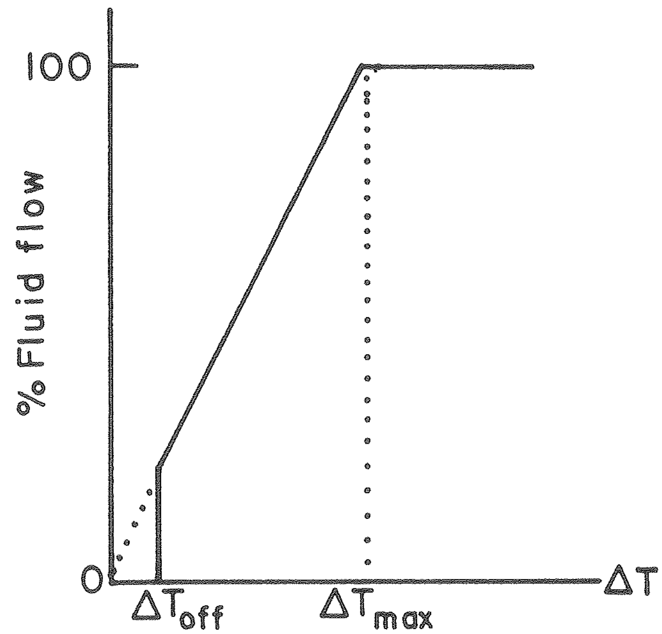
$$\dot{m} = \begin{cases} 0 \begin{cases} \text{if } \Delta T < \Delta T_{on} \text{ and last flow} = 0 \\ \text{or} \\ \text{if } \Delta T < \Delta T_{off} \end{cases} \\ \\ \dot{m} \begin{cases} \text{if } \Delta T \geq \Delta T_{on} \\ \text{or} \\ \text{if } \Delta T \geq \Delta T_{off} \text{ and last flow} = \dot{m} \end{cases} \end{cases}$$

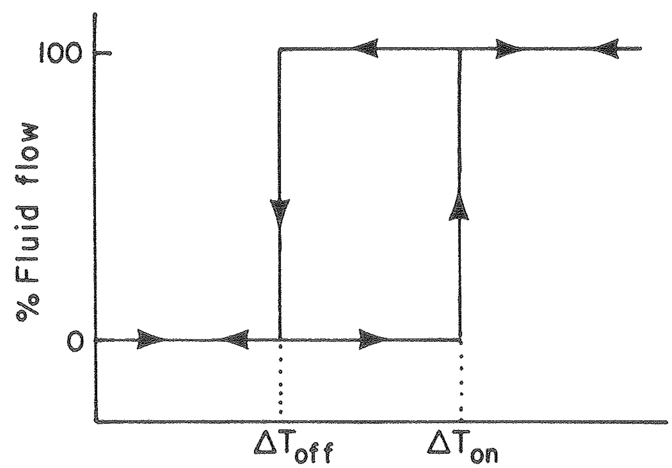
A timer is sometimes added to an on/off controller to limit pump cycling. The timer delay of 5 - 10 minutes holds the pump on after ΔT_{on} has been reached without considering the actual collector temperature. With this type of controller, though, it is possible for the pump to be on when there is a net energy loss from the collector loop.

Proportional Control (with saturation). In this type of feedback controller the fluid flow rate is also varied as a function of ΔT. The advantages of proportionally controlled systems are: fluid circulates at lower values of ΔT and pump cycling is minimized. Figure 3 shows the characteristics of a proportional controller. The fluid flow rate through the collector is described by the following equations:

$$\dot{m}(t) = \begin{cases} 0 & \text{for } \Delta T < \Delta T_{off} \\ K\Delta T & \text{for } \Delta T_{off} \leq \Delta T \leq \Delta T_{max} \\ \dot{m}_c & \text{for } \Delta T \geq \Delta T_{max} \end{cases}$$



PROPORTIONAL CONTROLLER DIAGRAM



ON/OFF CONTROLLER DIAGRAM

XBL7912-13326A

FIGURES 2 & 3

Where: $\dot{m}_c$ = maximum flow rate

K = proportional flow constant equal to ratio of maximum flow rate to temperature difference required for maximum flow: $K = \dot{m}_c / \Delta T_{max}$

ΔT_{max} = temperature rise across collector at which flow rate saturates to its maximum

ΔT_{off} = temperature rise across the collector sufficient to turn off the pump and can be also interpreted as as minimum temperature rise across the collector for which it is possible and/or profitable to turn on the pump

5) DETERMINATION OF CONTROLLER SET POINTS

In determining proper controller set points there are two major considerations: set points must be chosen to maximize energy collection and minimize pumping power(or cost); and set points must be within the capability of the sensors used. The importance of sensor sensitivity and location cannot be overemphasized since these two concerns have caused numerous problems in solar installations[5,8,25,36].

Off Set Point. The minimum temperature rise across the collector, ΔT_{off}, for which it is useful to turn on the collector loop pump is determined by 1) limitations of a given sensor to differentiate small temperature differences and 2) parasitic power (pumping costs). It has been shown[21,39] that if the collection system does not require parasitic power the ideal set points are: ΔT_{off} equal to zero and ΔT_{on} equal to some small value above zero. However since pumps do require power it is practical to circulate fluid only when the dollar value of the energy collected is greater than that required to run the pump. The following equalities can therefore be written:

value of collected power $\geq$ cost of required pumping power

$$\frac{(\text{heating power cost})(\dot{m}c_p)(\Delta T_{off})}{(\text{heating system efficiency})} \geq \frac{(\text{pumping power})(\text{pumping power cost})}{(\text{pump efficiency})}$$

$$\rightarrow \Delta T_{off} \geq \frac{(\text{pumping power})(\text{cost ratio})}{(\text{efficiency ratio})(\dot{m}c_p)}$$

This equation can be used for both on/off and proportional flow controllers. If a larger value of ΔT_{off} is used, say to meet the sensitivity requirements of an uncalibrated sensor, the pump will cycle more often and less energy will be collected since the pump will shut off sooner than necessary.

For a typical water flow rate of 15 gallons per minute, a one-half horsepower pump motor, an electricity to gas cost ratio of three, and an efficiency ratio of one, ΔT_{off} is only .51^{o}F (.28^{o}C). This value is much smaller than those typically used and therefore energy collection can be improved using more accurate and sensative temperature sensors.

<u>On Set Point</u>. Unlike ΔT_{off}, only a range of values can be determined for ΔT_{on} without knowledge of specific weather conditions. To determine an optimum range for ΔT_{on} the steady-state H.W.B. model is used to analyse the operation of a solar collector. Steady-state collector temperature for no flow conditions is:

$T_c = S/U_L + T_a$, and for flow conditions is given by;

$T_{out} = [A_c F_R/\dot{m}c_p][\,S - U_L(T_{in} - T_a)] + T_{in}$.

Where F_R is the collector efficiency factor.

The maximum practical value for ΔT_{on} would be one that insures that the pump never cycles. ΔT_{on} is set so that after the pump turns on at some level of absorbed insolation, S_{on}, and ambient temperature, $T_{a(on)}$, the temperature rise across the collector does not fall below ΔT_{off}. Applying this criterion the maximum ΔT_{on} can be shown to equal:

$$\Delta T_{on_{max}} = \frac{\Delta T_{off}}{F_R(U_L A_c/\dot{m}c_p)}$$

For stable control operation ΔT_{on} should be greater than ΔT_{off}. If parasitic power requirements are ignored, ΔT_{off} is zero and therefore the minimum value for ΔT_{on} is also zero. Thus the ratio of ΔT_{on} to ΔT_{off} should be greater than unity while less than or equal to the ratio of the capacitance flow rate to the approximate collector heat loss*.

$$1 \leq \frac{\Delta T_{on}}{\Delta T_{off}} \leq \frac{\dot{m}c_p}{A_c F_R U_L}$$

When the following typical values are inserted it is clear that the range of $\Delta T_{on}/\Delta T_{off}$ defined is too conservative.

$$\dot{m}c_p/A_c = 20 \text{ lbm/hr-ft}^2$$

$$U_L = 0.7 \text{ BTU/ft}^2\text{-}^\circ\text{F}$$

$$F_R = 0.95$$

$$1 \leq \frac{\Delta T_{on}}{\Delta T_{off}} \leq 30$$

[*] Analysis done by Davis[11] provides a similar result.

These limits for ΔT_{on} are not very useful since typical ratios used in the solar industry[5,41] are from 2-7 and they provide satisfactory results while allowing some cycling at low insolation levels.

Proportional Control Set Points. The constants K, ΔT_{max} and ΔT_{off} are used to determine the fluid flow rate in a proportionally controlled system. ΔT_{off} is the minimum temperature rise across the collector required for stable operation at the minimum flow rate and can be calculated using the method previously outlined.

The constant K is the slope of the control curve and is equal to the ratio of the maximum flow rate to the temperature required for maximum flow, ΔT_{max}. The maximum flow rate for a collection system is usually determined by the pump and the pumping resistance.

Herczfeld, et. al.[13] determine ΔT_{max} and ΔT_{off} by maximizing collection efficiency through minimizing collector temperature. This criterion leads to set points which are too small to be measured and a large slope, K, which produces, in effect, bang-bang control. In practice[33] these set points are determined by motor controllability, temperature sensor sensitivity, and operating experience. In general K is made small enough so that the controller does not lose its sensitivity and act as a bang-bang controller and large enough so that the flow rate reaches its maximum at modest levels of insolation.

6) RESULTS OF CONTROLLER AND SET POINT COMPARISONS

The controllers are compared on the basis of their performance with respect to: collection efficiency, pump running time and pump cycling. These comparisons are the results of digital computer simulations of the four-node version of the model previously described with a time step of 0.001 hours for high flow rates and 0.002 hours for low flow rates. The model is implemented on a PDP 11/60 computer.

A total of six controllers were compared under 12 different sets of conditions. The four on/off controllers have the following characteristics:

A) $\Delta T_{on} = 9^{o}F(5^{o}C)$, $\Delta T_{off} = 3^{o}F(1.7^{o}C)$

B) $\Delta T_{on} = 21^{o}F(11.7^{o}C)$, $\Delta T_{off} = 3^{o}F$

C) $\Delta T_{on} = 9^{o}F$ with a `perfect` timer

D) $\Delta T_{on} = 21^{o}F$ with a `perfect` timer

The proportional controllers have the following characteristics:

E) full flow at $\Delta T_c = 9^{o}F = \Delta T_{max}$, $\Delta T_{off} = 3^{o}F$

F) full flow at $\Delta T_c = 21^{o}F = \Delta T_{max}$, $\Delta T_{off} = 3^{o}F$

The set points, ΔT_{on}, ΔT_{off} and ΔT_{max}, were picked to represent upper and lower limits of values used in industry and research [5,10,13,15,23,28,33,39,41].

Timers are used to limit the cycling of a circulating pump; therefore, the `perfect` timer will allow the pump to come on when the ΔT_{on} criterion is met and stay on until it is no longer possible to collect energy. This type of controller was modeled for clear day cases only, since its operation is highly dependent on insolation pattern and timer delay. Thus any results from a particular cloudy day could not be generalized.

Collection efficiency (η) is used as a non- dimensional indicator of solar energy collection. It is defined as:

$$\eta = \frac{\text{energy collected per unit collector area}}{\text{energy incident per unit collector area}} \times 100$$

Efficiencies attained with the control strategies are compared against each other and a theoretical maximum efficiency. The theoretical maximum efficiency is achieved with a controller which circulates fluid, at a high rate that causes the collector temperature to equal the inlet temperature, whenever absorbed solar energy is greater than ambient losses. Using the H.W.B. steady-state model the maximum steady-state daily efficiency possible is:

$$\sum_{\Delta\tau=0}^{\infty} \int_{\Delta\tau} \left[\frac{\tau\alpha I - U_L(T_{in} - T_a)}{I}\right] dt$$

$$\Delta\tau = \text{time segment where } \tau\alpha I > U_L(T_{in} - T_a)$$

One day simulations of different control strategies indicate how their operation varies with set points, timers, meteorological conditions, and flow rates. Table II presents collection efficiencies, pump running times and amount of cycling for different control strategies under assigned conditions. Table III demonstrates the effect of pumping power on collection efficiency and Table IV compares the dynamic and steady-state model evaluations.

<u>Collection Efficiency</u>. For clear day cases collection efficiency

TABLE II: CONTROLLER STRATEGY COMPARISONS 12 Hour Totals

CONTROL STRATEGY		HIGH GAIN[a] HIGH FLOW[b] CLEAR DAY	HIGH GAIN LOW FLOW[c] CLEAR DAY	LOW GAIN[d] HIGH FLOW CLEAR DAY	LOW GAIN LOW FLOW CLEAR DAY	HIGH GAIN HIGH FLOW CLOUDY DAY[e]	HIGH GAIN LOW FLOW CLOUDY DAY	LOW GAIN HIGH FLOW CLOUDY DAY	LOW GAIN LOW FLOW CLOUDY DAY
Maximum Steady-State Efficiency(%)		65.7	65.7	39.5	39.5	56.1	56.1	26.5	26.5
ON/OFF On=9°F (5°C) Off=3°F(1.7°C)	efficiency(%)	60.3	59.6	35.0	34.9	45.2	45.2	8.6	8.5
	pumping time(hours)	8.72	9.27	2.76	5.98	3.34	3.83	.311	.496
	times cycled	10	2	61	10	14	12	4	10
ON/OFF On=21°F(11.7°C) Off=3°F(1.7°C)	efficiency(%)	59.7	59.1	31.9	33.9	44.1	44.2	5.2	5.4
	pumping time(hours)	8.39	8.98	1.39	5.44	2.47	2.92	0.095	0.16
	times cycled	6	2	22	6	12	18	2	2
ON/OFF With perfect timer On=9°F 5°C	efficiency(%)	60.5	59.9	35.7	35.3	--	--	--	--
	pumping time (hours)	9.87	9.88	7.68	7.69	--	--	--	--
	times cycled	0	0	0	0	--	--	--	--
ON/OFF With perfect timer On=21°F 11.7°C	efficiency(%)	60.4	59.8	35.5	35.1	--	--	--	--
	pumping time(hours)	9.71	9.72	7.38	7.39	--	--	--	--
	times cycled	0	0	0	0	--	--	--	--
PROPORTIONAL Full On=9°F 5°C Off = 3°F 1.7°C	efficiency(%)	60.2	59.7	35.0	34.7	45.4	45.0	9.6	9.5
	pumping time (equiv. hours)	7.54	8.85	3.58	4.63	3.20	4.03	0.52	0.72
	times cycled	0	0	0	0	0	0	0	0
PROPORTIONAL Full On=21°F 11.7°C Off = 3°F 1.7°C	efficiency(%)	59.6	59.0	34.4	33.9	44.8	44.3	9.4	9.1
	pumping time (equiv. hours)	4.92	6.33	2.34	3.01	2.16	2.84	0.38	0.51
	times cycled	0	0	0	0	0	0	0	0

a) high gain: insolation = 2292 BTU/ft^2-day
7224 watt-hrs/m^2-day
ambient temp. = 44.4° - 70°F
6.89° - 21.1°C

b) high flow = 25 lbm/hr-ft^2
122 kg/hr-m^2

c) low flow = 15 lbm/hr-ft^2
73.2 kg/hr-m^2

d) low gain: insolation=1146 BTU/ft^2-day
3612 watt-hrs/m^2-day
ambient temp.= 32.9° - 50°F
.5° - 10°C

inlet temperature = 115°F
46.1°C

collector capacitance = .7 BTU/ft^2-°F
14.3 kJ/m^2-°C

collector loss coefficient = .7 BTU/ft^2-hr-°F
3.97 watts/m^2-°C

e) for cloudy day cases, the total insolation is half of the clear day values given in (a) and (d)

TABLE III: CONTROLLER STRATEGY COMPARISONS

INCLUDING PUMPING POWER[a]

12 HOUR TOTALS

CONTROL STRATEGY	PUMP SIZE	HIGH GAIN[b] HIGH FLOW[c] CLEAR DAY	HIGH GAIN LOW FLOW[d] CLEAR DAY	LOW GAIN[e] HIGH FLOW CLEAR DAY	LOW GAIN LOW FLOW CLEAR DAY	HIGH GAIN HIGH FLOW CLOUDY DAY[f]	HIGH GAIN LOW FLOW CLOUDY DAY	LOW GAIN HIGH FLOW CLOUDY DAY	LOW GAIN LOW FLOW CLOUDY DAY
		COLLECTION EFFICIENCIES IN PERCENT							
ON/OFF On=9°F (5°C)	0.1 hp (7.46 watts)	60.1	59.4	34.9	34.6	45.0	45.0	8.6	8.5
Off=3°F (1.7°C)	0.5 hp (373 watts)	59.3	58.6	34.4	33.6	44.5	44.3	8.5	8.3
ON/OFF On=21°F (11.7°C)	0.1 hp (7.46 watts)	59.5	58.9	31.8	33.6	44.0	44.1	5.2	5.4
Off=3°F (1.7°C)	0.5 hp (373 watts)	58.8	58.1	31.6	32.7	43.6	43.6	5.2	5.3
ON/OFF With Perfect Timer	0.1 hp	60.3	59.6	35.4	35.0	-	-	-	-
On= 9°F 5°C	0.5 hp	59.4	58.8	34.0	33.6	-	-	-	-
ON/OFF With Perfect Timer	0.1 hp	60.2	59.6	35.2	34.8	-	-	-	-
On=21°F 11.7°C	0.5 hp	59.3	58.7	33.9	33.5	-	-	-	-
PROPORTIONAL Full On=9°F 5°C	0.1 hp	60.0	59.5	34.9	34.5	45.3	44.9	9.5	9.4
Off=3°F 1.7°C	0.5 hp	59.4	58.7	34.2	33.7	44.7	44.1	9.4	9.2
PROPORTIONAL Full On=21°F 11.7°C	0.1 hp	59.4	58.9	34.3	33.8	44.7	44.1	9.4	9.0
Off=3°F 1.7 C	0.5 hp	59.1	58.3	33.9	33.2	44.3	43.7	9.2	8.9

a) collector efficiency is equal to: (energy collected - pumping power)/total insolation

b) high gain: insolation = 2292 BTU/ft^2-day
7224 watt-hrs/m^2-day
ambient temp.= 44.4° - 70°F
6.89° - 21.1° C

c) high flow = 25 lbm/ft^2-hr
122 kg/m^2-hr

d) low flow = 15 lbm/ft^2-hr
73.2 kg/m^2-hr

e) low gain: insolation = 1146 BTU/ft^2-day
watt-hrs/m^2-day
ambient temp.= 32.9° - 50°F
.5° - 10°C

f) for cloudy day cases, the total insolation is half of the clear day values given in (b) and (e)

the collector area is assumed to be 500 ft^2 (46.45m^2)
the pump is assumed to require: 0.1 horsepower (74.6 watts)
or
0.5 horsepower (373 watts)

inlet temperature = 115°F (46.1°C)
collector capacitance = .7 BTU/ft^2-°F (14.3 kJ/m^2-°C)
collector loss coefficient = .7 BTU/ft^2-hr-°F
(3.97 watts/m^2-°C)

TABLE IV: COMPARISON BETWEEN STEADY-STATE AND DYNAMIC MODEL PREDICTIONS 12 Hour Totals

CONTROL STRATEGY		HIGH GAIN[a] HIGH FLOW[b] CLEAR DAY	HIGH GAIN LOW FLOW[c] CLEAR DAY	LOW GAIN[d] HIGH FLOW CLEAR DAY	LOW GAIN LOW FLOW CLEAR DAY	HIGH GAIN HIGH FLOW CLOUDY DAY[e]	HIGH GAIN LOW FLOW CLOUDY DAY	LOW GAIN HIGH FLOW CLOUDY DAY	LOW GAIN LOW FLOW CLOUDY DAY
		COLLECTION EFFICIENCY IN PERCENT							
	maximum possible	65.7	65.7	39.5	39.5	56.1	56.1	26.5	26.5
ON/OFF On=9^oF (5^oC)	dynamic model	60.3	59.6	35.0	34.9	45.2	45.2	8.6	8.5
Off=3^oF (1.7^oC)	steady-state model[f]	60.8	62.6	10.7	31.7	45.8	48.7	4.0	13.6
ON/OFF On=21^oF (11.7^oC)	dynamic model	59.7	59.1	31.9	33.9	44.1	44.2	5.2	5.4
Off=3^oF (1.7^oC)	steady-state model	60.8	62.6	10.7	31.7	45.8	48.7	4.0	13.6
ON/OFF With Perfect Timer	dynamic model	60.5	59.9	35.7	35.3	-	-	-	-
On=9^oF 5^oC	steady-state model	64.7	64.1	38.9	38.6	-	-	-	-
ON/OFF With Perfect Timer	dynamic model	60.4	59.8	35.5	35.1	-	-	-	-
On=21^oF 11.7^oC	steady-state model	64.7	64.1	38.9	38.6	-	-	-	-
PROPORTIONAL Full On=9^oF 5^oC	dynamic model	60.2	59.7	35.0	34.7	45.4	45.0	9.6	9.5
Off=3^oF 1.7^oC	steady-state model	64.0	63.9	36.5	37.4	52.2	53.5	23.7	25.1
PROPORTIONAL Full On=21^oF 11.7^oC	dyanmic model	59.6	59.0	34.4	33.9	44.8	44.3	9.4	9.1
Off=3^oF 1.7^oC	steady-state model	63.9	63.4	37.3	36.9	53.7	53.3	25.0	24.7

a) high gain: insolation = 2292 BTU/ft^2-day
7224 watt-hrs/m^2-day
ambient temp. = 44.4^o - 70^oF
6.89^o - 21.1^oC

b) high flow = 25 lbm/hr-ft^2
122 kg/hr-m

c) low flow = 15 lbm/hr-ft^2
73.2 kg/hr-m^2

d) low gain: insolation = 1146 BTU/ft^2-day
3612 watt-hrs/m^2-day
ambient temp. = 32.9^o- 50^oF
.5^o- 10^oC

inlet temperature = 115^oF
46.1^oC
collector capacitance = .7 BTU/ft^2-^oF
14.3 kJ/m^2-^oC
collector loss coefficient = .7 BTU/ft^2-hr-^oF
3.97 watts/m$^2C^o$

e) for cloudy day cases, the total insolation is half of the clear day values given in (a) and (d)

f) Steady-state model is: $T_{out} = [A_c F_r/\dot{m}c_p]\,[S-U_L(T_{in}-T_a)] + T_{in}$
(from reference 12)

for all but one of the controllers is approximately equal and not more than 6.7%* below the maximum steady-state efficiency. On/Off controllers, in general, do slightly better, with on/off controllers with timers achieving the best efficiency since they run the pumps for the longest amount of time. For low gain, clear day cases, excessive cycling of on/off controlled pumps can cause collection efficiency to be less with a high flow rate than with a low flow rate. Normally a higher flow rate leads to higher collection efficiencies; however, when a high flow rate causes excessive cycling the benefits can be outweighed by decreased circulation time.

The off set point, ΔT_{off}, has a direct effect on energy collection, the higher it is, the less time the pump will run and the lower the amount of energy collected. Therefore, the off set point should be as low as possible while staying within limits of sensor sensitivity and pumping power restrictions discussed previously.

Table II shows that a high on set point, for an on/off controller, can have an adverse effect on energy collection. During days of interrupted insolation or of very low insolation it can take hours longer for the pump to turn on if it does at all. This problem has been evidenced by collector installations that have very low efficiencies and which do not turn on until late in the day[25].

However, for high gain cases and clear days in general, raising or lowering the on/off controller's ΔT_{on} does not greatly affect collection efficiency. For example, it only takes 9.6 minutes longer for the

** When collection efficiencies are compared the criterion is difference between efficiency one and efficiency two ($\%_1 - \%_2$).

higher on set point to be reached in the high gain, clear day cases. For high gain, clear day cases the difference in collection efficiencies for a ΔT_{on} of 21°F and a ΔT_{on} of 9°F was an average of only 0.5%. For low gain, clear day and high gain, cloudy day cases they differ by an average of about 1.6%.

Relatively small differences in efficiencies between different set points can be explained by the fact that solar collectors act as storage devices. When fluid is not circulating, collectors heat up towards their stagnation temperature and store energy. This energy, equal to the product of the collector's "effective" capacitance and the difference between stagnation and operating temperatures, is released into the fluid once it begins to circulate through the collector. This result has been suggested by Herczfeld, et.al.[14], Pejsa[31] and, Orbach, et. al.[29].

Effects of collector capacitance are important and cannot be considered in steady-state analysis. Steady-state analyses tend to exaggerate the importance of cycling, ignore the effects of the turn on set point and cannot consider cumulative solar input. Thus the predicted amount of heat transferred to the fluid during initial circulation will be less than the dynamic model's prediction. These problems are demonstrated in Table IV where the H.W.B. steady-state model and the dynamic model often give very different predictions for collection efficiencies.

While proportional controllers have the advantage of circulating fluid when only a small temperature rise across the collector is experienced, proportional control will maintain lower average flow rates than on/off control; allowing higher collector temperatures and increased heat losses to the environment. While decreasing collection efficiency this may improve storage stratification and overall system efficiency.

Proportional controllers always perform better with a higher maximum flow rate. Generally, the larger the proportionality constant, K, or the lower ΔT_{max}, the better the collection efficiency. This is because the maximum flow rate becomes easier to obtain and collector operating temperatures are lower.

In all high gain cases, clear and cloudy days, along with low gain, clear day cases the advantage the proportional controller has by turning on early is eliminated by lower average flow rates. For these cases collection efficiencies are within the range for on/off controllers with the same set points. Only for low gain, interrupted insolation cases do proportional controllers show a clear advantage over on/off controllers. Under these conditions, proportionally controlled systems were able to collect a higher percentage of the maximum steady-state efficiency of 26.5%. Neither type of controller though, is able to achieve efficiencies close to maximum steady-state efficiency; thus, improved controller design may be appropriate for climates where this type of weather pattern is predominant.

<u>Pumping Time</u>. In table II the amount of time a pump is on, pumping time, is shown. Parasitic energy usage is equal to the product of average pump power required and pumping time. Pumping time for an on/off controller is simply the amount of time that fluid is circulating. For proportional controllers an equivalent pumping time is calculated, since the pump is not always producing full flow. For this study equivalent

pumping time is defined as:

$$\sum_{\Delta\tau=0}^{\infty} \int_{\Delta\tau} \left[\frac{\text{Flow Rate}(t)}{\text{Maximum Flow Rate}} \right] dt$$

Where $\Delta\tau$ = time segment where pump is on

Net efficiency which includes parasitic or pumping power is defined as:

$$\eta_p = \frac{\text{total energy collected less pumping energy required}}{\text{total energy incident on the collector(s)}} \times 100$$

In Table III, the effects of pumping time on collection efficiency are shown to be negligible for a typical collector array of 500 ft^2 ($46.5 m^2$) with 0.1 horsepower(74.6 watt) pump. In all cases, inclusion of pumping power does not change the ranking of any controller with respect to another; however, if a 0.5 horsepower(373 watt) pump is considered the effect of parasitic power makes a very slight change in rankings. For example, on/off controllers with 'perfect' timers are no longer always the most efficient, since they run the pumps for an extended period of time.

Pump Cycling. Since pump cycling is considered a problem with on/off controllers[5,14,23,25,35,41] the number of times a collector pump cycles during one day has been indicated in Table II. Figure 4 shows a typical cycling sequence as predicted by the computer model. As expected pump cycling decreases with the use of higher on set points, lower off set points or proportional controllers. If cycling is minimal, collection efficiency will not be affected significantly since

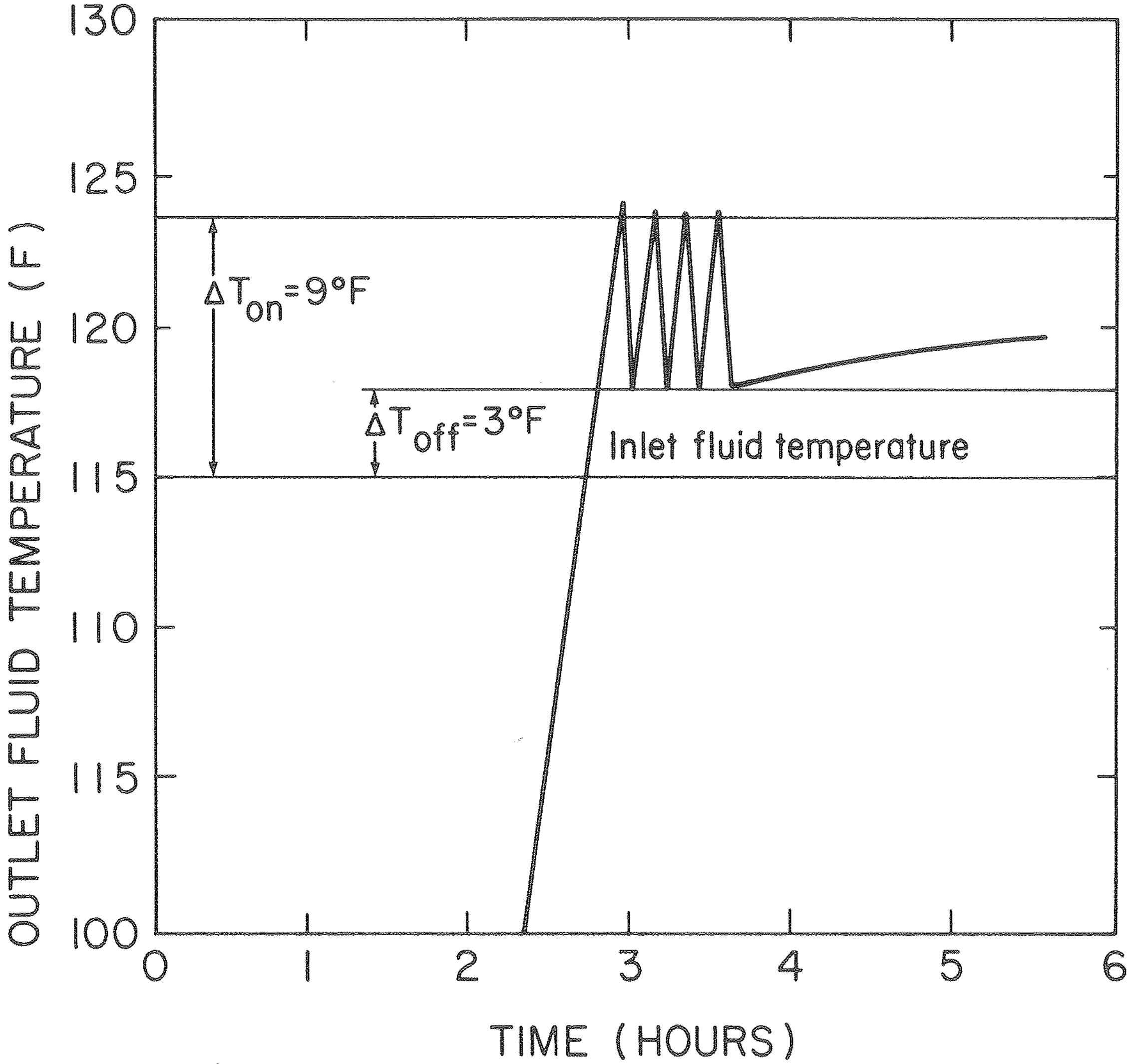


FIGURE 4:

OUTLET FLUID TEMPERATURE
LOW GAIN, LOW FLOW, CLEAR DAY

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1) cycling will occur over a short increment of the total collection time and,
2) the collector will store energy when fluid is not circulating.

7) CONCLUSIONS

In this study, a dynamic solar collector model is used to determine the characteristics and relative merits of proportional and on/off collector loop flow rate controllers. The importance and determination of controller set points are also discussed.

On/off and proportional controllers both have collection efficiencies which are close to the maximum possible during days of clear skies or very high insolation levels. It is doubtful that any other type of controller could do better under similar conditions. During periods of interrupted insolation neither proportional nor on/off controllers respond well to rapid changes in insolation rate and collection efficiency falls well below the maximum possible. Often this is because a significant portion of the energy incident on the collector can be collected only at collector temperatures less than those required for flow by the controllers. This indicates that improved temperature sensors, which allow smaller values of ΔT_{off} to be implemented, can improve collection efficiency.

However, proportionally-controlled collectors can collect more energy during periods of interrupted and very low insolation levels than on/off controlled systems. This is because proportional controllers are more sensative to changes in insolation and ambient temperatue than on/off controllers. This advantage of proportional controllers is minimized by the use of a relatively low ΔT_{on} valve ($9^{o}F$).

The on/off controller's on set point can have a minimal effect on energy collection as long as it is not so high that the circulator pump does not come on until late in the morning. This is because the collector's capacitance stores energy when the fluid is not circulating.

Because the collector acts as a storage device low to moderate cycling of the pump motor also has a minimal effect on energy collection.

If the proportional controller's set point for maximum flow is too high, the flow rate will never reach maximum and ambient losses are increased. However, if it is too low, the proportional controller's sensitivity will be lost and the controller will act as a bang-bang controller.

The off set point for on/off and proportional control has simple criteria: energy collection rate exceed parasitic pumping power and the point selected meet sensor error requirements. On set points, however, do not have simple criteria and can be defined only within a broad range.

Implications for the design and evaluation of proportional and on/off control are twofold. First, the difference between a steady-state and a dynamic analysis of control strategies is significant. Future work in modeling control systems must consider collector capacitance in order to describe accurately the transient response of fluid temperature. Second, neither on/off nor proportional control performs best for all conditions. Whether on/off or proportional control should be implemented is dependent on the weather conditions in the location being considered. It is hoped that the results of this analysis will be useful as a guideline to indicate meteorological and flow rate conditions for which on/off or proportional control are more advantageous.

Further work in comparing control strategies and controllers should include: 1) additional simulation studies using this or an improved dynamic solar system model which includes load loop dynamics, 2) experimental testing of control strategies on facilities which can duplicate meteorological and load conditions for comparisons and 3) field tests. Experimental testing is now under way at Lawrence Berkeley Laboratory by the authors.

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Andover Controls. P.O. Box 34 SUS, Andover, MA

Grundfos Pumps Corp. 2555 Clovis Ave., Clovis, CA

Helitrope General. 3733 Kenora Dr., Spring Valley, CA

Honeywell Energy Center. 2700 Ridgeway, Minneapolis, MN

Independent Energy. P.O. Box 732, E. Greenwich, RI

Johnson Controls Inc. Penn Division, 2221 Camden, Oakbrook, IL

March Manufacturing Inc. P.O. Box 87, 1819 Pickwick, Glenview, IL

Natural Power, Inc. New Boston, NH

Piper Hydro Inc. 3031 E. Coronado, Anaheim, CA

PPG Industries Glass Division. One Gateway Center, Pittsburg, PA

Rho Sigma Inc. 15150 Raymer St., Van Nuys, CA

Solar Control Corp. 5595 Arapahoe Rd., Boulder, CO

NOMENCLATURE

A_c Collector plate surface area

C_A Effective value of collector capacitance, per unit collector area

c_p Thermal capacitance of circulating fluid

F' Plate fin efficiency factor

F_R Collector efficiency factor

K Proportionality constant for proportional controllers

K_{flow} Represents the fluid flow rate, per unit area

K_{gain} Represents the collector's gain from insolation and losses to the environment, per unit area

I Solar insolation rate, per unit area

$\dot{m}$ Fluid mass flow rate

N Number of segments (or stirred tanks) that collector is divided up into

S Rate of absorption of solar insolation by collector plate, per unit area

t Time

T_a Ambient temperature

TM Ambient temperature calculation constant

TO Ambient temperature calculation constant

$T_{f,x}$ Fluid temperature at position x

T_{in} Inlet fluid temperature

T_{out} Outlet fluid temperature

U_L Collector loss coefficient, per unit area

W_c Width of collector in the direction to flow

x Displacement in flow direction

γ Pump control indicator

ΔT_c Temperature rise across collector, $T_{out} - T_{in}$

ΔT_{max} Temperature across collector at which flow rate is a maximum for proportional control

ΔT_{off} The temperature rise across the collector sufficient to turn off the pump

ΔT_{on} The temperature rise across the collector sufficient to turn on the pump

η Collector efficiency

η_p Collector efficiency including pumping power

$\tau\alpha$ Transmittance/Absorptance coefficient

APPENDIX I Additional Figures

Figure 5 shows the tube and fluid element on which the collector model's heat balance is performed. Figures 6, 7 and 8 indicate the insolation patterns for a clear day and a cloudy day, and the outdoor temperature profiles used, respectively.

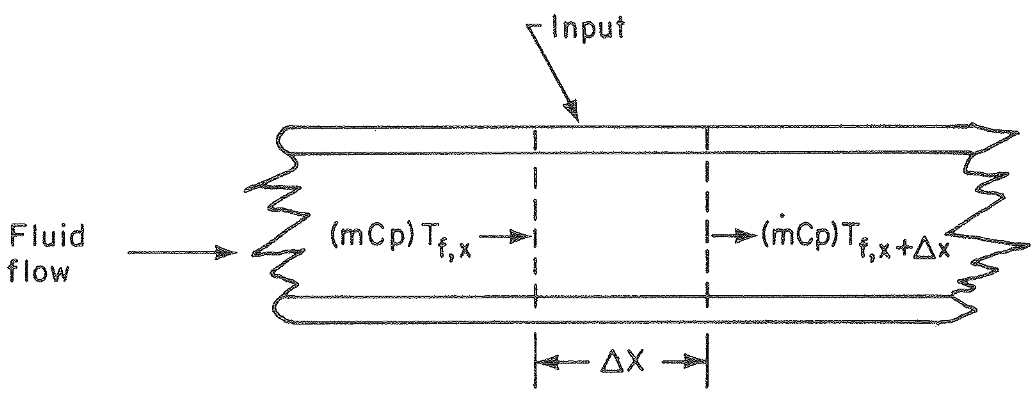

FIG. 5: COLLECTOR TUBE/FLUID ELEMENT

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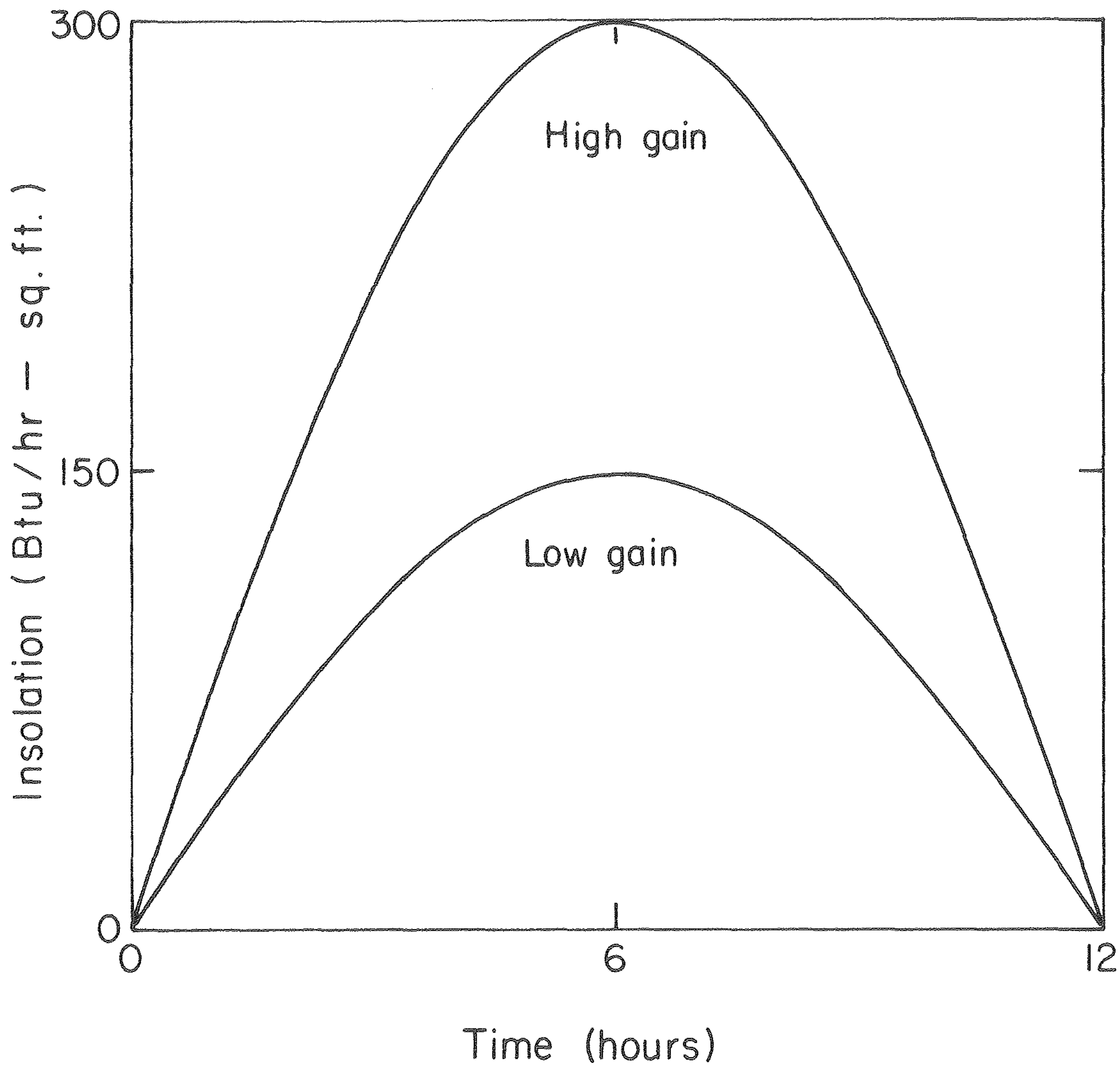

FIG. 6: INSOLATION ON A CLEAR DAY
HIGH AND LOW GAIN

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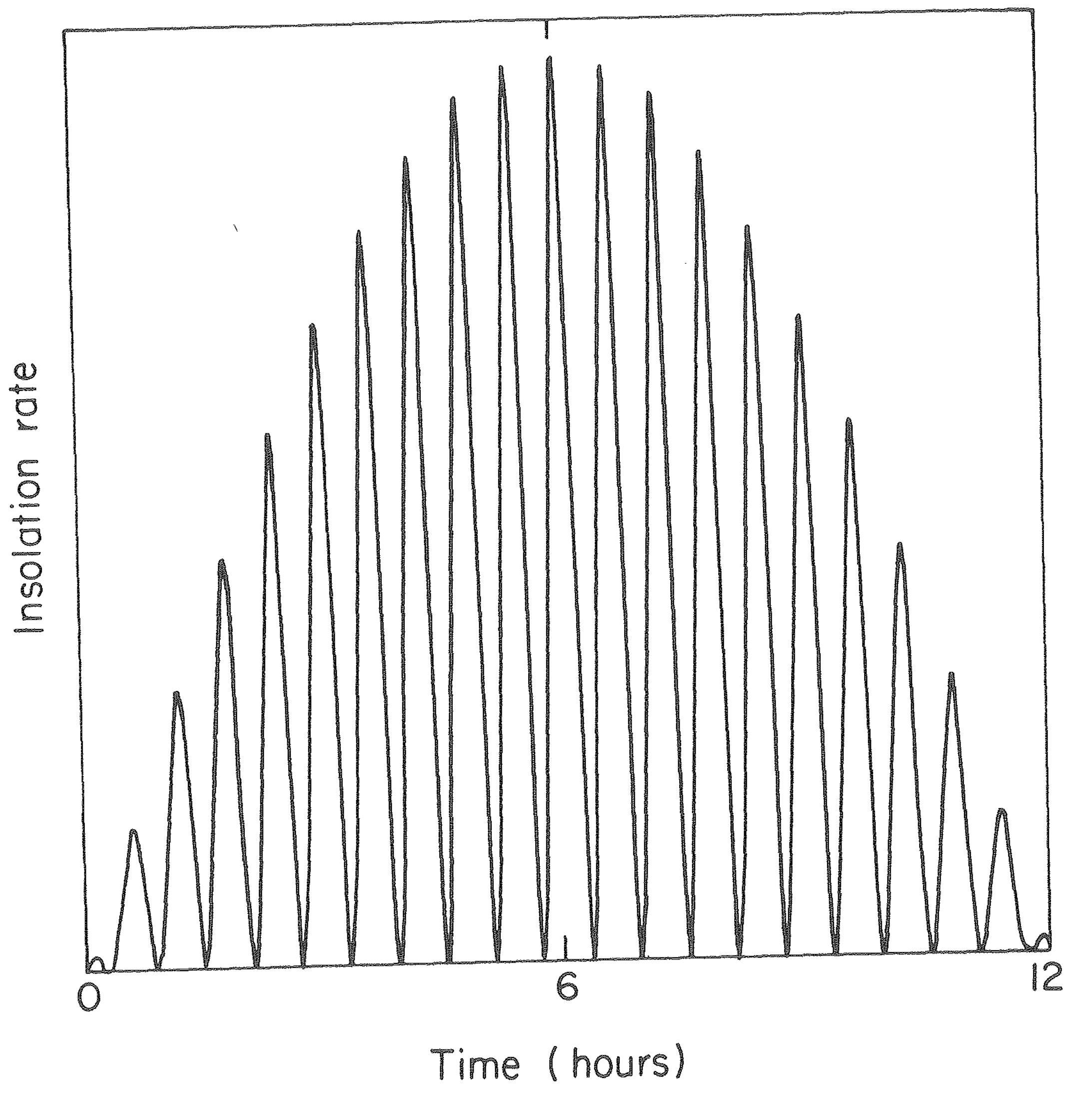

FIG. 7: SOLAR INSOLATION ON A CLOUDY DAY

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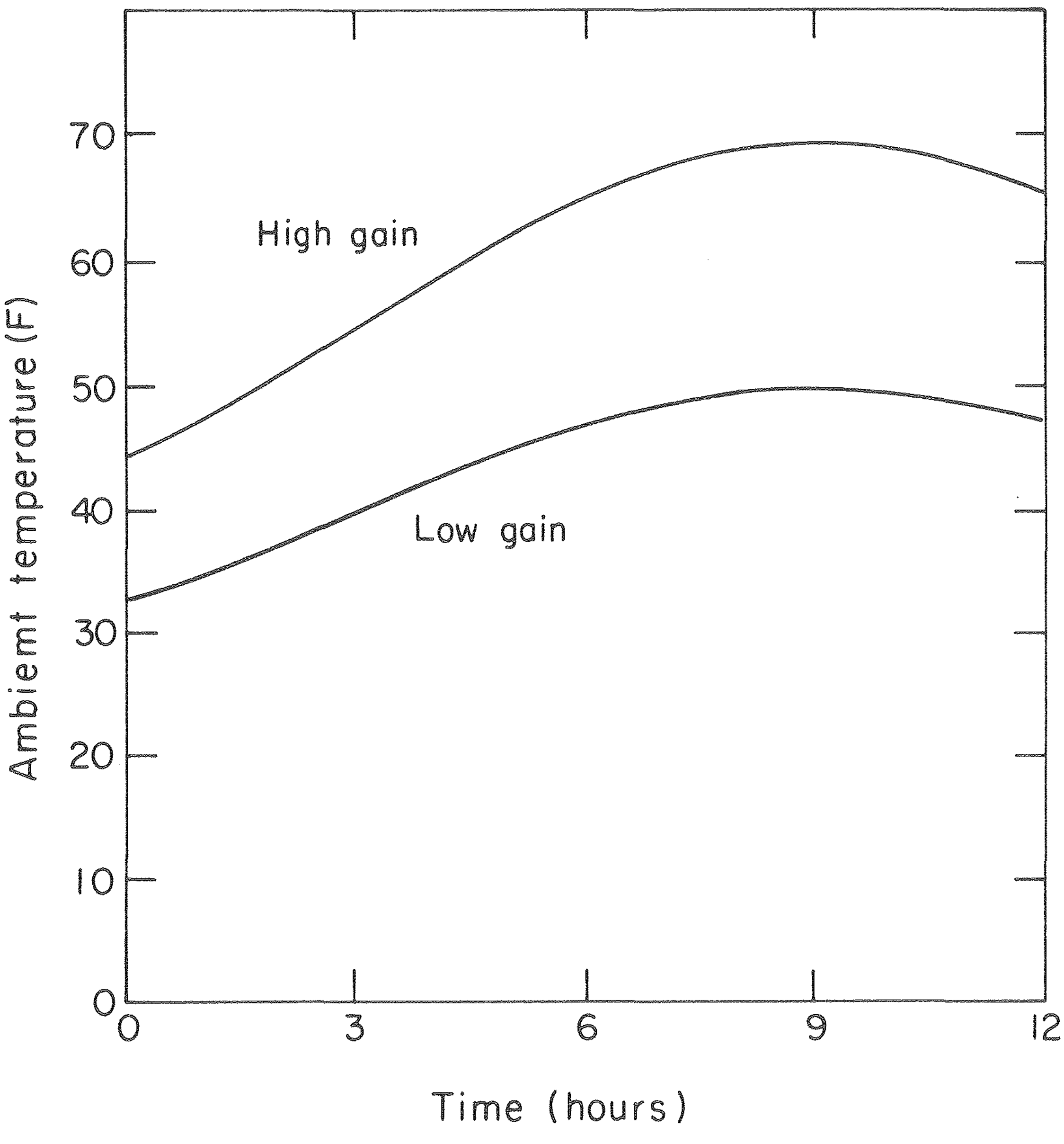

FIG. 8: AMBIENT TEMPERATURE
HIGH AND LOW GAIN

XBL7912-13323

APPENDIX II Simulation Runs With A Cold Slug Input

Table V shows collector efficiencies for different strategies with the additional condition that a cold slug of fluid enters the collector for a set period of time. The cold slug of fluid is a phenomenon experienced by many collectors when the fluid is first circulated. In a non-drain down collector system fluid is left in the collector inlet pipes, which lead from the storage tank to the collector, at the end of each solar day. Fluid in these pipes can reach ambient temperature by the start of the next day. However, the inlet sensor, which is located in the storage tank, does not indicate the inlet pipe fluid temperature.

Therefore, at the beginning of a new solar day, the controller will send fluid into the collector which it believes is at the storage temperature but is actually at or close to ambient. This will continue until the 'cold slug' has gone through the entire length of exposed inlet piping. This condition can obviously confuse a controller, which is the main reason for considering it in the comparisons.

For the cold slug cases, the inlet fluid is at the ambient temperature, and not the storage tank temperature, for the length of time required for a slug of fluid to transverse a 100 foot long, 1/2 inch diameter pipe. For the on/off controllers, which maintain a constant flow rate, it would take 72 seconds with the high flow rate and 119 seconds for the low flow rate. These times are appropriately adjusted for the proportional flow controllers. The cold slug is only modeled during clear days because its effect, like that of the timer, is dependent on insolation patterns; therefore, results can not be generalized.

With the input of a cold slug during the early morning the relative advantages of on/off and proportional controllers are unchanged from the cases without the cold slug (see Table II).

TABLE V: CONTROLLER STRATEGY COMPARISONS FOR COLD SLUG AT INLET

6 HOUR TOTALS

CONTROL STRATEGY		HIGH GAIN[a] HIGH FLOW[b] CLEAR DAY	HIGH GAIN LOW FLOW[c] CLEAR DAY	LOW GAIN[d] HIGH FLOW CLEAR DAY	LOW GAIN LOW FLOW CLEAR DAY
ON/OFF					
On = 9°F (5°C)	efficiency(%)	55.1	54.3	27.1	27.2
Off = 3°F (1.7°C)	pumping time (hours)	3.96	3.97	1.08	2.40
ON/OFF					
On = 21°F (11.7°C)	efficiency(%)	54.9	54.1	23.8	26.3
Off = 3°F (1.7°C)	pumping time (hours)	3.85	3.85	0.52	2.16
PROPORTIONAL					
Full On = 9°F (5°C)	efficiency(%)	54.9	54.3	27.2	26.8
Off = 3°F (1.7°C)	pumping time (equiv. hours)	3.34	3.9	1.32	1.71
PROPORTIONAL					
Full On = 21°F (11.7°C)	efficiency(%)	54.2	53.5	26.5	26.0
Off = 3°F (1.7°C)	pumping time (equiv. hours)	2.18	2.8	0.87	1.12

a) high gain: insolation = 2292 BTU/ft²-day, 7224 watt-hrs/m²-day; ambient temp. = 44.4° - 70°F, 6.9° - 21.1°C

d) low gain: insolation = 1146 BTU/ft²-day, 3612 watt-hrs/m²-day; ambient temp. = 32.9° - 50°F, .5° - 10°C

b) high flow = 25 lbm/ft²-hr, 122 kg/m²-hr; cold slug duration: 72 seconds

c) low flow = 15 lbm/ft²-hr, 73.2 kg/m²-hr; cold slug duration: 119 seconds

cold slug temperature = ambient temperature
collector inlet temperature = 115°F (46.1°C)
collector capacitance = 0.7 BTU/ft²-°F (14.3 kJ/m²-°C)
collector loss coefficient = 0.7 BTU/ft²-hr-°F (3.97 watts/m²-°C)

FIGURES

TABLES