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STATE-OF-THE-ART OF SOLAR CONTROL SYSTEMS IN INDUSTRIAL PROCESS HEAT APPLICATIONS

WEN S. SU
JAMES N. CASTLE

JULY 1979

TO BE PRESENTED AT
ISA 1979 ANNUAL CONFERENCE
OCTOBER 22-25, 1979
CHICAGO, ILLINOIS

Solar Energy Research Institute

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ABSTRACT

This paper addresses the state-of-the-art of solar control systems pertinent to industrial process heat applications. It presents solar system configurations currently being used or proposed, identifies parameters and functions deemed essential in solar system controls, describes operating deficiencies, and discusses possible future improvements.

INTRODUCTION

The United States energy consumption during 1978 amounted to 77.7 quads (1 quad = 10^{15} Btu), the equivalent of 36.7 million barrels of crude oil a day(1). It is estimated that the industrial sector currently consumes about 40% of the nation's gross energy demand, and that 50% to 70% of the industrial sector energy demand is for industrial process heat (IPH). IPH is defined as thermal energy used in the preparation and treatment of goods produced by manufacturing processes. Solar energy systems provide a promising means for satisfying low and intermediate IPH needs (below 300°C) with existing technology. At least 27% of the IPH requirement (4 to 6 quads) falls within the energy delivery capability of these solar systems. If preheating to 300°C for higher temperature requirements is considered, approximately 50% of the IPH requirements (8 to 11 quads) can be supplied with available solar equipment. The monetary value of this annual amount of energy ranges from 23 to 33 billion dollars at a modest energy cost of 3 dollars per million Btu.

Solar controls presently are an amalgam of conventional analog units, logic controllers, and custom electronic black boxes. Because of the transient character of the solar system and the small experience base, this equipment combination has not achieved the performance level desired by many potential users. The underlying control strategy which dictates the proper interplay among the solar energy delivery system, thermal storage (if present), the conventional energy source, and the load has not been formalized either. Consequently, further development efforts are required before widespread industrial acceptance of solar systems can be expected.

This paper illustrates several configurations of solar systems for generating process heat in the form of steam, hot water, or oil and hot air. It describes the fluid control techniques, collector tracking methods, and different modes of operation that are currently being used or are proposed for solar controls. The discussion also includes operating deficiencies reported from several solar projects and suggests development avenues along which noticeable improvements can be made.

SOLAR COLLECTORS

Several types of solar collectors are commercially available for providing thermal energy at temperatures up to 300°C(2). The basic solar resource tapped by the collector is approximately 1 kW/m^2 (315 Btu/h-ft^2) on a clear day. Collection efficiencies typically range from 40% to 60%. Simple, stationary collectors, such as the flat plate, vee-trough, and evacuated tube, are most cost effective at energy delivery temperatures below 100°C. Higher operating temperatures require more expensive, sun tracking, concentrating collectors. Concentration permits the reduction of thermal losses at the hot receiver pipe, thereby maintaining satisfactory collection efficiency at progressively higher temperatures.

The parabolic trough reflector and the linear Fresnel lens are the most widely used line focus concentrators. Solar flux concentration by factors of 25 to 75 in these two units permits solar energy to be transferred to a working fluid in the receiver pipe at temperatures up to 300°C. The higher energy delivery temperature, however, is achieved only at the expense of sun tracking about a single collector rotational axis. The moving portion of the collector consists of either or both the reflective or refractive element and the receiver pipe. Energy delivery about 300°C generally necessitates the added expense burden of two-axis tracking and more sophisticated materials of construction.

The physical orientation of line focus collector arrays is normally with an east-west, horizontal rotational axis (maximum wintertime energy collection) or north-south, horizontal axis (maximum year-round energy collection). The overall energy delivery efficiency of a solar energy collection system consisting of the collectors, field piping, controls, and heat exchanger at the load would be 30% to 40%. Installed system costs without thermal storage would range from $25 to $75 per square foot of collection area with existing line focus technology. A significant issue affecting cost in an industrial application is the availability of space (roof-top or nearby ground) for collector installation.

SYSTEM CONFIGURATIONS

Different solar-thermal system configurations are used in industrial process heat applications. Figure 1 shows a block diagram of these solar thermal systems. Basically, three stages of energy flow are present; namely, energy collection, energy distribution/storage/conversion, and energy utilization(3). The energy provided by the solar collectors may be converted to another energy form as required or may be distributed directly to the load. In the energy distribution/storage/conversion stage, the subsystem configuration can be a single or a combination of different energy manipulation processes. To illustrate basic control concepts, only representative baseline configurations will be presented.

Figure 2 depicts a typical solar process heat system where a heat transfer fluid is used to transport solar energy(4). A secondary heat exchanger is used to transfer energy to another working form for load usage. In some cases, a storage tank is available for thermal energy storage. An auxiliary heater (fired by a conventional fuel) is used to provide energy when solar energy is unavailable. Typically, the collector array outlet temperature is maintained at a set point by controlling the circulation pump speed. More discussions on fluid control will follow. The commonly used process heat is in the form of steam, hot water, or hot air. The following paragraphs briefly describe different configurations of process steam, hot water, and hot air systems.

Process Steam System

Solar systems are used to produce low temperature steam in the range of 212°F to 350°F (100°C to 180°C)(3) and are being designed to produce intermediate temperature steam ranging from 300°F to 550°F (150°C to 290°C)(5-12). Three alternative process steam systems are discussed here. Figure 3 is the flow diagram of a heat transfer fluid steam system, wherein the heat transfer oil flows through the collector field and the steam is generated by the heated oil in an unfired boiler. The main advantages of this system configuration are the low pumping heads, the absence of freeze protection provisions, and that no internal corrosion or scaling of pipes and collectors takes place.

Figure 4 is the flow diagram of a pressurized water flash steam system wherein the pressurized water flows through the collector field and flashes to steam in a flash tank. This system does not require a secondary heat exchanger and therefore can operate at lower temperatures with higher efficiency. However, the system requires freeze protection, a bigger pump, and is subject to erosion at the location where flashing occurs.

Figure 5 is the flow diagram of a two-phase flow flash steam system wherein water is heated in the collectors and steam is separated in a steam drum. This system is similar to the pressurized water flash steam system, except that the flash valves are located immediately at the collector outlet and flashing occurs there.

The steam generating systems are shown with flow and temperature controls in the collector field, steam line pressure control, and steam boiler condensate level control. Flow and temperature controls are discussed in a later section.

Hot Water System

Solar systems applied to hot water supply are presently found in concrete block curing, can washing, and bottle washing(3,13,14). Hot water temperature ranges from 140°F to 212°F (60°C to 100°C). Figure 6 shows a hot water system in which a working fluid such as glycol/water is circulating in the collector loop, and a heat exchanger is used to transfer energy to the hot water loop. This configuration is employed when freeze protection during cold weather operation is a design factor. If freeze protection is not critical, the hot water can be supplied directly from the collector field as shown in Figure 7. In the latter case, the cold water is pumped through the collectors where it is heated and then accumulated in the storage tank, which supplies hot water to the load when required by the process.

Hot Air System

Application of solar energy to hot air supply is found in industrial drying and food dehydration processes(3,15,16). Applicable hot air temperatures range from 120°F to 150°F (50°C to 65°C). Figure 8 shows a hot air system in which air, preheated by the heat recovery unit, is pumped through the solar collectors. The heated air is then fed to the dryer or into storage, depending upon the mode of operation (a common storage device in a hot air system is a bin of gravel). Air temperature and load demand determine the operating mode, which is implemented by changing the position of dampers in the air ducts. The dampers can be switched to fully open or closed or can be modulated to maintain energy balance between collector output, storage accumulation, and load consumption. Figure 9 shows another hot air system in which a heat exchanger is used to heat air using the energy transported by the hot water circulating in the collector. Hot air systems offer advantages in terms of eliminating corrosion, eliminating fire and toxic hazards presented by heat transfer fluids, and not being susceptible to freezing.

FLUID CONTROL

The amount of energy collected (Q, Btu) by a solar collector during a specified period (t, h) can be expressed as:

$$Q = \int_0^t \dot{m}\, Cp \;\; \Delta T \; dt$$

where $\dot{m}$ is the fluid mass flow rate (lb/h), Cp the specific heat (Btu/lb-°F), and ΔT the fluid temperature rise (°F) in the collector. This amount of energy is also equal to

$$Q = \int_0^t \; I \; \eta \; A \; dt$$

where A is the collector aperture area (ft^2), η is the collector efficiency, and I is the solar radiation intensity at the aperture plane ($Btu/h\text{-}ft^2$). Figure 16 shows the range of concentrating collector efficiencies that can be expected from commercially available units as a function of their operating temperature(24). The first equation indicates that controlling the collector fluid temperature and flow rate is essential in solar system control.

Collector fluid flow rate can be constant or varying. A constant flow rate control scheme has the advantage of control simplicity(6,9). When the process load imposes no fixed outlet temperature on the solar system, a constant flow rate system can be employed. The transport fluid temperature at the collector outlet will vary according to the variations in solar flux and ambient conditions. A constant speed pump or self-actuated flow control valve can be used to maintain constant flow rate.

Another approach to constant flow rate control is shown in Figure 10. A 3-way valve is used upstream of the process load to bypass a portion of the total flow around the load when the fluid temperature is below the operating temperature, thereby maintaining the load temperature and at the same time maintaining constant transport fluid flow in the collectors. This 3-way valve is also used during warmup or transient cloud-cover periods for constant flow control.

In some applications where the process load requires a constant temperature, the output temperature of the collector field is established by adjusting the flow rate(3,7,8,10,11,12). A simple approach to the constant temperature control by varying flow rate is shown in Figure 11, where a cascade temperature-flow control scheme is used. The temperature controller, the set point of which is adjustable and is determined by the process demand, sends an output signal to continuously adjust the set point of the cascade flow controller. The output of the flow controller determines the position of the throttling control valve (2-way or 3-way) used with a constant speed pump. When a variable speed pump is used to adjust the flow rate, the flow controller output is used to manipulate the pump speed controller. The temperature controller is usually a proportional-integral-derivative 3-mode controller, while a proportional-integral 2-mode controller would be adequate for use as the flow controller. With this control scheme, a fluid temperature rising above the set point tends to open the valve or to increase the pump speed, and a temperature falling below the set point tends to close the valve or to decrease the pump speed.

The collector field output temperature control scheme as just described is exposed to two unique aspects of a solar system; namely, the thermal lag in the collector field and uncontrollable transient cloud behavior which interrupts the energy source. The temperature-flow cascade control technique is in itself a solution to the collector outlet thermal lag problem(11). However, oscillation and overshoot of temperature responses have been found in a system where the controlling temperature sensor is not located properly(4). Apparently, the mid-field fluid temperature should be used together with the outlet temperature for temperature control, as shown in Figure 12. A simple way of implementing this multiple-temperature approach is to use the averaged temperature obtainable from the summation of all applicable temperatures so as to damp out temperature variations during the transient periods while still properly representing the collector temperature under steady operating conditions.

The disturbance created by intermittent clouds does present an additional transient character to the temperature control of a solar system. To compensate for the disturbance described, a signal proportional to the incident solar radiation is fed into the control loop as a feedforward signal as shown in Figure 12. A high or low signal selector is used such that temperature is the main controlling parameter until the occurrence of a low radiation signal which would set the flow during the transient cloud period. For better performance, an adjustable time delay should be included in the radiation controller. The time delay setting will depend upon the time constant of the collector loop. Another way to compensate for variations in radiation level is to incorporate the radiation signal with the temperature readings for input to the temperature controller of the temperature-flow cascade control scheme(18). However, in order to maintain the capability of radiation control adjustment, a radiation controller is suggested.

Also shown in Figure 12 are the solenoids in the pneumatic signal line to the control valve. The solenoids provide a way of bypassing the fluid control signal so as to fully open or close the valve for a specified period under all conditions.

In those cases where accurate fluid control is not required, the flow rate can be manually set or preprogrammed according to the load demand schedule as long as the outlet temperature is above a specified low limit. Generally, the degree of sophistication of a solar control system depends largely upon the load energy demand requirement. In addition to temperature and flow controls, pressure and level controls are also involved in a solar system for reasons such as suppression of cavitation, hot water steam flashing, maintaining steam line pressure, liquid level control, condensate level control, etc. Since these control functions are not features unique to a solar system, they will not be discussed.

COLLECTOR TRACKING

To maintain maximum efficiency, concentrating solar collectors are designed to track the sun as it moves across the sky. Figure 13 shows an example of tracking angles experienced at 35° North latitude for east-west oriented collectors(4). The discussions presented here on collector tracking are based primarily on requirements of the parabolic trough, line-concentrating collectors.

Collector tracking functions include sun sensing; sun tracking; collector focusing, defocusing, and stowing. A sun sensing device can be a pyranometer, photovoltaic cell, or phototransistor. When the sun illuminates the device, a small voltage or current signal is generated, representing the solar radiation intensity level (which has a peak value of about 315 Btu/ft^2-h on a clear day). The signal generated can be used to indicate sunrise, sunset, heavy cloudiness. Startup and shutdown of a solar system usually occur at approximately 100 Btu/ft^2-h.

Figure 14 shows a diagram of a shadow band sensing device and a block diagram of a typical sun tracking control circuit based on the shadow band device. The device includes two photocells, one on each side of the sun shade, and is usually mounted at the edge of the reflector. The two signals from the photocells are amplified and fed to a differential amplifier, the output of which determines the actuation and direction of the collector driving motor. The motor will turn in the appropriate direction until a zero balance signal is obtained (at which time the receiver pipe is properly illuminated by the reflected light). Typical features of a shadow band collector tracking system are:

- Each collector array row is equipped with a shadow band device, control circuit, and drive motor. For centralized control, a master controller is used for control of all collector arrays.
- Capability of tracking in both rotational directions is present. Two-speed or multiple-speed tracking is desirable. A typical rotating speed is a 90° rotation in 60 s for moderate-speed tracking and a 180° rotation in 60 s for high-speed tracking (the latter is useful in quickly reaching a stow condition in the event of high winds or hail).
- A digital shaft encoder is used to measure the angular position of the collector shaft. Tracking errors usually must be less than 0.25 angular degree. Limit switches mounted on the collectors are used for fail-safe end travel to prevent mechanical damage.
- A standby emergency power source is needed for defocus and stowage to prevent equipment damage from overheating in the event of loss of fluid flow. Collector defocusing is typically 10° of angular rotation to accomplish a temporary shutdown action, while collector stowage returns the collector to its home position.

Figure 15 shows a typical collector control loop flow chart. As an example, the master controller uses the system permissive signal and low flow detection prior to sending a start permissive signal to the individual collector array controllers. The individual array controller is responsible for detecting excessive temperatures and for determining when there is sufficient radiation for array operation.

Computer-command position tracking is another approach to collector focusing. It can be used as the primary control method or for backup. With this system a minicomputer is used to implement a tracking algorithm which calculates the position of the sun and commands the motor to drive the collector trough to the correct angle. This method can maintain the solar collector within 0.05 degree of perfect focus when a 14-bit shaft encoder is used to provide a feedback to the computer for checking the resulting orientation. A typical computer command procedure is as follows(4,19):

- With inputs of time and date, a computer program computes the sun azimuth and elevation and the proper solar collector orientation to be in focus; and
- The computer accepts as input the array position from the collector shaft encoder. If the array is within 0.05 angular degree of the correct position, no correction is made. If it is outside the error band, a position correction signal is furnished.

CONTROL SEQUENCE

Solar systems require extensive sequencing controls because of the transient characteristics of daily sunrise/sunset and uncontrollable disturbances in energy collection (stemming from rapid weather changes) as well as variation in load demand. Sequencing controls discussed here are illustrative only and are not intended to imply that all of the listed operating modes are required.

Warmup mode. At a pre-sunrise time, the circulating pump starts to circulate fluid through an auxiliary heat source for fluid preheating and the circulation bypasses the collectors. This mode enables a rapid start of process heat generation at sunrise.

Startup mode. When the sufficient light intensity level is sensed, usually between 50 and 100 Btu/ft^2-h, the circulating pump is turned on, the collectors start moving to a sun tracking position, the flow control valve is maintained at a minimum flow position, startup control and safety logic are activated. The startup mode continues until the system is stabilized and operating temperature is reached.

Normal production mode. Once the fluid reaches the operating temperature and the flow is stabilized, the collector tracking control and fluid control will be occurring. Energy will be collected according to the process demand.

In the normal production mode, different energy flow paths are exercised to maintain a balance between energy collection, storage, and usage. For example, the energy flow path could be one in which the energy collected is consumed by the load only, or in which the energy is accumulated in the storage device only, or in which the energy is fed to the load and storage simultaneously.

When the collector field output is insufficient to provide the energy delivery rate required by the load, alternative operations can be exercised; for example, activation of the auxiliary heat source or thermal storage as a booster, or thermal storage serving as a temporary sole heat source, or the system operating for low-grade (i.e., lower temperatures) energy generation.

Freeze protection mode. When the collector fluid, especially water, is subject to freezing in cold weather, a minimal flow of heated fluid is circulated to prevent freezing.

Normal shutdown mode. Normal shutdown occurs near the end of a solar day and during periods when the time-averaged radiation falls below a specified level. The collector array is stowed in the safest position (minimal wind loading and maximal reflective surface protection). The circulating pump is stopped after a time delay, and the whole system is shut down according to a predetermined sequence.

Emergency shutdown mode. The extent of the emergency determines whether defocusing the collectors for a certain period is required or whether stowing the collectors to the home position is needed. The system is shut down in a predetermined sequence. Typical emergency shutdown conditions are abnormal temperature; pressure, flow rate, or fluid level; pump failure; excessive wind speed (typically, 30 mph for 4 min); loss of power source; and excessive thermal expansion of the receiver pipe. Overheating of the receiver pipe is an emergency condition because it not only causes mechanical damage of the tube but also may change the composition of the transport fluid and the optical characteristics of the surface treatment.

Failure mode. The control valves should go to the safest position if instrument air pressure is lost or if the electrical power supply fails. The controllers should go to the safest position if the thermocouple circuit opens. Emergency shutdown logic circuitry should be fail-safe designed.

DEFICIENCY AND IMPROVEMENT

One deficiency of existing fluid control techniques is related to the relatively long thermal time constant and the transient character of the available insolation due to weather changes. It has been found that the time delay which occurs between a change in conditions (temperature of entering fluid, solar radiation, etc.), and the time the result is sensed at the receiver exit limits the degree to which the output temperature can be controlled at a constant value(21).

Because of the thermal lag and high transient heat loss of the collector receiver pipes at startup, it is difficult to maintain the field output temperature at the set point during startup. This is why it typically takes 15 to 20 min for a system to reach a steady operating condition. Possible ways of improving the startup situation are (i) to include a warmup mode of operation as described above, (ii) to use a blending tank for startup fluid circulation, (iii) to use a 3-way valve to bypass the process load during startup, or (iv) to use an auxiliary heater for preheating.

The inherent difference in response time of temperature and flow should be recognized. Adequate controller tuning (gain, reset constant, and derivation constant) based on the specific system time constants is necessary to improve system performance. The temperature-flow cascade control scheme, as described previously in the fluid control section, is an approach to improving the thermal lag difficulty. Mid-field temperatures as well as the outlet temperature should be used for temperature control. The temperature input to the controller can be an average temperature, or it can be a selectable temperature under startup, steady state, or other operating conditions.

With respect to the transient conditions due to radiation variations, the solar radiation level should be used as a feedforward control signal to the temperature-flow control loop. This will enable the system to adjust the flow in response to the ever-changing radiation level in a predictive way. The radiation controller, when worked with the temperature control scheme, can be used to implement a combined feedforward and feedback control technique which should significantly improve system performance in terms of reducing oscillation and overshoot about the set point.

The need for improvement in the control of the steam generator, heat exchanger, load device, etc., should not be more than conventional process control. A possible improvement is to configure the process so that load demand changes can remain minimal.

Deficiencies of the collector tracking method using the shadowband device include the difficulty in obtaining matched solar cells (as each cell has a different characteristic); unreliable operation of photocells at low flux density; difficulty in obtaining accurate mechanical alignment of the shadowband device with the collector; time-varying reflections from bright objects such as surrounding buildings, snow, and clouds; excessive sensitivity to variations between bright days and varying cloud cover which necessitate continuous manual adjustment of deadband and delay settings to obtain satisfactory accuracy and stability(17).

Collector positioning based on computer-calculated sun position has been found to be an adequate alternate approach to sun tracking(21). However, it is desirable to obtain a direct indication of whether the receiver pipe is exactly at the point of maximum radiation concentration. One means to accomplish this is to develop heat flux(20,21) or optical sensors which can be mounted directly at the receiver so that position control can be based upon the solar input to the receiver.

The shadowband sun tracking method could be improved by developing a control system which can automatically adjust the deadband and delay settings in response to the varying sky conditions, and which can modulate the tracking speed in proportion to the magnitude of the error signal. A deficiency of backlash in the collector driving shaft may occur when a mechanical actuation system driven by the electric motor is used and exposed to continuous wind buffeting loads. A hydraulic actuator is an alternative way to eliminate the backlash problem.

CONCLUSION

This paper has reviewed the state-of-the-art of solar control systems as applied to industrial process heat generation. The article could serve as an introduction to solar control systems or as a general evaluation and critique of existing solar control techniques for the benefits of those who are engaged in solar system design.

The improvement of solar control techniques in one of many solar related development efforts that are underway with the goal of utilizing solar energy as a source for a significant portion of the nation's energy demand. A solar system using a well-designed control scheme can operate reliably and efficiently, thus increasing its attractiveness to industrial users. The solar experience thus far has not revealed any major obstacle in the developing process of solar control techniques. It is apparent that further extensive design and development efforts, as well as more industrial demonstrations, will help to achieve satisfactory control techniques.

One should bear in mind that a solar control system, like a conventional process control system, is subject to the constraints established for a specific solar energy system installation. System design criteria should be based on individual system requirements, such as the service conditions, heat transfer fluid type, energy demand requirement, solar collector type, insolation availability, geological location, installation criteria, safety aspects, control tolerance, cost justification, and many other factors. Whatever the system configurations and control strategies, the importance of control simplicity, reliability, and cost effectiveness should be emphasized.

In addition to the existing solar IPH demonstration projects which continue to provide valuable experience data, a large-scale experimental system called Solar Energy Research and Applications in Process Heat (SERAPH) is being planned(22,23) at the Solar Energy Research Institute. The main objectives of the SERAPH facility are to (i) accumulate operating, maintenance, and reliability experience using an industrial-scale solar facility; (ii) develop optimal control strategies which integrate collector field, thermal storage, and load demands; and (iii) test and validate analytical models of solar system performance. The SERAPH is expected to generate experience and experimental data which will be of great benefit to potential solar IPH users.

ACKNOWLEDGMENT

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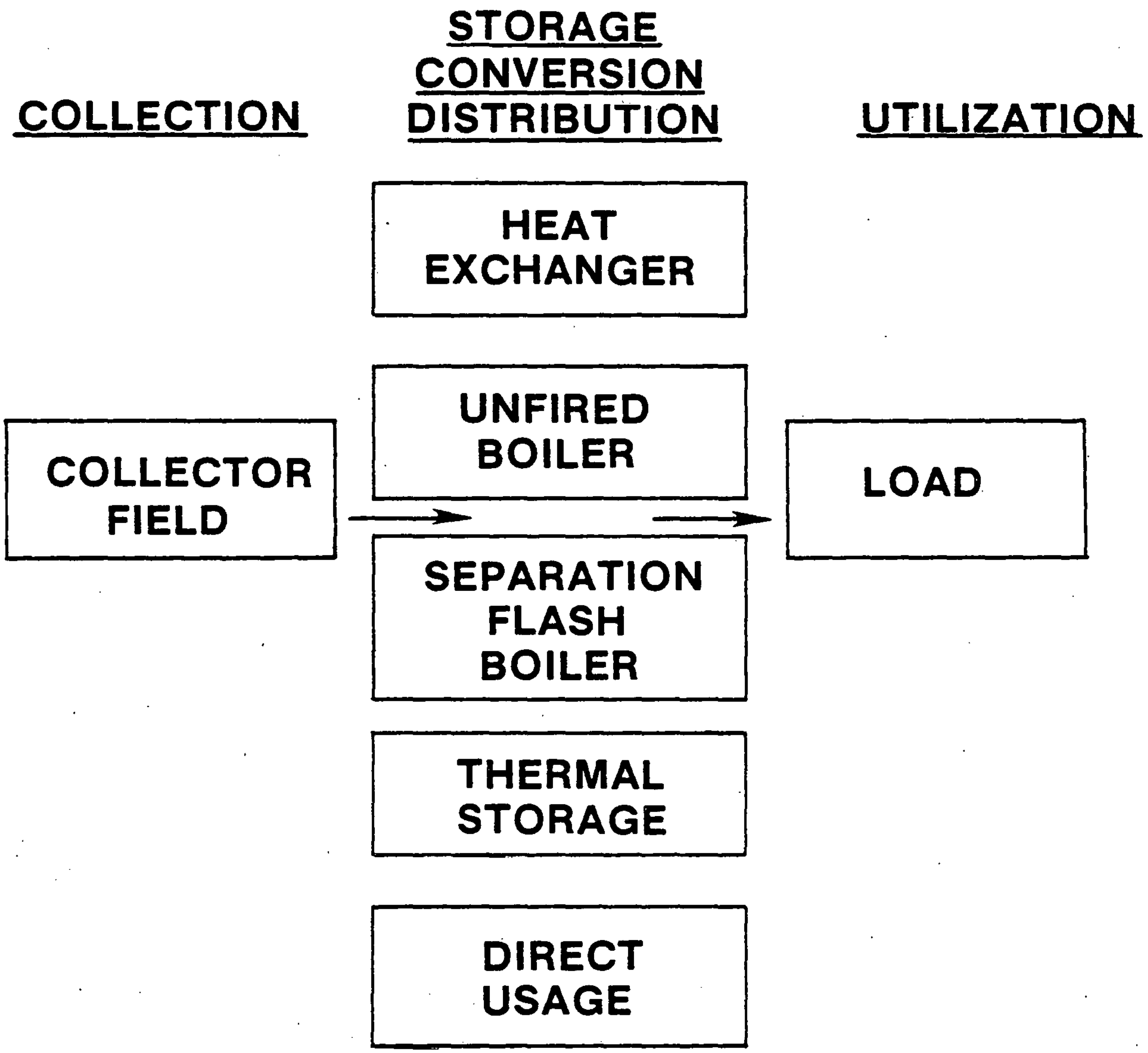

Fig. 1: Solar Thermal System Block Diagram

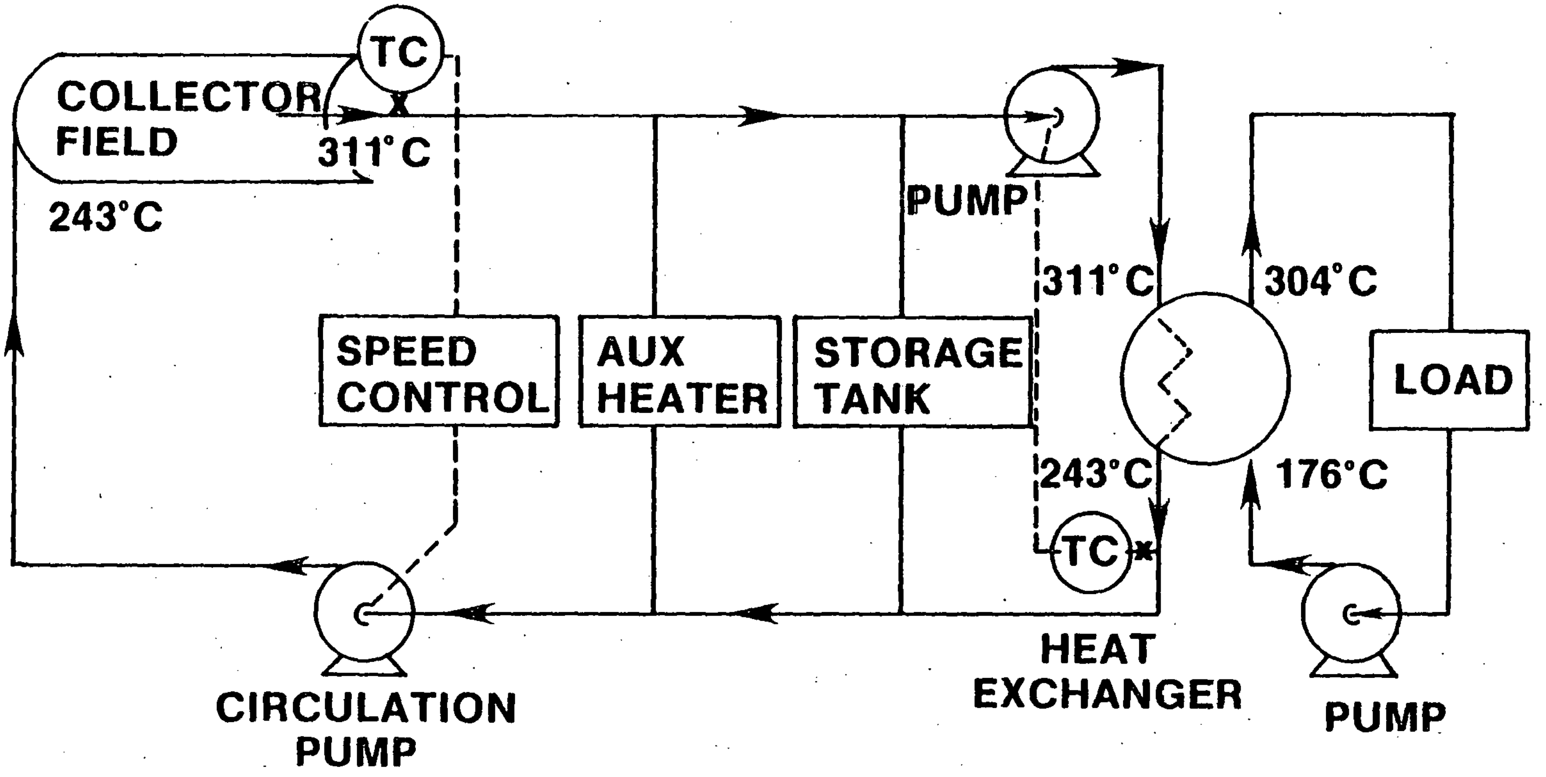

Fig. 2: Solar Process Heat System Flow Diagram

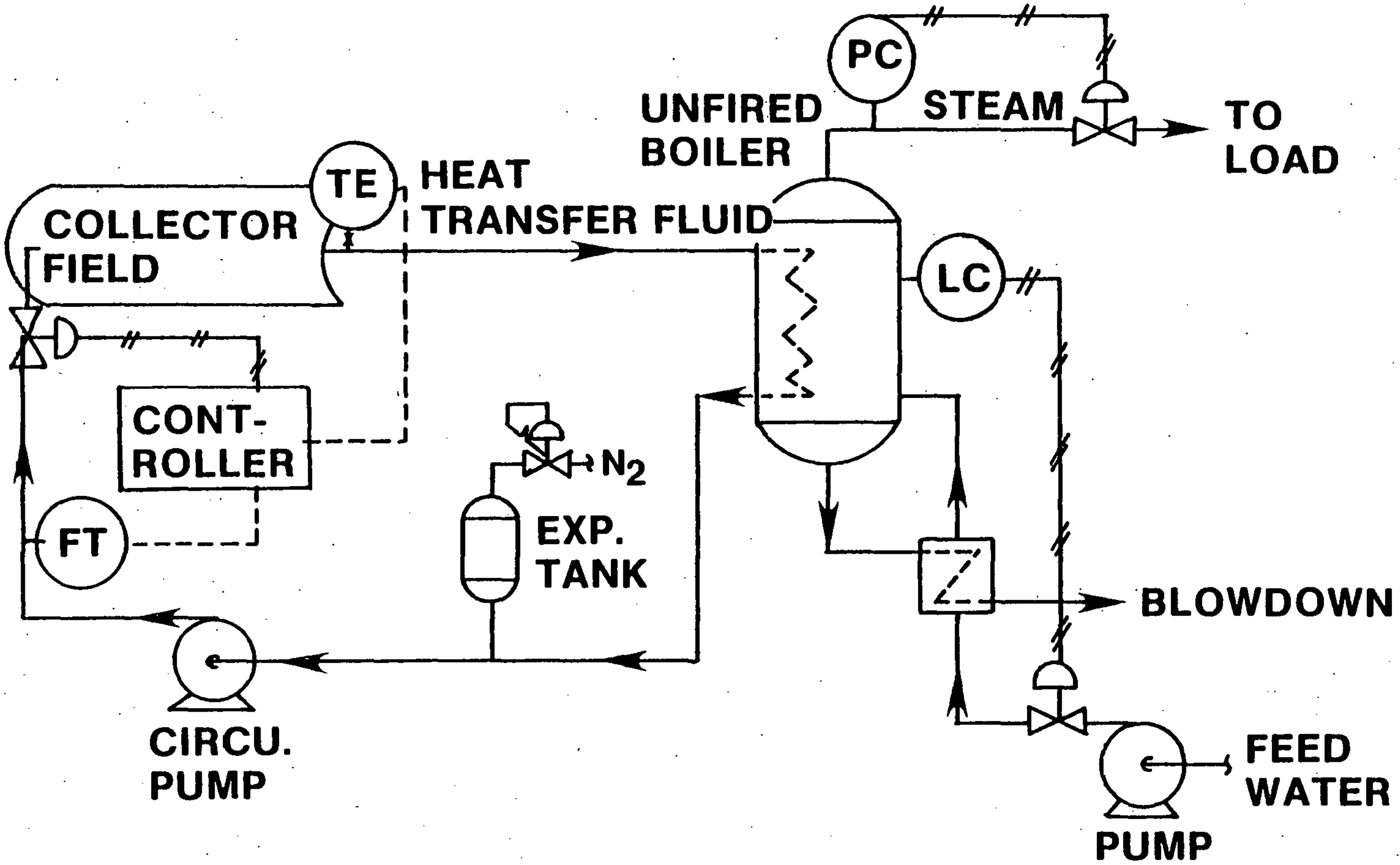

Fig. 3: Heat Transfer Fluid Steam System

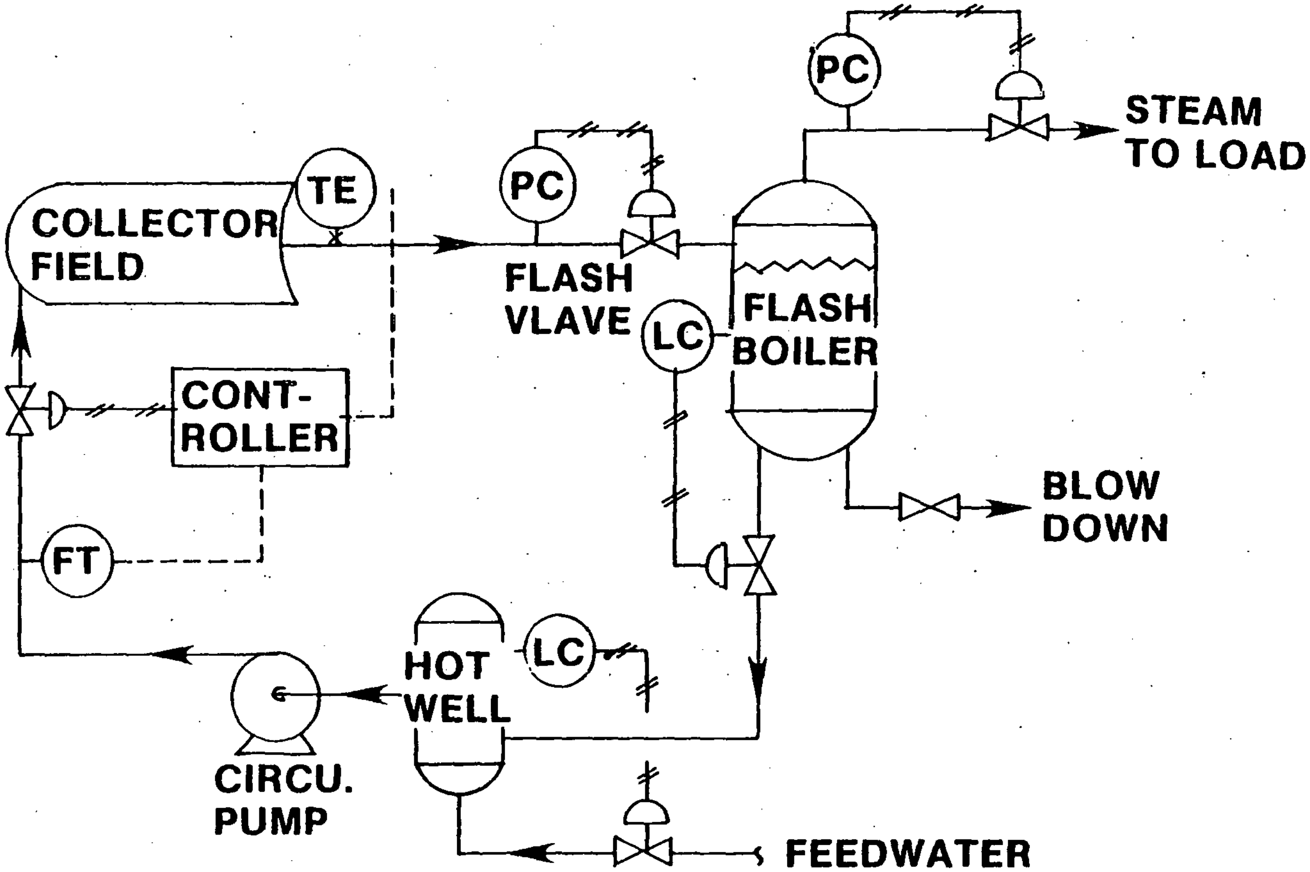

Fig. 4: Pressurized Water Flash Steam System

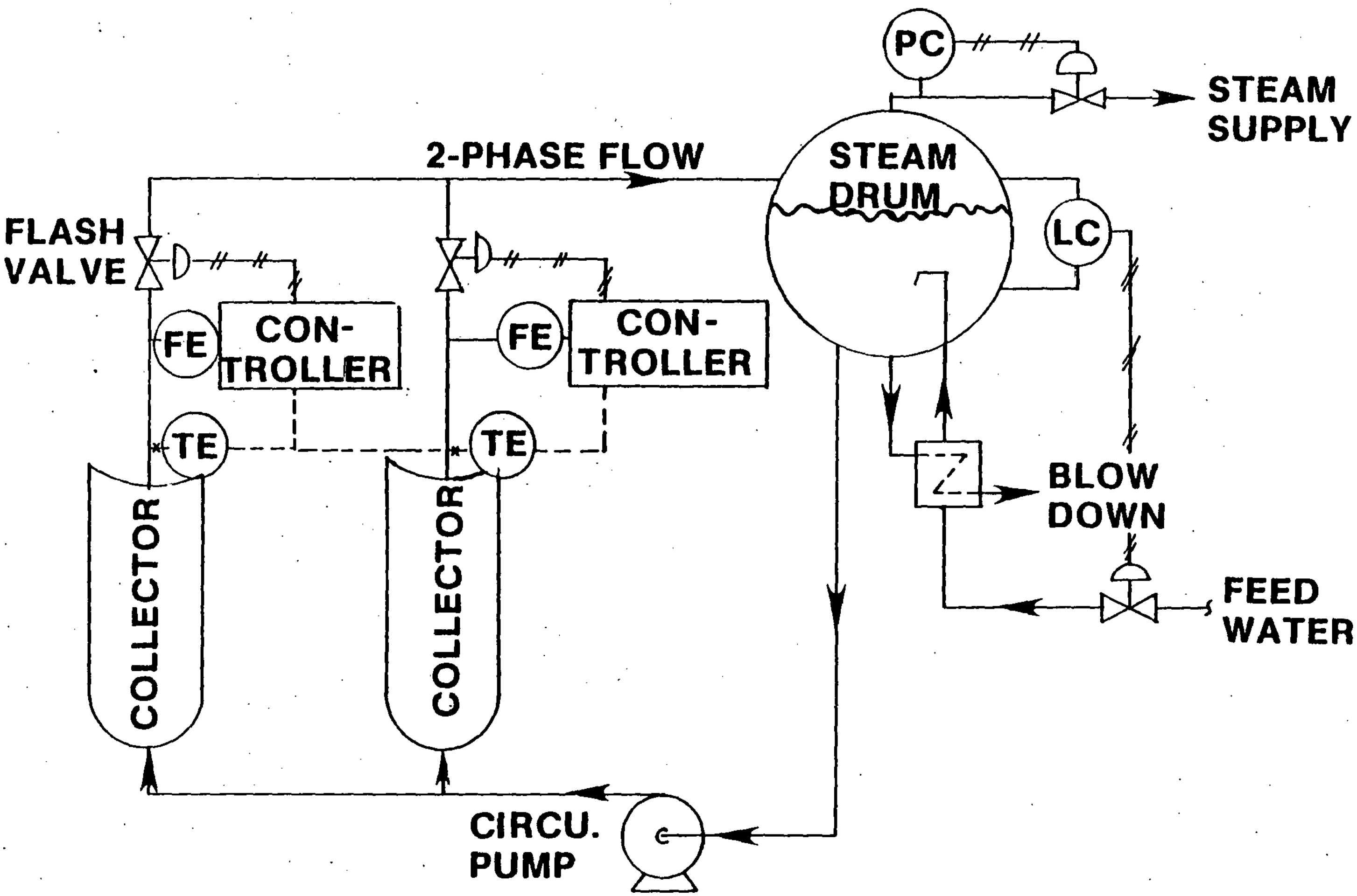

Fig. 5: Two-Phase Flow Flash Steam System

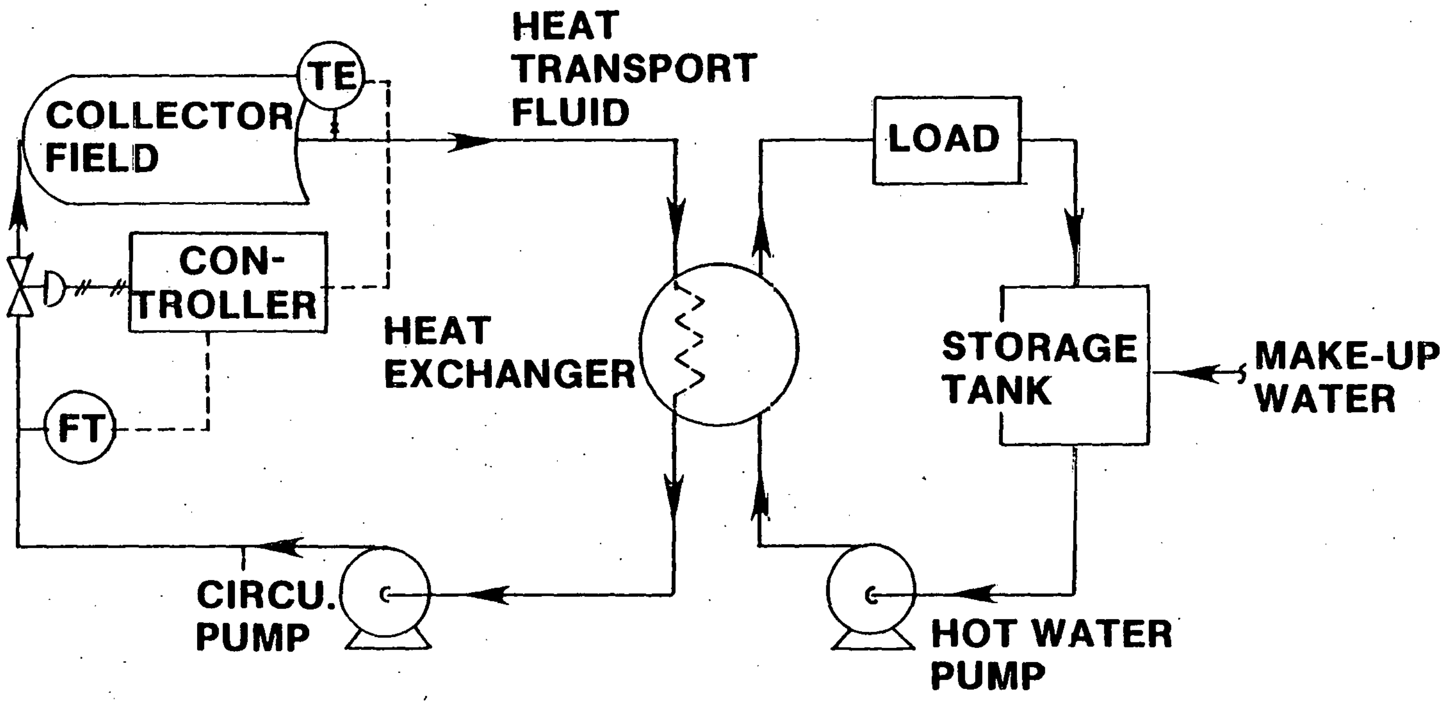

Fig. 6: Heat Exchanger Hot Water System

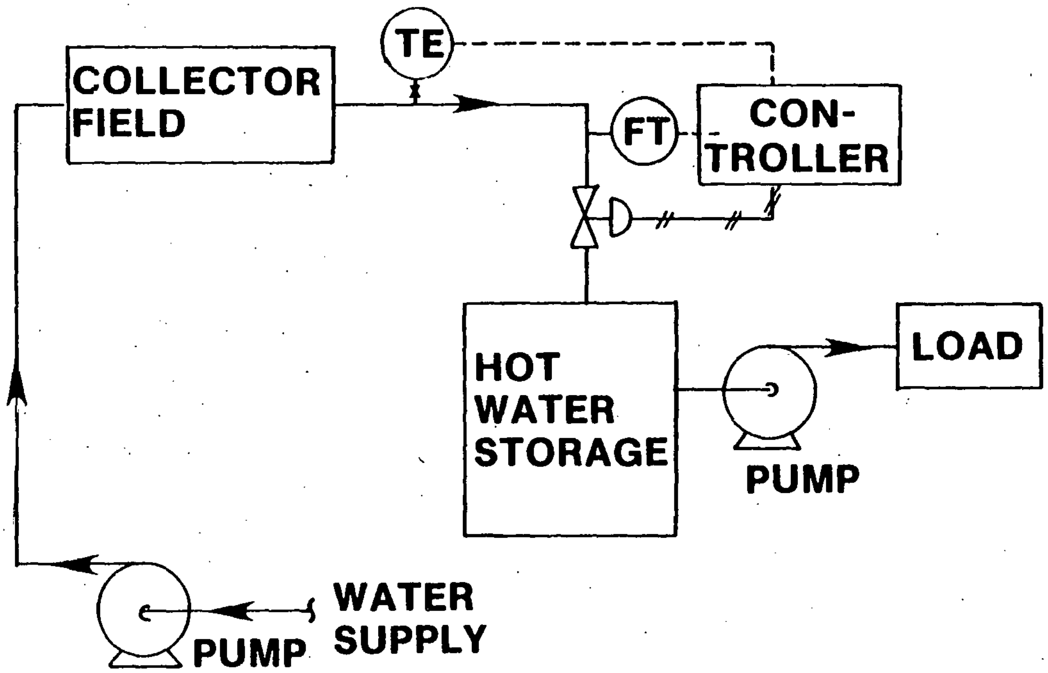

Fig. 7: Direct Heat Hot Water Supply System

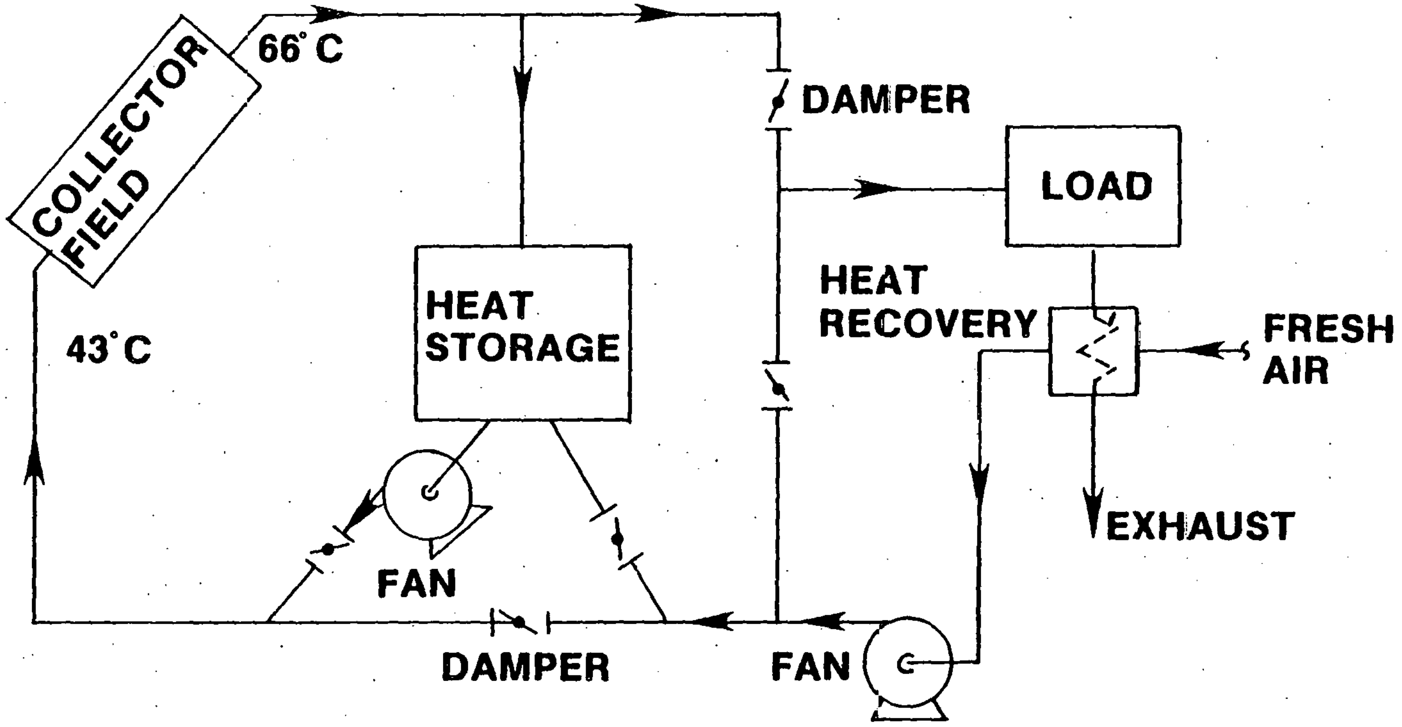

Fig. 8: Direct Heat Hot Air System

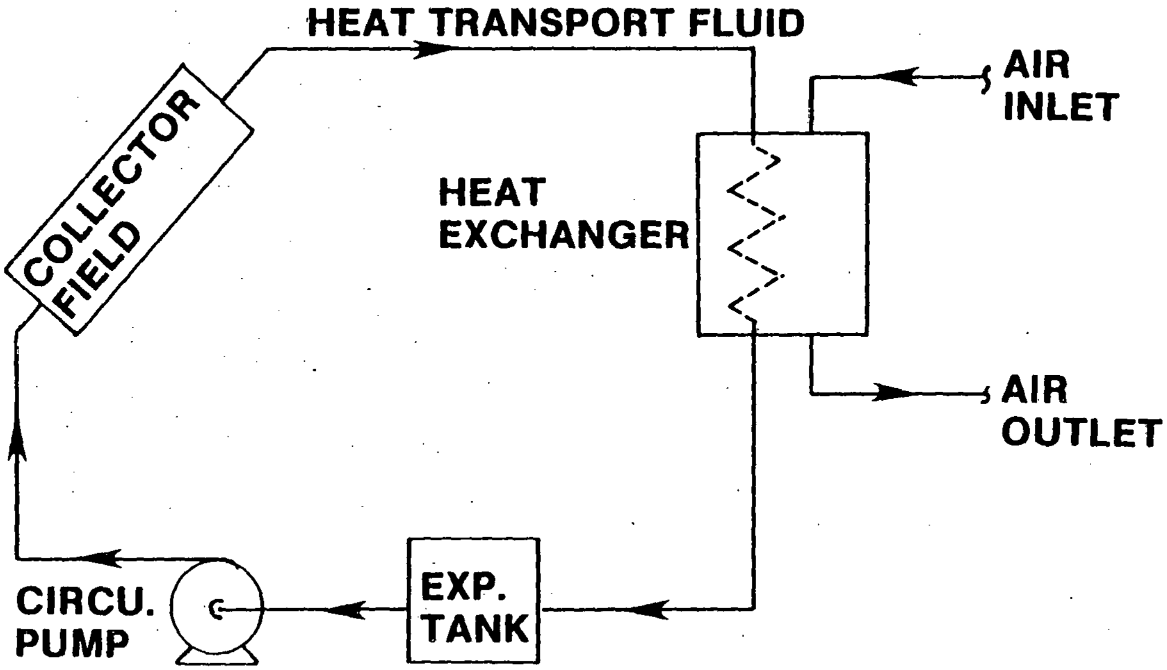

Fig. 9: Heat Exchanger Hot Air System

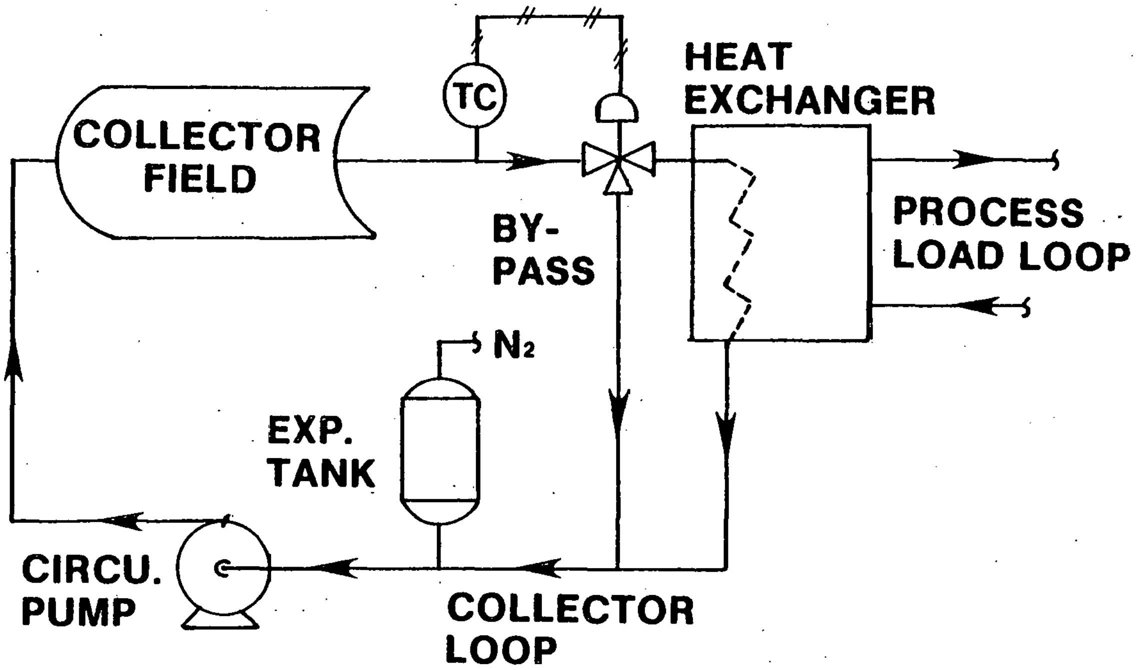

Fig. 10: Constant Flowrate Control Using 3-way Valve

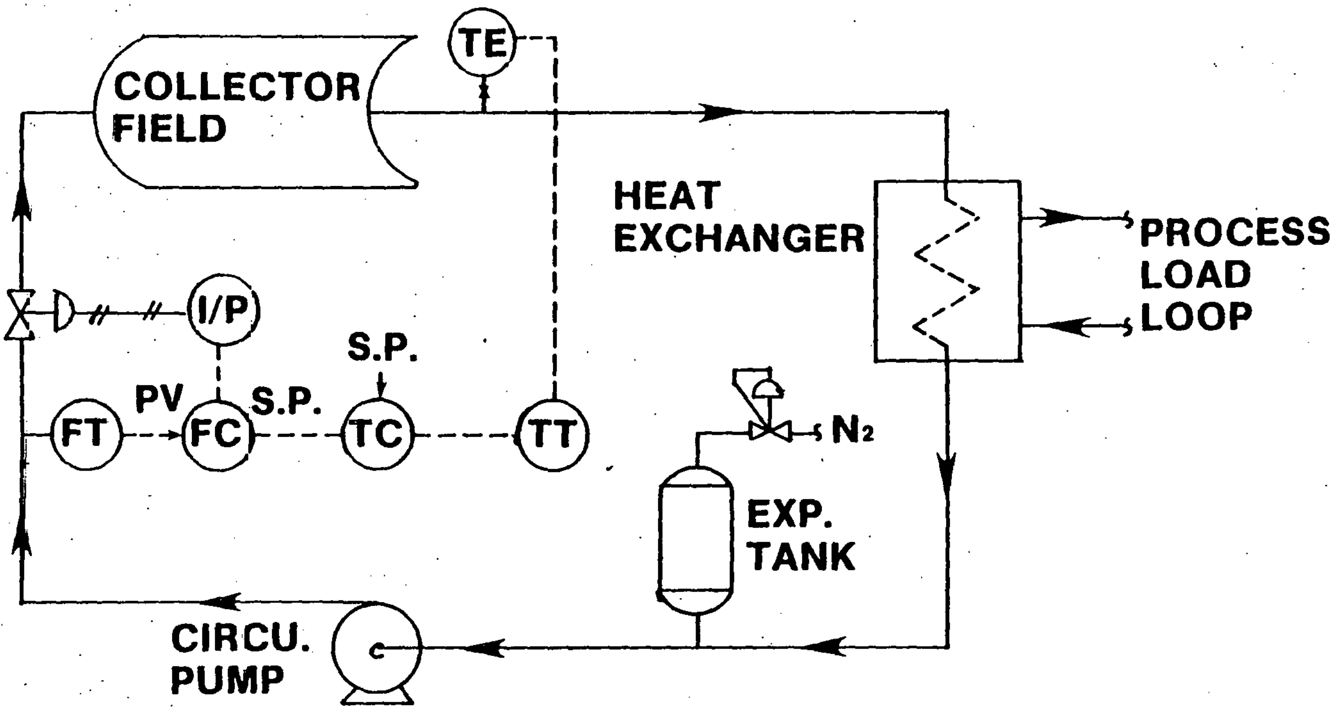

Fig. 11: Temperature - Flow Cascade Control

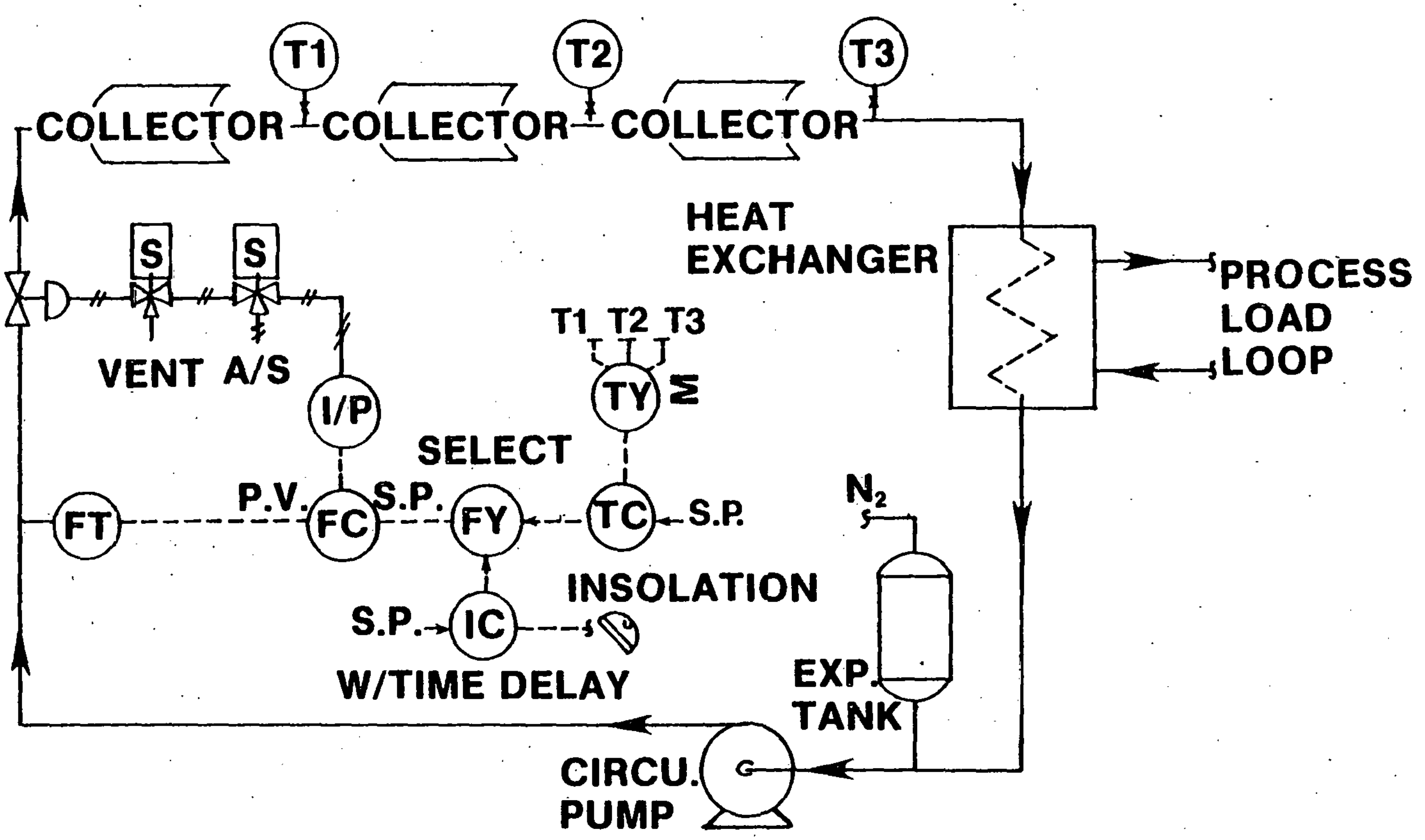

Fig. 12: Solar Feedforward - Feedback Control

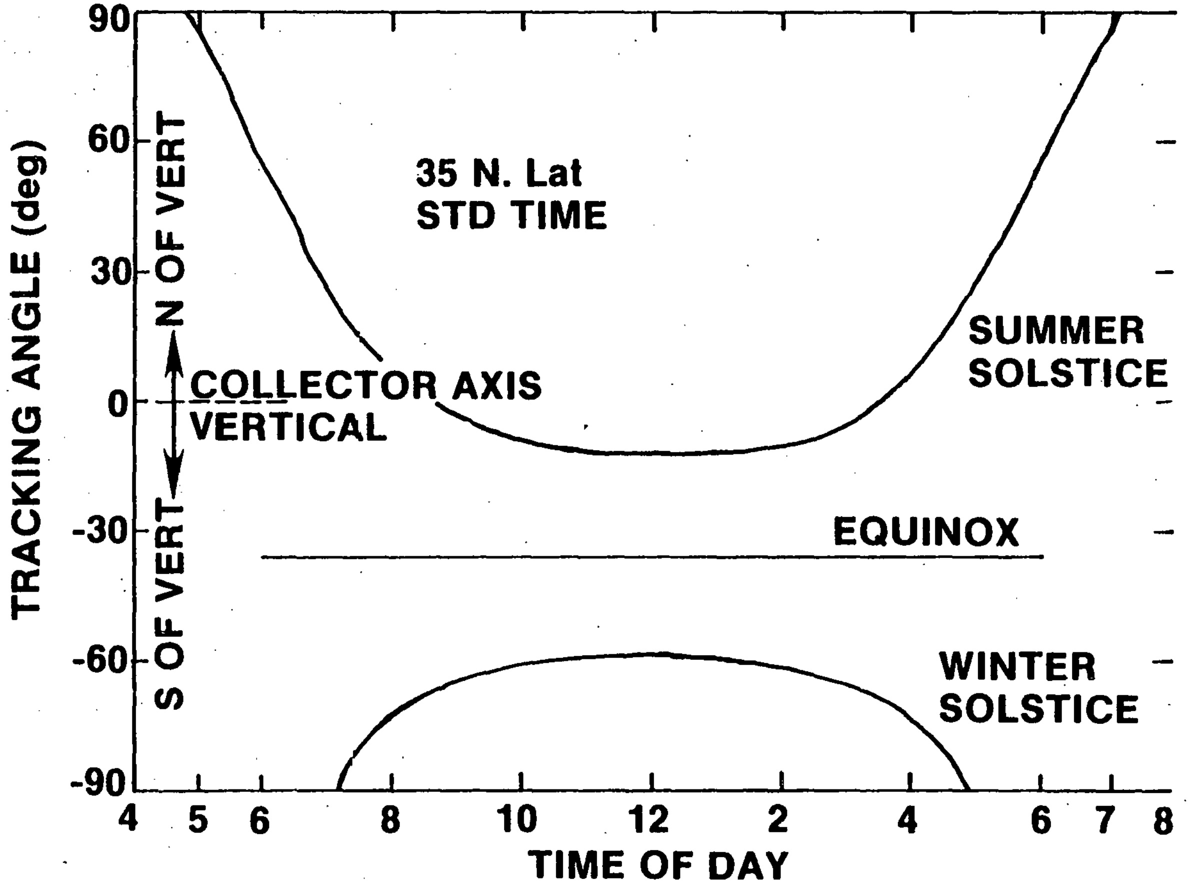

Fig. 13: Tracking Angle vs Time of Day for E/W Collector

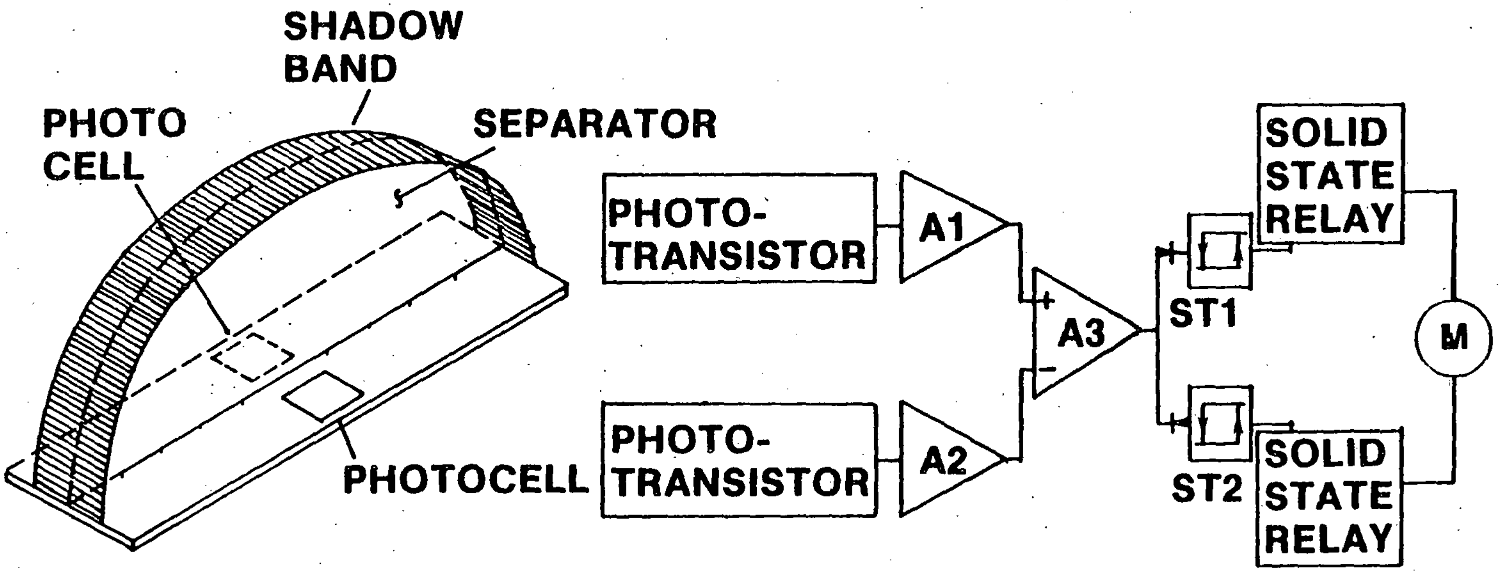

Fig. 14: Shadowband Sun Tracking Circuit

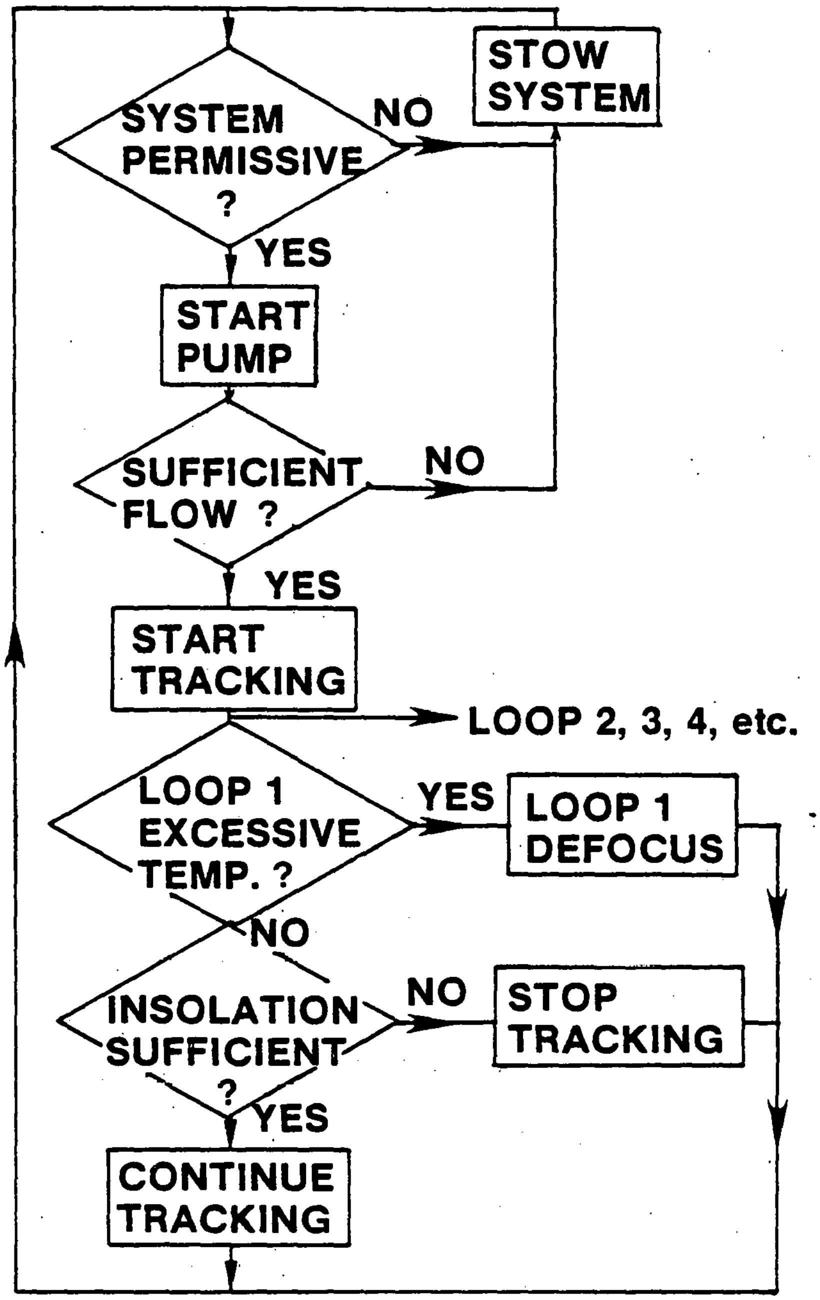

Fig. 15: Typical Collector Loop Tracking Control

10 x 12

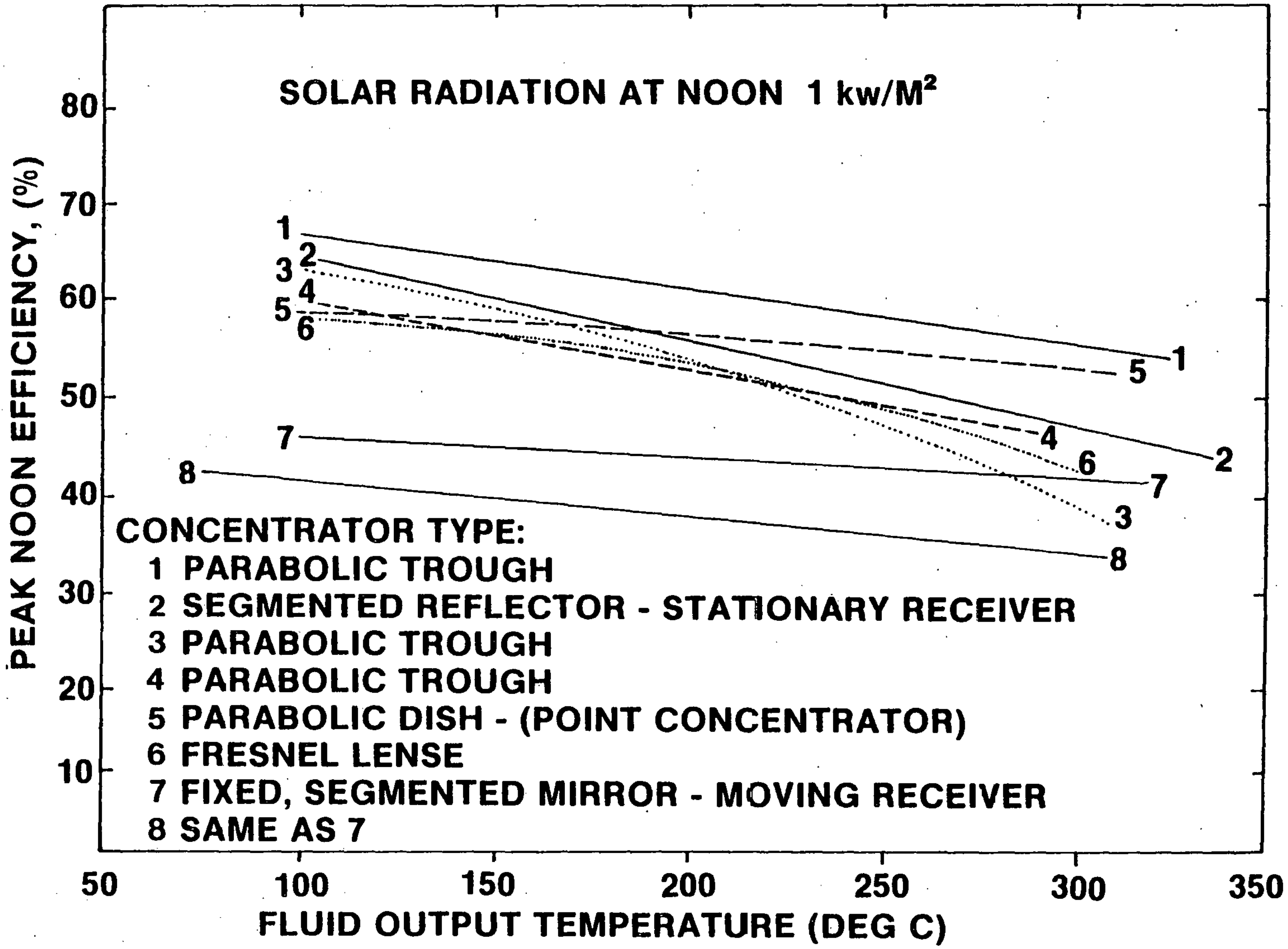

Figure 16. Concentrating Collector Efficiency - Test Results