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Control Strategies and Hardware Used in Solar Thermal Applications

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ABSTRACT

The control technology used in solar power production has gone through several changes over the past decade. To highlight some current aspects of solar collector control technologies, this report examines procedures and hardware for tracking the sun and regulating receiver temperatures. Requirements placed on controls for system protection and reliability are also reviewed. Control experiences in point- and line-focus concentrators, central receiver systems, and photovoltaic arrays are included in this study.

FOREWORD

The research and development described in this document was conducted within the U. S. Department of Energy's (DOE) Solar Thermal Technology Program. The goal of the Solar Thermal Technology Program is to advance the engineering and scientific understanding of solar thermal technology, and to establish the technology base from which private industry can develop solar thermal power production options for introduction into the competitive energy market.

Solar thermal technology concentrates solar radiation by means of tracking mirrors or lenses onto a receiver where the solar energy is absorbed as heat and converted into electricity or incorporated into products as process heat. The two primary solar thermal technologies, central receivers and distributed receivers, employ various point and line-focus optics to concentrate sunlight. Current central receiver systems use fields of heliostats (two-axis tracking mirrors) to focus the sun's radiant energy onto a single tower-mounted receiver. Parabolic dishes up to 17 meters in diameter track the sun in two axes and use mirrors to focus radiant energy onto a receiver. Troughs and bowls are line-focus tracking reflectors that concentrate sunlight onto receiver tubes along their focal lines. Concentrating collector modules can be used alone or in a multi-module system. The concentrated radiant energy absorbed by the solar thermal receiver is transported to the conversion process by a circulating working fluid. Receiver temperatures range from 100C in low-temperature troughs to over 1500C in dish and central receiver systems.

The Solar Thermal Technology Program is directing efforts to advance and improve promising system concepts through the research and development of solar thermal materials, components, and subsystems, and the testing and performance evaluation of subsystems and systems. These efforts are carried out through the technical direction of DOE and its network of national laboratories who work with private industry. Together they have established a comprehensive, goal directed program to improve performance and provide technically proven options for eventual incorporation into the nation's energy supply.

To be successful in contributing to an adequate national energy supply at reasonable cost, solar thermal energy must eventually be economically competitive with a variety of other energy sources. Components and system-level performance targets have been developed as quantitative program goals. The performance targets are used in planning research and development activities, measuring progress, assessing alternative technology options, and making optimal component developments. These targets will be pursued vigorously to insure a successful program.

A review of the controls that are used in solar collection systems is provided in this report. Control strategies and hardware options are discussed, along with the broader objectives and expectations for control systems in solar facilities. Information provided in this review will aid in the development of the highly automated and reliable control systems that will be required in future solar power facilities.

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Summary

Control failures have been a major source of downtime in past solar collector systems. In addition, solar collector controls often perform far below original design expectations and greatly reduce a system's overall performance and reliability. To highlight some of the current control problems and solutions, this report examines controls used for tracking the sun and regulating the receiver temperatures. Special attention is given to distributed receiver systems, but many of the findings are applicable to central receiver and photovoltaic systems. From this examination the following observations are made in this report:

Tracking Controls

* In systems that track the sun by sensing its position (i.e., closed-loop systems), shadow-band sensors can detect pointing errors of under one milliradian, but sensor misalignment, component degradation, and environmental reflections or shadowing may lead to new tracking errors in these systems.

* Flux sensors can provide information on aiming errors by measuring concentrated flux that misses the receiver aperture. Past optical flux sensors, however, have not been able to withstand the concentrated flux of dish concentrators, and thermal convection can degrade tracking accuracies in systems that use thermal flux sensors.

* From a technical standpoint, tracking systems that follow a computed sun position (i.e., open-loop systems) have always been an attractive option, but costs have been prohibitive. With recent cost reductions in programmable control systems and the development of low-cost position encoding devices, cost is no longer a major obstacle. Open-loop systems alone, however, still cannot correct for structural misalignments.

* A combined open-loop/closed-loop system, or "hybrid" tracking system, can provide the best tracking control capabilities. The open-loop and closed-loop systems must have comparable accuracies for a smooth transition between modes. Hybrid control systems can correct for

structural misalignment, but unsteady wind loads have caused control compensation for backlash to be ineffective in past systems.

* Commercially available programmable controllers now have the characteristics required to replace custom built tracking controllers. However, the cost of commercial controllers may limit their applications to small facilities where development costs of custom built controllers cannot be amortized over many copies.

* Hall-effect encoders, synchro/resolvers, and, despite previous problems, optical encoders are all valid options for collector position sensors in tracking control systems. Hall-effect encoders cost much less than the other two options, but they can only be used when there are large speed reductions in the drive train.

Receiver Controls

* Controlling receiver temperatures economically is not a simple task.

* Adjusting flow rates to control temperatures will present problems because system gains will vary with flow rates (and therefore insolation levels). Without the ability to change control gains, which is an expensive option in most controllers, the system may overreact at low insolation levels or perform sluggishly at high insolation levels.

* Altering inlet temperatures is an undesirable method for control because it increases system thermal losses and makes control actions subject to long time lags. Maintaining constant inlet temperatures, however, may stabilize temperature regulation in systems that control receiver flows.

* Passive flow balancing techniques (that is, adjusting hand valves or orifices at each receiver to obtain equal flows) have not been effective in maintaining close tolerances on receiver temperatures in collector fields.

* Offset tracking modes are used in many systems to prevent receivers from overheating. In systems that operate near maximum design temperature limits, offset tracking procedures often become a method of temperature control. This procedure tends to waste concentrated energy, and in systems with many collectors, the offset tracking collector can act as a heat sink and further degrade the system's performance.

* Control valve characteristics must be compatible with the rest of the flow system. To be effective over a wide range of operating conditions, the valve should provide the largest pressure drop in the system. Equal percentage characteristics are preferred over linear control valve characteristics.

* Temperature sensor failures have caused a number of problems in solar collection systems. Resistance Temperature Detectors (RTDs) temperature sensors are generally too fragile for harsh environments. Thermocouples provide a rugged and inexpensive means of measuring temperatures, but redundant sensors must be provided. Integrated circuit chips are now available to condition thermocouple signals and provide a reference junction temperature.

* Electric and electrohydraulic actuators are currently the main options for valve actuation tasks in the collector field. Pneumatic actuators should be considered only where a few valves are required, and the valves should be located near the air supply so that condensation problems are reduced in the compressed air lines.

* Control valves that are driven by the thermal expansion of special actuators may offer another option for temperature control in the future, but thermostatic actuators are not widely available for temperatures above 230°F.

System Considerations

* Varying degrees of field control autonomy have been used in past collector systems. Making more of the routine control decisions at the field level reduces the impact of communication delays on system operation and simplifies future expansion of a system.

* Dedicated wire cables and power cable carrier-current links are presently the best media for field communication. Radio frequency links may provide an inexpensive communication option in the future.

* The control system must actively protect the concentrator, power conversion system, and personnel from concentrated flux during all modes of operation (offset tracking, sun tracking, and sun acquisition and deacquisition). Control systems must also prevent wind loads from damaging the concentrator by sensing the onset of high winds and driving the collector to a relatively safe position.

* Special control features are required to recognize and react to a tracking control failure when the concentrator is focused on the sun. No generalized cost-effective form of protection is currently available.

* Control failures are most often caused by dirt or moisture in control units, sensors, and cable connectors. Failures are also frequently caused by electromagnetic surges in communication lines, arcing in relays and switches, and the exposure of components to low temperatures or concentrated flux. These problems can be avoided through the proper selection of control components and procedures.

* The long-term cost goal for dish concentrators is $130/m^2 of collector aperture area; tracking controls are included in this price. The cost goal for receivers in dish-electric systems is $70/m^2, and for receivers in solar thermal systems the goal is $30/m^2, these goals include the cost of receiver temperature controls. In the past, the cost of tracking controls has been roughly 10% of the total concentrator cost.

Recommendations

The results of this and other studies indicate that the following improvements should be considered in future control systems:

* Sun sensors should be used in tracking control systems to provide information on aiming errors. Signals from these sensors should be interpreted by software in the tracking control unit before position update commands are issued to the drive motors. The tracking control unit should have algorithms that predict error corrections for future position updates.

* Control systems must have an accurate open-loop tracking system even when sun tracking sensors are available. Problems with an unstable transition between control modes and component degradation in sensors can be reduced through the use of an accurate open-loop tracking control system.

* Tracking systems should use symmetric tracking limits about the true aim point to reduce parasitics and lessen the wear on control components and drive motors.

* Efforts must be made to improve the reliability of control systems. Weathertight enclosures and corrosion-resistant components should be selected when possible. Systems should be designed to operate at low temperatures and component pretesting should be performed to insure the survivability of control components at temperature extremes.

* For receivers that operate at temperatures close to the system's thermal limits, active flow control should be provided for each receiver. The flow controls must have characteristics that allow the system to operate at all insolation levels. An offset tracking option must be provided, but it should be used mainly as an emergency procedure to prevent the receiver from overheating.

* Requirements on the communication system should be minimized by distributing more of the routine control tasks to the field controllers.

* Solar collector systems must be capable of operating when the sun is available. Redundancy should be provided in control components that are required for the entire system to operate.

CHAPTER 1. INTRODUCTION

Methods to control solar power systems have been explored for centuries. One legend tells of Archimedes harnessing the sun in 212 B.C. by commanding Greek soldiers to focus their polished shields as "burning mirrors" on the sails of invading Roman ships. Although Greek soldiers might have been the solution to solar control problems in 212 B.C., today the emphasis is on controlling the solar collector fields at a reasonable cost with increased automation and reliability. A number of control systems have been developed to meet these objectives, but minor (and sometimes major) problems have consistently kept the controls from fulfilling original expectations. The purpose of this report is to provide an overview of controls that are used in solar thermal technologies and to identify control systems that work, and just as important, the controls that do not work.

In this paper the term "control system" refers to the hardware and procedures used to meet control objectives. There is a tendency to emphasize the hardware aspects of control systems (programmable controllers, sensors, relays, etc.), but hardware only makes up the visible portion of controls. Of equal importance are the strategies that define how the hardware is to be used and what the ultimate goals are in controlling the system. These strategies determine the configuration of the system and the logic that is programmed into the controls. To adequately describe a control system, it is necessary to discuss the hardware, the strategies, and the objectives for controlling a system.

In a power plant, the overall purpose for a control system is to coordinate the actions within and between plant subsystems. Solar thermal energy systems can typically be divided into three subsystems: (1) a solar collection subsystem, (2) a storage or auxiliary heat subsystem, and (3) a power conversion subsystem. This division is illustrated in Figure 1. For the system shown, the controls must regulate the flow temperatures to and from the field and in the receivers, provide the logic necessary for sun tracking, and adjust the storage subsystem heat exchange rates to allow for steady operation of the power conversion subsystem.

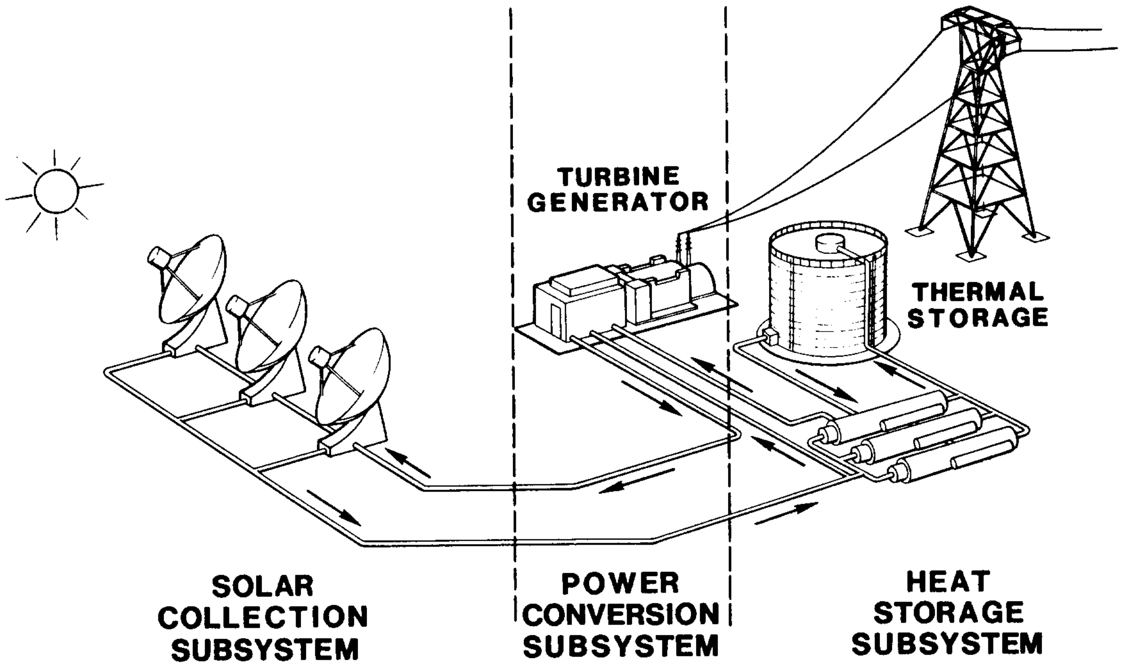


Figure 1. Subsystems of a solar thermal facility.

This report concentrates on the solar collection subsystem controls for distributed receiver systems. It is within the collector field that most control problems have occurred in the past, and it is also in the field where the balance between cost and reliability is the most difficult to obtain. In the power conversion and the auxiliary heat subsystems, the use of digital or analog control systems that are available for conventional power plants is acceptable since the number of hardware components will be relatively small. (The big challenge in these subsystems is to find the optimum strategies for using available hardware.) In the solar collection subsystem, however, the capital and maintenance costs of conventional control hardware could quickly become unacceptable because of the large number of control components required in a field of hundreds or perhaps thousands of collectors.

Although this study focuses on field controls for dish collector systems, much of the work is equally applicable to central receiver, line-focus receiver, and photovoltaic systems. Likewise, control experiences in other solar collection technologies have contributed to this study. Table 1 gives a brief description of the solar collection systems that were investigated in this study. Additional information on controls was also gathered from theoretical studies and past test results for individual control components.

Since the sun is a nonstationary power supply, one of the principal tasks for the collector control system is to track the sun. This task is complicated by the accuracy requirements for high performance collectors and the complex nature of the sun's motion. The difficulties in maintaining a perfectly aligned tracking structure also add to the problems of capturing the maximum amount of available energy and delivering it to the receiver. The hardware and tracking procedures that are available to overcome these problems are discussed in the next chapter.

Once the concentrated flux is intercepted by the receiver, the field controls must insure that the power is in a form that is useful to the power conversion or thermal storage subsystem. These subsystems generally accept only a narrow range of temperatures, but atmospheric attenuation will cause input power levels from the concentrator to vary throughout the day. The controls must not only adjust for the continual variation in flux levels, but they must also handle the rapid power transients caused by passing clouds and system start up. The strategies and hardware used in controlling the receiver are discussed in Chapter 3.

The design of a collector field control system is not determined by the tasks of tracking the sun and regulating the receiver temperature alone. Control designs will also be affected by the manner in which control tasks are distributed throughout the field and the environmental conditions that the controls must survive. Additional control tasks such as protecting the concentrator, the receiver, and the surrounding personnel will also affect the design of control systems. The biggest influence on the control system design, however, will probably come from the overall cost and reliability

Table 1. Solar facilities reference list.

NAME	SITE LOCATION (OWNER)	DESCRIPTION	SERVICE START-UP
Gila-Bend Solar Powered Irrigation System	Gila Bend, Arizona	50 HP Irrigation water pumping project with 9 single axis tracking troughs	1977
Modular Industrial Solar Retrofit (MISR)	Sandia National Laboratories Albuquerque, NM	1208 sq. meter single axis tracking trough system at the Solar Thermal Test Facility	1982
Small Solar Power Systems (SSPS)	Almeria, Spain	500 kWe central receiver system and 500 kWe single & two axis tracking troughs	1981
Solar One	Daggett, CA (So. Ca. Edison Co.)	10 MWe central receiver facility with 1,818 heliostat field	1982
Solarplant One	Warner Springs, CA (LaJet Energy Co.)	4.92 MWe distributed receiver facility with 700 point focus concentrators	1984
Solar Total Energy Project (STEP)	Shenandoah, GA	400 kWe & process steam distributed receiver facility with 114 parabolic dish concentrators	1982/ 1984
Solar Electric Generating Stations (SEGS-1)	Daggett, CA (Luz Engineering Corp.)	14.7 MWe distributed receiver facility with 71,680 m^2 parabolic trough collectors	1984
Central Receiver Test Facility (CRTF)	Sandia National Laboratories Albuquerque, NM	5 MWt central receiver facility with 222 heliostats	1970
Test Bed Concentrators (TBC)	Sandia National Laboratories Albuquerque, NM	82 kWt parabolic dish concentrators	

Table 1. Solar facilities reference list (Continued)

NAME	SITE LOCATION (OWNER)	DESCRIPTION	SERVICE START-UP
Enhanced Oil Recovery Pilot Plant (EOR)	Bakerfield, CA (ARCO Solar Inc.)	30 heliostat central receiver facility	
Parabolic Dish Concentrator No. 1 (PDC #1)	Edwards AFB, CA	12 meter diameter parabolic dish concentrator	1982
Vanguard Solar Dish Dish-Stirling Engine Module	Rancho Mirage, CA	10.7 meter diameter parabolic dish concentrator with 30 kWe peak power conversion unit	1984
Sky Harbor	Sky Harbor Airport, AZ (Az. Public Service Co.)	225 kWe photovoltaic system 80 two axis tracking PV arrays	1982
Suadi Solar Village (SOLERAS)	Al-Jubaylah, Saudi Arabia	350 kWe photovoltaic system with 160 two axis tracking PV arrays (SOLERAS Solar Energy Research Project American & Saudi)	1981

goals for distributed receiver technologies. These issues are discussed in Chapter 4.

Chapter 5 summarizes the findings of this report and gives recommendations for future control designs. Control technology is far from static though, so this report's main purpose is to provide a point of departure for future control designers.

CHAPTER II. TRACKING CONTROLS

To design a control system for tracking the sun, three questions must be answered; (1) What aiming accuracy is required? (2) What hardware is available? (3) How much can the system cost? The requirements on tracking accuracy and how to meet these requirements are discussed in this chapter. Cost data are also be presented, but a discussion of cost goals is postponed to chapter 4. Before delving into the intricacies of control systems, however, it might be prudent to review some fundamental aspects of locating and tracking the sun.

Sun Tracking Fundamentals

Specifying the Sun's Location

For most solar engineering purposes, it can be assumed that the sun orbits the earth on a celestial sphere as shown in Figure 2. As a result of this assumption, only two angles are needed to specify the sun's location. Typically the position is described in either azimuth-elevation (AZ-EL) or polar-declination (PO-DE) coordinates. Positive directions for these angles are illustrated in Figure 2.

The zenith in Figure 2 is a point that is vertically overhead at any given location on earth. The polar angle (or hour angle) is measured between two planes passing through the poles; one plane intersects the zenith and the other plane intersects the sun. The declination angle is measured between the equatorial plane and the center of the sun in a plane containing both the sun and the poles.

The geometry for AZ-EL coordinates is shown in Figure 3. Also shown in this figure are roll-tilt (RO-TI) coordinates, which will be discussed later. The elevation angle is measured between the local horizontal plane (a plane perpendicular to the zenith line) and the sun. The azimuth angle is measured between a due-south line and the vertical projection of the sun's position on the horizontal plane. AZ and EL can be calculated when PO, DE, and the local latitude, LA, are known.

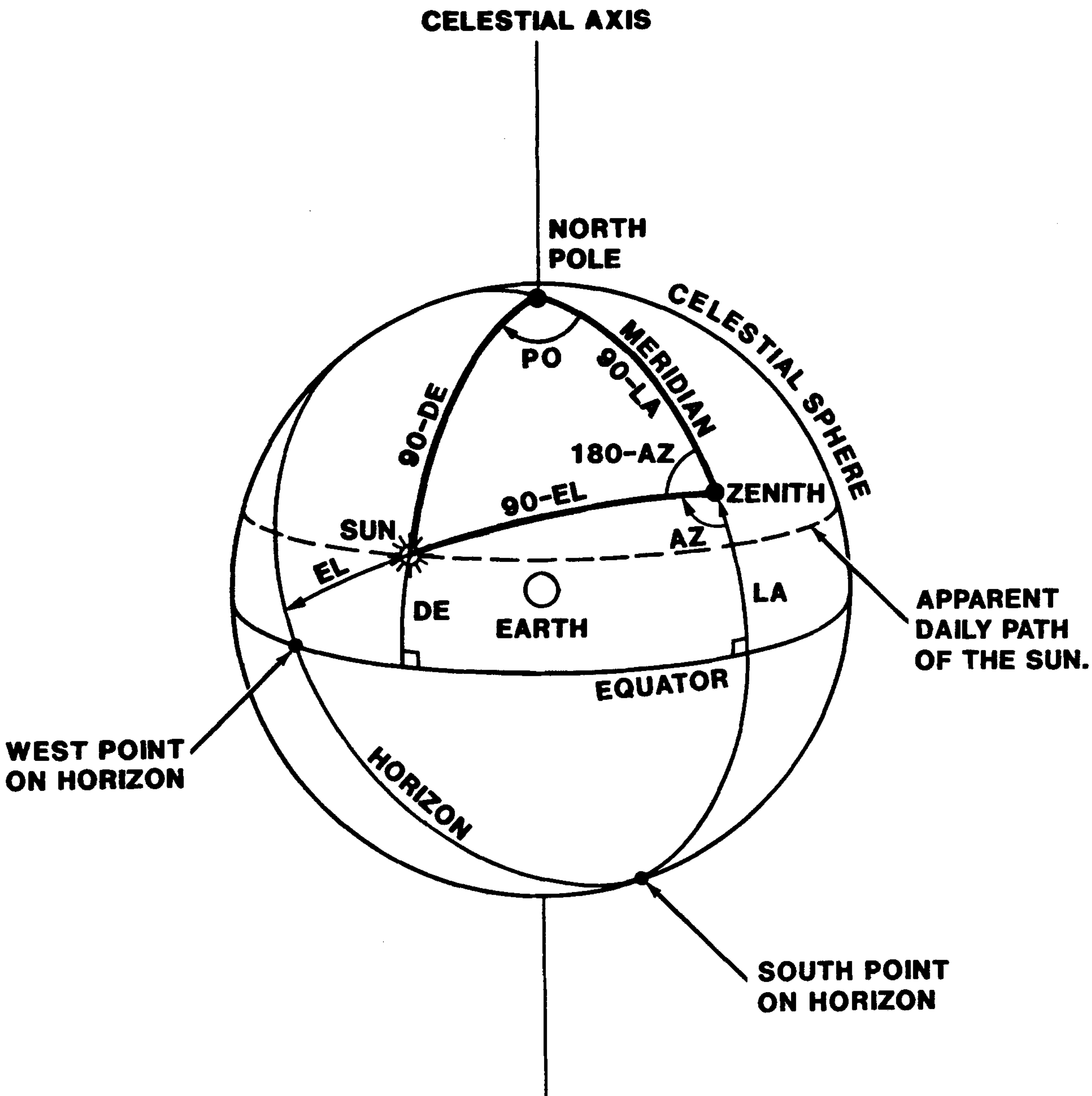
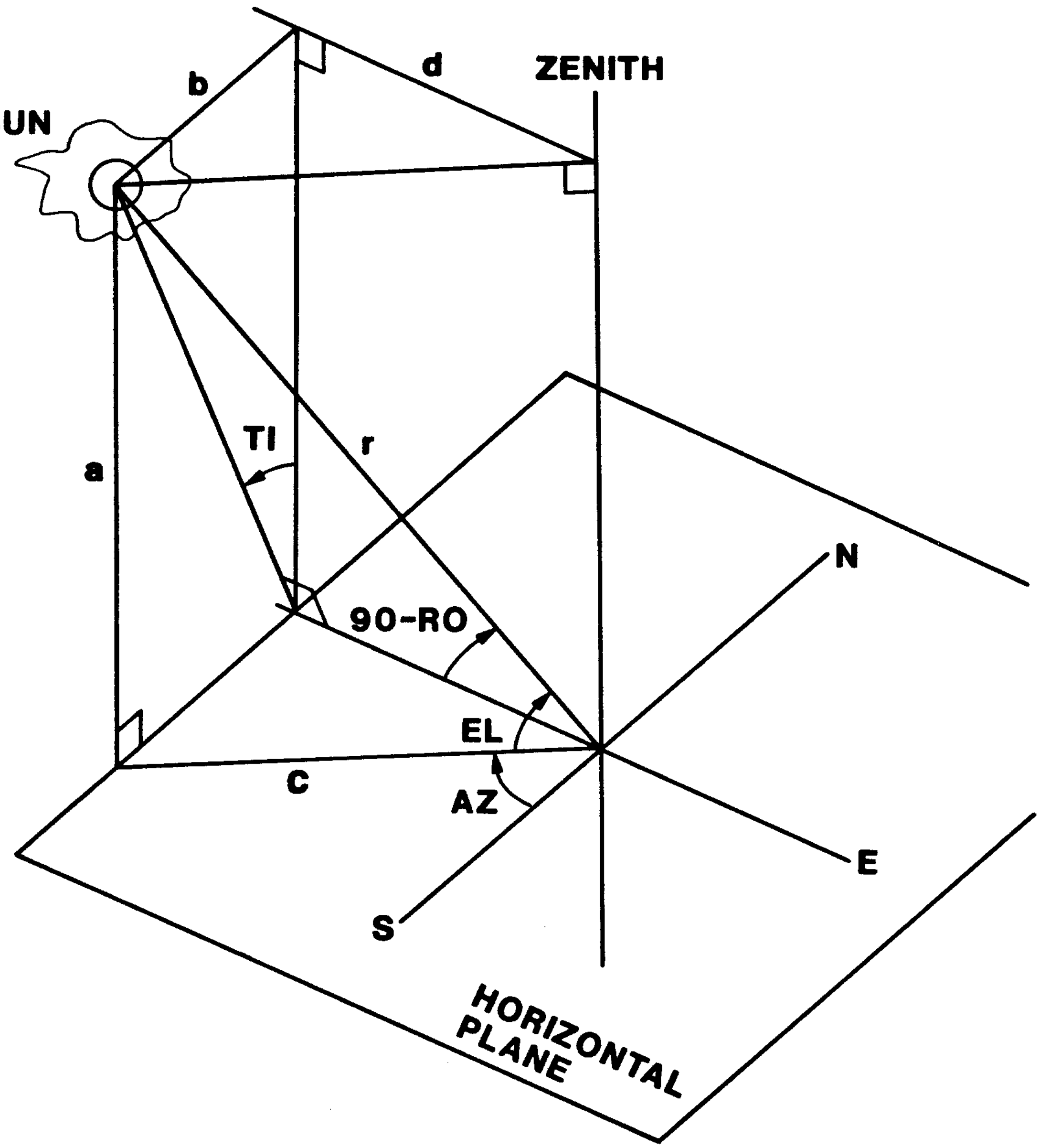


Figure 2. Geometric description of sun's location.



$$\tan EL = \frac{a}{c},\ \cos AZ = \frac{b}{c},\ \tan TI = \frac{b}{a}$$

$$\cos EL = \frac{c}{r},\ \sin AZ = \frac{d}{c},\ \sin RO = \frac{d}{r}$$

Figure 3. Azimuth-Elevation (AZ-EL) and Roll-Tilt (RO-TI) angles referenced from the earth's surface.

The PO-DE and AZ-EL angles can be found with respect to any position on earth if the latitude, longitude, and local time are known. For elevation angles less than 60 degrees, atmospheric refraction introduces a difference of 0.2 to 9 milliradians between the true sun position and observed sun position (the observed sun position will be the actual aim point for a solar collector). If the local temperature and barometric pressure are known, corrections can be made for refraction.

To calculate the sun's position to within 1 milliradian is not a difficult task, but it does require an accurate measurement of time and collector location. As an example of sun locating programs, a FORTRAN listing of the SUNAEP program by Walraven [1978] is presented in Appendix A. SUNAEP uses about 30 lines of FORTRAN to calculate the position of the sun and another 15 lines to correct for refraction. Tests conducted by Zimmerman [1981] indicate SUNAEP has a maximum error of 1 milliradian in azimuth and 0.2 milliradians in elevation over a period from 1979 to 1986.

Structures for Sun Tracking

Any number of structures could be devised for two-axis sun tracking, but there are currently three popular choices; (1) azimuth-elevation structures, (2) polar-declination structures, and (3) roll-tilt structures. These three systems are illustrated in Figures 4 a, b, and c.

In AZ-EL or "carousel" structures, the collector rotates about a vertical (zenith) axis for azimuth tracking and it turns on an axis parallel to the local horizontal plane for elevation tracking. This collector mounting system is often used for point-focus concentrators, photovoltaic (PV) arrays, and heliostats. Shown at the top of Figure 5 is a set of angles through which an AZ-EL tracking structure rotates when tracking the sun. Although Figure 5 is only for one particular day at one given location, it does demonstrate the complicated tracking instructions that a control system must provide for AZ-EL tracking.

PO-DE tracking structures (also called polar structures, equatorial mounts, or clock drives) are commonly used in dish receiver and PV applications. As shown in Figure 4b, polar tracking is accomplished by turning on an axis that is parallel to the earth's axis of rotation.

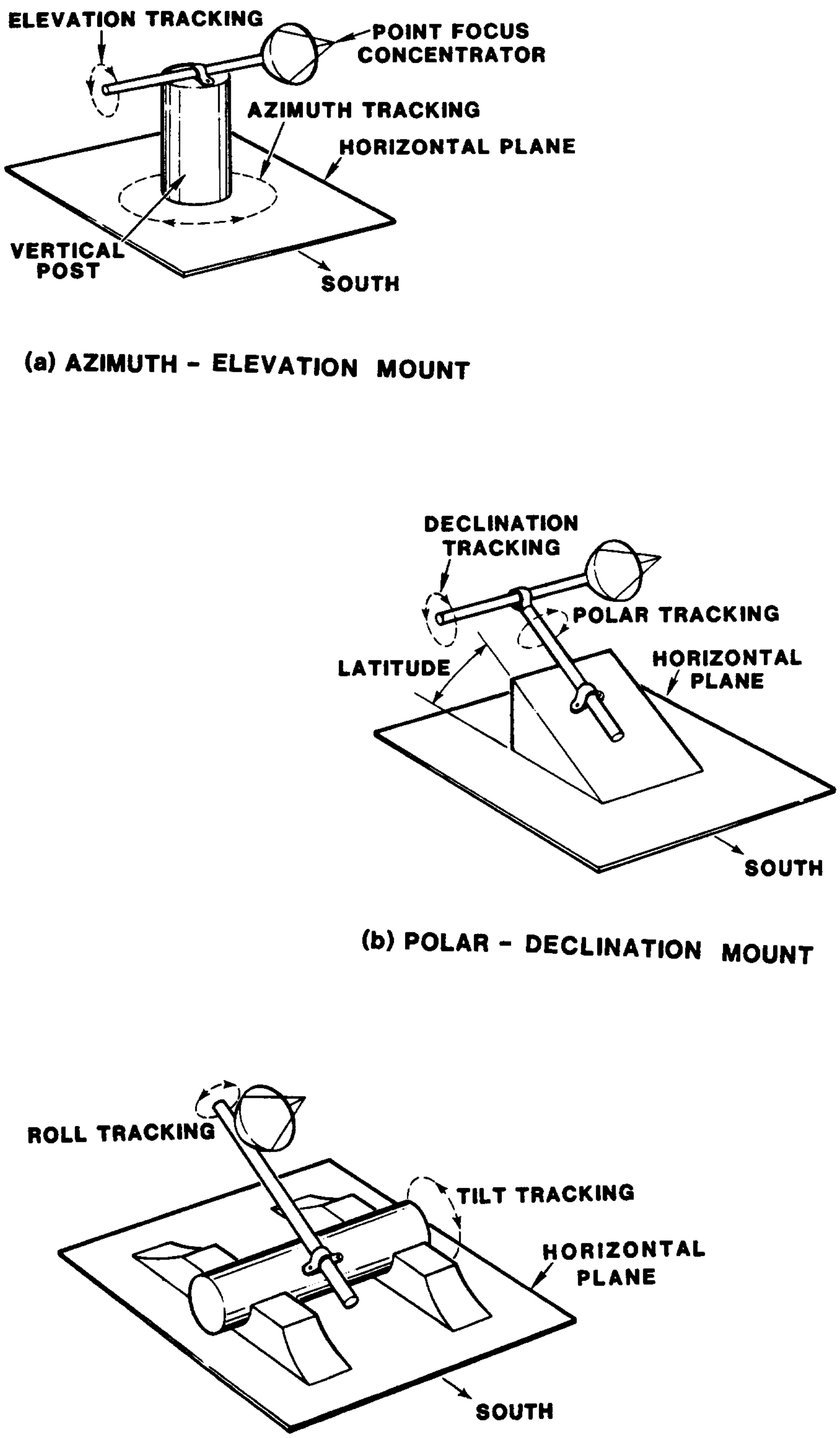


Figure 4. Collector mounts for two-axis tracking: (a) Azimuth-Elevation tracking structure, (b) Polar-Declination tracking structure, (c) Roll-Tilt tracking structure.

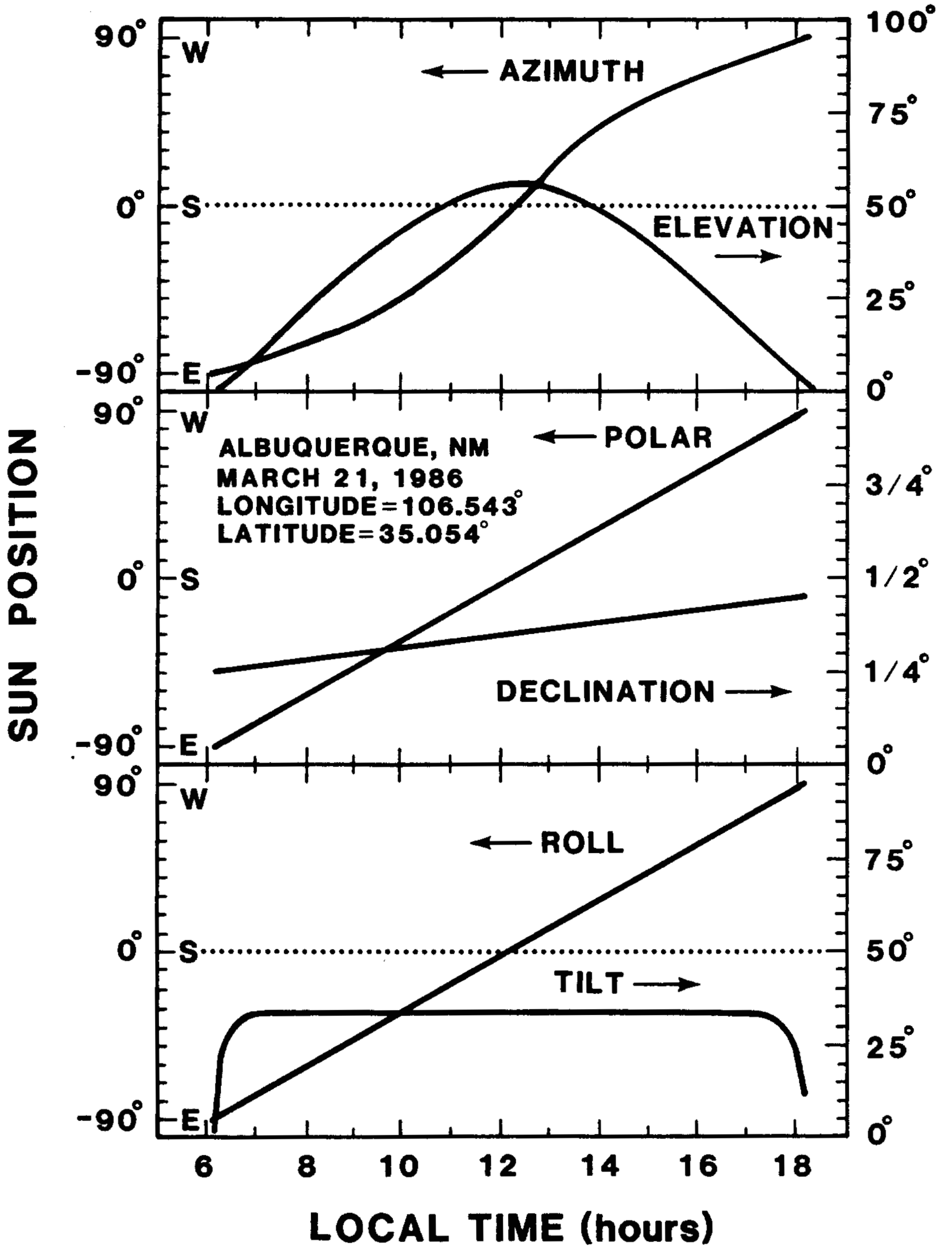


Figure 5. Sun position versus local time at Central Receiver Test Facility in Albuquerque, NM, on March 21, 1986. Shown are Azimuth-Elevation angles (top), Polar-Declination angles (middle), and Roll-Tilt angles (bottom).

Declination adjustments are made about an axis perpendicular to the polar axis. Shown in the middle of Figure 5 is a typical set of daily tracking angles for a PO-DE structure. With a clock drive structure, a constant rotational speed of 15 degrees/hour is needed for polar tracking. The declination speed varies over the course of a year, but it reaches a maximum rate of only 0.017 degrees/hour on the equinoxes. Therefore, with only a daily update on declination angle, the tracking error could still be less than 2 milliradians. Over a year, however, the declination angle will go from -23.45 degrees to +23.45 degrees.

Roll-tilt structures are used for PV arrays and two-axis tracking trough collectors. The relationship between roll-tilt (RO-TI) and AZ-EL angles is illustrated in Figure 3. For RO-TI tracking, the collector is tilted an angle, TI, below the zenith in a north-south-zenith plane and then rotated about the tilted axis to follow the sun. Figure 4c shows the rotating angle, RO, as it would be measured in a plane perpendicular to the tilted axis, between the focal axis of the collector and a north-south-zenith plane. RO and TI tracking angles are plotted as a function of time at the bottom of Figure 5. Once again, tracking angles do vary over the course of a year, so Figure 5 is provided only to demonstrate a typical daily rotation schedule.

Tracking Structure Problems

Tracking controls are directly affected by three structural and drive train problems: (1) structural misalignment, (2) motor coast, and (3) drive train backlash. These issues are introduced at this point because of the importance they have in later discussions.

In the previous description of tracking angles and structures, there was an implicit assumption that structures were properly aligned. However, structures are frequently not accurately aligned, and corrections are required. Mechanically aligning a structure is always possible, but it is usually expensive and time consuming. After the structure is mechanically aligned, the foundation can settle and the alignment will be lost. It is often simpler to compensate for alignment errors through the controls, rather than physically adjusting the structure. Correcting for structural alignment errors is one of the more important tasks of a control system, as will be shown in later discussions.

Another structurally related tracking error results from the discontinuous manner in which most collector systems track the sun. To continuously track the sun with a standard 1800 RPM drive motor, a speed reduction of nearly 2 million to 1 would be required. Most drive systems, however, have speed reductions of roughly 15,000 to 100,000 to 1 and the motors are pulsed on and off as tracking corrections are needed. The drive trains will continue to rotate for a short time after the motors are switched off and this in turn will rotate the collector. The distance a collector coasts before coming to a stop will depend on collector orientation, wind loading, and drive train characteristics.

Electromechanical brakes were used to reduce coast, but the braking system was unreliable and caused excessive wear on drive gears. Variable speed motors could be used to control acceleration and deceleration and to reduce both inertial shock and coast in the drive train. Controllers for these motors tend to be complex, though, making them expensive and prone to failure. A third option is to make allowances for coast in the tracking commands. This is an attractive option because no additional hardware is required.

A final structural problem that must be considered is caused by backlash in the drive train. With large speed reductions it is inevitable that some slop will exist in the drive train, but backlash might not be a problem if the collector is always driven in one direction by the motor. Unfortunately, wind and gravity loads can move the collector and reverse the backlash. Friction brakes and counterweights have been used to reduce backlash in previous systems, but these solutions place additional loads on the motors and drive trains.

Wind induced backlash was a serious problem in previous systems. It was cited as contributing to tracking instabilities at the Gila-Bend irrigation project [Alexander 1979], and similar instabilities were observed in the Omnium-G point-focus concentrator [Roschke 1984]. Because the wind provides so many possible loading conditions, it would be difficult to find a controls solution to backlash problems. However, backlash must be anticipated in the design of tracking controls, because of the limitations it places on pointing accuracies and the possibilities it creates for unstable tracking as conflicts arise between mechanical tolerances of a drive train and the sensitivity of instruments that measure tracking errors.

Required Tracking Accuracy

The magnitude of tracking error that is acceptable in a solar collector system directly impacts the cost and life span of control components. Systems with lower accuracy needs are cheaper to build and they require less cycling on motors, relays, etc. Lowered accuracies also reduce power parasitics since fewer motor starts are needed to reposition the collector (a typical induction motor draws 5 to 6 times more current to start than it uses to run continuously).

Accuracy requirements are a function of receiver target size, collector geometry, and sharpness of the reflected image at the receiver target. For the simple reflector/target system shown in Figure 6, a 1 milliradian (mrad) reflector rotation moves the focused image 0.4 meters (=2*0.001*100/cos 30). A 40 centimeter displacement might be acceptable if the target is large or if the displacement is imperceptible because the reflection is scattered by optical errors. However, the size of receiver targets and optical errors must be minimized in solar collector systems to reduce receiver thermal losses and required collector areas.

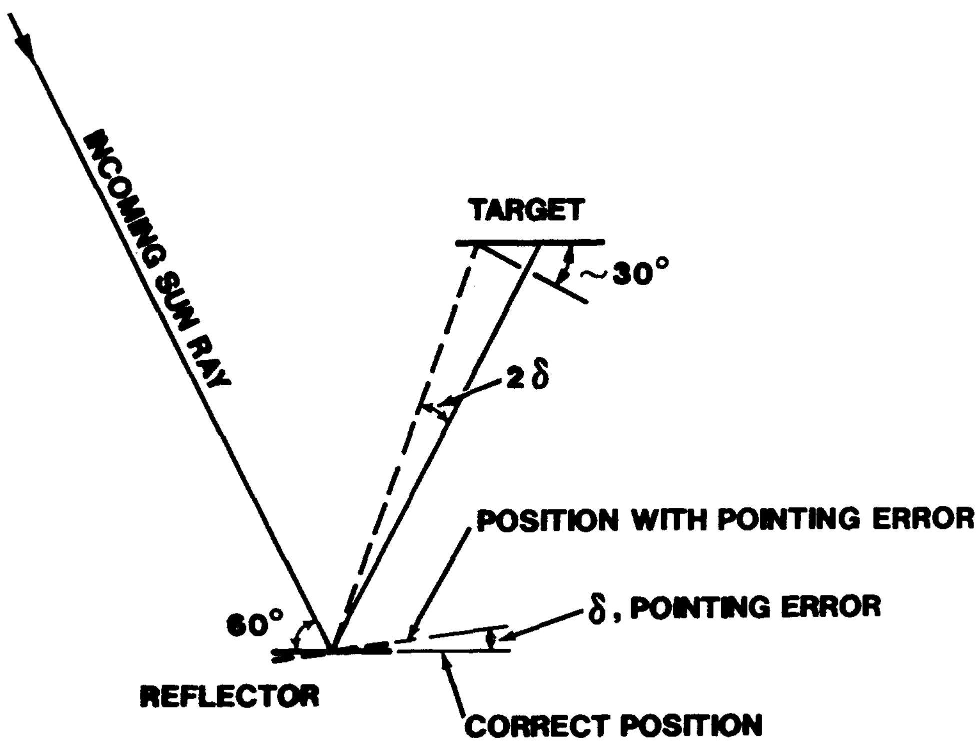


Figure 6. Pointing errors of a flat plate reflector.

Intercepting Sunlight

For optimizing point-focus collector designs, Jaffe [1982] developed expressions that correlate receiver target sizes, thermal losses, insolation levels, and concentrator errors (both optical and pointing). In Jaffe's model all errors are assumed to have Gaussian distributions so that the overall standard deviation of errors is given by,

$$\sigma^2 = (2\sigma_s)^2 + \sigma_\Omega{}^2 + \sigma_\alpha{}^2 + \sigma_p{}^2 \ , \tag{1}$$

where,

σ_s = standard deviation of collector slope errors,

σ_Ω = standard deviation of specular spread caused by the optical surface,

σ_α = standard deviation of angular spread resulting from the sun shape,

and,

σ_p = standard deviation of concentrator pointing errors.

Duff and Lameiro [1974] have shown that σ is related to the standard deviation of a Gaussian flux distribution at the focal plane by the transformation,

$$\sigma_r = \sigma \ F \ H(\Theta), \tag{2}$$

where,

σ_r = standard deviation of the focal plane flux distribution,

Θ = concentrator rim angle = 2 arctan(D/4F),

F = concentrator focal length,

D = concentrator diameter,

and,

$$H^2(\Theta) = 4 \ \{(2-\cos\Theta-1/\cos\Theta)/(3\sin\Theta) + 2(1-\cos\Theta)/\sin\Theta + 4\sin\Theta/3\cos\Theta + \ln[\tan(\pi/4-\Theta/2)/\tan(\pi/4+\Theta/2)]\}/\Theta.$$

Once the Gaussian flux profile is known, the ratio of energy entering the receiver aperture (which is assumed to be in the focal plane and along the focal axis) to concentrated energy reaching the focal plane is given by,

Φ = the intercept factor = $1 - \exp(d^2/8\sigma_r^2)$, (3)

where d = the receiver aperture diameter.

The intercept factor can illustrate the effect that tracking errors have on the amount of energy entering a receiver. For the baseline concentrator properties given in Table 2, Figure 7 shows the intercept factor as a function of standard deviations in tracking errors. Energy intercepted by the receiver drops only from 97% to 96% by going from zero pointing error to σ_p = 2 mrads. The intercepted energy drops rapidly, though, for any standard deviation in tracking error larger than a few milliradians.

Variations in collector properties from the baseline design are also shown in Figure 7. If the standard deviation of collector slope error is improved by 1 milliradian, tracking errors will have a small impact on the intercept factor (at least for smaller tracking errors). For the increase in σ_α that occurs at lower insolation levels (see Vittitoe and Biggs 1981), the intercept factor again shows a smaller decrease as tracking errors increase than was observed with the baseline concentrator.

It is assumed in Jaffe's model that the pointing errors have a Gaussian distribution with the highest probability of being directly on target. Most tracking systems, however, operate in a discontinuous manner by waiting for pointing errors to exceed some maximum before the collector is repositioned. This suggests that a better description of the error distribution might be a uniform distribution within predetermined limits.

The effect that deadband tracking (which is also called pulsed, on-off, or bang-bang tracking) has on the amount of energy passing through a receiver aperture was investigated by Hughes [1980]. Shown in Figure 8 is a focal-plane flux distribution that has been displaced at the target by a pointing error, δ_r (units of length, see note below). If the flux distribution, f(z), is radially symmetric, then the instantaneous intercept factor for any given tracking error is

Table 2. Baseline Properties for a Point-Focus Concentrator and Receiver.

COLLECTOR:

Dish Diameter, D=14 m
Focal Length/D, F/D=0.604
Reflectivity, ρ=0.96
Standard Deviation of Slope Errors, σ_s=3.5 mrad
Standard Deviation of Specularity Errors, σ_Ω=1.5 mrad

RECEIVER:

Aperture Diameter, d=0.4 m
Temperature, T_r=800°C
Absorptivity, α=0.96
Emissivity, ϵ=0.98
Heat Convection Coefficient, h_c=8 W/m^2

SURROUNDINGS:

Insolation, I=1000 W/m^2
Standard Deviation of Sun Shape Error, σ_α=2.3 mrad
Temperature, T_a=27°C

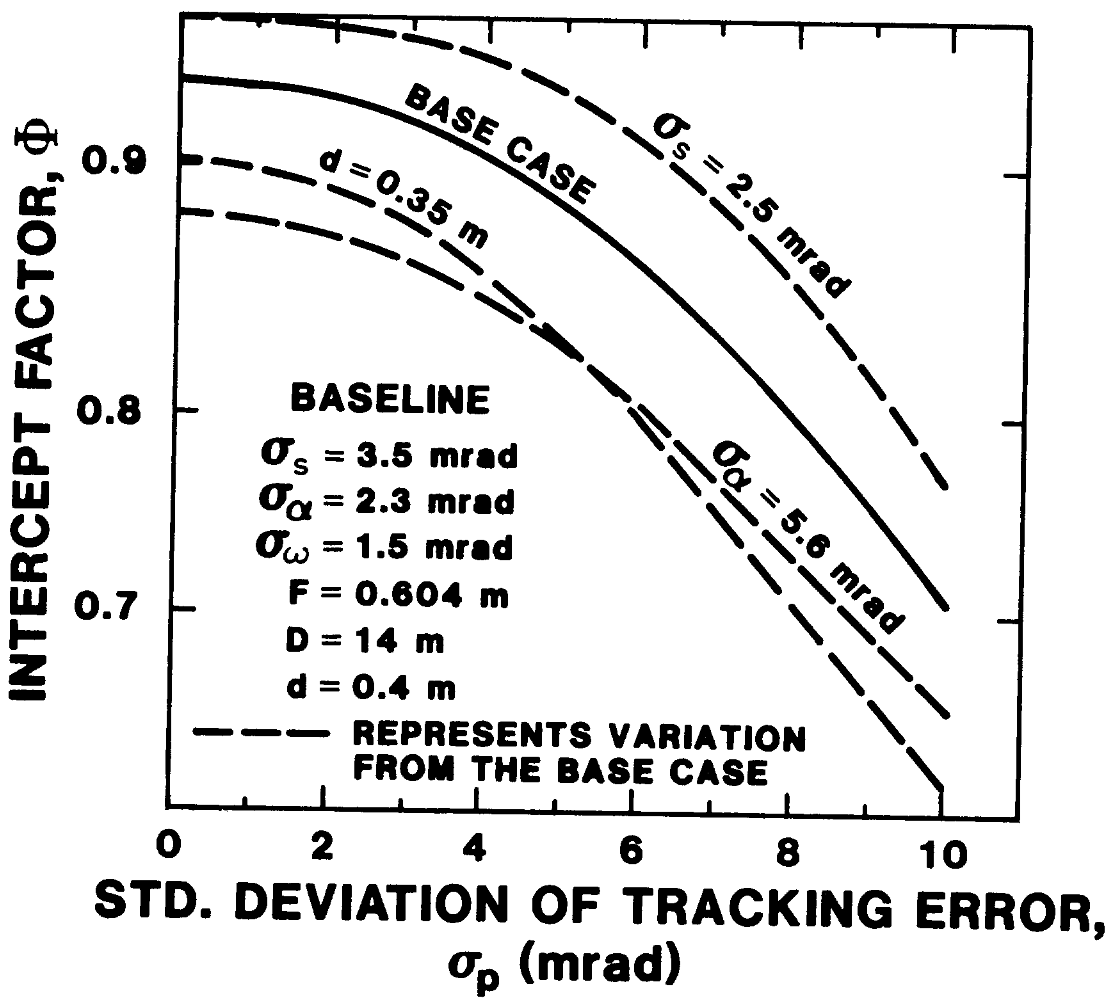


Figure 7. Variation of intercept factor with standard deviations in tracking errors (σ_p), slope errors (σ_s), and sun shape distributions (σ_α) for the baseline collector in Table 2.

$$\Phi(d,\delta) = \int_0^{1/2\ d - \delta_r} 2\pi z f(z) dz + \int_{1/2\ d - \delta_r}^{1/2\ d + \delta_r} 2 z f(z) \arccos\left[(z^2+\delta_r^2-d^2/4)/2z\delta_r\right] dz, \quad (4)$$

$$0 \le \delta_r \le d/2 \ .$$

The instantaneous intercept factor can then be integrated over the deadband tracking error distribution shown in Figure 9 to give the average intercept factor,

$$E[\Phi(d,A)] = \int_0^{2\sqrt{A_r}} h(r)\Phi(d,r)dr, \qquad 0 \le A_r \le d/2\sqrt{2}, \quad (5)$$

where,

A_r = the tracking error deadband limits (units of length),

and,

$h(r)$ = the pointing error density function

$$= \begin{cases} \pi\ r\ /2\ A_r^2, & 0 \le r \le A_r \\ 2\ r\ [\pi/4 - \arccos(A_r/r)]/A_r^2, & A_r < r \le \sqrt{2}A_r . \end{cases}$$

Using Equations (4) and (5), the instantaneous and average intercept factors were calculated for the baseline collector properties in Table 2. The Gaussian flux distribution was assumed not to be affected by tracking errors. Because of this assumption, σ_r = 7.65 cm at the focal plane for all pointing errors. Both $\Phi(d,\delta)$ and $E[\Phi(d,A)]$ are presented in Figure 10 as functions of tracking errors, δ, and tracking error deadband limits, A.

(Note: Pointing errors δ and A are both in mrads. The relationship between displacement of the flux distribution at the receiver, δ_r, and concentrator pointing errors, δ, is not a simple function, but the expression $\delta_r = F\cdot\delta$ is often used for small tracking errors. For the example shown in Figure 10, the CIRCE cone optics code [Ratzel et al. 1986] was used to determine the correlation between δ and δ_r.)

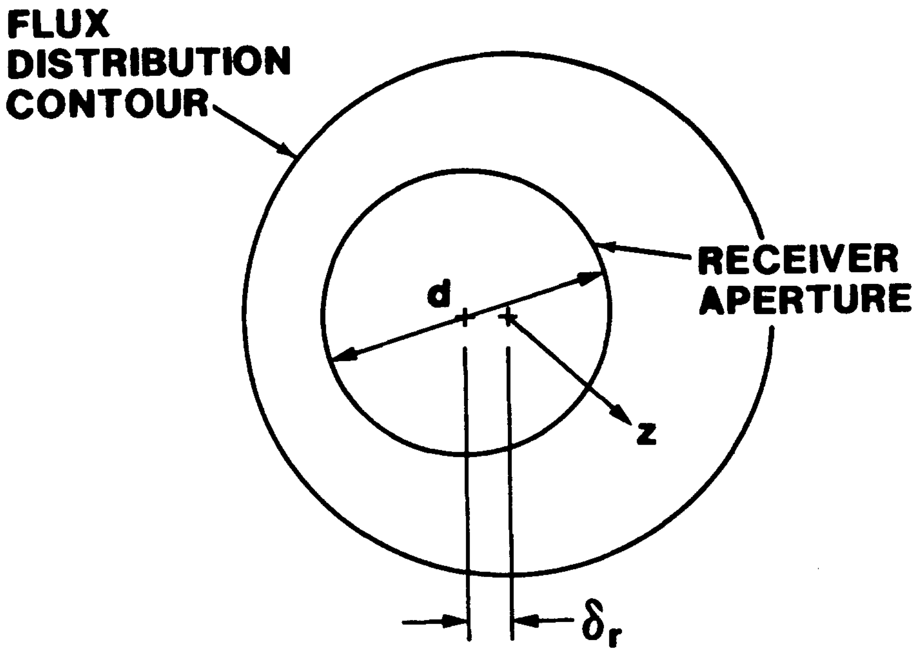


Figure 8. Geometry of flux at the focal plane.

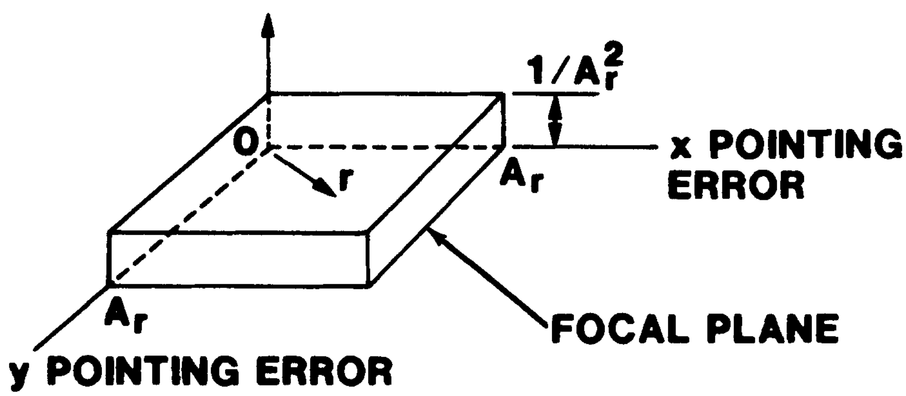


Figure 9. Geometry of deadband limits on tracking errors.

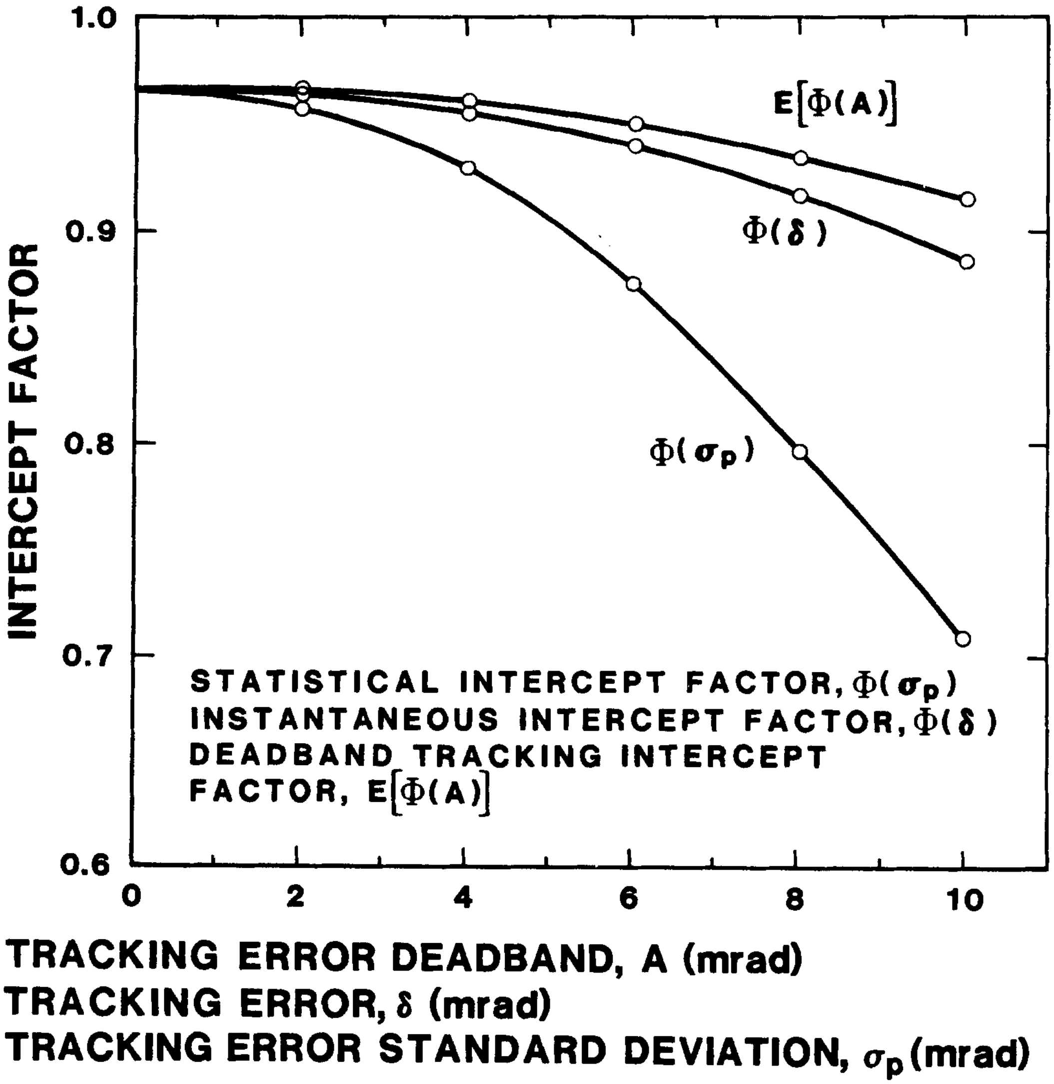


Figure 10. Comparison of intercept factors for baseline collector properties in Table 2 calculated by three procedures: (a) Statistical intercept factor $\{\Phi(\sigma_p)\}$ for standard deviation in pointing errors $\{\sigma_p\}$, (b) Instantaneous intercept factor $\{I(\delta)\}$ for fixed tracking errors $\{\delta\}$, and (c) Expected intercept factor $\{E[\Phi(A)]\}$ for deadband tracking errors A.

If an initially focused dish remains stationary for 1 minute before it is refocused, the value of A would equal 4.36 mrads. In going from zero tracking error to a 4-mrad limit on pointing errors, the average intercept factor drops from 97% down to 96%. A similar drop was predicted to occur in Figure 7 with a 2-mrad standard deviation of tracking errors. This indicates that tracking restrictions less stringent than those predicted by Jaffe's model might be used in deadband tracking systems. It also should be noted that average intercept factors identical to those in Figure 10 would be obtained if the deadband extended from -A to +A. By using symmetric deadband limits the tracking mechanism will remain stationary longer and the duty cycle on tracking hardware will be reduced.

Before concluding that tracking errors will have less of an adverse effect on intercept factors than was predicted by Jaffe's model, it should be restated that Hughes' model assumed tracking errors had no effect on the focal plane flux distribution. However, work by Ratzel et al. [1986] appears to justify this assumption for small tracking errors. This justification is illustrated in the next section.

<u>Flux on the Aperture Plate</u>

Energy that is not intercepted by the receiver will heat the plate that surrounds the aperture. This plate is usually not actively cooled, so special tracking considerations must be made to avoid destroying it. In the central cavity receiver used in Almeria, Spain, for example, certain portions of the field cannot be used in mornings and evenings because of energy that they spill onto the front of the cavity. For point-focus receivers it is also important to know the intensity of radiation on the aperture plate.

The CIRCE cone optics code by Ratzel and Boughton [1986] produces target plane flux maps for dish concentrators. In this code, the target flux density distribution is computed by convolving concentrator errors with the solar intensity profile (sunshape). Presented in Figure 11 are flux profiles at the receiver plane for the baseline concentrator in Table 2 and four levels of tracking errors, 2, 4, 6, and 8 mrads. The size and shape of the flux profiles remain relatively constant for these small aiming errors. For tracking errors of 2, 4, and 6 mrads the flux impinging on the lip of

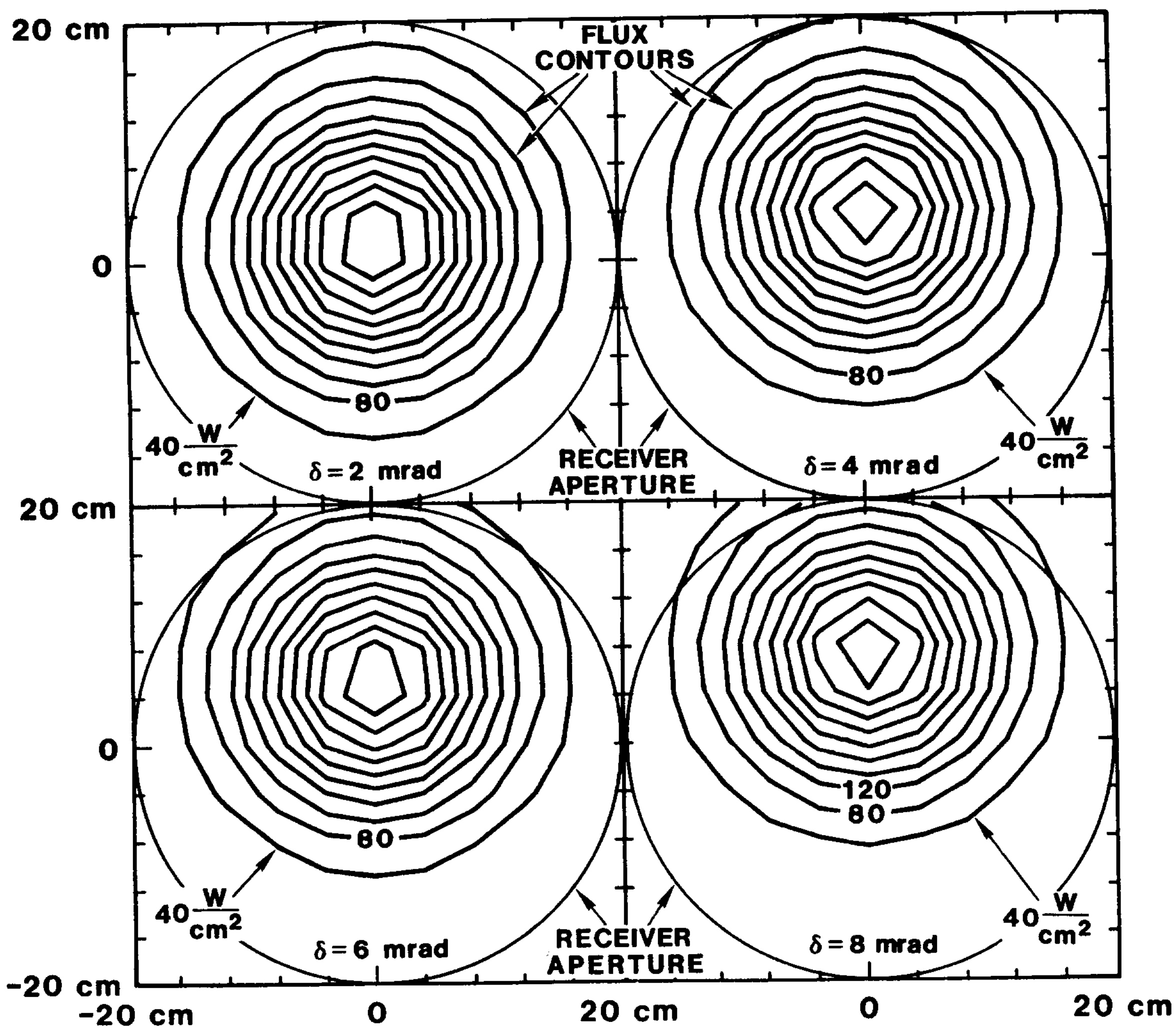


Figure 11. Flux distributions at the receiver for 2, 4, 6, and 8 milliradian tracking errors and baseline collector properties in Table 2.

the aperture plate is approximately 10, 40, and 70 W/cm². This result implies that the thermal flux on the aperture lip would reach about 46 W/cm² after the initially focused collector remained stationary for 1 minute.

The maximum thermal flux allowed on a receiver aperture lip was 10 W/cm² in the innovative concentrator design requirements [Thostesen 1984]. However, the maximum survivable flux intensity is a function of the aperture plate design and material. There is still controversy as to the levels of thermal flux that should be accepted. Limited tests have shown that passively cooled copper plates can survive flux levels in excess of 500 W/cm² for more than 2 minutes [Jaffe 1983]. Theoretical analyses by Wen and Roschke [1982] also indicate that copper aperture plates could withstand high insolation levels (approximately 200 W/cm²) for a few minutes between position updates. Further studies are needed to determine the effects of thermal cycling on aperture plate materials.

Overall Collector Efficiency

Intercept factors can be increased, and thermal flux on the receiver aperture can be decreased by using a larger receiver aperture. However, there is a penalty for increasing the receiver aperture because the thermal losses also increase.

The acceptable size of a receiver aperture is a function of the reflector's optical quality, the receiver's absorptivity, and the receiver's thermal losses. This relation is generally expressed in terms of the collector efficiency,

$$\eta_{coll} = \frac{\text{(heat transfer to the working fluid)}}{\text{(direct solar power incident upon the concentrator)}}$$

$$= \rho G \Phi \alpha - [\epsilon\sigma_{SB}(T_r^4 - T_a^4) + h_c (T_r - T_a)](d/D)^2/I, \qquad (6)$$

where,

Φ, D, and d were defined in Equation (3),

I = direct solar flux incident upon a plane perpendicular to the concentrator,

ρ = reflectance of the concentrator mirror,

G = geometric shadowing factor (fraction of direct insolation not blocked from the concentrator),

α = absorptance of the receiver for sunlight,

ϵ = emittance of the receiver for thermal radiation,

σ_{SB} = Boltzmann's constant,

T_r = absolute temperature of the receiver,

T_a = absolute temperature of the surroundings,

and,

h_c = convection coefficient at the receiver aperture.

Equation (6) is similar to the definition found in Jaffe's work [1982], except here conduction losses are neglected. The ratio $(D/d)^2$ in Equation (6) is usually referred to as the geometric concentration ratio, since it relates the collector aperture area to the receiver aperture area. This is not the same as a power concentration ratio, which includes reflection losses and optical errors.

Figure 12 shows the effect that receiver aperture size has on collector efficiency. For the example baseline collector properties of Table 2, the maximum collector efficiency is obtained for a geometric concentration ratio 1100, which corresponds to a receiver aperture diameter of 42 cm. As the concentrator slope errors become larger, the optimum geometric concentration becomes smaller (the receiver aperture becomes larger) and more narrowly defined as shown in Figure 12. For a decrease in receiver temperature, thermal losses will also decrease and a larger receiver aperture can be used.

Off-design operating conditions must be considered in selecting the diameter for a receiver aperture. Both reflectivity and insolation levels will vary from design conditions. Figure 12 shows that as reflectivity decreases, the optimum concentration ratio will increase but the collector effeciency peak will broaden and become less defined. As the insolation decreases and the sun shape distribution, σ_α, increases, the optimum geometric concentration ratio becomes smaller, and the peak is more narrowly defined. Based on these observations, it would probably be reasonable to

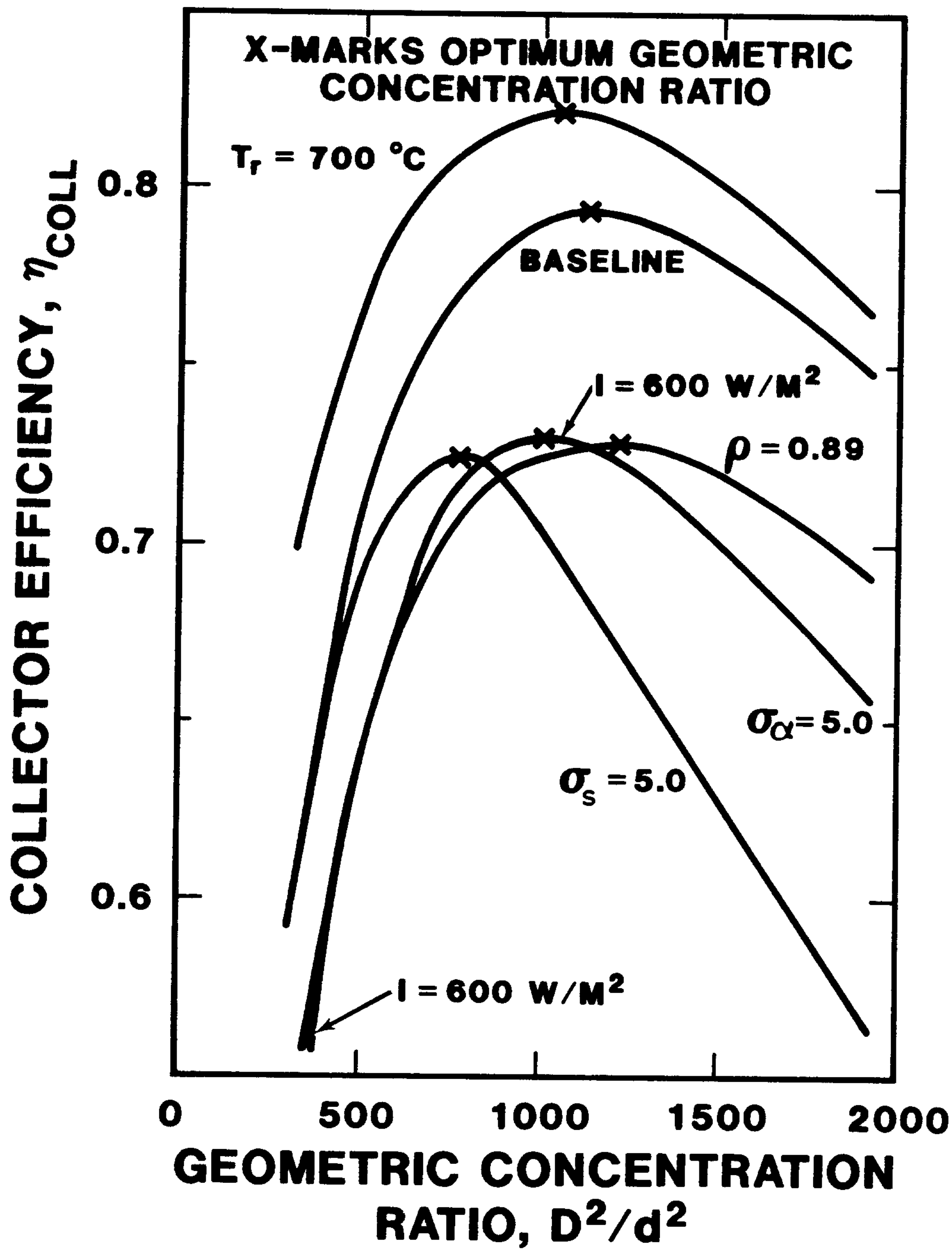


Figure 12. Collector efficiency as a function of geometric concentration ratio (i.e., receiver aperture diameter) for the baseline collector properties in Table 2 with no tracking errors.

choose a diameter for the receiver aperture that is slightly larger than that determined by design conditions to accommodate off-design operating conditions. Selecting a slightly larger receiver aperture will, of course, also reduce the tracking accuracy requirement.

Open-Loop vs. Closed-Loop Tracking

Sun tracking procedures are generally classified as either open-loop or closed-loop. In an open-loop system, the collector is aimed toward a calculated location of the sun, and for closed-loop tracking, the collector is aimed toward a sensed sun position. Open-loop tracking is also referred to as clock, ephemeris or synthetic tracking, and closed-loop tracking is also called sensor tracking. Line-focus collectors and photovoltaic arrays commonly use closed-loop tracking and heliostats generally use open-loop tracking. Many systems use a hybrid combination of open- and closed-loop systems.

In an open-loop tracking system the controls find the position of the sun, either through calculations or look-up tables, and then they calculate the required orientation of the collector. This required orientation is compared with the collector's measured orientation and, if aiming errors are beyond acceptable limits, the drive motors are started to update the collector's position.

Even though open-loop tracking sounds simple, there are some inherent problems because of the aiming accuracy required for solar collectors. First, the sun-position calculations require high-level programming capabilities and an accurate assessment of time. Second, the precise alignment of the tracking structure with respect to the earth must be known. Third, an accurate measurement of the collector's orientation with respect to the tracking structure is required. This need for accuracy can make open-loop tracking expensive, and it can make a system vulnerable to errors caused by aging structural components and settling foundations.

Many of these problems are avoided in closed-loop tracking systems. In a closed-loop system, feedback on aiming errors is provided by instruments that sense either the presense of shadows cast by the sun or the location of the sun's reflected image. When the sensed errors exceed some predetermined threshold value, the tracking motors are activated to drive the collector into the proper position.

Closed-loop tracking has one major drawback; the sun must be visible to the sensor. If the sun is hidden by a cloud or is in a portion of the sky that is not in the sensor's field of view, no tracking error will be measured and no position update commands will be issued. (Some systems have used search routines to scan the sky when the sensors lose the sun, but this solution has not been entirely satisfactory [Cameron and Dudley 1986].) A second problem with closed-loop tracking is that sensor outputs are usually dependent on insolation levels. This problem, which is discussed further in the section on tracking sensors, makes it difficult to obtain the same level of tracking accuracies at low insolation levels that were available at high insolation levels.

Many system use a hybrid combination of open- and closed-loop tracking to take advantage of the best features of each option. Open-loop tracking is used to position the collector at the begining of a day and to provide tracking during cloud cover. Closed-loop tracking gives the system an accurate aiming capability that is not affected by structural misalignments or imprecise measurements of the collector's position. Using the sensor tracking system to "fine tune" the collector's aim also allows less expensive harware to be used in measuring the collector's orientation and less precise computations to be performed in calculating the sun's position (at least this has been the general perception in the past).

One major problem that remains in a hybrid tracking system is determining the insolation level at which the system should switch from a closed- to an open-loop mode. If the insolation threshold is too high, the system may be forced to rely on a crude ephemeris tracking system at moderate insolation levels. In the Vanguard system, using a high threshold resulted in melted receiver components because the concentrator was improperly aimed [Droher 1986]. Too low a threshold can also cause problems, since it would permit sensor tracking during cloud cover, and the collector could end up following the brightly back-lit edge of a cloud.

When sensor tracking is used to predict and correct errors in a synthetic tracking system, the problem of selecting a threshold to switch between the tracking modes is avoided. Baheti and Scott [1980] proposed such a system and they also gave an algorithm for estimating alignment errors and projecting the error corrections for different collector orientations. Some heliostat and dish collector systems are currently using methods to predict and correct tracking errors when feedback on tracking errors is available (see section on tracking systems). Of course, these systems require a fairly sophisticated synthetic tracking system to use an error-predicting scheme, but as computational prices decrease this is becoming less of an obstacle.

Hardware Considerations

Tracking controls vary from one system to another. In some systems the control logic is provided to a field of collectors from a central computer, and in other systems the logic originates from a controller located at each collector. There are also tracking systems in which control logic is hardwired (i.e., not resident in software), and in other systems, the logic is programmed into microprocessors. Because of all the differences, there is no generic description that will cover all tracking control systems.

To avoid trying to describe all control systems in detail, a general hybrid (open/closed-loop) tracking control system is presented in this section, and then the available hardware options are discussed. Hardware and control strategies that are used in existing solar facilities are described in the next section on tracking systems.

Six components that are commonly found in hybrid tracking systems are shown in Figure 13. The four essential elements are (1) A tracking control unit (TCU) to provide tracking logic for the system, (2) Sun sensors to provide feedback on aiming errors, (3) Motor controllers to start and stop the motor when commanded by the TCU, and, (4) Encoders to provide information on the collector's orientation to the TCU. Two other elements that should also be included in the system are (5) Reference switches to set or recalibrate encoders, and (6) Limit switches to prevent the collector from overshooting rotational limits in the event of a control failure.

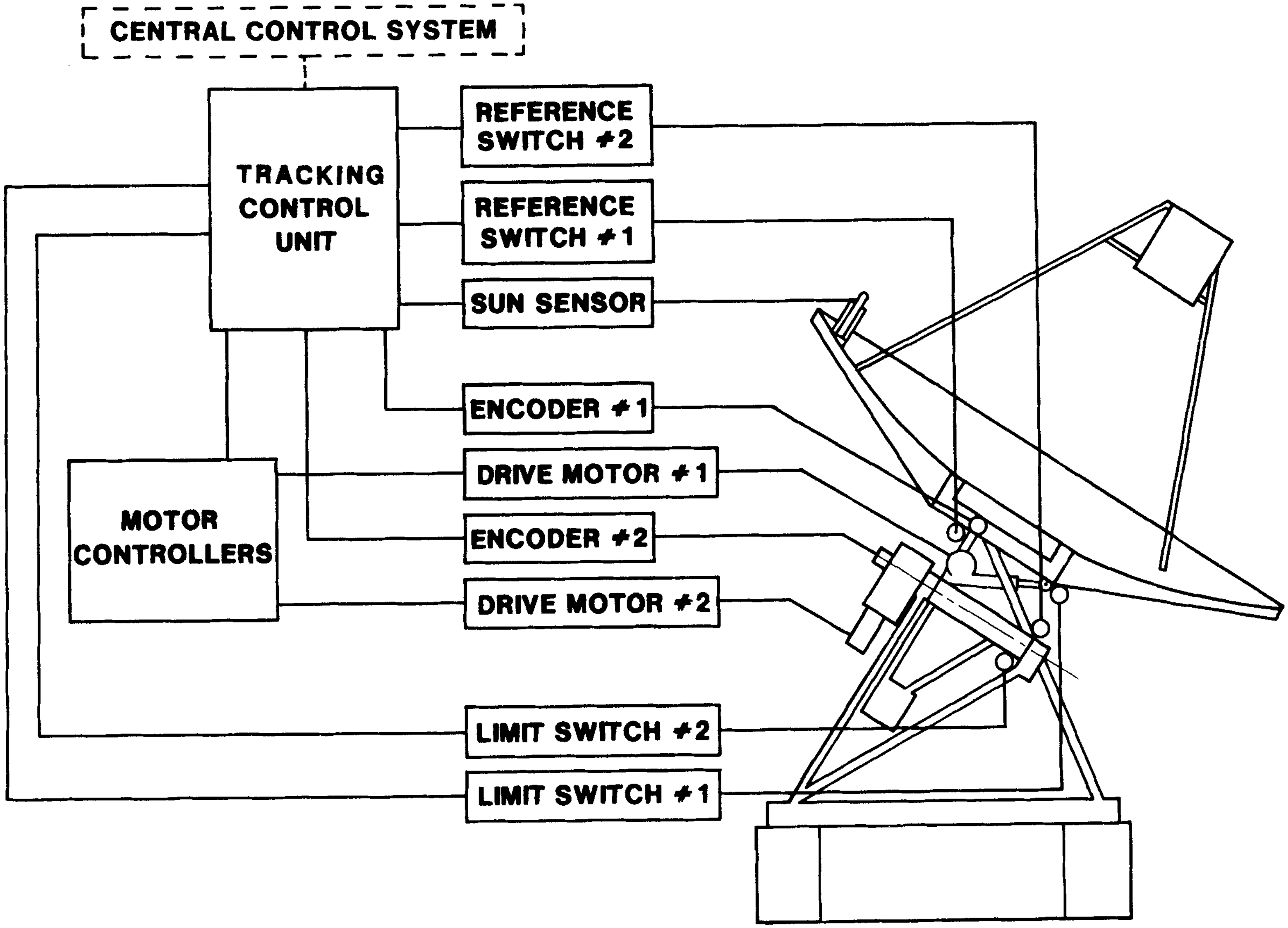


Figure 13. Components of a tracking control system.

Tracking Control Unit

A TCU is the local brain for tracking control, and as such, it needs to communicate with sensors on the collector and a master control unit for the field of collectors. Illustrated in Figure 14 is a block diagram of the communication route in a typical tracking control system. All logic in a TCU is performed by a microprocessor. Input/output (I/O) interfaces are provided for communication between the microprocessor and the sensors. Based on information about the sun's location and the collector's orientation (as indicated by the encoders), tracking commands are issued to the motor controllers and the collectors are driven to the proper orientation.

Most tracking systems use custom-made TCUs. Tailoring electronics to the application was necessary in early systems because low-cost controllers with the sophisticated logic needed for tracking were not available. Today, industrial programmable computers (IPCs) are available in sizes and with capabilities that are compatible with the needs of collector tracking systems.

Customized Electronic Controllers--Customized controllers are usually built around a single programmable microprocessor chip with enhanced arithmetic logic. Memory capacities in these systems vary from 16 to 128 kilobytes depending on the tasks that the controller must perform. Typically, 8 kilobytes (or more) of random access memory (RAM) is available to allow programs to be modified easily. The remaining memory is either EPROM (erasable programmable read only memory) or EEPROM (electrically erasable read only memory). EEPROM has an advantage over EPROM in that programs can be altered with a manual programming unit or a host computer. [Read only memory (ROM) is the system memory that is generally reserved for microprocessor executive programs and is not included in the applications programming specifications.]

In the evolution of customized controllers several features have surfaced that should be included in future systems. These features are as follows:

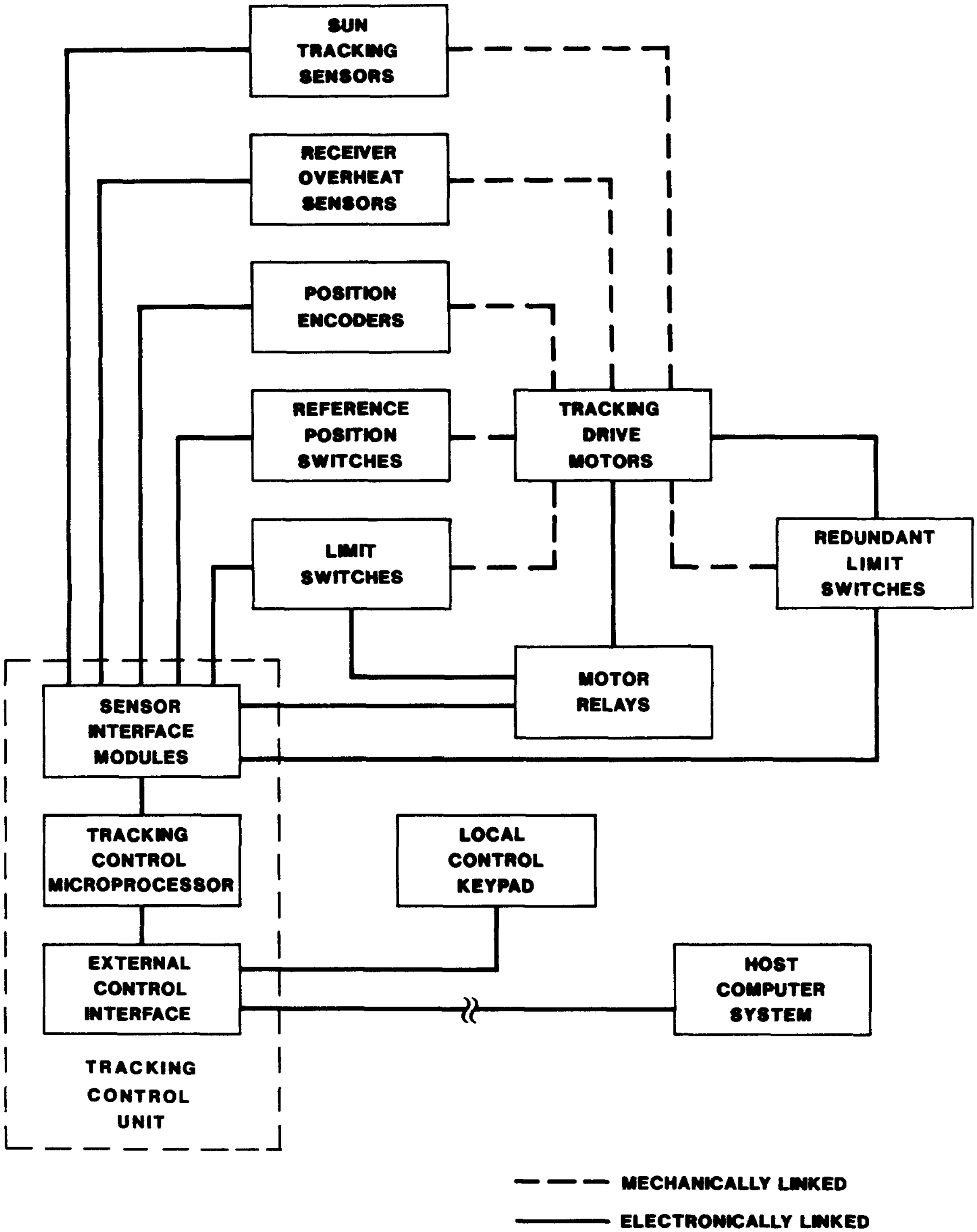


Figure 14. Communication routes in a tracking control system.

(1) A battery back-up on the RAM and an internal clock (if applicable).
(2) Manual control capability at the concentrator.
(3) Diagonistic routines to detect malfunctions in the controller and controlled devices.
(4) Fail-safe measures that drive the concentrator to a safe position during control failures.
(5) Simplified maintenance procedures that can be done by nonspecialized personnel.
(6) The ability to download program modifications to a field controller from a host computer and the ability to transmit error messages from the field to the host.
(7) Software interpretation of sun sensor signals rather than hardwired control logic.

Two other attractive options for prototype TCUs are (1) the ability to modify operating strategies through software changes, and (2) the use of higher level programming languages. The ability to change control characteristics with a simple, English-like programming language may not be important in a system with established control routines, but until routines are thoroughly tested there will be a need to make modifications. Cumbersome control languages and hardwired control logic have led to unresolved control issues in previous prototype control systems [Stallkamp 1985; Droher and Squier 1986].

Temperature extremes have frequently caused problems in CCUs. Solid-state electronics do have limitations on operating temperatures, typically 0° to 60°C. At the CRTF in Albuquerque, NM, failures were reported to occur at temperatures around 0°C [Holmes 1981]. Simply replacing the components as they fail has been the normal solution to this problem [Stallkamp 1985], but after a few seasons of thermal cycling, the problems are likely to recur. Thermal pretesting of components before they are installed and selecting components with extended operating ranges have apparently eliminated temperature-related TCU failures at Solarplant One [Payne 1987].

Condensation or water leakage in the TCU enclosure has also been a major source of control failures. As a result of moisture in the TCU, oxide films will form at connector interfaces and cause intermittent open-circuit connections. Digital control systems can be quite susceptible to these high impedance transients, and the origin of the problem is usually difficult to locate [Martin and Noon 1986]. Moisture can also permeate the polymer-coated protective jackets surrounding most resistors and capacitors and destroy the sensitive materials inside these components. For analog circuits, moisture-related failures are usually caused by electrical leakage between adjacent connectors on a circuit board.

Installing seals and rainproof vents reduced water intrusion problems in the CRTF heliostat controllers [Holmes 1981], but constructing completely sealed enclosures is not the solution to condensation problems. Heat dissipation is required for digital electronic systems, so some ventilation to the environment must be provided. In the Vanguard system moisture buildup was reduced by leaving the TCU continually activated [Droher 1986], and in some of the MISR controllers, resistance heaters were provided to reduce condensation and protect the control electronics from low temperatures [Dudley 1987]. Heating the enclosure air appears to have worked for the limited periods in which these systems were tested. Corrosion problems, however, are long-term problems, so long-term testing is required to assess the effectiveness of any solution.

Industrial Programmable Controllers--IPCs are built for an industrial environment, they are thoroughly tested, and they already include many of the features cited as desirable in customized controllers. What follows are some of the aspects that might make using IPCs an attractive option for concentrator controls.

(1) Modular I/O interfaces that plug in and allow failed modules to be quickly replaced.
(2) Special interfaces that allow certain devices (such as thermocouples and strain gages) to connect directly to the controller.
(3) Interfaces with built-in protection features such as optical isolators on I/O ports.
(4) High-level programming languages (such as BASIC) and floating point math that allows greater programming ease.
(5) Capability of self-diagnosis and diagnosis of the controlled machine or process.

(6) Automatic power reset that allows the IPC to start up and resume operating after a power failure or brown-out.
(7) Lowered power requirements (and therefore lowered cooling requirements) through the use of CMOS technology.
(8) Surface-mounted circuitry that allows electronics to be cooled by conduction and limits the exposure of electrical components to ambient air.

Even if IPCs are not used as TCUs, many of the above features should be adopted in the customized TCUs. (Some of them already have been adopted in custom TCU designs on a rather limited basis). Like custom-made TCUs, IPCs still have limits of about 0° to 60°C on operating temperatures, and they should not be used in condensible atmospheres. Special enclosures must be provided to operate in the collector field environment.

IPCs have an established foundation for technical support and they are compatible with many commercial computer systems. Presently, industrial personal computers and interfacing modules cost about $1500 to $2000 (which is estimated to be two or three times the cost of components in custom-made controllers). This might limit their use to small or prototype facilities where development costs of custom controllers cannot be spread over a large number of copies.

<u>Position Encoders</u>

Encoders (or position transducers) are used to measure the rotation of the collector. These measurements are made in either an absolute or an incremental sense. Absolute encoders give a unique signal for every rotary position of the encoder shaft, and incremental (or differential) encoders register only that the encoder shaft has rotated through a predetermined step. To find the absolute angular rotation using a differential encoder, it is necessary to count the number of steps that are registered.

<u>Optical Encoders</u>--In this form of absolute encoder, light from a filament lamp or a light emitting diode (LED) passes through a rotary disk and illuminates phototransistors. The disk has transparent and opaque sections that allow only certain phototransistors to be illuminated. By arranging transparent sections in a binary or gray code pattern, angular positions of

the rotary disk are converted to binary or grey code signals. The signal produced has a digital format that can be directly interpreted by a CCU microprocessor. A 13-bit optical encoder can provide an angular resolution of 0.8 mrads ($2\pi/2^{13}$ radians). However, optical encoder readings are generally considered to be the least significant bit, so if accuracies better than 1 mrad are needed, a 14-bit optical encoder should be chosen.

Optical encoders are very susceptible to soiling. Rust, dust, and moisture frequently caused problems in the CRTF optical encoders. These encoders also experienced difficulties because manual adjustments were required to change the light sensitivity of photosensors as the encoder aged [Holmes 1981]. (In many newer optical encoders, photosensor sensitivity levels are automatically adjusted.) By using special weathertight seals, soiling problems were reduced in optical encoders at Solar One. However, Solar One's optical encoders had recurring problems with filament lamp failures [Lopez 1986]. This problem was eliminated by replacing the filament lamps with LEDs.

Optical encoders with an extended operating temperature range (-55° to +85°C) and weathertight shaft and cable seals will cost from $900 to $1200 when purchased in small quantities. If hundreds of optical encoders are being purchased, these prices will drop by about 50%. Very little price reduction will be obtained past this 50% decrease.

Potentiometers--This form of absolute encoder costs about one-half to one-fourth as much as an optical encoder with an equivalent accuracy rating (≈0.8 mrads). In potentiometers a wiper moves along a coiled resistance wire so that angular rotation can be measured as an electrical resistance. Unlike optical encoders, potentiometers offer analog signals so their signals must be digitized to be interpreted by a microprocessor. Accuracy of a potentiometer is limited by the coiled wire's length and property linearity. The wire length affects the encoder's resolution. Linearity effects can be minimized by referencing the midpoint of an encoder's travel to the midpoint of a collector's rotation [see Alvis and Rosborough 1982].

At the STEP facility, wipers in potentiometers tended to foul because of insufficient weatherproofing. This caused gross errors in determining dish orientations and eventually led to the replacement of potentiometers with Hall-effect transducers [Hicks 1986]. Trough systems frequently use potentiometers with internal pendulums so that the absolute inclination of a collector is given. These potentiometers or "inclinometers" can offer resolutions of about 0.5 mrad [Alvis and Rosborough 1982], but they are susceptible to oscillations induced by wind loads on the collector [Dudley 1986].

Synchros--In synchros and resolvers, coils around a rotor are sinsuoidally excited to induce a current in a coil around the stator. The rotor's absolute position is indicated by the phase shift between the excitation and induced voltages. Synchros commonly use 60-Hz excitation voltages, and voltage measurements are obtained from three positions around the stator. Resolvers are usually excited at 400 Hz and voltage measurements are made at four stator positions. A converter transforms voltage measurements from the stator coil to a binary (or digital) reading of the rotor position. Converters are available in even-number bit sizes, so a 14-bit converter is needed for 0.4-mrad resolution.

Few problems were reported with the synchros used in the Vanguard and PDC-1 tracking systems (these encoders are used in aircraft controls, so they tend to be very reliable). The price of synchros and resolvers ranges from $300 to $550, where the higher price buys a weathertight enclosure and an extended range of operating temperatures. The converter costs from $350 to $500. A single converter can process the signals from two or more synchros (or resolvers), but a few seconds is required for signals to settle after switching from one synchro to another. With only two synchros, however, using a single converter is uneconomical. The excitation power supply will cost from $100 to $200. AC line current can provide excitation to a synchro, but more power is required when synchros use 60-Hz rather than 400-Hz excitation frequencies. Prices drop by about 50% when quantities in the hundreds are purchased.

Hall-Effect Transducers--A Hall-effect encoder consists of a magnet placed on a rotating disk and a stationary Hall-effect sensor that registers when the magnet poles pass. Hall-effect encoders are incremental encoders, and because relatively few (≈2 to 60) pulses are registered per revolution, they are usually mounted on drive motor shafts. A TCU must count the number of pulses from a Hall-effect encoder to keep track of the concentrator's location. With an encoder that gives two pulses/revolution and a drive train gear reduction of 18,000 to 1, the encoder system will give a resolution of 0.2 mrad on an azimuth tracking drive. Unfortunately, taking advantage of the large gear reductions also subjects encoder measurements to errors caused by backlash in the drive train.

In the simplest configuration, Hall-effect encoders indicate only that a shaft is rotating but will not tell the direction of rotation. This could present a problem when external forces (i.e. wind loads, inertial coast, etc) move the collector, and the TCU does not know if an encoder pulse should be added or subtracted from the turn count. This problem is solved at the STEP facility by placing two Hall-effect sensors side by side to register the direction or "phase" of shaft rotation.

Early Hall-effect sensors were prone to drift, had low production yields, and required expensive magnets. These problems have been overcome [Lantzsch and Hines 1986] and Hall-effect sensors now offer an inexpensive and reliable means of encoding shaft rotation. Hall-effect encoders have proven their reliability in tracking controls in ARCO's EOR facility heliostats, McDonnell-Douglas's Dish/Stirling Solar Electric Power Module dish concentrators, and LaJet's Solarplant One concentrators.

Commercial Hall-effect encoders that give two pulses/rev are available for about $15/encoder ($16 for an extended temperature range); however, a large selection of enclosures is not available. Weathertight enclosures on commercial Hall-effect encoders are difficult to find at this time. The encoders are rather insensitive to soiling, but moisture intrusion can cause problems. To avoid moisture problems, the STEP facility uses Hall-effect sensors that have been dipped in epoxy [Hicks 1987] and Solarplant One uses commercial Hall-effect switches that are ceramically encapsulated [Payne 1987].

Stepper Motors--Encoders measure the concentrator's orientation, but this feedback is not required when stepper motors are used. The rotor of a stepper motor is a gear-shaped permanent magnet and the stator is a series of windings that produces electromagnetic poles when energized. The number of windings determines the number of phases of a stepper motor. Energizing a particular phase (typically with a square wave input) will cause the motor shaft to translate through a step. The shaft position can be determined by counting the number of phase transitions.

Stepper motors are expensive, but they do eliminate the need for encoders. They also have a high stiffness that allows them to hold a position. The stepper motors originally used in the CRTF heliostat drives demonstrated good tracking characteristics. Due to problems with low torque at higher speeds and excessive power requirements, they were eventually replaced with dc motors [Edgar 1986]. Low torque problems can be overcome by increasing the number of phases [Batten 1986], but unfortunately the cost of adding more phases has not been overcome.

Sun-Tracking Sensors

Sun-tracking sensors either mount on the concentrator and view direct solar insolation, or they are placed near the receiver aperture where concentrated solar insolation can be measured. The basic concepts behind collector-based sensors and receiver-based sensors are presented in this discussion. Test results on two commercial sun-tracking sensors can be found in a report by Gee [1982].

For collector- and receiver-based tracking sensors, the sensor gain (volts/degree of aiming error) often depends on the insolation level. For a given tracking error, a large error signal may be produced during high insolation periods and a small error signal could be produced during low insolation periods. Since tracking update commands are typically issued when sensor error signals exceed some threshold value, the tracking deadband will be a function of insolation level. Making the system very sensitive to error signals by choosing a low error threshold or increasing the sensor's gain can cause the system to oscillate during periods of high direct insolation [Alexander 1979]. Decreasing the sensitivity of the tracking sensor will cause large tracking errors during low insolation periods.

To operate over a wide range of insolation levels in systems with hardwired tracking logic, it has often been necessary in the past to manually adjust pots that control the sensor's gain [Alexander 1979; Maish 1986]. Manually adjusting pots in a field of collectors has not been a popular solution to the problem of variable gain. It is generally recommended that all sun sensor signals be interpreted by a microprocessor so that tracking logic can be provided through software rather than hardware adjustments [see Droher and Squier 1985, or Stallkamp 1985].

Shadow-Band Sensors--The earliest collector-based sensors were made of two photocells separated by a vertical partition, as shown in Figure 15a. When the sensor is aimed directly at the sun, all photocells are equally illuminated and give equal outputs. If the sensor is turned oblique to the sun, one cell will be shadowed by the vertical partition and the differential output of the two cells will indicate a pointing error exists.

Several problems have been observed with shadow-band trackers.

(1) The sensor is unable to find the sun when both cells are shadowed.
(2) The output of photocells changes with light intensity.
(3) Reflected light from clouds or buildings can bias the sensor's output when a wide field of view is used. A wide field of view can assist in acquiring the sun, but even a slight aiming bias will degrade the collector's performance.
(4) Photocells can experience differential aging characteristics causing tracking accuracies to deteriorate with time.
(5) Photocells and photoresistors often have a directional dependence in their outputs. The directional dependence mainly affects single-axis tracking systems where incident angles change throughout the day. (Some of the problems can be attributed to irregularities in hemispherical domes covering the sensors [Dudley 1986].)
(6) Shadow-band trackers are difficult to align. Adjustable mounting brackets make alignment easier, but some procedure is still required to initially characterize tracking accuracies.
(7) Sun sensors are susceptible to soiling. Moisture intrusion into the sensors has caused problems in previous tracking systems [Stallkamp 1985; Droher et al. 1985]. (In the Vanguard system, venting the sensors to the atmosphere solved this problem.)

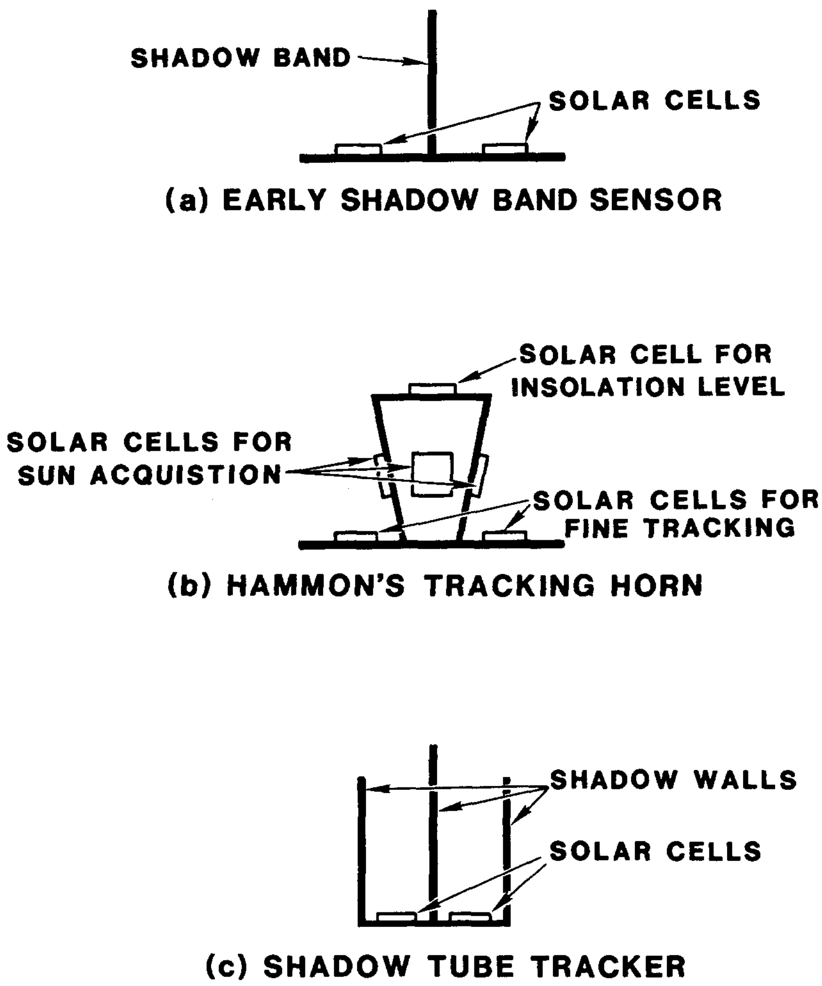


Figure 15. Collector-based sun-tracking sensors: (a) Early shadow band sensor, (b) Hammon's tracking horn, and (c) Shadow tube tracker.

Tracking Horns--Some of the problems with shadow-band sensors were overcome in a sun sensor developed by Hammons [1977]. This sensor uses a perpendicular "horn" in place of the vertical shadow band (see Figure 15b). In addition to silicon solar cells at the base of the horn, cells are also placed on the sides and top of the horn. Light filters of 1% transmission cover the cells to reduce problems caused by reflections. When properly aimed, the horn completely shades cells on the side and partially (but equally) shades cells at the base. For small pointing errors the base solar cells produce an error signal. If misalignments are severe (>90°), cells on the horn's side will provide error signals for rough aiming adjustments. The top cell detects when direct insolation levels drop below a threshold at which sensor tracking is discontinued.

The tracking horn sensor was tested on a two-axis tracking PV array, and aiming resolutions on clear days were reported to be better than 2 mrad [Hammons 1977]. However, tracking performance did decrease on cloudy days and days with low direct insolation.

Shadow Tubes--On some collector-based sensors, photocells or photoresistors are placed at the bottom of boxes or long tubes as shown in Figure 15c. When the sensor is misaimed, the tube walls will cast shadows on certain cells and thereby produce tracking error signals. If a long tube is used, the sensor will provide tracking information for only a narrow range of pointing errors. Additional cells outside the tubes are sometimes used to give a wide-angle tracking capability. Pointing errors of less than 1 mrad have been reported [Stallkamp 1985; Maish 1986] in two-axis tracking systems that use a shadow-tube tracking sensor manufactured by Mann Russell.

By placing photocells at the bottom af a long tube, the viewing angle of the sensor is decreased. One problem with using too narrow a viewing angle is that the sensor may track local bright spots in the sky. The collector could follow the bright edge of a cloud that passed in front of the sun. After the cloud was gone, the sun might be out of the sensor's field of view, thereby leaving the sensor incapable of locating the sun.

Alternate Sensors--Not all collector-based sensors rely on shadowing light sensors to indicate pointing errors. Alpha Solarco has developed a tracker that uses a small concentrator to focus sunlight on a line between two thermistors. When the sensor is improperly aimed, one thermistor is heated and an error signal is produced [Gee 1982].

Passive sun-trackers have also been developed that use the thermal expansion of a gas (either Freon or hydrogen) to aim the concentrator. For single-axis, passive trackers, cylinders are placed on each side of a collector and lines connect them to a hydraulic actuator. The collector will shadow one of the cylinders unless it is aimed directly at the sun. Vapor pressure in the shaded cylinder will drop and cause the actuator to correct the collector's aim. By using two actuators and four cylinders, it is possible to perform two-axis tracking. Tracking errors of less than 2 degrees have been reported [Robbins 1986], but recent work in Sandia's photovoltaic division is showing errors closer to 10 degrees for passive tracking systems [Post 1986].

Receiver-Based Sensors

Even if the collector tracks the sun perfectly, there is no guarantee that the concentrated energy will enter the receiver. Deformations of the receiver mounting structure can cause energy to miss the receiver aperture. This has led many designers to place sensors on the receiver and measure energy that hits them. Others have chosen to put sensors around the receiver aperture to detect flux that spills over the receiver. Both options tend to correct for only a narrow range of tracking errors, so a coarse tracking system is also required.

Receiver Flux Sensors--Detecting the flux that hits a receiver is difficult because the receiver area tends to be hazardous to instrumentation. This has limited the use of receiver flux sensors to trough systems where concentration ratios are low.

Kohler and Wilcoxen [1980] developed a receiver flux tracking sensor that uses a fine resistance wrapped wire around the receiver tube of a parabolic trough collector. Tracking was accomplished by maximizing the temperature (and therefore the resistance) of the wire. This procedure requires iteratively searching for a maximum, since the direction of a tracking error vector is not indicated by one resistance measurement. When this tracking process was implemented, it had an additional complication, because the maximum wire resistance did not coincide to the maximum heat input to the receiver. This problem occurred because more of the spirally wrapped wire was exposed to a concentrated flux when the collector was offset than when it was properly aimed.

A fiber-optic system proposed by Wiczer [1981] would have avoided the offset maximum problem experienced with a wrapped wire sensor. Wiczer suggested placing a fiber-optic cable on the underside of a receiver tube to directly sense light reflected off a trough collector. Light traveling along the cable as a result of absorption and reemission could be measured with a photodiode. The resulting signals could then be used to maximize flux upon the cable (and therefore the receiver).

<u>Flux Trap Sensors</u>--The most common receiver-based sensors rely on "trapping" the concentrated flux between sensors surrounding the receiver aperture. Both light and temperature sensors have been in flux trap systems (see illustration in Figure 16). As the sun's focused image walks off the receiver and onto a sensor, an error signal is produced. The concentrator is then driven to a position that recenters the focal spot.

For trough collectors, Boultinghouse [1982] developed and tested a flux trap sensor that used two nickel wires placed on opposite sides of a receiver tube. When tracking, the trough was rotated to a position where the two wires had equal resistances. Natural convection caused an offset in the tracking until corrections based on the receiver temperature and tracking angle were made. Honeywell has also developed a trough tracking system in which photodiodes are placed on each side of the receiver tube. Tests conducted by Gee [1982] demonstrated that tracking errors of under 2 mrad could be obtained using this system.

For the dish collectors at Solarplant One, LaJet used four resistive temperature detectors (RTDs) placed symmetrically around the receiver aperture. The sensors worked well in this polar tracking system, but the RTDs would burn out after about 2 minutes of exposure to the concentrated

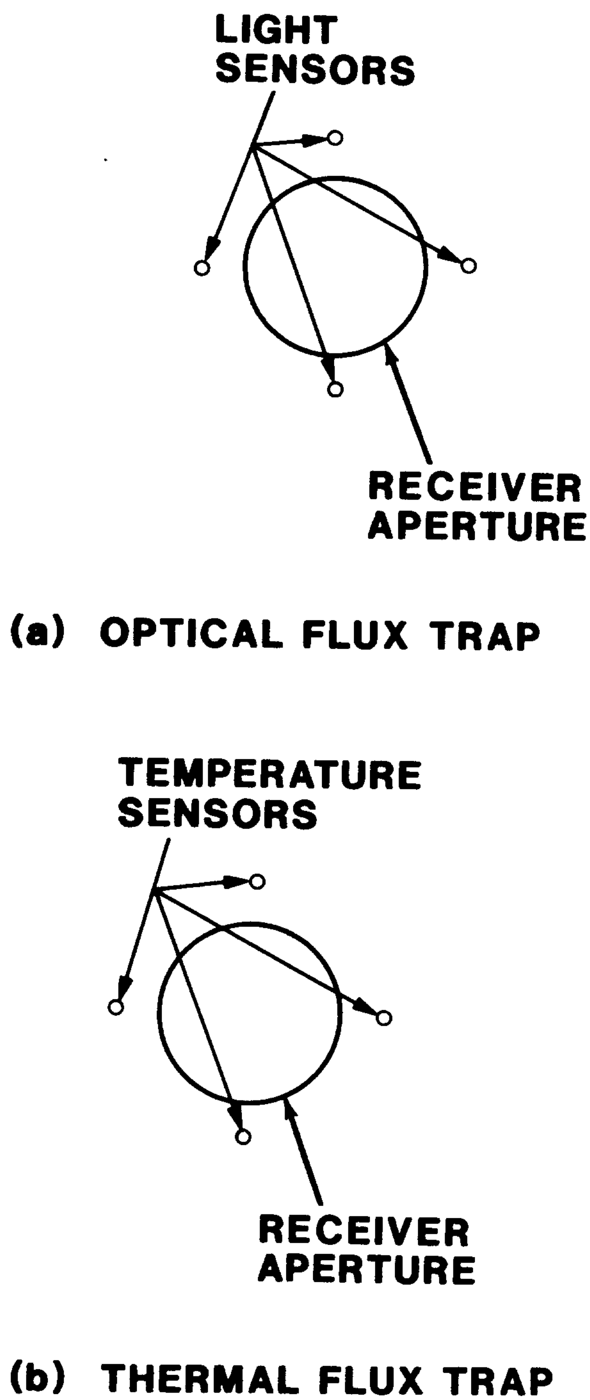


Figure 16. Receiver-based sensors: (a) Optical flux trap and (b) Thermal flux trap.

flux. LaJet has since replaced the RTDs with thermocouples. The effect of thermal convection on the tracking accuracy is unknown for this system but it is believed to be small [Payne 1987].

The flux trap system at the STEP facility used four quartz rods placed around the receiver aperture. The rods were connected to fiber-optic cables that attached to photocells, which would issue pointing error signals to the controller. This system delivered approximately 3 mrad of tracking accuracy. Unfortunately, the joint between the quartz rod and the fiber optic cable would darken because of the concentrated energy and degrade the system's sensitivity, and in some instances the brass fittings that held the sensors in place would melt [Stine and Heckes 1986]. Eventually the flux trap system was abandoned at STEP in favor of an open-loop tracking system.

Limit Switches, Reference Switches, and Motor Controllers

The limit and reference switches and motor controllers will not be discussed in any detail in this paper. However, a few of the observations about these components that others have made are presented.

Limit Switches--Limit switches should be considered failsafe equipment and not used in normal operating procedures. Mechanical switches, such as mercury, push-button contact, and magnetic reed switches, are often chosen as limit switches because they offer a reliable means of turning off the drive motors. When used repeatedly, however, these switches do wear out. A few notable problems that have been encountered with limit switches are as follows:

(1) By abruptly interrupting the power supply, limit switches can possibly cause motor controller relays to fail (see Cameron and Dudley 1986).
(2) Magnetic reed switches appeared to work well in the MISR facility but weak magnets have caused some problems (Cameron 1986).
(3) At Solar One, diodes are placed across the mercury limit switch so the motor can be reversed once the switch is tripped. On occasions, these diodes have failed and the heliostats have been destroyed by rotating past their limits (Mavis 1986).

Reference Switches--Fairly precise and repeatable switching is needed in a reference indicator. When contacts are mechanically closed inside a switch, contact does not always occur at the same switch position. Mechanical switches can also wreak havoc on digital circuits because they tend to bounce after closing. These problems can be avoided using Hall-effect position sensors or "debouncing" circuitry (Horwitz and Hill 1985). Since there are no mechanical contacts in Hall-effect switches, they are generally expected not to wear out. The reliability and accuracy of magnetic reed limit switches and Hall-effect reference switches are currently being tested for PV tracking control systems.

Motor Controllers--Motor controllers range in complexity from simple relays used on ac induction or dc brush motors to complex microprocessor-controlled power units used with stepper and variable speed motors. They also vary with the power supply that is available to the collector field. A simplified schematic of a single-speed ac motor controller is shown in Figure 17.

Two problems that occur with some regularity are failures in silicon-controlled rectifiers and failures in both solid-state and mechanical relays (see for example Alexander et al. 1979; Stallkamp 1985, Droher and Squier 1986; or Cameron and Dudley; 1986). In some cases the problems have been identified as undersized components, and in other instances the difficulties have been attributed to a back emf that is generated when a motor's direction is rapidly reversed. Two general recommendations can be made:

(1) Circuits should provide a delay before allowing the motor direction to reverse.

(2) Relays should survive frequent starting power levels. (For example, ac induction motors generally draw 5 to 6 times more current when starting than when operating at steady state, and for ± 2 mrads of tracking accuracy motors must be switched more than once per minute.)

(3) If electrical or line noise is likely to be a problem for the control or communication system, mechanical relays should be avoided or at least isolated from the rest of the electronics.

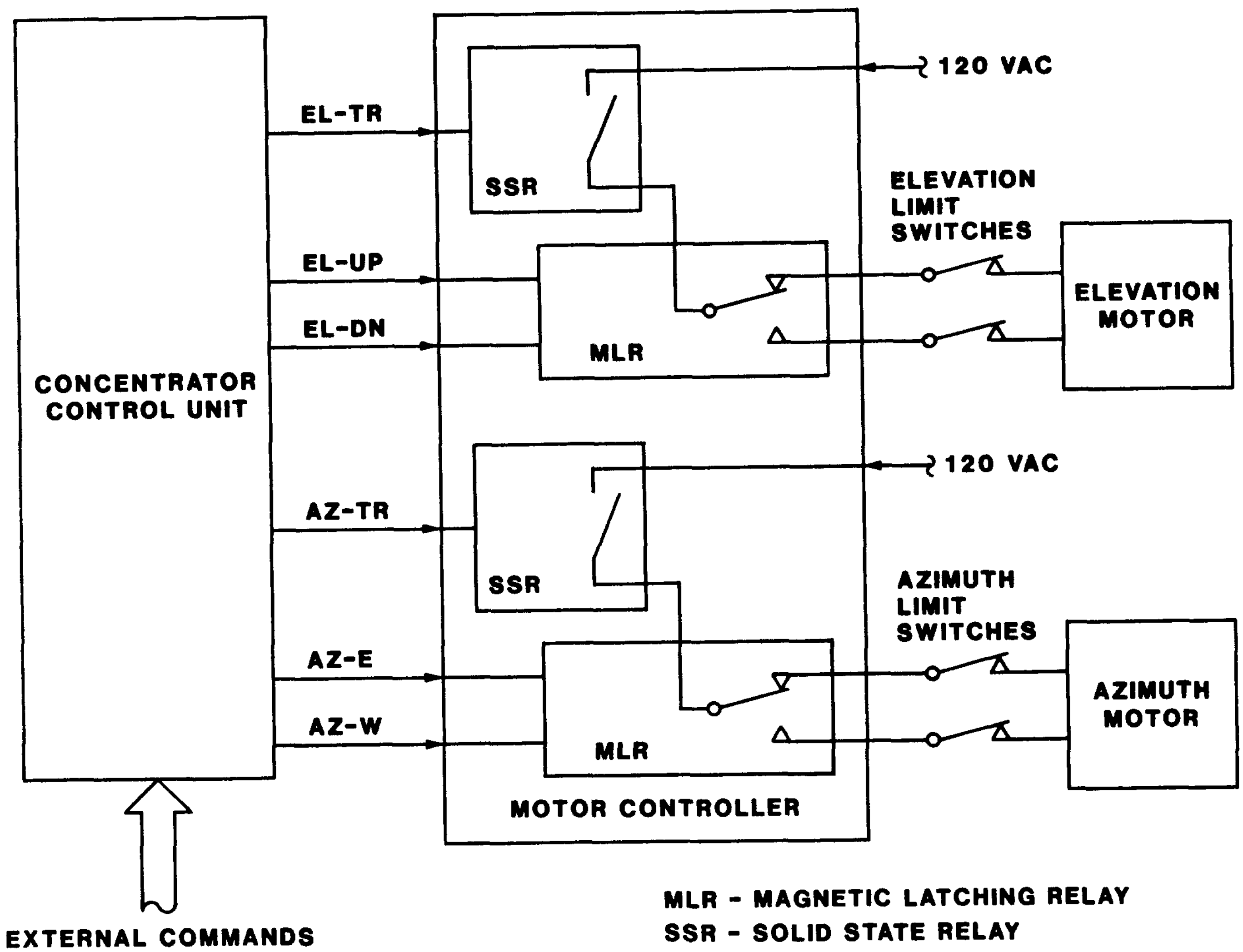


Figure 17. Motor controller for single-speed ac motors.

Tracking Systems

Past solar projects have offered a number of lessons on tracking the sun. Some of the operational experiences for two-axis tracking systems found in central receiver heliostats, point-focus, and photovoltaic arrays are presented in this section.

Central Receiver Heliostats

Central receiver heliostats are aimed along a vector that is halfway between a heliostat-sun vector and a heliostat-target vector. Because the sun is not followed directly, heliostat systems almost exclusively use an open-loop tracking procedure. However, early attempts were made by Martin Marietta and McDonnell-Douglas to provide feedback on tracking errors by placing sun detectors on long poles between the heliostat and target. These efforts were abandoned by 1976 because the expense of accurately positioning the pole outweighed the advantages of having a feedback sensor [Mavis 1986].

In the Solar One heliostat control system, a central computer issues information on the sun's position every second to controllers on each heliostat. The controllers then calculate aiming coordinates for the collector and compare the result with optical encoder measurements of the heliostat's orientation. Tracking updates are made when calculated pointing errors exceed about 1 mrad. Without a means to sense absolute tracking errors though, inaccurate encoder reference points and structural misalignments can still cause significant tracking errors.

Absolute tracking errors in the Solar One heliostats are found using a silicon diode array camera that maps the reflected flux pattern a heliostat produces on a special target. Targeting errors can be measured on up to 60 of the 1818 heliostats three times daily with this beam characterization system (BCS). Based upon BCS measurements, the central computer calculates tracking corrections, which will compensate for structural misalignment and optical encoder offsets. These corrections are then incorporated in control software for the heliostat tracking system [Tanner 1986]. The beam characterization system allows tracking to be maintained within a 1.5 mrad error limit [King 1982].

The Solar One heliostats, like those in most central receiver systems, use an AZ-EL tracking structure. During installation of the heliostats a BCS was not available, so other techniques were used to align the system. Misalignments in the azimuth axis of rotation were measured with an electronic level placed on the drive unit. By rotating the unit in azimuth and observing electronic level readings, a field assessment was made of vertical tilt in the structure. The azimuth tracking axes for the production heliostats at Solar One were aligned to within 0.2 mrads of vertical by selectively tightening mounting bolts at the base of the pedestal. This procedure was cumbersome, so most of the second-generation heliostats used software routines and electronic level measurements to correct for azimuth tilt [King 1982]. Second-generation heliostat systems by Boeing Engineering and Construction Company and McDonnell-Douglas Aeronautics Company also had software provisions to correct for horizontal tilt of the elevation drive axis.

As part of the tracking characterization tests, second-generation heliostats at Solar One were subjected to simulated wind loads [King 1982]. Backlash in the drive train (which in the worst case was measured to be approximately 1 mrad) prevented controls from making corrections when encoders were located on the input shaft of the drive unit. For collectors with encoders located on the output shafts of the drive units, the controls were observed to compensate for steady wind loads. Under gusting wind conditions, however, the controls could not respond fast enough to make the necessary corrections. Because some unsteadiness is often associated with wind loads, these results cast some doubt on the effectiveness of a controls solution to wind-induced tracking errors.

Dish Concentrators

In the Vanguard collector system a central computer can monitor 32 collectors and give supervisory control [Droher and Squire 1986]. A concentrator control unit based on a Motorola 6809 microprocessor provides logic at the concentrator for both open- and closed-loop tracking. Program modifications can be made in the field using a keyboard with a 20-character display included on the TCU. A dual-axis photovoltaic shadow-band sun sensor is located on the dish concentrator to report tracking errors. These tracking error signals are processed by software in the TCU to arrive at tracking commands.

Sun position data are calculated at 30-minute intervals in the Vanguard control system, and tracking starts only after the calculated sun elevation is above 0°. At times tracking will not begin until the sun is 5° above the horizon because of the 30-minute delay in sun position data. By comparing calculated sun position data to synchro encoder measurements, a correction table for the ephemeris data is computed when the system is in a sensor tracking mode. The differences recorded in this table were noted to be large at times with alternating signs. When such data were used for tracking, they would cause the drive motors to oscillate the dish. This problem was difficult to correct because programmable read-only memories were used, and any alterations had to be done by the tracking system supplier.

Concentrators in LaJet's Solarplant One facility are mounted on equatorial drive structures. For closed-loop tracking, information on pointing errors is supplied to the TCU by RTDs placed around the receiver aperture. Sun tracking data are collected from Hall-effect encoder measurements of the collector's orientation, and on following days these data are available for open-loop tracking. Corrections on the ephemeris data are made by algorithms in the microprocessor-based TCU. After 30 minutes of sun sensor tracking, these algorithms will extrapolate data adjustments for an entire day. At the end of a a day, corrections are uploaded to a host computer for analysis [McGlaun 1986; Payne 1986].

The control system for the STEP dish concentrators has recently been renovated, so both the old and the new control systems will be described. In the early system, open-loop tracking commands came from a central computer and local TCUs provided logic for closed-loop tracking [GE 1979]. Even when the system was sun sensor tracking, commands to update the collector's position still came from the central computer. (At times this arrangement caused collectors to overshoot the aiming destinations, but this matter is discussed in Chapter 4).

The STEP dish concentrators are mounted on polar tracking structures. Accuracy requirements in this system were fairly low (≈9 mrad) because of the low concentration ratio (=235), so for synthetic tracking, declination adjustments were made only once per day. The accuracy delivered by the synthetic tracking system was about ±3.5 mrad as measured with polar and declination pots. Closed-loop tracking provided a ±3-mrad absolute pointing accuracy using signals from four fiber-optic cables placed around the receiver aperture. Optical signals were translated by photosensors and the resulting electrical signals were sent to the TCU for interpretation. The calculated sun position would be compared to potentiometer readings of the dish orientation while the system was sensor tracking. When the difference between the measured and calculated sun position exceeded 20-mrads, control was returned to the open-loop tracking system.

As was already mentioned, the optical flux sensors tended to burn out frequently in the STEP system. This problem was further aggravated by a sun acquisition procedure that constantly brought the sun's focused image across one of the sensors. Brightly lit clouds passing between the sun and the concentrator were also known to lure the concentrators off course just enough for the sun to be focused on a sensor cable after the cloud passed. In the new control system closed-loop tracking was eliminated. The pots, which soiled easily and gave very unreliable position measurements, were replaced with Hall-effect encoders in the new system. Initial tests on this new control system have shown it to be fairly reliable.

Dish collector development programs have also provided several lessons about tracking systems. In the PDC-1 closed-loop tracking control system, the dead-band for sensor tracking was designed to be about 2 mrad, but actual testing showed only a 1-mrad error existed. This presented a problem for PDC-1 because the drive motors were being cycled on and off much more frequently than was necessary. It was not possible to add a delay to the system because signals from the Mann Russell sun sensors went directly to motor control relays. It was suggested that in future systems, sensor signals should be brought into the microprocessor used for open-loop tracking [Stallkamp 1985]. Not only could the microprocessor adjust tracking dead-bands, but it could also be used to position the concentrator two-thirds of the way to the next limit. This would further reduce cycling on the drive motors.

For the TBC-1 concentrator it was necessary to have a high degree of pointing accuracy in both open- and closed-loop tracking modes. The TBC-1 collector is brought to within ±2 degrees of sun acquisition using ephemeris data, and then a 1-mrad tracking accuracy is obtained with a Mann Russell shadow-tube sun-sensor [Selcuk 1985]. Insolation measurements are used to recalibrate tracking-sensor gains at various insolation levels. The weight of test loads will cause the receiver aperture to be deflected from the focal axis, but a look-up table gives the magnitude and direction of these gravity-induced deflections for every 5 degrees of elevation. This information is used in conjunction with ephemeris data and synchro encoder measurements to obtain tracking accuracies of 0.5 mrad. (A similar procedure of compensating for motor coast is also used in ARCO's EOR system heliostats.)

Photovoltaic Arrays

The 80 Sky Harbor arrays used a first-generation control unit designed by Martin Marietta [Lepley 1986]. In this AZ-EL tracking system, open- and closed-loop tracking logic was hardwired into the TCU. For synthetic tracking, the TCU would rotate the collector in azimuth to one of five positions based on time and an azimuth potentiometer measurement. A sun sensor, similar to Hammon's tracking horn, was used to obtain tracking errors of less than 2 mrad. Because the logic is hardwired into the TCU, manual adjustments of pots were required to compensate for imbalanced signals from the sun sensor. Misalignments of several degrees were observed when wide-angle sensors were improperly adjusted [Maish 1986].

First-generation AZ-EL tracking arrays in the Photovoltaic Advanced Systems Test Facility (PASTF) at Sandia National Laboratories have a Mann Russell tracking control unit. This unit also uses hardwired control logic and manually adjustable tracking deadbands. The first shadow-tube sun sensor used in this system could provide 1-mrad aiming accuracies, but it had only a narrow viewing angle. When the sun was outside the sensor's field of view manual acquisition was required. A newer version of the sun sensor gave both wide and narrow viewing angles but a slight degradation of tracking accuracy was observed [Maish 1986].

For roll-tilt arrays at the PASTF, a tracking sensor with seven GaAs photocells provides a closed-loop sun acquisition and tracking capabilities. When sensors signal that a tracking error exists, roll motors are switched on for a fixed time period. Tilt motors, on the other hand, are only left on until the sensor indicates that the aiming error is corrected. This procedure gives a 3.5-mrad accuracy for roll angles and 2-mrad accuracy for the tilt angles. While the system is sensor tracking, a microprocessor-based TCU on one array collects and stores tilt and roll potentiometer measurements at 10-minute intervals. This information is used for open-loop tracking of several arrays during cloudy periods. Because the control logic was software-based, tracking parameters such as deadbands, insolation threshold levels, and start-up and stow instructions could easily be modified.

CHAPTER III. RECEIVER TEMPERATURE CONTROL

Whereas tracking controls govern how much solar energy is intercepted, the receiver controls determine how usable this energy is to a facility. What is considered usable energy depends on the range of inlet properties a given power conversion system (PCS) can accept. For heat engines that use a receiver's output directly, it is often necessary to maintain narrow tolerances on the PCS inlet properties. In facilities where supplemental heating or storage is available, a broader range of receiver discharge conditions might be tolerated. Control in this latter situation could be simply to maintain the thermocline in a storage vessel or to avoid overheating the receiver and the heat transfer fluid.

At an initial glance the goals of a receiver control system might look rather simple. Receiver controls must be "intelligent" enough to handle a continuous variation of input energy, and yet they must not overreact to temporary disturbances caused by clouds or tracking adjustments. In addition, the controls must compensate for an overabundance of input power on days when insolation levels are well above the system design point. The difficulties begin when the random nature of solar transients are considered.

Insolation Transients

The intensity of solar energy that reaches earth varies throughout the day. Variations are primarily caused by clouds and the distance rays must travel through the atmosphere, but incident solar energy is also influenced by atmospheric temperature, pressure, humidity, smog, and dust. Presented in Figure 18 is an example of direct normal insolation measurements on a clear day in Albuquerque, New Mexico. As shown in this figure, about 15 minutes is required for insolation levels to reach 400 W/m^2 and almost 90 minutes will pass before levels exceed 800 W/m^2. If 800 W/m^2 was considered the design point of a collection system, then conditions would be below design about for 25% of the daylight hours and above design for the remaining 75%. So even though a state is referred to as a design point, the system may spend very little time operating at design conditions.

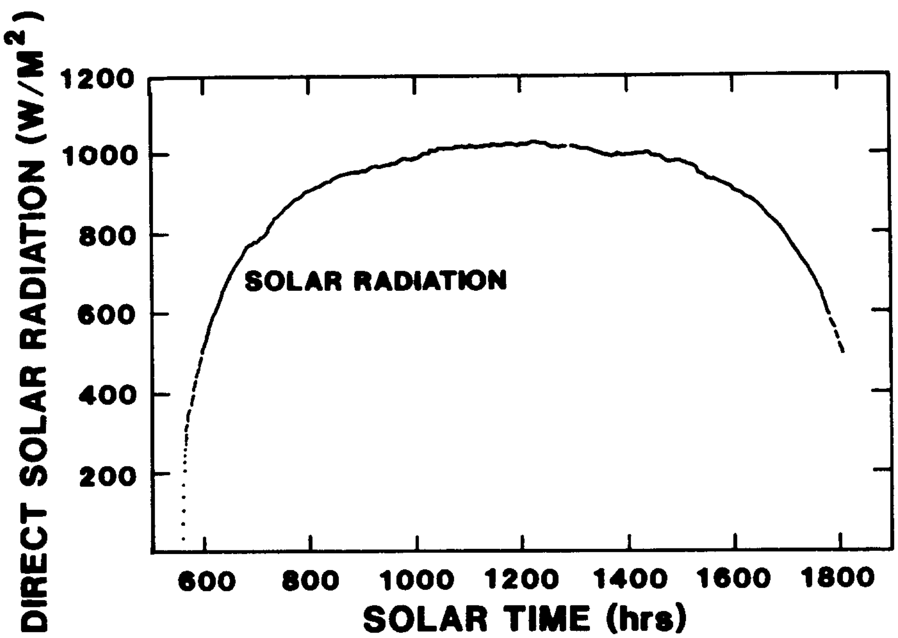


Figure 18. Insolation levels on a clear day in Albuquerque, New Mexico.

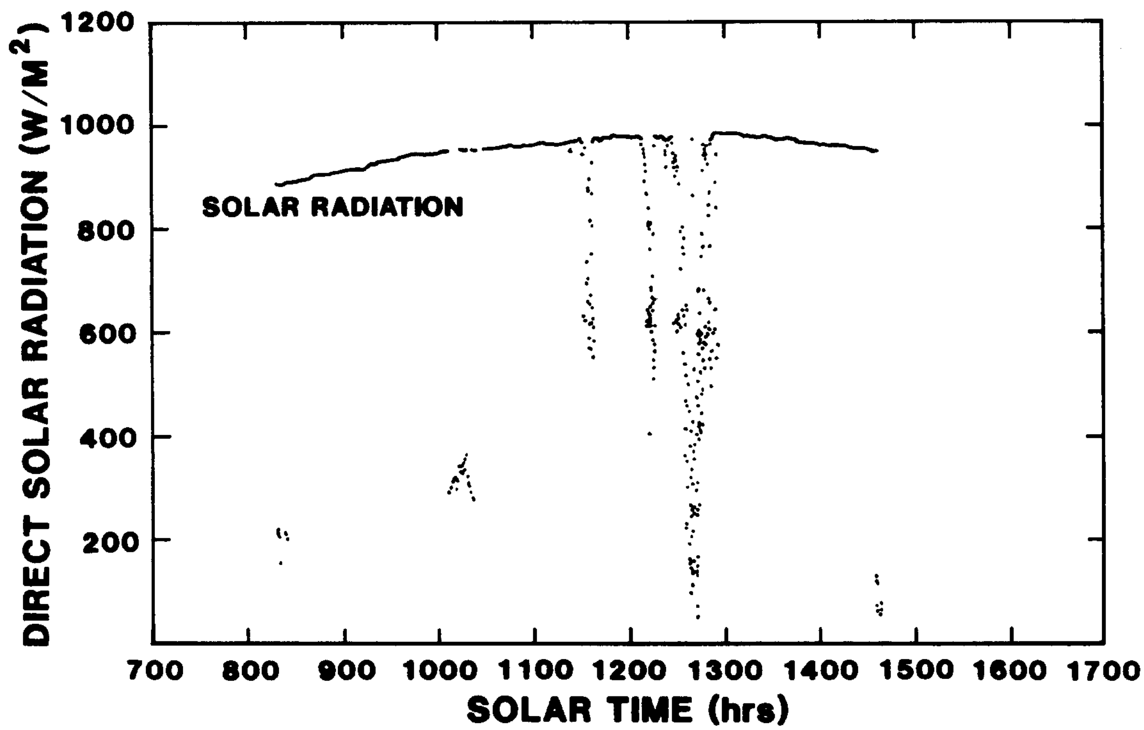


Figure 19. Transients in insolation on a cloudy day in Albuquerque, New Mexico.

The effect that clouds have on direct normal insolation is shown in Figure 19. It is difficult to characterize the disturbances caused by clouds because they can effectively eliminate direct normal insolation for a few seconds, or they can cause a slight dimming of the sun for an entire day. Studies have been undertaken in the past to quantify the influence of clouds on insolation levels in terms of frequency, duration, and percentage of blockage [Norris 1968]. For all practical purposes though, receiver controls must compensate for any form of cloud disturbance at any insolation level.

In models for central receiver control systems, the rate at which a cloud's shadow moves across the field is assumed to be 24 to 48 kph (15 to 30 mph) [Kolb 1986]. Heliostats at the CRTF are stowed when winds exceed 48 kph, so the maximum cloud speed is also assumed to be 48 kph. For the innovative concentrator development project, the maximum rate at which a cloud shadows a concentrator was given as 72 kph (45 mph) [Thostesen 1984]. A 72-kph cloud would completely shadow a 15-m dish in about three-quarters of a second.

A third factor that must be considered in designing receiver control systems is that solar flux on the receiver cannot gradually be increased or decreased, except in the case of central receiver facilities. Once the energy is focused on the receiver the entire load must be accommodated, often before the system has reached an operating temperature. Special procedures are required in the control schemes to compensate for the step input of solar flux.

Temperature Control Options

It is difficult to develop a receiver model that is both accurate and simple because of the complicated nature of flux distributions and heat loss mechanisms. Crude models, however, can provide some insights into the performance of receivers under various operating conditions. To identify the important parameters involved in regulating receiver flow temperatures, a simplified steady-state energy balance can be written as,

$$q = \dot{m}\ Cp\ (To - Ti) = \Phi\ I\ \eta\ \pi D^2/4\ , \qquad (7)$$

where,

q = heat transfer rate,

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

Cp = heat capacity of the receiver fluid,

Ti, To = inlet and outlet flow temperatures,

Φ = the intercept factor,

I = insolation normal to concentrator aperture,

D = diameter of the concentrator aperture,

and,

η = the overall efficiency of the collector/receiver system (see Eq. 6).

Once the collector/receiver system is constructed, the fluid heat capacity, the efficiency, and the concentrator diameter can no longer be varied (however, both and Cp are temperature dependent). This leaves the mass flow rate, inlet temperature, and intercept factor as the control parameters available for regulating receiver discharge temperatures.

Adjusting Flowrates

Equation 7 indicates that flow rates must vary proportionally with insolation to maintain a constant receiver discharge temperature. This concept is rather straightforward, but regulating receiver temperatures by altering flow rates does have its problems. One difficulty arises when several receivers are connected in parallel across two headers. If the system is improperly designed, a flow-rate change in one receiver can alter pressure drops, and therefore flow rates, across other receivers. Normally, control valves should be the dominant pressure drops in the system so that the independent valve actions are somewhat decoupled from each other. Having a valve as the major pressure drop in the system will also give a greater degree of system control since the entire valve stroke will be effective.

A second problem arises because most proportional-integral-derivative (PID) controllers offer only linear control features (see the next section). This problem was investigated for trough collector systems by Wright [1982], but much of the discussion is equally applicable to other solar thermal systems. To illustrate why linear control is a problem, Equation 7 must be solved for the controlled variable (To-Ti) and the result differentiated with respect to the manipulated variable (flow rate) to obtain the process gain,

$$Kp = d(To-Ti)/d\dot{m} = -(To-Ti)/\dot{m} \ . \tag{8}$$

Since solar power systems are typically required to operate with insolation levels from 250 to 1000 W/m^2, and $\dot{m}$ is proportional to I, the process gain can vary by a factor of 4 throughout the day. The sensitivity of the process to flow-rate changes will be greatest when insolation levels are low. If control gains are chosen for high insolation levels (high flow rates), the system becomes too sensitive to temperature perturbations during low insolation (low flow-rate) periods. This situation can cause the system to overreact in the mornings and evenings to the temporary disturbances caused by clouds. On the other hand, if the controls are designed for low insolation levels, the system will respond sluggishly during high insolation periods. Under these circumstances a receiver can overheat when it is subjected to high flux levels after long cloud transients.

One solution to the variable gain problem is to use a control system with nonlinear characteristics. This can be accomplished by indexing the controller gains with insolation levels, but PID controllers with programmable gains are more expensive than standard PID controllers. Nonlinear control characteristics can also be obtained by using an equal percentage valve rather than a linear flow control valve [Wright 1982]. An equal percentage valve is characterized by the relationship,

$$\dot{m} = R^{n-1}\dot{m}_{max} \quad , \tag{9}$$

where n is the fractional valve stem position and R, the valve rangeability, is the ratio of maximum controllable flow to minimum controllable flow (typically R is on the order of 50). For equal increments of valve travel, an equal percentage valve will give equal percentage changes in the exiting flow. The gain of an equal percentage valve is given by,

$$Kv = d\dot{m}/dn = \dot{m} \ln R. \tag{10}$$

When the equal percentage valve gain is combined with the process gain, the mass flow terms will cancel and the total system gain will be independent of flow rate. This flow-rate independence allows the system to be designed for optimum performance at any insolation level using only one set of controller gains. Of course, it still may be necessary to change gains over time, as fouled receivers and dirty collectors alter the system's operating characteristics.

Altering Inlet Temperatures

Receiver temperatures can also be regulated by mixing heated fluid (either from storage or the receiver discharge) with the cooler flows normally entering the receiver. With no thermal losses in the receiver, a unit change in the inlet temperature would give a unit change in the outlet temperature. Since there are thermal losses, however, operating more of the system at higher temperatures would be undesirable. An additional problem with inlet temperature control is that a relatively long time lag will exist between inlet temperature changes and the resulting changes in discharge temperatures. In some systems this lag can be on the order of two or more minutes, which is easily enough time to inadvertently overheat the receiver.

Active control of the receiver inlet temperature does appear to have some benefits. This point was demonstrated in a simulation model of the SSPS trough collector system, which is shown schematically in Figure 20. Under the existing operating strategy, the bypass valves allow fluid (Santotherm-55) to recirculate in the field until the outlet temperature reaches 275°C. After reaching this temperature, all of the heated oil is sent to storage and the power conversion system (PCS) begins operating. When the PCS starts, the field inlet temperature drops and flow to the field has been observed to undergo large oscillations. A simulation model of the SSPS system has shown, however, that start-up oscillations can be eliminated if a portion of the heated flow is recirculated to maintain a constant field inlet temperature [IEA SSPS 1986]. Such a result is very much tied to the operating characteristics of this particular system, but it does demonstrate the need to consider the impact of inlet temperatures on control schemes.

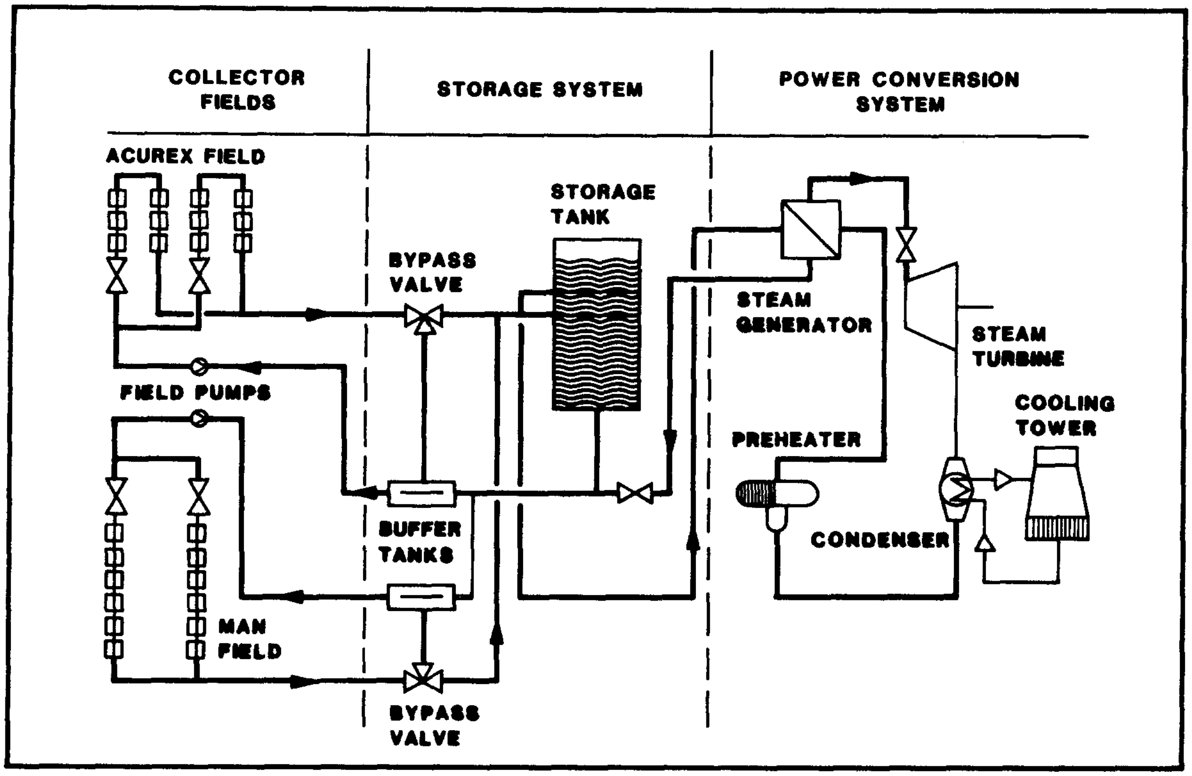


Figure 20. Simplified diagram of the line-focus collector field in Almeria, Spain.

Intercept Factor and Time Constant Effects--A third option for controlling receiver temperatures is to shunt some of the incoming energy by removing the focus from the receiver. The most common method of defocusing is simply to use an offset tracking mode. Defocusing allows only the upper temperature to be limited, so it is usually looked upon as overheat protection more than temperature control. Because spilling flux is a natural consequence of on-off tracking, it is necessary to understand the effects that defocusing and other transients have on receiver temperatures.

Insolation transients and receiver characteristics must be modeled to study a receiver's response to changes in input power levels. The tracking errors shown at the top of Figure 21 were combined with the instantaneous intercept factors shown in Figure 10 to obtain the intercept distribution as a function of time. The resulting time distribution of intercept factors is shown in the center of Figure 21, along with a plot of insolation as a function of time. Hughes [1979] developed a simple model to illustrate how a receiver responds to these time varying insolation levels. In the model no external temperature control is used and the receiver is treated as a first-order system described by,

$$MC\ dT_r/dt + H\ (T_r - T_a) = \rho\ G\ \Phi\ \alpha\ I\ \pi D^2/4 = \Phi\ I\ \Gamma \tag{11}$$

where,

MC = combined heat capacity of the receiver and fluid,

H = total heat transfer coefficient,

T_r = average receiver and fluid temperature,

T_a = ambient temperature and fluid inlet temperature,

and,

$\Gamma \equiv \rho G\ \Phi\ \alpha\ \pi D^2/4$.

(The remaining terms are defined in Equation 6).

Using this expression with the insolation and intercept distributions in Figure 21, the receiver temperature, T_r, can be determined as a function of time. According to Hughes, receiver time constants (τ = MC/H) are typically on the order of 100 to 900 seconds. At the bottom of Figure 21, T_r is presented for two time constants, τ = 100 and 400 seconds.

With a small time constant, receiver temperatures change quickly in response to flux variations, and with a long time constant the receiver is less influenced by transients. In Figure 21, the largest disturbance to receiver temperatures is caused by a hypothetical cloud passing between the concentrator and the sun. For τ = 100 and 400 seconds, tracking updates in Figure 21 have relatively little impact on the receiver temperature. The wind-induced pointing error had only a minor influence on receiver temperatures when τ = 400 seconds, but it had a more pronounced effect with τ = 100 seconds.

All of the above observations are what one would expect for this simplified model. In any realistic model, it would be necessary to include the effects of external temperature control (such as a flow control system) and spacial dependent effects that are caused by variations of the flux

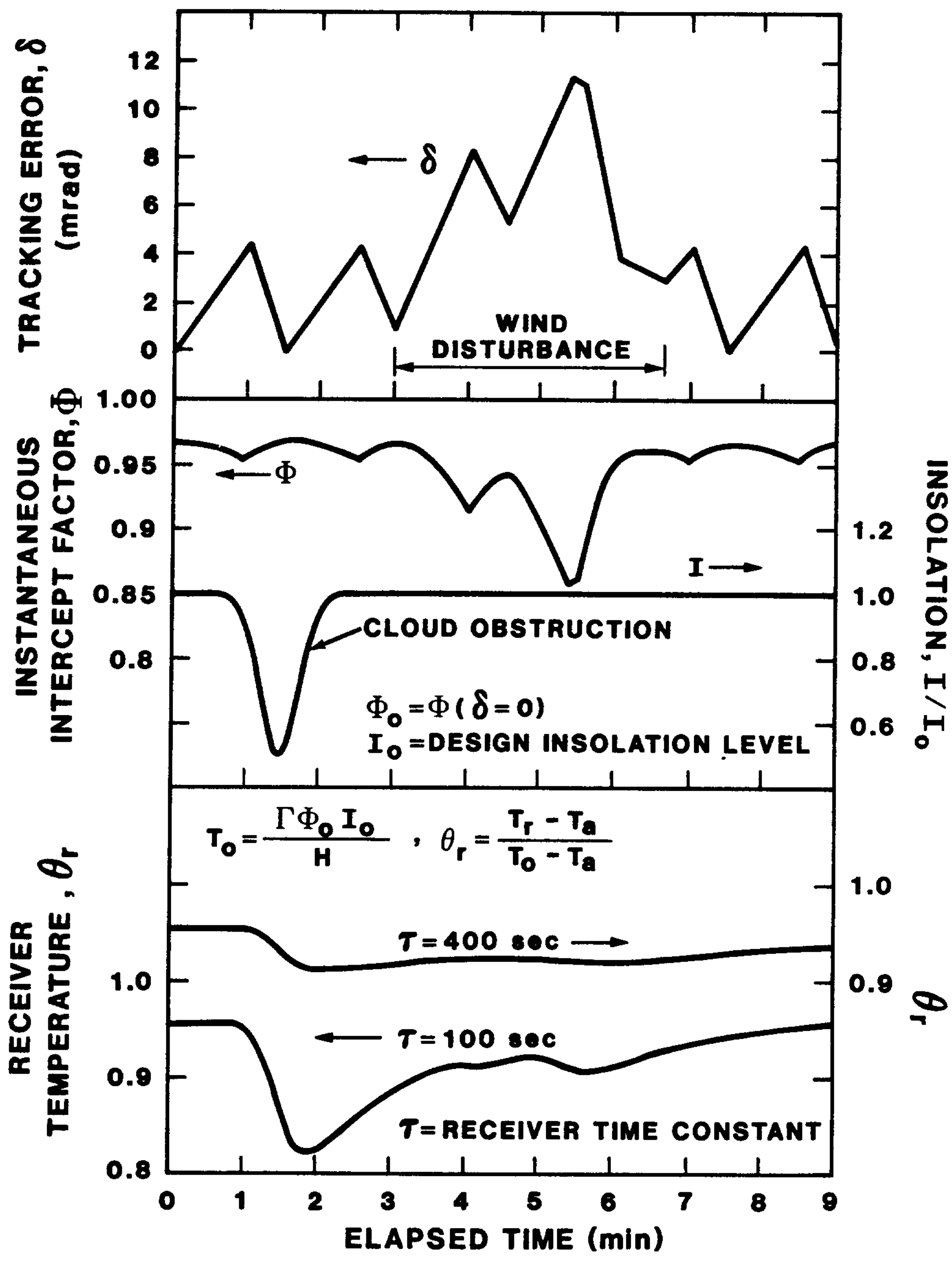


Figure 21. Transient response of a receiver. Shown are the tracking errors (top), the instantaneous intercept factor and insolation levels (middle), and the temperature response of two receivers.

profiles inside the receiver. Complete simulation models can be very complex, but such models are necessary to determine the receiver characteristics that are compatible with the rest of the system.

Hardware Alternatives

There is no universal design for receiver temperature controls, so only a general control system is described here. Illustrated in Figure 22 are the key hardware components used in receiver temperature control systems. These components are

(1) A receiver control unit (RCU) to provide the temperature control logic.

(2) Temperature sensors that give information on inlet, outlet, and receiver surface temperatures.

(3) A control valve to regulate the flow of heat exchange fluids through a receiver.

(4) An insolation sensor to measure direct solar insolation. The manner in which these components are combined to make temperature control systems is discussed in the next section. In this section the emphasis is on exploring hardware options and hardware problems.

Receiver Control Unit

Discussion on the RCU will be somewhat limited because temperature control logic is seldom provided by a unit that handles only receiver control tasks. For systems with a power conversion system (PCS) mounted directly to a receiver, temperature control logic is often provided by the PCS controls. Similarly, systems that rely on offset tracking to limit receiver temperatures normally have a portion of the tracking control unit's time dedicated to monitoring receiver shell temperatures and issuing the offset tracking commands. Combining tasks is desirable in most situations, since it reduces overall control costs by integrating more control functions into a single microprocessor. This reduces not only the number of microprocessors required, but it also eliminates the interface circuits between the TCU and RCU microprocessors.

In many instances receiver temperatures must be limited to a narrow range about a desired operating temperature, say Tset. Excursions from this operating point are interpreted as errors, ϵ = T-Tset, and the RCU acts to reduce these errors. Proportional, integral, and derivative (PID) control algorithms are often used in the RCU to reduce ϵ. PID controllers have the response characteristic,

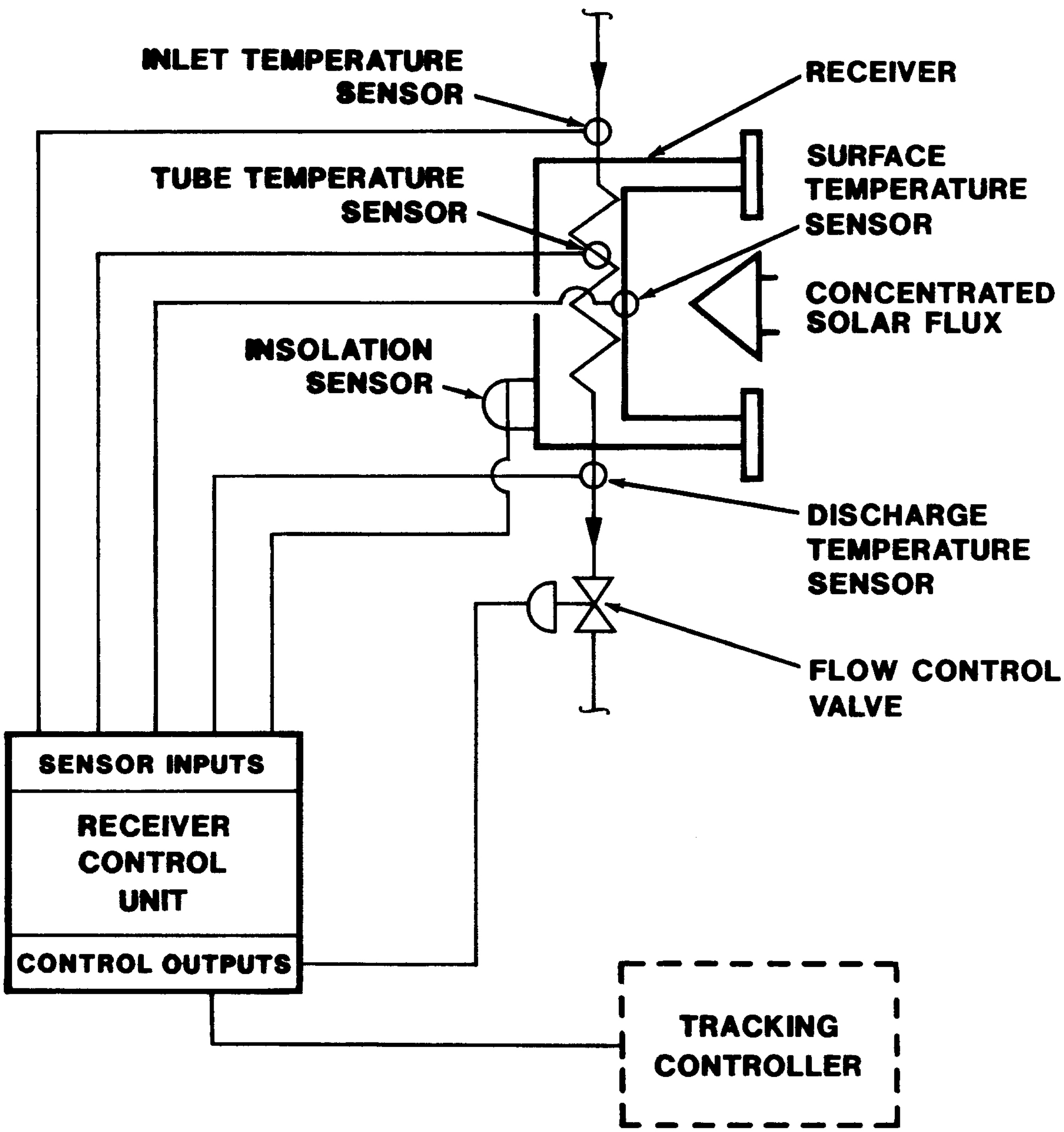


Figure 22. Schematic of a receiver temperature control system.

$$O = Kp\ \epsilon + Ki \int \epsilon\ dt + Kd\ d\epsilon/dt + Oo \qquad (12)$$

where O is the controller output, Oo is the output at $\epsilon=0$, and Kp, Ki, and Kd are the proportional, integral, and differential control gains respectively. The output might be thought of as the force that drives the control valve until ϵ and its time integral and derivative components are eliminated.

In a paper by Wright [1982] some of the problems associated with using PID control in solar thermal systems are discussed. If proportional control alone is used, the controller is unable to bring the error to zero at off-design insolation levels. This temperature offset can be eliminated with the addition of integral control characteristics, but integral control tends to make the system oscillate. Oscillations can be eliminated by using derivative control characteristics, but in systems that are subjected to rapid changes in operating conditions (e.g. solar thermal systems), derivative control can cause large and abrupt swings in the controller output.

Many of the problems that are associated with traditional PID control can be eliminated by using the advanced control capabilities offered by some microprocessors. It is now possible to use programmable control gains that stabilize system operation over a wide range of solar fluxes. Many of these advanced capabilities can be found in commercially available controllers that cost about $1200 - $1800. However, with the computing abilities already located in the tracking controller, it may be better to combine the receiver and tracking control tasks into one unit. If valve characteristics are such that programmable gains are not required, it might be possible to control receiver temperatures with a simple PID controller that costs as little as $100.

<u>Temperature Sensors</u>

Temperature sensors provide the information needed for closed-loop control of the receiver temperature. Readings may come from the receiver inlet, outlet, or surface. Surface temperature readings are often used to avoid the time lag that occurs between insolation changes and the corresponding changes in the receiver outlet temperatures. Using surface temperatures also allows temperature measurements to be made when there is no flow through the receiver. Measurements are usually taken from several locations on the receiver surface to detect localized heating caused by nonuniform flux profiles and flow distributions.

On some MISR troughs, the thermal expansion of receiver pipes will activate switches that initiate an overheat stow [Cameron 1986]; however, this is an unusual temperature sensing technique. A number of sensors are available for measuring temperatures, but the three most common are thermocouples, thermistors, and resistance temperature detectors (RTDs) [see Burr-Brown 1986; or Holman 1984].

Thermocouples--These are rugged and easy-to-mount temperature sensors that are also the least expensive of the three sensor options mentioned above. (Even though thermocouples are rugged, redundant sensors should be provided because thermocouples frequently fail.) Thermocouples can measure temperatures from -200°C to +2300°C and the output voltages are normally in the range of -10 to 50 mV. Material and manufacturing variations, however, limit accuracies to ±1°C.

Thermocouple output signals are the result of an electrical potential developed at the junction of two dissimilar metals. The potential is roughly proportional to the junction temperature, but cubic functions are frequently used to relate output voltages to junction temperatures. Any junction of dissimilar metals will produce a potential, so a second junction is required to connect a thermocouple to the measuring device. The temperature at this second junction must be known to determine the temperature at the first junction.

The need for a reference junction was a major obstacle to using thermocouples in the past. With today's data acquisition equipment, however, the temperature of a reference junction can be measured with a thermistor, RTD, or IC sensor, and the results can then be used to correct for both reference junction effects and nonlinear outputs. In fact, single integrated circuit chips are now available for about $12 that make all of the necessary corrections, and then amplify and scale the thermocouple output. These reference temperature ICs are currently in use at the STEP facility [Stine and Heckes 1986].

Thermistors--Thermistors are metal oxide or semiconductor devices in which the resistance decreases with temperature increases. These devices are relatively inexpensive, and their accuracies are typically 10 times better than those of thermocouples. Thermistor sensitivities though, drop off rapidly above a few hundred degrees Celcius. The output of a thermistor is an exponential function of temperature, but combinations of thermistors and other resistive devices can give linear outputs over narrow ranges (typically -50 to +100°C).

The biggest problem with thermistors is that they are extremely fragile. Stresses placed on the devices during mounting can either destroy the accuracy or crush the thermistor outright. Thermistor properties also tend to drift over time and the devices have self-heating errors caused by the excitation current used in measuring the resistance.

Resistance Temperature Detectors--RTDs are usually wire-wound or metal-film devices in which resistances change proportionally with temperatures. The devices tend to have fairly linear characteristics, but third-order polynomials should be used for added accuracy. Self-heating problems are not as bad in RTDs as they are in thermistors, but sensitivities are typically lower than those of thermistors and thermocouples.

RTDs are somewhat expensive (approximately $35 each) and they have presented some major problems in existing solar facilities. At both Solarplant One and STEP, for instance, RTDs were estimated to give measurement errors of ±30°F [Stine and Heckes 1986; Payne 1986]. RTDs and their lead wires were also prone to burning out and they had a low degree of reliability at both of these facilities.

Control Valves

Two valve characteristics that are attractive from a controls standpoint have already been mentioned; the valves should be the largest pressure drop in the system, and the valves should have equal percentage rather than linear flow characteristics. If a valve does not provide the largest pressure drop in a system, a linear control valve has the "installed" flow characteristics of an on-off valve, and an equal percentage valve has the installed characteristics of a linear valve. In other words, a valve will only have a significant influence on flow rates near the shutoff position. Improper valve characteristics have caused problems in regulating receiver flows in past solar facilities [Stine and Heckes 1986; Dudley 1987]. Equal percentage valves are generally used in pressure control applications, but they are also used for systems in which the pressure drops tend to vary [Gas Processors Suppliers Association 1981].

Other than the two flow aspects mentioned above, most of the interest in control valves has centered around how they are actuated. Since the flow is being modulated and not simply turned on and off, the valve stem positioners tend to be fairly complicated and expensive devices. Four valve stem positioning mechanisms that are in common use are - pneumatic actuators, electric actuators, electrohydraulic actuators and thermostatic actuators.

Pneumatic Actuators--Pneumatic actuators can provide a large power output for positioning valve stems, but they do require a supply of compressed air. Because the actuator must leak air to regulate the valve stem position, the parasitic costs for pneumatic actuators are high. Spring and diaphragm pneumatic actuators, which are often chosen because of their simplicity and dependability, require from 3 to 15 psig pressure. Piston and cylinder actuators require anywhere from 20 to 120 psig operating pressures. Both of these actuators can be fast acting, with typical actuating times (the time required to go from fully open to fully closed) of only a few seconds for quarter-turn valve applications.

Running compressed air lines hundreds and perhaps thousands of feet through a collector field is a major drawback to using pneumatic actuators. The initial cost of running air lines is not the only problem; there will also be problems with condensation as the compressed air cools in the long lines. At the STEP facility measures were taken to reduce condensation by drying the control air and burying air lines below the frost line. These measures were unsuccessful though, since water still condensed in the lines and caused actuators to stop operating. Normally the actuators did not fail, but the electronic-to-pneumatic (E/P) interface valves were destroyed by slugs of water in the air lines. (E/P valves are used to convert an electronic control signal to a pneumatic control signal).

Even though there are problems associated with pneumatic actuators, their use in solar facilities cannot be entirely discredited. Pneumatic actuators are widely used in industry and they are quite dependable when supplied with dry air. They should be considered for situations in which only short runs of compressed air lines are required. (One such application is for a case in which main headers lead into the collector field, but variable speed pumps should also be considered for main header flow control.) Restrictions imposed by the requirements for dry air may limit the use of pneumatic actuators, but the cost of these actuators has always restricted their use anyway. Modulating valves that are pneumatically actuated typically cost between $1000 to $1500.

Electric Actuators--Electric actuators are not as common as pneumatic actuators, but they are beginning to appear in applications such as oil-field steam-injection systems. Electric motors and gear reduction systems usually provide the torque needed to rotate a valve stem. Quarter-turn actuating times under no load conditions are typically between 10 to 20 seconds, but they can be over a minute. Variable speed controls are available for electric actuators.

Electric actuators with built-in feedback position control cost about the same as their pneumatic counterparts - $1000 to $1500. Without feedback control, electric actuators cost about $400. Conceivably, feedback control for valve positioning could be provided by the RCU controls if an encoder were available to indicate the valve's stem position.

When power is lost to an electric actuator, the valve stem normally remains in a fixed position until it is manually opened (both pneumatic and electrohydraulic actuators can spring open or closed on power loss). This fixed-position failure mode has led to some reservations about using electric actuators in solar applications; presumably, a receiver could be destroyed if the valve were stuck in a low-flow position when the receiver was on sun. Since other means are usually available to remove the sun from the receiver when a failure occurs, it is unclear that this consideration should rule out the use on electric actuators. Where electric actuators are used in industry, they seem to perform reliably.

Electrohydraulic Actuators--Electrohydraulic actuators use fluid pressure developed by a small oil pump to position a valve stem. Actuation times for a 90° stroke range from 30 to 60 seconds, but faster response times are available. The actuators cost around $350, and they are primarily used to control dampers and to modulate gas flows to burners. An electrohydraulic actuator was used at the MISR facility to regulate flow to a steam generator, and no failures or shortcomings were observed in this application [Cameron 1987]. However, there was some concern that parasitics might be high for these actuators because the small hydraulic pumps must run continuously to maintain a valve position.

Thermostatic Actuators--Thermostatic actuators rely on the thermal expansion of solids or gases to provide the work needed to drive a control valve. Common examples of these actuators are the bimetallic switches used in thermostats, or the paraffin actuators used to control flows in automobile coolant systems. Thermostatic actuators are also found in tempering valves used in domestic solar hot water systems. In some instances the actuator is an integral part of the valve, such as in the case of an automobile thermostat, and in other instances the thermally expanding material and the valve being actuated are located in separate parts of the system. Figure 23 shows a possible configuration for a thermostatically controlled valve in a solar receiver application. In the temperature sensing bulb a thermally expanding material would drive a piston or bellows that forces fluid through the pressure line and into the valve actuator. The actuator opens or closes the valve until the receiver flow and the bulb temperature reach a point of equilibrium.

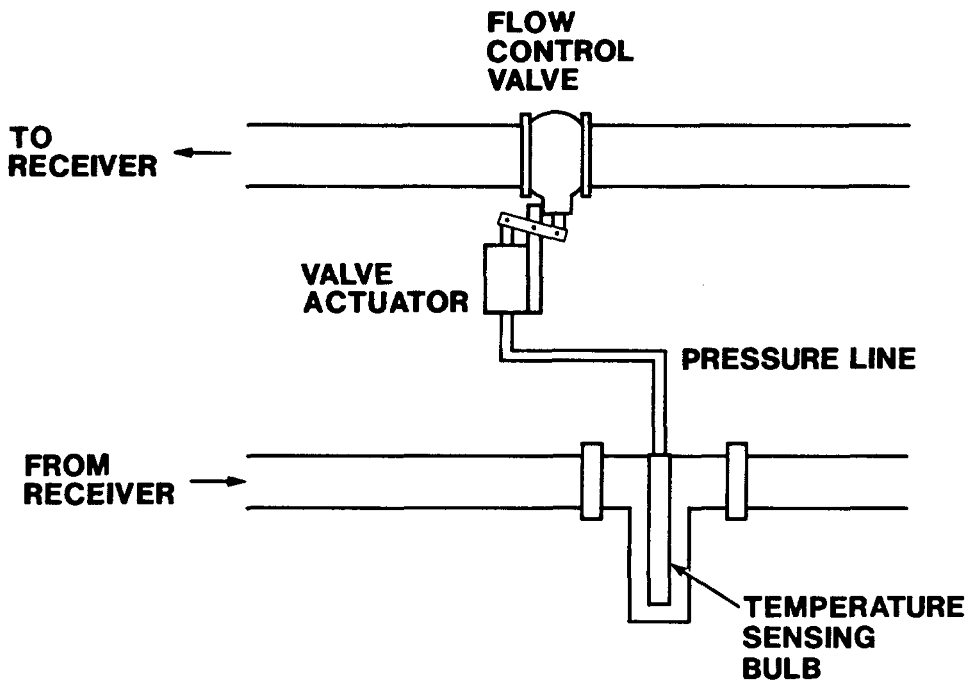


Figure 23. Thermostatically actuated control valve.

When the expansion of a solid-to-liquid phase change is used as a driving force, the actuator stroke is linear with the temperature. This means that the valve cannot drive the system to a given set-point temperature, Tset, but it can only limit the temperature to a given range, say Tset ±15°F. The rate at which a thermostatic actuator responds to temperature changes will depend on the mass of the sensor and the properties of the liquid in which it is immersed. To be compatible with the rest of the system a thermostatic actuator must have a response time faster than the receiver time constant. It is currently unknown if this criterion can be met for high-temperature solar receivers.

Commercial thermostatic actuators have operating temperatures below those required for most distributed receiver systems. Wax actuators have an upper temperature limit of 230°F, and most solar receivers are being designed for a 700 to 1500°F operating range. The highest temperature thermostatic actuator seems to be a 500°F actuator used in controlling the gas flows to pizza ovens. The potential low cost of thermostatically actuated valves (under $100) may justify the development of these actuators for high-temperature solar applications.

Insolation Sensors

Insolation measurements are needed to determine if solar radiation levels are sufficient for a system to begin operating. The readings are also used in selecting flow control gains and in interpreting error signals from the sun-tracking sensor. In addition, insolation measurements may be used in initiating pre-emptive flow-rate changes to avoid overheating receivers during rapid solar transients.

The standard commercial instruments for measuring solar insolation levels are pyranometers and pyrheliometers (see The Spec Guide 1986; Duffie and Beckman 1980). Pyranometers, which are also called solarimeters or radiometers, measure global radiation (direct + diffuse) by exposing a light detector to a hemispherical portion of the sky. Pyrheliometers (also known as actinometers) use a collimating tube so that a detector is exposed to only a 5.7° aperture angle. When a pyrheliometer is aligned directly with the sun, the detector measures direct radiation and circumsolar radiation from a portion of the sky two orders of magnitude larger than the sun.

The more expensive (~$1000) pyranometers use a thermopile detector in which thermocouples are placed in light and dark concentric or pie-shaped segments of a circle. Thermopiles may also be used to measure the temperature difference between the blackened detector surface and the housing of the instrument. Less expensive pyranometers ($175 to $700) use a photovoltaic cell as the detector. Thermopile detectors typically have a response time of about 5 seconds to steady state and a temperature dependence of ±1.5% from -10 to +40°C. Silicon photovoltaic detectors have a faster response time, ~10 microseconds, but their output may vary by ±7.5% over a -10 to +40°C ambient temperature range. Photovoltaic detectors are often equipped with diffusers to compensate for output variations with incident angles.

Pyrheliometers also use a thermopile and photovoltaic detectors. Pyrheliometers with thermopile detectors cost around $1500 and have response times of about 1 second, while instruments with photovoltaic detectors cost about $350 and have a 1 millisecond time constant. These prices, however, do not include the cost of a tracking mechanism. Temperature sensitivities for each of these detectors are similar to those found in pyranometers.

Periodic inspections are recommended for both pyrheliometers and pyranometers to insure that sensor windows or domes are clean. Air-drying crystals are sometimes used in these sensors to reduce condensation problems. These desiccants must be changed periodically, though, to remain effective.

Temperature Control Systems

Several methods have been used in the past to control receiver temperatures. The following examples illustrate some of the receiver control procedures tested in solar thermal facilities.

Central Receiver Facilities

The central receiver at Solar One is made of 6 preheater panels and 18 panels of single-pass boiler tubes [Tanner 1986]. Control valves at the inlet of each of the 18 boiler panels are used to modulate water flow rates through the receiver. Inlet conditions are also regulated by controls on the receiver feed water pump. Receiver discharge pressures are regulated by control actions taken downstream on either the receiver flash tank, the thermal storage system, the turbine throttle valve, or the steam dump pressure controllers.

During start-up at Solar One, the receiver control valves are set to a fixed position until the receiver tube temperatures reach 400°F. Between 400°F and 600°F the valves are adjusted to maintain a constant flow rate through the receiver panels. Above 600°F control valves work to drive the metal receiver tubes to a desired set-point temperature. When all of the receivers are in the metal temperature control mode, the set-point temperatures are ramped from 605°F to 775°F at a rate of 30°F/minute. The procedure of ramping set-point temperatures is necessary to avoid overshooting temperature limits or obtaining large temperature gradients during sudden and extreme flux transients.

In Solar One's metal-temperature control mode, the difference between tube temperatures and set-point temperatures is combined with a feed-forward signal from measured flux levels on the receiver panel to derive flow adjustment commands. Variable control gains are used in the receiver control system to compensate for variations in system characteristics with flow rates.

Metal temperature control is the primary method for controlling receiver temperatures in the Solar One facility, but other temperature control strategies were tested. One alternative procedure used metal-temperature control during transient conditions and receiver discharge temperature control during steady-state operation. This blended control system provided little improvement over control on metal temperatures alone, so it was not used for routine operation.

Successful receiver control has been demonstrated over a wide range of operating conditions at the Solar One facility. However, short cloud transients (approximately 1 minute in duration) can cause the receiver to cool to a point that superheated steam is no longer produced [Kolb 1987]. At that point the turbine trips, flow to the receiver is shut off, and heliostats go to an offset tracking mode. To return to an operating status after this interruption can then take up to 45 minutes. Control is further complicated because there is only one steam header from the Solar One receiver, so all of the boiler panels must be producing superheated steam to operate the turbine [Nagel 1986]. Clouds over a portion of the field can upset normal operations under the current configuration. It has been suggested that a second steam header and a second set of control valves would provide better control of the receiver and allow the system to operate longer [Nagel, 1986]. The same study notes that a lack of redundant control valves leaves the system vulnerable to a complete shutdown if a single valve fails.

Other central receiver systems use control strategies similar to those for Solar One. In the Molten Salt Subsystem Component Test at Sandia National Laboratories, a control input signal is derived from flux gauges mounted at the front of the receiver and temperature measurements made at the back [Smith 1986]. This signal, in conjunction with the discharge temperature, is used to determine the optimum flow rate through the receiver.

The central receiver system in Almeria, Spain goes one step further in the feed forward loop by placing a sun monitoring sensor in the field to generate a control input signal. If there is a sudden change in the insolation level, the sun sensor initiates a corresponding change in the receiver flow rate. This is reported [Grassee 1985] to work well for cloud interruptions of about 50 seconds, but for longer cloud interruptions (100 seconds or more) the pump will surge after the sun emerges and cause the receiver to rapidly cool. While the surge in flow prevents the receiver from overheating, it causes too much of a drop in receiver temperature. It was noted that this problem might be avoided if a better evaluation of the flux reaching the receiver were available.

Distributed Receiver/Central Power Conversion Systems

Shown in Figure 24 is a schematic of the STEP collector field. Pneumatic control valves regulate the flow of Syltherm 800 to 12 rows (or branches) of ten collectors. Flow to each row of collectors is controlled by a single pneumatic valve and receiver temperatures within a row are balanced using hand valves. Seven collectors that are shadowed less than others have individual pneumatic control valves. Flow to the entire field is regulated by two pumps and one main control valve. A central processor controls receiver temperatures based on two temperature measurements from each receiver, branch outlet temperatures, field inlet and outlet temperatures and flow rates, stem positions for each valve, and pump operating modes (on/off) [General Electric 1979].

Concentrators at STEP are brought on-sun after direct normal insolation exceeds 236 W/m^2. During the warm-up procedure, flow is recirculated in the field until the field outlet temperature reaches 500°F. Above 500°F, flow is directed through a storage tank in order to prevent the inlet temperature from exceeding 525°F. The added thermal mass also stabilizes the system's approach to a desired outlet temperature by providing a relatively constant field inlet temperature.

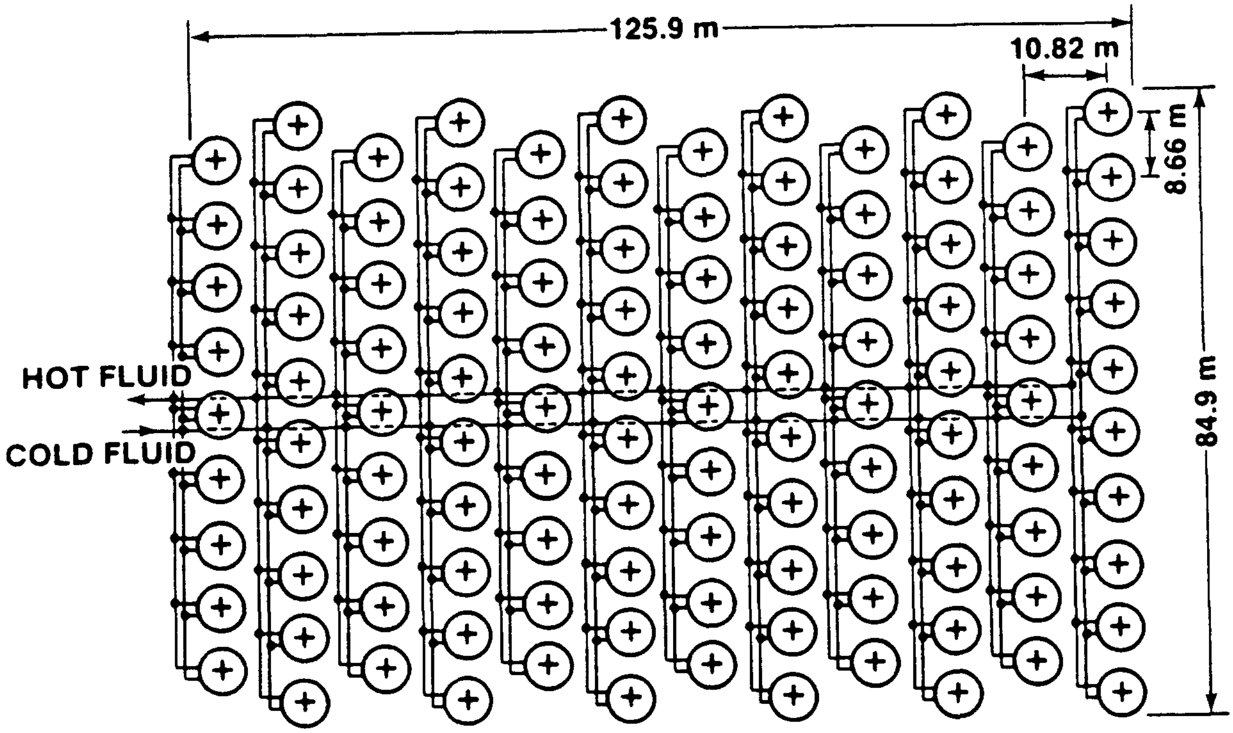


Figure 24. Collector field at the Solar Total Energy Project in Shenandoah, Georgia.

The current STEP control system does not use flow control in the collector field. Because of pneumatic control valve failures and problems with accurately regulating receiver temperatures, branch valves and hand valves are now left completely open and only the main control valve is used to regulate the field temperatures. This procedure causes the field outlet temperature to be somewhat lower than desired, but it does keep receivers from overheating. To understand what led to the abandonment of flow control within the field, a brief discussion of the original control system is warranted.

Position set points for the main control valve were based on the branch valve positions in the original system. Branch valve commands were found using a PID control algorithm, a temperature set point, and the hottest receiver temperature reading along the branch. When the hottest receiver was 15°F above the row's average temperature, that receiver was driven to an offset tracking position 30° east of the sun's true position. Control commands were then based on the next hottest receiver in a row and the defocused collector would not resume tracking without operator intervention. If several dishes along a branch were offset tracking, the entire row would be defocused, and flow to that branch would be isolated from the rest of the system.

The original STEP flow control system was designed to limit field outlet temperatures to a range between 685°F (the minimum temperature required to avoid condensation in the turbine) and 750°F (the maximum temperature at which Syltherm-800 is stable). Maintaining a field outlet temperature of 685°F was not difficult, but the turbine/alternator output was degraded at this lower temperature [Stine and Heckes 1986]. It was preferred to have a field discharge temperature between 725 and 750°F. Achieving even a 700°F outlet temperature was a very difficult task, however, requiring a crew of about 10 persons working constantly to adjust hand valves on each collector. Small flow perturbations would drive receiver temperatures above the 750°F limit, which initiated the offset tracking mode. The defocused receiver would then act as a heat sink to the system until the operator issued a new tracking command. These were the reasons that the original flow control scheme was abandoned and the lower operating temperature was accepted.

Solarplant One experienced similar problems in using flow balancing techniques to regulate receiver temperatures. Orifices are used in this system to balance receiver flows; this made the process of obtaining uniform field temperatures somewhat more complicated to implement than it was at STEP. If a receiver overheats at Solarplant One, however, the collector is driven to an offset tracking position for 6 minutes. Tracking is then resumed automatically so the receiver will not act as a heat sink to the system.

Selecting pressure drops to obtain equal temperatures in a field of collectors is not a simple task. Adjustments made for one receiver will affect flow rates in other receivers, so the entire field must be tuned in an iterative fashion. Furthermore, once a field of collectors is properly tuned there is no guarantee that the receiver temperatures will remain equal for long. Pressure drop changes caused by viscosity variations with temperature and plugged receiver tubes, and changes in concentrated insolation due to collector soiling and shadowing cause receiver temperatures to become unequal over time. The end result of these uneven temperatures is that hotter flows are mixed with cooler flows and the performance of the entire field is degraded.

Dish-Mounted Heat Engine Systems

In most dish-mounted heat engine systems, receiver temperatures are controlled by regulating the mass flow rate through the engine. Varying flow rates by continually altering engine speeds is, in general, not possible because speeds are restricted by grid connection requirements or engine design considerations. Usually it is the performance characteristics of the engine that must be altered.

For the kinematic Stirling engine used in the Vanguard dish electric system, the engine performance is altered by varying the operating pressure of the hydrogen working fluid [Droher and Squier 1986]. The engine controls compare thermocouple readings of receiver tube temperatures with a set-point temperature (typically 720°C) to determine the appropriate engine pressure. As insolation increases, pressure in the engine is increased, thereby increasing the mass flow rate through the receiver. Below the hydrogen reservoir pressure of 4 MPa, temperatures are allowed to decrease while pressures remain constant. For engine speeds above 1840 and below 1800 RPM, the induction generator, which is directly coupled to the heat engine, disconnects from the grid. Over-temperature and over-pressure conditions initiate a detrack command.

The United Stirling engine in the McDonnell-Douglas dish electric system uses similar pressure control procedures. Both of these engines received extensive on-sun testing. During the tests the controls responded quickly to solar transients and performed well in regulating receiver temperatures. In the Vanguard system the thermal time lag was about 60 seconds, whereas the engine power output response time to pressure and temperature changes was on the order of 10 seconds.

Free-piston Stirling engines and Stirling Thermal Motor's kinematic Stirling engine have the capability of altering the engine's stroke to change flow rates through the receiver. For the Barber-Nichols Organic

Rankine Cycle engine, a 750 F receiver temperature is maintained by throttling the receiver discharge flow. When insolation levels drop too low, the ORC turbine speed drops from a 50,000 RPM running mode to a 35,000 RPM idle mode. All of these systems are in the design and/or testing phase, so it would be premature to state how engine and receiver control will ultimately be accomplished.

CHAPTER IV. SYSTEM REQUIREMENTS AND CONSIDERATIONS

Up to this point the controls discussion has focused on tracking the sun and regulating receiver temperatures. However, the choice of control hardware and procedures is often based on considerations beyond these primary objectives. Additional factors that will impact control designs are (1) the manner in which control is distributed throughout the system, (2) the role that controls play in system protection, (3) the reliability and durability of control components, and (4) the burden of control costs on overall cost goals. The influence that these factors have on control designs is discussed in this chapter.

System Communication

Solar power plants represent one of the first large scale applications of digital control electronics in a distributed control system. In designing any distributed system it is necessary to consider two points carefully; (1) how information is to be transferred between control elements, and (2) how control tasks are to be divided among control elements.

Communication Networks

Field communication requirements are a function of the number of controllers, the distribution of control tasks, and the rate at which messages must be relayed. The high-speed medium-distance communication networks suitable for solar facility control systems are normally referred to as industrial local area networks or "LANs." Differences between LANs are often reflected in the type of network topologies and transmission media used in a system. A brief review of these differences is presented here. For a more detailed discussion of LANs see Jones & Bryan [1983] or Friend et al. [1986].

Network Topologies--The topology of a system defines how devices or "nodes" are connected in the communication network. Network topology will affect the speed, reliability, and cost of a communication system. The three most common forms of network topology, star, ring, and common bus, are shown in Figure 25.

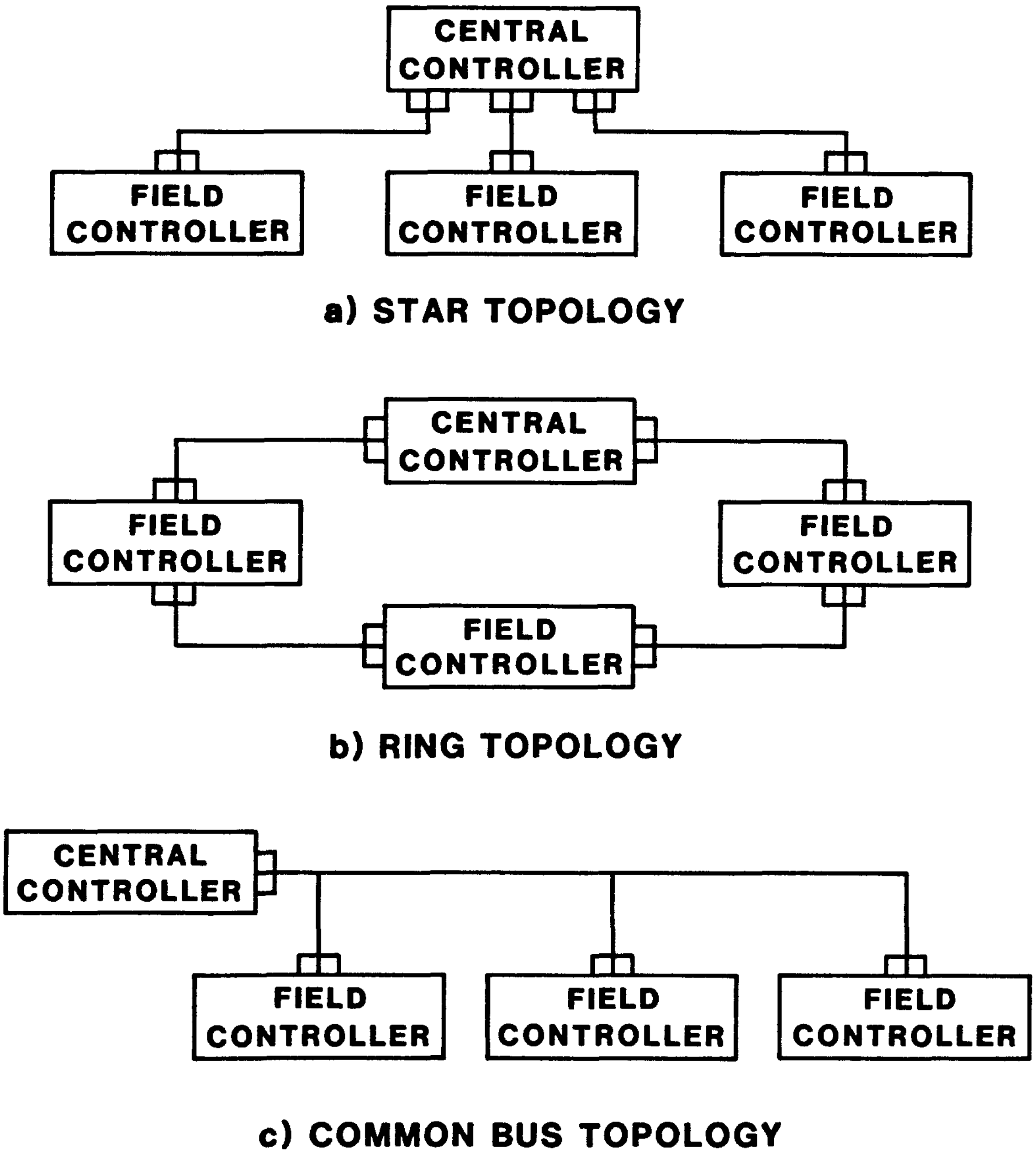


Figure 25. Communication topology options: (a) Start topology, (b) Ring topology, and (c) Common bus topology.

In a star topology, nodes (i.e., field controllers) are connected directly to a multiport host computer. The major advantage of this topology is that field controllers can communicate directly with the host computer using a simple point-to-point protocol. Major disadvantages are that messages between nodes must pass through the central computer, wiring costs are relatively high (compared to star and common bus topologies), expanding the network can be difficult, and a failure of the central node will bring the entire network down.

In a ring topology network each controller receives and retransmits messages. By connecting controllers in this daisy chain fashion the entire network could be incapacitated if any one node failed. Each node must be assigned a unique address in a ring topology so coded messages are received and acted upon by the proper controller. Wiring requirements are reduced with this topology and ring networks are well suited for the application of fiber-optic cabling.

In a common bus topology all nodes are connected along a main trunk line. This multidrop system often requires less cabling than star topology systems, and controllers can communicate between themselves without passing messages through the central computer. Adding or subtracting nodes from a common bus network is generally a simple task. The main disadvantage of this topology is that a communication protocol must be established to avoid data collisions along the main trunk line.

There is no clear advantage to using one network topology over another. The choice of which system to use will ultimately depend upon the amount of data that must be transmitted, the rate at which data are needed, the transmission media chosen, and the relative cost of each option.

Field Communication Links--In a distributed control system it is necessary to have a reliable, cost-effective communication network. Pearson and Chen [1985] recently completed a study that compared five options for communication links between the heliostats and central computer at Solar One. These options included dedicated wire cabling, fiber-optic cabling, radio-frequency links, carrier-current links, and optical air links.

Dedicated Wire Cables: Dedicated wire cabling, which includes both twisted-pair conductors and coaxial cables, is the most common communication medium applied to control systems. Twisted-pair wiring is relatively inexpensive and it is used extensively in industrial applications. It can be used at distances up to 4000 ft and at transmission rates up to 250 kilobaud (although many electronic manufacturers recommend transmission rates of only 19.2 kilobaud). Performance in twisted-pair wiring degrades rapidly as nodes are added in a common bus topology and there are also limitations imposed by nonuniformities in the wires [Jones and Bryan 1983]. These problems are eliminated in coaxial cabling because of its extreme uniformity. Smaller coaxial cables (3/8-in. diameter) have been used at speeds up to 2 megabaud and distances up to 18,000 ft, and larger cables (1/2 to 1 in.) are typically used at 10 megabaud rates at distances up to 30 miles. The cost of the dedicated wire network used at the Solar One facility was approximately $250/collector [Pearson and Chen 1985].

Dedicated wiring is fairly immune to noise (especially if it is shielded), but it is susceptible to electromagnetic interference from lightning and other electrical transients. Lightning strikes, even at distances up to 3 miles away, have caused a number of control failures in solar facilities [Lopez 1986; Lepley 1986; Payne 1987; Hicks 1987]. In some instances the control electronics are blown out of the enclosures after a strike, so it is difficult to identify the exact mode of failure. In other cases it appears that current induced from a lightning strike travels along the communication cable and arcs across connection pins where the cables terminate [Hicks 1987]. In facilities where commercially available transient surge suppressors have been installed at each end of communication lines, electromagnetic interference problems have been largely eliminated [Payne 1987].

Fiber-Optic Cables: Transmission rates of up to 800 megabaud have been obtained at distances of 30,000 ft using fiber-optic cables. In addition to high-speed and long-distance capabilities, fiber-optic lines are small, lightweight, and totally immune to all forms of electrical interference. However, the use of fiber-optic cables in large bus topologies is currently hampered by the losses associated with tapping into a main trunkline. Typically a tap in the line results in a signal loss of approximately 2 dB.

A maximum loss of 25 dB is recommended before a signal repeater must be installed. Because signals are repeated at every node in ring topologies, fiber-optic cables are well suited for ring topology networks. Fiber-optic cables are sometimes used in star topologies with a rotating mirror placed at the central node to relay messages.

Contrary to Pearson and Chen's assertions, fiber-optic networks cost at least twice as much as dedicated wire networks. The cost of fiber-optic cables is twice that of coaxial cables, and optical couplers are several times more expensive than electrical interfaces. Advances are being made in reducing costs and simplifying the installation of fiber-optic cables, but a widespread use of these cables in distributed control systems is likely to be several years away [see Brown and Krohn 1986; Jones and Bryan 1983].

Radio-Frequency (RF) Links: RF links are used in a number of common applications such as TV receivers, remote phones, and pager systems. Transmitter and receiver chips are now fairly inexpensive and several companies are producing them. Pearson and Chen estimated that an RF communication network would cost under $50/concentrator for a field of 2000 collectors. Antennas would be required at each collector, and transmission rates would be limited to about 10 kilobaud (this is the same baud rate now used in Solar One's dedicated cable network). RF links were designated by Pearson and Chen as one of the best options for a collector field communication medium, but they did express some reservations about the possible path interference caused by a field of metal structures (i.e. solar collectors).

Carrier-Current Links: Power cable carrier-current control (CCC) links use the power cables as a data transmission medium. This concept, which was first conceived at Sandia National Laboratories [Alvis and Rosborough 1982], has gained enough popularity that transmission and reception hardware is now available as "off-the-shelf" items. Pearson and Chen estimated that a CCC network would cost about $70/collector for a field of 2000 units.

CCC links are susceptible to electromagnetic interference, but hardware improvements have been made over the past few years to reduce the effects of current spikes [Lee 1982]. The data transmission rate for CCC links is limited to about 4 kilobaud. A recent project at Sandia's MISR facility showed that CCC communication links can operate successfully in small distributed control systems, and scale-up was determined not to be a major problem [Cameron and Dudley 1986].

Optical Air Links: This would be a simplex (one-way) communication system consisting of an optical transmitter located on a central tower that broadcasts messages to optical receptors in the collector field. The control signal is transmitted by either a wide-angle beam spreader or a computer-directed prism. Data transmission rates are about 100 kilobaud, and the system is not susceptible to electromagnetic interference. There is some concern, however, that light scattering from dust and moisture might reduce the performance of an optical air link. Pearson and Chen estimated that an optical air link communication would cost about $285/collector for a field of 2000 concentrators, but significant price reductions were predicted if components were produced in large quantities.

Control Hierarchy

Several options exist for distributing control logic through a collector field. One option would be to provide control logic for all of field elements (collectors, pumps, valves, etc.) with one central computer. This procedure would reduce the cost of field control units, but it would increase the communication costs and it might hamper future expansion of the plant. A second option would be to provide local autonomous control at the collectors and power conversion system(s). This would increase the cost and complexity of the field controls, but it would reduce the burden on a communication network and it might make a future expansion of the plant easier.

Most of the existing collector fields use an option somewhere between the two extremes in control hierarchy mentioned above. Some of the different approaches to control hierarchy can be highlighted by examining the Solar One, STEP, and Solarplant One tracking control systems. All three of these facilities use two levels of control, a central computer and a local collector controller, but the distribution of control logic differs from system to system.

At Solar One a central computer monitors the status of heliostats, issues global commands (such as wake-up, stow, move focus to standby position, etc.), and informs the 1818 heliostat controllers of the sun's position. Based on the information from the central computer, heliostat controllers calculate aiming instructions and issue commands to the drive motors if a position update is required [Tanner 1986].

Messages to Solar One's heliostat controllers are relayed to the central computer through 64 intermediate field controllers. The field controllers, which act mainly as communication buffers, are connected along eight sets of redundant serial data lines to the central computer. Each field computer is connected with 14 to 32 heliostat controllers along a star topology network. Operating at a 10 kilobaud transmission rate, this half-duplex (one-way at a time) system can issue updated sun position vectors to all 1818 heliostats every second. The status of a heliostat (on-off) can be relayed from the field to the central computer in 8 seconds.

In the original STEP control system, logic for open-loop tracking was supplied by the central computer and logic for closed-loop tracking was provided by local concentrator controllers. For open-loop tracking during sun acquisition, stowing, or cloudy periods, the concentrator's measured orientation was relayed through the concentrator controller to the central computer. Drive-motor start and stop commands were then generated by the central computer and relayed back to the local controllers. When insolation levels were sufficient for closed-loop tracking, collector position updates were determined by the local controllers. Commands that actually initiated update actions, however, still came from the central computer in the original control system.

The STEP facility uses a ring topology network to link the 114 concentrators to the central computer through a buffer control unit. Problems were encountered in this network because of the extensive amount of data that was being transferred and the overreliance on a central computer. If a command was issued to a concentrator controller, it would take 3 seconds to issue a second command to the same controller. At times, this long delay in communication caused concentrators to be driven past the proper aim point and focused on the receiver aperture.

Because of problems in aiming the concentrators, both in open- and closed-loop tracking modes (see Chapter 2), the STEP tracking, control system was recently overhauled. The new system uses only open-loop tracking and more of the control responsibility has been shifted to the local controllers. Local controllers now compare predicted motor turn counts supplied by the central computer to actual motor counts to determine motor switching commands.

To a large extent, concentrator controllers at the Solarplant One facility operate in a stand-alone fashion. The local concentrator controllers provide logic for both open- and closed-loop tracking. While in a closed-loop tracking mode the local controllers generate a tracking error table by comparing stored ephemeris tracking data with measured collector position data. Based on this error table, collector controllers update ephemeris aiming instructions for the entire day (see Chapter 2). At the end of a day error tables are uploaded to the central computer for analysis. Corrected ephemeris tables are transferred back to the field controllers for use in open-loop tracking on the following day.

Global commands, such as start-up, shutdown, and emergency stow, are transferred from the central computer to the 700 concentrator controllers through communication interface controllers. Each communication interface controller is connected through a 32-bit parallel bus to the central computer. Up to 31 concentrator controllers are connected to each communication interface controller through a multi-drop common bus that operates at a 2400-baud rate. There can be up to a 5-second delay before messages from the field reach the host computer in the Solarplant One Communication system. This delay, however, does not cause problems since most of the control logic has been placed at the field level [Payne 1986].

Active System Protection

Almost all measures to actively protect solar concentrators and receivers will in some way involve the control system. First, the control system must recognize that an emergency exists, either through sensor inputs or operator warnings, and second, the controls must implement the protective action. Design specifications for the controls generally include the following requirements:

1. The controls must prevent damage to the concentrator, the power conversion unit, and personnel.
2. Controls must minimize heating of the concentrator structure and the power conversion unit when acquiring the sun, and driving off the sun during routine or emergency operations.
3. The concentrator must detrack from the sun when there is a control system failure or a loss of electrical power. The appropriate protective action will depend on the source of the problem.

Avoiding Wind Damage

Solar collectors are required to withstand high or gusty wind loads, hailstone impacts, excessive rain, extremes in temperature and humidity, repetitive freezing and thawing, snow and ice accumulation, blowing dust and sand, seismic loads, and nearby lightning strikes. The control system must operate reliably under all of these conditions and, when possible, the controls must prevent damage to the concentrator.

One of the major protective functions for a control system is to prevent wind damage. Wind loads probably have a greater influence on a collector's structural design than any other factor. Wind speeds are very site specific, so there is no single, universally recommended design wind speed. However, Randall and Grandjean [1982] have shown that 97.5% of all direct insolation occurs at wind speeds under 15 m/s (33 mph) for 26 SOLMET stations across the United States. This result suggests that little of the available solar energy will be lost by sending a collector to a safe stow position at wind speeds over 15 m/s.

Collector development programs currently use stow requirements close to a 15-m/s wind-speed limit. In the innovative dish concentrator project, tracking without performance degradation is required at wind speeds up to

7 m/s* (15 mph) (referenced at 10 m) [Thostesen 1984]. Tracking with only limited degradation is required at mean hourly wind speeds up to 12.5 m/s (28 mph) with occasional 21 m/s (46 mph) gusts. For heliostats, tracking must not degrade in winds under 12 m/s (27 mph) and tracking must continue in winds up to 16 m/s (35 mph) [Mavis 1985]. Above these maximum operating wind speeds the concentrator must be capable of going from any orientation to a stow position.

Under normal conditions, the maximum rate of wind rise was specified as 0.01 m/s (1.34 mph/min) by Mavis [1985]. If stowing begins in 16 m/s winds, the wind speed will be 22 m/s (50 mph) within 10 minutes under these "normal" conditions. Mavis did note, however, the wind speeds may exceed this maximum rate of wind rise under abnormal conditions, such as severe thunderstorm fronts.

The size of drive motors is often determined by the power required to stow a concentrator from any orientation under maximum operating wind loads. Ignoring or miscalculating wind loads has in the past led to undersized drive motors that were incapable of stowing collectors even in moderate winds [Alexander and Busch 1978]. Information on calculating collector wind loads on solar collectors is available in papers by Roshke [1984] and Peterka et al. [1986].

Wind conditions tend to be localized, so wind speeds are usually measured at or near the collector field. Wind speed measurements from several locations may be advisable in large fields because of the effect blockage has on reducing wind loads. Some experiments have shown a 70%

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* According to Thostesen, a 7-m/s wind velocity is exceeded only 5% of the time on sunny days at typical solar collector sites. This observation conflicts Randall and Grandjean's finding that 95% of available direct insolation occurs at wind speeds under 11 m/s. The resolution to this conflict may lie in how one defines a "typical" solar collector site.

reduction in wind loads resulting from field blockage [Peterka et al. 1986]. The practicality of placing wind-speed sensors on individual PV arrays is currently being investigated in Sandia National Laboratories' photovoltaic division [Maish 1986].

Avoiding Concentrated Flux Damage

In addition to protecting the concentrator from external forces, the control system also has the task of preventing the collector from damaging itself and surrounding structures or people. The concentrated solar flux presents the biggest source of damage, and most solar thermal facilities have scorched areas that show the true potential of this problem. In designing controls and selecting control routines, the location of the concentrated flux must be considered at all times during all modes of operation (acquisition and deacquisition of the sun, offset tracking, etc.). Emergency control measures are also required to defocus the sun (and/or protect the receiver and receiver aperture plate) when the tracking system fails.

For routine operation of a solar collector, it is necessary to bring the concentrated flux on and off of the receiver target. During this procedure a path must be chosen that avoids placing a partially focused solar image on components that could be degraded by repeated heating. This is not a simple task because it may require a different acquisition path for different times of the day and different days of the year. Finding the proper approach has been a problem in the past. There have been a number of instances in which electrical cables and components, power conversion equipment, and structural supports have been routinely burnt during sun acquisition and deacquisition [see for instance Droher and Squire 1986].

Overheating the receiver aperture plate is another problem that must be avoided when driving a concentrator on or off the sun. Collector drives are presently designed with the capability to slew on or off the sun at rates varying from 0.5 to 1.7°/s. At the higher speeds, the controls must be able to gradually stop the concentrator without overshooting the target, and at lower slew rates, the controls may be required to follow a specially protected acquisition path. For instance, controls for the slow-moving TBCs at Sandia's distributed receiver test facility are required to drive the concentrated solar image along a water-cooled aluminum plate when acquiring the sun.

Special precautions are also required for offset tracking. First, the offset tracking position should be east of the sun to avoid inadvertently acquiring the sun if the tracking system fails. Second, the collector must not accidentally focus on surrounding equipment or people while offset tracking. It has been observed that even partially focused collectors can create major problems. At Solarplant One the partially focused collectors were known to melt vacuum hoses on forward collectors and cause a cascade of failures across a collector field [Payne 1986]. Since people are even more vulnerable than hardware, it is important to avoid placing a partially focused solar image in areas where people may have access.

All of the problems to this point have assumed that the tracking systems are operable. If a collector is focused on the sun and the tracking system fails, the sun's focused image will continue to travel across the aperture plate at a rate of 1/4°/minute because of the earth's rotation. This event, which is known as a solar walk-off, can easily destroy the receiver and any other equipment located near the focal point. At this time, no material has been identified that can withstand the intense flux from a high-performance concentrator except water-cooled metal plates and some graphites [Jaffe 1983].

There are three primary causes for solar walk-off: loss of power to the field, failure of the drive system or tracking control components, and human error. If the walk-off is due to a drive failure, flow through the receiver can continue, so there could be a few minutes to respond to the failure. If the failure is caused by a power failure and flow through the receiver stops, the required response time may be on the order of tens of seconds.

The first problem is recognizing that a failure has occurred. Encoder readings made after a position update command or temperature measurements from the receiver aperture could signal a walk-off is occurring. To make these measurements though, the local controller must still be operable. A measured power loss to the field or failed communication between field and host controllers could also indicate that a walk-off is in progress.

Previous systems have relied on all of these signals to initiate emergency detrack procedures.

Once a tracking failure is detected, the collector must be driven away from the sun. Past solar thermal systems have tried a number of walk-off protection measures, such as gravity slew mechanisms (Vanguard), air motors and gas cylinders (TBC & PDC-1), water-cooled aperture plates (TBC & Vanguard), and back-up diesel generators (Solarplant One). A number of other alternatives, such as umbrellas, smoke bombs, PV back-up power, and mechanisms to lower the receiver, have also been proposed for future systems [Jaffe et al. 1982]. However, a generalized, cost-effective, high-reliability protection system does not exist at this time.

In a study by Awaya and Bedard [1985] diesel-generated back-up power was identified as the most cost-effective option for walk-off protection (of the choices now available). However, their results are likely to be very dependent on the size of field that was considered (62 collectors) and the prescribed modes and frequencies of failure (one grid failure per year and one tracking failure every 22 years).

System Reliability and Durability

Solar collector systems are designed to have a 30-year service life. Idealistically, the controls in these systems should have a similar lifespan, but realistically, controls seldom last as long as other plant hardware. In fossil-fuel power plants, which also have a 30-year service life, controls are often replaced after 15 to 18 years of operation. The control systems are usually overhauled because technological advances have rendered the earlier systems obsolete, and replacement parts and services become difficult to obtain. With the rapid advances being made in digital control systems, service life expectancies are actually decreasing since many suppliers only promise to stock replacement parts for about 10 years. This trend disturbs most utility companies and it has made them leery of installing controls that quickly become outdated.

To regain the confidence of utility companies, control system designers must concentrate on increasing both service life and system reliability. Unfortunately, the reliability of control systems in some recent solar projects has been somewhat less than inspiring. At the SOLERAS PV facility for instance, 83 out of 160 tracking control systems failed over a 21-month period, and each failure required an average of 4 hours to diagnose and repair [Williamson 1983]. Reliability was somewhat better at Solar One where the mean time between heliostat controller failure was reported to be 6745 hours [Nagel, 1986]. However, when one considers that there are 1818 heliostats at Solar One, this failure rate still translates to two or three failed controllers per day.

Component failures can often be attributed to following three causes: (1) infant mortality, (2) normal wear and aging, and (3) poor component selection. The following discussion highlights problems that have frequently surfaced in previous systems and offers some suggestions for avoiding these problems in future systems.

Infant Mortality--In any production run of electronic components there will be a certain percentage of parts that does not meet specifications. When this fraction is multiplied by the thousands of parts that go into a control system, it is inevitable that failures will occur. To reduce start-up failures, either the number of parts should be reduced or the components should be tested prior to installation. Pretesting each component would be too costly in many situations, but testing an entire assembly before installation might be possible, and advisable. Even if general pretesting is not done, fail-safe equipment such as limit switches and emergency detrack systems should be examined before they are installed.

Normal Wear and Aging--Two of the most frequently failed components in any electrical system (solar control systems included) are switches and connectors. Connectors on remote programming interfaces have been especially prone to wear because of repeated connecting and disconnecting. Cables have also been known to fail due to the continuous flexing they receive from the drive system. Aging is often accelerated in solar facilities because of exposure to UV radiation and the frequent cycling that components must endure.

On occasions, alternative designs or procedures can be chosen to avoid or reduce wear problems. For instance, the use of symmetric rather than one-sided tracking deadbands could halve the number of motor start-ups and possibly double the life of switches and motors. In many instances though, some aging must be accepted. Under these circumstances the best strategy is to identify parts that are subject to wear and then design the system to fail in a safe manner.

Since any component can fail, measures must be taken to make the routine inspection and replacement of parts a simple procedure. In some collector systems the inability to access encoders has been a major problem. At both Sky Harbor and the CRTF, for example, the entire collector must be disassembled to service the encoders, which are mounted inside the tracking structure [Holmes 1981; Eckert 1986]. Although placing encoders inside tracking structures would conceivably eliminate the need for weather-resistant enclosures (which proved to be a bad assumption in both cases), service costs have overshadowed any possible savings.

Poor Component Selection (or improper use of components)--In selecting components, certain considerations must be made for the less-than-ideal location where they will be. Many of the problems in past systems could have been avoided by using the following measures.

(1) Use weathertight enclosures that can keep dirt and moisture away from control electronics. Provide filtered ventilation on parts that cannot be made weathertight.
(2) Select components with properties that reduce corrosion problems [see Martin and Noon 1986]. Choose connectors that have thicker or less-porous platings (also use contact lubricants to reduce wear on the platings). Avoid circuit boards with exposed copper connections. (The corrosive chemicals used in etching circuit paths on printed-circuit boards tend to wick into the epoxy-fiberglass substrates. The residual etchants often corrode exposed copper connections.)
(3) Place desiccants or resistance heaters in components (sun sensors, control units, valve actuator controllers, etc.) where condensation may cause problems.

(4) Design systems to operate in ambient air temperatures from -20 to +120 F [Thostesen 1984]. Avoid placing enclosures in direct sunlight. Provide temperature control when the components cannot survive low temperatures. Thermal cycle pretesting should also be considered.
(5) Provide fuses, grounds, circuit isolation, and transient suppressors on all field equipment and communication cables.
(6) Use redundant systems for key components such as limit switches, temperature sensors, and main flow control valves.
(7) Avoid placing unprotected cables and other control components in areas where concentrated flux might be focused either by design or by accident.
(8) Avoid feeding the controls to animals. Rabbits seem to prefer insulation on communication cables over most desert vegetation.

Following all of the above suggestions may not be possible for economic reasons. However, if these protective measures are not taken, the consequences in terms of maintenance costs and lost operating time should also be considered in the economic analysis.

Cost Goals

The long-term goal for dish collector systems is to produce electricity for $0.05/kWh or process heat for $7/MBtu (1984$). From these figures, the Department of Energy has determined component cost goals for solar collection and conversion systems (see Five Year R&D Plan 1986-1990). For dish concentrators the component cost goal is \$130/m^2 of concentrator aperture area, and for receivers the cost goal is \$70/m^2 for dish electric systems, and \$30/m^2 for dish thermal energy systems. The cost of field tracking controls is included in the concentrator component goals and the cost of integral receiver controls is included in the receiver component goals. For the 15-m dishes that are currently being designed, the cost goal for a concentrator is $23,000 and the receiver cost goal is $12,370 for dish electric systems and $5,300 for thermal energy systems.

Although separate cost breakdowns are not available for controls, certain limits can be inferred from the overall component cost goals. A $10,000 tracking control system will not be compatible with current goals, and neither will a $3000 receiver flow control system. In fact, tracking control costs for previous heliostat projects have been roughly 10% of the collector's total cost [Mavis 1986]. Using 10% as a rough estimate of future control costs, a 15-m dish might use a $2,300 tracking controller and a $1,200 receiver controller in dish electric applications or a $530 controller in thermal energy systems.

In terms of dollars/m^2 the control cost goals would be $13/m^2 for tracking controls, $7/m^2 for dish electric receiver controls, and $3/m^2 for dish thermal receiver controls. Unfortunately, control costs are more a function of collector performance than size. A 10-m dish and a 15-m dish with the same optical performance would probably need identical control systems since both would require the same tracking accuracy and reliability. The $/m^2 goal does indicate though, what controls might be considered affordable for systems of various sizes.

Long-term goals provide only rough estimates on future control costs. A more accurate assessment of control costs is available from previous system expenses. Figure 26 gives the approximate cost of tracking controls for five solar facilities and one tracking dish antenna. (The dish antenna cost is included only for comparison purposes.) For the STEP collectors, the cost of tracking controls was about $14/m^2. To some extent the prices in Figure 26 correlate with tracking accuracy requirements. STEP dish collectors and PV arrays require 9 mrads of pointing accuracy, whereas heliostats track to within ±1.5 mrads. Dish antenna control systems provide tracking accuracies with less than 1-mrad error.

Receiver control costs are difficult to judge at this time because most large-scale systems do not provide flow control on each receiver. For systems that regulate receiver temperatures by offset tracking, the costs would be less than $100 for thermocouples and interfaces with the tracking controls. If flow controls were used on each receiver, the current cost would be between $350 and $1700 depending on the type of actuator and controller used (the lower cost estimate assumes that the tracking controls can provide logic for the valve actuator). Active receiver flow control costs could drop below $100 if thermostatically actuated valves were available for high-temperature applications.

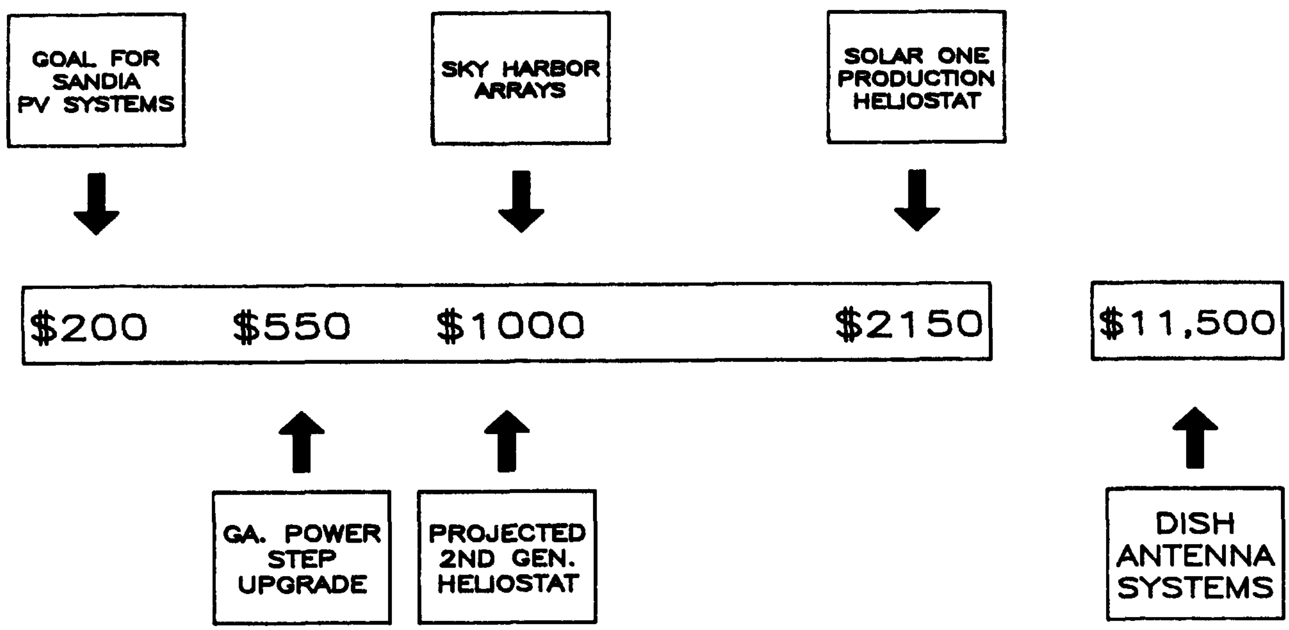

Figure 26. The cost of tracking control systems per collector for recent solar thermal and photovoltaic projects.

The best current estimate on communication costs is probably the $250 per heliostat for the dedicated cable network at Solar One [Pearson and Chen 1985]. Pearson and Chen also noted that the central computer costs for the Solar One collector field ran about $165 per heliostat. Substantial reductions in both communication and central computer expenses are possible with current distributed control system components.

At this early stage there are insufficient data to judge the status of receiver control costs; however, tracking control costs are close to the estimated long-term goals. Increasing the control reliability while maintaining a reasonable cost should be the major goal at this time. The total maintenance cost goal for a 15-m dish system is $1767 per year, and the balance-of-plant cost goal (which includes spare parts) is a one-time cost of $3534. Because a control failure in a distributed receiver system can easily consume the entire maintenance budget by burning up a receiver or allowing a concentrator to be destroyed by the wind, the controls must be the most reliable component in the entire concentrator system.

* Hall-effect encoders, synchro/resolvers, and, despite previous problems, optical encoders are all serious contenders for collector position sensors. Hall-effect encoders cost much less than the other two options, but they can only be used when there are large speed reductions in the drive train.

* Controls can correct for structural misalignment, but unsteady wind loads make control compensation for backlash ineffective.

<u>Receiver Controls</u>

* Controlling receiver temperatures has been more difficult than most designers imagined it would be.

* Adjusting flow rates to control temperatures will present problems because system gains will vary with flow rates (and therefore insolation levels). Without the ability to change control gains, the system may overreact at low insolation levels or perform sluggishly at high insolation levels.

* Altering inlet temperatures is an undesirable method for control because it increases system thermal losses and makes control actions subject to long time lags. Maintaining constant inlet temperatures, however, may stabilize temperature regulation in systems that control receiver flows.

* Passive flow balancing techniques have not been effective in maintaining close tolerances on receiver temperatures.

* Offset tracking modes are used in many systems to protect the receiver from overheat conditions. In systems that operate near maximum design temperature limits, offset tracking procedures have become a method of temperature control. This procedure tends to waste concentrated energy, and in systems with many collectors, the offset tracking collector can act as a heat sink.

* Control valve characteristics must be compatible with the rest of the flow system. To be effective over a wide range of operating conditions, the valve should be the largest pressure drop in the system. Equal

percentage characteristics are preferred over linear control valve characteristics.

* RTD temperature sensors are generally too fragile for harsh environments. Thermocouples provide a rugged means of measuring temperatures, but redundant sensors should be provided. Integrated circuit chips are now available to correct for reference junction effects.

* Electric and electrohydraulic actuators are currently the main options for valve actuation tasks in the collector field. Pneumatic actuators should be considered only where a few valves are required, and the valves should be located near the air supply so that condensation problems are reduced.

* Thermostatically actuated control valves may offer another option for temperature control in the future, but thermostatic actuators are not widely available for high-temperature solar applications.

<u>System Considerations</u>

* Dedicated wire cables and power cable carrier-current links are presently the best media for field communication. Radio frequency links may provide an inexpensive communication option in the future.

* Varying degrees of field control autonomy have been used in past collector systems. Making more of the routine control decisions at the field level reduces the impact of communication delays on system operation.

* The control system must actively protect the concentrator, the power conversion system, and personnel from concentrated flux during all modes of operation (offset tracking, sun tracking, and sun acquisition and deacquisition). Control systems must also prevent wind loads from damaging the concentrator.

* Special control features are required to recognize and react to a solar walk-off situation. No generalized cost-effective form of walk-off protection is currently available.

* Control failures are most often caused by dirt or moisture in control units, sensors, and cable connectors. Failures are also frequently caused by electromagnetic surges in communication lines, arcing in relays and switches, and the exposure of components to low temperatures or concentrated flux. These problems can be avoided through the proper selection of control components and procedures.

* The long-term cost goal for dish concentrators is $130/m^2 of collector aperture area; tracking controls are included in this price. The cost goal for receivers in dish electric systems is $70/m^2 and for receivers in solar thermal systems the goal is $30/m^2; these goals include the cost of receiver temperature controls. In the past, the cost of tracking controls has been roughly 10% of the total concentrator cost.

Recommendations

Control technologies are not static, so recommendations are likely to become dated soon after they are made. However, the results of this and other studies indicate that the following improvements should be considered in future control systems:

* Sun sensors should be used in tracking control systems to provide information on aiming errors. Signals from these sensors should be interpreted by software in the tracking control unit before position update commands are issued to the drive motors. The tracking control unit should have algorithms that predict error corrections for future position updates.

* Control systems must have an accurate open-loop tracking system even when sun-tracking sensors are available.

* Tracking systems should use symmetric tracking limits to reduce parasitics and lessen the wear on control components and drive motors.

* Efforts must be made to improve the reliability of control systems. Weathertight enclosures and corrosion-resistant components should be selected when possible. Systems should be designed to operate at low

temperatures, and component pretesting should be performed to insure the survivability of control components at temperature extremes.

* For receivers that operate at temperatures close to the system's thermal limits, active flow control should be provided for each receiver. The flow controls must have characteristics that allow the system to operate at all insolation levels. An off-set tracking option must be provided, but it should be used mainly as an emergency procedure to prevent the receiver from overheating.

* Requirements on the communication system should be minimized by distributing more of the routine control tasks to the field controllers.

* Solar collector systems must be capable of operating when the sun is available. Redundancy should be provided in control components that are required for the entire system to operate.

Follow-Up Issues

Over the course of this study certain issues surfaced that should receive more attention in future studies. These issues can be summarized as follows:

* Investigations are needed to determine the best operating strategy for temperature control systems. Tolerances on flow-field temperatures are actually determined by the operating characteristics of the entire system. Studies should be conducted to find the optimum field temperatures and flow rates over a broad range of operating conditions for systems with and without fossil fuel boilers that supplement the solar energy input.

* The possibility of using thermostatically actuated control valves should be investigated further. These valves may offer the most cost-effective method for controlling receiver temperatures in distributed receiver/central engine systems.

* A better understanding of receiver losses is needed because of the influence these losses have on tracking accuracy requirements.

* Dynamic modeling is required for all solar collection systems so that the interactions between components and the impact of solar transients can be more thoroughly understood.

* A tracking test facility should be developed to evaluate tracking components and routines. This system should also be capable of testing methods for aperture plate protection during sun acquisition and solar walk-off.

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APPENDIX A

```
      SUBROUTINE SUNAEP(YEAR,DAY,XNHR,MIN,SEC,ZONE,DASVTM,LAT,
     $LONG,AZANGR,ELANGR,NOUTANS,PRESSA,TA,PAZANS,POAZPR,PODCPR)
      CHARACTER*3 PAZANS,NOUTANS
C
C     THIS PROGRAM CALCULATES THE LOCAL AZIMUTH AND ELEVATION OF
C     THE SUN AT A SPECIFIED LOCATION AND TIME USING AN APPROXIMA-
C     TION TO THE EQUATIONS USED TO GENERATE THE NAUTICAL ALMANIC.
C
C     THIS IS COPIED FROM AN ARTICLE BY ROBERT WALRAVEN OF THE
C     UNIVERSITY OF CALIFORNIA, DAVIS IN SOLAR ENERGY VOL 20 NO.5-C
C     PUBLISHED IN NOVEMBER OF 1978.
C     ERRATUM IN SOLAR ENERGY VOL. 22, P. 195, PUBLISHED IN 1979
C
C     THIS TRANLATION OF THE SUNAEP PROGRAM WAS ORIGINALLY
C     PRESENTED BY J.C. ZIMMERMAN IN SAND REPORT SAND81-0761
C
C     INPUT PARAMETERS
C       YEAR          - THE YEAR NUMBER (E.G., 1977).
C       DAY           - THE DAY NUMBER OF THE YEAR STARTING WITH 1 FOR
C                       JANUARY 1,EXCEPT IN LEAP YEARS WHEN 1 SHOULD BE
C                       SUBTRACTED FROM THE DAT NUMBER BEFORE MARCH 1.
C     XNHR,MIN,SEC  - THE TIME OF THE DAY
C     ZONE          - THE LOCAL INTERNATIONAL TIME ZONE (E.G.,PST =8)
C     DASVTM        - =1 IF DAYLIGHT SAVINGS TIME IN EFFECT,ELSE = 0.
C     LAT           = THE LOCAL LATITUDE IN DEGREES (NORTH IS
C                       POSITIVE)
C     LONG          = THE LOCAL LONGITUDE IN DEGREES WEST OF
C                       GREENWICH.
C     PRESSA        - THE LOCAL AIR PRESSURE IN MILLIBARS
C     TA            - THE LOCAL AMBIENT TEMPERATURE IN DEGREES F
C     NOUTANS       - DO YOU WANT LONG INPUT (YES/NO)?
C     PAZANS        - DO YOU WANT POLAR AZIMUTH AND DECLINATION
C                       CALCULATED (YES/NO)
C
C     OUTPUT PARAMTERS
C       A             - AZIMUTHAL ANGLE OF THE SUN (POSITIVE IS EAST
C                       OF SOUTH)
C       E             - ELEVATION OF THE SUN
C       AZANGR        - AZIMUTHAL ANGLE OF THE SUN IN RADIANS
C       ELANGR        - ELEVATION ANGLE OF THE SUN IN RADIANS
C       POLAZ         - POLAR AZIMUTH ANGLE OF THE SUN IN DEGREES
C       POLDEC        - DECLINATION OF THE SUN IN DEGREES
C
C-------------------------------------------------------------------
      TWOPI=6.2831853
      RAD=TWOPI/360.
      DPR=1./RAD
      DELYR = YEAR-1980.
      LEAP=INT(DELYR/4.)
      T=XNHR+(MIN+SEC/60.)/60.+ZONE-DASVTM
      TIME=DELYR*365.+LEAP+DAY-1.+T/24.
      IF(DELYR.EQ.LEAP*4.)TIME=TIME-1.
      IF((DELYR.LT.0.).AND.(DELYR.NE.LEAP*4)) TIME=TIME-1.
      THETA=(360.*TIME/365.25)*RAD
```

```
      G=-0.031271-4.53963E-07*TIME+THETA
      EL=4.900968+3.6747E-07*TIME+(0.033434-2.3E-09*TIME)*DSIN(G)
     $+.000349*DSIN(2.*G)+THETA
      EPS=0.409140-6.2149E-09*TIME
      SEL=SIN(EL)
      A1=SEL*COS(EPS)
      A2=COS(EL)
      RA=ATAN2(A1,A2)
      IF(RA.LT.0.)RA=RA+TWOPI
      DECL=ASIN(SEL*SIN(EPS))
      ST=1.759335+TWOPI*(TIME/365.25-DELYR)+3.694E-07*TIME
      IF(ST.GE.TWOPI)ST=ST-TWOPI
      S=ST+(T*15.-LONG)*RAD
      IF(S.GE.TWOPI) S=S-TWOPI
      H=RA-S
      PHI=LAT*RAD
      ER=SIN(PHI)*SIN(DECL)+COS(PHI)*COS(DECL)*COS(H)
      ER=ASIN(ER)
      A=COS(DECL)*SIN(H)/COS(ER)
      A=ASIN(A)/RAD
      IF(SIN(ER).GE.SIN(DECL)/SIN(PHI))GO TO 15
      IF(A.LT.0)A=A+360.
      A=180.-A
15    E=ER/RAD
C
C-----------------------
C    REFRACTION CORRECTION
C-----------------------
C
      IF(E.GE.-0.575)GO TO 20
      IF(E.GE.5.)GO TO 10
      TANE=TAND(E)
      R=58.1/TANE-.070/TANE**3+.000086/TANE**5
      GO TO 30
10    R=1735.+E*(-518.2+E*(103.4+E*(-12.79+E*0.711)))
      GO TO 30
20    R=-20.774/TAND(E)
30    CONTINUE
      RFAC=(PRESSA*510.)/(1013.*(460.+TA))
      RC=R*RFAC
      RC=RC/3600.
      EC=E+RC
      A=180.-A
      AZANGR=A*RAD
      ELANGR=EC*RAD
C
C-----------------------------------------------------------
C    CONVERSION FROM AZIMUTH ELEVATION TO POLAR DECLINATION
C-----------------------------------------------------------
C
      IF(PAZANS.EQ.'YES')GO TO 23
      Z=SIN(ELANGR)
      E=SIN(AZANGR)*COS(ELANGR)
      XN=COS(AZANGR)*COS(ELANGR)
      XNROF=XN*COSD(LAT)+Z*SIND(LAT)
      ZROF=-XN*SIND(LAT)+Z*COSD(LAT)
```

```
      POAZPR=ATAN2(E,ZROF)
      TEMP=SQRT((ZROF**2)+(E**2))
      PODCPR=ATAN2(XNROF,TEMP)
      POLAZ=POAZPR*DPR
      POLDEC=PODCPR*DPR
      IF(NOUTANS.EQ.'YES')GO TO 11
      PRINT *,' Z=',Z,' IHE=',E,'  XN=',XN,' XNROF=',XNROF,
     $' ZROF=',ZROF,' POLAZ=',POLAZ,' POLDEC=',POLDEC
23    CONTINUE
      IF(NOUTANS.EQ.'YES')GO TO 11
      PRINT *,' A=',' E=',E,' LEAP=',LEAP,' T=',T,' TIME=',TIME,
     $' DELYR=',DELYR,' THETA=',THETA,' G=',G,' EL=',EL,' EPS=',EPS
      PRINT *,' SEL=',SEL,' RA=',RA,' DECL=',DECL,' ST=',ST,' S=',S,
     $' H=',H
      PRINT *,' ER=',ER,' E=',E,' EC=',EC,' R=',R,' RC=',RC,' RFAC=',
     $RFAC
11    CONTINUE
      RETURN
      END
```

Notes:

(1) ATAN is the arc-tangent function that selects the correct quadrant and returns an angle in the range of $\pm\pi$ radians.

(2) TAND is a tangent function that uses degrees as an argument.

Sample Results:

Input:	
Date	21 March 1981
Latitude	35.05437°
Longitude	106.54329°
Atmospheric Pressure	839.7 millibars
Average Temperature	50°F
Local Time	8:00 am

Output:	
TIME	444.625
A	105.7754404458
E	21.77438187618

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