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10 MW_e Solar Thermal Central Receiver Pilot Plant Heliostat and Beam Characterization System Evaluation November 1981 — December 1986

C. L. Mavis

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**10 MW_e SOLAR THERMAL CENTRAL RECEIVER
PILOT PLANT
HELIOSTAT AND BEAM CHARACTERIZATION
SYSTEM EVALUATION
NOVEMBER 1981 – DECEMBER 1986**

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ABSTRACT

Test and evaluation results for the heliostats and beam characterization system at the 10 MW_e Solar Thermal Central Receiver Pilot Plant are described in this report. Southern California Edison operated and maintained the plant during the five years covered by this evaluation. Therefore, the results represent what can be expected from a large number of heliostats that are operated over a long period of time in a power plant environment. The heliostats and beam characterization system were evaluated for their ability to meet performance and survival requirements. Heliostat evaluation results are reported for mirror soiling rates, mirror corrosion, wind loads, availability, maintenance requirements, tracking accuracy, beam quality, component temperatures, and operating power requirements. The heliostat beam characterization system accuracy is given for the measurement of beam quality, heliostat tracking accuracy, and power in the reflected beam. The heliostat technical specifications and design description are provided, and a detailed design description of the beam characterization system is included.

* Now with Systems Engineering Division III.

ACKNOWLEDGEMENTS

The Pilot Plant collector field has been operated by Southern California Edison since November 1981. Heliostat evaluation data and analysis has been obtained from several sources. E. V. Decker, M. A. Danzo, and R. L. Velazquez—Southern California Edison summer employees—surveyed the heliostats for mirror corrosion. J. Green, Solar Energy Research Institute, analyzed the wind speed data. T. D. Brumleve, Sandia National Laboratories Livermore, performed heliostat beam safety tests and analysis. Heliostat operating experiences have been provided by P. Skvarna and C. W. Lopez, who work for Southern California Edison at the Pilot Plant. Heliostat maintenance data have been provided by J. Clark, Southern California Edison, and J. W. Smith, Sandia Livermore. Other Sandia personnel who contributed were: B. J. Moy prepared the report for publication; A. L. Hogan provided writing and editing assistance; D. L. Atwood provided assistance with data analysis, computer operation, and computer-generated graphs and tables; J. E. Noring provided computer codes to analyze beam characterization system data.

SOLAR THERMAL TECHNOLOGY FOREWORD

The research described in this report was conducted within the U.S. Department of Energy's Solar Thermal Technology Program. This program directs efforts to incorporate technically proven and economically competitive solar thermal options into our nation's energy supply. These efforts are carried out through a network of national laboratories that work with industry.

In a solar thermal system, mirrors or lenses focus sunlight onto a receiver where a working fluid absorbs the solar energy as heat. The system then converts the energy into electricity or uses it as process heat. There are two kinds of solar thermal systems: central receiver systems and distributed receiver systems. A central receiver system uses a field of heliostats (two-axis tracking mirrors) to focus the sun's radiant energy onto a receiver mounted on a tower. A distributed receiver system uses three types of optical arrangements—parabolic troughs, parabolic dishes, and hemispherical bowls—to focus sunlight onto either a line or point receiver. Distributed receivers may either stand alone or be grouped.

This evaluation report is one of a series of reports designed to cover topics of interest on the 10MW_e Solar Thermal Central Receiver Pilot Plant, at Barstow, California. These reports provide information obtained or developed during the two-year Test and Evaluation period when the plant was undergoing various engineering tests under the direction of Sandia National Laboratories. For a list of reports, contact the Solar Energy Department, 6220, Sandia National Laboratories, Albuquerque, New Mexico 87185.

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SUMMARY

Introduction

The 10 MW_e Solar Thermal Central Receiver Pilot Plant (Solar One) is the world's largest solar central receiver electric generating station. This pilot-scale research and development experiment is a cooperative effort between government and private industry to demonstrate technical feasibility, economic potential, and environmental acceptability of the solar central receiver concept.

This report presents a general description of the overall plant, a description of the collector subsystem, a description of the beam characterization system, the results of the collector system design and construction, and the results of a program to evaluate the heliostats and the beam characterization system (BCS). Lessons learned for the heliostats and the BCS are also included.

The contents of the report are summarized in this section. A brief description of the plant is provided. The heliostat and beam characterization system—test and evaluation program—is outlined, and the results of the evaluation are summarized. Lessons learned from the heliostats and BCS are also summarized.

Siting and General Design Data

The pilot plant (Solar One) is located east of Daggett, California, which is approximately 12 miles east of Barstow, California. The plant is designed to produce at least 10 MW of electrical power to the utility grid (after supplying the plant parasitic power requirement) for 4 hours on the plant “Worst Design Day” (winter solstice) and for 7.8 hours on the plant “Best Design Day” (summer solstice).

Plant Systems

The central receiver concept being demonstrated at Solar One integrates the operation of six major systems as depicted in Figure 1. The collector system, consisting of large sun-tracking mirrors (heliostats), redirects the solar energy incident on the mirrors and concentrates it on a tower-mounted receiver (boiler). There the solar energy transforms water into superheated steam that can be used directly to drive the turbine-generator, or the energy is diverted to the thermal storage system. The thermal storage system can store the energy as sensible heat to extend turbine-generator operation after sunset. The electric power generation system (turbine-generator) can generate 10 MW from receiver steam and 7 MW from thermal storage steam. The master control system is a series of computers

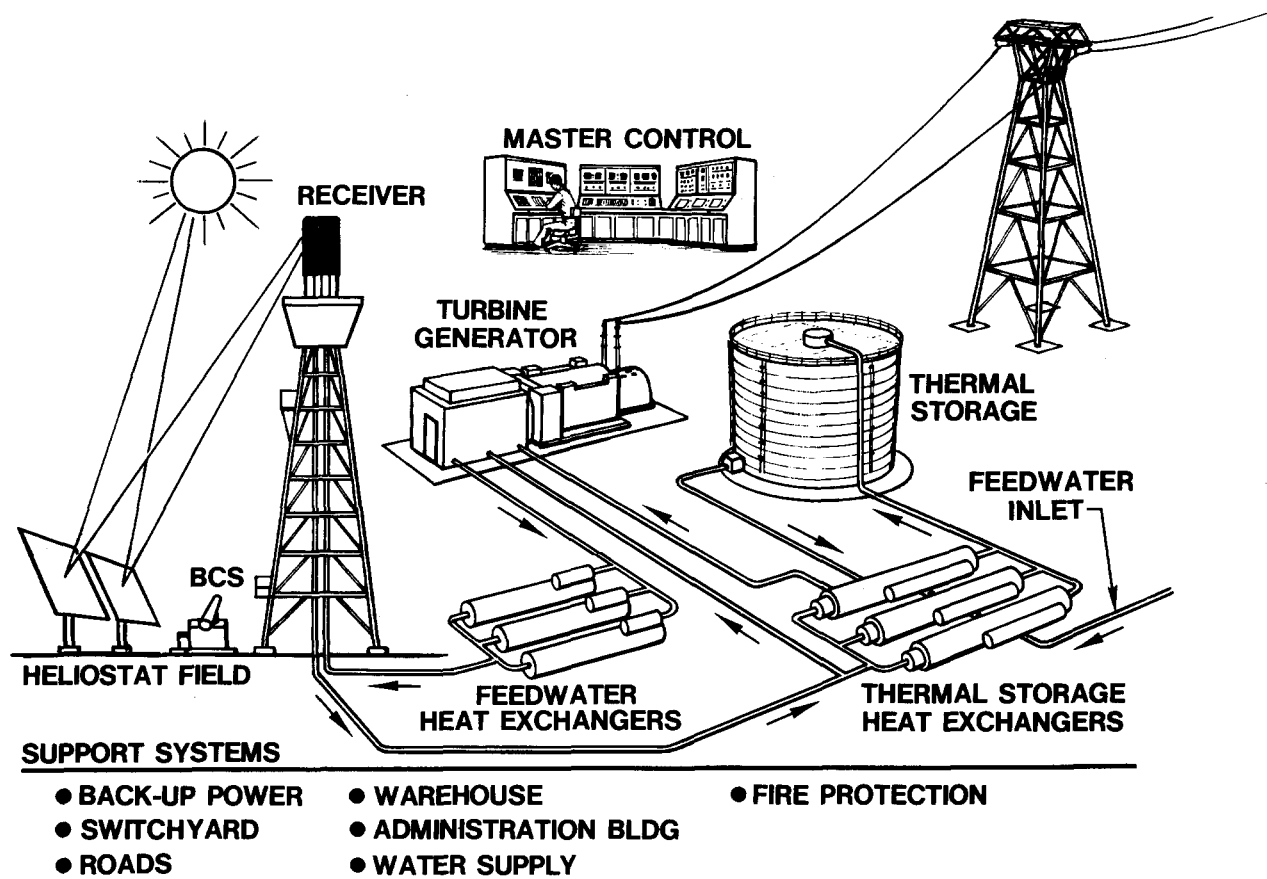


Figure 1. Six Major Systems of Solar One

that monitors and controls each of the major systems. The beam characterization system is used to align the heliostats and ensure their efficient operation.

Collector System—The collector system is a 360 degree array of 1818 heliostats as shown in Figure 2. A photograph of an individual heliostat is shown in Figure 3.

The heliostat field with a reflective area of 782,000 ft² is divided into four quadrants. There are 1240 heliostats in the two northern quadrants and 578 in the two southern quadrants. Each heliostat is made of 12 slightly concave mirror modules totaling 430 ft² of mirror surface. The mirror assembly is mounted on a gear-driven drive mechanism for azimuth and elevation control.

The collector control system consists of individual microprocessor heliostat controllers (HC), a heliostat field controller (HFC) for control of groups of 32 heliostats, and a central computer called the heliostat array controller (HAC). The heliostats can be controlled individually or by groups in either manual or automatic modes through the HAC, which is located in the plant control room. The heliostats are designed to operate in winds up to 50 mph and will withstand winds up to 90 mph when stowed with the mirrors horizontal. Normally, each heliostat is moved from the nighttime stow position to standby at some time before

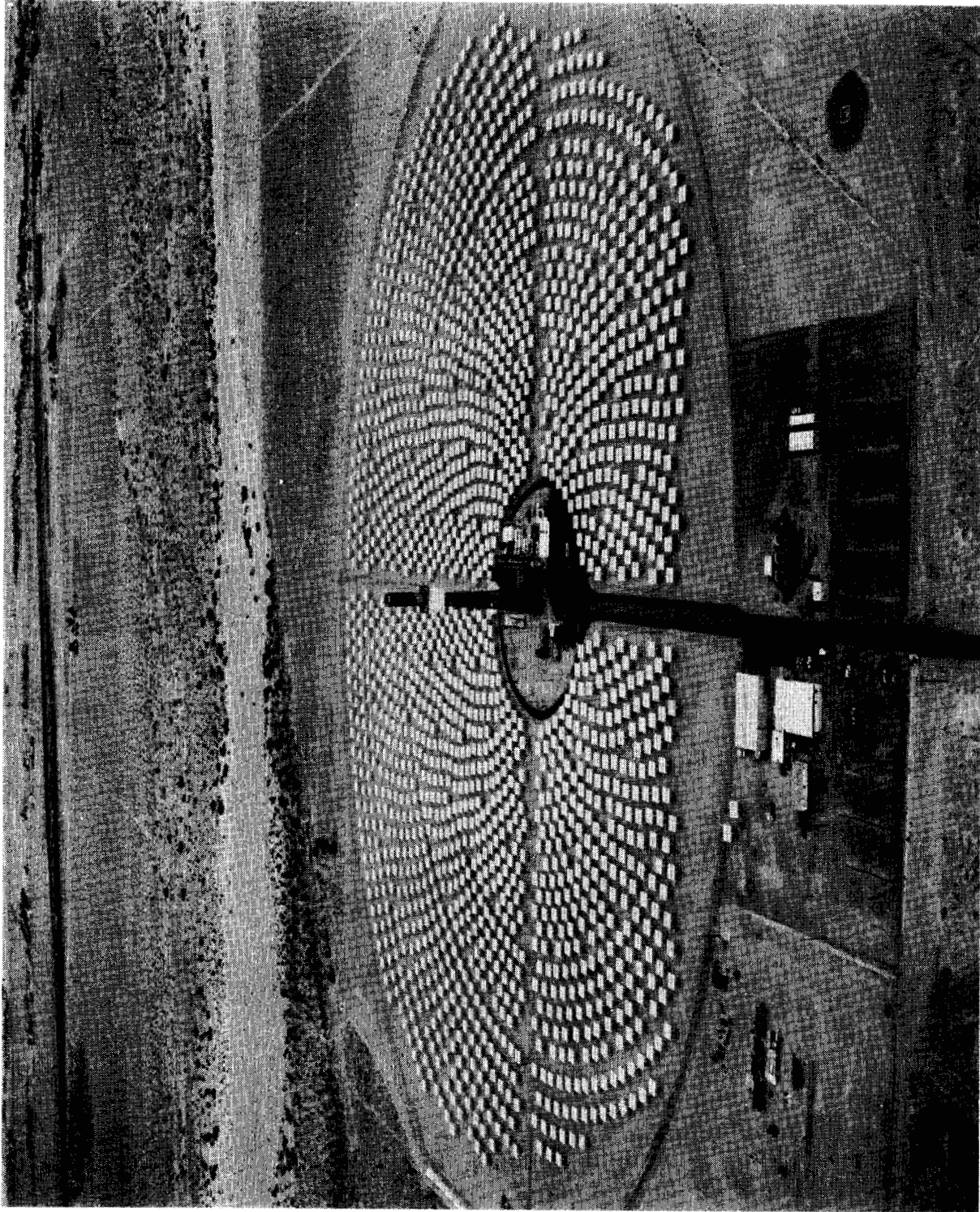


Figure 2. Solar One Collector System Photograph

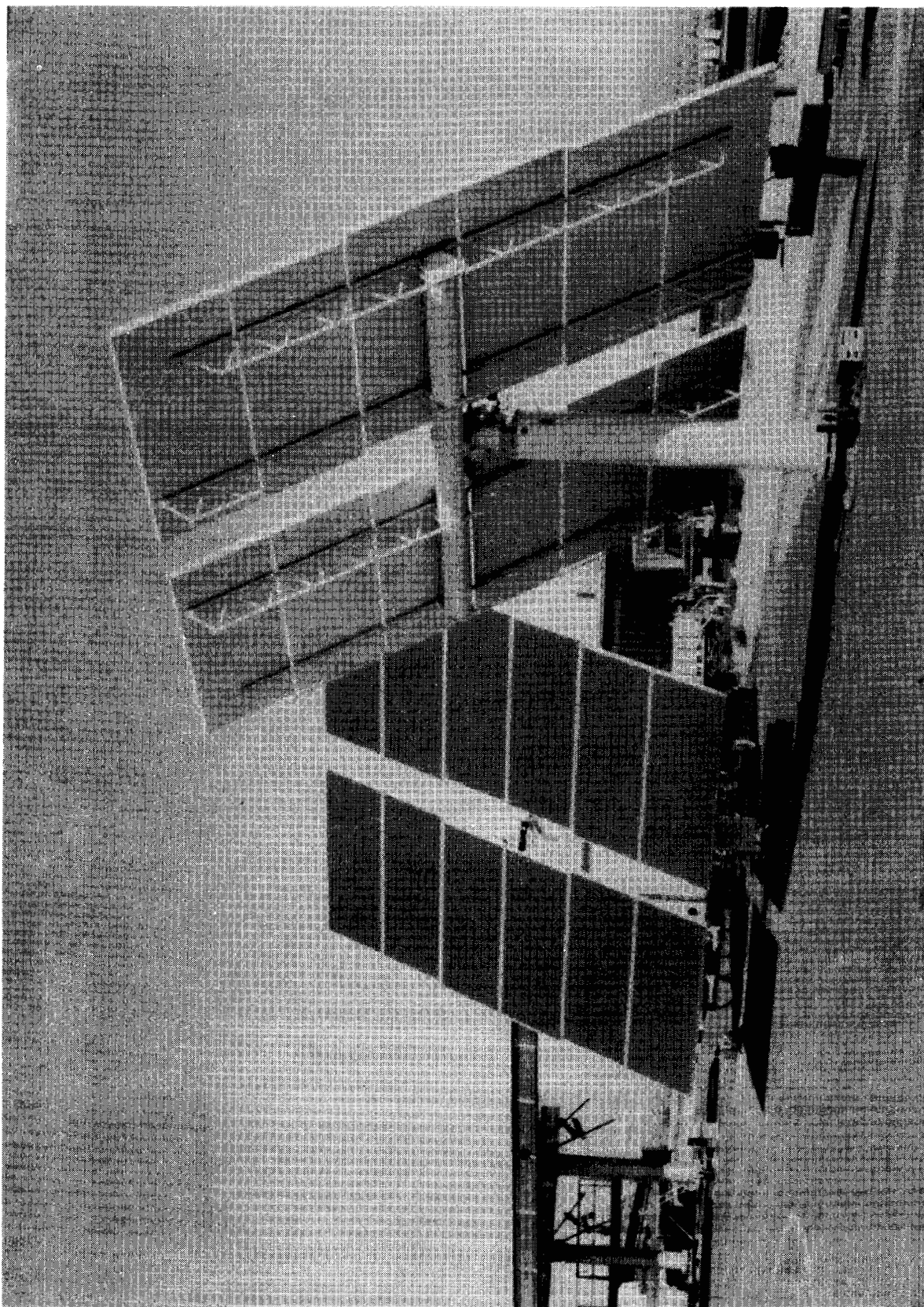


Figure 3. Solar One Heliostat

sunrise. There are four standby aimpoints located at the receiver elevation approximately 100 ft out from the receiver surface.

The high-wind stow position is "mirror face down" with the torque tube aligned east/west, parallel to the prevailing wind direction. This alignment reduces the wind load on the gear train and reduces the chance of gear failure. During 1982, the mirrors were normally stowed facing down. However, in January 1983, normal stow was changed to "mirrors vertical" to minimize water standing on the mirror module seals and on the mirror backing paint.

Receiver System—The receiver system consists of a single-pass-to-superheat boiler with external tubing, a tower, pump, piping, wiring, and controls necessary to provide the required amount of steam to the turbine. The operator in the control room can vary steam demand, or the receiver steam can react to a demand from the electric power generating system up to the receiver's rated output.

The receiver is designed to produce 950°F steam at 1465 psia at a flow rate of 112,000 lb/hr. The receiver has 24 panels (6 preheat and 18 superheat), each approximately 3 ft wide and 45 ft long.

A lattice steel tower holds the receiver approximately 250 ft above the desert floor. Four white aluminum sheet-metal targets are mounted directly beneath the receiver for use by the heliostat beam characterization system to determine beam pointing errors and beam quality for individual heliostats.

Thermal Storage—The thermal storage system extends the plant's electrical power generating capability into nighttime or during periods of cloud cover by storing thermal energy from the receiver. It also provides steam for maintaining selected portions of the plant in a warm status during nonoperating hours and for starting up the plant the following day.

The thermal storage tank, 45 ft high and 65 ft in diameter, sits on a special lightweight, insulating concrete foundation that reduces heat loss to the ground. The walls are made of steel plate with 1 foot of insulation, and the roof is made of aluminum plus 2 feet of insulation. The 946,000 gallon capacity tank, filled with 7,000 tons of rock and sand and about 240,000 gallons of thermal oil (Caloria HT-43), acts as a heat storage vessel.

De-superheated steam from the receiver is routed through a heat exchanger in which cold thermal storage oil from the bottom of the tank is heated. The heated oil is pumped back to the top of the tank, and thermal energy is transferred to the rock and sand. When the system is fully charged, the temperature of the thermal storage mixture (oil, rock, and sand) is approximately 575°F. When it is discharging, the hot oil is pumped from the top of the tank through another heat exchanger to boil water, and the cold oil is returned to the bottom of the tank. Steam at 525 degrees F and 385 psia can be produced from the thermal storage

system and delivered to the turbine at a rate of 105,000 lbs/hr. The rated electrical capacity of plant operation on thermal storage energy is 28 MW-hr net output, e.g., 7 MW_e power for 4 hours. After the system discharges, sufficient thermal energy is still available in the tank for heating, sealing steam, and restarting the plant the next day.

As with other plant systems, the thermal storage system has computer controls, but it can also be controlled manually. By selecting plant operating modes, the operator can use receiver steam to charge the thermal storage system alone or to drive the turbine and charge the thermal storage system simultaneously.

Master Control—The master control system is a series of computers that control the plant from the central control room. It supplies overall coordinated supervisory control to individual systems. A sketch of the master control console is shown in Figure 4.

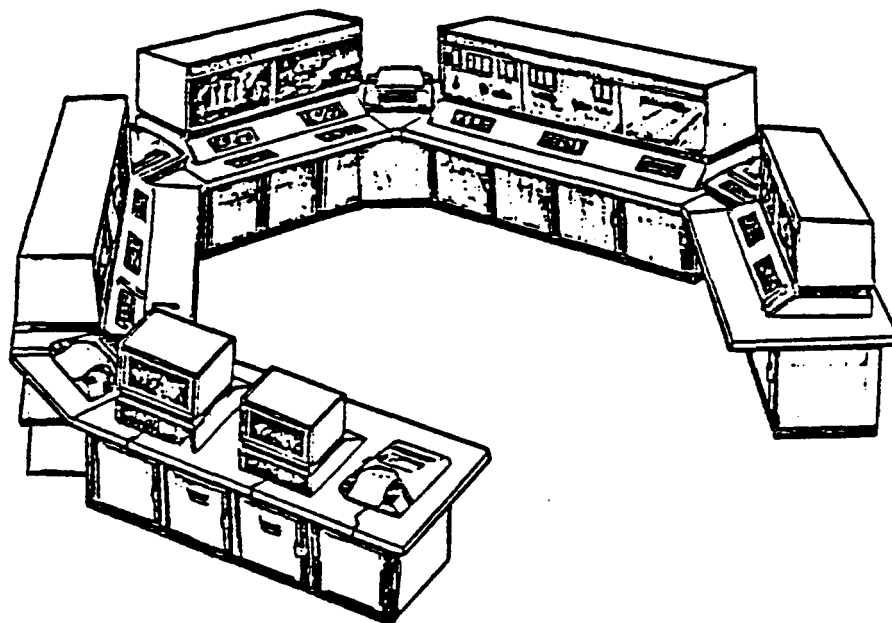


Figure 4. Master Control Console

Approximately 2,000 continuous, discrete measurements from throughout the plant are transmitted to the master control system and recorded. Operating data, alarms, and alerts are displayed on control consoles and on graphic displays. Additionally, plant piping and instrumentation diagrams are displayed with live-time process parameters and valve operating configurations for system status.

To augment the master control system and to provide individual system control and trouble isolation, each system has its own distributed process controller. The process controllers, which are digital computers tied into the master system,

control the system valves, motors, pumps, relays, and other equipment. They are located near the respective system's hardware in remote stations. For example, the process controller for the receiver is located in the tower within a remote station immediately below the receiver.

The control system hierarchy is shown in Figure 5. Four Modcomp Classic 7863 computers are located in the control room and are designated as follows:

OCS - Operational Control System, which provides a console for single operator control.

DAS - Data Acquisition System, which records selected control and monitoring data.

HAC - Heliostat Array Controller, which supervises the collector field. Two Modcomp units are used. One provides full redundancy for the other.

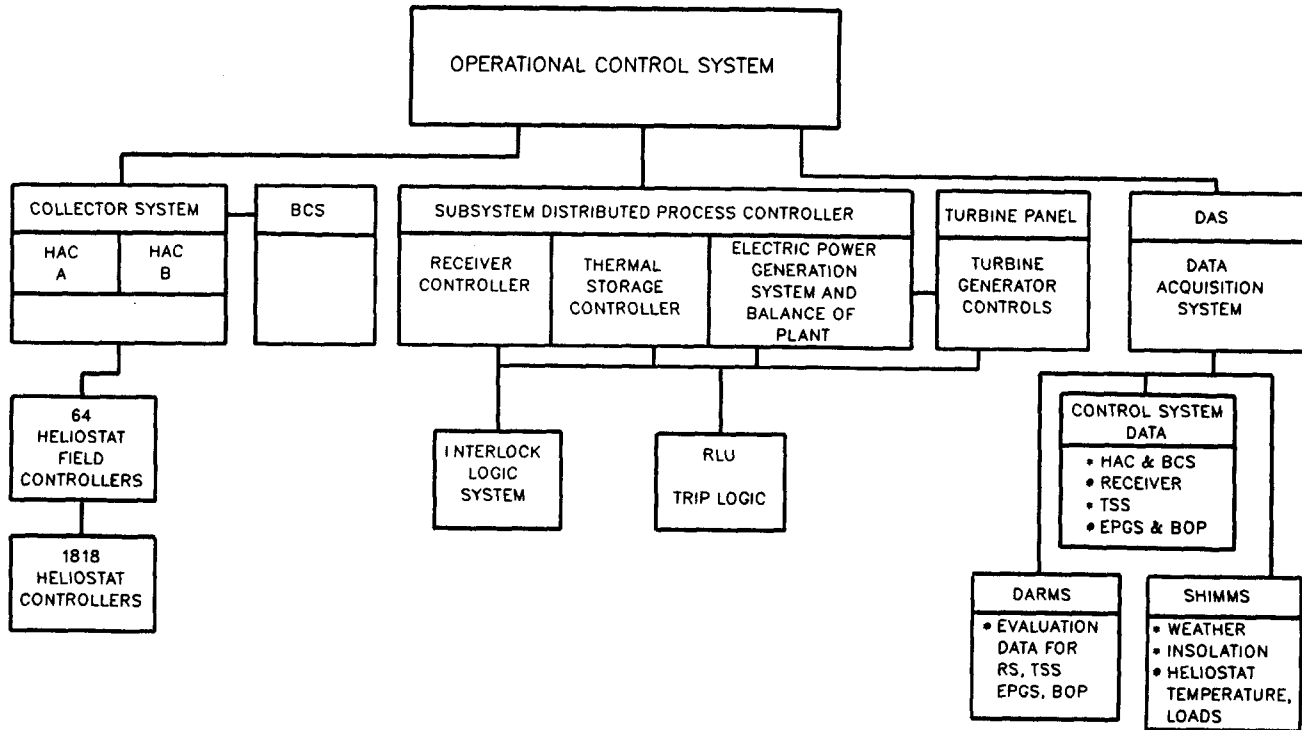


Figure 5. Control System Hierarchy

Control and monitoring data are collected and processed from field instruments by way of the distributed process controllers (SDPC). This control hardware is a Beckman MV 8000 system. Five remote processing stations are located outside the control room.

Turbine-Generator—The General Electric turbine-generator is rated at 12.5 MW and is a single case design for cyclic duty. It is the same general machine

used for marine drives. The turbine has two steam admission ports, one high-pressure port for receiver steam and a lower pressure port for thermal storage steam. The rated turbine thermal-to-electric efficiency from receiver steam is 35%, and from thermal storage steam 25%. Receiver steam conditions are 112,000 lb/hr, 950°F, 1465 psia, throttle valve capacity for 10 MW net. Thermal storage steam conditions are 105,000 lb/hr, 525°F, 385 psia admission valve capacity for 7 MW net.

Figure 6 shows a schematic diagram of the plant. Spent steam is condensed by circulating water from the evaporative cooling tower. Condensed steam is then routed back to the receiver through a full-flow demineralizer and a series of feedwater heaters. The turbine has four steam extraction ports used for three feedwater heaters, and a deaerator. The second-point and first-point feedwater heaters only operate during receiver operation. The generator is air cooled with a static exciter and 13.8-kv-rated output voltage.

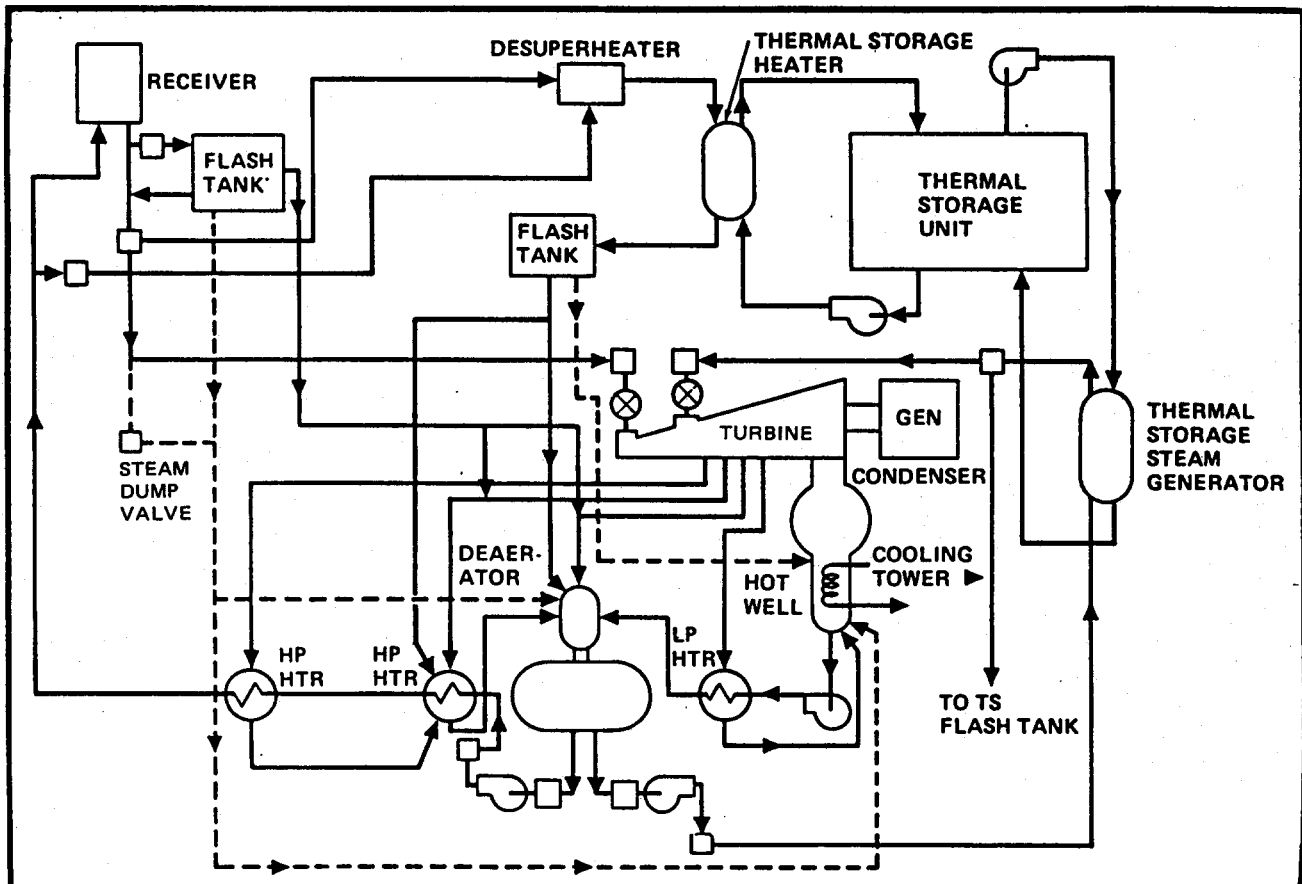


Figure 6. Schematic of Solar One

Beam Characterization System—The Beam Characterization System, (BCS), (Reference 34), includes the hardware and software required to permit rapid and automatic characterization of the reflected beams directed to the receiver by any single heliostat and simultaneous measurements of sun shape. A block diagram is shown in Figure 7. The data available from the BCS includes beam size and shape, beam centroid, flux distribution, total beam power, and as required, the radial radiance distribution of the sun. Data gathered by the BCS equipment are digitized, calibrated, processed to characterize the image, and stored. These data can then be used to align and evaluate the heliostats during plant operation. The system is designed to sequentially evaluate reflected images on an individual heliostat basis.

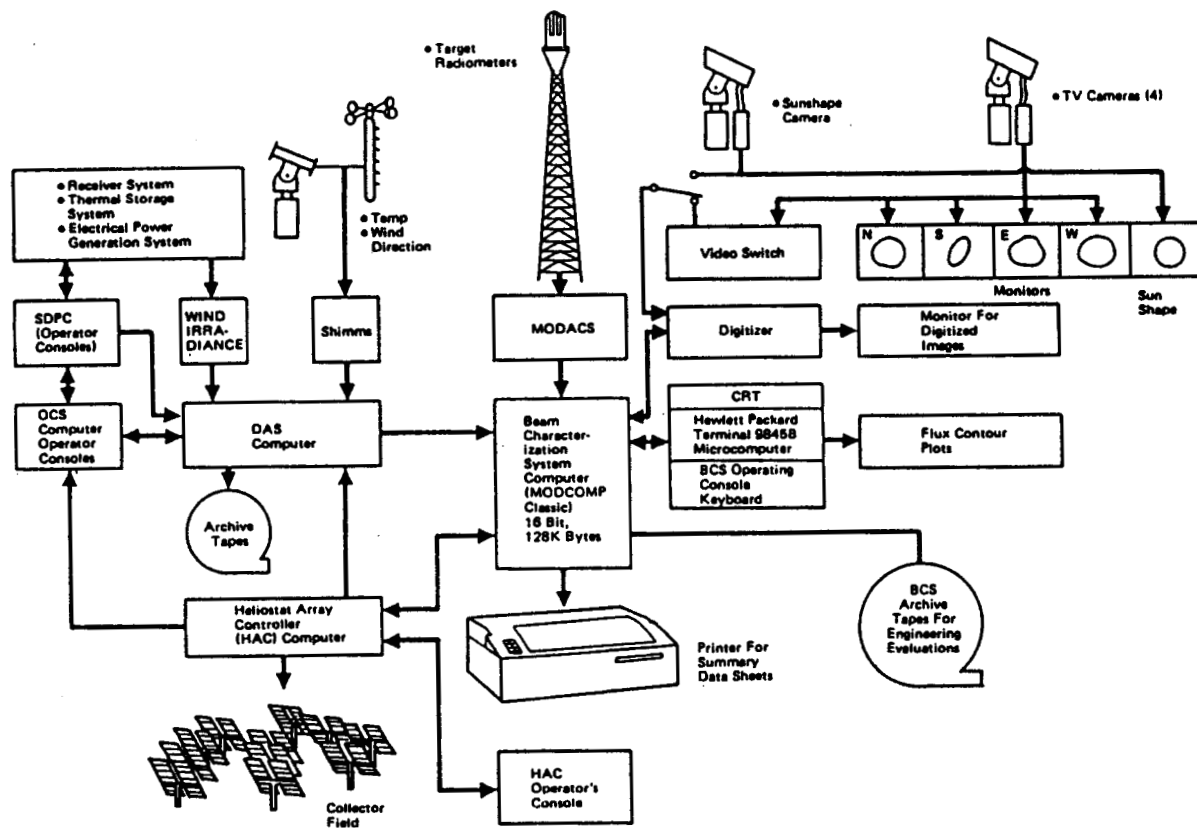


Figure 7. BCS Interface Block Flow Diagram Landscape

Test Program

Collector System Functional Tests

The initial collector system functional tests were performed from November 9, 1981, through November 18, 1981. This testing was performed to demonstrate the systems level operational performance of the collector system on a stand-alone basis.

Heliostat Tests

The objectives of the heliostat tests were to characterize heliostat performance and identify areas where heliostat research and development might lead to performance improvement and to establish whether a Beam Characterization System would be needed in future plants.

Reflectivity measurements were made by trained SCE operators with a portable specular reflectometer. Biweekly measurements were taken of several heliostats throughout the field. Some of these heliostats were used in an experimental washing program to assess different washing techniques and frequencies.

Heliostats are designed to have a service life in excess of 30 years. The major environmental conditions which affect this lifetime are the drive and structure loads imposed by high winds, corrosion of mirror module silvering as a result of water attack, and survival of controllers and motors under operating thermal loads. Data were obtained and analyzed to evaluate wind load distributions for individual heliostats throughout the field as a function of wind speed and angle of attack. Results were used to derive aerodynamic design criteria for future heliostats.

Sensors, which provide measurements of motor, controller, mirror module, and structure temperatures, were installed on the six heliostats. These measurements are compared with design specifications including ambient operating conditions, allowable temperature rise under load, and duty cycle.

Mirror module silver corrosion occurs when water attacks the silvering on the back surface of the mirror. Leak testing, controlled thermal cycling, in-situ temperature and humidity measurements, and radiography to locate water were performed to determine the extent and source of water in modules and possible remedies.

Mirror Corrosion Tests

Silver corrosion is occurring in the Pilot Plant mirror modules. Corrosion caused by water inside the modules diffuses through the mirror backing paint and dissolves the copper, and then the silver corrodes. The corrosion will not affect plant performance for several years; however, the existence of corrosion has been one factor in the adoption of alternate mirror module designs by industry. These new designs do not require sealing of a box type structure to keep water away from the silver.

Optical Performance

Heliostat optical performance is derived from beam pointing, beam quality, and reflectivity data. Beam pointing and quality are measured by the BCS. Individual heliostats are aimed to reflect their beams onto large tower-mounted targets. Field-mounted cameras send the target images to a computer where the images are analyzed to determine the flux distribution (quality) and the centroid (pointing). The BCS interfaces directly with the Heliostat Array Controller (HAC). Daily operation is automatic and only requires that the operator input the list of heliostats to be tested. This system is capable of characterizing the entire field every 36 days. If the heliostats do not change much with time, it is possible that future plants will not require a BCS of the type used at the Pilot Plant.

Assessment of beam quality requires the analysis of the flux distribution using HELIOS or MIRVAL. Because of the time and expense of running these computer codes, detailed analysis of beam images is performed for selected heliostats throughout the field. A simplified functional approximation, developed from these analyses, will provide a method for quantifying heliostat images and will allow rapid evaluation of beam quality by the operator.

Other Mirror Module Types Being Evaluated

Several different types of laminated glass mirror modules have been installed at the Pilot Plant for comparison with the Pilot Plant design. These mirrors use different glasses and laminating adhesives and should demonstrate that a long-life mirror module can be made.

Summary of Evaluation Results

Heliostat Availability

Since January 1982, the heliostats have operated about 3000 hours per year, and the heliostat controllers have been powered 100% of the time. The average heliostat availabilities have been above 96% even though heliostat maintenance was not initially a high priority activity. Maintenance personnel were primarily engaged in the completion of plant start-up activities during the Experimental Test and Evaluation Phase. Heliostat availabilities greater than 99% have been achieved since May 1985 during the Power Production Phase.

Reflectivity

Reflectivity measurements were performed biweekly on a selected number of heliostats throughout the field. The data indicates a decrease in cleanliness (expressed as a percent of the clean mirror reflectivity) of about 0.25%/day (8%/month) for months with little rainfall and 0.1%/day (3%/month) for months with frequent rainfall. The heliostat mirrors regained about 97% of their clean reflectivity when there was 0.5 in or more of rain. To maintain this recovery behavior, however, several artificial washes per year are required to remove dirt buildup that cannot be washed away by rainfall.

Washing

A mechanical scrubbing with a brush and water will remove all of the dirt, and this type of cleaning is required for the Pilot Plant environment. Based on the cleaning results for 1982 through 1986, and historical rainfall data, the field requires three to six artificial washings per year to maintain the reflectivity above 90% of the clean value. Recent analysis also shows that it would be cost effective to wash the Pilot Plant mirrors more frequently. A biweekly wash would achieve an average cleanliness of 97%, and the cost of washing would be more than offset by the additional output from the plant.

Tracking Accuracy

Pilot Plant heliostat tracking accuracy data was taken with the Beam Characterization System (BCS). During 1985, 1546 measurements were made, and heliostat bias updates were made to correct tracking errors. Prior to 1985 bias updates were made once a year from visual estimates of the error on the BCS target. In October 1985 a group of 95 heliostats was selected for periodic BCS measurement to evaluate how tracking accuracy changed with time. These BCS data show that the heliostats are meeting the tracking accuracy requirement, and that

over a six-month period, there is no discernable change in the tracking accuracy. However, the data also show that a small number of the heliostats developed a tracking error because of a fault in the optical encoder. The cause of the fault is under investigation.

Mirror Corrosion

A major environmental condition that affects heliostat lifetime is the corrosion of mirror module silvering as the result of attack by water. Corrosion surveys of the entire heliostat field were performed during the summers of 1983, 1984, and 1985, and a random sample of 98 heliostats was surveyed in 1986. The major findings of the surveys were as follows:

RESULTS OF MIRROR CORROSION SURVEYS

Item	1983	1984	1985	1986
1. Percent of the total reflective surface of the collector field that was corroded	0.015	0.029	0.052	0.061
2. Growth rate of mirror module corrosion (%/yr)	1000	92	78	24
3. Most prevalent heliostat field location for mirror module corrosion (Quadrant)	NE	NE	NE	NE
4. Percent of mirror modules with some amount of corrosion	15	27	48	57

Heliostat Wind Loads

Heliostat wind loads are a major design concern because they are the major contributor to heliostat costs. Wind loads determine the strength requirements of the drive mechanism, pedestal, mirror modules, and the mirror support structure. Mirror module wind loads were measured at the Pilot Plant and analyzed to determine

1. Wind velocity profile versus height
2. Adequacy of ASCE flat plate wind load coefficients for heliostat design
3. Wind angle of attack for heliostats in a stow position
4. Potential reduction of wind loads within a heliostat field
5. Suitability of mean versus peak wind speeds for design

A summary of the test results is provided below. The need for a statistical long-term test is evident from the data. This is due to the large and frequent changes in wind speed and direction. However, these first-of-a-kind tests at the Pilot Plant have verified that the method used to calculate heliostat wind loads is adequate for design and errs on the conservative side. Additional data will probably justify reducing the heliostat wind load requirements.

Wind Speed Profile—The wind velocity profile is used to determine wind speed at heights other than the reference height, which is usually 32.8 ft. The equation specified for wind speed vs. height above ground is

$$V(h) = V(32.8) \left(\frac{h}{32.8} \right)^{.15}$$

$$V(h) = \text{speed at height } (h)$$

$$V(32.8) = \text{speed at 32.8 ft}$$

$$h = \text{height above ground (ft)}$$

The .15 exponent was found to be the best fit to the data for the average wind speed. However, this does not mean that the speed profile should be used for design since the peak wind speed, or some fraction of the peak, is what actually determines the load on the heliostat.

Wind Load Coefficients—The ASCE Paper 3269, Reference 31, provides the recommended wind load coefficients for heliostat design. When the average wind speed incident on the field is used to calculate the heliostat wind loads, there is good agreement with the measured data. There is less agreement and a much wider spread in the results when the measured wind speed at the heliostat is used to calculate the wind load. The measured wind loads were not uniform across the heliostats, and they were not predictable from the wind speed profile because the speed varies widely with height and the direction is continuously changing. The data also show that only a fraction of the peak wind speed is effective in loading the heliostat. The results indicate that the 90 mph wind speed for survival could be reduced to about 75 mph. However, additional long-term statistical data is needed to confirm this finding.

Wind Angle of Attack—The wind angle of attack specification is $\pm 10^\circ$ from the horizontal. The conclusions from this data are that the maximum angle of attack was 4° and that the wind speed within the field is probably not indicative of the load on a heliostat. The angle of attack is significantly less than the 10° angle in the current heliostat specification. References 32 and 33 suggest that the maximum angle of attack for 90 mph winds should be 4° for smooth terrain and 5.5 to 6° for outskirts of towns and suburbs. Therefore, until additional data is available, a 6° angle of attack is recommended.

Wind Loads Within the Heliostat Field—For either the 50 mph or 90 mph survival wind conditions, there is no evidence from the Solar One wind load data that heliostat survival wind loads are reduced as you move into the field. The peak loads on inside heliostats were just as large as for outside heliostats when the rest of the heliostats in the field are in a stow position, as would be the case for a 90 mph wind. Under thunderstorm gust front conditions, the field could be in any condition; therefore, we could not depend on wind shielding from upwind heliostats. Any roads into the field would make this especially true. Unless wind shields are placed throughout the field, all heliostats should be designed for the same wind loads.

Heliostat Component Temperatures—Three heliostats were instrumented for component temperatures. Temperatures were recorded for the elevation motor, front and back of one mirror module, heliostat control box (inside air and box exterior), and the pedestal exterior while the heliostats were tracking. None of the measured temperatures were outside of the expected range. The heliostat controller inside temperature rises the farthest above ambient. The inside temperature was 20°F above ambient on a 102°F day. This caused the air temperature inside the box to reach 142°F on the hottest (122°F) specified day. This is 10°F below the qualification environmental test temperatures on tests that were performed during production, which included operation in a 132°F test chamber for 160 hours as a burn-in and a thermal cycle test to 176°F. The elevation motor temperature was also monitored while the heliostats operated continuously for 15 minutes. The temperature rise was only 2 to 3 degrees for the three heliostats that were monitored. However, since the motors are only rated for continuous duty at 104°F, the motor temperature rating may be marginal on a 122°F day if the motors run continuously as they would when moving the heliostat from stow to standby.

Beam Characterization System

The BCS is required and is well-suited for measuring heliostat tracking errors. The system is fully automatic once it is started, and very little operator time or skill is required to run the system and make heliostat tracking error corrections. Although the BCS is adequate for Solar One, a much faster system will be required for plants having a larger number of heliostats. The BCS at Solar One measures 50 to 60 heliostats per day. Three measurements on each heliostat are made each day, once in the morning, around noon, and again in the afternoon. These three measurements are required so that tracking errors can be averaged to arrive at an error correction angle. This means that 36 days are needed when the sky is clear all day to measure all 1818 heliostats. A large solar plant, which might contain 5000 heliostats, requires a BCS speed increase of at least a factor of 10. The system at Solar One has been evaluated for faster operation, and it was concluded that with software changes and state-of-the-art hardware, a factor of 10 increase in the speed is possible.

Although the BCS can accurately measure heliostat beam quality (total reflected light and the distribution and size of the beam), it cannot uniquely characterize the error sources which cause the beam quality to be poor. The BCS cannot help determine what is wrong with a heliostat. A system that looks back at the heliostat, rather than at the reflected beam on a target, is required to evaluate the errors that contribute to beam quality.

Lessons Learned

The major lessons learned relative to the Collector Subsystem and Beam Characterization System (BCS) at the pilot plant are summarized in the following two tables. Table I summarizes the collector subsystem lessons learned since the heliostats were installed and Table II covers the BCS.

TABLE I
COLLECTOR SUBSYSTEM LESSONS LEARNED

<u>Lessons Learned</u>	<u>Comments</u>
1. Heliostat maintenance cost is not a major concern.	Component burn-in may have helped. Maintenance costs are less than predicted.
2. Heliostats can be maintained with conventional maintenance skills, and control only requires an operator's attention on an exception basis.	Electricians, instrument technicians, and mechanical technicians--control requires less than one quarter of an operator's time.
3. Glass pitting from sand has not occurred.	Mirrors are stowed horizontally during high winds.
4. Vertical stow over a 37-month period has not been a problem.	Horizontal stow is used during high winds.
5. Heliostat beam-safety has not been a problem.	Control of reflected beams is required. Heliostats are normally stowed and unstowed after dark and before sunrise, respectively.
6. Mechanical mirror washing will be required to maintain plant efficiency - a spray rinse is not adequate.	Dirt accumulates during periods of low rainfall and after 1 to 2 years without a mechanical wash.
7. The following items should be completed before heliostat installation begins: a. Data cabling to each heliostat b. Power to each heliostat c. Control room available for permanent heliostat control console d. BCS installed (includes targets).	Reduces heliostat installation and checkout costs

- | | |
|--|--|
| 8. Heliostat tracking errors can be determined by visual observation. | The pilot plant field has operated for 2.5 years with visually determined tracking errors. |
| 9. Moontracking is an effective method to identify misaligned mirrors and large tracking errors. | Moontracking software and aimpoints are required |
| 10. Morning, noon, and afternoon tracking errors are required to make tracking error corrections. | Tracking errors vary with time of day and not all heliostats track with the same error profile |
| 11. Mirror silver corrosion will occur if water directly contacts the paint or copper layers which protect the silver. Laminate glass mirrors show promise for very long life. | The type of mirror module construction used at the pilot plant is very difficult to seal against water intrusion. |
| 12. Adhesives and sealants require good quality control during production. | Preparation of the bonded or sealed surfaces is critical, and proper mixing and curing of the adhesive is important. |
| 13. Heliostat field wiring requires proper grounding and shielding to prevent lightning damage | A nearby lightning strike damaged heliostat control electronics prior to proper grounding |
| 14. Noise separation between d.c. motors and HC requires careful consideration. | Causes communication problems |

TABLE II
BEAM CHARACTERIZATION SYSTEM
LESSONS LEARNED

<u>Lessons Learned</u>	<u>Comment</u>
1. A BCS is required and well suited for measuring heliostat tracking errors.	The BCS cannot uniquely characterize errors that affect beam quality. A high measurement rate is required.
2. A very fast BCS will be necessary for a large heliostat field.	Several hundred heliostats should be measured three times during a day.
3. BCS availability is desirable when the heliostats are installed.	Reduces the time required to make tracking error corrections.
4. A BCS should be a stand-alone system furnished by the heliostat supplier.	The system would not depend on completion of another system and the heliostat supplier/BCS supplier interface would be eliminated.
5. BCS implementation is not an easy task; the many software details require careful attention.	System accuracy is difficult to verify - subtle software or hardware errors are difficult to find and quantify - standards are needed.
6. Tower shadow and heliostats in gimbal lock complicate making three measurements per heliostat per day.	Complicated software will be required to schedule BCS measurements.

SECTION I PLANT DESCRIPTION

Introduction

The 10 MW_e Solar Thermal Central Receiver Pilot Plant (Solar One) is the world's largest solar central receiver electric generating station. This pilot-scale research and development experiment is a cooperative effort between government and private industry to demonstrate technical feasibility, economic potential, and environmental acceptability of the solar central receiver concept. The project has been constructed in the Mojave Desert on 130 acres of Southern California Edison Company's Cool Water Generation Station near Barstow, California. Solar One is a joint project of the Department of Energy (DOE), Southern California Edison (SCE), the Los Angeles Department of Water and Power (LADWP), and the California Energy Commission. The solar portion of the plant was designed and constructed under the direction of the DOE, and the turbine-generator facilities, including the control building, were designed and constructed by SCE.

This section presents a general description of the overall plant, a summary description of the collector subsystem, and an outline of the collector subsystem test program.

Siting and General Design Data

The pilot plant is located east of Daggett, California, which is approximately 12 miles east of Barstow, California. The site is at a latitude of 34.87 degrees north and a longitude of 116.83 degrees west. The nominal elevation of the site is 1946 ft above mean sea level.

The plant is designed to produce at least 10 MW of electrical power to the utility grid (after supplying the plant parasitic power requirement) for 4 hours on the plant "Worst Design Day" (winter solstice) and for 7.8 hours on the plant "Best Design Day" (summer solstice). During certain periods of the year (near noon from March through September), the plant power collection capability can exceed the 12.5 MW turbine generator rating.

Plant Systems

The central receiver concept being demonstrated at Solar One integrates the operation of six major systems as depicted in Figure 1. The collector system, consisting of large sun-tracking mirrors (heliostats), redirects the solar energy incident

on the mirrors and concentrates it on a tower-mounted receiver (boiler). There the solar energy transforms water into superheated steam, which can be used directly to drive the turbine-generator or is diverted to the thermal storage system. The thermal storage system can store the energy as sensible heat to extend turbine-generator operation after sunset. The electric power generation system (turbine-generator) can generate 10 MW from receiver steam and 7 MW from thermal storage steam. The master control system is a series of computers that monitors and controls each of the major systems. The beam characterization system is used to align the heliostats and ensure their efficient operation. Other plant support systems include the raw water, fire protection, demineralized water, cooling water, nitrogen, compressed air, liquid waste, oil supply, and electrical distribution systems.

Collector System—Figure 2 shows the collector system 360 degree array of 1818 heliostats. Figure 3 is a photograph of an individual heliostat.

The heliostat field has a reflective area of 782,000 ft², divided into four quadrants. There are 1240 heliostats in the two northern quadrants and 578 in the two southern quadrants. Each heliostat is made of 12 slightly concave mirror modules totaling 430 ft² of mirror surface. The mirror assembly is mounted on a gear driven, drive mechanism for azimuth and elevation control. A complete description of the heliostat requirements and design description is provided in Appendices I and II, respectively.

The collector control system consists of individual microprocessor heliostat controllers (HC), a heliostat field controller (HFC) for control of groups of 32 heliostats, and a central computer called the heliostat array controller (HAC). The annual and daily sun position information for aiming each heliostat is stored within this control system. The heliostats can be controlled individually or by groups in either manual or automatic modes through the HAC, which is located in the plant control room. The heliostats are designed to operate in winds up to 50 mph and will withstand winds up to 90 mph when stowed with the mirrors in a horizontal position. Normally, each heliostat is moved from the nighttime stow position to standby at some time before sunrise. There are four standby aimpoints located at the receiver elevation approximately 100 ft out from the receiver surface. The heliostats are brought to the standby points by following an aimpoint up an imaginary line from a starting point that is below ground level. The aimpoint moves from the focal point at ground level to the standby position adjacent to the receiver in about 6 minutes. When the reflected beams are directed onto the receiver from standby, the beam path is not controlled in any special manner. Motion from standby to stow is normally made after sunset and it reverses the start-up path.

The high-wind stow position is “mirror face down” with the torque tube aligned east/west, parallel to the prevailing wind direction. This alignment reduces the wind load on the gear train and reduces the chance of gear failure. During 1982, the mirrors were normally stowed facing down. However, in January 1983, normal stow was changed to “mirrors vertical” to minimize water standing on the mirror module seals and on the mirror backing paint.

Receiver System—The receiver system consists of a single-pass-to-superheat boiler with external tubing, a tower, pumps, piping, wiring, and controls necessary to provide the required amount of steam to the turbine. From the control room the operator can vary the steam demand; also, the receiver steam can react to a demand from the electric power generating system up to the receivers rated output.

The receiver is designed to produce 950°F steam at 1465 psia at a flow rate of 112,000 lb/hr. The receiver has 24 panels (6 preheat and 18 superheat), each approximately 3 feet wide and 45 feet long.

The panels are arranged in a vertical cylindrical configuration, 23 feet in diameter, with a total surface area of 3252 ft². Each panel has 70 small tubes; each with an outside diameter of 0.5 in and an inside diameter of 0.27 in through which high-purity feedwater is pumped and converted to superheated steam. Under normal operating conditions, the external surface temperature of the receiver tubes is approximately 1150°F. The receiver tubes are made of Incoloy 800 to withstand the effects of daily heat cycling as well as cloud transients. Within each panel, the tubes are welded to each other throughout their full length. The panel is coated with a special black paint (Pyromark) to increase thermal energy absorption. The black surface of each panel is heavily insulated and sealed against light leaks.

The lattice steel tower holds the receiver 300 feet above the desert floor. The heliostat beam characterization system determines beam pointing errors and beam quality for individual heliostats, using four white aluminum sheet-metal targets mounted directly beneath the receiver.

Thermal Storage—The thermal storage system extends the plant's electrical power generating capability into nighttime or during periods of cloud cover by storing thermal energy from the receiver. It also provides steam to maintain selected portions of the plant in a warm status during nonoperating hours and to start up the plant the following day. For example, sealing steam is required in the turbine casing even when it is not running in order to maintain vacuum in the condenser and hold proper feedwater chemistry. Even though the primary source for this turbine sealing steam is thermal storage, a small auxiliary electric boiler is available if the thermal storage system is depleted or not operating.

The thermal storage tank is 45 feet high and 65 feet in diameter. It sits on a special lightweight, insulating concrete foundation to reduce heat loss to the ground. The walls are made of steel plate with 1 foot of insulation, and the roof is made of aluminum plus 2 feet of insulation. The 946,000 gallon capacity tank, filled with 7,000 tons of rock and sand and about 240,000 gallons of thermal oil (Caloria HT-43), acts as a heat storage vessel.

De-superheated steam from the receiver is routed through a heat exchanger that heats cold thermal storage oil from the bottom of the tank. The heated oil is pumped back to the top of the tank, and thermal energy is transferred to the rock

and sand. When the system is fully charged, the temperature of the thermal storage mixture (oil, rock, and sand) is approximately 575°F. When it is discharging, the hot oil is pumped from the top of the tank through another heat exchanger to boil water, and the cold oil is returned to the bottom of the tank. Steam at 525°F and 385 psia can be produced from the thermal storage system and delivered to the turbine at a rate of 105,000 lbs/hr. The rated electrical capacity of plant operation on thermal storage energy is 28 MW-hr net output, e.g., 7 MW_e power for 4 hours. After the system discharges, sufficient thermal energy is still available in the tank for heating, sealing steam, and restarting the plant the next day.

As with other plant systems, the thermal storage system has computer controls, but it can also be controlled manually. By selecting plant operating modes, the operator can use receiver steam to charge the thermal storage system alone, or to drive the turbine and charge the thermal storage system simultaneously.

Master Control—The master control system is a series of computers that control the plant from the central control room. It supplies overall coordinated supervisory control to individual systems. A sketch of the master control console is shown in Figure 4.

Approximately 2,000 continuous, discrete measurements from throughout the plant are transmitted to and recorded by the master control system. Operating data, alarms, and alerts are displayed on control consoles and on graphic displays. Additionally, plant piping and instrumentation diagrams are displayed with live-time process parameters and valve operating configurations for system status.

To augment the master control system and to provide individual system control and trouble isolation, each system has its own distributed process controller. The process controllers, which are digital computers tied into the master system, control the system valves, motors, pumps, relays, and other equipment. They are located near the respective system's hardware in remote stations. For example, the process controller for the receiver is located in the tower within a remote station immediately below the receiver.

The control system hierarchy is shown in Figure 5. Four Modcomp Classic 7863 computers, located in the control room, are designated as follows:

OCS - Operational Control System, which provides a console for single operator control.

DAS - Data Acquisition System, which records selected control and monitoring data.

HAC - Heliostat Array Controller, which supervises the collector field. Two Modcomp units are used. One provides full backup for the other.

Control and monitoring data are collected and processed from field instruments by way of the distributed process controllers (SDPC). This control hardware

is a Beckman MV 8000 system. Five remote processing stations are located outside the control room.

Turbine-Generator—The General Electric turbine-generator, a single case design for cyclic duty, is rated at 12.5 MW. This same general machine is used for marine drives. The turbine has two steam admission ports, one high-pressure port for receiver steam and a lower pressure port for thermal storage steam. The rated turbine thermal-to-electric efficiency from receiver steam is 35 percent, and from thermal storage steam 25 percent. Receiver steam conditions are 112,000 lb/hr, 950°, 1465 psia, throttle valve capacity for 10 MW net. Thermal storage steam conditions are 105,000 lb/hr, 525°F, 385 psia admission valve capacity for 7 MW net.

Figure 6 shows a schematic diagram of the plant. Spent steam is condensed by circulating water from the evaporative cooling tower. Condensed steam is then routed back to the receiver through a full-flow demineralizer and a series of feedwater heaters. The turbine has four steam extraction ports used for three feedwater heaters, and a deaerator. The second-point and first-point feedwater heaters only operate during receiver operation. The generator is air cooled with a static exciter and 13.8-kv-rated output voltage.

Additional support functions in the electric power generating system include the water chemistry control facilities and an uninterruptible power supply battery system for providing power to the computers if the main and backup power sources fail.

Beam Characterization System—The Beam Characterization System (BCS), includes the hardware and software required to permit rapid and automatic characterization of the reflected beams directed to the receiver by any single heliostat and simultaneous measurements of sun shape (Reference 34). A block diagram is shown in Figure 7.

The BCS data include beam size and shape, beam centroid, flux distribution, total beam power, and as required, the radial radiance distribution of the sun. BCS beam data are gathered by four vidicon cameras (each dedicated to a separate target) which view tower-mounted targets located below the receiver. Incident irradiance data are obtained by radiometers located on each target. The cameras are located as shown in Figure 1-1 to be near-perpendicular to their respective targets. Figure 1-2 shows the physical characteristics of targets, along with the locations of the radiometers.

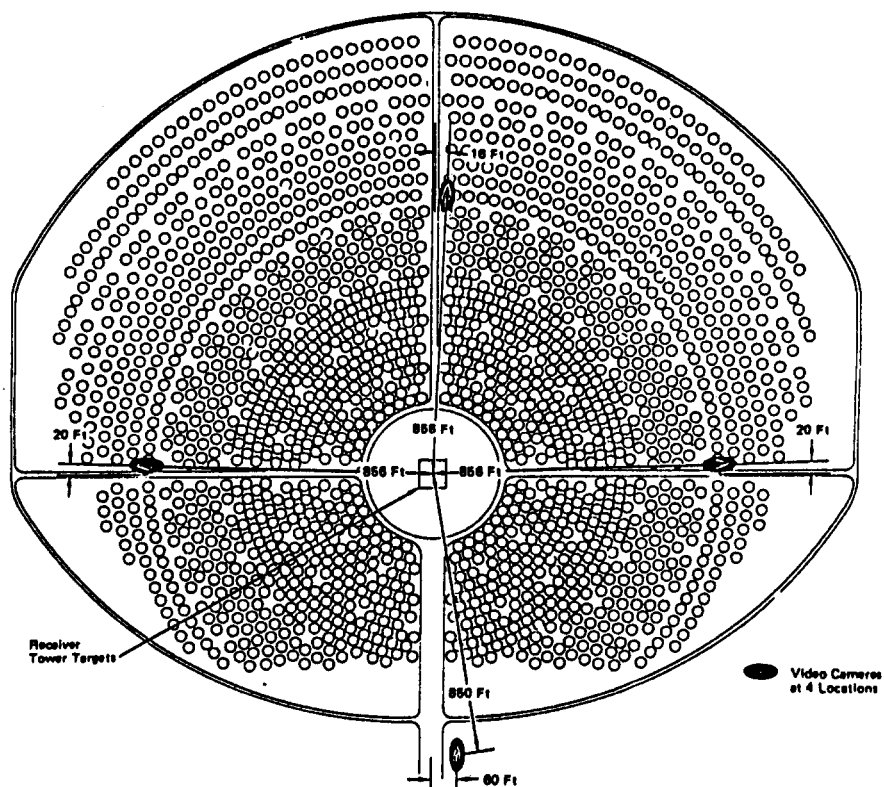


Figure 1-1. BCS Camera Locations

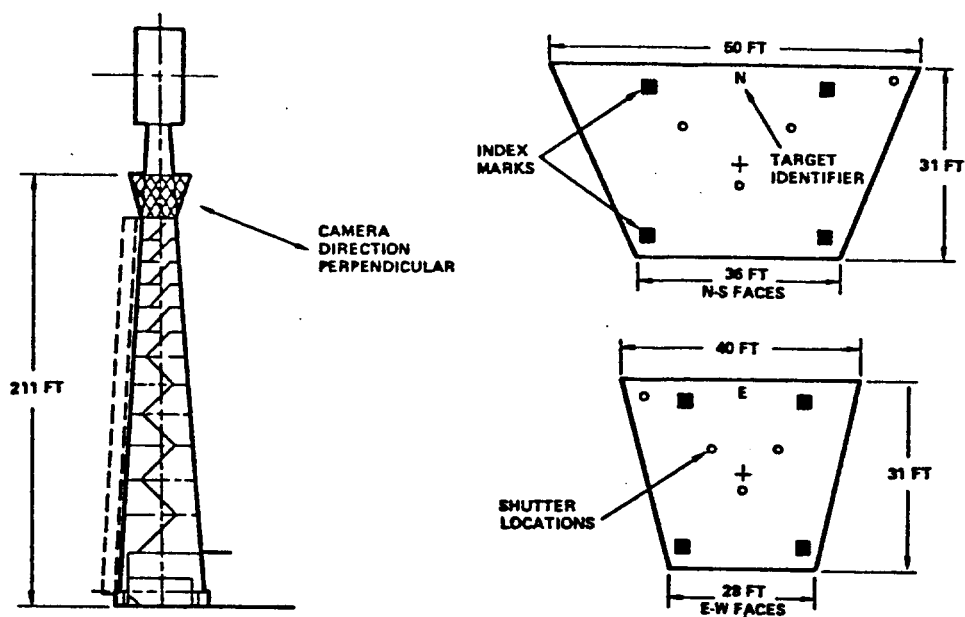


Figure 1-2. BCS Targets

Data gathered by the BCS equipment are digitized, calibrated, processed to characterize the image, and stored. These data can then be used to align and evaluate the heliostats during plant operation. The system is designed to sequentially evaluate reflected images on an individual heliostat basis. Simultaneous operation of the four targets and cameras for the calibration of individual heliostats is possible. However, to eliminate stray beams crossing a target during data acquisition, opposite targets (N-S or E-W) are normally run simultaneously.

A complete description of the BCS design is provided in Appendix III.

Special Heliostat Instrumentation and Meteorological Measurement System (SHIMMS)—The SHIMMS was installed to obtain data for heliostat evaluation. The data includes wind speed and direction throughout the field, ambient temperature, heliostat component temperatures, heliostat wind loads, and insolation. The heliostat data was obtained from seven specially instrumented heliostats. The meteorological data has been published in References 3, 4, and 5. Heliostat evaluation data is provided in this report.

Figure 1-3 shows the heliostat field and the locations of the meteorological stations, the wind towers, and the specially instrumented heliostats. At each of the wind towers, there are anemometers located at 10 ft, 20 ft, and 32.8 ft above the ground. The meteorological stations have anemometers at 32.8 ft only. Further details of the heliostat field layout and specifications for the anemometers are given in Reference 3.

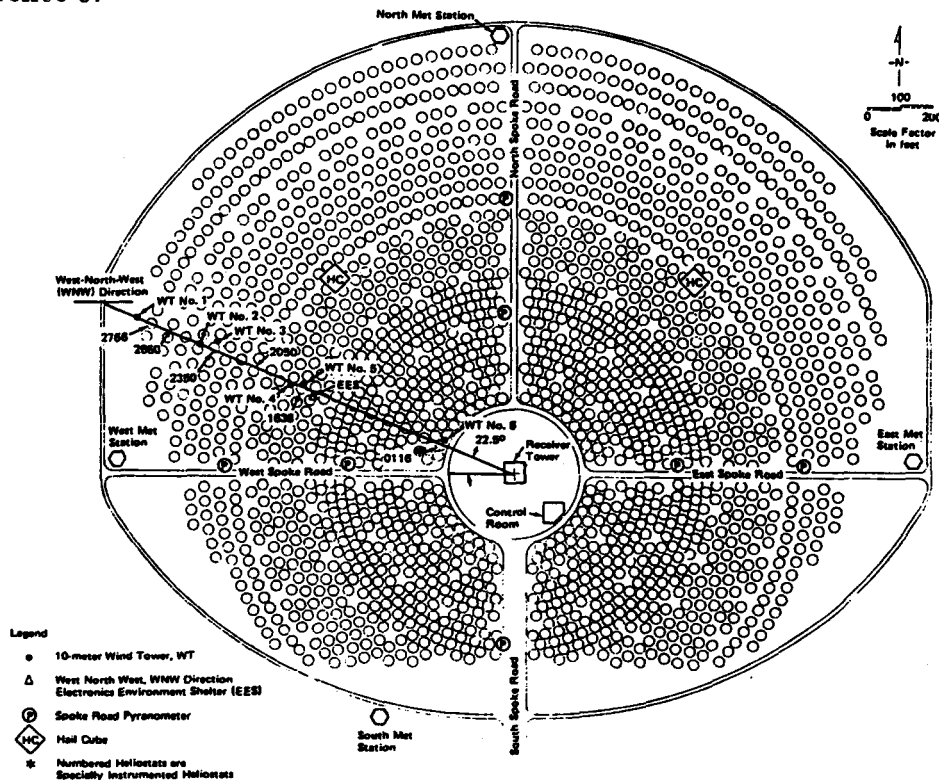


Figure 1-3. Collector Field Locations of Meteorological and Specially Instrumented Heliostats

Test Program

Collector System Functional Tests

The initial collector system functional tests were performed from November 9, 1981, through November 18, 1981. This testing was performed to demonstrate the systems level operational performance of the collector system on a stand-alone basis. The testing involved issuing commands from the Heliostat Array Controllers (HACs) and verifying responses by visual observation of the heliostat movements in the field, and by observation of the readouts on the HAC displays and printer.

The collector system functional tests consisted of the following:

1. HAC control verification of legal commands/modes
2. Wire-walk verification
3. Heliostat response verification to singularity condition
4. Illegal commands verification for each operating mode
5. Graphics display console segment verification
6. Emergency commands verification
7. Special commands verification
8. Heliostat targeting verification

Heliostat Tests

The objectives of the heliostat tests were to characterize heliostat performance and identify areas where heliostat research and development might lead to performance improvement and to establish whether a Beam Characterization System would be needed in future plants.

Heliostat optical performance is derived from beam pointing, beam quality, and reflectivity data. The BCS measures beam pointing and quality. Individual heliostats are aimed to reflect their beams onto large tower-mounted targets. Field-mounted cameras send the target images to a computer which analyzes the images to determine the flux distribution (quality) and the centroid (pointing). The BCS interfaces directly with the Heliostat Array Controller (HAC). Daily operation is automatic and only requires that the operator input the list of heliostats to be tested. This system is capable of characterizing the entire field every 36 days. If the heliostats do not change much with time, it is possible that future plants will not require a BCS of the type used at the Pilot Plant.

Assessment of beam quality requires the analysis of the flux distribution using HELIOS or MIRVAL. Because of the time and expense of running these computer codes, detailed analysis of beam images is performed for selected heliostats

throughout the field. A simplified functional approximation, developed from these analyses, will provide a method for quantifying heliostat images and will allow rapid evaluation of beam quality by the operator.

Reflectivity measurements were made by trained SCE operators with a portable specular reflectometer. Biweekly measurements were taken of several heliostats throughout the field. Some of these heliostats were used in an experimental washing program to assess different washing techniques and frequencies.

Heliostats are designed to have a service life in excess of 30 years. The major environmental conditions which affect this lifetime are the loads imposed on the drives and support structure by high winds, corrosion of mirror module silvering caused by water intrusion, and survival of controllers and motors under operating thermal loads.

SHIMMS data were analyzed to evaluate wind load distributions for individual heliostats throughout the field as a function of wind speed and angle of attack. The results were used to derive aerodynamic design criteria for future heliostats.

Sensors, which provide measurements of motor, controller, mirror module, and structure temperatures, were installed on the six SHIMMS heliostats. These measurements are compared with design specifications including ambient operating conditions, allowable temperature rise under load, and duty cycle.

Mirror module silver corrosion occurs when water attacks the silvering on the back surface of the mirror. Leak testing, controlled thermal cycling, in-situ temperature and humidity measurements, and radiography to locate water were performed to determine the extent and source of water in modules and to develop possible remedies.

Mirror Corrosion Tests

Silver corrosion continues to occur in the Pilot Plant mirror modules. Corrosion occurs when water inside the modules diffuses through the mirror backing paint and dissolves the copper layer on the back of the silver, thereby initiating silver corrosion. The corrosion will not affect plant performance for several years; however, the existence of corrosion has been one factor in the adoption of alternate mirror module designs by industry. These new designs do not require sealing of a box type structure to keep water away from the silver. Several activities are under way to establish the cause of the corrosion and estimate the corrosion growth rate and area affected. These are summarized in Section III of this report.

Other Mirror Module Types Being Evaluated

Several different types of laminated glass mirror modules have been installed at the Pilot Plant for comparison with the Pilot Plant design. These mirrors use

different glasses and laminating adhesives and should demonstrate that a long-life mirror module can be made. A summary of the different designs is provided in Section III of this report.

SECTION II

COLLECTOR SYSTEM CONSTRUCTION AND OPERATION EXPERIENCES

This section provides a summary of the 10 MW_e Solar Central Receiver Pilot Plant heliostat and Beam Characterization System (BCS) installation and operating experiences. (References 21, 22, 26, 27, 28).

Heliostat Installation

The collector field at the Pilot Plant was installed beginning in November 1980 and completed in September 1981. Installation experience by major component is summarized in Table II-I.

TABLE II-I
PILOT PLANT INSTALLATION EXPERIENCE

Component	Installation		Units per Day	
	Start	Complete	Min	Max
Pedestals	Nov. 1980	June 1981	27	60
Drives	Nov. 1980	Aug. 1981	5	50
Mirror Assemblies (12 mirrors)	Feb. 1981	Sept. 1981	4	40
Heliostat Controls	Feb. 1981	Sept. 1981	10	40

Table II-II summarizes the problems which have been experienced with the heliostats during the fabrication, production testing, assembly, installation, and initial operation. Problems after the initial operation are discussed in a later section.

Based on Pilot Plant experience, Martin Marietta has recommended for future central receiver plant installations that the following site construction items be completed prior to the start of heliostat installations:

- Data cabling installed in entire field
- Power cabling energized in entire field
- Control room available for permanent control console
- BCS targets installed
- BCS operational

TABLE II-II
HELIOSTAT EXPERIENCES

Problem	Resolution
Production drive failed during simulated 90 mph wind load test	Additional elevation pinion gears tested without failures; high wind stow position revised to reduce loading
High glass breakage occurred during start-up of mirror module fabrication on ceramic tools	Standard float glass used for approximately 136 heliostats; field performance impacted less than 1%
Sixty-nine doubler pad bond failures occurred at site. Doubler pads hold mirror modules to structural rack assembly	Adhesive process control improved; pad pull test initiated; riveting retrofit performed on 5400 modules
Random communication failures occurred in heliostat control boxes	Boxes modified to increase capacitor size and jumper connections added
Lightning storm caused failure of I/O communications couplers in field and control room	Additional grounding protection of control cable in core and field areas provided to protect against electromagnetic pulses

HAC software communication timing caused numerous problems. Symptoms included loss of communication between the HAC and the field, HAC failure to the backup, and lockup of the operators terminal. The problems increased when the HAC was connected to the BCS and testing started. HAC software and BCS hardware and software problems caused many delays in BCS checkout and evaluation.

Initial Heliostat Alignment

The Beam Characterization System was not available for the initial heliostat alignment. Therefore, the heliostat pointing errors were determined by visually estimating the beam centroid on the BCS target. Heliostat tracking correction (bias) values were then made. Because there have been numerous problems with the BCS, as discussed below, the field operated with visual bias values until 1985.

Beam Characterization System

The BCS was not completed as initially planned due to limited construction funds and higher priority work during the initial plant start-up. The circumsolar

telescope for sunshape measurements was not installed, and there were numerous system calibration and software refinements that were not completed.

Operating Experiences

The collector system has been operating since November 18, 1981, when the functional testing was completed. The collector field was stowed after sunset, with the mirrors face-down, during 1982 and was brought up to a standby position prior to sunrise. There have been no major problems with the heliostats and the plant operators had no trouble learning how to control the field. The heliostats have operated for approximately 3000 hours per year. The controllers have been powered up 100% of the time since January 1982.

Collector Field Reliability and Plant Maintenance Priority

The collector system is equipment intensive, and one would thus anticipate that such an equipment system would require unusually high levels of operation and maintenance to achieve normally accepted reliability. Reliable equipment design has resulted in less than the anticipated maintenance manpower expenditure. During the initial operating period, the main heliostat controller (Heliostat Array Controller or HAC) required one operator full time. As we gained experience in its operation, operator demand was reduced to one quarter time.

Because the collector field has a large redundancy in its 1,818 heliostats, maintenance priority has generally concentrated on potential single-point failures within the receiver and electrical power generation systems. Regardless of the limited maintenance expended on the collector system during the first three years of operation, 1,700 heliostats were generally available for service. During preparation for plant field power tests, during the two years of the power production phase of the plant's operation, a concentrated effort was made to improve the number of heliostats available for service. As a result of this effort, more than 1,800 heliostats were available for service most of the time.

Electrical Grid and Computer System

The two most significant problems with the operation of the collector field were in the electrical subtransmission grid to which the plant is connected and in the computer interface communication. The plant is connected electrically to a 33KV line which is approximately 32 miles long, originating in Barstow and terminating in Newberry, California. This line has been subject to undervoltage conditions and occasional power interruptions due to a combination of lightning strikes, wind, heavy equipment electrical loads, and on one occasion, vehicle impact with a supporting power pole. The undervoltage or power interruptions have resulted in loss of collector field power, which resulted in loss of power to both the heliostat motors and heliostat controllers that share common power supplies. Although field digital communications are on an uninterruptible power source, the microprocessor-based heliostat controller, on being de-energized, loses its volatile

memories and requires reprogramming through the Heliostat Array Controller (HAC).

Heliostat Array Controller

The original Heliostat Array Controller (HAC) operating procedure was an excellent working document. When the HAC computers operated independent of other plant controls, shortly after plant start-up, software revisions were often made which reduced operator demands, and such software revisions generally worked successfully the first time around. The only significant aggravation experienced during the plant's early operation—which continues through the present time—was the 26 minute delay that was imposed on heliostat field controllers prior to their taking charge of the collector field, following loss of both the prime and back-up HAC computers. As the HAC computers were interfaced with other computer systems, supplemental instructions were required, making operation of the collector field through the HAC terminal somewhat complex. Many of the problems were corrected through software revisions. These computer interface problems all too often required long-term resolution, and many of these efforts at resolution were not successful or caused secondary problems even though software design engineers were on site to facilitate problem corrections.

Beam Safety

Control of the reflected sun images (beams) from the collector field was important for site personnel safety as well as for minimizing off-site personnel exposure to stray beams. The heliostats are daily repositioned from their horizontal face down or vertical stow position to the standby tracking position, whereby all heliostat images are concentrated at either of four standby points adjacent to the receiver's outer circumference. Heliostat images, in going to the standby position, travel up imaginary wires from four ground points to the four receiver standby points. In transitioning from the ground points to or from the standby points, the heliostat images were measured to be equal to four to five sun intensities along collector field access roads and up to thirty sun intensities five feet above their ground points. (The heliostat focal point is twelve feet below the ground surface at the bottom of the wire.) Because retinal damage to the eye is reported to occur at four to five sun conditions, personnel were not allowed in the collector field or on collector field access roads during wire-walks. As an additional precaution, heliostat pedestals near the wire ground points have been banded red to define the area of highest flux intensity. During wire-walks, personnel in the collector field and access roads are required to report to the core area to avoid a potentially hazardous condition. During early heliostat testing, personnel would lose their orientation while working in the collector field when they saw themselves reflected in heliostat mirrors. Accordingly, it was most expeditious to have personnel report to the core area by using the receiver as a landmark rather than having persons attempt to exit to the collector field's outer circumference during wire-walks. Also, during the plant's start-up, when wire-walking during the day, heliostat reflected images, noted by drivers on adjacent area roadways, often distracted the driver. Therefore, the heliostat wire walks were normally performed

before sunrise and after sunset. The control of heliostat reflected beams and the restriction of selected plant areas during wire-walks were successful.

Beam Safety Tests

Several helicopter fly-overs were made to measure the reflected light above the field. Measurements at ground level were also made at the bottom of the wires and along the roads to the center of the field and around the perimeter road. Above the field there is no safety hazard for the human eye above 1000 ft. The area around the bottom of the wires is an eye hazard region for a short time during the wire-walk. A stay-out area is marked off around these hazardous areas. No one is authorized to enter the field without being informed of the potential hazard areas and how to avoid the hazard. A warning horn is sounded whenever the heliostat beams are moving along the imaginary wires.

Heliostat Operating Strategy

There are four standby aimpoints located at the receiver elevation approximately 100 ft. out from the receiver surface. The heliostats are brought to the standby points by following an aimpoint up an imaginary line from a starting aimpoint that is below ground level. Motion from standby to stow is normally made after sunset, and it reverses the start-up path. The aimpoint moves from the focal point at ground level to the standby position adjacent to the receiver in about six minutes. When the reflected beams are directed onto the receiver from standby, the beam path is not controlled in any special manner. This has not caused any problems, probably because the potentially unsafe condition exists for such a short time, and no aircraft have been above the field during this time.

The high wind stow position is "mirror face down" with the torque tube aligned east/west, parallel to the prevailing wind direction. This alignment reduces the wind load on the gear train and reduces the chance for gear failure. During 1982, the normal stow position was with the mirrors facing down. However, in January 1983, normal stow position was changed to "mirrors vertical" to minimize water standing on the mirror module seals and on the mirror backing paint. The water problem is discussed later in the mirror corrosion section.

Special Instrumentation

The wind measuring instruments and heliostat load cells have caused problems. Late in 1982 when a meteorological report was prepared, the wind speed and direction data were found to be faulty. Most of the electronics interface cards were found to be incorrectly installed and most of the instruments had worn-out bearings and/or potentiometers. At this time it was determined that maintenance

must be done every six months in a desert environment. The meteorological data are recorded and stored in one of the plant control computers which was off-line for repair or for software changes during much of 1982. Therefore, even when the instruments were working, the data were incomplete. The meteorological data system should have been periodically checked and maintained independent of the plant control computers. Since January 1983, this data system has generally been available.

One hundred twenty heliostat load cells, containing strain gages, for measureg mirror module wind loads. The strain gages started to fail in mid-1982 because of water corrosion that entered through a hole that should have been sealed during production. There were 21 bad load cells in November 1982, 24 in January 1983, and 30 in March 1983. The hole in the load cells was plugged early in January 1983, to prevent additional water from entering the load cell. Subsequently, another 9 load cells have failed.

SECTION III

HELIOSTAT EVALUATION RESULTS

Mirror Corrosion

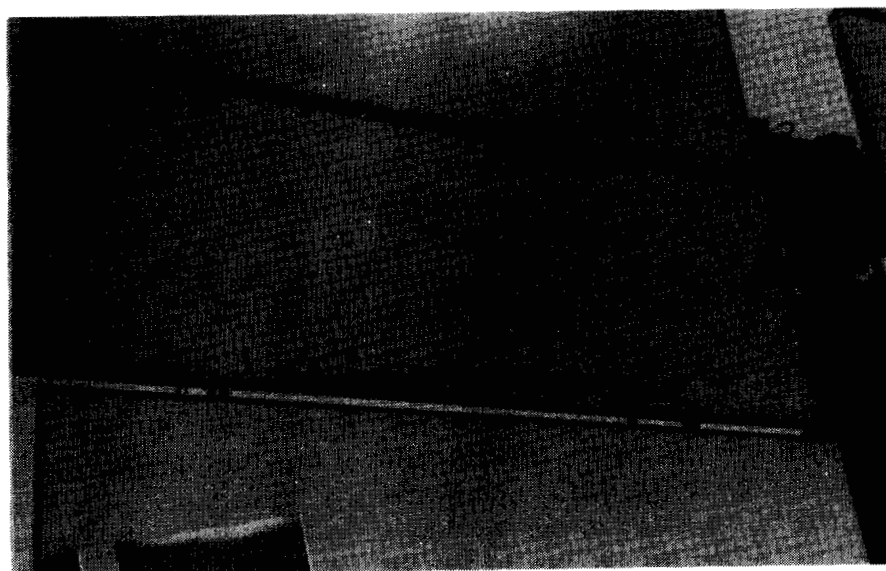
Silver corrosion was first observed on some of the mirror modules in the collector field in February 1982, approximately one year after the 1,818 heliostats were installed (Reference 15). The corrosion forms as a result of water penetration through the paint and copper backing layers to the silver layer of the mirrors, causing the uniform silver layer to agglomerate (Reference 16). Figure 3-1 shows photographs of typical corroded mirror modules. (Appendix II contains general information about the heliostats and the mirror modules used at the Pilot Plant.)

In May 1982, Sandia National Laboratories, Livermore (SNLL), x-rayed and photographed 100 randomly selected mirror modules and found that the reflective area corroded was 0.0003% and that 75% of these mirror modules contained water (References 15 and 17). Sandia rephotographed the same modules in December 1982, and found that the corroded area had increased to 0.002% (Reference 18). In February 1983, SNLL completed a field survey of 98 randomly selected heliostats and found that approximately 0.006% of the reflective surface of the 1,176 examined mirror modules was corroded. On the basis of SNLL's data and extrapolations (assuming the growth rate remains constant), the corroded area was estimated to be from 20 to 60% of the total mirror surface after five years. (A historical summary of SNLL's research on mirror corrosion performed on-site at the Pilot Plant is given in Table III-I.)

In August 1983, and again in July 1984 and 1985, a survey of all 1,818 heliostats was completed (References 19, 25, 29). A random sample of 98 heliostats was surveyed in July 1986, since it had been determined that these heliostats represented the entire field. The purpose of this survey, performed by Southern California Edison (SCE), was to inspect all of the mirror modules in the collector field (21,816), to document their condition, and to identify trends and/or patterns in the corrosion so that steps could be taken to halt the growth rate. The growth rate was significantly less than had been predicted previously. This reduction may be partially due to a vertical stow position that was initiated in January 1983 and to vents that were added to 10,036 mirror modules.



Heliostat No. 2703, Mirror Module No. 7; 35 in² of Corrosion



Heliostat No. 0813, Mirror Module No. 7; 27 in² of Corrosion

Figure 3-1. Photographs of Typical Corroded Mirror Modules

TABLE III-I
HELIOSTAT INSTALLATION, MIRROR CORROSION,
AND ON-SITE TESTS AT THE 10MW_e SOLAR THERMAL
CENTRAL RECEIVER PILOT PLANT

Mirrors Installed (21,816)	Feb. 1981 - Sept. 1981
Mirrors with Corrosion (estimates)	Feb. 1982 - 100
	May 1982 - 439
	Aug. 1982 - 665
	Feb. 1983 - 3900
Mirror Module Leak Test	Mar. 1982 - pressure test, 12 of 13 leaked
	Aug. 1983 - vacuum test, 13 of 17 leaked
Mirror Module Rapid Cooling Test	Aug. 1983 - A 15 mm Hg vacuum effected inside module when doused with water
Mirror Module X-ray	
100 Modules	May 1982 - Water in 75
11 Modules	Dec. 1982 - Water in 10
11 Modules - Vented Feb. 1983	June 1983 - Decrease in water
Photographed Corrosion	May 1982 - Corrosion .0003%
Growth (100 Mirror Modules)	Aug. 1982 - Corrosion .0007%
	Dec. 1982 - Corrosion .002%
Field Survey - 98 Heliostats	Feb. 1983 - Corrosion .006%
Mirror Module Venting Tests	June 1983 - Test vents installed in Feb. 1983 decreased water content of the modules
	Aug. 1983 - Prototype vents installed on 15 modules
	Mar. thru May 1984 - 4 vents installed in each of 10,036 mirror modules
Full-Field Corrosion Survey	July 1983 - Corrosion .015%
	3217 modules were corroded
	July 1984 - Corrosion .029%
	5890 modules were corroded
	July 1985 - Corrosion .052%
	10442 modules were corroded
Field Survey - 98 Heliostats	July 1986 - Corrosion .061%

The vertical stow position is a change from the design face-down position, which had been used since the heliostats were installed in the summer and fall of 1981. During 1982, the heliostat stow position at night and during bad weather was with mirrors horizontal, facing the ground. This was also the case during rainstorms until July 1982, when rain washing was started. Starting in January 1983, the stow position was vertical except during high winds when face-down stow was used. Rain washes occurred during rainstorms when the heliostats were

at a 45° angle with the mirrors facing up. These stow and washing positions minimize water standing on the mirror module seals and tend to keep any water in the modules from standing on the mirror backing paint.

Vent tubes were added on 10,036 mirror modules in a further attempt to reduce the mirror corrosion growth rate. The purpose of these add-on vents was to "open-up" the air space inside the mirror modules to the ambient air so that drying would be greatly enhanced. These vents also reduce the intake of water through the edge seals by eliminating the slight vacuum formed inside each mirror module as a result of sudden cooling from rain or cold air. Tests had shown that four 0.5 in diameter tubes would be more than adequate to dry out the mirror modules in a few months. The 10,036 mirror modules were vented during March, April, and May 1984. The vent consists of a size 4 silicone rubber stopper containing a bent aluminum tube. Four of these vents were "corked" into each mirror module through holes drilled in the ends, two vents on each end. A 90° angle bent tube was used so that water from rain and washing cannot enter the module.

The results of the mirror corrosion surveys are shown in Table III-II and are more fully covered in References 19, 25, and 29.

TABLE III-II
RESULTS OF MIRROR CORROSION SURVEYS

Item	1983	1984	1985	1986
1. Percent of the Total Reflective Surface of the Collector Field that was Corroded	0.015	0.029	.052	.061
2. Growth Rate of Mirror Module Corrosion (%/year)	1000	92	78	24
3. Most Prevalent Heliostat Field Location for Mirror Module Corrosion (Quadrant)	NE	NE	NE	NE
4. Percent of Mirror Modules with Some Amount of Corrosion	15	27	48	57

The fraction of the mirror modules corroded versus serial number and month of manufacture is shown in Figure 3-2. This figure clearly shows the sharp decrease in the fraction of the modules that are corroded after serial number 17,000. The primary reason for the improved quality is an improved clamping procedure that was used to hold the metal mirror edge strips while the adhesive and silicon sealant cured. Prior to this time the clamps were over-tightened so that the adhesive and sealant were in tension after the clamps were removed. This prevented the metal pan and edge strips from springing back to their shape before clamping.

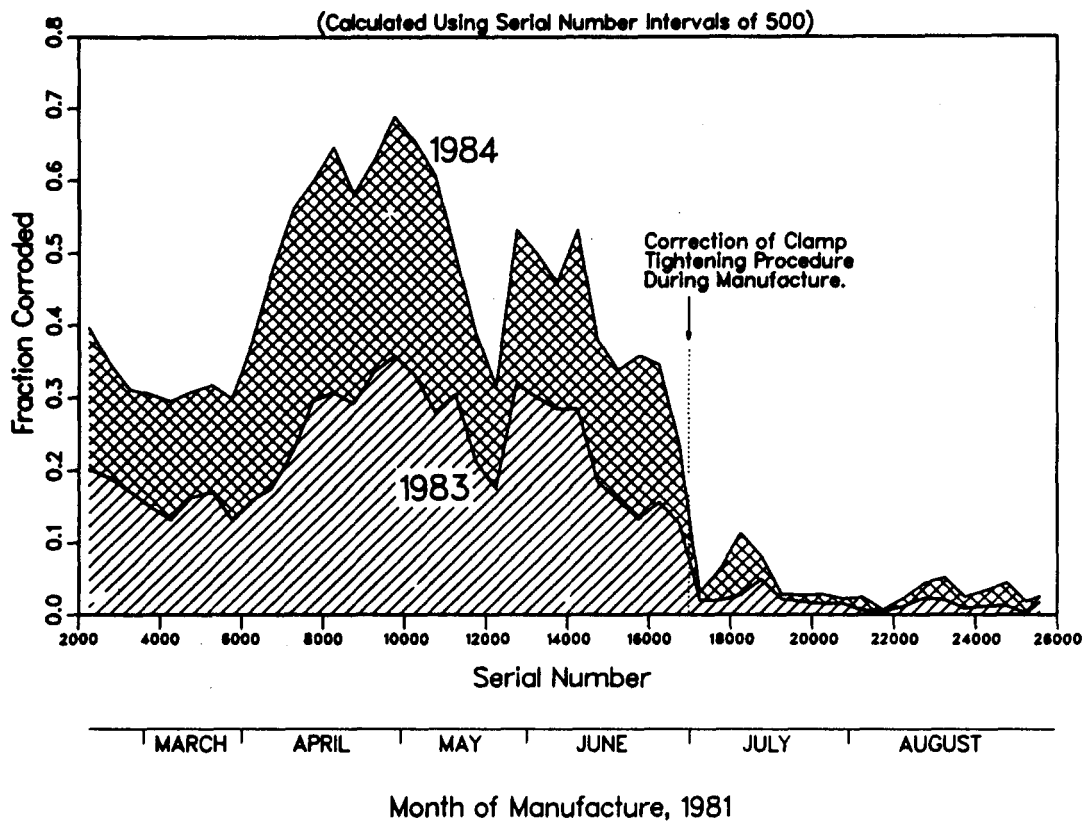


Figure 3-2. Correlation of Corrosion to Mirror Module Serial Number, 1983 & 1984

Other Mirror Module Types

The occurrence of silver corrosion on the Pilot Plant mirrors prompted testing of alternate designs at the same site. Solar Kinetics, Inc. (SKI), under contract to Sandia, designed and fabricated 150 direct replacement mirror modules, and one of each of the Second Generation heliostats is installed at the Pilot Plant. As Table III-III shows, the 150 direct replacement mirror modules were all made using five different types of laminated glass.

Laminated glass mirrors were chosen because of their resistance to water intrusion and the absence of oxygen on the back of the mirror. Laminated glass has been used for many years in automobile windshields without delamination, and laminated glass mirrors have been in the field since 1978 at the Central Receiver Test Facility (CRTF) with no apparent silver deterioration. Martin Marietta Corporation (MMC) and McDonnell Douglas Astronautics Company (MDAC) have been testing laminated glass mirrors for heliostats since the early 1970's. They have found that in some environments an edge seal is required because the silver will corrode near the edge of the lamination because the edge can be penetrated by water. This edge penetration has not occurred at the CRTF, but it has

at Sandia Laboratories in Livermore, California, and at Huntington Beach, California. The MDAC Second Generation Heliostat mirrors are laminated glass with an edge seal that consists of a silicone seal around the edge of the mirror held in place and protected by a U-shaped metal edge cap. This mirror design has not corroded after three years of outdoor exposure at the CRTF and MDAC's Huntington Beach test site. One heliostat with these mirrors on it has been installed at the Pilot Plant for long-term testing. Two other laminated glass mirror designs which have a long life expectancy, are made by Glaverbel Inc., Brussels, Belgium, and by Flabeg, a subsidiary of Glachglas AG, German Flatglass Company. Both of these companies have mirrors under test at solar plants around the world.

TABLE III-III
SOLAR KINETICS LAMINATED MIRROR MODULE TYPES

Type No.	Quantity At Solar One	Type of Lamination	Glass Thickness & Type		Reflectivity
			Substrate	Mirror	
A	85	PVB ¹ Autoclave	3 mm Float	3 mm Float	83%
B-1	10	Glaverbel ²	5 mm Float	.7 mm Glaverbel	94%
B-2	22	SKI Acrylic	5 mm Float	.7 mm Glaverbel	94%
B-3	25	SKI Acrylic	5 mm Float	1 mm Buckmin	93.5%
B-4	1	SKI/Glaverbel	5 mm Float	.7 mm Glaverbel	94%
B-5	6	SEA-200 Silicone Adhesive	5 mm Float	1 mm Buckmin ³	93.5%

Notes:
1. Polyvinylbutyrol
2. Glaverbel Inc., Brussels, Belgium
3. Buchmin Industries

The Second Generation Heliostat mirror modules using laminated glass are summarized in Table III-IV.

TABLE III-IV
SECOND GENERATION HELIOSTAT MIRROR MODULE TYPES

Heliostat Supplier	Quantity At Solar One	Type of Lamination	Glass Thickness & Type Substrate Mirror	
Boeing Engr. & Constr. Co. ¹	43.7 m ²	Glaverbel ² Adhesive	5 mm Float	.7 mm Glaverbel
ARCO Solar Inc.	52.7 m ²	Silicone Grease	Steel Sheetmetal	2.4 mm Float
Martin Marietta Corp. ¹	57.4 m ²	PVB ³ Autoclave	3 mm Float	3 mm Float
McDonnell Douglas Astronautics	56.9 m ²	PVB Autoclave	5 mm Float	1.5 mm Fusion ⁴

Notes:

1. Boeing and Martin Marietta modules are not the original Second Generation Heliostat design.
2. Glaverbel, Inc., Brussels, Belgium
3. Polyvinylbutyrol
4. Fusion Glass Produced by Corning Glass Works

These alternate mirror module types have not been at the Pilot Plant for as long as the Pilot Plant mirrors; however, there are no signs of corrosion through 1986.

Reflectivity, Soiling and Clean Reflectivity

The clean reflectivity for the majority of the Pilot Plant mirrors is 91.1%; however, there are 1,500 mirror modules which have lower transmissivity glass that is 79.8% reflective. Reflectivity is specular for an air mass 1.5 solar spectrum. The cleanliness of a selected group of mirrors has been periodically measured since January 31, 1982, using a portable single wavelength reflectometer (Devices and Services Co., Model No. 15R). This instrument measures the specular reflectance in a small wavelength band at 660 nm; it does not provide a solar averaged reflectance value. However, the reflectance values are converted to solar averaged values by multiplying by a correction factor. The correction factor used for the low iron (higher reflectance) mirrors is .973 and for the high iron (low reflectivity) mirrors the correction factor is .944. The corrected solar weighted reflectivity is accurate to 1%. Because of the two types of glass, the percent of clean values is reported rather than reflectivity. The average reflectivity for the Pilot Plant field is 90.3%. This number is multiplied by the percent of clean values for the measured mirrors to obtain the average reflectivity to be used for plant performance calculations.

Reflective Area

The actual reflective area of the mirrors is less than the size of the glass because of the edge seal. The glass area for a heliostat is 430 ft² while the measured reflective area is 420.94 ft². (See Reference 20.)

Reflectivity Measurement Points

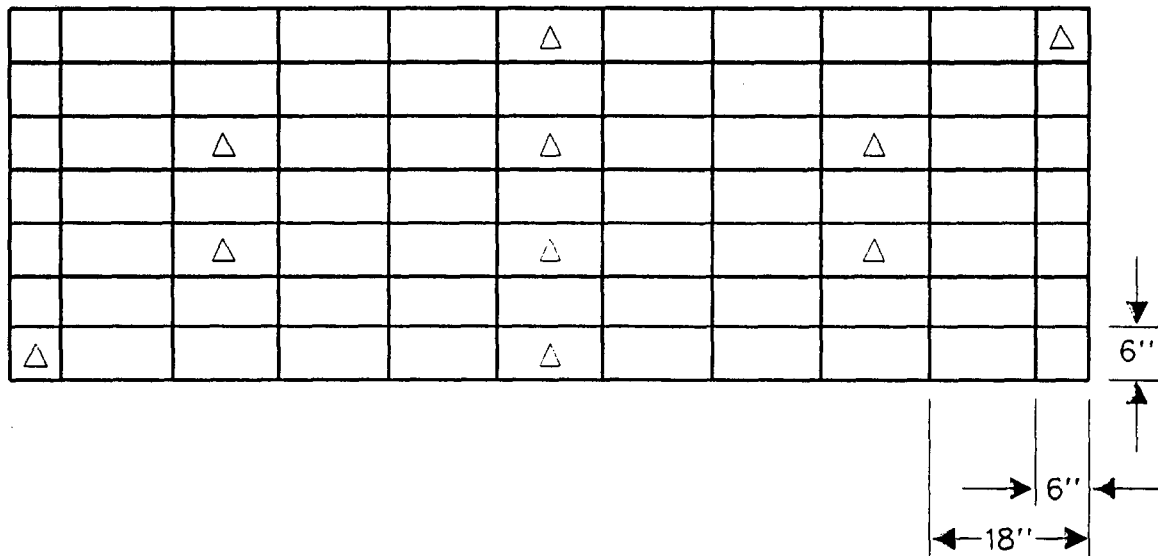
Ten data points are used to determine the reflectivity (or cleanness) of a heliostat mirror module, and the bottom two mirrors are measured for each heliostat. Figure 3-3 shows the location of the 10 data points. These locations were checked against measurements made in each of the 77 boxes in Figure 3-3. A Devices and Services Co., Model 15R, portable specular reflectometer was used to make the measurements in the approximate center of each box on six soiled mirror modules. We then calculated a weighted average of reflectivity for each mirror module using the 77 data points and the area of each sector. This average was then taken as the average reflectivity. A solar weighted reflectivity and percent clean value were also calculated for the six mirror modules.

The average reflectivity for the 10 data points normally used when determining the reflectivity of a mirror module was then compared with the average for the 77 data points.

The comparison used both solar weighted reflectivity and percent of clean values. The comparison is shown in Table III-V. The average reflectivity for the six modules is low by 0.1% when only 10 data points are measured as compared to the 77 data points. The percent clean value for the 10 data points was low by 0.2% when compared to the 77 data points. The 10 data points accurately determine the reflectivity or percent clean value for a mirror module.

Mirror Soiling and Cleaning

A portable specular reflectometer, Devices and Services Co., Model 15R, has been used to measure mirror cleanness at the Pilot Plant since January 31, 1981. Mirror cleanness is the fraction of the perfectly clean reflectivity expressed as a percentage. Measurements are made at two-week intervals. The bottom two mirrors of selected heliostats are measured as described in the previous section. Mirrors on 18 heliostats were measured between January 31, 1981, and May 6, 1984. After this date, a different group of 16 heliostats were measured that are more uniformly distributed throughout the field. The initial group of heliostats was divided into three subgroups as shown in Table III-VI. The differences between the subgroups are whether the heliostats are at high wind stow position or whether the mirrors are washed with the rest of the field (rain washes were done). The field average reflectivity was always determined from the five Group 2 heliostats. Starting in June 1983, the 18 heliostats in Table III-VII were used for reflectivity measurements. The "mirror up" stow position and no-wash heliostats were not included; however, the normal stow position is still vertical.



- One reflectometer reading was taken from each sector.
- Sectors with a triangle represent areas from which the original 10 data points are taken.

Figure 3-3. Mirror Module Sectors for Reflectivity Measurements

TABLE III-V
COMPARISON OF REFLECTIVITY DATA POINTS
USING 77 DATA POINTS AND 10 DATA POINTS

Heliostat	<u>Solar Weighted Reflectivity</u>			<u>%Clean</u>		
	77 Pts.	10 Pts.	Difference	77 Pts.	10 Pts.	Difference
1424	77.2	76.3	- .9	84.7	83.8	- .9
1512	82.5	82.8	.3	90.5	90.9	.4
2254	76.6	76.8	.2	89.1	89.3	.2
2340	79.1	79.1	0	86.8	86.8	0
2632	77.0	76.7	- .3	84.5	84.2	- .3
2712	80.5	80.2	.3	88.4	88.0	- .4
Average	78.8	78.7	- .1 %	86.5	86.3	- .2 %

TABLE III-VI
HELIOSTAT CONDITIONS AND HELIOSTATS USED FOR MIRROR
REFLECTIVITY DATA, JANUARY 31, 1981, THROUGH MAY 6, 1984

	Group 1	Group 2	Group 3
Normal Stow	Vertical*	Vertical*	Vertical*
High Wind Stow	Mirrors Up	Mirrors Down	Mirrors Down
Wash	Never	Yes	Never
Heliostat No.'s	2766	0636	1363
	2650	2313	2368
	0116	1913	1463
		1929	1579
		2833	2366
			2943
			2945
			1581
Reflectivity (10 Readings)	Mirror 11 & 12	Mirror 11 & 12	Mirror 11 & 12

* Horizontal Stow was used prior to January 1, 1983.

TABLE III-VII
HELIOSTATS USED FOR MIRROR REFLECTIVITY DATA
STARTING JUNE 1, 1984

SW Quadrant	SE Quadrant
736	735
1458	1457
1660	1659
NW Quadrant	NE Quadrant
1422	915
1510	1509
2252	2251
2338	2337
2628	2625
2710	2709

Notes:

1. Reflectivity is measured in 10 places on Mirrors 11 and 12.
2. Normal stow is vertical.
3. High wind stow is horizontal, mirrors down.
4. All heliostats are washed whenever the remainder of the field is washed.

Since the heliostat reflectivity was not measured in 1981, Figure 3-4 shows only the rainfall for 1981. Figures 3-5 through 3-8 show the Solar One mirror cleanliness and rainfall data for 1982 through 1985. The rainfall figures are from the Daggett Airport which is about 2.5 miles from the solar plant; therefore, the rainfall values probably are not accurate. However, the occurrence of reasonable amounts of rain is always accompanied by an improvement in mirror cleanliness. This improvement was the basis for how the cleanliness lines were drawn through the data points. For example, the lines were drawn through data points and extrapolated in both directions until rainfall occurred, then the next one or two data points were treated in the same way. Between late July and mid-September, when only one data point was available between rains, the line was drawn through this point approximately parallel to neighboring lines, as shown in Figure 3-5.

The slope of the percent clean lines is the rate of the decrease in cleanliness (soiling rate). As shown in the figures, there can be a wide variation in the soiling rate. The biggest variation occurred in 1982. When there was little rainfall in May and June, the soiling rate was about 0.25% per day (8%/month), while during the months when it rained, the soiling rate was 0.1% per day (3%/month). In July 1982, 700 heliostats were washed with an electrical substation insulator wash truck just prior to the two rainy days. The mirror cleanliness improved from about 75% to 95% as a result of the wash and rainfall. Then, the 2.5 cm (1 in) rain in August improved the cleanliness to 98%. This 98% cleanliness was then restored by rains in December 1982, and in January and February 1983. However, after the summer of 1983, neither rainfall nor the insulator wash truck was able to restore more than about 90 to 95% of the clean reflectivity until December 1984, when there were several heavy rains and a 5-10 cm snowfall.

Severe mirror soiling occurred between February and July 1984 because of farming activities around the Pilot Plant. Large areas of land were plowed and cultivated around the plant except on the north side. Many days of high winds caused severe dust storms. In an attempt to keep the mirrors clean during this period, the insulator wash truck was used regularly. As can be seen in Figure 3-7, the cleaning was not very effective for three reasons. The mirror cleaning rate was slow (2,028 heliostats in 1.5 months), the dust storms were frequent, and the dust particles were small which made them harder to remove. As a result, the average mirror cleanliness was only 80% even though the freshly cleaned mirrors were 95% clean. The soiling rate during this period for unwashed mirrors was 10 to 12% per month as can be seen for February and October/November in Figure 3-7.

The 1.7 in rain in July 1984, Figure 3-7, did not provide the significant cleaning expected. On the other hand, the 0.25 in rain in November was more effective than might be expected. One possible explanation is that the rainfall at the Pilot Plant was not the same as it was at the Daggett Airport.

Mirror soiling is the most severe on the outer 3 to 6 inches of the mirror. There is typically a 10-12 percentage point difference in cleanliness between the center and the outside edge of a soiled mirror (85% average cleanliness). Possible reasons for this effect are that:

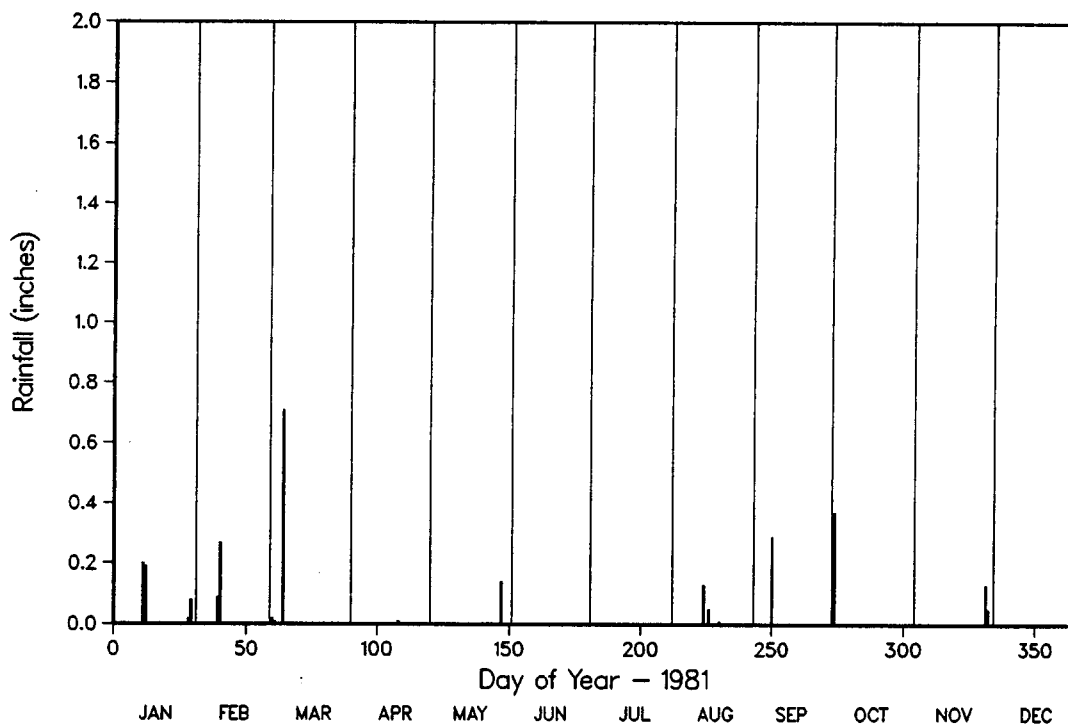


Figure 3-4. Solar One Rainfall - 1981

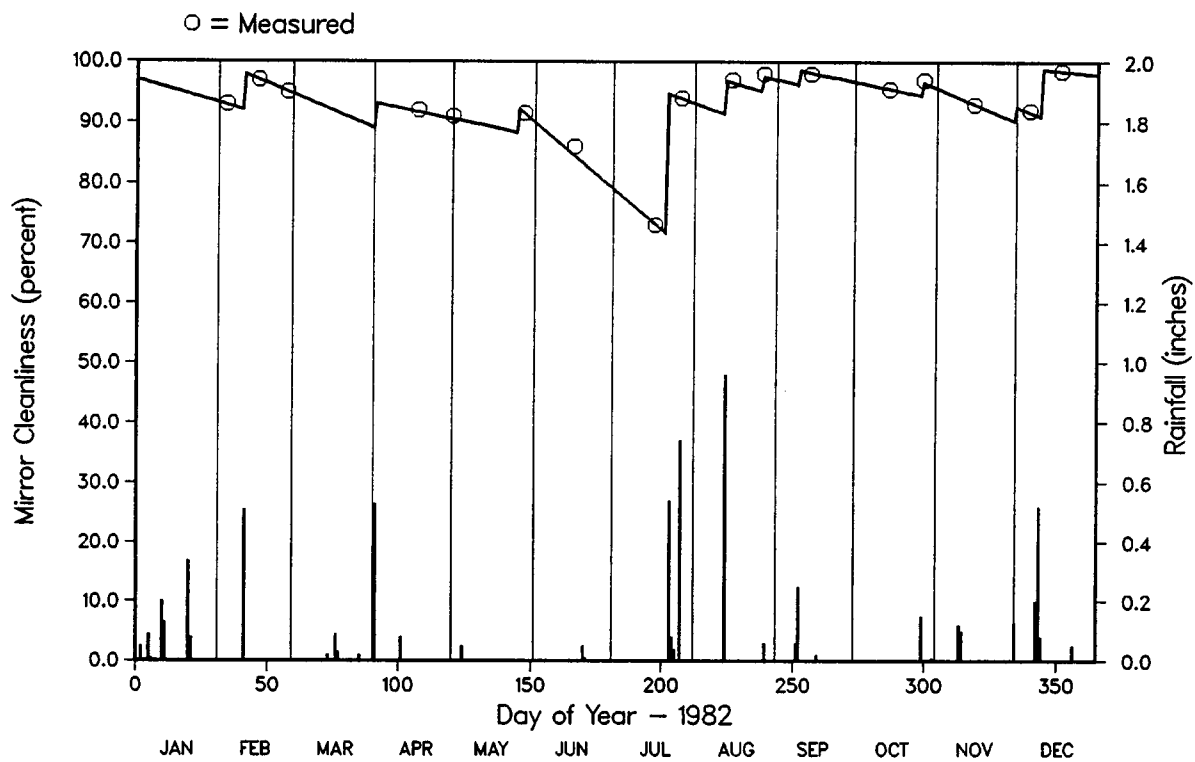


Figure 3-5. Solar One Mirror Cleanliness and Rainfall - 1982

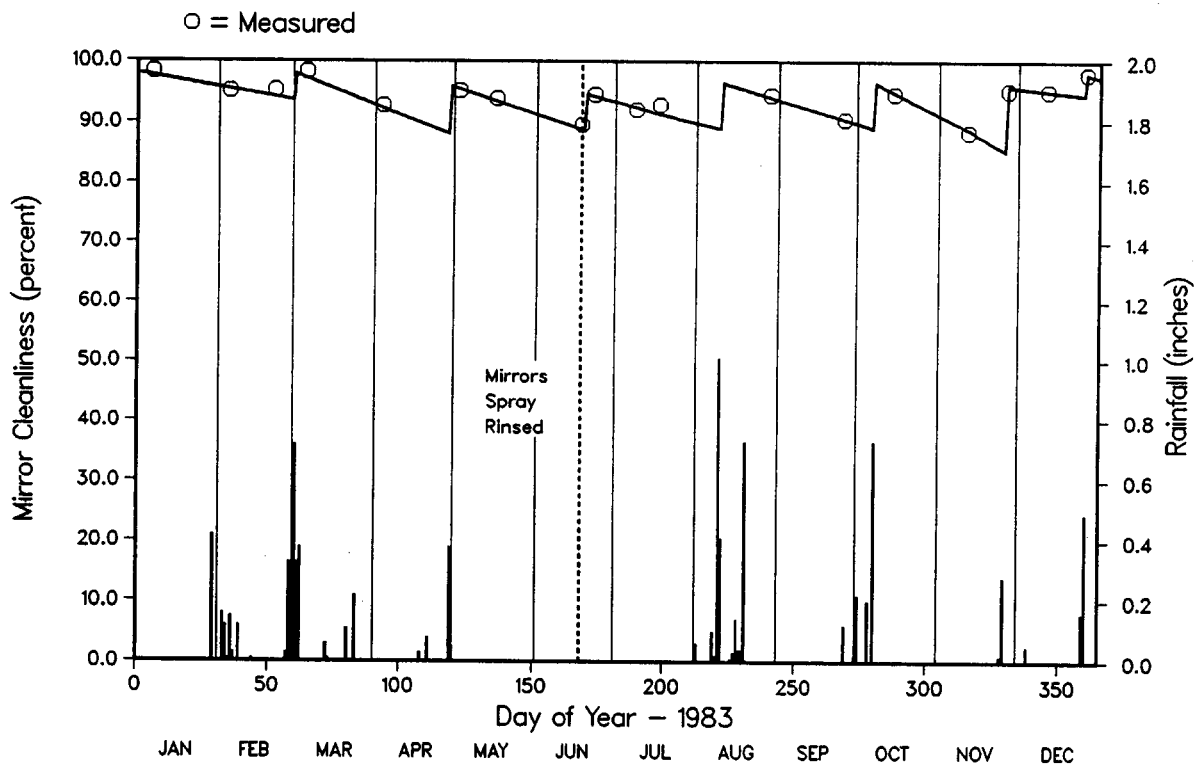


Figure 3-6. Solar One Mirror Cleanliness and Rainfall - 1983

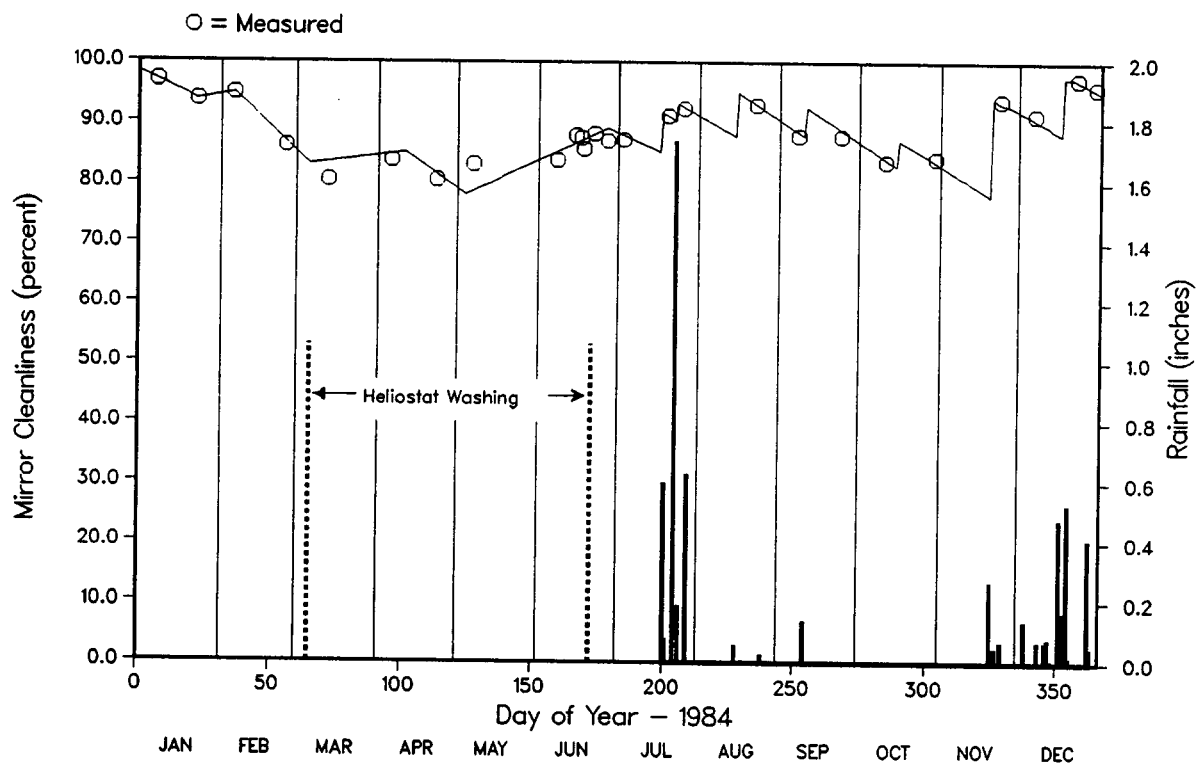


Figure 3-7. Solar One Mirror Cleanliness and Rainfall - 1984

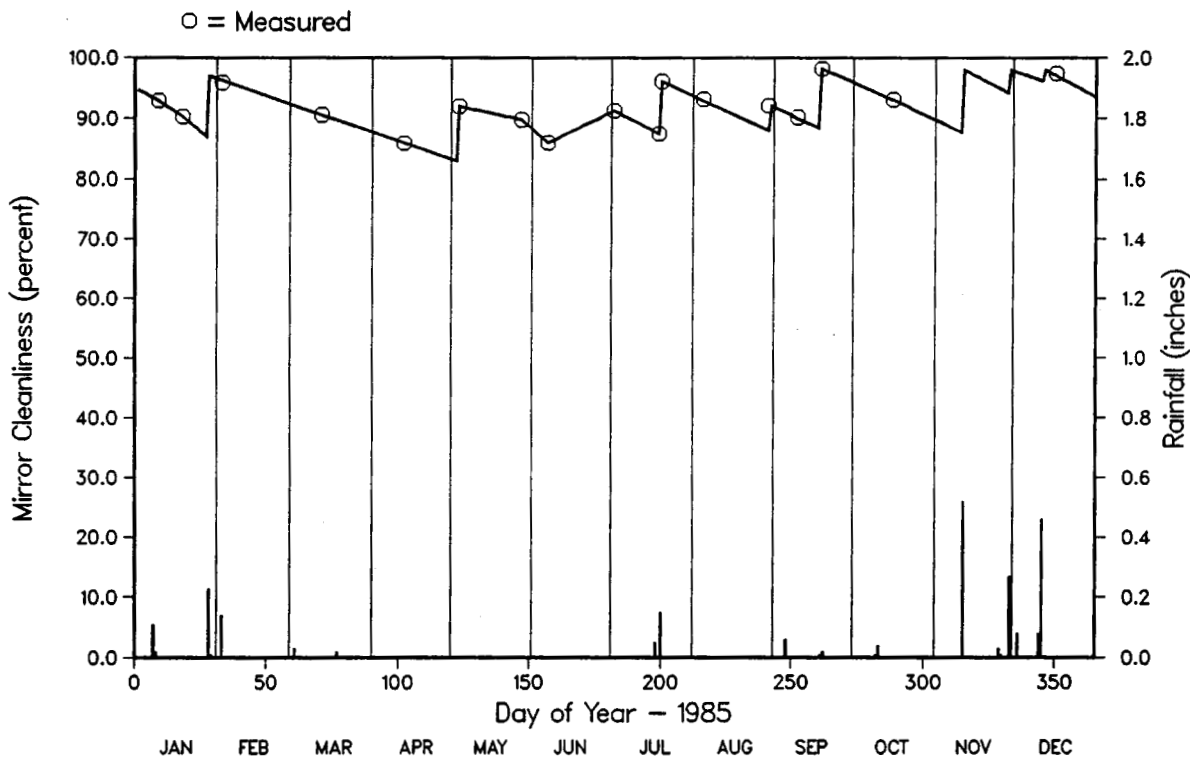


Figure 3-8. Solar One Mirror Cleanliness and Rainfall - 1985

1. to protect the edge seals, the spray rinse from the insulator wash truck was not directed at the mirror edges
2. the mirror temperature near the edge is cooler, and moisture condenses there first and evaporation dries the mirror edges long after the center is dry. This causes more dirt to be collected on the edge, and the water causes the dirt to bond more firmly. The water spray with brush heliostat wash truck has been used to clean heliostats and it will clean the entire mirror face.

The conclusions that can be drawn from the Pilot Plant mirror soiling and cleaning experience are:

1. Rainfall should be used to clean mirrors.
2. Snow should be used to clean mirrors. This was not demonstrated at Solar One; however, it was demonstrated at the Themis plant in France.
3. Mechanical cleaning is required. A wash truck is required that provides more than a spray rinse (brushes or high pressure).
4. Farming upwind from the plant severely affects mirror cleanliness.
5. Fine dust accumulates over a period of time and is heavier near the edges.

Wind Speeds in the Heliostat Field

The heliostat field at the 10 MW_e Solar Thermal Central Receiver Pilot Plant was instrumented to obtain wind speed and wind direction data at various heights and locations in the field. The purpose was to gain an understanding of the interaction of wind with the heliostats. Of particular interest were the possibilities of sheltering of heliostats in the interior of the field and attenuation of wind with height. Evidence of either of these effects could have an influence on design of heliostats for future central receiver installations. Wind data from the Pilot Plant heliostat field is of special value because it is the first such data available.

Figure 3-9 shows the heliostat field and the locations of the meteorological stations and or the wind towers. Table III-VIII gives the exact locations of the wind towers. At each of the wind towers, there are anemometers located at 10 ft, 20 ft, 32.8 ft above the ground. The meteorological stations have anemometers at 32.8 ft only. The data discussed below is taken only from the six wind towers and the east and west meteorological stations. The anemometers have a time constant of 1/2 s for a wind speed of 20 mph. Further details of the heliostat field layout and specifications for the anemometers are given in Reference 3.

The data used for this analysis are instantaneous wind speeds at three minute intervals. The six days and the various anemometers from which data sets are taken are summarized in Table III-IX. Each data set is two hours long with a total of 40 data points per set. The data sets are from periods during which wind speeds and direction are relatively constant. Included are periods during which the heliostats were tracking as well as periods when they were stowed in a vertical position with the north field heliostats facing south and the south field heliostats facing north.

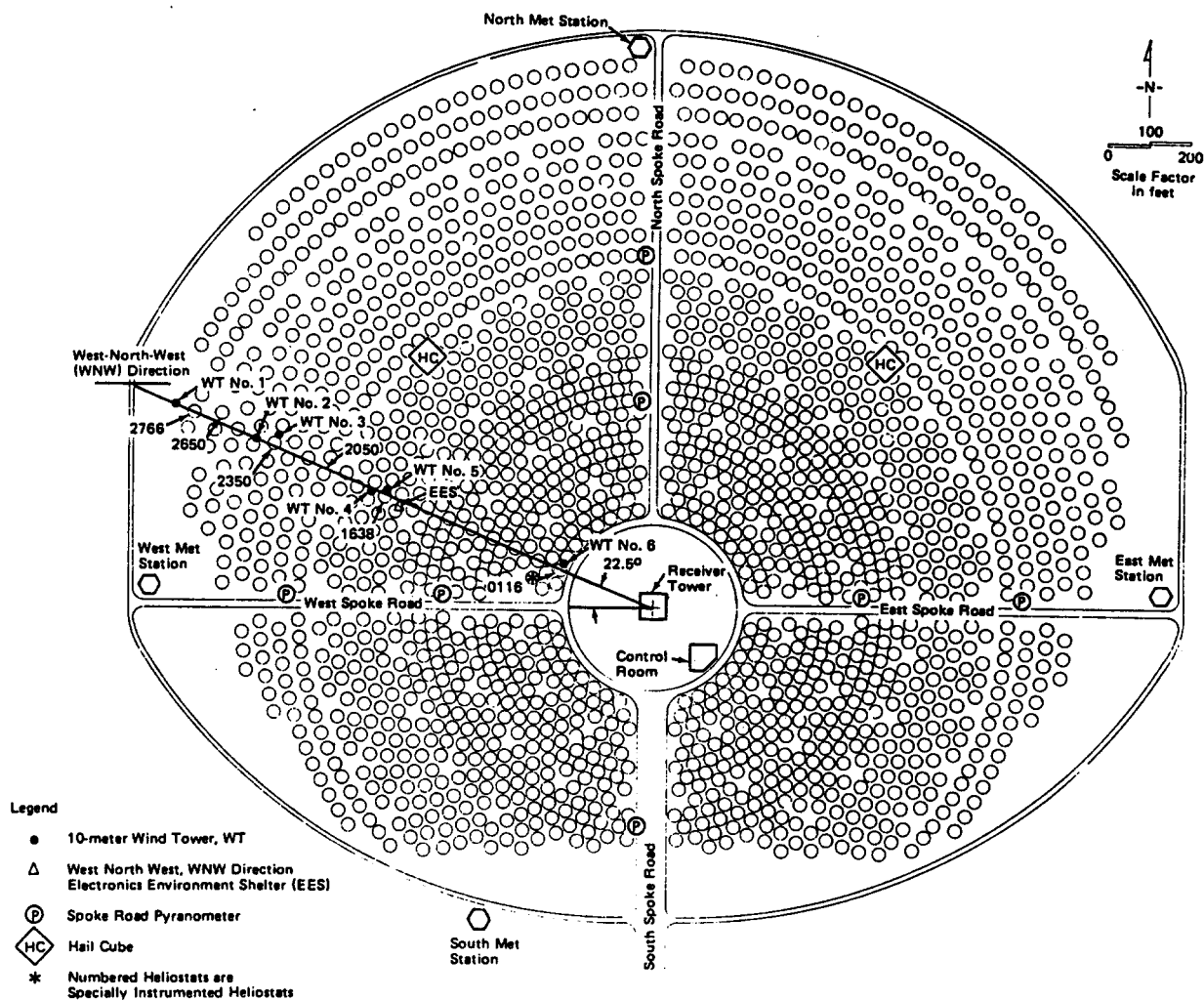


Figure 3-9. Collector Field Locations of Meteorological and Specially Instrumented Heliostats

TABLE III-VIII
WIND TOWER AND METEOROLOGICAL STATION
COLLECTOR FIELD LOCATION
Coordinates (reference point (0,0) is directly under the receiver tower)

Collector Field Coordinates (ft)		
	X	Y
Tower 1	-481.72	-1162.98
Tower 2	-405.54	- 958.82
Tower 3	-408.75	- 906.75
Tower 4	-275.25	- 680.87
Tower 5	-281.84	- 639.15
Tower 6	-205.75	- 214.53
West Meteorological Station	- 50.0	- 1,239
East Meteorological Station	- 50.0	+ 1,248

TABLE III-IX
SUMMARY OF WIND DATA SETS

Date	Day	Start/ Stop Time	Wind Direction	Heliostat Field Status	Anemometer Location	Gust Factor	Median Wind Speed (mph)
11/13/83	317	1100/1000	West	Tracking	Tower 6, 10 ft	1.58	14.5
					Tower 6, 20 ft	1.50	15.5
					Tower 6, 32.8 ft	1.66	19
					Tower 5, 10ft	1.51	13
					Tower 5, 20 ft	1.56	14
					Tower 5, 32.8 ft	1.43	16
					Tower 2, 10 ft	1.46	15.5
					Tower 2, 20 ft	1.42	18
					Tower 2, 32.8 ft	1.48	21
11/25/83	329	1100/1000	West	Tracking	East Station 32.8 ft	1.61	15
					Tower 4, 32.8 ft	1.44	22
					West Station 32.8 ft	1.27	23.5
12/22/83	356	1300/1500	West	Stowed	Tower 6, 32.8 ft	1.32	26
					West Station 32.8 ft	1.29	27
					Tower 1, 10 ft	1.42	20
					Tower 1, 20 ft	1.32	24
					Tower 1, 32.8 ft	1.29	26.5
12/24/83	358	1400/1600	East	Stowed	Tower 3, 10 ft	1.40	29
					Tower 3, 20 ft	1.29	11
					Tower 3, 32.8 ft	1.31	12.5
4/10/84	101	1220/1420	West	Stowed	Tower 6, 32.8 ft	1.32	33
					Tower 1, 32.8 ft	1.27	37
					West Station 32.8 ft	1.23	36
					Tower 5, 10 ft	1.47	23
					Tower 5, 20 ft	1.58	30
					Tower 5, 32.8 ft	1.42	35
4/19/84	110	1140/1340	West	Stowed	Tower, 3 10 ft	1.35	29
					Tower 3, 20 ft	1.26	34
					Tower 3, 32.8 ft	1.33	38
					Tower 5, 32.8 ft	1.39	40
					West Station 32.8 ft	1.25	39

Variability

Figure 3-10 is a typical plot of wind speed data. The most striking feature of the plot is the spread in the data. The wind speeds vary from less than 30 mph to nearly 50 mph. Adjacent data points, three minutes apart, differ by as much as 15 mph.

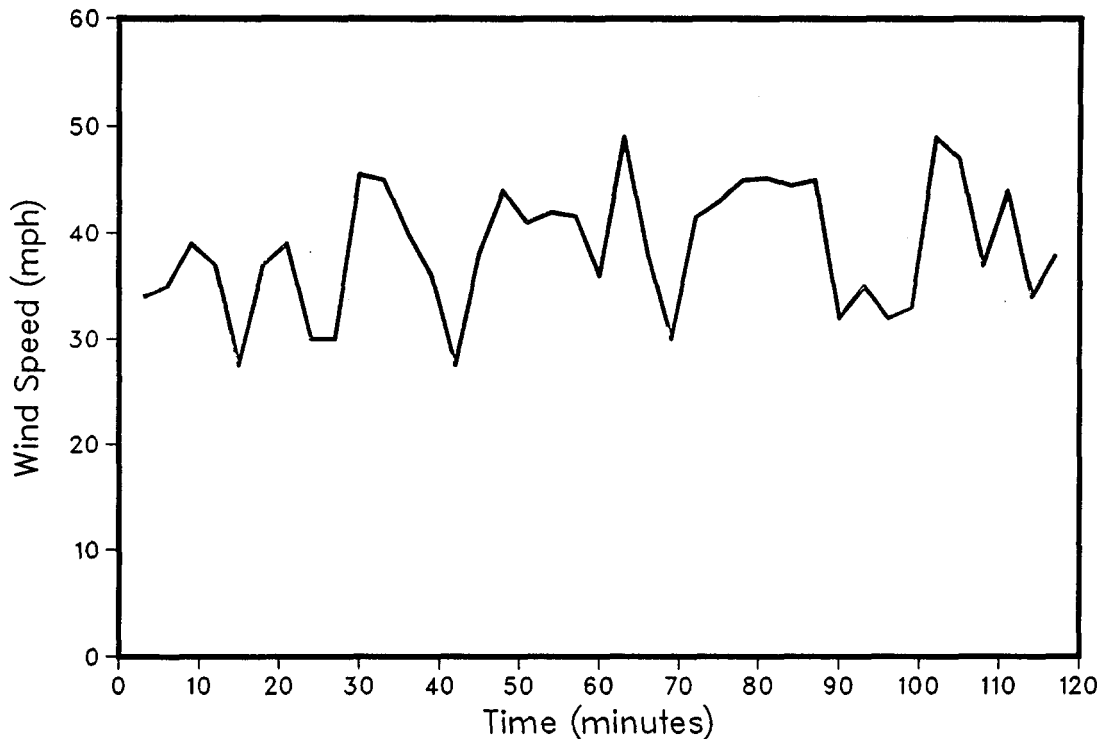


Figure 3-10. Typical Wind Speed Data Plot

It is important that this variability in the wind speed be quantified. Wind speeds are usually reported as a single number, an average wind speed. Such averages are not adequate, however, where heliostat survivability or performance is concerned. The instantaneous peak wind speed is needed as well.

The variability of the wind speed can be quantified as a gust factor, GF, defined as:

$$GF = \frac{\text{deviation from average} + \text{average wind speed}}{\text{average wind speed}}$$

If typical values of this gust factor are known, they can be applied to the commonly recorded average wind speed data to estimate peak instantaneous wind speeds.

To determine GF from the heliostat field wind speed data, a least squares cubic curve fit to the data in each set was used as a nominal "average" wind speed for that data set. This method was used because the wind speeds were usually drifting up or down during the two hours included in a given data set. An example is in Figure 3-11 which shows the data points from Figure 3-10 and the "average" wind speed curve fit. (For additional examples, see Appendix IV). A value of GF was determined for each data point in a given set using the value of the curve fit at that point as the average wind speed. The entire data set was then assigned a single value of GF which was the maximum GF for all of the points in that set.

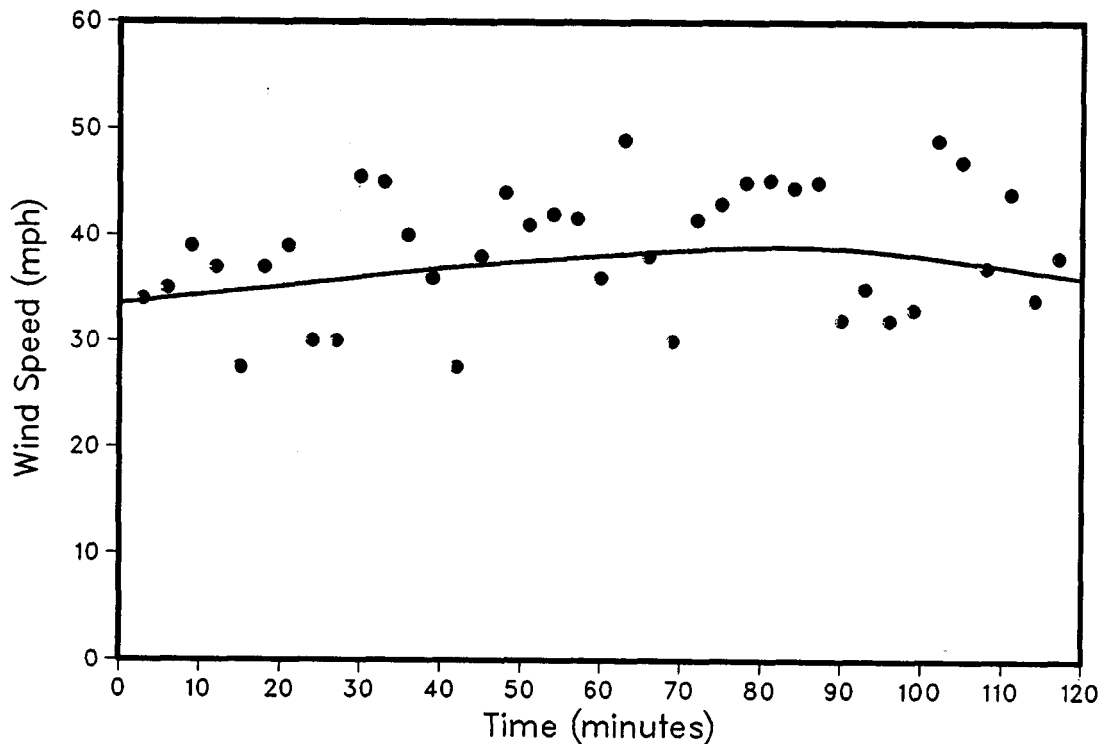


Figure 3-11. Wind Speed Plot with Average Wind Speed (day 101)

The values of GF for each of the 31 data sets are listed in Table III-IX. GF ranges in value from 1.23 to 1.66. The average gust factor of 12 data sets for which the heliostats were tracking is 1.49. The average of 19 data sets for which the heliostats were stowed is 1.34.

The variation in GF is most likely the result of filtering due to use of data at three minute intervals. Even so, the highest values of GF are in good agreement with data given by Sachs (1978) Reference 24. The highest GF, while the heliostat field is tracking, 1.66, agrees with a value of 1.67 given by Sachs for exposed sites in windy areas, i.e., desert. The highest value while the field is stowed, 1.58, compares to a value of 1.52 given by Sachs for exposed sites in less windy areas, i.e., open inland country with hedges and buildings.

A plot of GF versus wind speed is shown in Figure 3-12. Each GF is plotted against the median wind speed for that data set. Although there is a gradual drop in GF as wind speed increases, additional data at higher wind speeds is needed to determine if this trend will continue for higher speeds.

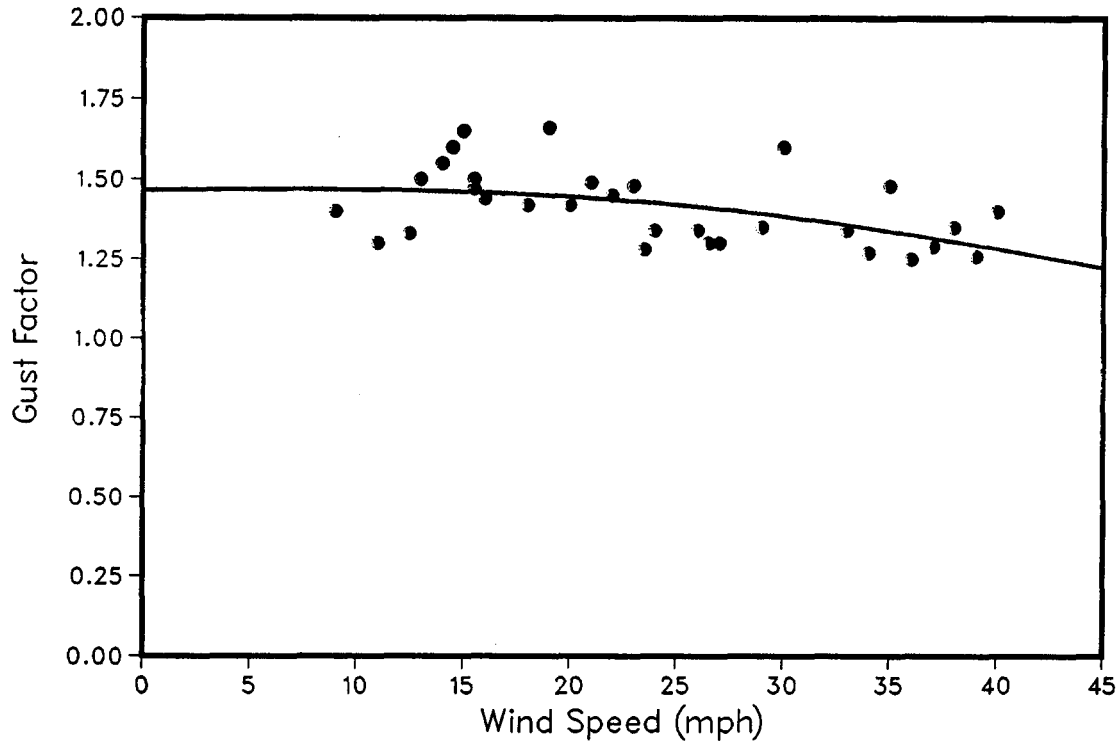


Figure 3-12. Gust Factor vs. Wind Speed

The Effect of Height and Location—The variability of the wind makes it difficult to predict the relationship between wind speeds at different locations or heights in the heliostat field. This is seen in Figure 3-13 where the instantaneous wind speed data are plotted for the three anemometers on wind tower 3. At any given time, the wind speed at 10 ft may be higher than the speed at 20 ft and nearly equal to the speed at 32.8 ft.

When we plotted the cubic curve fits, the “average” wind speeds of the same data (Figure 3-14) revealed the expected trend, that the average wind speed does decrease with decreasing height. This trend, while interesting, is not especially useful because of the exceptions to the trend shown in Figure 3-13. Plots of average wind speed versus location in the field do show some trend toward reduction in wind speed with distances into the field, though it is much less consistent than the reduction with height. Further examples of wind data can be found in Appendix IV.

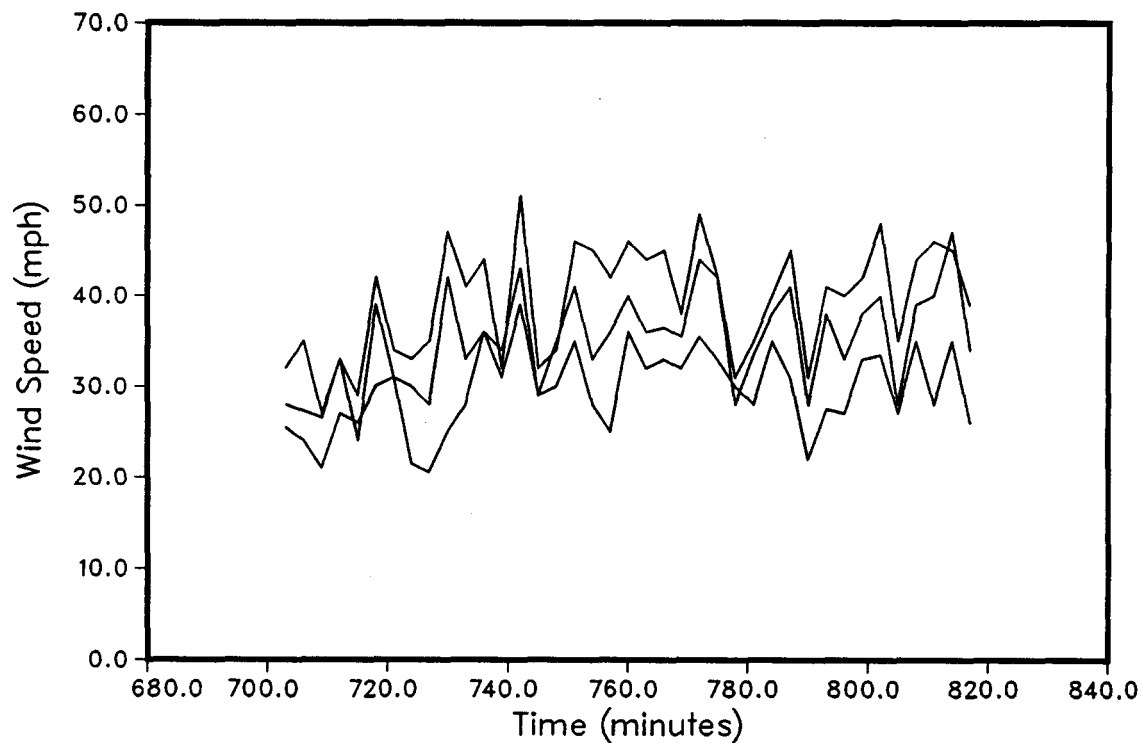


Figure 3-13. Wind Speeds at Wind Tower 3 (day 110).

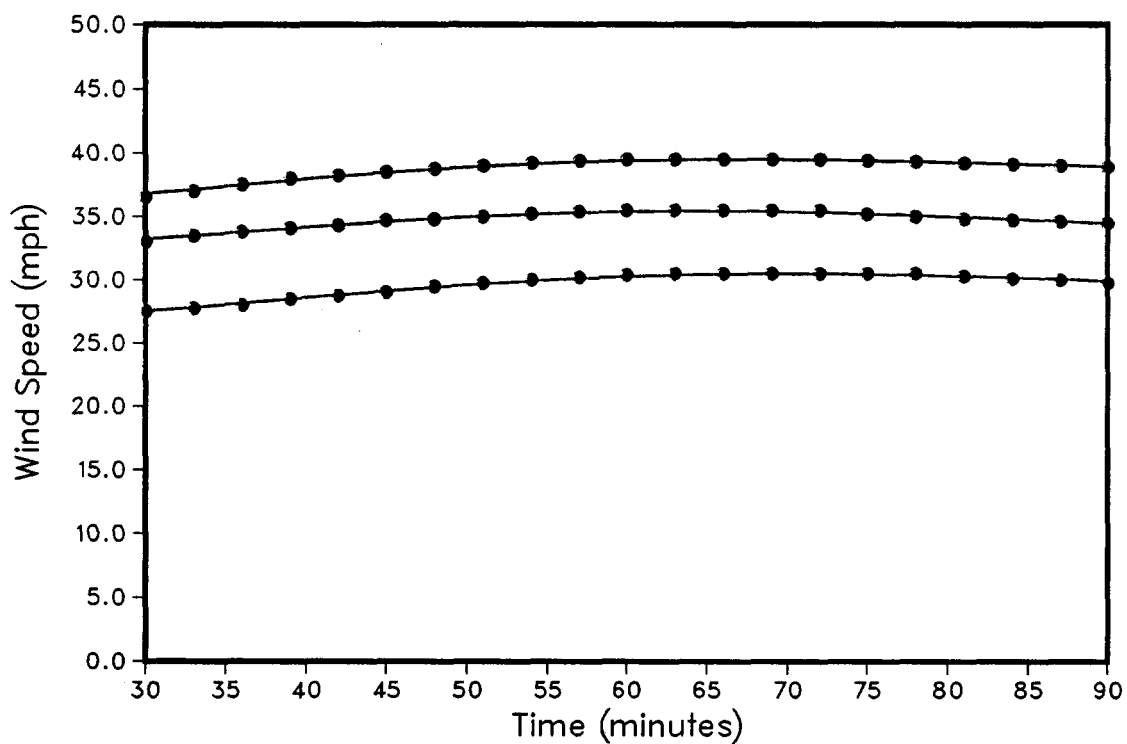


Figure 3-14. Effect of Height on Average Wind Speed (wind tower 3, day 110).

If we assume that heliostat survivability is the central issue, it is important to consider the peak wind speed that occurs at a given location. Comparison of peak wind speeds at various heights and locations to the peaks at the west meteorological station indicate to what extent there is sheltering from the wind due to position in the field or due to decreasing height. Table III-X lists peak wind speeds from the two-hour data sets for the five days with west winds. Data from the west station and the six wind towers are included.

TABLE III-X
PEAK WIND SPEEDS FROM TWO HOUR DATA SETS (MPH)

	Day	West Meteoro- logical Station	Tower 1	Tower 2	Tower 3	Tower 4	Tower 5	Tower 6
Wind Speed at 32.8 ft								
	317	—	30.5	31.7	34.1	28.5	27.0	29.9
	329	31.4	26.9	27.8	27.6	29.9	30.4	28.2
	356	38.6	36.1	—	37.2	34.5	35.8	31.3
	101	45.7	47.7	48.4	47.6	—	48.5	45.8
	110	55.5	51.1	50.0	50.8	—	56.7	48.3
Wind Speed at 20 ft								
	317	—	24.7	30.9	27.7	27.8	23.3	23.1
	329	—	24.2	23.8	24.4	26.4	26.1	24.8
	356	—	33.0	34.0	32.7	32.3	33.8	28.0
	101	—	42.8	44.7	49.1	44.8	46.1	42.0
	110	—	46.5	49.9	46.5	53.0	47.6	45.9
Wind Speed at 10 ft								
	317	—	22.3	24.3	24.2	24.0	22.0	26.5
	329	—	22.1	22.4	25.9	24.8	21.4	17.9
	356	—	27.5	28.2	27.3	29.4	26.6	23.4
	101	—	34.6	41.1	40.7	35.5	33.5	31.8
	110	—	42.7	39.0	39.1	38.9	34.8	36.9

At 32.8 ft, no decrease can be seen as distance into the field increases. For example, compare Tower 5, days 101 and 110, to the west station. At 20 feet, the peak wind speeds are generally lower, but not at all times. Examples are Tower 3, day 101, and Tower 4, day 110. At 10 feet, there is a consistent reduction in peak wind speed compared to the west station at 32.8 feet. On day 101, at Tower 2 and 3, that reduction is only 10%. For all other days and locations, the reduction is at least 20%. While there is sheltering due to reduction in height, there is

no similar trend with location in the field. This is seen on day 317 at 10 feet comparing Tower 1 and Tower 6. A best fit wind speed profile versus height is shown in Figure 3-15 for wind tower 1 on April 29, 1984 for a one hour time interval. The best fit profile for the data has a 0.15 exponent which is the value used in the heliostat requirements specification, Appendix I.

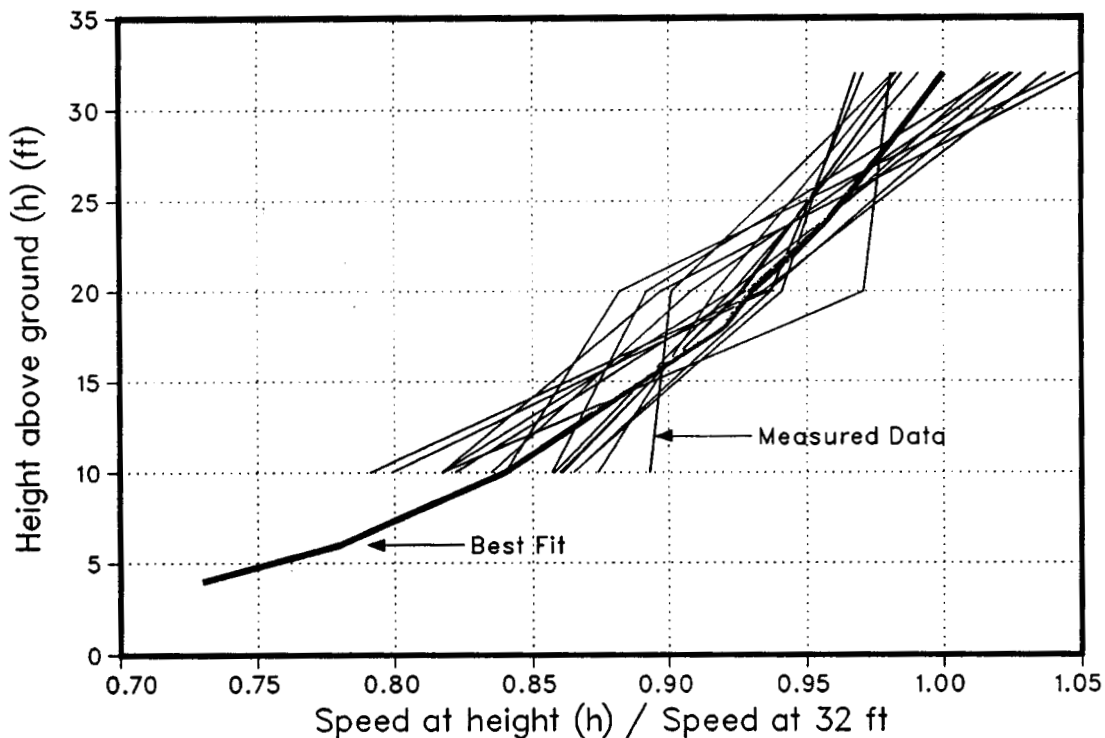


Figure 3-15. Wind Speed Profile

This sheltering with reduced height can have an impact on heliostat design. Under high wind conditions, the heliostats are stored in a horizontal position. For the Pilot Plant heliostats, that position is about 12 feet above the ground, the height of the heliostat pedestals. The "official" wind speed is usually taken as the speed measured at 32.8 feet in an unobstructed area, such as at the west station for a west wind. Thus, the heliostats will be exposed to winds 10% to 20% less than this official wind speed. Because aerodynamic drag is a function of the square of the wind speed, wind load reductions of 19% to 36% can be expected compared to calculations with the official wind speed. If future central receiver plants use larger heliostats, e.g., 150 m heliostats with pedestal heights greater than 20 feet, these wind speed and wind load reductions will not be present.

Conclusions

The rapidly varying nature of wind must be included in any analysis of wind speed and wind effects. Whereas most wind speed measurements are a nominal average, momentary peaks in the wind speed have been observed up to 66% above the average (GF of 1.66) at Solar One. The gust factor was observed to decrease gradually with wind speed for mean wind speeds up to 42 mph; however, data for higher wind speeds will be needed to determine if this trend continues for higher speeds. Despite filtering due to the three minute intervals between data points, the gust factors observed in the Pilot Plant heliostat field agree well with published data.

On average, the expected trend of decrease in wind speed with height and, to a lesser extent, decrease with distances into the field can be seen. It is clear, however, that these trends can be misleading because they ignore the momentary peaks in wind speed. Analysis of the peak wind speeds at various locations in the field does not show any sheltering as a function of distance into the field. This is true at all three heights, 10 ft, 20 ft, and 32.8 ft. Some sheltering as a function of height can be seen; however, the ability of the wind peaks to load a heliostat must be determined from wind load data. The duration of the peak and the uniformity of the speed over the heliostat surface will significantly affect the wind loads, as discussed in the following section.

Wind Loads in the Heliostat Field

There are six specially instrumented heliostats for wind load data at the 10 MW_e Solar Thermal Central Receiver Pilot Plant. Figure 3-16 shows the heliostat field and the locations of the six heliostats. The locations of six wind towers are also shown. These wind towers provided wind speed near each heliostat at 10 ft, 20 ft, and 32.8 ft, and wind direction at 10 m. Three of the six heliostats have load cells on each mirror module attachment point and three have load cells on mirror modules 1 and 12 only. These heliostats are located on a line 22.5° north of east to be in line with the prevailing wind direction.

The objectives of the wind load tests were to determine the following in a real heliostat field:

1. Wind velocity profile versus height
2. Adequacy of ASCE flat plate wind load coefficients for heliostat design
3. Wind angle of attack for heliostats in a stow position
4. Potential reduction of survival wind loads within a heliostat field
5. Suitability of mean versus peak wind speeds for design

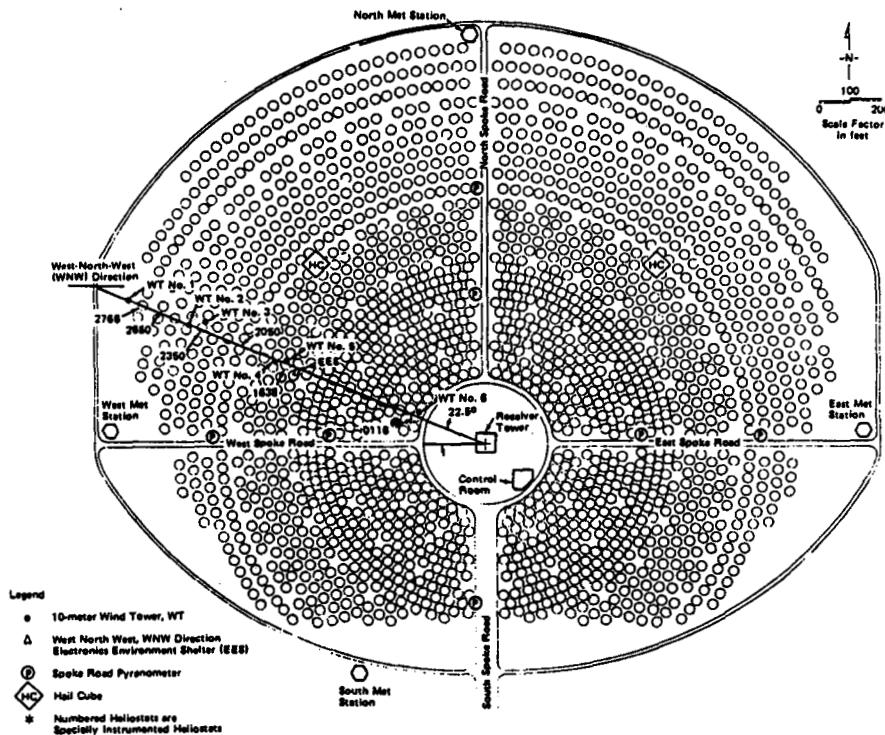


Figure 3-16. Collector Field Locations of Meteorological and Specially Instrumented Heliostats

A description of the heliostat wind load tests and a summary of the results are provided below. The test results would have been more convincing if more data had been analyzed. The need for statistical long duration data is evident from the tests. This is due to the large and frequent changes in wind speed and direction as shown in the previous section on wind speed. However, enough data was analyzed to conclude that the method used to calculate heliostat wind loads is adequate.

Wind Load Test Conclusions

Wind Velocity Profile—The wind velocity profile is used to determine the wind speed at heights other than the reference height, which is normally 32.8 ft. The equation specified for windspeed vs. height above the ground is:

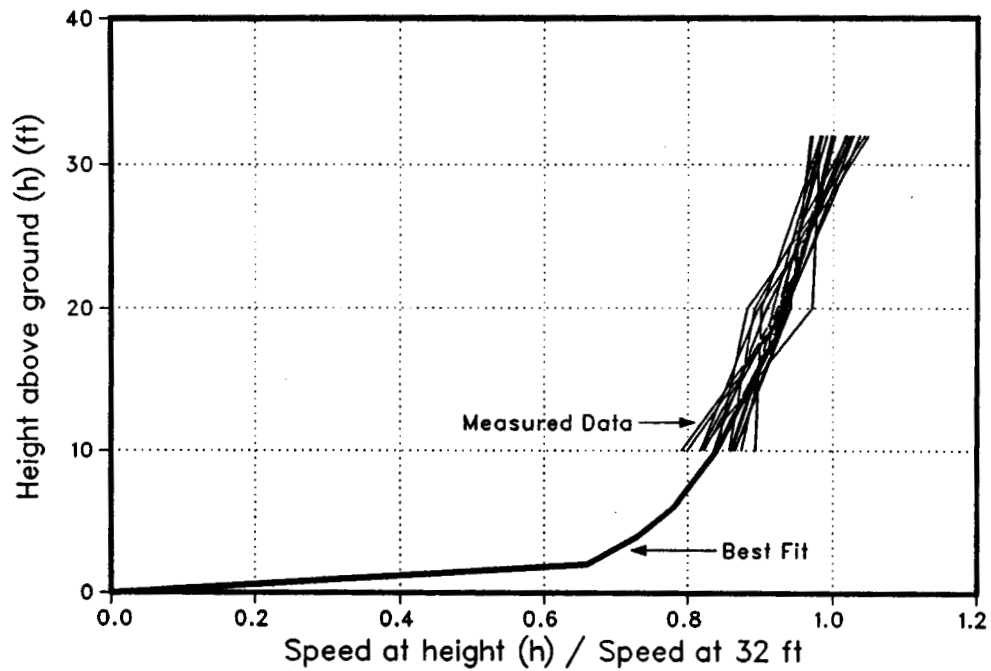
$$V(h) = V(o) \left(\frac{h}{10} \right)^{.15}$$

$V(h)$ = speed at height h (mph)
 $V(o)$ = speed at 10 m (mph)
 h = height above ground (m)

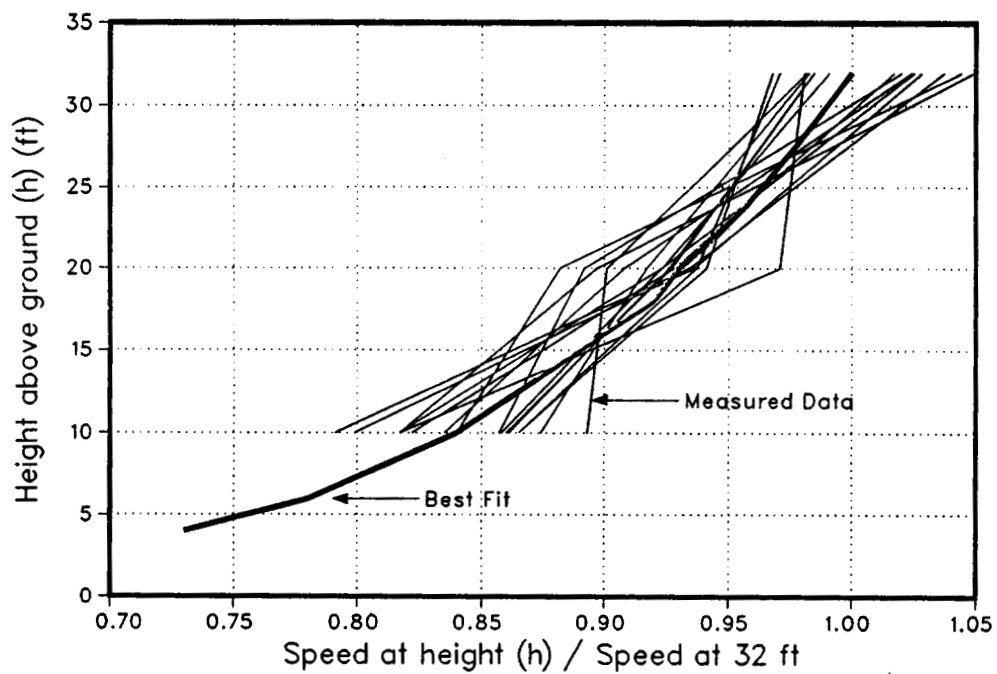
The 0.15 exponent was found to be the best fit to the data for wind tower 1 on April 19, 1984. Sixteen sets of wind speeds (at 10, 20 and 32.8 ft.) at 3-minute intervals were analyzed when the wind speed was between 30 and 50 mph. This data is plotted in Figures 3-17a and 3-17b. The only difference in these figures

is the scale of the horizontal axis. These figures show there is a good fit for the average wind speeds at the 3 heights and that there is a wide variation at each height. The data do not shed any light on whether a windspeed profile should be used for heliostat design. Heliostat wind load data are required to justify the use of a windspeed profile.

Wind Load Coefficients—The recommended wind load coefficients for heliostat design are provided by ASCE Paper 3269, Reference 31. Heliostat wind load data from November 17, 1983, for a vertical heliostat were analyzed for peak wind speeds between 15 and 38 mph. During this time, the entire heliostat field was stowed horizontally except for the test heliostats. Instantaneous data were taken at 3 minute intervals for various heliostat azimuth and elevation angles. The windspeed and direction data was taken at the same time as the load cell data. The measured heliostat load data were normalized for 27 mph at 32.8 ft for comparison to the calculated load. The calculated loads were determined by using the calculated windspeed at the center of the heliostat assuming a 0.15 exponent for the wind speed profile. The normalization results change dramatically depending upon the wind speed and direction data which are used to normalize the load cell data. When the wind speed and direction from the wind tower nearest to the heliostat is used, there seems to be no correlation between the measured and the calculated loads. This observation prompted a comparison of wind speeds and direction from each wind tower in the field. Table III-XI shows the wind direction data for each wind tower at each time when load cell data were taken. The wind direction is shown in degrees from north (west is 270 degrees). The average wind direction for wind towers 1 (WT-1) through 6 (WT-6), which are located in the field next to the instrumented heliostats, do not agree with the south, west, and east averages. The average from the north station is also different. This is either due to errors in the wind vanes or the local wind direction is changed by the nearby heliostats. When the wind loads are normalized using the average wind direction from the east, south and west wind stations, there is better agreement among heliostats as well as with the calculated loads. Table III-XII shows the wind speed for each wind tower at each time when load cell data was taken. At each measurement time, there is a wide variation in speed from one station to another. This variation causes a wide spread in the normalized wind loads. The results are much more consistent between heliostats and agree better with the calculated loads if an average field wind speed is used to normalize the data. As a result, the average wind speed from all 32.2 ft anemometers was used to normalize the measured data. The results are discussed below.



(a) Windspeed Profile - Scale 0.0 to 1.2



(b) Windspeed Profile - Scale 0.7 to 1.05

Figure 3-17. Windspeed Profiles Using Different Wind Speed for Normalization.

TABLE III-XI
SOLAR ONE WIND DIRECTION NOVEMBER 17, 1986

Time	WT-1	WT-2	WT-3	WT-4	WT-5	WT-6	South	West	North	East	Ave S,W,E
1430	216	230	223	199	195	242	247	231	211	245	241
1433	222	217	225	200	197	241	240	243	212	249	244
1436	218	229	220	205	215	248	250	256	218	225	244
1439	229	237	256	214	220	250	254	236	213	244	245
1442	226	242	230	216	222	254	244	243	208	264	250
1445	215	226	213	189	190	244	252	223	207	248	241
1448	226	232	227	209	222	241	224	235	221	226	228
1451	225	238	228	209	204	241	238	247	201	247	244
1454	236	226	215	209	208	249	231	239	220	243	238
1457	231	225	207	223	221	242	248	244	206	245	246
1500	220	227	211	206	205	247	241	243	216	229	238
1503	224	233	224	195	204	255	243	244	224	255	247
1506	222	232	207	194	192	245	245	247	217	230	241
1509	215	216	201	204	204	248	240	224	222	259	241
1512	224	243	230	197	200	247	224	236	208	230	230
1515	238	209	195	203	207	263	252	228	222	244	241
1518	221	219	221	191	210	236	257	244	224	225	242
1521	204	225	215	187	196	248	235	234	195	236	235
1524	242	241	229	202	206	241	242	253	217	246	247
1527	242	229	215	197	203	256	244	232	213	234	237
1530	231	234	224	217	219	259	238	242	222	236	239
1533	240	229	214	210	213	250	255	237	196	243	245
1536	260	240	226	216	214	252	241	259	215	243	248
1539	238	225	217	207	220	265	256	255	223	250	254
1542	228	239	230	212	217	248	251	256	227	241	249
1545	230	239	220	201	211	247	245	250	208	251	249
1548	224	228	227	196	205	235	257	225	215	248	243
1551	246	237	228	198	208	247	250	246	215	236	244
1554	238	215	210	213	211	247	237	247	216	235	240
1557	236	232	217	214	212	249	250	255	222	235	247
1600	228	232	217	203	206	252	262	247	221	241	250
1603	225	238	238	222	225	263	250	246	247	248	248
1606	250	264	238	210	219	267	279	237	229	264	260
1609	245	253	239	214	211	262	237	257	236	271	255
1612	248	241	225	214	221	275	263	253	217	256	257
	230	232	222	205	210	250	246	243	217	243	244

TABLE III-XII
SOLAR ONE WIND SPEED NOVEMBER 17, 1983
ELEVATION = 32.2 FT

Time	WT-1	WT-2	WT-3	WT-4	WT-5	WT-6	South	West	North	East	Ave	Max	Min	Ave S,W,
1430	29.6	29.3	26.1	20.5	22.6	20.8	34.7	30.3	29.5	31.8	27.52	34.7	20.5	32.26
1433	24	32.7	27.7	23.9	24	24.7	34.5	32.7	23.1	27.7	27.5	34.5	23.1	31.63
1436	28.3	28.4	29.2	33.1	31.6	25.1	24	30	30	26.5	28.62	33.1	24	26.83
1439	30	27.2	24.8	21.6	20.5	26.4	23	23.1	29	25.4	25.1	30	20.5	23.83
1442	29	28.6	34.5	32.8	31.6	29.3	32.7	25.3	31.1	28.9	30.38	34.5	25.3	28.96
1445	35.9	33.7	29.7	26.6	33.5	21.7	23.7	31.6	27.5	23.4	28.73	35.9	21.7	26.23
1448	34.7	30.2	31.5	28.1	29.9	36.2	32	21	21.7	29.1	29.44	36.2	21	27.36
1451	32.7	21.9	28	32.9	31.9	28.6	20.1	25.5	37.6	28.4	28.76	37.6	20.1	24.66
1454	30.8	27.4	27.6	28.5	30.8	32.2	31.4	22.7	20.5	29.9	28.18	32.2	20.5	28
1457	29.7	26.7	32	33.5	37.8	29	24.6	33.1	26.3	24.4	29.71	37.8	24.4	27.36
1500	28.6	36.2	38.5	32.3	31.7	26.6	31.8	24.6	29.8	22.3	30.24	38.5	22.3	26.23
1503	28.5	28.6	29	21.1	22.6	32.5	24.3	21.9	26.6	31.7	26.68	32.5	21.1	25.96
1506	23.9	20	21.5	22.7	25.8	33.6	30.2	21.6	20.5	22.3	24.21	33.6	20	24.7
1509	28	23.7	26.2	29.8	28.4	25.5	31.9	29.9	30.6	25.4	27.94	31.9	23.7	29.06
1512	34	31.4	35.2	29.1	27.7	28.7	27.3	24.5	29.9	15.3	28.31	35.2	15.3	22.36
1515	23.4	17.9	22.4	22.4	25.5	29.6	20.3	29	34.5	26.1	25.11	34.5	17.9	25.13
1518	30.5	24.6	20.5	34	31.3	24.4	33	30.7	23.8	29.9	28.27	34	20.5	31.2
1521	25.6	34.7	36.5	28.9	31.7	32.4	31.5	25.5	33.8	29.2	30.98	36.5	25.5	28.73
1524	20.3	25.1	28.3	31.4	32.8	33.8	32.2	27	21.1	20.7	27.27	33.8	20.3	26.63
1527	24.5	23.2	20	30.3	30	28.1	31.1	25.6	29.6	27.3	26.97	31.1	20	28
1530	30.4	23.4	24.9	25.4	24.9	25.3	27	24.6	29.5	26.9	26.23	30.4	23.4	26.16
1533	27.7	23.2	27.5	30.2	30.3	21.3	24	27	30	25.9	26.71	30.3	21.3	25.63
1536	26.3	19.7	21.2	21.7	21.9	24.4	25.6	25.4	18.6	20.8	22.56	26.3	18.6	23.93
1539	22.3	28.1	30.6	27	28.8	18.2	17	27	30.4	27.2	25.66	30.6	17	23.73
1542	27.3	26	22.5	21	17.6	22.3	23.9	19.2	23.9	20.9	22.46	27.3	17.6	21.33
1545	25.7	21	21.7	23.5	24	24.8	22.4	23.8	21.7	23.1	23.17	25.7	21	23.1
1548	23	22	24.8	18.8	16.6	19.8	25.8	30.1	30	19.8	23.07	30.1	16.6	25.23
1551	20.8	24.6	26.8	18.4	19.4	24.3	19.6	17.3	20.2	20	21.14	26.8	17.3	18.96
1554	22.2	22.1	22.2	24.8	24.5	23.2	22	26.3	25	21.5	23.38	26.3	21.5	23.26
1557	19.1	26.5	30.8	22.6	25.4	22.4	21.5	22.1	23.2	17.3	23.09	30.8	17.3	20.3
1600	21.9	21.8	23.1	19.4	18.3	23.8	24.4	20.6	22.6	18.6	21.45	24.4	18.3	21.2
1603	30.1	30.9	29.2	29.8	30	23	27.2	28.5	29.1	21.3	27.91	30.9	21.3	25.66
1606	28.5	24.7	23.9	31.1	32.8	25.8	33.9	29.6	32.2	28.4	29.09	33.9	23.9	30.63
1609	22.1	22.2	21.1	25.3	23.3	36.5	30.2	29	35.5	24	26.92	36.5	21.1	27.73
1612	31.7	28.4	28.8	37.7	35.6	32.7	29.8	35.8	28.1	35.1	32.37	37.7	28.1	33.56

Figure 3-18 is a plot showing the maximum, minimum, and average wind speeds at 32.8 ft. from the 10 field instruments. The data points coincide with times when heliostat load cell data were recorded. This figure shows the wide variation in windspeed throughout the field.

Figures 3-19 through 3-23 show how the various wind speeds compare to the average from the east, south, and west wind stations.

Figure 3-22 shows that the average wind speed for wind towers 1-6 is higher for the first hour and then it approximates the east, south, west average. Wind tower 1 has the largest difference as shown in Figure 3-19. The effect of wind towers 1-6 on the field average can be seen in Figure 3-23 during the first hour where the field average speed is higher than the east, south, and west average.

Figures 3-24 and 3-25 show the difference between normalizing the data with the field average wind speed and with the wind speed from the wind tower next to the heliostat (WT's 1-6). The values plotted at 20, 45 and 57° are in much better agreement when the field average windspeed is used. Under ideal conditions and with no measurement errors, the normalized data at each wind angle would have the same value for each heliostat. Local wind speed and direction differences at the surface of the heliostat will affect the wind load.

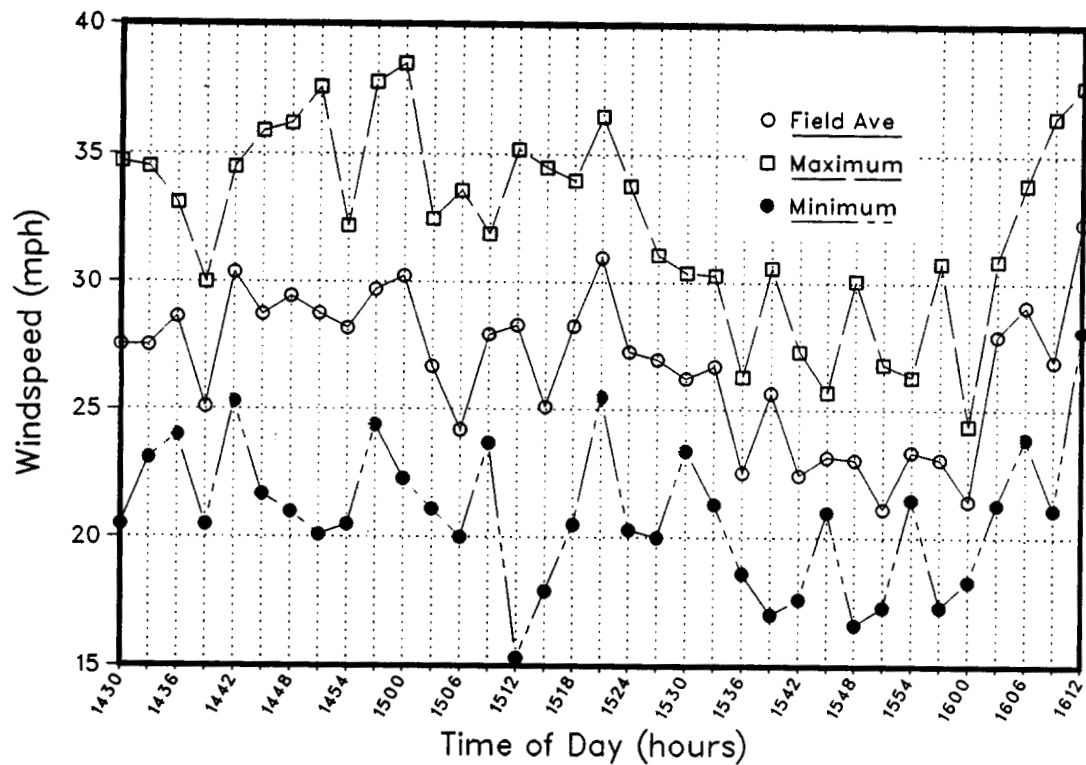


Figure 3-18. Wind Speeds at Solar One November 17, 1983, 1430 to 1612 Hours

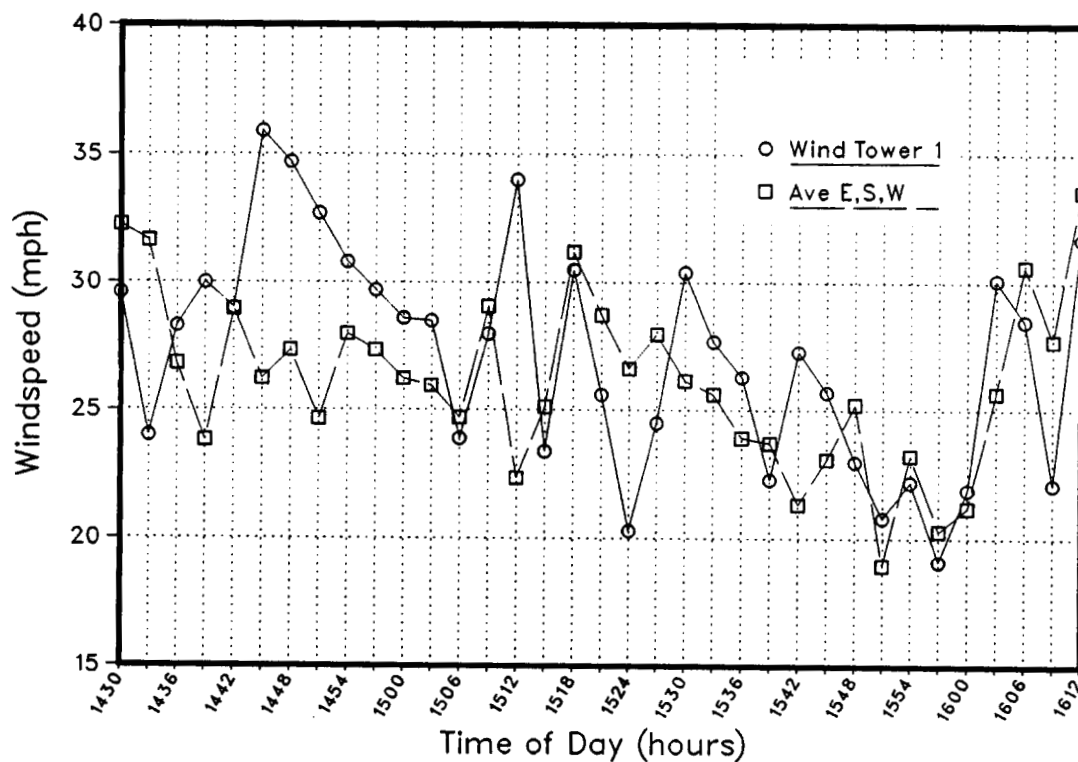


Figure 3-19. Wind Speed at Solar One November 17, 1983, 1430 to 1612 Hours, Wind Tower 1 and East, South, West Wind Stations

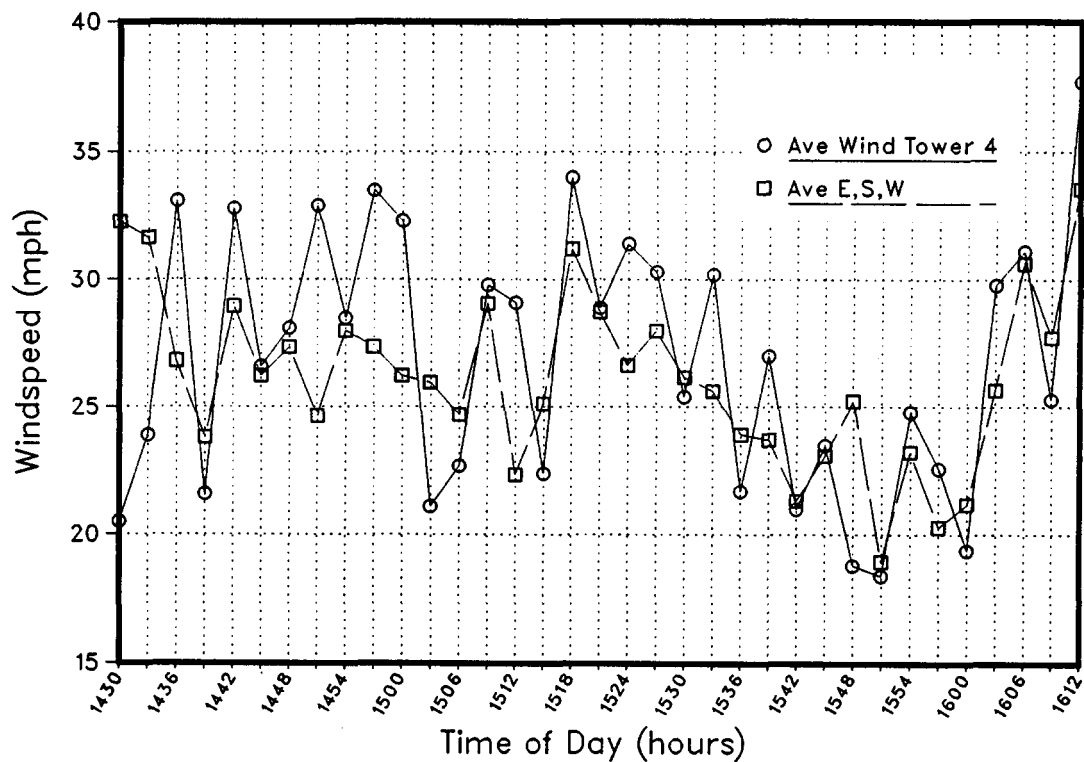


Figure 3-20. Average Wind Speeds at Solar One November 17, 1983, 1430 to 1612 Hours, Wind Tower 4 and East, South, West Wind Stations

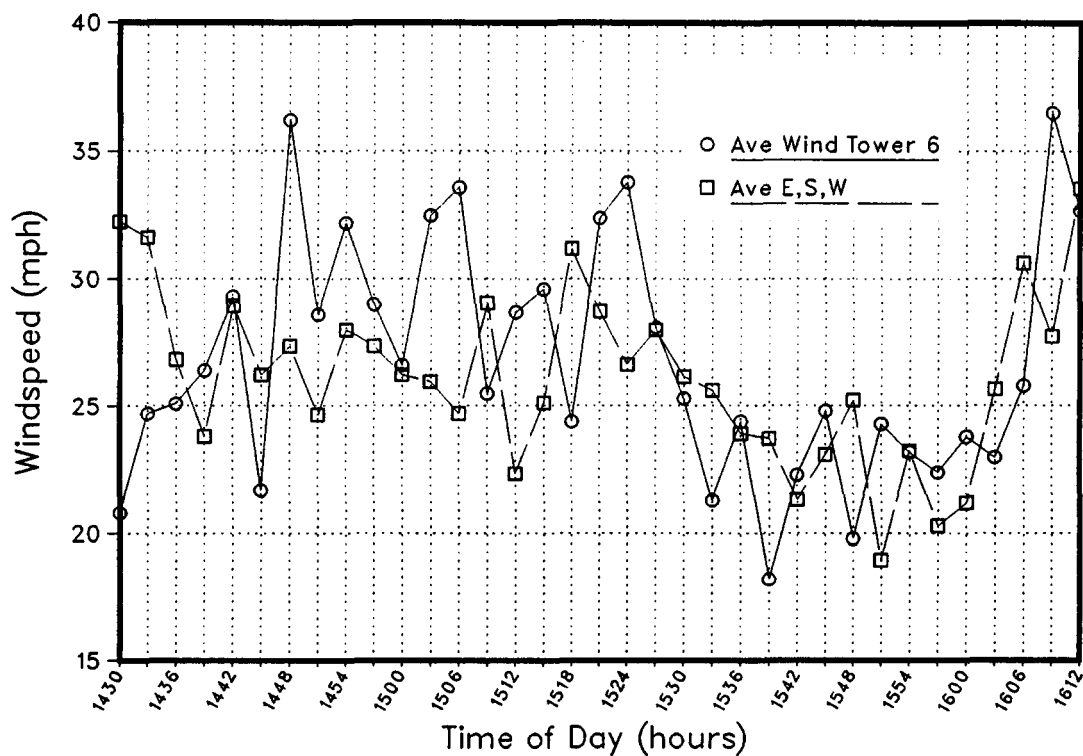


Figure 3-21. Average Wind Speeds at Solar One November 17, 1983, 1430 to 1612 Hours, Wind Tower 6 and East, South, West Wind Stations

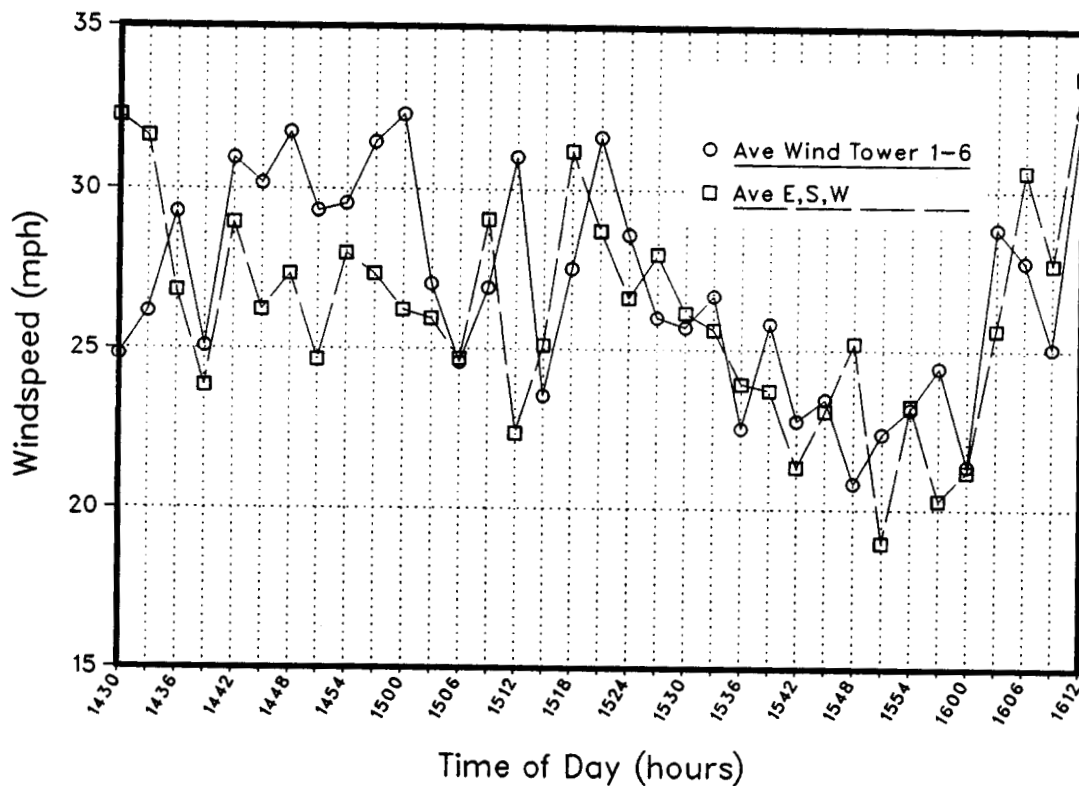


Figure 3-22. Average Wind Speeds at Solar One November 17, 1983, 1430 to 1612 Hours, Wind Towers 1-6 and East, South, West Wind Stations

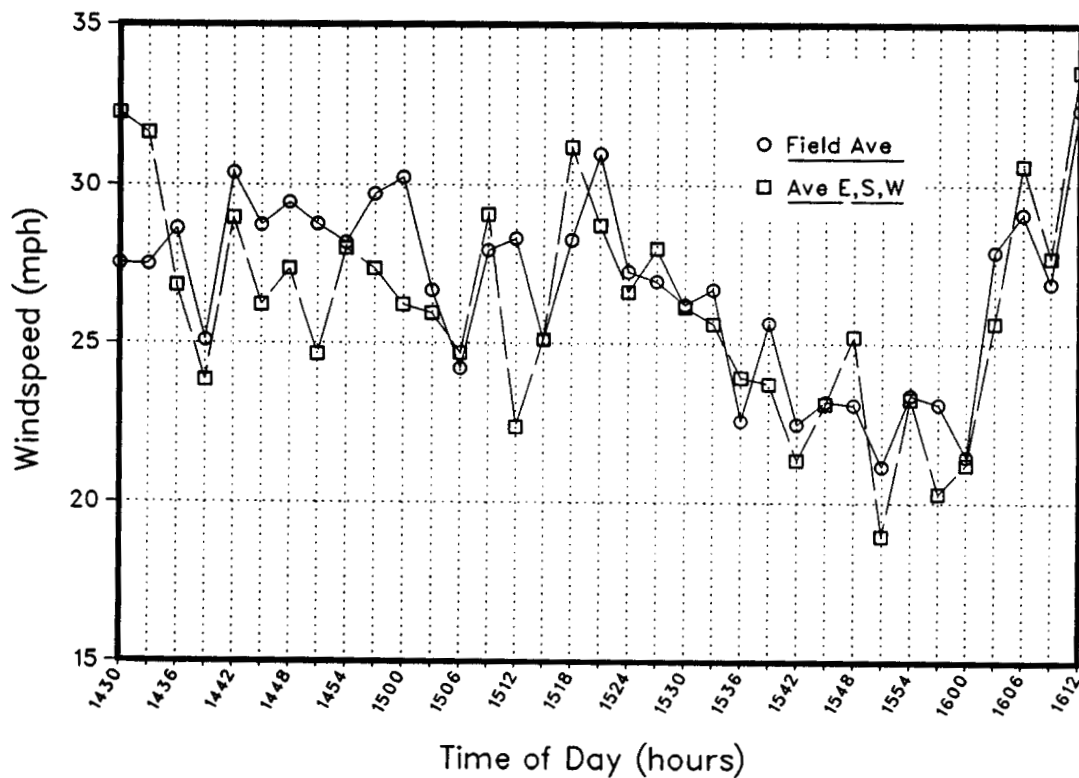
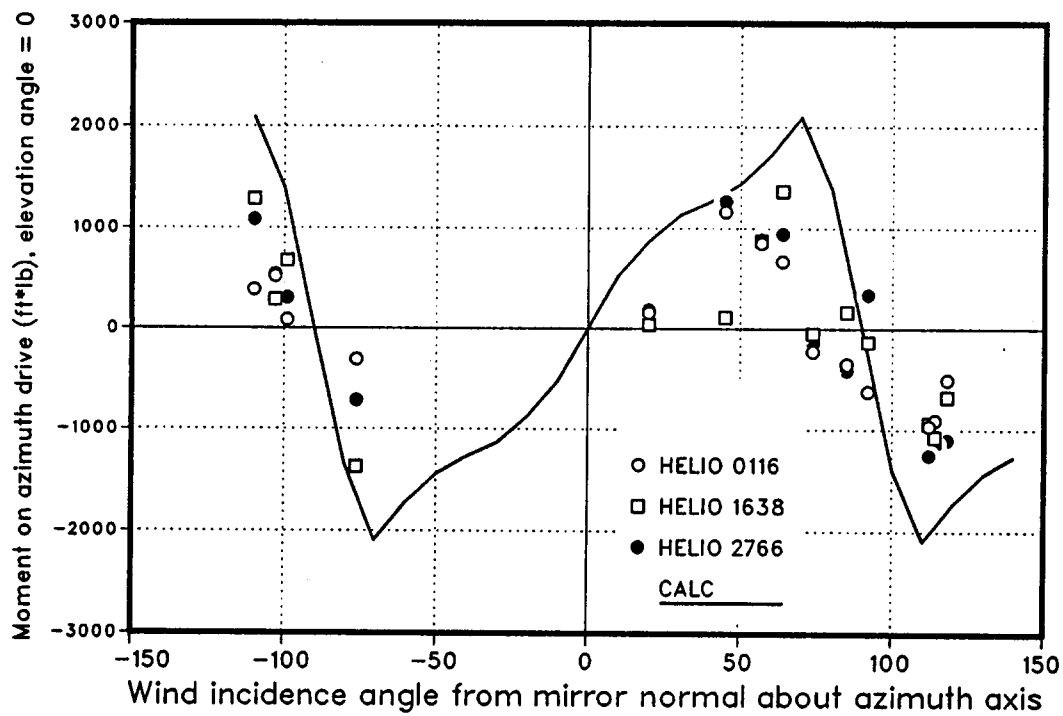
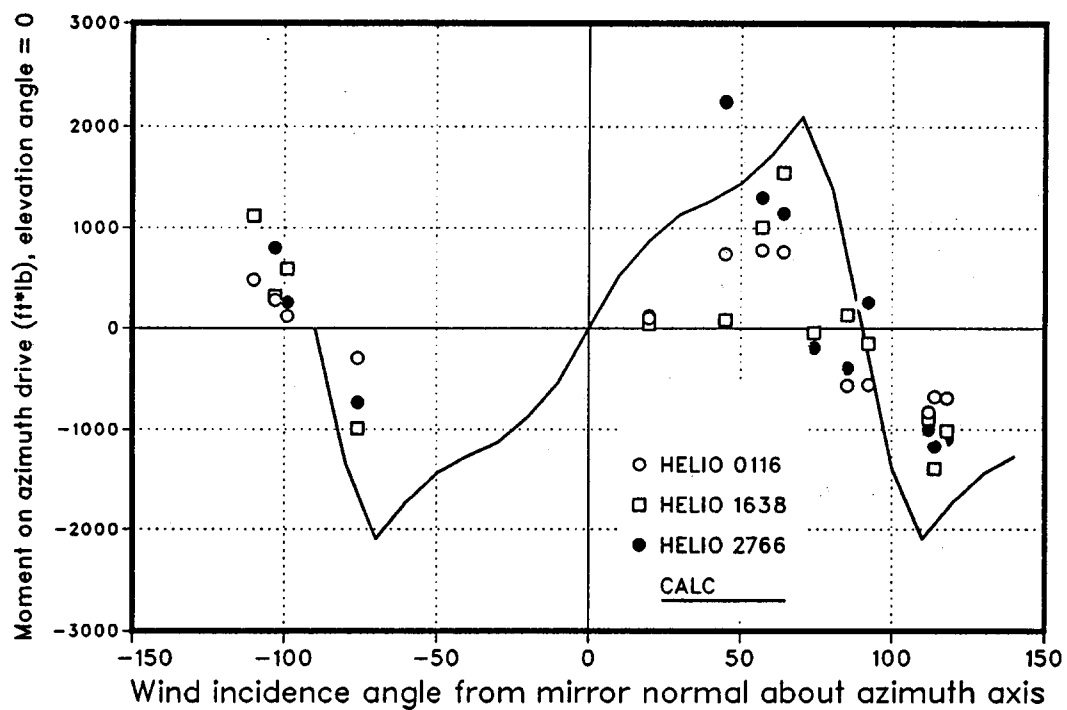


Figure 3-23. Average Wind Speeds at Solar One November 17, 1983, 1430 to 1612 Hours, Field Ave. and East, South, West Wind Stations

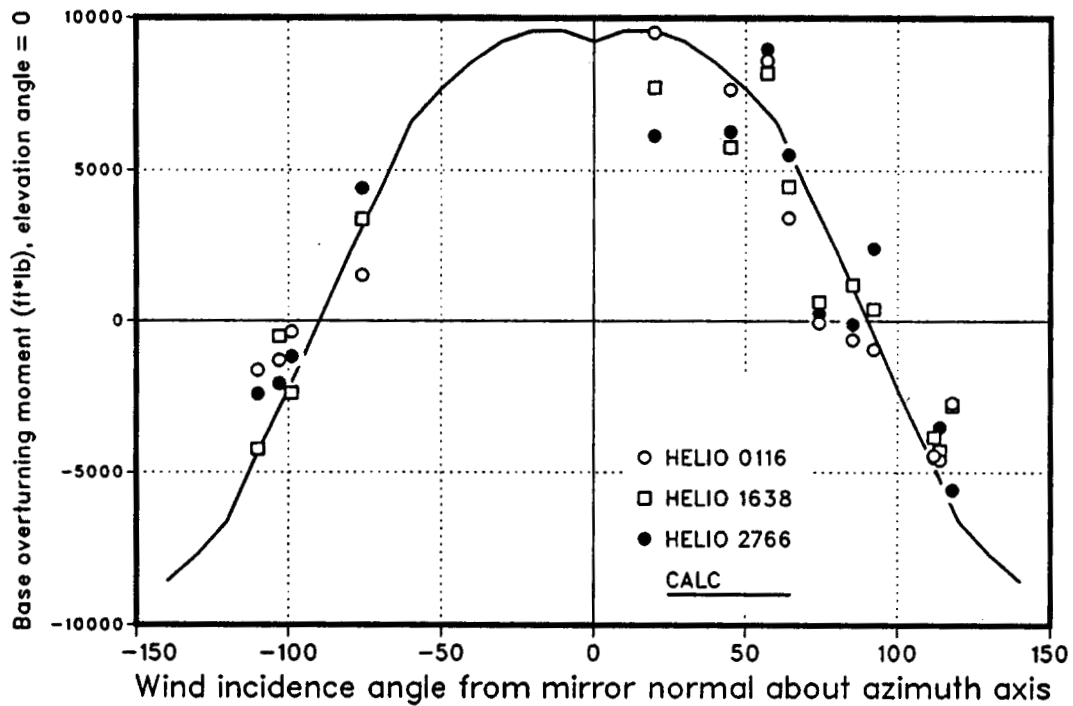


(a) Data Normalized to 27 MPH from Field Average Wind Speed

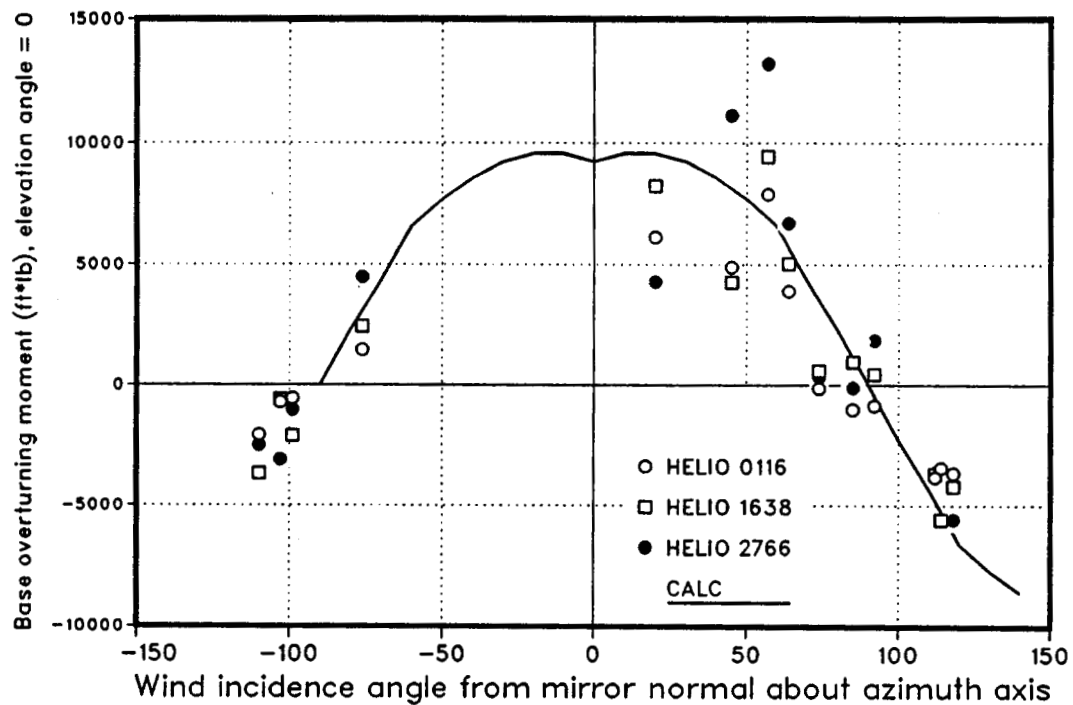


(b) Data Normalized to 27 MPH from Wind Speed at Wind Tower Next to Each Heliostat

Figure 3-24. Comparison of Azimuth Drive Moments Using Different Wind Speed for Normalization



(a) Data Normalized to 27 MPH from Field Average Wind Speed



(b) Data Normalized to 27 MPH from Wind Speed at Wind Tower Next to Each Heliostat

Figure 3-25. Comparison of Base Overturning Moments Using Different Wind Speed for Normalization

Heliostat wind load data for a vertical heliostat is shown in Figures 3-26 through 3-31. Figure 3-26 shows the center of pressure for the elevation axis for a vertical heliostat versus the incidence angle about the azimuth axis. A zero center of pressure would occur for a uniform wind speed profile. A positive wind incidence angle is to the right of the mirror normal. A positive center of pressure is above the center of the heliostat. Most of the data is slightly above the center which would indicate a non-uniform wind profile with speed increasing with height. However, there are quite a few points below zero indicating an inverted wind profile. There is no indication of any difference due to the location of the heliostat in the field.

Figure 3-27 shows the center of pressure for the azimuth axis for a vertical heliostat versus the incidence angle about the azimuth axis. Positive values are to the right of the center of the heliostat and a positive incidence angle is to the right of the mirror normal. There is a considerable scatter in the data, but it generally agrees with the calculated values. The two outlying points are near a 90° incidence angle where wide variations can be expected.

Figure 3-28 shows the wind pressure for the three heliostats for a vertical heliostat which generally agrees with the calculated values. There is a wide variation between heliostats which reflects the difference in wind speed throughout the field.

Figure 3-29 shows the moment on the elevation drive for a vertical heliostat versus the incidence angle about the azimuth axis. For a uniform wind speed profile you would expect a zero moment. In general, the moments are not zero, but they are small relative to the maximum expected moment of about 2100 ft. lb. at the worst angle of attack when the mirrors are about 70° from vertical.

Figure 3-30 shows the moment on the azimuth drive for a vertical heliostat versus the wind incidence angle about the azimuth axis. The data follows the calculated curve and the peak values are less than the expected values. Also a wide variation occurs between the three heliostats which reflects the large differences in windspeed throughout the field. This figure can also be used to infer what the maximum moments would be on the elevation drive since the moments should be the same if the azimuth wind incidence angle was zero, and the elevation angle was varied.

Figure 3-31 shows the base overturning moment for the three vertical heliostats versus wind incidence angle about the azimuth axis. There is a wide variation between heliostats due to the large difference in wind speed throughout the field; however, the overturning moments generally agree with the calculated values.

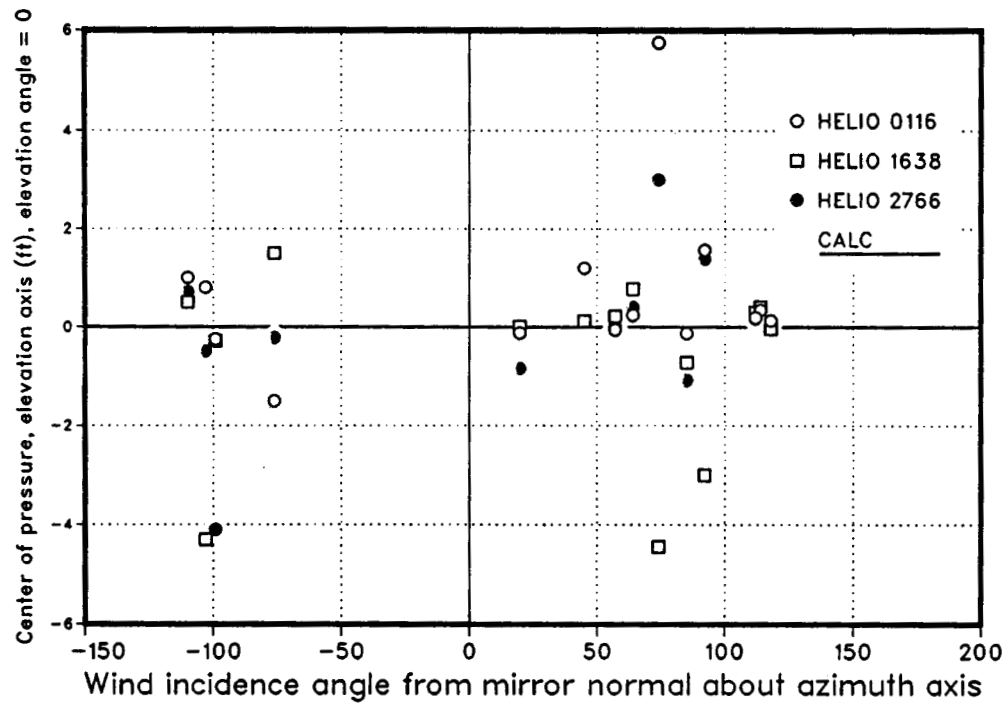


Figure 3-26. Solar One Heliostat Wind Loads, November 17, 1983, Field Ave.
Wind Speed Normalized to 27 MPH at 32.2 ft

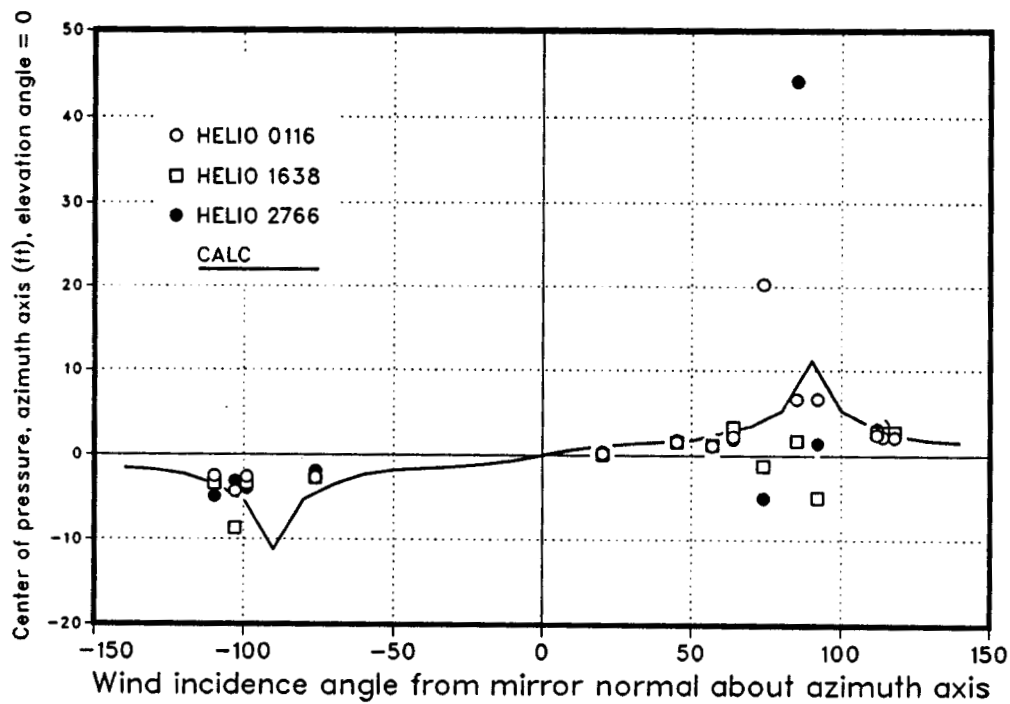


Figure 3-27. Solar One Heliostat Wind Loads, November 17, 1983, Field Ave.
Wind Speed Normalized to 27 MPH at 32.2 ft

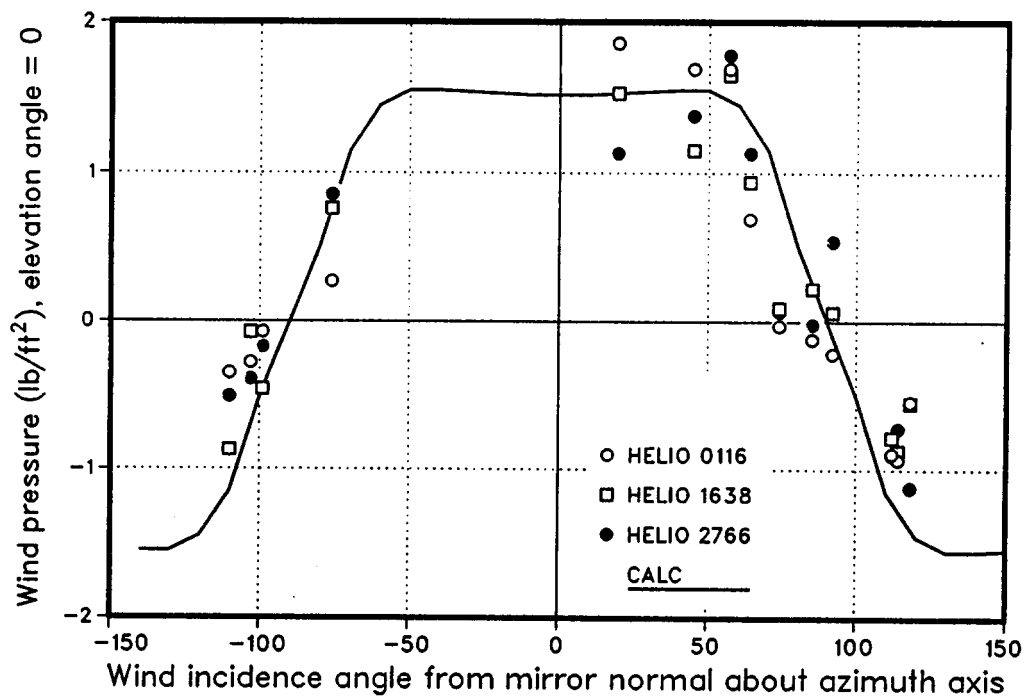


Figure 3-28. Solar One Heliostat Wind Loads, November 17, 1983, Field Ave.
 Wind Speed Normalized to 27 MPH at 32.2 ft

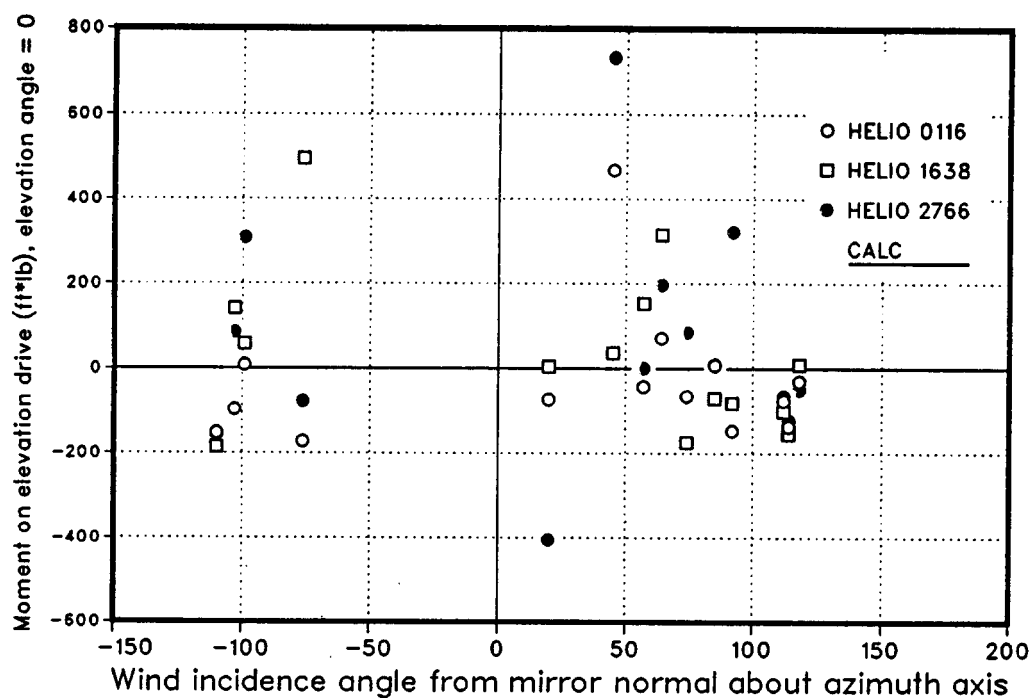


Figure 3-29. Solar One Heliostat Wind Loads, November 17, 1983, Field Ave.
 Wind Speed Normalized to 27 MPH at 32.2 ft

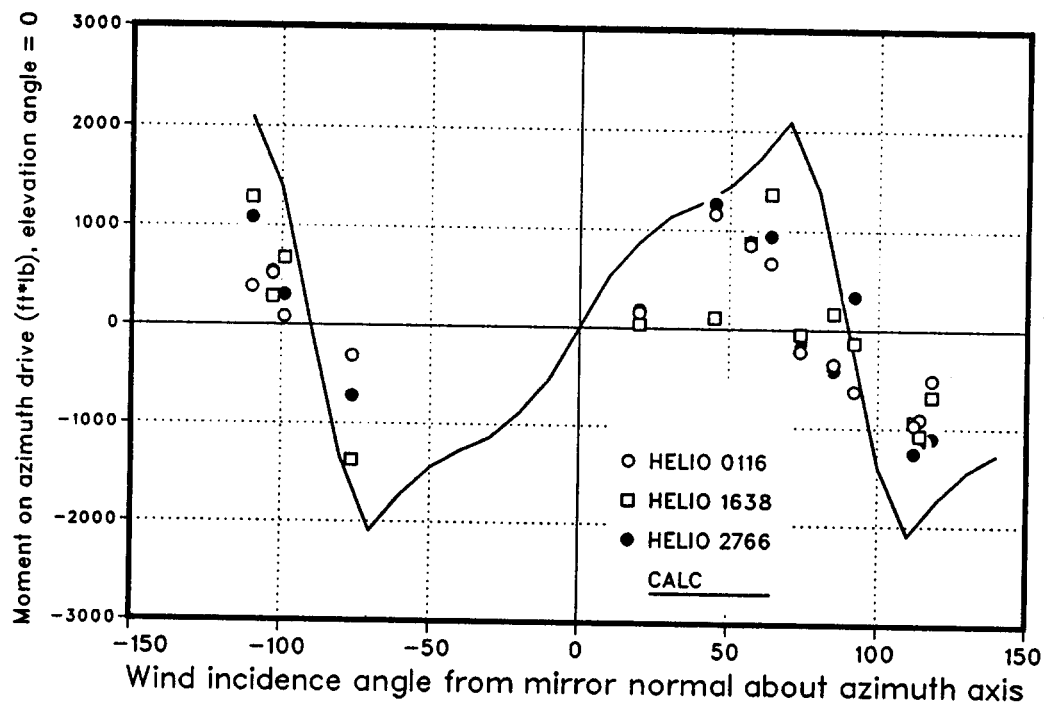


Figure 3-30. Solar One Heliostat Wind Loads, November 17, 1983, Field Ave.
Wind Speed Normalized to 27 MPH at 32.2 ft

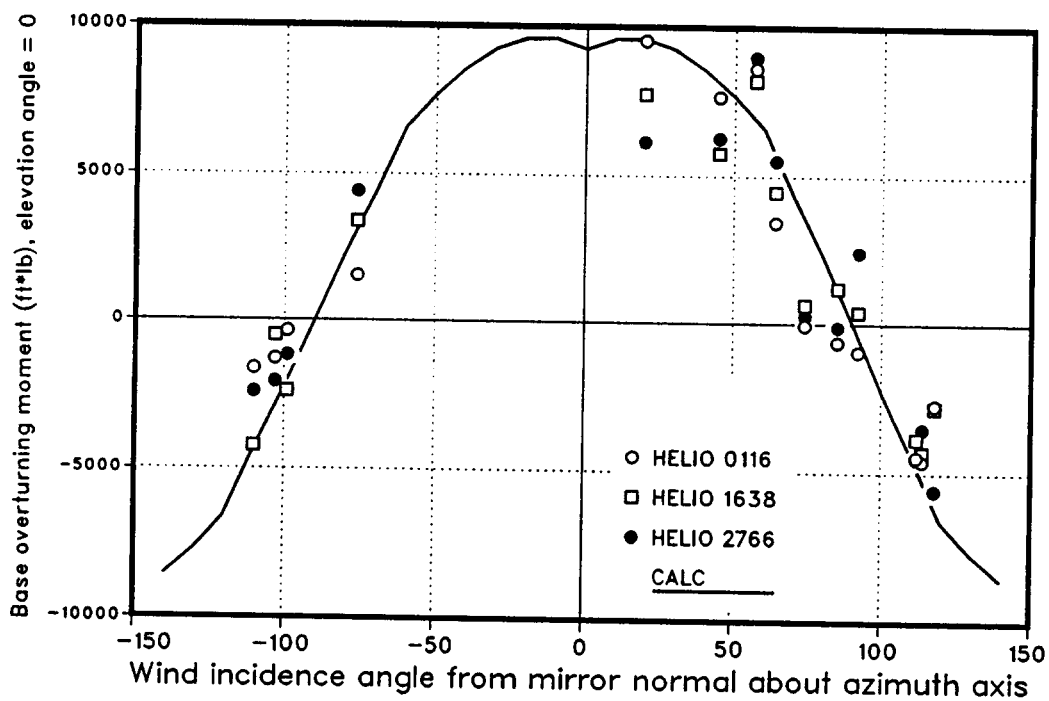


Figure 3-31. Solar One Heliostat Wind Loads, November 17, 1983, Field Ave.
Wind Speed Normalized to 27 MPH at 32.2 ft

Heliostat wind load data is plotted in Figures 3-32 through 3-37 for different wind incidence angles from the mirror normal about the elevation axis. For these tests the six instrumented heliostats were oriented with the mirrors facing west, and the elevation angle was varied between plus and minus 90° (plus 90° places the mirrors facing up). During these tests, the wind was from the southwest at angles which varied between 238 and 250° from north. Expected wind loads were not calculated because wind-load coefficients are not available when the wind is off axis in both azimuth and elevation at the same time. The data is normalized to 27 mph using the field average wind speed at each data point as the speed incident on the heliostat. The data has more variation between heliostats than was the case when the heliostats were vertical (Figure 3-26 through 3-31), but the peak values are about the same, and the design limits are generally equal to or above the peak values.

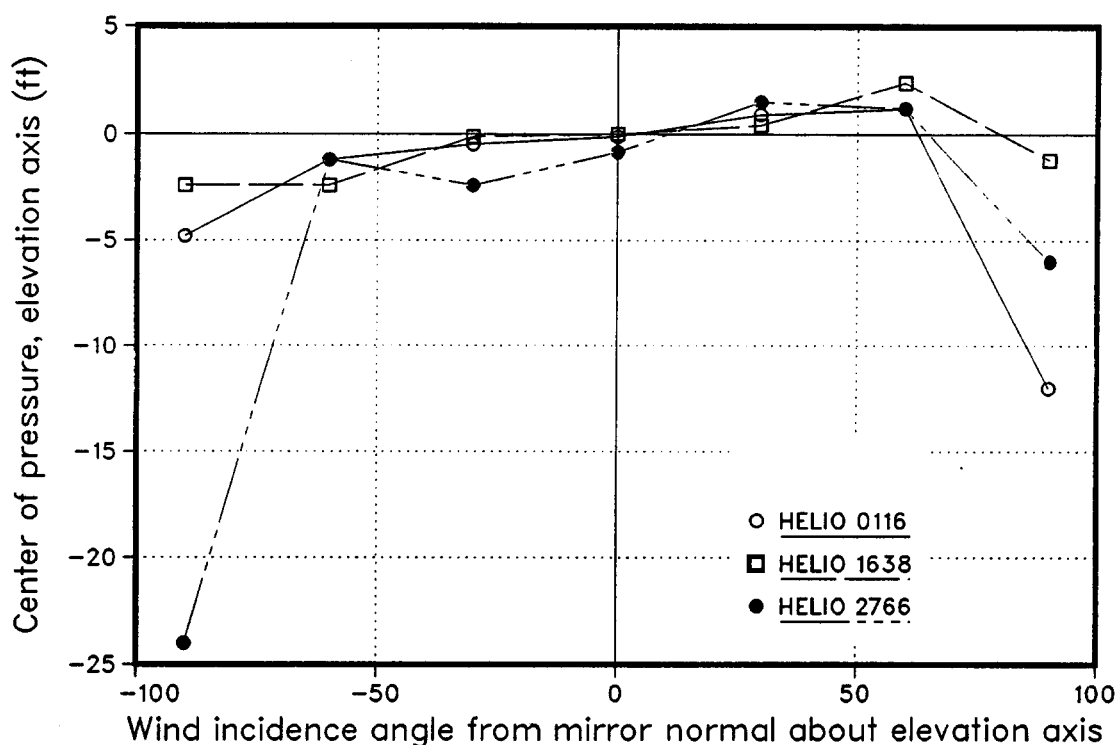


Figure 3-32. Solar One Heliostat Wind Loads - Field Ave. Wind Speed, Wind Azimuth Angle 20 to 32° from Mirror Normal, Normalized to 27 MPH at 32.2 ft., November 17, 1983

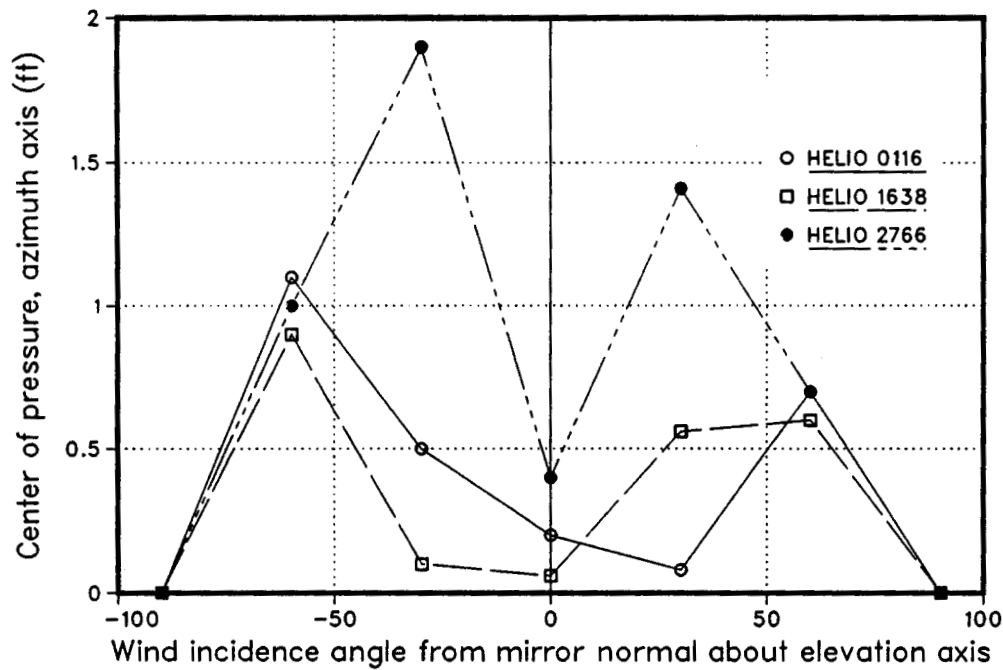


Figure 3-33. Solar One Heliostat Wind Loads - Field Ave. Wind Speed, Wind Azimuth Angle 20 to 32° from Mirror Normal, Normalized to 27 MPH at 32.2 ft., November 17, 1983

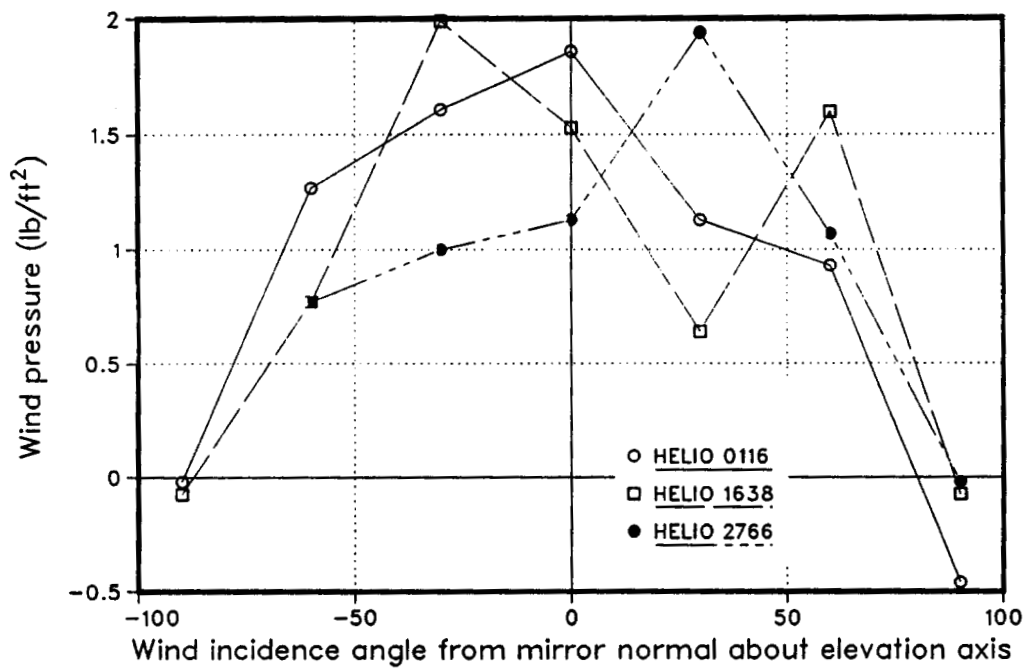


Figure 3-34. Solar One Heliostat Wind Loads - Field Ave. Wind Speed, Wind Azimuth Angle 20 to 32° from Mirror Normal, Normalized to 27 MPH at 32.2 ft., November 17, 1983

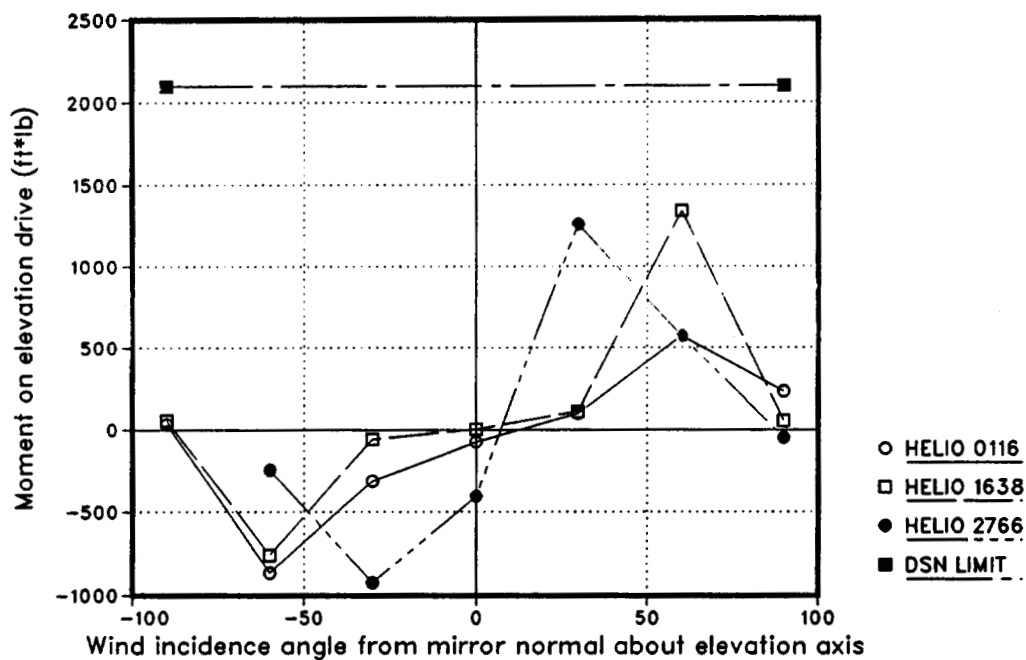


Figure 3-35. Solar One Heliostat Wind Loads - Field Ave. Wind Speed, Wind Azimuth Angle 20 to 32° from Mirror Normal, Normalized to 27 MPH at 32.2 ft., November 17, 1983

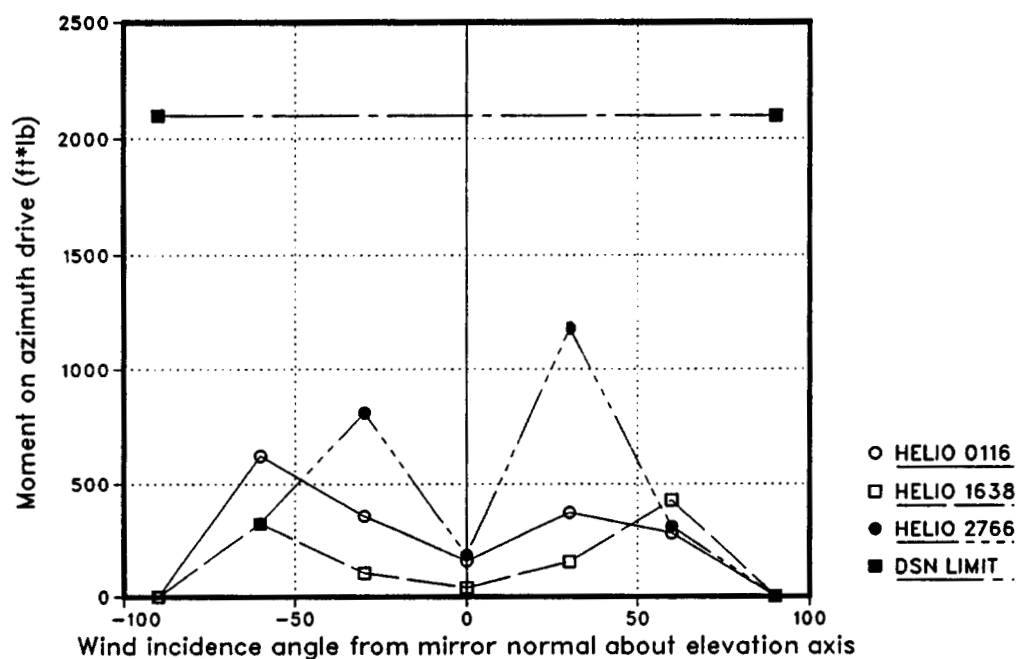


Figure 3-36. Solar One Heliostat Wind Loads - Field Ave. Wind Speed, Wind Azimuth Angle 20 to 32° from Mirror Normal, Normalized to 27 MPH at 32.2 ft., November 17, 1983

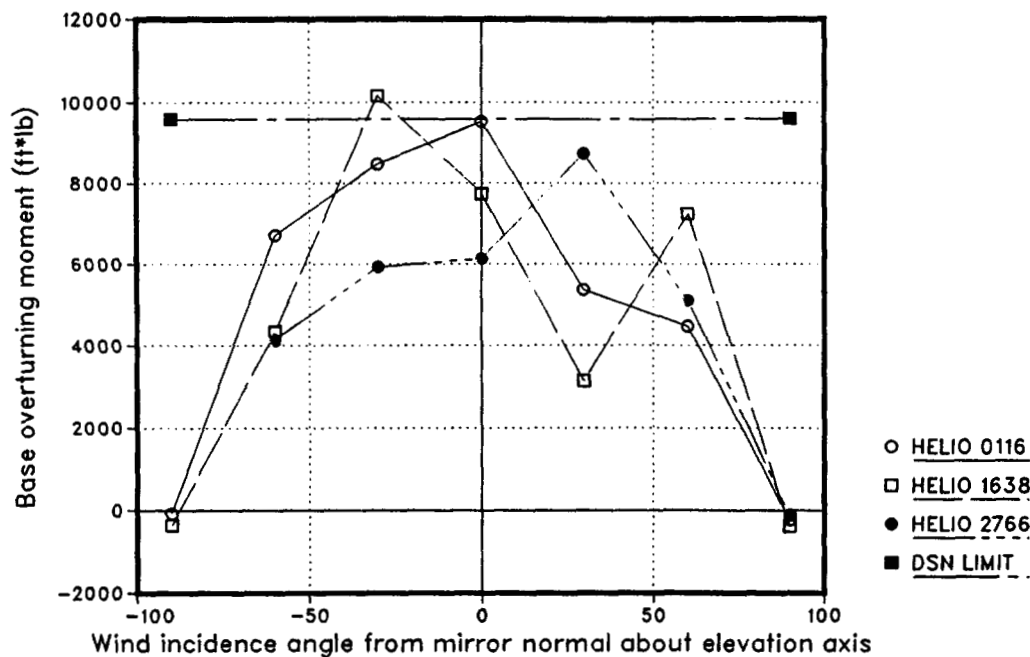


Figure 3-37. Solar One Heliostat Wind Loads - Field Ave. Wind Speed, Wind Azimuth Angle 20 to 32° from Mirror Normal, Normalized to 27 MPH at 32.2 ft., November 17, 1983

Wind Angle of Attack—For this test all of the heliostats in the field were in a horizontal stow position with the top mirrors toward the west facing the ground. The test data were recorded at 3 minute intervals on April 19, 1984, over a one hour period. The field average for the north, south, and west wind stations varied between 250 and 300 degrees from north (west is 270) as shown in Figure 3-38. Wind speed for the north, south, and west wind stations is shown in Figure 3-39. Tabulated wind data are shown in Table III-XIII. The average wind speed at each point in time, from the north, south, and west wind stations, was used to normalize the heliostat moments for a 90 mph wind. Under these conditions, there would be a zero moment on the heliostat drive if the wind direction were horizontal. Deviations from horizontal cause a moment on the drive which can be compared to the calculated moments versus angle of attack. The measured moments and the expected moments at 4, 5, and 6° angles of attack are plotted in Figure 3-40 at 3-minute intervals. In this case, the angle of attack is measured from the mirror surface rather than the normal.

The plotted moments are the elevation drive moment and azimuth drive moment. The azimuth moment is small because the wind is nearly perpendicular to the top edge of the mirrors. The elevation moments are mostly negative indicating that the wind is hitting the backs of the mirrors. The angle of attack is above the horizontal. The maximum moment is about 6000 ft. lbs. which is equivalent to about a 4° angle attack.

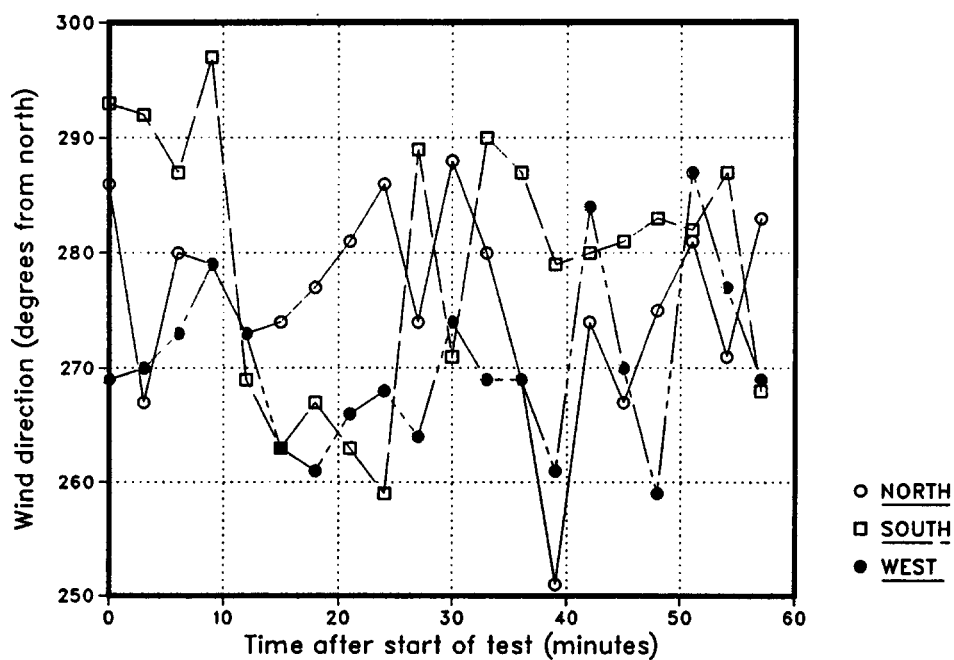


Figure 3-38. Heliostat Test Wind Direction April 19, 1984, 1211 to 1311 hours, North, South, and West Wind Stations

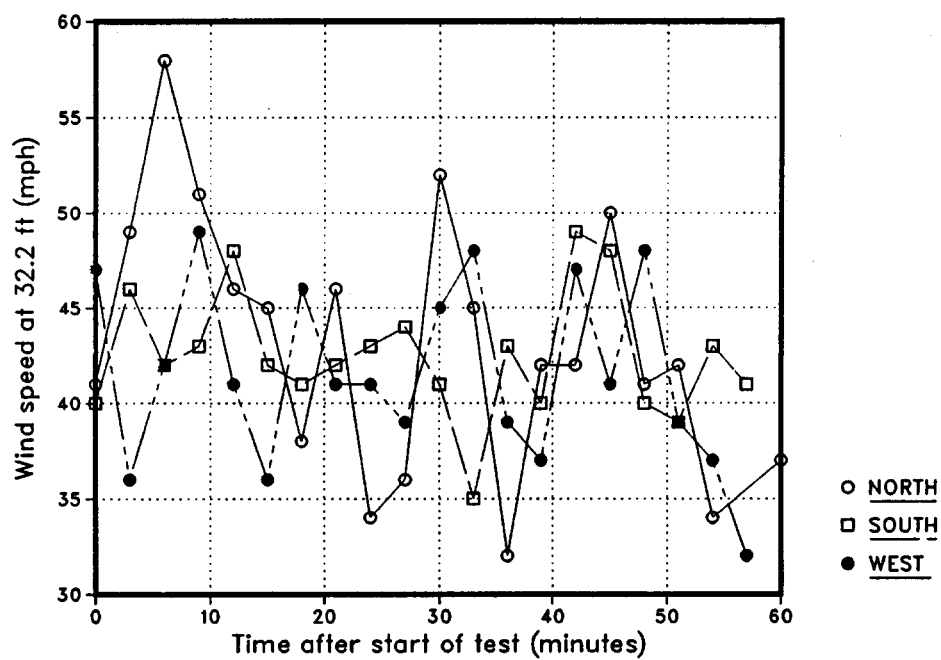


Figure 3-39. Heliostat Test Wind Speed April 19, 1984, 1211 to 1311 hours, North, South, and West Wind Stations

TABLE III-XIII
WIND DATA AT SOLAR ONE APRIL 19, 1984

Time	Windspeed (mph)						Tower #4	Tower #5
	South Station	West Station	North Station	East Station	Average S,W,N,E	Average S,W,N		
1211	40.2	47.4	41	31.6	40.05	42.86		
1214	45.8	35.8	49.4	45.2	44.05	43.66		
1217	42.4	42.4	58	26.6	42.35	47.6		
1220	42.5	49.4	51	26.8	42.42	47.63		
1223	48.3	41.4	46	53.3	47.25	45.23		
1226	42	36	44.9	37.9	40.2	40.96		
1229	41.3	45.6	38.1	34	39.75	41.66		
1232	41.5	41.3	46	37.4	41.55	42.93		
1235	43.4	41.1	33.5	27.8	36.45	39.33		
1238	43.7	38.7	35.8	37.5	38.92	39.4		
1241	41.2	44.5	51.7	33.8	42.8	45.8		
1244	35.2	47.8	44.8	39.3	41.77	42.6		
1247	43.4	39	32	45	39.85	38.13		
1250	40	37	41.6	38.4	39.25	39.53		
1253	49.3	46.8	42.4	38.3	44.2	46.16		
1256	47.5	40.5	49.7	47	46.17	45.9		
1259	40	48.4	41	48.5	44.47	43.13		
1302	48.7	39.2	42	37.1	39.25	39.96		
1305	43	36.6	33.5	38.5	37.9	37.7		
1308	40.8	32.2	36.9	46.4	39.07	36.63		
Average	42.51	41.55	42.96	38.52	41.38	42.34		

Wind Direction (Degrees from North)

1211	293	269	286	280	282	282.6	238	236
1214	292	270	267	277	276.5	276.3	254	258
1217	287	273	280	267	276.7	280	255	252
1220	297	279	279	266	280.2	285	254	250
1223	269	273	273	263	269.5	271.6	235	245
1226	263	263	274	277	269.2	266.6	245	248
1229	267	261	277	271	269	268.3	236	255
1232	263	266	281	252	265.5	270	228	241
1235	259	258	286	267	270	271	265	269
1238	289	264	274	246	268.2	275.6	254	256
1241	271	274	288	260	273.2	277.6	232	244
1244	290	269	280	190	257.2	279.6	252	252
1247	287	269	269	280	276.2	275	225	243
1250	279	261	251	273	266	263.6	243	248
1253	280	284	274	267	276.2	279.3	245	249
1256	281	270	267	268	271.5	272.6	230	239
1259	283	259	275	274	272.7	272.3	214	228
1302	282	287	281	288	284.5	283.3	239	260
1305	287	277	271	278	278.2	278.3	243	252
1308	268	269	283	272	273	273.3	240	249
Average	279.3	270.2	275.8	265.8	272.8	275.1	241.3	248.7

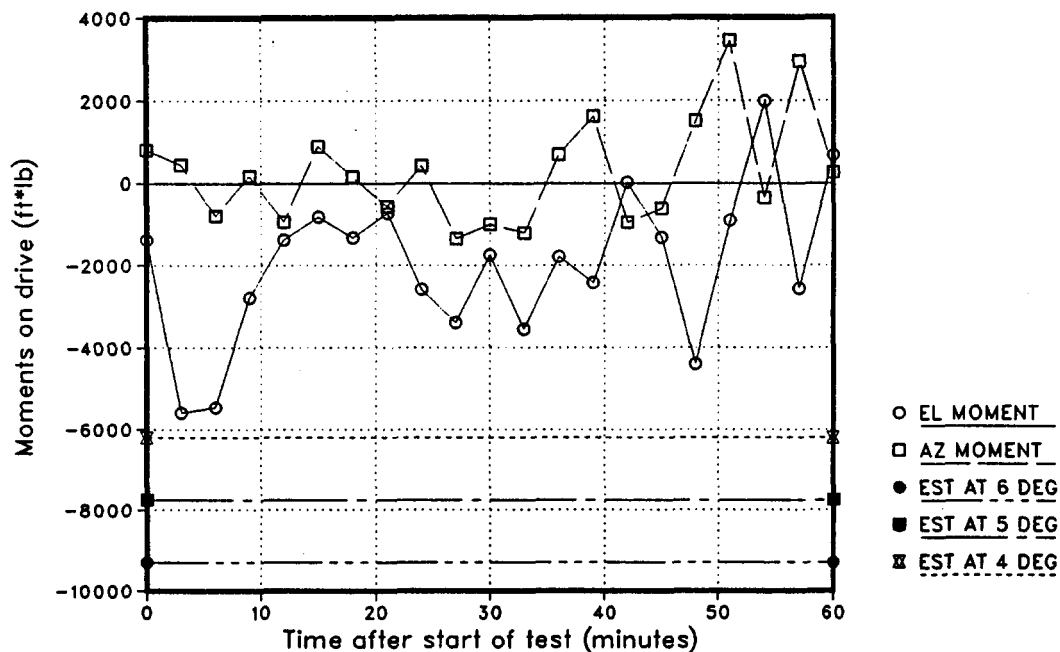


Figure 3-40. Solar One Heliostat Wind Loads April 19, 1984, 1211 to 1311 Hours, Heliostat 1638 in Stow Position

Figure 3-41 shows the moments on the drive when the wind speed at tower 4 or 5 are used to normalize the data to 90 mph. In this case the maximum moments are also equal to a 4° angle of attack; however, there is a significant difference from the results when wind speed outside of the field is used.

The conclusion from this data is that the maximum wind angle of attack was 4° and that the wind speed within the field is probably not indicative of the load on the heliostat. This angle of attack is significantly less than the 10° angle in the current heliostat requirements specification. References 32 and 33 suggest that the maximum angle of attack for 90 mph winds should be 4° for smooth terrain and 5.5 to 6.0° for outskirts of towns and suburbs. Large heliostat fields are likely to look like the suburbs. Therefore, until additional data are available, a 6° angle of attack is recommended.

Survival Wind Loads Within a Heliostat Field—Heliostat survival wind loads occur at 50 mph when a heliostat can be in any orientation and at 90 mph when the heliostats are all in a horizontal stow position. The 50 mph requirement takes into account thunderstorm gust fronts which can occur within a minute or two; therefore, the heliostats do not have time to reach a stow position. A comparison of the various windloads is shown in Table III-XIV which shows that the 90 mph wind drives the design of everything except for the pedestal which sees a maximum load at 50 mph.

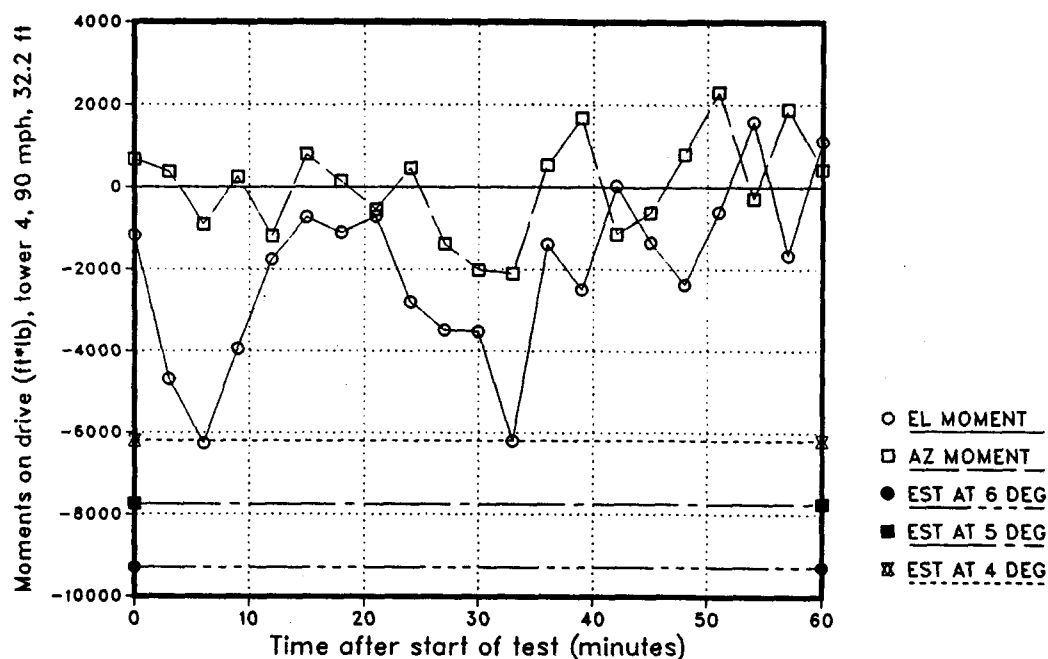


Figure 3-41. Solar One Heliostat Wind Loads April 19, 1984, 1211 to 1311 Hours, Heliostat 1638 in Stow Position

TABLE III-XIV
COMPARISON OF HELIOSTAT WIND LOADS

Wind Load	Operating Condition	
	Any Orientation (50 mph)	Stow (90 mph)
Max Az Drive Moment (ft.lb)	7200	9300 @ 6° 6200 @ 4°
Max El Drive Moment (ft.lb)	7200	9300 @ 6° 6200 @ 4°
Max Base Overturning Moment (ft.lb)	33000	1500
Peak Wind Pressure (lb/ft ²)	5.4	11 @ 6° 7 @ 4°
Max Base Twisting Moment (ft.lb)	7200	less than 7200

If the wind angle of attack was less than 4°, the 50 mph wind would drive the design for all loads. Likewise, if the 90 mph windspeed was reduced so that the drive moment was less than 7200 ft.lb. (22% reduction), then the 50 mph wind would drive the design for all loads. This observation led to an examination of wind gusts and how they load the heliostat. In the past, the average wind speed has been increased by the gust factor to determine the maximum wind speed to use for design. The wind load data from Solar One make it possible to estimate

how effective wind gusts are at loading a heliostat. The results are discussed in the next section.

For either the 50 mph or 90 mph survival wind conditions, there is no evidence from the Solar One wind load data that heliostat survival wind loads are reduced as you move into the field. The peak loads on the heliostats 116 and 1638 were just as high as for 2766 when the rest of the field is in a stow position, as would be the case for a 90 mph wind. Under thunderstorm gust front conditions, the field could be in any condition; therefore, you could not depend on wind shielding from upwind heliostats. Any roads into the field would make this especially true. Unless wind shields are placed throughout the field, all heliostats should be designed for the same wind loads.

Mean or Peak Wind Speeds—The Solar One Wind Load data have been analyzed to determine how effective wind gusts are at loading a heliostat. These data show that only a fraction of the peak windspeed is effective.

The wind load data for a vertical heliostat with various azimuth angles were analyzed to determine the gust factors for moments on the drives, base overturning moment, and wind pressure. Figures 3-28, 3-30 and 3-31 show the data. The loading gust factor was first determined relative to the calculated load; then the equivalent wind gust factor was obtained by:

$$LGF = \frac{CL + DL}{CL}$$

Where: LGF =Load Gust Factor
 CL =Calculated Load
 DL =Deviation of Normalized Measured Load
 Data from the Calculated Load

$$WGF = \sqrt{LGF}$$

Where: WGF=Wind Gust Factor

These wind gust factors are shown in Table III-XV along with the wind gust factor as determined from wind speed data. The maximum gust factor is 1.4 in all cases;

TABLE III-XV
 WIND GUSTS FACTORS FROM WIND LOAD DATA

	Equivalent Wind Gust Factor			
	Wind Pressure	Drive Moment	Base Overturning Moment	Wind Gust Factor from Windspeed Data
Average	1.14	1.25	1.14	1.36
Maximum	1.38	1.40	1.35	2.10
Std. Deviation	.109	.093	.094	.136

however, the standard deviation of the gust factor, based on wind speed measurements, is about 1.4 times as big as the equivalent gust factor obtained from the wind load data. The two and three standard deviation limits for the gust factors are shown in Table III-XVI.

TABLE III-XVI
EQUIVALENT WIND SPEED GUST FACTORS

	3 Std Dev	2 Std Dev
Wind Speed	1.77	1.63
Drive Moment	1.52	1.44
Wind Pressure	1.47	1.36
Base Overturning Moment	1.33	

This table shows that there is a significant difference between the peak wind speed and the wind speed that loads the heliostat. The drive moment is the easiest for the wind gust to affect where the 3 standard deviation gust factor is 1.52 versus 1.42 for the base overturning moment. These gust factors can be used for the trade-off of heliostat costs versus the probability of wind damage and the associated repair costs. If the gusts have a normal probability distribution then 46 heliostats out of a 1000 will experience drive moments greater than about 1.4 times the average wind speed, and 2 out of 1000 will have loads greater than 1.5 times the average wind speed. The significance of this finding is that the specified 90 mph survival wind speed (which includes gusts) can be reduced to 84 mph (mean plus 2 std. dev.) for the drive moments, 78 mph for the overturning moment, and 81 mph for wind pressure. Or if the 90 mph specification is assumed to be a 3 standard deviation limit the corresponding wind speeds would be 78, 72, and 75 mph. This is a significant percentage reduction from the 90 mph wind speed that was used for design of the Solar One heliostats. Choosing an equivalent wind speed of 75 mph for heliostat design would reduce the moments by 30.6%.

Component Temperatures

Three heliostats (0116, 1638 and 2766) are instrumented for component temperatures. Temperatures were recorded for the elevation motor, front and back of one mirror module, heliostat control box (inside air and box exterior), and the pedestal exterior while the heliostats were tracking. These component temperatures versus ambient air temperatures are discussed below.

Mirror Module Temperatures

The front glass and back steel pan temperatures on one mirror module were recorded on the instrumented heliostats. Representative data from four days are shown in Table III-XVII. The data are useful for predicting mirror curvature at

different ambient air temperatures. The data show that the difference between the front and back temperature is larger at lower ambient temperatures and that the glass temperature rises further above ambient at lower temperatures. The front and back temperatures are about the same when the sun is not shining. From this data the temperatures of the mirror modules are not a concern.

TABLE III-XVII
MIRROR MODULE TEMPERATURES

Date:		1/13/83	5/25/84	5/25/83	5/28/83	5/28/83
Time:		1:11 p.m.	10:02 a.m.	2:02 p.m.	1:21 p.m.	4:42 p.m.
Amb. Air Temp (°F)		52	82.5	99.5	102.3	103.7
Wind Speed (mph)		10	10	10	10	20
Insolation (W/m ²)		856	790	800	790	0
Heliostat No.	Sensor Location	Temp. (°F)	Temp. (°F)	Temp. (°F)	Temp. (°F)	Temp. (°F)
0116	Front of Glass	74.4	96.6	107.8	111.8	101.7
	Back of Pan	68.0	90.1	105.6	107.4	100.9
	Difference					
	Front-Back	6.4	6.5	2.2	4.4	.8
	Glass-Ambient	22.4	14.1	8.3	9.5	2.0
1638	Front of Glass	67.6	92.0	102.8	107.0	94.0
	Back of Pan	60.4	84.6	100.4	102.0	94.2
	Difference					
	Front-Back	7.2	7.4	2.4	5	-0.2
	Glass-Ambient	15.6	9.5	3.3	4.7	-9.7
2766	Front of Glass	70	92.0	102.7	108.0	101.5
	Back of Pan	*ND	88.0	101.8	105.0	96.6
	Difference					
	Front-Back	*ND	4	0.9	3	4.9
	Glass-Ambient	18	9.5	3.2	5.7	-2.2

*ND = No Data

Motor Temperatures

The elevation motor temperature on the instrumented heliostats is shown in Table III-XVIII. The motor was slightly below ambient when there was no sun and rises slightly above ambient in the sun while tracking. Data were also examined while the heliostats operated continuously for about 15 minutes. The ambient temperature was 80°F and the motor temperature rise was only 2° - 3°F. The motors are rated for continuous duty at 104°F. This rating will be marginal on a 122°F day if the motors run continuously as they would when moving the heliostat from stow to standby.

TABLE III-XVIII
ELEVATION MOTOR TEMPERATURES

Date:		1/13/83	5/25/84	5/25/83	5/28/83	5/28/83
Time:		1:11 p.m.	10:02 a.m.	2:02 p.m.	1:21 p.m.	4:42 p.m.
Amb. Air Temp (°F)		52	82.5	99.5	102.3	103.7
Wind Speed (mph)		10	10	10	10	20
Insolation (W/m ²)		856	790	800	790	0
Heliostat No.	Sensor Location	Temp. (°F)	Temp. (°F)	Temp. (°F)	Temp. (°F)	Temp. (°F)
0116	Motor Frame	*ND	86.2	101.6	103.5	99.4
	Difference					
	Motor-Ambient	*ND	3.7	6.1	1.2	-3.8
1638	Motor Frame	59.3	81.8	98.2	*ND	*ND
	Difference					
	Motor-Ambient	7.3	-.7	-1.3		
2766	Motor Frame	63.1	84.7	100.4	102.0	98.7
	Difference					
	Motor-Ambient	11.1	2.2	.9	-.3	-4.5

*ND = No Data

Pedestal Temperature

The heliostat pedestal temperature is measured on the outside surface about 5 feet above the ground. The pedestal temperatures are shown in Table III-XIX. The data show that the pedestal temperature is below ambient when it is shaded by the mirrors and will be 7 - 12° above ambient when sun hits it. This temperature rise only occurs when the sun can shine through the slot between the two mirror sides and hit the pedestal. When this occurs, one side of the pedestal will be heated more than the other; thus, some bending of the pedestal will occur. The effect will show up as a pointing error. The amount of bending is believed small; however, it has not been measured.

TABLE III-XIX
HELIOSTAT PEDESTAL TEMPERATURES

Date:		1/13/83	5/25/84	5/25/83	5/28/83	5/28/83
Time:		1:11 p.m.	10:02 a.m.	2:02 p.m.	1:21 p.m.	4:42 p.m.
Amb. Air Temp (°F)		52	82.5	99.5	102.3	103.7
Wind Speed (mph)		10	10	10	10	20
Insolation (W/m ²)		856	790	800	790	0
Heliostat No.	Sensor Location	Temp. (°F)	Temp. (°F)	Temp. (°F)	Temp. (°F)	Temp. (°F)
0116	Pedestal Exterior	60	94.6	97.6	100.6	98.6
	Difference					
	Pedestal-Ambient	8	12.1	-1.9	-1.7	-4.6
1638	Pedestal Exterior	53.7	89.1	93.9	96.4	93.8
	Difference					
	Pedestal-Ambient	1.7	6.6	-5.6	-5.9	-9.4
2766	Pedestal Exterior	56.7	91.7	97.4	100.3	98.4
	Difference					
	Pedestal-Ambient	4.7	9.2	-2.1	-2.0	-4.8

Heliostat Controller Temperatures

There are two temperature sensors for the Heliostat Controller (HC). The HC is the electronics box that is located inside the pedestal. One sensor is on the top of the box on the outside surface. The second sensor is inside the box near the Sorenson Power Supply and measures air temperature at this location. The measured temperatures are shown in Table III-XX. The data show that the maximum air temperature inside the HC box is about 20°F above ambient on a hot day. This will cause the air temperature inside the HC box to reach 142°F on the hottest (122°F) specified day. This is 10°F below the qualification environmental test temperatures that were performed during production, which included operation in a 132°F test chamber for 160 hours as a burn-in and a thermal cycle test to 176°F.

TABLE III-XX
HELIOSTAT CONTROLLER TEMPERATURES

Date:		1/13/83	5/25/83	5/25/83	5/28/83	5/28/83
Time:		1:11 p.m.	10:02 a.m.	2:02 p.m.	1:21 p.m.	4:42 p.m.
Amb. Air Temp (°F)		52	82.5	99.5	102.3	103.7
Wind Speed (mph)		10	10	10	10	20
Insolation (W/m ²)		856	790	800	790	0
Helio- stat No.	Sensor Location	Temp. (°F)	Temp. (°F)	Temp. (°F)	Temp. (°F)	Temp. (°F)
0116	Box Exterior	70.4	93.8	106.4	108.9	107.4
	Box Interior	82.5	101.3	113.7	118.7	117.6
	Difference					
	Box Interior-Exterior	12.1	7.5	7.3	9.8	10.2
	Box Interior-Ambient	30.5	18.8	14.2	16.4	13.9
1638	Box Exterior	64.1	88.2	102.1	104.3	102.4
	Box Interior	79.4	100.1	112.7	114.9	114.2
	Difference					
	Box Interior-Exterior	15.3	11.9	10.6	10.6	11.8
	Box Interior-Ambient	27.4	17.6	13.2	12.6	10.5
2766	Box Exterior	71.4	94	106.2	109.4	108.6
	Box Interior	89.3	108	119.9	122.5	122.4
	Difference					
	Box Interior-Exterior	17.9	14	13.7	13.1	13.8
	Box Interior-Ambient	37.3	25.5	20.4	20.2	18.7

Power Requirements

The electrical power required by a heliostat was measured on 5 heliostats. While tracking, each heliostat draws about 28 watts with 1 to 5 minutes duration peaks to 35 watts. When the motors run at a slew (high) speed, the power requirements jump to 120 to 250 watts per heliostats depending on whether both motors are running. The transformer power draw for a large number of heliostats increases by 15 to 30% when all heliostats are commanded to move in a track mode at the same time as when they move from standby to track or when they do a transition from stow to standby. Commanding all heliostats on a transformer to slew at the same time would increase the load by a factor of 4 to 9 depending on whether both motors were running. The total energy used by a typical heliostat is 380 Whr in a 10 hour day.

Heliostat Control, Availability, and Maintenance

Reliable equipment design has resulted in low maintenance manpower requirements. During the initial operating period, heliostat control required one operator full time. As we gained experience in the collector field operation, we modified the Heliostat Array Controller (HAC) software to facilitate the collector field's operation, reducing the operator demand to one quarter man-day.

Because the collector field has a large redundancy in its 1818 heliostats, maintenance priority has generally concentrated on potential single point failures within the receiver and electrical power generation systems. Regardless of the limited maintenance expended on the collector system, 1700 heliostats were generally available for service during the 2 year engineering test period. However, in preparation for a plant summer solstice field power test, effort was concentrated on improving the number of heliostats available for service. This plus the realization by Southern California Edison that there was a need to keep better records of failures resulted in identifying heliostat controllers that needed repair due to frequent failures. As a result of this effort, 1800 to 1818 heliostats were made available for service. Heliostat availability has been improved during the power production phase which started in August 1984. Figure 3-42 shows the number of heliostats operating each day between August 1, 1984, and August 1, 1987. A significant improvement was made in March and April 1985 when a concerted effort was made to improve the plant's power output. A power transformer failure in November 1985 damaged several hundred heliostats because of power surges to the heliostat controller.

Maintenance of the heliostats has been performed by people with conventional skills. An electrician and instrument repair technician performed most of the repair with minimal help from machinists and mechanics. Approximately one man-year of labor has been expended each year for heliostat repair.

The number of heliostat maintenance work orders written through April 1985 is shown below:

Heliostat Work Order History

<u>Year</u>	<u>No. of Work Orders</u>
1981	23
1982	906
1983	1370
1984	1600
Jan 1985 - April 1985	800

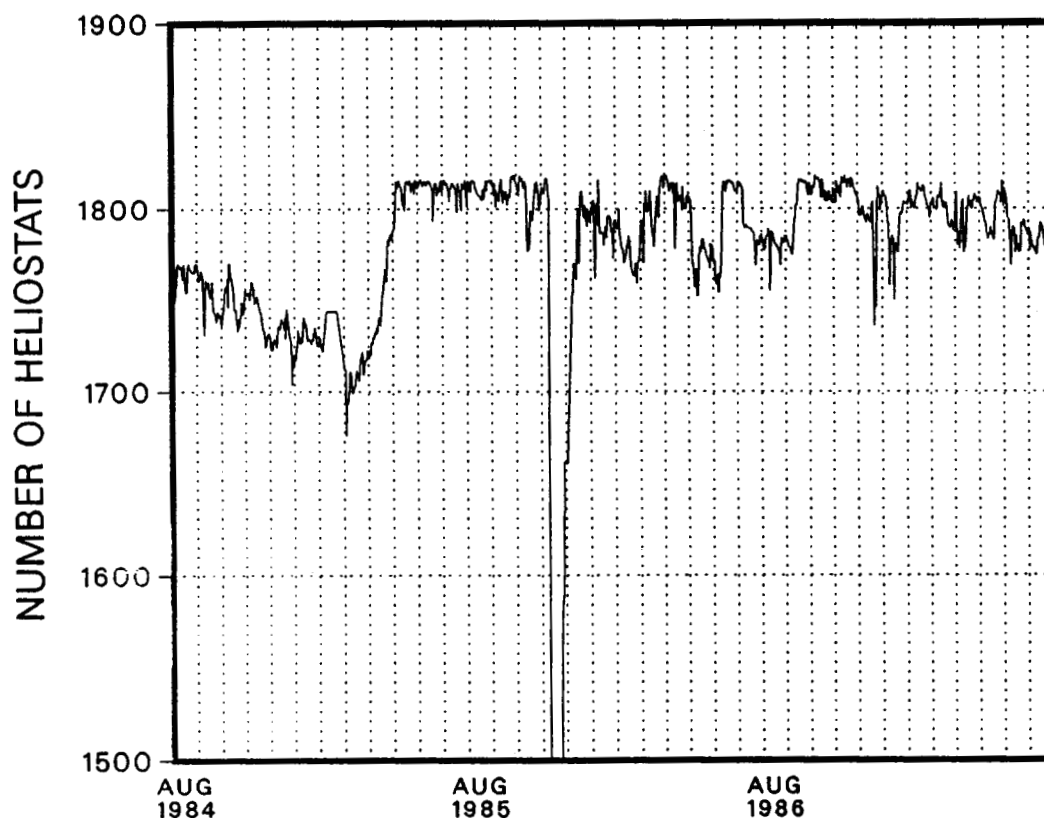


Figure 3-42. Solar One Heliostats On-line August 1984 - March 1986

The large number of work orders in the first four months of 1985 accounts for the significant improvement in availability during this period as shown in Figure 3-42. During this time period, a faulty capacitor in one of the heliostat controller power supplies was identified as the cause of loss-of-communications with the heliostats. The faulty capacitor would cause the power supply to lose regulation and drop the voltage to zero, this caused a loss-of-communications. Before the capacitor problem was identified, the operators would merely turn the power off then back on and the fault would disappear; thus they believed there was a communications problem. Intermittent lamp failures in the encoders were also causing many heliostat outages. SCE started doing their own lamp replacement which reduced the turn-around-time for repair and improved availability. Repairing these two problems was the major reason for the improved availability.

Tracking Accuracy

Heliostat tracking accuracy refers to the ability of a heliostat to maintain its reflected beam accurately upon a desired aimpoint. For this evaluation, the aimpoint was on the center of the Beam Characterization System (BCS) target. The BCS was used to determine the beam centroid location on the BCS target relative to the center of the target. Two angular errors are associated with any beam centroid location, a horizontal error, and a vertical error.

The tracking accuracy specification, to which the heliostats are supposed to comply, required that the one standard deviation vertical or horizontal angular error for the reflected beam be less than 1.5 mrad under no wind conditions and 3.4 mrad with a 27 mph wind.

Tracking Accuracy Error Sources (Reference 40)

The Pilot Plant heliostats are two-axis tracking devices using an open loop control system to operate separate azimuth and elevation drive mechanisms. As a result of peculiarities and/or field installation procedures, the effective azimuth axis of the heliostat may be tilted with respect to the ideal vertical axis. Manufacturing tolerances and/or fabrication procedures may also result in the elevation axis being non-orthogonal to the azimuth axis. For the same reasons, the effective normal vector to the composite mirrors mounted on the heliostat may deviate from the ideal reference normal vector that is perpendicular to the elevation axis. The mirror module canting procedure can, therefore, influence tracking accuracy since the canted assembly may be at an angle to the reference normal. This is, in effect, a second type of non-orthogonality.

Gravity loading of the structure may also influence tracking. The mass of the mirror assembly may produce moments that are high enough in relation to the structural stiffness of the drive unit or mirror support assembly to produce an angular displacement of the mirror normal relative to the reference normal. The effect of this gravitational influence depends on the heliostat design, but typically varies with the elevation angle of the heliostat.

The finite resolution of the angular encoders also contributes to the overall tracking accuracy since the heliostat can only be positioned to within the resolution of the encoder. In addition, the encoders on each heliostat axis must be physically attached and referenced to the heliostat structure. The zero readings of the encoders must be accurately referenced to a known orientation of the heliostat reflective surface. An error in this referencing (encoder bias error) will result in a tracking error. Errors in the surveyed location of the heliostat relative to the target can also produce a tracking error.

All of these tracking error sources might be termed hardware errors. In addition to hardware errors, there are several sources of tracking error that are called computational errors. Heliostat azimuth and elevation angles are calculated with vectors that define the position of the sun and the position of the target relative to the heliostat. The position of the heliostat relative to the target was surveyed to a high degree of accuracy, so the error remaining is the determination of the position of the sun relative to the heliostat.

Tabular solar ephemeris data are typically regarded as providing the "correct" position of the sun, and different computational models have been derived that closely approximate the tabular ephemeris data. These sun position models are often capable of providing azimuth and elevation angles that are accurate to within 1 s of arc (0.0048 mrad) relative to the tabulated ephemeris data. Minicomputer round-off error and compromises that reduce computational time can result in a calculated sun position with a much larger degree of error.

A heliostat control system must be capable of calculating the apparent position of the sun in addition to the actual position. The apparent position of the sun differs from the actual position because of the refraction of the sun's rays as they pass through the earth's atmosphere. Atmospheric refraction results in the apparent elevation of the sun differing from the actual elevation by greater than 1 mrad for sun elevation angles of less than 0.26 mrad (15°). Consequently, an atmospheric refraction correction must be estimated in the sun position calculation.

Prototype Tracking Accuracy Tests (Reference 40)

Three Pilot Plant prototype heliostats were tested for tracking accuracy at the Central Receiver Test Facility (CRTF) prior to production of the 1818 Pilot Plant heliostats. Figures 3-43 through 3-45 present mirror normal tracking accuracy data for these prototypes of which two were actual prototypes and one was a preproduction heliostat. The data was taken with the CRTF BCS. These heliostats were field-leveled, and no provisions were made in the control system to compensate for pedestal tilt and nonorthogonality error sources. The computer controller used while taking these data was a Sandia designed system that simulated the Pilot Plant control algorithms. The shapes of the curves in these figures indicate the presence of tilt and nonorthogonality type error sources even though the heliostats were leveled during installation. The plots of azimuth error in Figure 3-43 and 3-44 also indicate an offset (encoder bias error) that could be improved. This improvement was made by rebiasing the azimuth encoder and the results are shown in Figure 3-45.

The tracking accuracy in Figures 3-43 and 3-44 is slightly out of specification (1.7 mrad reflected beam rms vs 1.5 mrad) for these two azimuth cases but is well within specification after the azimuth encoder bias was refined. Figure 3-46 gives tracking accuracy data on the same day for all three heliostats. Similar tracking characteristics are demonstrated by all three.

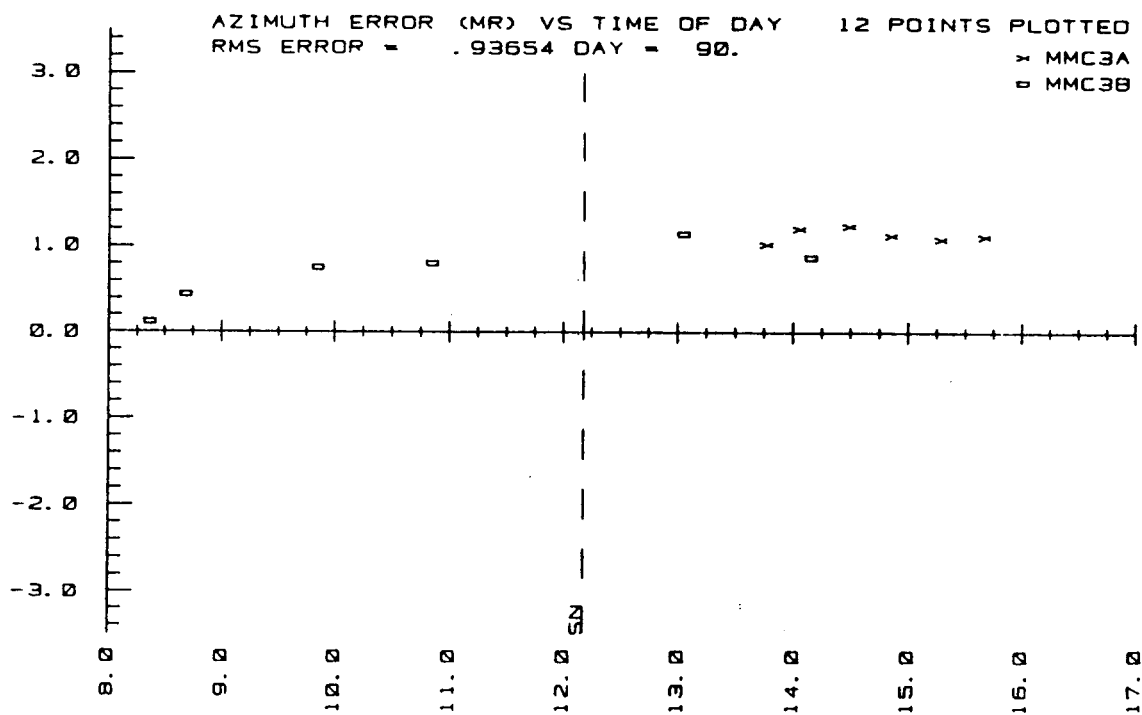
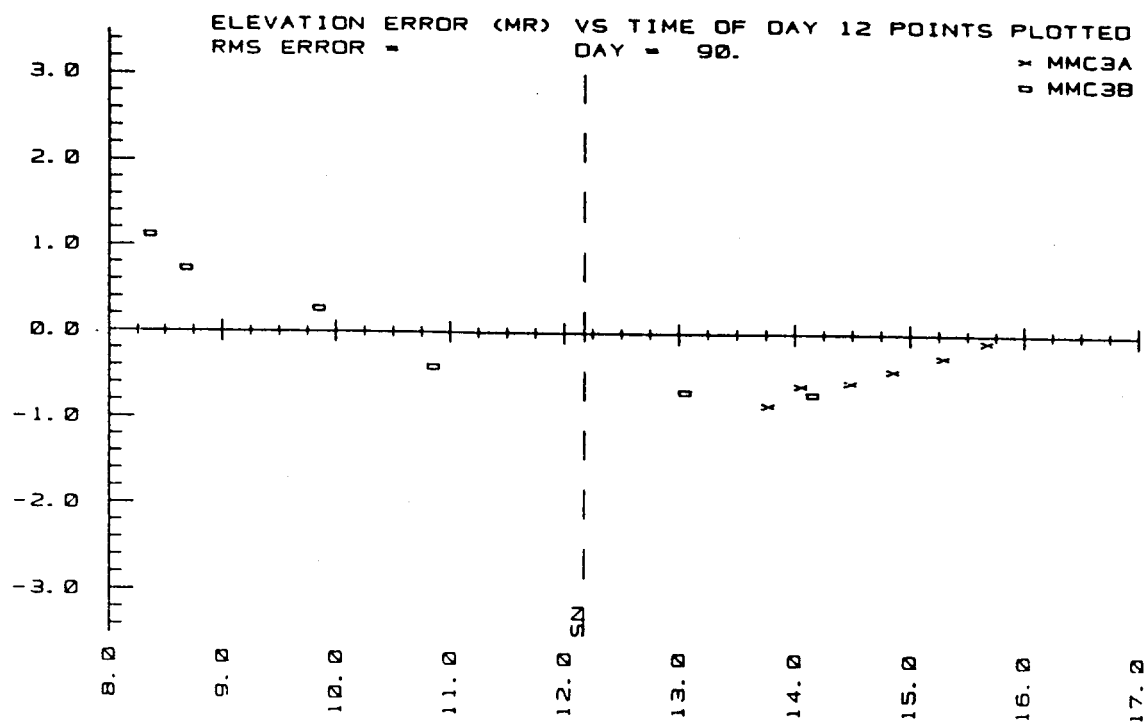


Figure 3-43. Solar One Production Heliostat Tracking Accuracy Data
 (mirror normal angles)

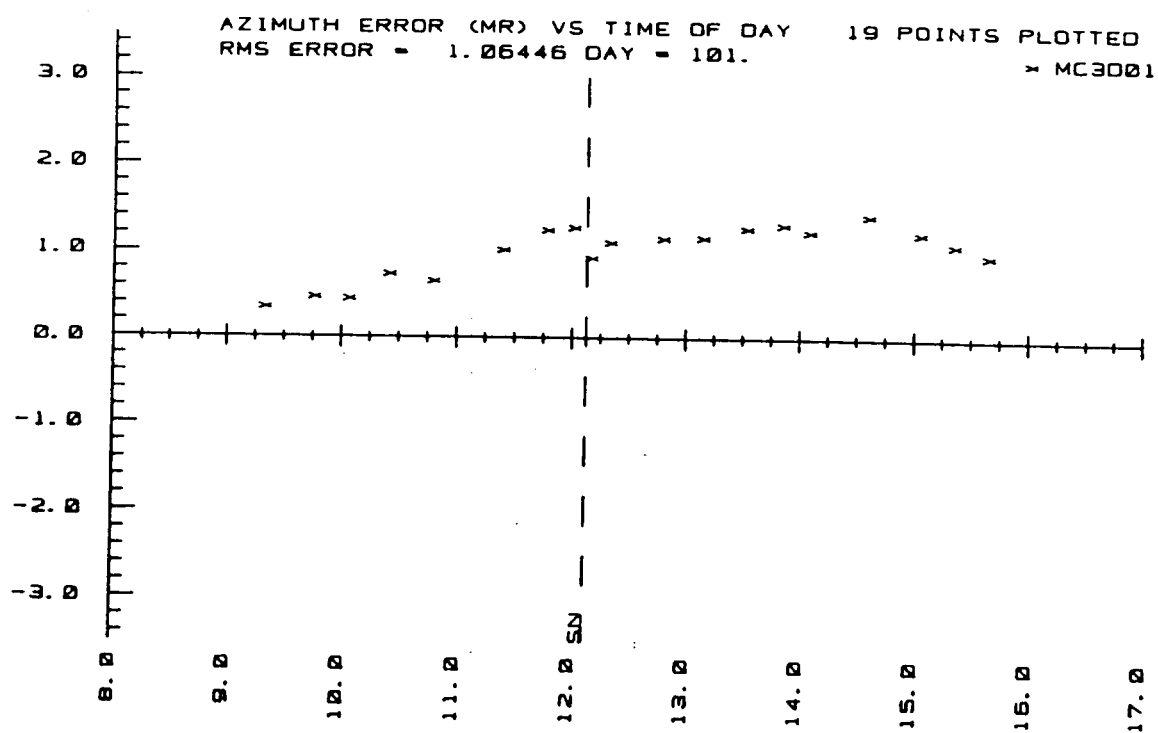
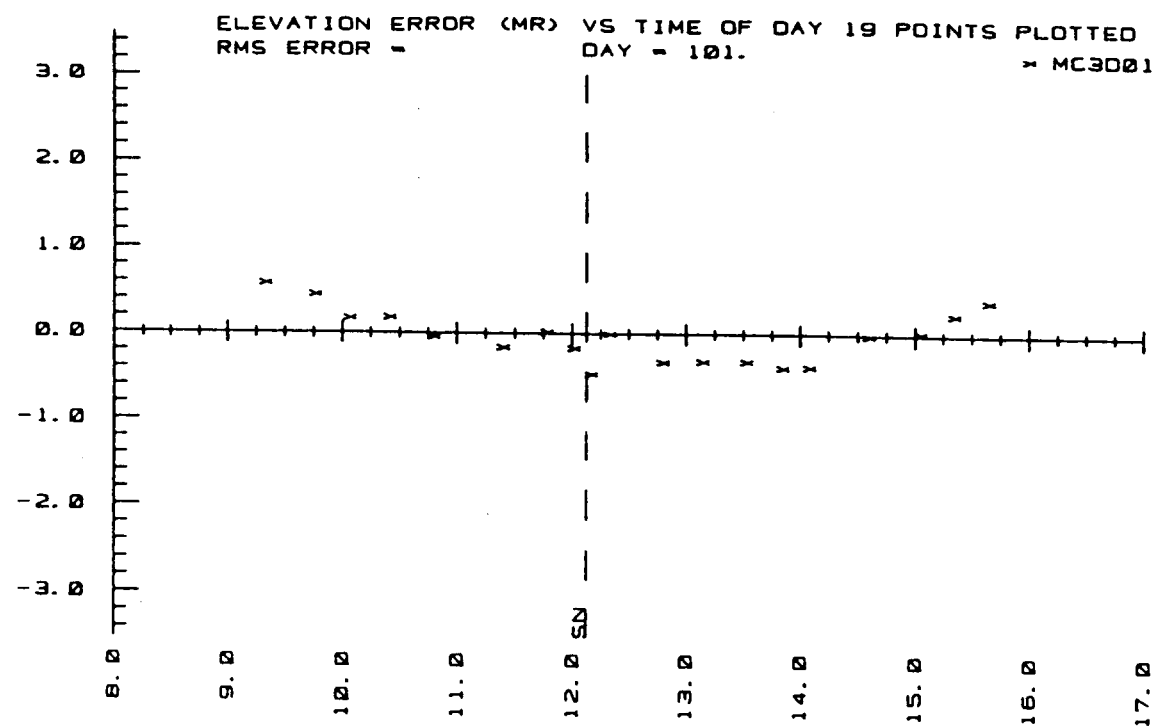


Figure 3-44. Solar One Production Heliostat Tracking Accuracy Data
 (mirror normal angles)

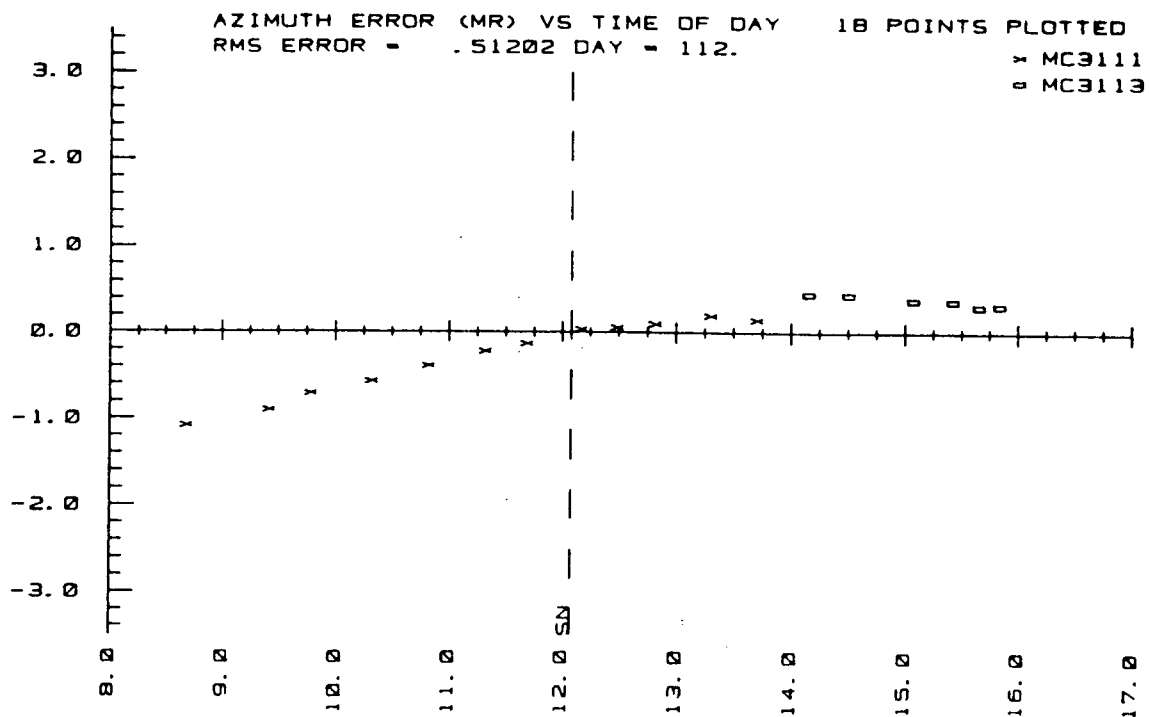
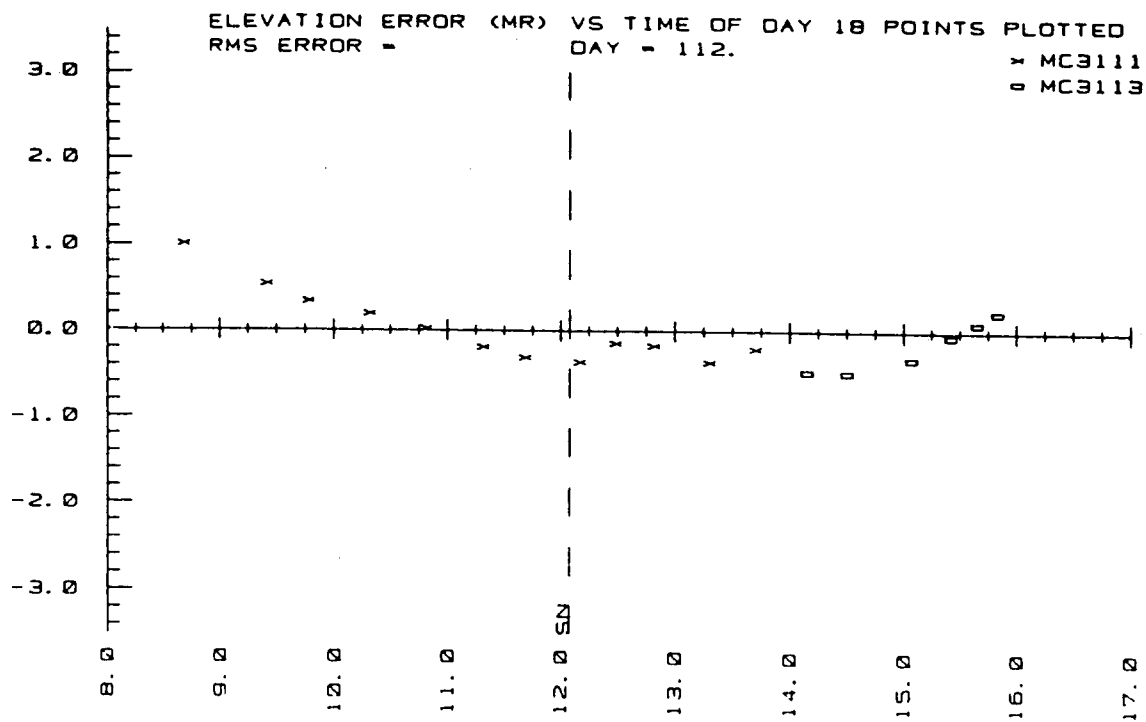


Figure 3-45. Solar One Production Heliostat Tracking Accuracy Data
 with Azimuth Encoder Rebiased

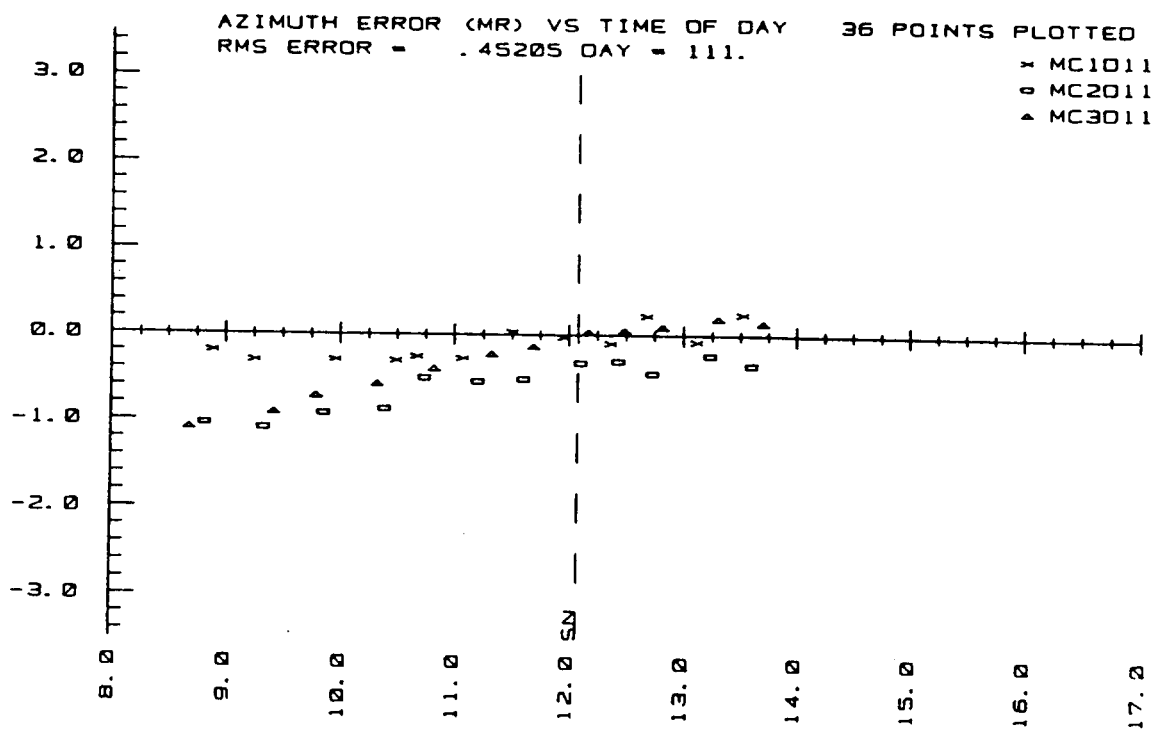
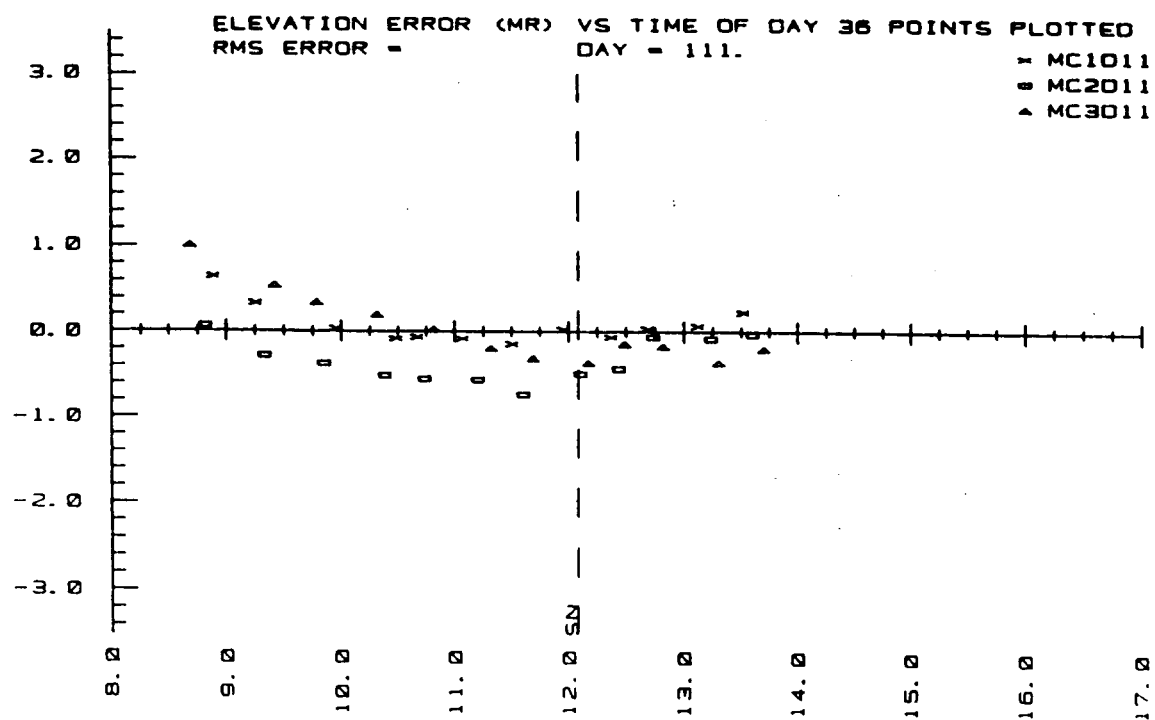


Figure 3-46. Tracking Accuracy Data on all Three MMC Solar One Heliostats
(mirror normal angles)

The tracking data were also analyzed in terms of reflected beam angular error. The rms values of the daylong reflected beam angular errors were found to be 0.9 mrad for both azimuth and elevation after encoder bias corrections.

The influence of wind loading on tracking accuracy was also evaluated at the CRTF. When the BCS was used to evaluate tracking accuracy, many samples of the centroid locations were obtained. By calculating the standard deviations for the azimuth and elevation errors obtained, an assessment of the dispersion of the data was made. This dispersion was due to tracking updates for low windspeeds; however, as the windspeed increases, wind induced movements of the heliostat produced a larger dispersion of the data. Table III-XXI gives the average values of the standard deviations obtained under different levels of windspeed. Windspeed in this table is the average windspeed during the interval when the data was taken. In determining these values, it was not possible to identify the actual angle-of-incidence conditions that were present during each sample period. However, the average of several data sets for each windspeed range was calculated. These values should, therefore, provide at least a semiquantitative assessment of the dispersion in azimuth and elevation tracking error as a result of wind load conditions.

TABLE III-XXI
TYPICAL DISPERSION (STANDARD DEVIATION)
OF REFLECTED BEAM TRACKING ERROR VS WINDSPEED

Average									
Windspeed (mph):		0-10		10-15		15-20		20-25	
Dispersion (mrad):		Az	E1	Az	E1	Az	E1	Az	E1
		0.8	0.4	1.0	0.6	—	—	2.0	1.8

A more detailed evaluation of tracking accuracy under actual wind loads was made for a limited range of wind speeds. The BCS sampled centroid location at 0.5-s intervals vs 4-s intervals previously and also sampled windspeed at 1-s intervals during the scan. Figure 3-47 presents tracking data obtained on a very windy day. Also shown in this figure are the mean tracking error, the standard deviation about the mean, and the average windspeed during the scan.

The above data from testing at the CRTF show that the Pilot Plant heliostat should meet the tracking accuracy specification requirements. The BCS at the Pilot Plant was used to evaluate the tracking accuracy of the production heliostats. The results of this evaluation are provided in the following paragraphs.

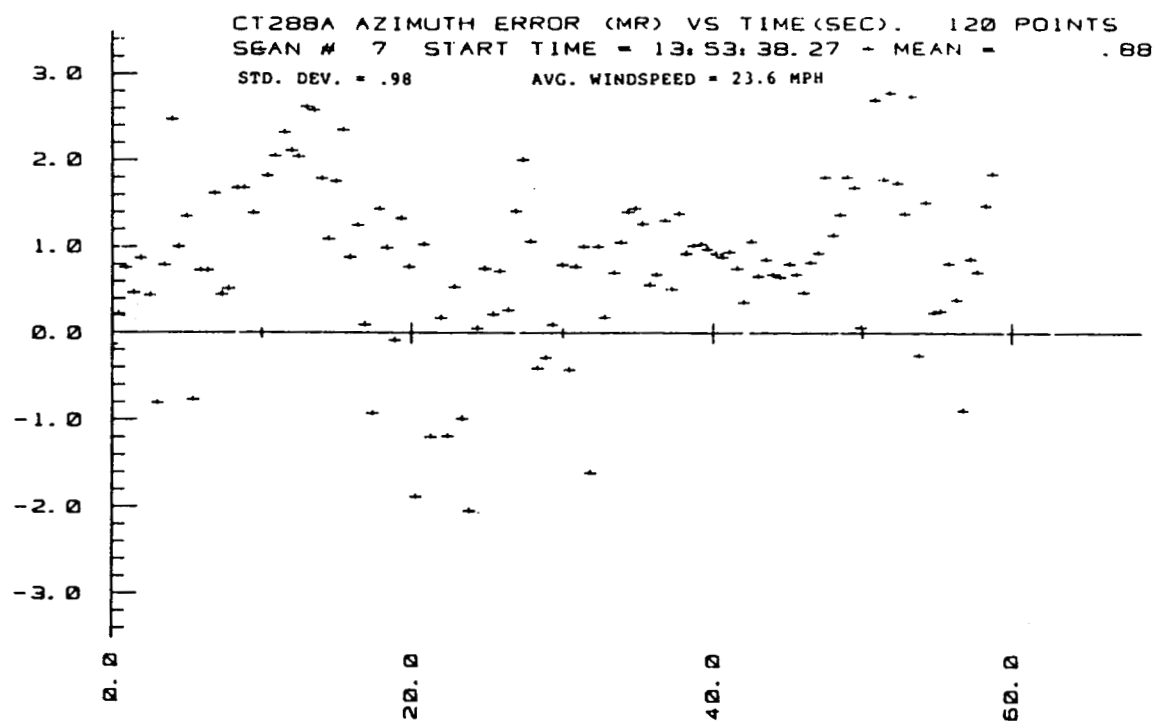
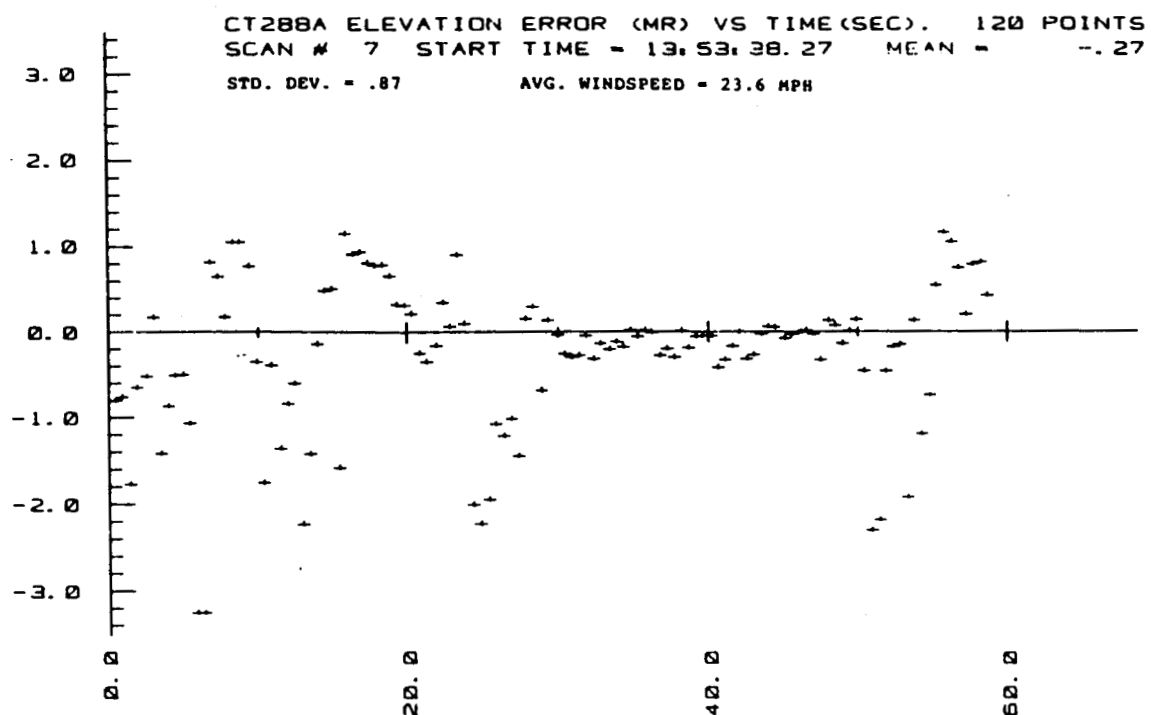


Figure 3-47. Solar One Tracking Accuracy Data in a High-Wind Condition
 (mirror normal angles)

Plant Heliostat Tracking Accuracy Tests

Pilot Plant tracking accuracy data were taken with the Beam Characterization System which is described in Appendix III. Prior to 1985 bias updates had been made using visual estimates of the tracking errors. These visual estimates were made by the plant operators by observing the beam on the BCS target and estimating the tracking error. Only one observation was made for each bias update which normally occurred between 10:00 a.m. and 2:00 p.m. During 1985, 1546 BCS measurements were made, and heliostat bias updates were made to correct tracking errors.

In October 1986, a group of 95 heliostats were selected for periodic BCS measurements to evaluate how tracking accuracy changed with time. These 95 heliostats were measured for tracking errors at three different times during the day. Bias updates were then made and tracking errors were measured again on several occasions over a six-month period without further bias updates. When the data were analyzed, we found that many of the heliostats were not reaching the aim-point due to some problem in the controller.

This controller problem was verified by entering a large tracking error into the computer. A bias update was then made and the location of the beam on the BCS target was observed. The results were that the tracking error was of the same magnitude but of opposite sign. At first it was thought that there might be an error in the bias calculation software, but this was checked and the calculations had been made correctly. The problem was fixed by replacing the encoder; although, the specific fault in the encoder was not isolated.

Because of this controller problem, the data were analyzed in two ways. First the data from heliostats with bad controllers were deleted to determine what the heliostat tracking error is when the controllers work properly. However, since the controller problem is real and the heliostats continue to operate, the complete set of data were also analyzed. Both results are reported below.

Table III-XXII shows the heliostats on the Special BCS Measurement List, the BCS target used, and maintenance performed during the period when the special measurements were made.

Figures 3-48 and 3-49 show beam centroid errors versus the time of day for the 95 heliostats on the Special List. The data were taken on October 24 and 25, 1986, and then a bias update was made. Figures 3-50 and 3-51 show the errors for the same heliostats for several months after they were bias updated. Because the heliostats were measured several times after the bias update, there are more data points for the period after the bias update. During this measurement period the heliostats were not bias updated so it could be determined how the errors change with time. The plots clearly show less scatter in the data after the bias update and indicate that time of day is not very significant, although Figure 3-50 shows a slight upward slope for the X-centroid error versus time of day. Figures 3-52 and 3-53 show the wind speed and direction that goes with the data in both figures and the predominant direction for wind speed above 5 mph is either

Helio No.	Target	Heliostat Maintenance	Helio No.	Target	Heliostat Maintenance
203	N		213	E	
204	N	HC 11/27/85	214	W	
231	S	AZ MTR, HC 12/7/85	221	E	HC 11/22/85
232	S	HC 11/24/85	222	W	
609	N	HC 11/25/85	621	E	AZ ENCR 9/20/85
643	S	AZ&EL MTR 12/23/85	622	W	
644	S		629	E	
910	N		630	W	
1005	N	AZ MTR, HC 12/23/85	1027	E	
1006	N		1028	W	
1015	N		1039	E	
1016	N		1040	W	
1057	S		1051	E	
1058	S	AZ MTR 12/3/85	1052	W	
1067	S		1727	E	
1068	S		1728	W	
1463	S		1733	E	AZ ENCR 12/14/85
1464	S		1734	W	
1703	N	HC 11/21/85	1743	E	
1711	N	EL ENCR 9/15/85	1744	W	HC 12/2/85
1712	N	HC 12/3/85	1749	E	AZ ENCR 9/9/85
1719	N		1750	W	
1720	N		1757	E	
1773	S	HC 11/22/85	1758	W	HC 11/23/85
1774	S	AZ MTR 1/2/86	1763	E	HC 11/22/85
1775	S		1764	W	HC 11/23/85
1776	S		2135	E	HC 11/22/85
1875	S		2136	W	
1876	S		2145	E	HC 12/8/85
2123	N		2146	W	
2124	N		2157	E	
2403	N		2158	W	
2404	N		2167	E	
2415	N		2168	W	HC 11/24/85
2416	N	HC 12/3/85	2173	E	
2709	N	HC 11/21/85	2174	W	HC 11/24/85
2410	N	AZ ENCR 10/1/85	2185	E	
2905	N		2186	W	
2906	N	Mirrors 12/15/85	2435	E	
2915	N	HC 11/21/85	2436	W	
2916	N	Mirrors 12/15/85	2443	E	
			2444	W	HC 12/2/85
			2451	E	
			2452	W	
			2461	E	
			2462	W	
			2735	E	
			2736	W	
			2743	E	
			2744	W	
			2761	E	HC 11/20/85
			2762	W	
			2945	E	HC 11/21/85
			2946	W	

NOTES

1. AZ=Azimuth
2. EL=Elevation
3. HC=Heliostat Controller
4. MTR=Motor
5. ENCR=Encoder
6. N=North
7. S=South
8. E=East
9. W=West

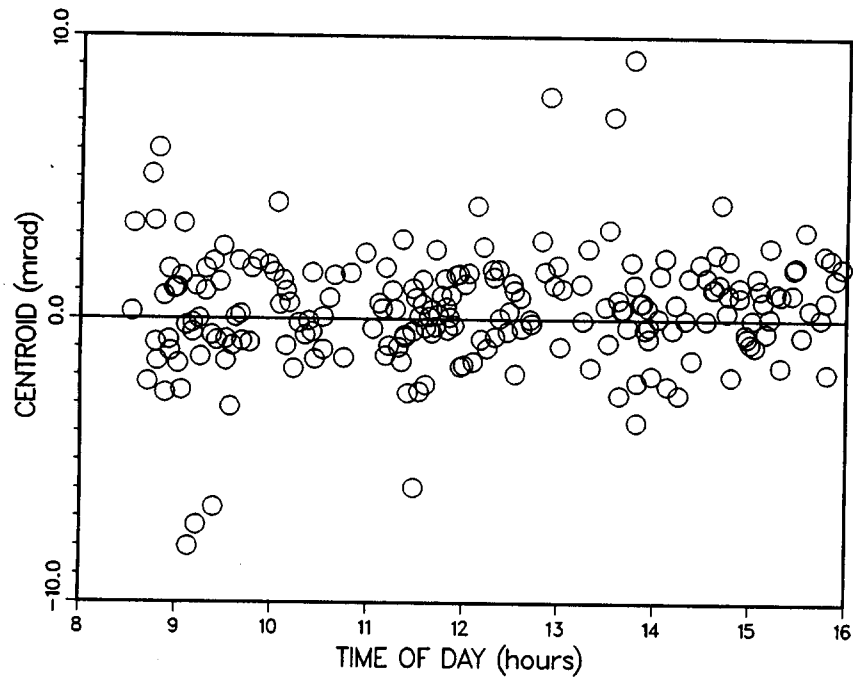


Figure 3-48. Y Centroid of BCS Data Before Bias Up-date

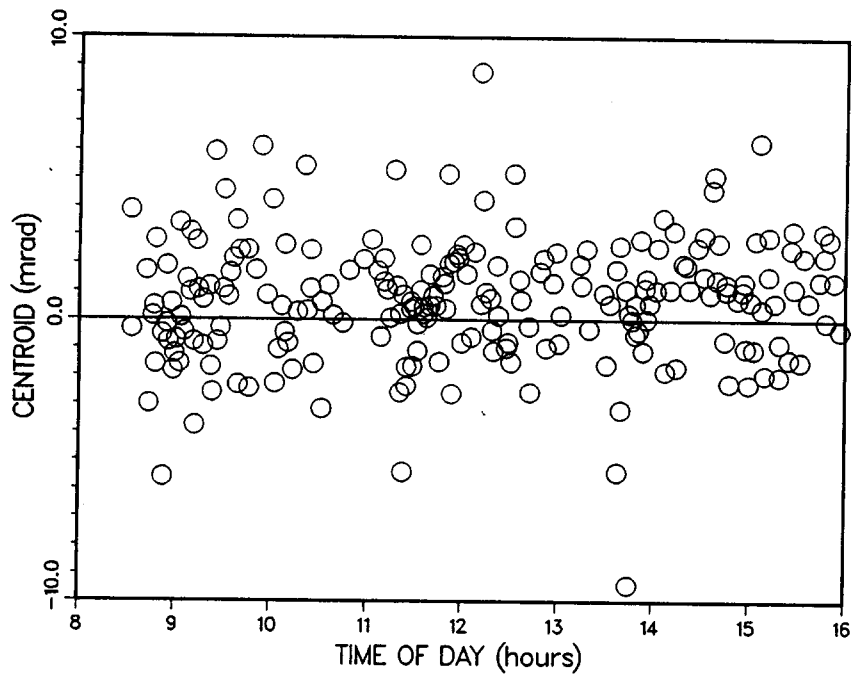


Figure 3-49. X Centroid of BCS Data Before Bias Up-date vs. Time of Day

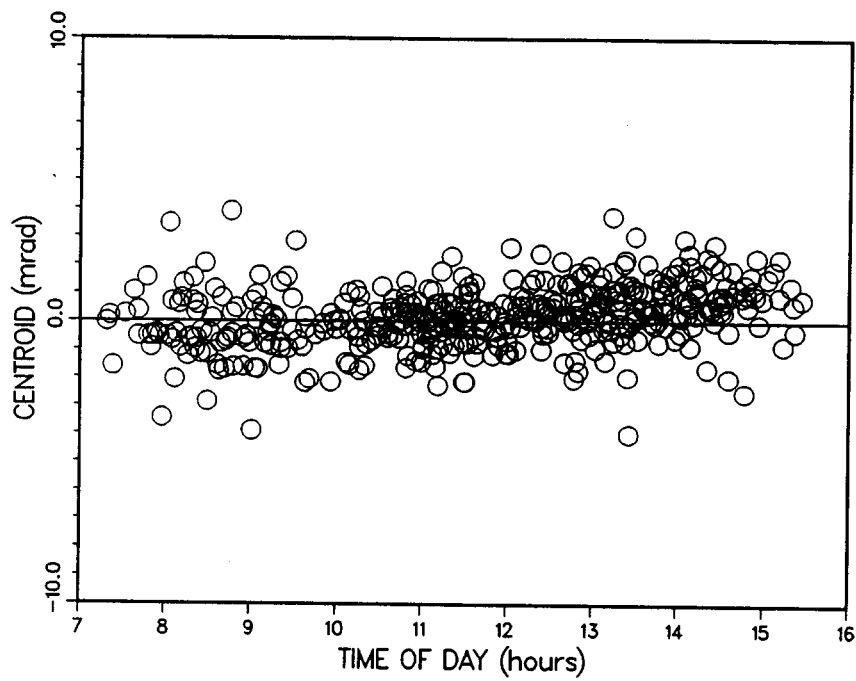


Figure 3-50. X Centroid of BCS Data After Bias Up-date vs. Time of Day

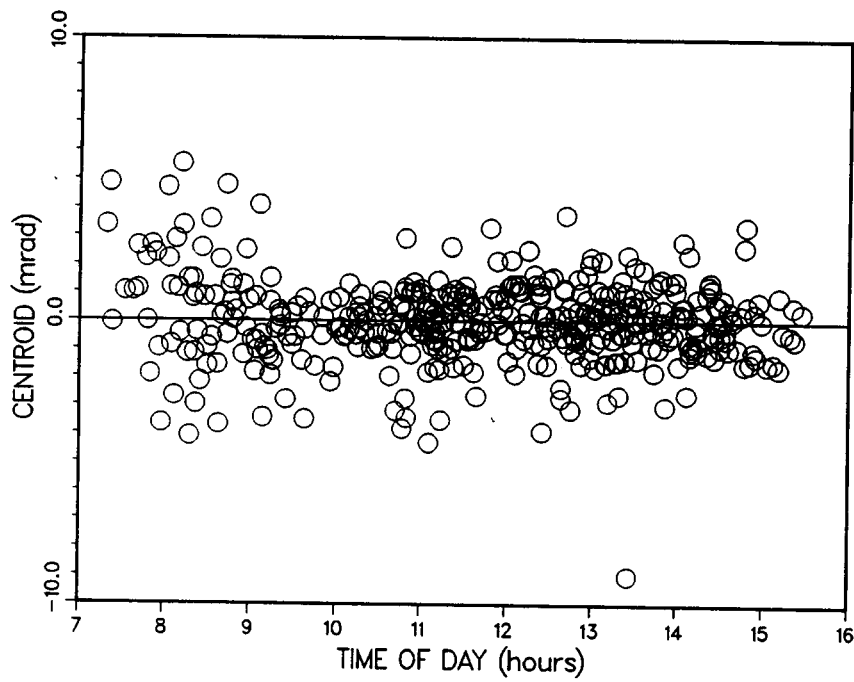


Figure 3-51. Y Centroid of BCS Data After Bias Up-date vs. Time of Day

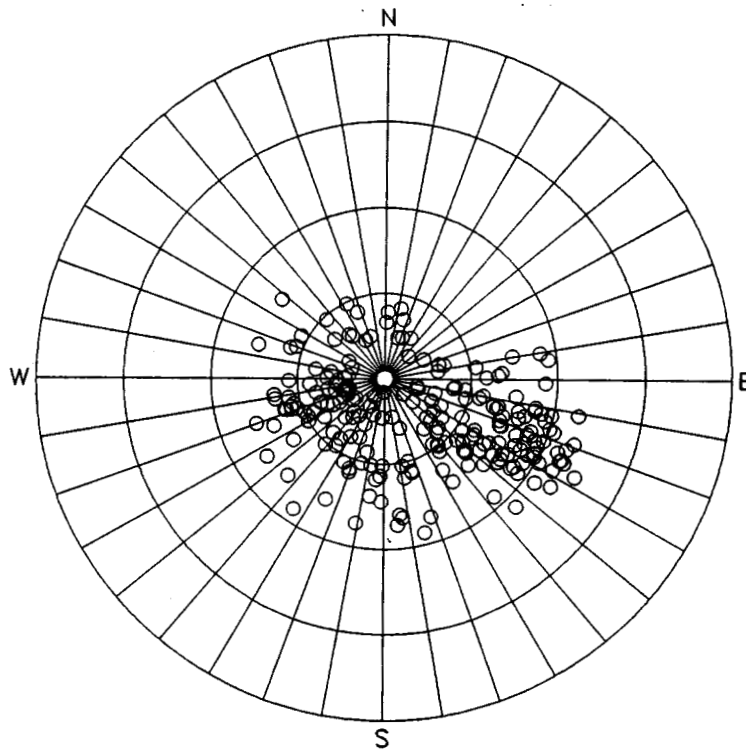


Figure 3-52. Wind Speed and Direction of BCS Data Before Bias Up-date

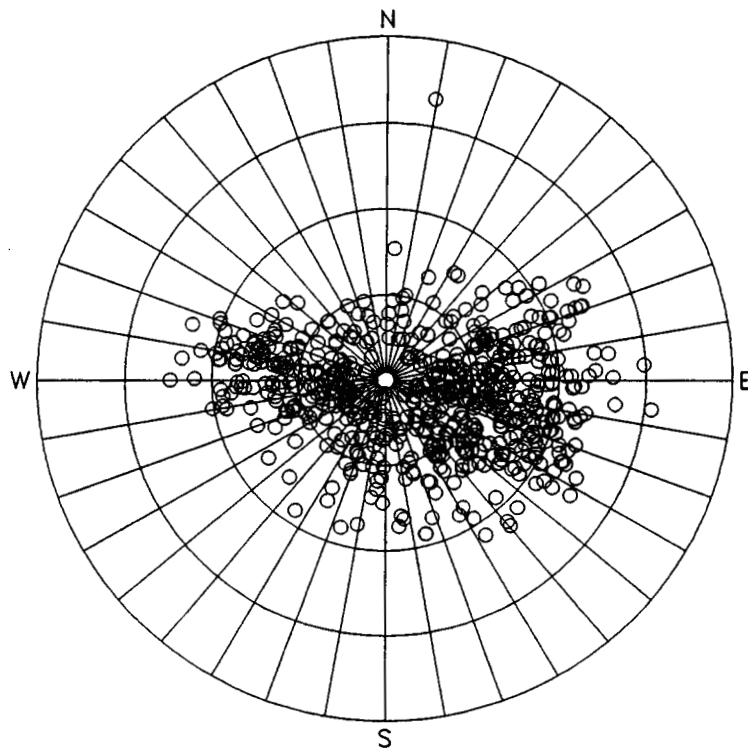


Figure 3-53. Wind Speed and Direction of BCS Data After Bias Up-date

from the east or west. The pointing error versus wind speed is discussed below but errors versus wind direction were not determined.

The statistics for the data in Figures 3-48 through 3-51 are given in Table III-XXIII. The first two columns show the improved pointing accuracy after the bias update. The mean error decreased to an insignificant value, and the one standard deviation pointing error decreased to 1.3 and 1.65 mrad for the X and Y errors, respectively. The power effectivity, which is equivalent to the mirror reflectivity if there is not atmospheric attenuation, also improved after the bias update. However, this is due to the way the reflected power is measured rather than an actual improvement. The improvement occurs because the heliostat beams are more nearly centered on the pyrheliometers in the BCS target. The percent spillage increased after the bias update due to an operator error during one of the measurement days. The operator forgot to switch to the normal aimpoints after the morning startup when the heliostats are re-aimed at the slow warm-up receiver panels. This causes the BCS to miscalculate the spillage since the BCS always assumes the aimpoint is on the radial line between the heliostat and the center of the receiver. The spillage was decreased on all other measurement days as will be shown in a later table.

TABLE III-XXIII
BCS DATA BEFORE AND AFTER BIAS UPDATE

	Before Bias Update	After Bias Update	After Bias Update vs Windspeed				After Bias Update vs Time		
			0-5 mph	5-10 mph	10-15 mph	15-20 mph	A.M.	Noon	P.M.
Tracking Errors									
Mean Error-X									
Inches	7.9	1.9	1.4	2.3	1.5	5	- 3.1	1.9	6.6
MRAD	.7	.2	.16	.22	.17	.79	- .28	18	.66
Mean Error-Y									
Inches	6.01	- .71	- .1	- 1.2	- .28	- .86	- 3.2	1.3	- .3
MRAD	.64	.02	.03	-.08	.08	-.14	-.11	.098	- .057
1 Std Dev Error-X									
Inches	23	12.2	12.6	12.3	9.9	7	11.4	10.5	12.4
MRAD	2.63	1.3	1.31	1.31	1.15	1.11	1.26	1.104	1.33
1 Std Dev Error-Y									
Inches	24	13.8	12.5	15	11.9	5.06	16.1	12.2	12.3
MRAD	2.73	1.65	1.34	1.81	1.82	.81	2.04	1.31	1.51
Pwr Effectivity	77	87.9	88.5	87.1	91.3	62.5	91.1	87	85.6
Percent Spillage	.56	2.2	3.1	1.9	.93	0	3.9	2.7	.17
Wind Speed									
(mph)	5.8	6.3	3.4	7.3	11.4	16	6.7	5.8	6.4
Data Points	220	429	160	223	44	2	140	141	148

Also shown in Table III-XXIII is the effect of wind speed and time of day on heliostat errors. The mean errors are negligible at all wind speeds while the one standard deviation errors change only slightly. The one standard deviation pointing error in the X-axis actually decreased above 10 mph while in the Y-axis it increased from 1.34 mrad at 0-5 mph to 1.81 between 5 and 15 mph. The lack of more data points above 15 mph probably accounts for the severe drop off above 15 mph. The mean errors versus time of day are small but the error in the X-axis is slightly larger in the morning and afternoon than around noon, and the one standard deviation error is also smallest around noon. Morning measurements should normally be made between 9:00 and 11:00, mid-day measurements between 11:00 and 1:00, and afternoon measurements between 1:00 and 3:00. However, it is not unusual for the BCS to be started as early as 7:30 a.m. and to not be completed until 3:30 p.m.

Table III-XXIV and Table III-XXV tabulate the results of BCS measurements taken on the special list of heliostats for several months after a bias update. Table III-XXIV is for heliostats measured on the north and south BCS targets, and Table III-XXV is for the east and west targets. None of these heliostats were bias updated during this period so that any changes over time could be identified. It is important to know if changes occur over time so that bias updates can be made before plant performance suffers. Again, heliostats that were not operating correctly were not included in the statistics. The data show that there were no significant changes in the tracking errors during this measurement period. The mean errors are no larger than the BCS resolution, and the standard deviation errors are well within the accuracy of the BCS.

TABLE III-XXV
BCS DATA VS TIME AFTER BIAS UPDATE
E-W TARGETS

E-W BCS Targets				
	E-W Date Before Bias Update	All Date After Bias Update	E-W 2.5 Months After Bias Update	E-W 4 Months After Bias Update
Date	10-25-85	10-27-85/ 4-19-86	1-8-86	3-4-86
Mean Error-X				
Inches	8.4	1.9	1.89	-.05
MRAD	.705	.197	.2	-.032
Mean Error-Y				
Inches	10.6	-.71	1.98	.15
MRAD	1.174	-.024	.227	.26
Std Dev Error-X				
Inches	23.2	12.2	11.7	11.8
MRAD	2.68	1.3	1.31	1.2
Std Dev Error-Y				
Inches	27.6	13.8	13.6	13.4
MRAD	3.08	1.65	1.75	1.63
Pwr Effectivity	78	91.1	86.1	92.8
Percent Spillage	.44	2.21	9	.51
Wind Speed (mph)	5.9	6.3	5.8	5.5
Data Points	115	429	95	56

TABLE III-XXIV
BCS DATA VS TIME AFTER BIAS UPDATE
N-S BCS TARGETS

N-S BCS Targets					
	N-S Date Before Bias Update	All Date After Bias Update	N-S 2 Months After Bias Update	N-S 4 Months After Bias Update	N-S 5 Months After Bias Update
Date	10-24-85	10-27-85/ 4-19-86	12-25-85	2-28-86	4-19-86
Mean Error-X					
Inches	6.11	1.9	2.67	-.43	4.62
MRAD	.492	.197	.31	-.02	.423
Mean Error-Y					
Inches	.36	-.71	2.66	-2.1	-6.3
MRAD	-.062	-.024	.28	-.143	-.673
Std Dev Error-X					
Inches	23.9	12.2	11.2	12.4	13.3
MRAD	2.68	1.3	1.26	1.34	1.32
1 Std Dev Error-Y					
Inches	23.1	13.8	16.3	12.5	10.4
MRAD	2.81	1.65	1.83	1.53	1.2
Pwr Effectivity	81.2	87.9	103	84	81.6
Percent Spillage	.97	2.21	.26	.29	.11
Wind Speed (mph)	5.8	6.3	5.2	7.7	7.1
Data Points	125	429	97	97	86

Beam Quality

Beam quality, the actual flux density distribution of the reflected heliostat beam on a target, is a measure of the optical performance of the reflecting surface of a heliostat (See Reference 40). The beam quality of the Solar One heliostats was evaluated at the CRTF for prototype and preproduction heliostats. The primary objective of the evaluation was to obtain measured beam quality data and to use these data in conjunction with analysis to determine compliance with the specified requirements as well as to determine the correct error value to use for field performance calculations. The theoretical beam quality was determined using the HELIOS computer code. The method of analysis and the evaluation results are presented below.

Beam Quality Specification

The beam quality specification used in evaluating the Solar One heliostats is defined in Appendix III. The specification is defined in terms of a theoretical contour to which an allowable margin or fringe is added. The theoretical contour was determined with the computer code HELIOS and is defined as the isoflux density contour on the BCS target that contains 90% of the power from the heliostat. The fringe was added by extending the 90% contour by 1.4 mrad (measured from the center of the beam). The new contour, defined by adding the fringe, had to contain 90% of the power from the heliostat if the specification was to be met.

Theoretical Beam Shape

Several parameters must be defined in the HELIOS model in order to determine the theoretical 90% contour that corresponds to each BCS measured test case. First, the physical dimensions and geometry of the heliostat must be defined. The technique used to align or cant the mirror modules with respect to each other (on-axis or off-axis) was also defined in the HELIOS model. Since the size of the 90% contour is also a function of the angular distribution of the radiant intensity of the sun's disc (sunshape), the sunshape was also measured during the BCS evaluation of a heliostat. These measured sunshape data are input to the HELIOS model to determine the theoretical contour. The remaining assumptions used in the model to determine the theoretical contour were that the mirror modules were perfectly flat and that there were no beam quality errors (mirror waviness, mirror canting error, gravity influence, etc). Once all of these parameters were identified for a particular test case, the specification contour was determined, and the measured data were compared to determine if the heliostat met specification for that particular case. This was a straightforward determination.

However, there are other aspects of the specification that complicate the problem of determining compliance.

The complete heliostat performance specification also requires that beam quality meet specification for a temperature range of 0 to 50°C for any position in the heliostat field and for any day of the year or time of day when the sun is greater than 15° above the horizon. Since gravity affects the heliostats reflecting surface differently at different elevation angles and since the mirror modules change focal length with temperature, it was necessary to use HELIOS to evaluate performance under a variety of possible conditions.

Beam Quality Error Sources

There are several reasons why the beam quality of an actual heliostat may be less than ideal. It is somewhat difficult to separate these error sources into completely independent factors. However, Figure 3-54 illustrates the primary sources of heliostat beam quality error.

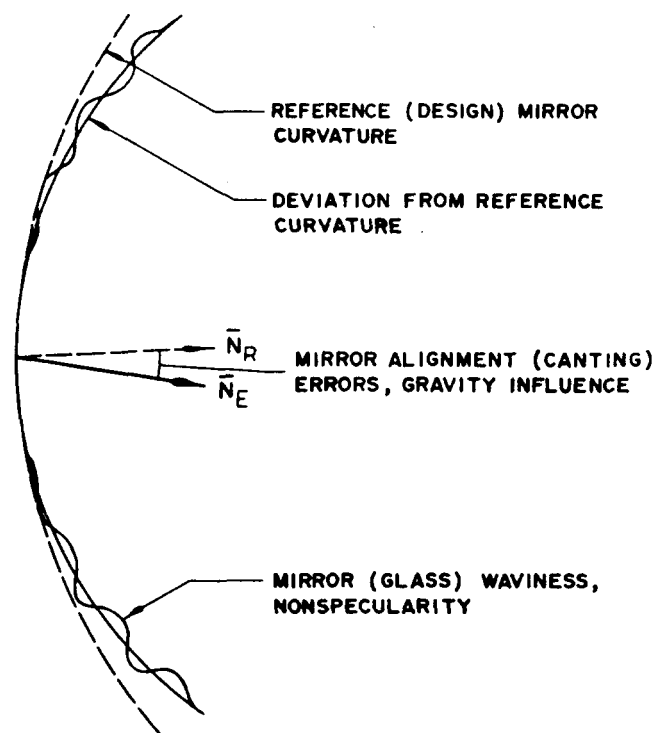


Figure 3-54. Heliostat Beam Quality Error Sources

Reference Mirror Curvature

Prior to fabrication of mirror modules, the manufacturer defines a desired reference (design) curvature. In addition, he may define a tolerance about this reference that is acceptable. Martin Marietta chose a spherical shape with a 1200 ft

focal length for Solar One. However, in production there was a significant deviation from one module to the next as a result of manufacturing tolerances in tooling and fabrication processes. For a heliostat composed of several mirror modules or for a heliostat field composed of thousands of mirrors, this curvature deviation from the reference curvature is a primary source of beam quality error that is most easily treated in a nondeterministic or statistical sense in a performance code such as HELIOS.

Mirror Waviness

Mirror “waviness” is the term that is often used to describe mirror slope errors that manifest themselves on a smaller spatial scale than the large-scale curvature deviations described above. This “waviness” may be the result of striations on the glass surface produced during the manufacturing process, distortion of the mirror surface caused when it is bonded to another material or substrate, or any other mechanism that produces a nonspecular reflection. During the Solar One preproduction heliostat testing, this small-scale waviness was measured using a laser ray trace scheme. The mirror modules were measured by taking three scans along both the short and long dimension of the mirror. Figure 3-55 illustrates a typical set of data for two scans on a preproduction mirror module. The periodic data across the short dimension of the module were the result of waviness that was unknowingly milled into the mirror module bonding tool. This periodic waviness was eliminated prior to production of the Solar One mirrors.

During the analysis of the laser ray trace data, the influence of the large-scale curvature of the mirror module was removed by assuming that the large-scale curvature could be modeled by a parabolic curve. A least-squares fit to the data taken along each scan was generated. Using this parabolic fit, the large-scale curvature influence was subtracted prior to obtaining a value for the rms waviness for the module. The rms waviness values for the Solar One production mirror modules was 0.49 mrad in the short direction and 0.58 mrad in the long direction of the mirror. Reference 42 contains a more detailed discussion of these data and of large-scale curvature measurements.

Mirror Module Alignment (Canting) Error

The other major factor influencing the optical performance (beam quality) of an entire heliostat is the alignment or canting of one mirror module relative to the other mirror modules on the heliostat. After completion of this canting the mirror modules are typically in one of two configurations: an on-axis alignment or an off-axis alignment. The Solar One mirrors are canted on-axis; they approximate a spherical surface. In this case, the normals to the center of each mirror are orthogonal to the surface of an imaginary sphere with a desired radius of curvature. At Solar One all of the heliostats are canted for a focal length of 365.74 m

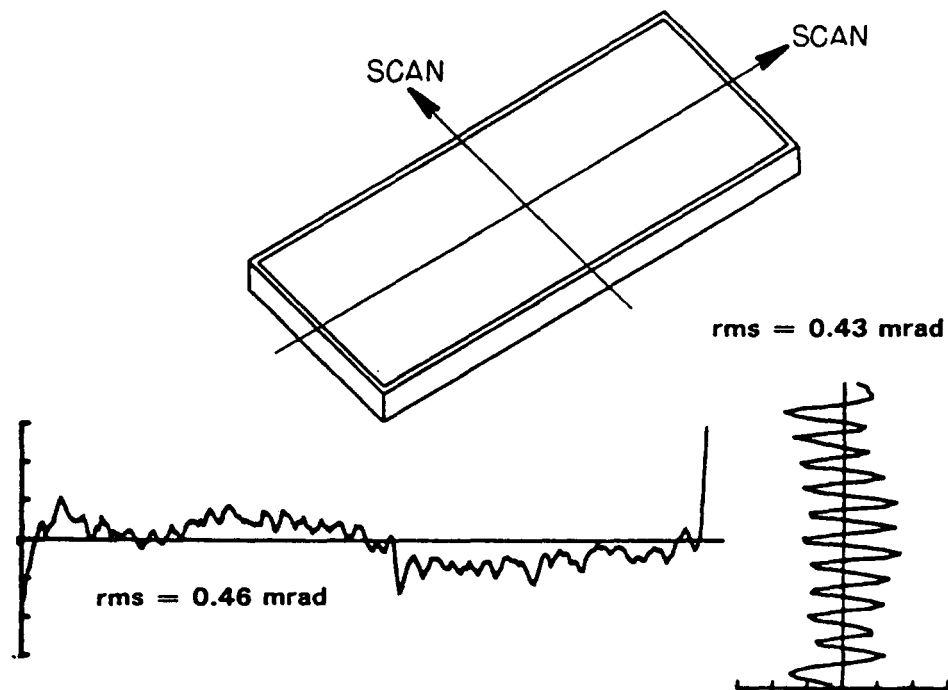


Figure 3-55. Typical Mirror Waviness Data on Preproduction Solar One Mirror Modules Using Laser Ray Trace Technique

(1200 ft). The canting error is due to errors in alignment as a result of the particular mechanical procedure used to position the mirrors during final assembly of the heliostat.

In addition to mirror canting errors introduced during assembly, effective canting errors are introduced by the influence of gravity on the heliostat structure. At different elevation angles of the heliostat, the influence of gravity alters the relative direction of the normal vector to each mirror module in a manner related to the structural rigidity of the heliostat. A stress-analysis computer code was used during the second generation heliostat test program to model the second generation heliostats. This code was used to predict the influence of gravity on mirror module canting, and these results were then used in the optical model HELIOS to evaluate the impact of gravity on the predicted beam size. Detailed results from the stress code are given in Reference 43. HELIOS beam size predictions showed that the beam sizes increase by 1 to 10 percent for representative elevation angle changes. The Solar One heliostat was not analyzed; however, similar results are expected since the structural rigidity is about the same.

Preproduction BCS Beam Quality Data

The BCS at the CRTF was used to measure the actual flux density distribution of the beam on the target for two Solar One preproduction heliostats and one production heliostat (See Ref. 17). Several beam measurements were made for each heliostat at different times of day to assess optical performance at different angles of incidence. In matching the BCS-measured data with HELIOS predictions, we considered a horizontal and a vertical slice through the beam, and the isoflux contour that contained 90% of the total beam power. Figure 3-56 indicates the isometric view of a heliostat beam. A measured beam matched when a good visual comparison between HELIOS and the BCS data was obtained for the two beam slices and the 90-percent contour indicated in this figure. Figure 3-57 gives the matched data for preproduction Heliostat No. 1. Analysis of other measured cases resulted in the error distribution standard deviations given in Table III-XXVI. The values in this table give the standard deviation in milliradians of the circular normal error distributions in the reflected ray reference system that gave a reasonable match to the majority of the BCS measured cases for each heliostat.

Comparison of the standard deviation values determined for beam measurements before and after life cycling indicated no observable change in beam quality during the three-month test period at the CRTF.

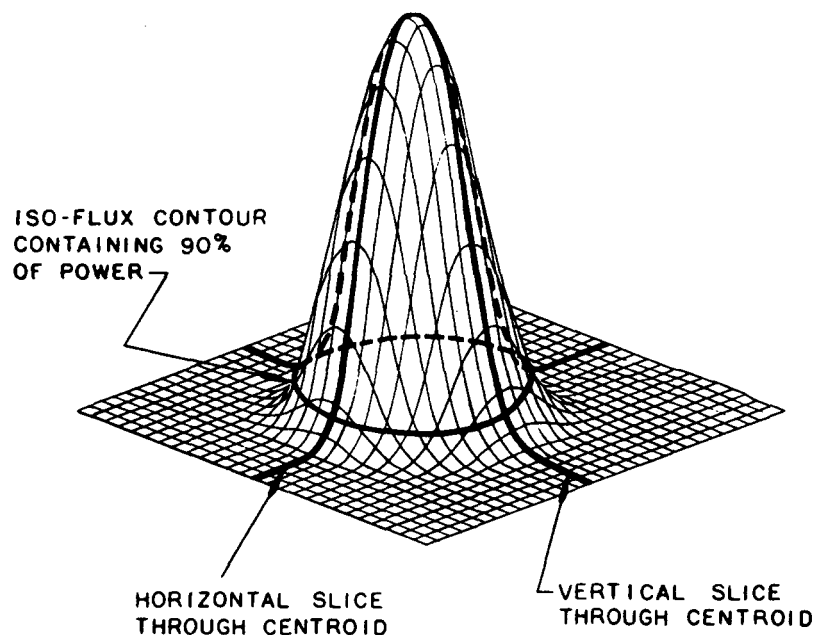


Figure 3-56. Beam Characteristics Used During BCS/HELIOS Analysis of Measured Data

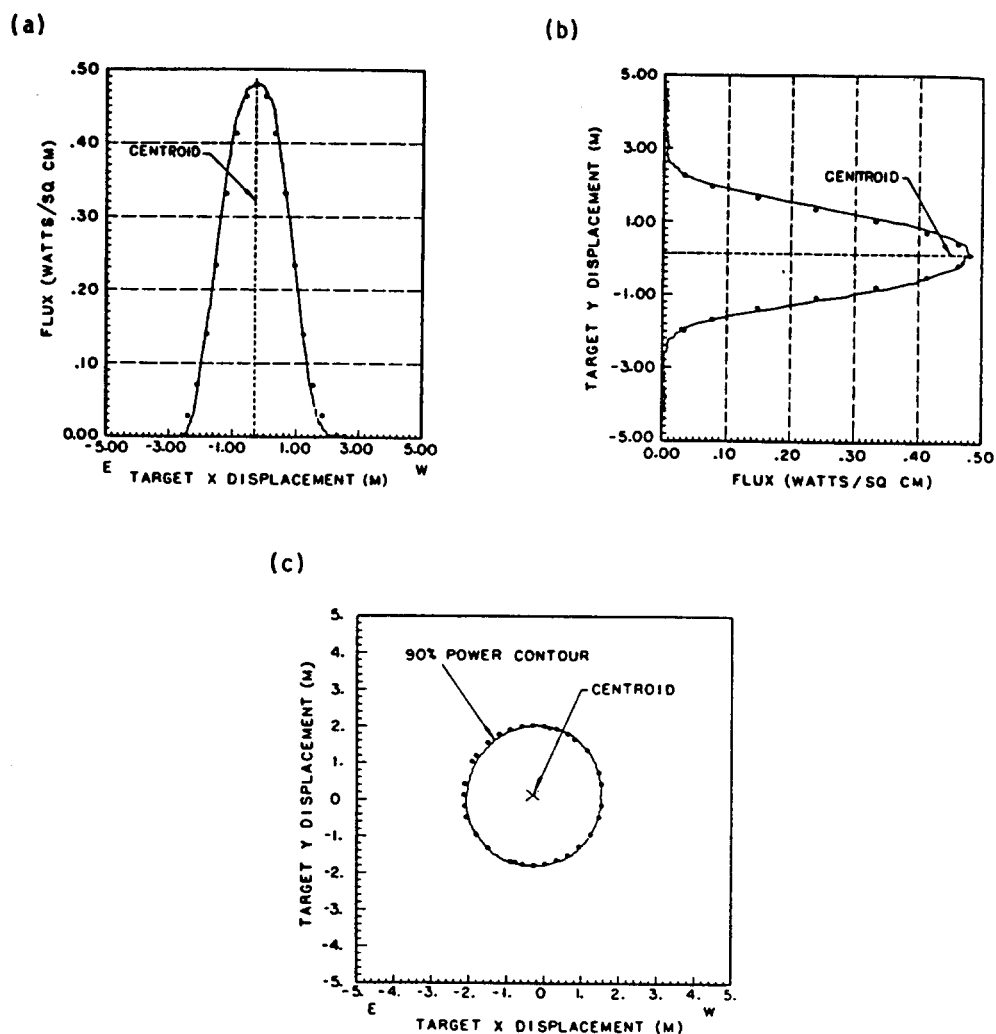


Figure 3-57. Comparison of Preproduction HelioStat No. 1 BCS and HELIOS Data for (a) a Horizontal Slice and (b) a Vertical Slice Through the Beam Centroid, and (c) an Isoflux Density Contour Containing 90% of the Power

TABLE III-XXVI
HELIOS ERROR DISTRIBUTION STANDARD DEVIATIONS
FOR THE REFLECTED BEAM THAT BEST MATCHED
BCS MEASURED BEAM DATA

HelioStat	Standard Deviation
Preproduction No. 1	1.6 mrad
Preproduction No. 2	1.6
Production	2.2

SECTION IV

BEAM CHARACTERIZATION SYSTEM EVALUATION

Introduction

Early in the development of solar central receivers, it was recognized that some means of aligning, monitoring, and evaluating large numbers of heliostats would be required. To meet these objectives, a Digital Image Radiometer (DIR) was developed in 1974 at McDonnell Douglas Astronautics Company (MDAC). This was used to evaluate heliostats in desert tests conducted in 1974-1975 and in 1976-1977 at the Naval Weapons Center (Reference 35).

An improved version was installed in late 1977 at the MDAC Huntington Beach Solar Energy Test Facility and used to evaluate various mirror modules and heliostats. A similar device called the Heliostat Beam Characterization System (BCS), was developed at Sandia National Laboratories Central Receiver Test Facility in 1978, and was used extensively in the evaluation of various heliostat designs (References 36-40).

The basic DIR approach was originally selected because it offered very high resolution, high acquisition rates, real-time visual monitoring, used passive targets, required little maintenance, and was the lowest cost system, when compared to the use of calorimeters or arrays of moving or stationary point detectors mounted on the tower.

These advantages, coupled with the successful experience with the first DIR system at MDAC and Sandia, led to the selection of the DIR as the BCS at the Solar Thermal Central Receiver Pilot Plant. The basic system is shown in Figure 4-1. Additional requirements imposed on the system involved automatic operation, sophisticated integration with other subsystems, and a variety of options for acquiring, storing, and analyzing data. The principal uses of this system are to provide heliostat tracking errors for making tracking error corrections and for engineering evaluation of heliostat performance.

In addition to heliostat beam measurements, simultaneous measurements of the sun's radiance distribution are made with a specially modified video camera which tracks the sun. These data, coupled with the absolute measurements of incident irradiance, are used to compare actual and theoretical heliostat irradiance distributions. Additional radiometers located in the field as part of the data acquisition system determine the incident solar irradiance, which is used to establish heliostat reflective efficiency as measured at the BCS target.

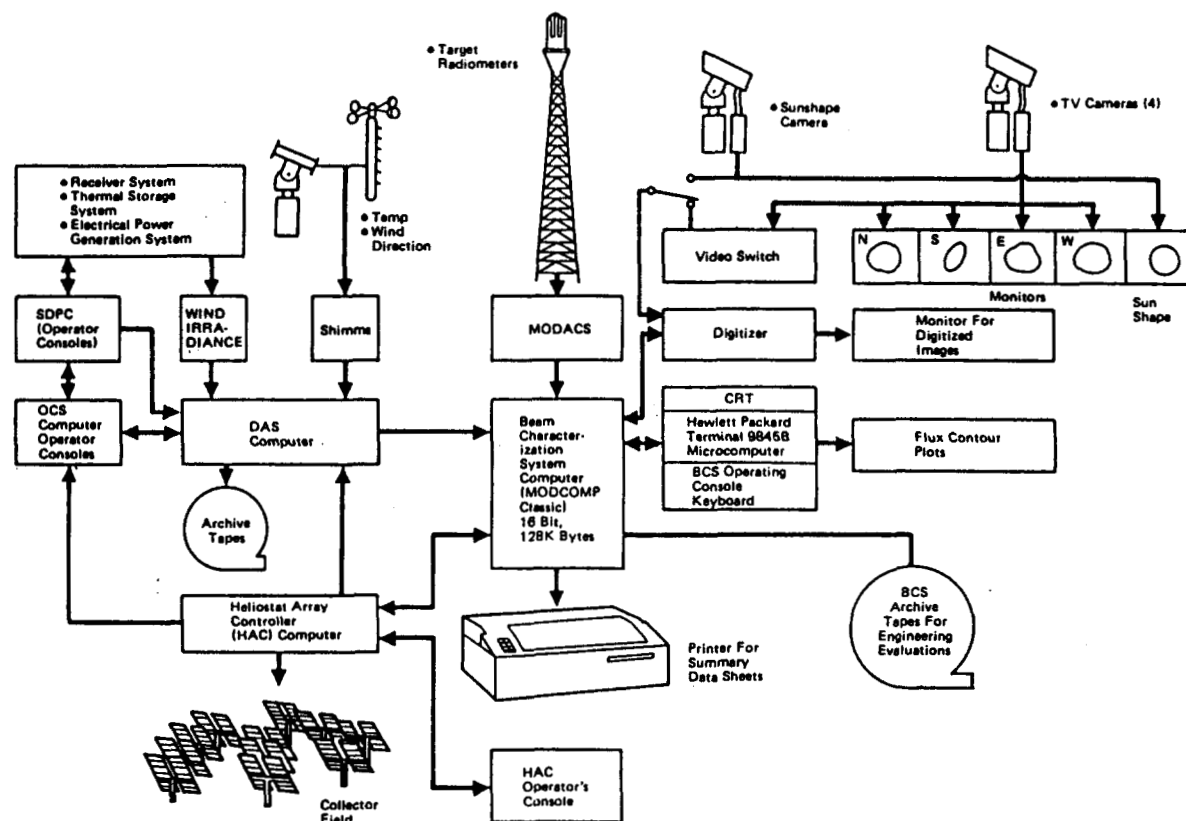


Figure 4-1. BCS Interface Block Flow Diagram Landscape

Beam centroid data are obtained to establish heliostat tracking errors, which are then corrected as necessary by changing bias values in the Heliostat Array Controller software. Supporting data on heliostat performance consist primarily of net power, tracking error variations, spillage power, and total incident power on the target. Environmental conditions required by the BCS are wind speed and direction, temperature, and solar irradiance. These data coupled with displays of the heliostat beam contour on the target and, as required, solar radiance distribution, are provided for operator usage and engineering evaluation.

The evaluation results show that the Pilot Plant BCS is an excellent tool for determining heliostat tracking errors; however, the measurement speed needs to be increased by a factor of 10 for a large solar plant, and improvements are needed for beam power measurements, and heliostat slope and alignment errors cannot be uniquely determined.

A summary description of the BCS is provided in Appendix III and Reference 34 provides a complete design description along with the detailed requirements. The evaluation results for the BCS are provided in the following paragraphs.

Operator Interface

Operator interface with the BCS has been minimized by (1) providing automatic data validity algorithms to verify that bias update data can be used by the HAC and (2) providing automatic responses of the BCS to message status inputs from the HAC. The operator is only required to initialize: BCS measurement candidate list generation; BCS operation at the start of a day; and start-up of the heliostat bias update routine after BCS data is taken. A review of the data should be done before a bias update although it is not required. Procedures for operating the BCS are detailed in the BCS Operator and User's Manual (Reference 41).

The BCS data are required for both tracking error bias updates and detailed engineering evaluation; therefore, the types of data displays vary from data summary sheets, which are scanned by the operator prior to bias updating, to detailed results of beam irradiance distribution over a field of 65,000 pixels with attendant sun shape data, and a complete set of environmental conditions.

The first level results are given as a "Summary of BCS Data," such as that shown in Table IV-I. The summary gives for each heliostat and time (each measurement):

- (1) The beam centroid error as a mean and standard deviation
- (2) Theoretical power from that heliostat, at that time, assuming 100% reflectivity, no atmospheric attenuation, and using the projected area of the heliostat with respect to the plane normal to the ray from the target center to the center of the heliostat
- (3) The "power effectivity" which is in theory the same as heliostat reflectivity except for atmospheric attenuation and scattering losses due to soiling, mirror waviness, solar radiance distribution in the circumsolar region, etc.
- (4) Invalid data flags, to caution the operator to examine the results prior to a bias update
- (5) Environmental conditions (solar insolation as measured by the Normal Incidence Pyrheliometer), wind speed, and temperature.

Generally, for bias update purposes, any power effectivity result which is reasonably close to the expected heliostat reflectivity is sufficient evidence that the centroid values are valid. Large errors indicate off-nominal occurrences such as no beam on target or multiple beams.

Whether or not bias updating will be applied requires that several conditions be met. For example, if the centroid error is small (less than 3 in), a bias update is not necessary. If the standard deviation of a centroid is large compared to the error, and wind speed is high, it is evident that wind induced heliostat oscillations are too large to justify a bias update. Low insolation values, especially values that change significantly from one run to another, imply cloud coverage, and thus bias updates would not be applied until further checks are made.

Table IV-I Summary of BCS data

Summary of BCS Data 9/13/83												
HEL No.	Centroid Average Time	Normalized Centroid and Standard Deviation (in.)		Theo Power (W)	Power Effectivity (%)	Std Dev Power (%)	Ave Spill Power (%)	Std Dev Spill Pwr (%)	Invalid Data Flags	INSOL (W/SQM)	Wind Speed (MPH)	Ambient Temp (Deg F)
		(Horizontal)	(Vertical)									
2903	12:13:41	19.9 ± 9.6	-9.0 ± 6.2	31125	86.0 ± 1.8	2.1	0.4	0.0	0000000000	886.2	6.8	98.2
2917	12:19:42	33.0 ± 5.4	29.1 ± 1.3	30603	83.4 ± 1.6	1.9	2.0	0.0	0000000000	884.3	7.2	98.5
2904	12:26:24	44.8 ± 4.2	68.5 ± 1.8	31363	72.0 ± 0.9	1.3	11.9	0.0	0000000000	887.0	9.7	99.1
2918	12:31:25	21.1 ± 4.2	-39.1 ± 9.5	31411	89.6 ± 1.2	1.3	1.1	0.0	0000000000	892.4	7.2	99.1
2803	12:37: 6	10.0 ± 6.1	-15.0 ± 1.2	31495	87.6 ± 1.1	1.3	2.0	0.0	0000000000	891.1	11.5	99.3
2817	12:43:50	7.5 ± 5.4	-13.7 ± 2.3	31132	84.7 ± 0.9	1.1	0.0	0.0	0000000000	886.9	5.7	99.3
					83.88 ± 6.2							

Invalid Data Flags Definition	
Position	Definition
1	The Horizontal or Vertical Centroid is Greater Than 150 In.
2	The Standard Deviation of the Centroid is Greater Than 2 Ft.
3	The Power Effectivity is Greater Than 140 or Less Than 60%
4	The Percent Std. Dev. of Effectivity is Greater Than 8.0%
5	Percent Std. Dev. of Measured Power is > 5.0%
6	Wind Speed is Above 25 mph
7	Irradiance Defaulted to 1000.0 Watts Per Meter Sq.
8	Default Cal Curve Used and Effectivity Set to 80 if Bit 3 Set
9	Background Update Factor Not Used. Default = 1.0
10	Sunshape Data Not Acquired

Trained operators are able to make evaluations rapidly using data such as that shown in Table IV-I. Plots of beam shape can be generated if additional data is needed to evaluate individual runs. A sample plot of a test run is shown in Figure 4-2. This run was made shortly after the heliostat (number 2404) was cleaned and its reflectivity measured. The measured Power Effectivity 89.9% compares favorably to the measured reflectivity of 91.8%. The beam shape corresponds to the isoflux contour which contains 90% of the total beam power. This is a transformed beam shape (i.e., normalized) as it would appear projected onto a plane normal to the central ray from the center of the heliostat to the center of the target. Overlayed on this beam is the view of the cylindrical receiver as seen from the heliostat; that is, in the normal plane. The normalized plot is required since heliostat beams are incident on a given target over the entire quadrant ($\pm 45^\circ$), and these oblique views of the beam do not correspond to the beam

Normalized Plot	
HCNUM	2404
Date	9/13/83
Time of Day	12:08
Centroid Error +/- Std. Dev. (Horiz.) . .	-6.73 +/- 2.82 In.
Centroid Error +/- Std. Dev. (Vert.) . . .	-22.26 +/- 7.67 In.
Theoretical Power.	31727.8 Watts
Power Effectivity +/- Std. Dev.	89.9 +/- 0.9%
Spillage Power.	0.0 +/- 0.0%
Insolation Level	888.4 W/M**2
Wind Velocity	3.85 mph
Temperature.	97.64 degf
Invalid Data Flags.	0000000010

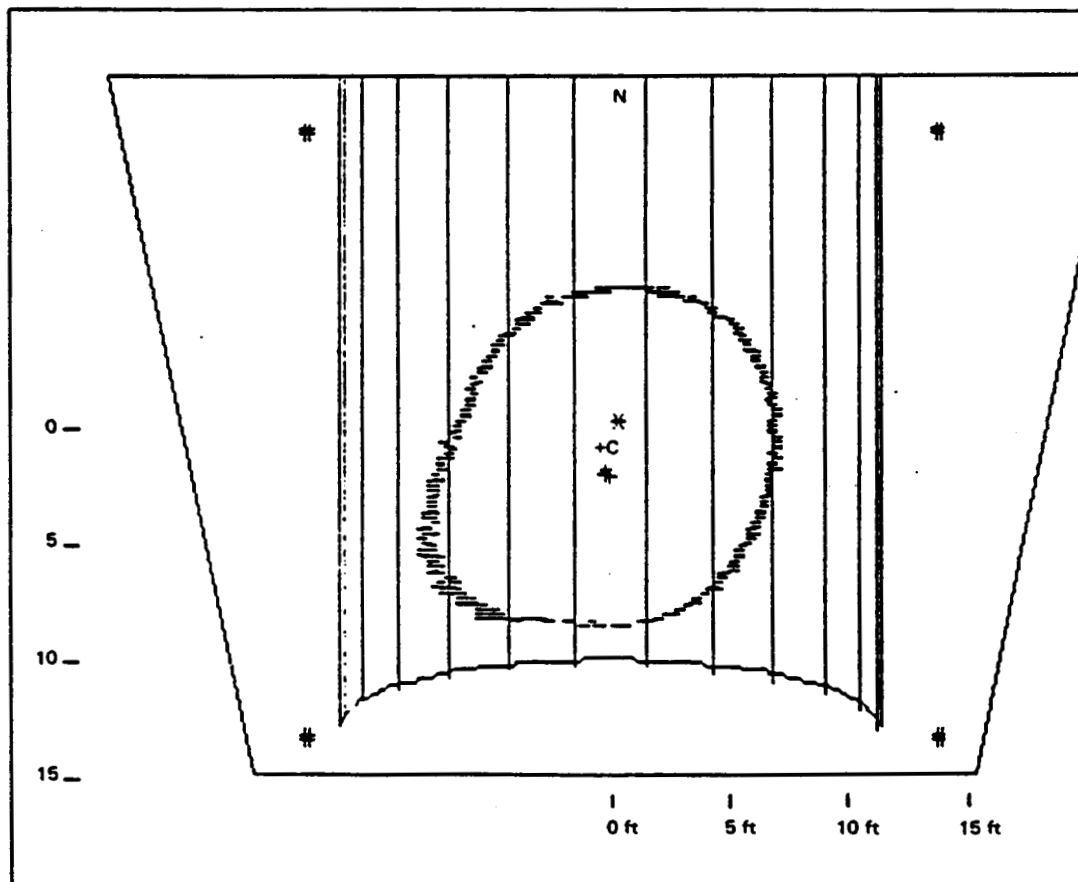


Figure 4-2. Typical Plot of Normalized Beam Relative to Receiver

distribution on the receiver. Receiver panels are also drawn as seen from the heliostat.

Only the last beam captured by the BCS is plotted, and "C" designates the centroid for this beam. The other four centroids that were measured in this run are shown as crosses (+). The aim point on the receiver surface is shown as the figure that looks like reversed parentheses with a dash between them. This aimpoint is changed by the HAC depending on receiver flux distribution requirements. The aimpoint shown corresponds to the aimpoint in use at the time the BCS run was made. The trapezoidal figure is the BCS target size and shape as seen from the camera. This is not transformed to appear as seen from the heliostat.

Figure 4-3 shows a beam for heliostat 2904 which has large aiming errors, and, consequently, spillage power (power that missed the receiver) is significant at 11.9%.

Figure 4-4 shows an abnormal condition in which two heliostats are reflecting light onto the target during the measurement. Annotations on the figure point out that the shape and power effectivity indicate inadvertent movement of a close-in heliostat beam across the target from left to right. This is an example of a condition which would render centroid data invalid automatically, and thus prevent an error in bias update.

Centroid Measurement Accuracy

Three methods were used (Reference 34) to establish that the BCS centroid measurement accuracy is of the order of ± 1 pixel for nominal test conditions. This corresponds to a centroid location uncertainty on the target of ± 2 in.

The first method involved the use of 1.0 x 2.0 in visually uniform white targets on a uniformly black background, placed approximately 10 ft in front of a BCS camera. Calculated centroids were compared with the geometric centroid and found to be within ± 1 pixel. This result eliminates errors due to beam or tower movement.

The second method involved the use of a 5 x 5 in mirror reflecting sunlight onto a target which was about 9 m in front of a BCS camera. In this case, the actual centroid could not be determined, but repeated measurements over a period of about a minute gave a centroid standard deviation. A series of 10 tests showed that the centroid standard deviation corresponded to ± 0.2 inches in X and 2.5 inches in Y. This test eliminates uncertainties due to target nonuniformity and beam movement.

The third method involved monitoring the standard deviation for a series of close-in heliostats tested under moderately low wind conditions of approximately 9 mph. Test results are shown in Table IV-II which shows a standard deviation in X and Y of 1.6 and 1.7 in, respectively. Testing close-in heliostats minimized the error due to beam movement, and results are conservative because of beam shape. A similar test was run on heliostat 2063, one of the outer heliostats, at a

Normalized Plot	
HCNUM	2904
Date	9/13/83
Time of Day	12:25
Centroid Error +/- Std. Dev. (Horiz.) . .	44.61 +/- 4.16 In.
Centroid Error +/- Std. Dev. (Vert.) . .	68.53 +/- 1.79 In.
Theoretical Power.	31363.1 Watts
Power Effectivity +/- Std. Dev.	72.0 +/- 0.9%
Spillage Power.	11.9 +/- 0.0%
Insolation Level.	887.0 W/M**2
Wind Velocity.	9.69 mph
Temperature.	99.14 degf
Invalid Data Flags.	0000000000

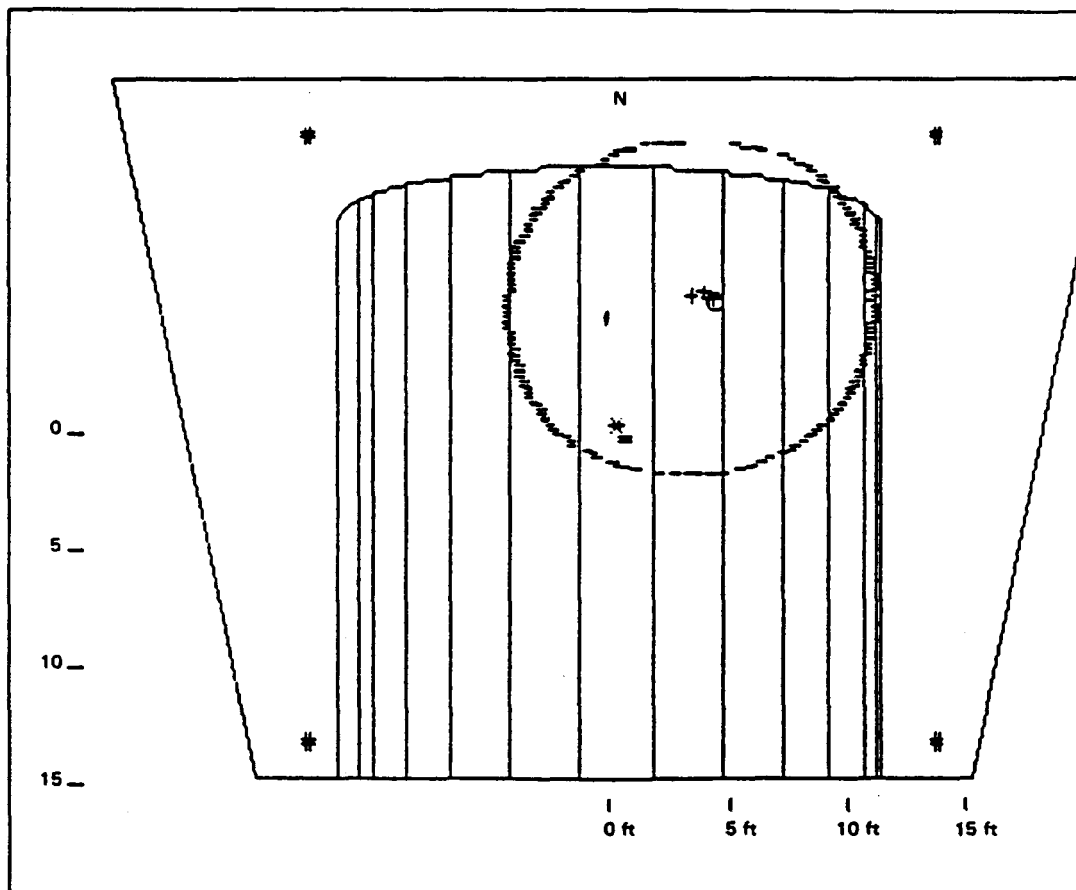


Figure 4-3. Typical Beam With Spillage

HNUM	2650
Date	7/8/83
Time of Day	13:7
Centroid Error +/- Std. Dev. (Horiz.)	3.67 +/- 12.83 In.
Centroid Error +/- Std. Dev. (Vert.)	-30.19 +/- 1.29 In
Theoretical Power.	23882.3 Watts
Power Effectivity +/- Std. Dev.	199.9 +/- 31.9%
Spillage Power.	6.0 +/- 3.6%
Insolation Level.	868.8 W/M**2
Wind Velocity.	5.59 mph
Temperature.	92.07 degf
Invalid Data Flags.	0011100110

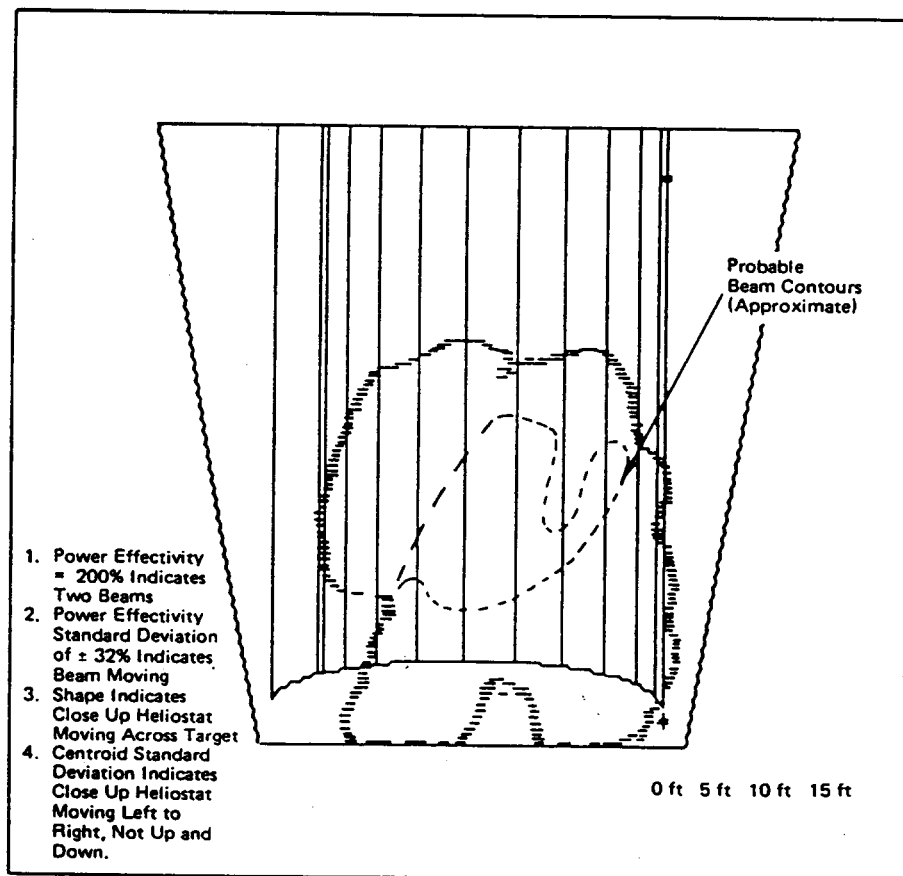


Figure 4-4. Second Heliostat on Target During Measurement Phase

wind speed of about 15 mph; the X and Y centroid standard deviations were 1.4 and 3.5 in respectively even for these relatively severe conditions.

Table IV-II
CENTROID STANDARD DEVIATION FOR RELATIVELY
LOW WIND SPEED CONDITIONS
Date: 4/21/84

Heliostat #	Standard Deviation X	Standard Deviation Y	Wind Speed
115	1.06	1.61	11.9
117	1.07	.95	8.1
121	.61	1.87	12.2
123	.75	1.2	10.1
125	.85	1.81	10.2
128	1.46	1.1	7.2
104	4.15	2.78	8.9
129	.78	2.1	5.7
130	.72	.92	6.4
106	2.98	1.75	6.1
131	.68	1.15	2.6
107	2.6	2.1	3.6
132	1.16	1.09	5.5
108	4.48	3.53	10.8
115	1.7	.93	5.5
117	1.04	1.61	3.8
119	.68	1.69	4.8
121	.3	1.19	5.6
123	1.35	1.39	9.9
125	.37	1.83	11.8
104	1.23	2.49	12.7
130	1.45	2.02	5.8
108	3.55	3.09	9.1
131	0.63	1.71	11.4
132	1.45	1.86	10.9
117	4.84	2.2	9.9
119	1.66	1.54	17.1
121	1.75	2.07	9.8
	1.6 in average	1.71 in average	8.5 mph average

The angular error associated with these centroid position uncertainties is of the order of ± 0.15 mr for heliostats at 1000 ft. Part of the uncertainty is due to wind or control system movement of the beam, tower movement, etc., and thus the BCS can provide centroid measurements that are an order of magnitude better than the heliostat requirement. Multiple centroid measurements are made for each heliostat (normally 10), so that beam movement effects can be assessed. If

the standard deviation is low, then centroid data is applicable for bias updating, assuming it is valid in all other respects.

Beam Power Measurement Accuracy

Accurate determinations of beam power are important for two reasons. First, beam power is needed to assess heliostat performance, to determine receiver spillage power, to assess the need for cleaning heliostats, and to evaluate plant performance. Second, power measurements are needed to assess data validity for heliostat bias updates. The latter reason is more applicable to normal plant operation. Generally, if the power measurement is accurate; centroid measurements are accurate. However, inaccurate power measurements do not necessarily invalidate centroid data because the major reason for inaccurate power is that the slope of the calibration curve is in error. Since this effect increases or decreases each irradiance value proportionately, the centroid location is not affected.

The most practical method of determining power measurement accuracy is to determine power effectivity (ratio of measured to theoretical power) for a particular heliostat over a day. The standard deviation is an indication of the measurement repeatability. However, this method does not determine the actual error, even if the heliostat reflectivity is known, because of uncertainties in the amount of beam power lost due to atmospheric attenuation and scattering at the heliostat. Both of these effects can be minimized by testing heliostats close to the target. However, since all of the heliostats have the same focal length, the mirror module beams have very little overlap for heliostats that are close to the target. As a result, beam irradiance is low, significant irradiance value variations can occur over a few inches, and the overall effect is to reduce power measurement accuracy for close-in heliostats.

Other errors include the effect of wind and tracking motion on beam movement at the target and the limitation of having a single pyrheliometer for solar irradiance measurement which, although located in the center of the field, is relatively far from the heliostats, and thus can not necessarily determine heliostat incidence irradiance accurately. Test with low winds and clear sky conditions eliminate most of this uncertainty.

A sample of a BCS data summary printout is shown in Table IV-I. These results are from a relatively low wind and high insolation day and are limited to heliostats with a long slant range. Measurement repeatability (for 5 to 10 runs over approximately 1 minute) is shown by the power effectivity standard deviation, which is usually less than 2%. The mean value for a series of heliostats is usually within ± 5 to 10% of the field average reflectivity, for clear sky, low wind conditions. Sequential power effectivity measurements on the same long-slant-range heliostat, over the course of a day, are typically within $\pm 5\%$. However, variations of $\pm 50\%$ are not uncommon, because of the peculiar beam shapes for close-in heliostats and the limited number of radiometers on the target.

The following system improvements would improve power measurement accuracy (these are relatively unimportant for centroid data):

- (1) Modification of the data acquisition system solar insolation sampling rate to acquire data more frequently and simultaneous with each power scan.
- (2) Addition of at least one more target radiometer to assure that relatively high irradiance regions of the beam strike at least one radiometer.
- (3) Data acquisition under low wind, clear sky conditions.
- (4) Measurement of heliostat reflectance on the same day or at least within a few days of the test.
- (5) Incorporation of software to assess calibration curve data scatter so that conditions leading to inaccurate results can be identified.

Sunshape Measurement Accuracy

A typical measured sunshape radial radiance distribution is shown in Figure 4-5. These radial radiance distributions, including the corresponding characteristic angle associated with a pixel and the calibration coefficient which transforms the DIR number (0 to 255) into radiance (W/m^2 steradian), are recorded on tape. Results are then used in heliostat analysis codes to calculate the effect that sunshape has on beam shape. The accuracy of this data is adequate for high insolation values when there is very little circumsolar radiation. However, when there is significant circumsolar radiation, the system sensitivity is not sufficient. The camera requires an insertible spot filter to increase the dynamic range by at least an order of magnitude.

Measurement Speed

As stated previously the BCS measurement speed is adequate for a small plant such as the Pilot Plant. However, for a larger plant, where there might be 4000 to 6000 heliostats, a much faster BCS will be required. The present measurement speed is between 150 and 170 seconds per heliostat (21 to 24 heliostats per hour). Which allows only 50 to 60 heliostats to be measured at three different times in a day, once in the morning, around noon, and again in the afternoon. For the Pilot Plant heliostats, these three measurement times are required so the tracking errors can be averaged to arrive at an error correction angle. Tracking errors vary over the day because of any or some combination of all of the following sources of error: pedestal tilt, nonorthogonal drive axes, drive backlash, encoder accuracy and resolution, errors in the position of the heliostat and target, and sun position errors.

A breakdown of the times required for each BCS operation is shown in Table IV-III. The estimated minimum time possible with software changes and new improved hardware is also shown. These times were arrived at by considering the use of state-of-the-art hardware and improved heliostat control strategies, such

Sunshape Radial Distribution Data

HCNM	134
Date	10/2/83
Time of Day	11:46
Sun Angle in Milli-Radians/Pixel	.092
Brightness in W/M**2 - Steradian-Dir No.	84265.4

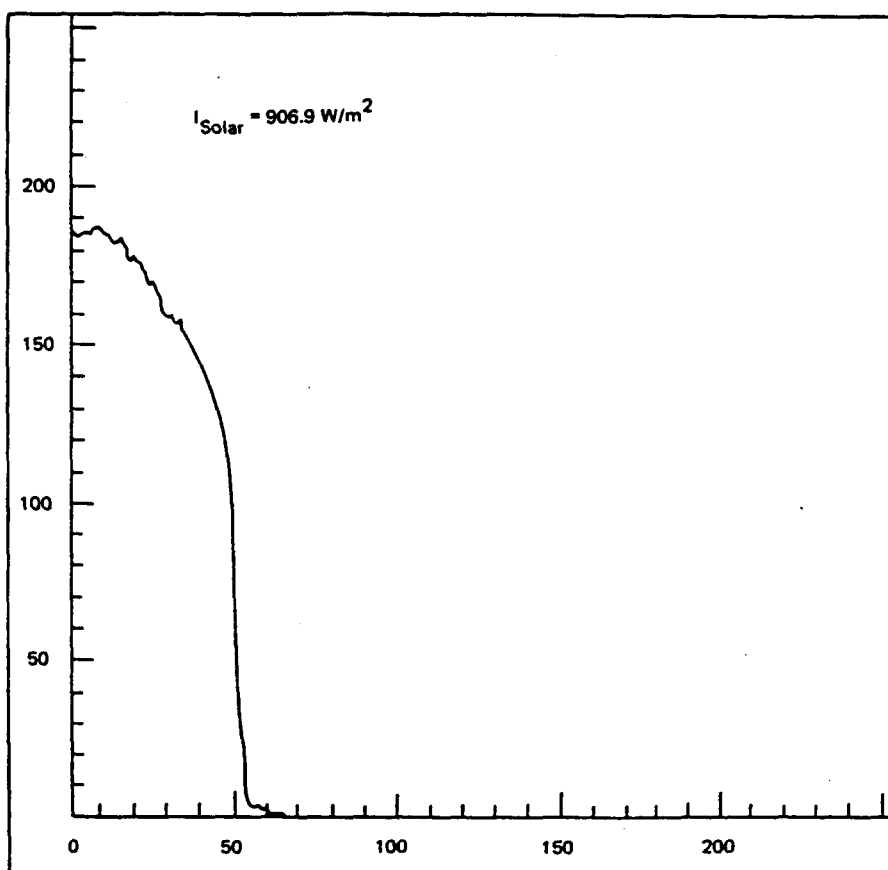


Figure 4-5. Typical Radial Distribution of Radiance

as having all blocking and shadowing heliostats in a stow position before measurements are started. The strategy now used moves the blocking and shadowing heliostats after the heliostat to be measured is directed to go onto the BCS target. As the table shows, the present system can be improved by at least a factor of 10 which would allow 300 heliostats to be measured in an hour and 500 to 600 at three different times in a day.

Table IV-III
BCS MEASUREMENT TIMES

BCS Operation	Time Required (seconds)	Minimum Time (seconds)
1. Image Grab, 10 times	.33	.1
2. Read & Digitize, 10 times	10	.05
3. Jump to Memory, 10 times	10	.05
4. Time to Move Heliostat	10 to 30	10.0
5. Background Measurement	12	.6
6. Camera Iris Setting	10	.2
7. Data Analysis, 10 times	100	1
Totals	152 to 182	12

SECTION V

LESSONS LEARNED

This section discusses the major lessons learned relative to the Collector Subsystem and Beam Characterization System (BCS) at the pilot plant. Table V-I summarizes the collector subsystem lessons learned since the heliostats were installed and Table V-II covers the BCS. A brief discussion of each item follows the two tables.

TABLE V-I
COLLECTOR SUBSYSTEM LESSONS LEARNED

<u>Lessons Learned</u>	<u>Comments</u>
1. Heliostat maintenance cost is not a major concern.	Component burn-in may have helped. Maintenance costs are less than predicted.
2. Heliostats can be maintained with conventional maintenance skills, and control only requires an operator's attention on an exception basis.	Electricians, instrument technicians, and mechanical technicians--control requires less than one quarter of an operator's time.
3. Glass pitting from sand has not occurred.	Mirrors are stowed horizontally during high winds.
4. Vertical stow over a 37 month period has not been a problem.	Horizontal stow is used during high winds.
5. Heliostat beam-safety has not been a problem.	Control of relected beams is required. Heliostats are normally stowed and unstowed after dark and before sunrise, respectively.
6. Mechanical mirror washing will be required to maintain plant efficiency - a spray rinse is not adequate.	Dirt accumulates during periods of low rainfall and after 1 to 2 years without a mechanical wash.

TABLE V-I (continued)

<u>Lessons Learned</u>	<u>Comments</u>
7. The following items should be completed before heliostat installation begins: a. Data cabling to each heliostat b. Power to each heliostat c. Control room available for permanent heliostat control console d. BCS installed (includes targets).	Reduces heliostat installation and checkout costs
8. Heliostat tracking errors can be determined by visual observation.	The pilot plant field has operated for 2.5 years with visually determined tracking errors.
9. Moontracking is an effective method to identify misaligned mirrors & large tracking errors.	Moontracking software and aimpoints are required
10. Morning, noon, and afternoon tracking errors are required to make tracking error corrections.	Tracking errors vary with time of day and not all heliostats track with the same error profile
11. Mirror silver corrosion will occur if water is in direct contact with paint or copper layers which protect the silver. Laminate glass mirrors show promise for very long life.	The type of mirror module construction used at the pilot plant is very difficult to seal against water intrusion.
12. Adhesives and sealants require good quality control during production.	Preparation of the bonded or sealed surfaces is critical, and proper mixing and curing of the adhesive is important.
13. Heliostat field wiring requires proper grounding and shielding to prevent lightning damage	A nearby lightning strike damaged heliostat control electronics prior to proper grounding
14. Plant start-up and checkout require a high heliostat operational wind speed to reduce lost time.	Operation to 45 mph can significantly increase operating time during windy periods.
15. Noise separation between d.c. motors and HC requires careful consideration.	Causes communication problems

TABLE V-II

BEAM CHARACTERIZATION SYSTEM
LESSONS LEARNED

<u>Lessons Learned</u>	<u>Comment</u>
1. A BCS is required and well suited for measuring heliostat tracking errors.	BCS cannot uniquely characterize errors that affect beam quality. A high measurement rate is required.
2. A very fast BCS will be necessary for a large heliostat field.	Several hundred heliostats should be measured three times during a day.
3. BCS availability is desirable when the heliostats are installed.	Reduces the time required to make tracking error corrections.
4. BCS should be a stand-alone system furnished by the heliostat supplier.	System would not depend on completion of another system, and the heliostat supplier/BCS supplier interface would be eliminated.
5. BCS implementation is not an easy task; the many software details require careful attention.	System accuracy is difficult to verify - subtle software or hardware errors are difficult to find and quantify - standards are needed.
6. Tower shadow and heliostats in gimbal lock complicate making three measurements per heliostat per day.	Complicated software will be required to schedule BCS measurements.

Collector Subsystem Lessons Learned

1. Heliostat Maintenance Costs

Heliostat maintenance costs for parts and labor have been slightly less than were predicted by Martin Marietta when they supplied the heliostats. Approximately 160 hours per month are required to maintain the heliostats including the controllers that are located in the field. These hours are fairly evenly divided between an electrician and an instrument technician. The screened commercial parts in the heliostat controller and a component burn-in have undoubtedly helped reduce failures.

2. Heliostat Maintenance Skills

The heliostats have been maintained with people having conventional maintenance skills. The vast majority of the work has been done by an electrician and an instrument technician. A machinist and a mechanic have been used infrequently.

3. Glass Pitting from Sand

There have been many windy days with blowing sand without any visible damage to the glass mirrors. For the first 27 months, the heliostats were always stowed horizontally. For the 16 months since January 1, 1984, the heliostats were stowed vertically except during high winds or under severe dust conditions at which time a mirror face-down horizontal stow was used. The paint on many of the pedestals is pitted, giving evidence of blowing sand, and rust is evident for the first 4-6 feet above the ground.

4. Vertical Stow

A vertical mirror stow position has been used since January 1, 1983, with no problems. Horizontal stow has been used during high winds and under severe dust conditions. There have been no operational problems, and mirror cleanliness is not significantly different.

5. Heliostat Beam Safety

Heliostat beam safety has not been a problem; however, control of the reflected beams is necessary to prevent high concentrations of the reflected light which could damage equipment or be a personnel hazard. Although it is not necessary, the plant operators normally stow and unstow the heliostats when the sun is not up. This reduces the number of occasions when a potential hazard exists near the ground; however, daylight stow has been demonstrated many times.

6. Mechanical Mirror Washing

At the pilot plant, a mechanical mirror washing is required to remove dirt that has accumulated over a period of time because spray rinses or rain will only restore 95% of the clean reflectivity after two years of exposure. A mechanical scrubbing with a brush and water will remove all of the dirt, and this type of cleaning is required for the Pilot Plant environment. Additional experience is needed to determine if rain or a spray rinse will keep the mirror clean for a period of time after a mechanical scrubbing. A heliostat wash truck which uses brushes and water has been used at the Pilot Plant to learn how to keep the mirrors clean and what the cleaning costs will be.

The plant operators normally rain wash the heliostats whenever possible. The mirrors are placed at 45 degrees facing up and into the wind. A 0.5 in rain cleaned the mirrors to better than 97% of the clean reflectivity during the first two years; however, during 1984 only 95% of the clean reflectivity was obtained. This is believed to be due to the accumulation of very fine dust on the outside 6 in of the glass surface that is not removable by rain or a low-pressure water rinse. A water spray with a brush will remove the fine dust.

There was one snowfall where the mirrors were face-up and snow cleaning was attempted during early February 1985. There was about 2 in of snow on the mirrors and 4 in on the ground. The snow was dumped before it started to melt, and the mirrors were restored to 96% of their clean reflectivity. It is believed that the

cleaning would have been more effective if the snow had not been dumped until it started to melt.

7. Items to Complete before Heliostat Installation

Martin Marietta, who installed the Pilot Plant heliostats, recommends that the following items be available when the heliostats are installed:

- a. Data cabling to each heliostat
- b. Power to each heliostat
- c. Control room for permanent heliostat control console
- d. BCS installed including targets

These items were not available when the Pilot Plant heliostats were installed which meant the heliostats could not be powered up and checked out until later. The lack of BCS prevented beam quality checks during the assembly period, and tracking error corrections could not be made or identified in a timely manner. There were no complete system checks made to identify production process problems. The lack of a control room means that a temporary room must be setup, and then the equipment must be disassembled and moved when the permanent control room becomes available.

8. Visual Heliostat Tracking Errors

The Pilot Plant has operated for 2.5 years with tracking error corrections based on visual estimates of the error. This does not provide the accuracy of a BCS, but the errors can be approximated. The operator merely directs the heliostat to track the BCS target aimpoint and estimates the error. Only one measurement is made during a day, so the tracking error correction may cause large errors at other times of the day instead of minimizing the error over a day's time. This is due to the fact that the tracking error is seldom constant over a day's time because of pedestal tilt or nonorthogonal axes for example. The time required and the inaccuracy of visual tracking error measurements point out the need for a fast and reliable BCS at the time the plant is started up or preferably when the heliostats are installed.

9. Moontracking

Moontracking has been demonstrated as an effective method to identify misaligned mirrors and large heliostat tracking errors. The method used was to have the heliostats reflect moonlight at an observation point near the receiver. An observer at this point can identify which heliostats have large tracking errors or misaligned mirrors. These heliostats can then be scheduled for maintenance and/or BCS measurements to correct the errors. The heliostats can all be viewed at one time; however, it is easier to identify a particular heliostat when only a small group is tracking the aimpoint at one time.

10. Tracking Error Corrections

Morning, noon, and afternoon heliostat tracking error measurements are required to make tracking error corrections. This is due to the fact that the errors vary with the time of day. The error is not constant for the majority of the heliostats because of pedestal tilt or nonorthogonal heliostat axes, for instance.

11. Silver Corrosion

Silver corrosion on the Pilot Plant mirrors has occurred because water and oxygen have been in contact with the backs of the mirrors. The water penetrates through the protective paint layers; it then dissolves the copper and then the water and oxygen corrode the silver. The Pilot Plant mirror module design lends itself to this problem because of the air volume inside the module and the very small vent pipe. The small vent pipe has a relatively large pressure drop which causes a small vacuum inside the module when the module is suddenly cooled by rain. This vacuum then draws in water through leaks in the seals. The lesson to be learned is that it is very difficult to seal this type of mirror module in production. A better design would not develop a vacuum, would contain no air, and would not depend on a production process to prevent leaks.

12. Quality Control for Adhesives and Sealants

The pilot plant heliostats have demonstrated the need for good quality control when adhesives or sealants are used. Mixing, cleaning and a proper cure are required in addition to proper preparation of the bonded or sealed surfaces. Doubler pads used for mounting the mirror modules have failed due to improper bonding and many of the mirror edge seals leak water under a slight pressure.

13. Lightning

A lightning storm near the plant during plant construction occurred on August 18, 1981, and caused control system failures. The lightning damaged several hundred heliostat controllers, with the majority of the damage being failure of the I/O communication couplers in the field and control room. After the lightning damage occurred, the rodent shield on the control cable at each heliostat was connected to the green power cable wire, which was already grounded through the foundation reinforcing steel and through ground rods at the field power transformers. The field does not have a ground grid or lightning arrestors, and we considered and rejected a retrofit because of the expense. Since the additional grounding was added there have been many lightning strikes near the plant without any significant heliostat controller failures that can be directly attributed to lightning.

14. Operational Wind Speed

The maximum operational wind speed for heliostats is usually 35mph. This speed was increased at the Pilot Plant to 45mph during plant start-up to increase the operating time and thus reduce the plant outage time due to high winds. The

plant has continued to use this higher shut-down wind speed without any problems; however, the operators seem to be very conscious of the wind speed and watch it closely when it is near the shut-down speed.

15. Motor Noise

Care must be taken to keep power circuits and grounds separate from low voltage logic circuits to prevent logic and communication problems.

Beam Characterization System Lessons Learned

1. A BCS is Required

A BCS is required and well-suited for measuring heliostat tracking errors. However, the measurement speed must be several hundred heliostats per hour for a large solar plant which might contain 5,000 to 10,000 heliostats. This is due to the need for morning, noon, and afternoon tracking measurements to correct for errors that vary with the time of day. The pilot plant BCS can measure about 50 heliostats per day which means 36 days is needed to measure all of the 1818 heliostats when the sky is clear all day.

Although the BCS can accurately measure heliostat beam quality (total reflected light and the distribution and size of the beam), it cannot uniquely characterize the error sources which cause the beam quality to be poor. The BCS cannot help you determine what is wrong with a heliostat.

2. A Fast BCS is Required

As discussed above, a very fast BCS will be necessary for a large heliostat field.

3. BCS is Needed During Construction

The BCS should be available when the heliostats are installed. This would provide a check on heliostat performance as installation progresses and reduce the time required to make tracking error corrections. This would reduce installation costs and identify production or installation problems when they occur.

4. BCS Supplier

The BCS and the heliostat control system (HAC) at the Pilot Plant were provided by different contractors. A single supplier is desirable since the interface between the two systems is so complicated.

5. BCS Implementation is Difficult

BCS implementation is not an easy task as there are many complicated software details which require careful attention. Such things as the math operations, geometry problems and hardware timing can have minor errors which are difficult to find and quantify since there are no standards available to check the system.

6. Tower Shadow and Gimbal Lock

Since a heliostat must be measured three times during a day, there are many heliostats that will be in the shadow of the tower or in gimbal lock (control system singularity) during one or more of these times. This complicates the software required to schedule the BCS measurements. Suitable software has not been developed at the pilot plant to schedule the required measurements although the affected heliostats can be identified and dropped from the measurement list.

SECTION VI

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APPENDIX I

TECHNICAL SPECIFICATIONS FOR THE 10 MWE SOLAR CENTRAL RECEIVER PILOT PLANT COLLECTOR SUBSYSTEM

The technical specifications for the Pilot Plant collector subsystem are included in this appendix. These specifications are extracted from the Request for Quotation for the collector subsystem that was issued by the Department of Energy Solar Ten Megawatt Project Office (STMPO). There are three specifications included which are:

1. Technical Specification for the Collector Subsystem Phase II
2. Specifications for Pilot Plant Heliostat Glass
3. Environmental Conditions - Barstow, California

The heliostat design specifications can be broken up into four categories: operational modes, optical performance, survival, and 30-year life. These requirements are briefly summarized in Table AI-I.

The Collector Subsystem (C5) interface requirements with the Master Control Subsystem (MCS) and the Plant are defined in the following report. The contents of this interface requirements report are shown in Table AI-II.

McDonnell Douglas Astronautics Company, "10 MWe Solar Thermal Central Receiver Pilot Plant Solar Facilities Design Integration, CS-MCS and CS-Plant Interface Requirements (RADL Item 2-30-1)," SAN/0499-51, U.S. Department of Energy, June 1982.

TABLE AI-I
HELIOSTAT DESIGN REQUIREMENTS

Operational Modes:	*Normal modes (track, standby, wire walk, stow) *Track to 16 m/s (35 mph) wind *Slew in 22 m/s (50 mph) wind *Resolve singularity in 15 minutes *Reposition in 15 minutes *Emergency defocus in 3 minutes *Electrical transients (3 -cycle dropout)
Optical Performance:	*Beam pointing(1.5 mrad RMS maximum, reflected) beam error for each axis) *Beam quality (theoretical beam shape plus 1.4 mrad fring, 0°C - 50°C (32°F - 122°F)) *Wind load deflection (3.6 mrad RMS maximum reflective surface deflection in 123 m/s (27 mph) wind, discounting foundation) *Foundation deflection (0.45 mrad maximum set after survival wind, 1.5 mrad maximum twist or tilt in 12 m/s (27 mph) wind
Survival:	*45 m/s (90 mph) wind, heliostat stowed *22 m/s (50 mph) wind, heliostat in any orientation *Temperature, -30°C to +50°C (20°F to 122°F) *Hail, 20 mm at 20 m/s (3/4 in at 65 ft/sec), any orientation 25 mm at 23 m/s (1 in at 75 ft/sec), heliostat stowed *Cold water shock
30-Year Life:	*Life of all components must be cost-effective for 30 years *Mirrors and drive mechanism are critical components.

Technical Specification for the Collector Subsystem

1. GENERAL

1.1 Scope

This specification establishes the performance, design, fabrication, construction, operation, maintenance and test requirements for the Pilot Plant Collector Subsystem.

2. DOCUMENTS

The equipment, material, design, installation and checkout procedures, and construction of the Collector Subsystem shall comply with all Federal, State, Local, and user standards, regulations, codes, laws, and ordinances which are currently applicable for siting in Daggett, California, and to the using utility, the Southern California Edison Company. These shall include, but are not limited to, the documents itemized below. If there is an overlap in or conflict between the requirements of these documents and the applicable Federal, State, County, or Municipal codes, laws, or ordinances, STMPO will resolve the issue.

The following documents are in effect on the date of contract award and form a part of this specification to the extent specified herein. Conflict between the documents referenced herein and the contents of this specification are to be resolved by STMPO.

2.1 Standards

MIL-STD-454, Standard General Requirements for Electronic Equipment

MIL-STD-1472, Human Engineering Design Criteria

National Electrical Manufacturers Association (NEMA) Standards

Manual of Steel Construction, 8th Edition, 1974, American Institute of Steel Construction

Uniform Building Code - 1976 Edition, Vol. I, by International Conference of Building Officials

National Electrical Code, NFPA 70-1975

ANSI C1-1975, American National Standards Institute

ANSI A58.1-1972, Building Code Requirements for Minimum Design Loads in Buildings and Other Structures

DOE-SAN CHAPTER 0501, Pattern of Health and Safety Responsibilities

DOE MANUAL CHAPTER 0820, Quality Assurance

2.2 Other Publications

"Wind Forces on Structures," ASCE Paper No. 3269,
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Environmental Conditions - Barstow, California, Exhibit V
of Enclosure III

3. REQUIREMENTS

3.1 Collector Subsystem Definition

The Collector Subsystem is composed of an array of heliostats and supporting power and control elements which interact with the master control. The heliostat array reflects solar radiation onto the elevated absorber (boiler/superheater) of the receiver system in a manner which satisfies receiver incident heat flux requirements.

The Collector Subsystem components are:

a. Heliostats

- (1) Mirror modules
 - * Reflector
 - * Mirror Support
- (2) Structural support
- (3) Drive units
- (4) Control sensors
- (5) Pedestal and mounting interface
- (6) Heliostat cabling
 - * Power
 - * Signal

b. Heliostat Controllers

- (1) Controller
- (2) AC/DC power supplies
- (3) AC motor control electronics

c. Heliostat Array Controller (HAC)

- (1) Master control interface including electronics
- (2) Main and backup computers

- (3) Time base
- (4) Beam characterization system interface including electronics
- (5) Software

d. Heliostat Field Controllers (HFC)

- (1) Controller
- (2) AC/DC power supplies
- (3) Heliostat controller interface including electronics
- (4) Heliostat array controller interface including electronics
- (5) Software

e. Support Equipment and Procedures

- (1) Alignment
- (2) Washing
- (3) Operation and Maintenance
- (4) Installation and Removal

3.1.1 Collector System Diagram

Figure 1 represents the basic heliostat configuration. Figure 2 shows the collector field control configuration and interfaces, and Figure 3 shows a block diagram of the control system and interfaces.

3.1.2 Interfaces

3.1.2.1 Collector/Physical Site. The physical arrangement, outer boundaries of the array of heliostats, and the foundations shall be supplied by the Solar Facility Design Integrator (SFDI). Interconnecting control field wiring shall be supplied by SFDI.

3.1.2.2 Collector/Receiver Subsystem. The Collector Subsystem shall concentrate the redirected energy onto the receiver. The receiver is a vertical cylinder approximately 8.0 m (26 ft) in diameter and 14.0 m (46 ft) high and the center is 92 m (302 ft) above ground level. (Actual dimensions will be finalized by the Solar Facilities Design Integrator.)

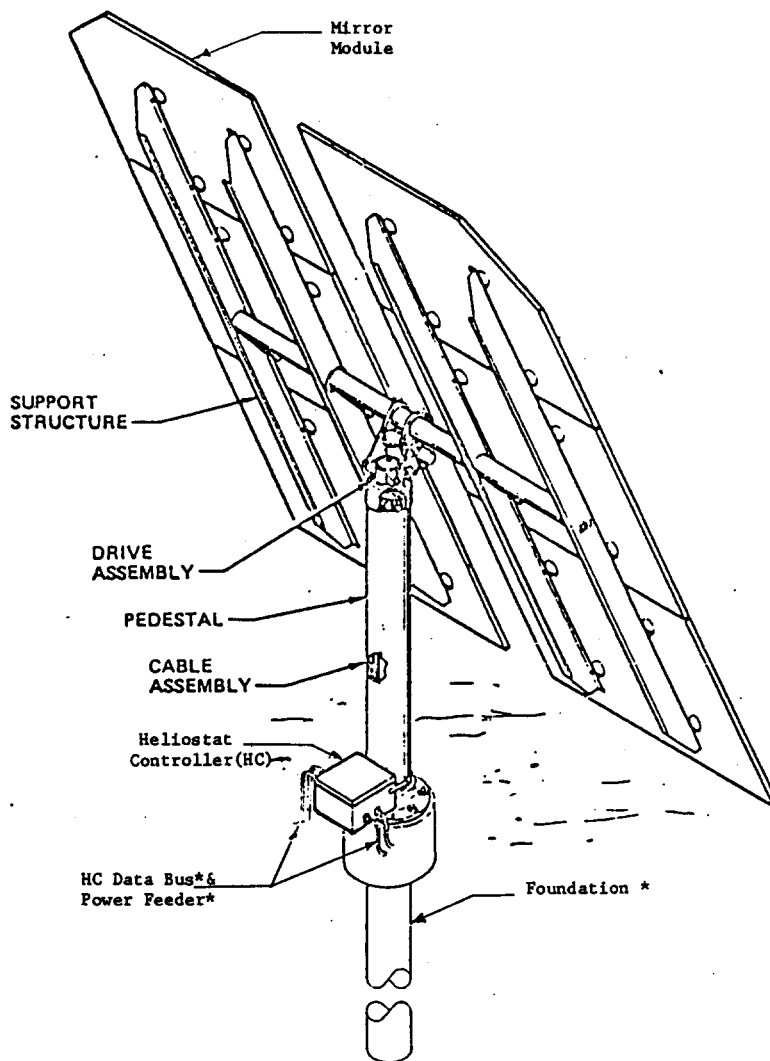


Figure AI-1. Heliostat Configuration

3.1.2.3 Collector/Plant Power. Uninterruptible plant power is to be supplied to the heliostat array controller, heliostat field controllers, and each heliostat junction box.

3.1.2.4 Heliostat Array Controller (HAC)/Master Control System (MCS).

HAC shall be configured such that the MCS can automatically achieve integrated control of, and alarm, the Collector Subsystem. The overall interface signals for Pilot Plant operation are as follows:

- * Control Commands
- * Operational Data Requests
- * Operational/Alarm Data Outputs

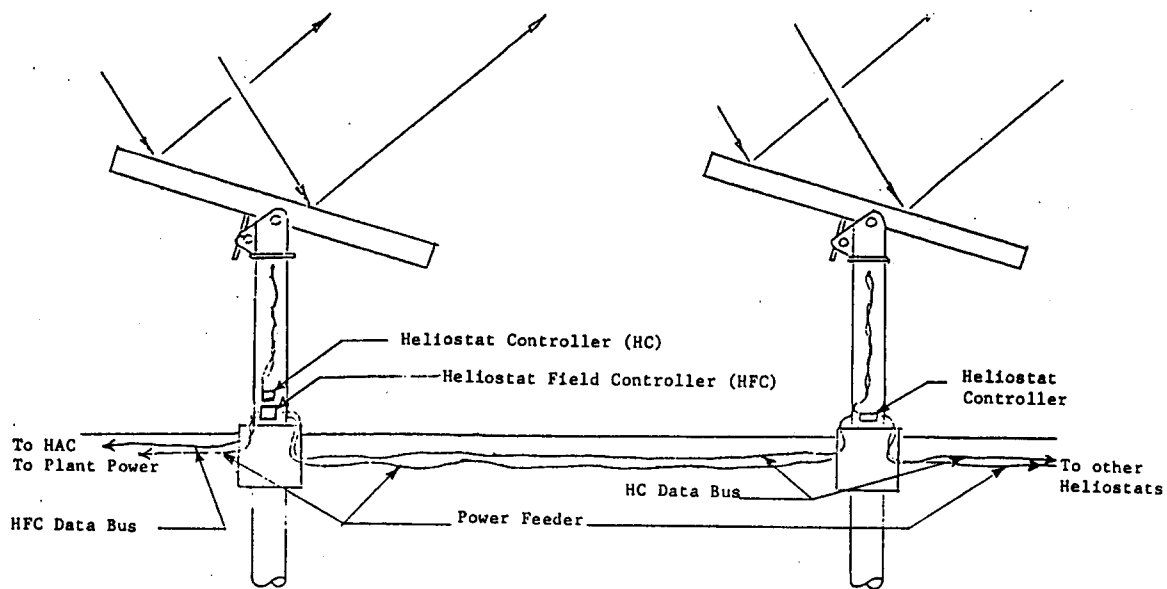


Figure AI-2. Heliostat Field Control Configuration

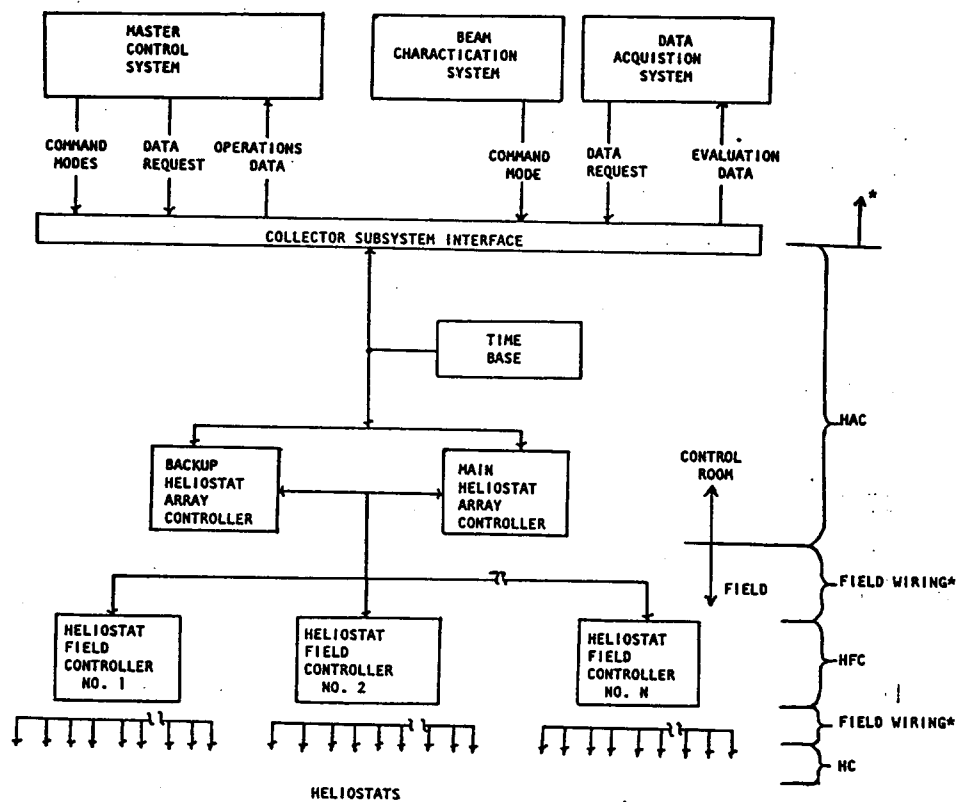


Figure AI-3. Pilot Plant Collector Subsystem Control and Interface

3.1.2.5 HelioStat Array Controller (HAC)/Data Acquisition System (DAS).

The DAS will perform the data collection function for evaluation of the Pilot Plant system. The evaluation interface signals for the Pilot Plant are as follows:

- * Evaluation Data Requests
- * Evaluation Data Outputs

Each of these sets of signals in 3.1.2.4 and 3.1.2.5 is further designated as either continuous (i.e., automatically generated at regular preprogrammed intervals) or on-demand by an operator (i.e., issued upon request or over selectable intervals). Error checking shall be employed in all message transfers.

3.1.2.6 HelioStat Array Controller (HAC)/Beam Characterization System.

The HAC shall provide heliostat data, control, and positioning requested by SFDI for beam characterization.

3.2 Specification

3.2.1 Performance

In order to attain overall Pilot Plant field performance such that 95% of the redirected energy will be incident at less than 60° on the receiver, the following requirements have been established for each heliostat.

- a. Maximum beam pointing error shall be 1.5 mrad standard deviation whenever the sun is at least 0.26 rad above the horizon.
- b. Beam quality shall be such that a minimum of 90% of the reflected energy at target slant range shall fall within the area defined by the theoretical beam shape plus a 1.4 mrad fringe width. Heliostat beam quality shall be met throughout 60 days without realignment. Theoretical beam shape shall be determined by computer code (HELIOS) available through STMPO.
- c. Structural support including foundation shall limit reflective surface static and dynamic deflections to

1.7 mrad standard deviation under normal operational environmental conditions.

- d. A maximum allowable foundation settlement or plastic displacement of 0.05 mrad standard deviation and elastic displacement of 0.5 mrad standard deviation must be included in the allowable structural support deflection limit for any environmental condition excluding earthquake.

Trade-offs among the above requirements relative to a proposed heliostat configuration must be coordinated with and approved by STMPO.

3.2.2 Operation

Operational control requirements are as follows:

- a. The Collector Subsystem shall function as appropriate for all steady-state modes of plant operation. This shall include the capability of controlling the number of heliostats in tracking mode so as to vary the redirected flux to the receiver between zero and the maximum achievable level.
- b. Drive systems must be capable of positioning a heliostat to stowage, cleaning, or maintenance orientation from any operational orientation within 15 minutes.
- c. Elevation and azimuth gimbal drives shall not drift from last commanded positions due to environmental loading.
- d. Drive systems must be capable of resolving south field control singularity (i.e., "over-the-shoulder" limits or gimbal lock) within 10 minutes.
- e. Drive system shall provide for face down horizontal stowage of the reflective surface.
- f. Heliostat control shall be by computer with gimbal axis and motor shaft sensors. Control functions shall be accomplished as follows:

Heliostat Array Controller (HAC) shall:

- * Initiate operational mode commands to HFC
- * Address commands to HFC groups or individual HC

- * Respond to MCS commands
- * Respond to DAS requests
- * Interface with Beam Characterization System
- * Provide time base

Heliostat Field Controller (HFC) shall:

- * Determine individual heliostat azimuth and elevation position requirements
- * Transmit position requirements to HC
- * Transmit status and data to MCS and DAS
- * Initiate safe stowage command upon loss of HAC communication
- * Control groups of HCs

Heliostat Controller (HC) shall:

- * Control drive motors
- * Check gimbal axis sensors
- * Provide gimbal axis position data to DAS

3.2.3 Safety

Operational control requirements are as follows:

- a. The Collector Subsystem shall be capable of emergency defocusing upon command to reduce peak incident radiation on the receiver to less than 3% of initial value within (TBD) seconds.
- b. Heat fluxes on tower and normally unirradiated portions of the Receiver Subsystem are limited to (TBD)kW/m² ((TBD) BTU/FT²).
- c. Beam control strategy and equipment will protect personnel and property within and outside the Pilot Plant facility including air space.

3.2.4 Maintainability

The collectors will be designed so that they do not require routine field maintenance, with the exception of periodic washing.

The Collector Subsystem shall be designed to report any subsystem malfunctions at the HAC console and provide fault

isolation information on critical components. Critical components are those components that, because of failure, risk, downtime, or effect on overall Pilot Plant performance, materially affect the system availability, or the system safety with respect to the reflected beam in the surrounding air space or on the ground.

3.2.5 Physical Characteristics

The Collector Subsystem detailed design shall be based on the following basic configuration:

- a. Reflective surface of approximately 40 m² (400 ft²).
- b. Reflective surface as follows:
 - * Nominal 3mm (0.125 in) low iron (approximately 0.05%) float glass (Government Furnished Equipment)
 - * Second surface reflector
 - * Chemically deposited silver reflective surface
 - * Copper and paint mirror backing
 - * Thermally induced tensile stress limited to 1.4 MPa (200 psi)
 - * Maximum tensile stress (parallel to edge and averaged through thickness) under any environmental loading limited to 7 MPa (1000 psi). Tensile stress will be evaluated by the Government with birefringent photoelastic technique utilizing a Photoelastic Inc. reflection polariscope.
- c. Reflective surface envelope of approximately 6.5m x 6.5m (21 ft X 21 ft).
- d. Local override of heliostat controller.
- e. Single pedestal from foundation to drives.
- f. Metal structure.
- g. Environmentally sealed drive and sensor systems.

- h. Heliostat focal lengths of 100 to 400m (300 to 1200 ft) shall be allowed by canting of mirror modules.
- i. Azimuth and elevation gimbal axis located near centroid of reflective surface.
- j. Limit switches provided on each gimbal axis.
- k. Control sensors (position transducers) located on each gimbal axis and motor shaft.
- l. Corrosion protection of all parts.
- m. Mirror facet adjustment for realignment.

3.2.6 Environmental Design Conditions

“Environmental Conditions - Barstow, California” (Exhibit V of Enclosure III) describes representative site conditions to be encountered and survived by the Collector Subsystem. The Collector Subsystem must maintain structural integrity in any applicable combination of the environments.

- 3.2.6.1 Wind Loading.** The natural wind environment specified produces a vibratory response both from the oscillatory nature of the gusts and from periodic vortex shedding. The Collector Subsystem shall be designed to withstand, and/or operate when subjected to, the loads produced by this vibration. The actual loads must be computed taking into account structural configuration and dynamic characteristics, and the velocities of the winds.

In computing the angle between the wind direction and the plane of the heliostat reflective surface, the wind shall be assumed to deviate by up to, plus or minus, 10° from the horizontal.

- 3.2.6.2 Operational Limits.** The Collector Subsystem must meet performance requirements for the following conditions:

<u>Environment</u>	<u>Level</u>
Wind, including gusts	12 m/s maximum (27 mph)
Temperature	0°C to 50°C (30°F to 120°F)
Gravity	All elevation angles

3.2.6.3 Stowage Initiation. The heliostats will continue to track the target with wind speeds up to 16 m/s (35 mph), above which stowage action will be initiated as a result of an externally provided signal. The heliostat must maintain structural integrity in a non-operational state in a 22 m/s (50 mph) wind in any orientation.

3.2.6.4 Hail. The heliostat, in any orientation, must survive 20 mm (0.75) in diameter, 0.9 specific gravity hail impacting at 20 m/s (65 ft/s).

Heliostat may be in stowed position to survive hail conditions sited in Exhibit V or Enclosure III, Environmental Conditions - Barstow, California.

3.2.6.5 Lightning. The Collector Subsystem shall have lightning protection consistent with the following guidelines:

Direct Hit - Total destruction of a single heliostat and its controller subjected to a direct lightning strike is acceptable.

Adjacent Strike - Damage to a heliostat adjacent to a direct lightning strike should be minimized within appropriate cost-risk limits.

Controller - The HAC's, HFC's, and HC's, adjacent to a direct lightning strike must be protected.

3.2.7 Transportability

Collector Subsystem components or assemblies shall be designed for transportability by highway handling equipment within applicable Federal and State regulations.

3.3 Design and Construction

Commercial design and construction standards shall be employed. Where applicable, the Uniform Building Code (1976 ed.) and the American Institute of Steel Construction's Manual of Steel Construction (8th ed.) shall be used. ANSI A58.1-1972 and ASCE paper No. 3269, Wind Forces on Structures (ASCE Transactions, Vol. 126, Part II, 1961) shall be used during design when determining loading due to winds. For electrical components, the National Electrical Code (ANSI C1), the National Electrical Manufacturers Association (NEMA) and

MIL-STD-454 standards for electronic equipment shall be used.

Design and material selection is to be based on a 30-year life.

3.3.1 Materials, Processes, and Parts

To the maximum extent possible, standard materials and processes, and off-the-shelf components shall be used. Wherever possible, commercial specifications shall be employed. All non-commercially available parts shall be defined and documented in deliverable documents. Commercial items shall not be proprietary.

3.3.2 Electrical Transients

The Collector Subsystem operation shall not be adversely affected by external or internal power line transients caused by normal switching or fault clearing functions which result in fewer than six cycles of the fundamental frequency (100 milliseconds) and 1.7 PU voltage (1.7 per unit or 170%).

3.3.3 Electromagnetic Radiation

The Collector Subsystem control wiring shall be designed to minimize susceptibility to electromagnetic interference and to minimize the generation of conducted or radiated interference.

3.3.4 Nameplates and Product Marking

All parts shall be labeled with a permanent nameplate listing, as a minimum: manufacturer, part number, serial number, and date of manufacture.

3.3.5 Workmanship

The level of workmanship shall conform to practices defined in the codes, standards, and specifications applicable to the Pilot Plant site and Southern California Edison. Where specific skill levels or certifications are required, current certification status shall be maintained with evidence of the status available for examination. All work shall be finished in a manner that presents no unintended hazard to operating and maintenance personnel, is neat and clean, and presents a uniform appearance.

3.3.6 Interchangeability

Items with a common function shall have a common part number and be interchangeable. Components with similar appearance but different functions shall incorporate protection against inadvertent erroneous installation. All heliostats shall be interchangeable regardless of their position in the heliostat array.

The HAC Central Processor Unit (CPU) elements (components) shall be interchangeable with the MCS CPU elements.

- 3.3.7** The Collector Subsystem shall be designed to minimize safety hazards to operating and service personnel, the public, and equipment. Electrical components shall be insulated and grounded. All components with elevated temperatures shall be insulated against contact with or exposure to personnel. Any moving elements shall be shielded to avoid entanglements, and safety override controls/interlocks shall be provided for servicing.

3.3.8 Human Engineering

The Collector Subsystem shall be designed to facilitate manual operation, adjustment, and maintenance as needed and provide the optimum allocation of functions between personnel and automatic control. The Collector Subsystem design shall provide electrical and electronic packaging which ensures rapid repair and replacement, placarding of hazardous work areas, and equipment for item removal and handling. MIL-STD-1472, Human Engineering Design Criteria, shall be used as a guide in designing equipment.

3.4 Documentation

3.4.1 Characteristics and Performance

Equipment functions, normal operating characteristics, limiting conditions, test data, and performance curves shall be provided for inclusion in Overall Plant Design Description (OPDD). (Format for the OPDD will be provided by STMPO).

3.4.2 Instructions

Instructions shall cover assembly, installation, alignment, adjustment, checking, lubrication, maintenance, and operation

of the Collector Subsystem. All instructions shall include reference to applicable system engineering data and guides to troubleshooting instruments and controls. All phases of Collector Subsystem operation shall be addressed, including start-up, normal and synthetic tracking operation, on-line and off-line maintenance, shut down, contingency operation, and emergency operations.

3.4.3 Construction

Engineering assembly and installation drawings shall be provided to show the equipment construction, including assembly and disassembly procedures. Engineering data, wiring diagrams, and parts lists shall be provided.

3.4.4 Format

Pilot plant documentation (drawing, specifications, instructions, etc.) shall be compatible with Southern California Edison format. (Format to be provided by STMPO).

4. QUALITY ASSURANCE-L (See Enclosure III, Exhibit IV)

Contractor's efforts and products shall be governed by an approved Quality Assurance Plan which shall be included as part of the program management plan.

4.1 General Requirements

Quality Assurance activities shall be conducted in accordance with a plan to be prepared by the contractor and approved by STMPO.

4.2 Responsibility

The Contractor shall participate in all Quality Assurance activities. These activities may be witnessed by STMPO or its representatives or the witnessing may be waived. In either case, substantive evidence of hardware compliance with all requirements is required.

Specifications for Pilot Plant Heliostat Glass

1. SCOPE

- 1.1 This specification applies to glass used as the primary transparent substrate for second surface mirrors on heliostats for central power tower solar conversion concepts.
- 1.2 The specification reflects the specific requirements placed on the glass for the Barstow Ten Megawatt Solar Pilot Plant Facility.

2. APPLICABLE PUBLICATIONS

- 2.1 The following publications have been used extensively in the preparations of this specification:
 - 2.1.1 Federal Specification for Glass, Float or Plate, Sheet, and Figures (Flat, for Glazing Mirrors and other uses). DD-G-451D, April 25, 1977
 - 2.1.2 Canadian Government Specifications Board Standard for Glass, Polished Plate or Float, Flat, Clear. CAN12.3-M76, August 1976.
 - 2.1.3 American Society for Testing and Materials (ASTM) C162 Definition of Terms Relating to Glass and Glass Procedures.

3. REQUIREMENTS

- 3.1 General Requirements - minimum acceptable.
 - 3.1.1 Total Solar Energy Transmittance (TSET) 0.88 (k)
 - 3.1.2 Effective Figure (Flatness)
 - (A) 90% of light area 1.5 mrad (j)
 - (B) 100% of light area 2.5 mrad (j)
 - 3.1.3 Thermal Coefficient of Expansion
 - 8.5-10.0 x 10⁻⁶C (4.7-5.5 x 10⁻⁶F) (m)
 - 3.1.4 Residual Stress 1.4 MPa (200 psi) (n)

3.2 Dimensions - all lights score and cracked to size

3.2.1	Width and Length	1.08 m x 2.85 m	(42.5 x 116")
3.2.2	Size Tolerance	± 1.6 mm	(± .062")
3.2.3	Thickness	2.4-3.3 mm	(.095 - .130)
3.2.4	Thickness Variation	0.25 mm/m	(.003"/ft)
3.2.5	Squareness	3.0 mm	(.12")
3.2.6	Bevel	0.8 mm	(.03")
3.2.7	Corners On and Off	3.2 mm	(.12")

3.3 Bulk and Surface Defects - maximum acceptable limits

3.3.1	Gaseous Inclusions	6.5 mm	(0.25")	(a,e,f,g)
3.3.2	Open Gaseous Inclusions	3.0 mm	(0.12")	(a,e,g,i)
3.3.3	Knots	3.0 mm	(0.12")	(a,e,g,i)
3.3.4	Stones	1.5 mm	(0.06")	(a,e,g,i)
3.3.5	Crush	Heavy, 6.5 mm	(0.25")	(a,d,i)
3.3.6	Scratches	Medium		(a,d,i)
3.3.7	Rubs	Heavy		(a,d,i,h)
3.3.8	Digs	6.5 mm	(0.25")	(a,g,i)
3.3.9	Ream, String, Lines, Wave 90°VIA, Heavy			(b,c)
3.3.10	Dirt	Clean		(o)

3.4 Edge Defects - maximum acceptable limits

3.4.1	Flake Chip	3.0 mm	(0.12")	(1)
3.4.2	Flares	1.5 mm	(0.06")	(1)
3.4.3	Vee Chips and Checks	NONE		(1)

4. FOOTNOTES

- (a) Separate by at least 0.3 m (12")
- (b) Vision interference angle for examination of Ream, String, and Wave is determined by placing the sample in a vertical position at a distance of approximately 1 m (39") using a background light suitable for observing each type of defect. The line of vision shall be perpendicular to the background. The sample is viewed at an angle to the surface of not less than the specified vision interference angle. Slight movements of the head horizontally through an angle of two to three degrees will make waves or lines more perceptible.
- (c) Intensity - Ream, String and Wave. When evaluated using the shadow-graph method described below, the intensity is

defined as having readouts at distances greater than or equal to the following:

<u>Intensity</u>	<u>Minimum Distance</u>
Light	75 mm (3")
Medium	50 mm (2")
Heavy	25 mm (1")

The shadowgraph method uses a projector with a 500 watt lamp and an objective lens with an approximate 5 cm (2") aperture and an approximate 30 cm (12") focal length to focus the light on a flat white projection screen positioned 7.6 m (25') from the light source in a dark room. The glass is placed in a vertical position parallel to the screen between the light and the screen. The glass is moved slowly toward the screen with a vertical oscillating motion. The shadowgraph readout is the distance at which the distortion just blends with the glass on the screen.

- (d) Intensity - Scratches, Rubs and Crush. When looking through the glass and perpendicular to it, using daylight without direct sunlight or with a background light suitable for observing each type of defect, the defects shall not be detectable when viewed at the following distances:

<u>Intensity</u>	<u>Distance</u>
Faint	0.2 m (9")
Light	1.0 m (39")
Medium	3.0 m (10')
Heavy	3.0 m (10')

- (e) For elongated defects, the maximum size specified shall be determined by adding the length and the width of the defect and dividing by two $(L+W)/2$.
- (f) For defects of smaller size or less intensity, the minimum separation may be proportionally less. The larger of the two defects shall govern separation. Defects not specifically mentioned shall be compared to the defect they most closely resemble.
- (g) Sharp edges, fissures, small cracks, chips or other imperfections on the surface of the glass which may result in high internal stress at or near the defect, are not acceptable.

- (h) In no case shall more than 0.1% of the total surface area of the light be affected by the combined area of all defects.
- (i) The defects cannot destroy the pristine surface of the glass to an extent that will adversely affect the strength of the glass or result in spontaneous fracture during its anticipated thirty year service life.
- (j) The effective figure of the glass light used in mirror applications shall be determined by a laser ray trace technique. The peak to peak deviation of the second surface reflection shall be used as the acceptance criterion. The measurement shall be performed using a 6328A laser beam with a diameter between 1mm and 3mm (.04-.12 in) incident at 45° to the first surface of the glass specimen. The glass may be supported by a flat horizontal table for the measurement, but the glass light cannot be forced to conform to the shape of the table except under its own weight. A one miliradian correction to the data every 30cm (12") is permitted to allow for overall bow or warp in the glass light.
- (k) The minimum total solar energy transmittance (TSET) requirement shall apply over 99.9% of the entire surface area of the light. This requirement applies to the glass as received and includes the effects of any bulk or surface defects produced during the manufacturing and handling process.
- (l) Edge defects which may result in spontaneous fracture of the light during its expected 30 year lifetime are not acceptable.
- (m) Thermal coefficient of expansion is the linear expansion of the glass per unit length per degree temperature rise over the range of -30°C to +50°C (-10°F to +120°F).
- (n) Residual stress to be determined by quartz wedge or laser measurements.
- (o) The glass surface must be cleanable by non-abrasive means to the extent required for silvering.

5. DEFINITIONS

Bevel - The difference in length between the upper and lower surface of the glass at the edge after cutting.

Bubbles - Gas inclusions in any glass. These inclusions are almost always brilliant in appearance. The term is applied to all such inclusions larger than 1.0 mm in maximum dimension. The term "small bubbles" refers to sizes between 1.0 and 2.5 mm (see Seeds).

Check - An imperfection or surface crack in the glass.

Cords (see Ream) - Heavy strings incorporated in the sheet rather than on the surface, occurring without any regularity of direction and appearing to be of considerable thickness.

Corner On and Off - Glass chipped off remaining on the corners due to imperfect cutting.

Crush - A lightly pitted area resulting in a dull gray appearance over the region.

Digs - Deep, short scratches.

Dirt - A small particle of foreign matter imbedded in or adhered to the glass surface.

Effective Figure - The exact effective optical shape of the glass as measured against a theoretical "perfect" shape. The effective figure of a glass second surface mirror is a result of the actual surface figure of both surfaces of the glass as well as any index variations within the glass.

Flake Chips - Seashell-like fracture of the surface at the edge of the glass sheet caused by the cutting process.

Flare - An extension of glass remaining or absent from the surface after breaking during the cutting process.

Gaseous Inclusions - Round or elongated bubbles in the glass.

Knot - A transparent area of incompletely assimilated glass having an irregular knotty or tangled appearance.

Lines - Fine cords or strings, usually on the surface of sheet glass. Waves that extend continuously across the sheet, so that the reflection from the surface appears as a line or series of lines extending either the full width or a considerable distance across the sheet.

Open Gaseous Inclusions - Bubbles at the surface of glass that are open, leaving a cavity in the finished surface.

Ream (see Cords) - Inclusions within the glass, or layers of strings of glass, that are not homogeneous with the main body of the glass. An area of unhomogeneous glass incorporated in the sheet, producing a wavy appearance.

Residual Stress - The average tensile stress remaining in the glass after manufacture.

Rubs - Abrasion of the glass surfaces producing a frosted appearance. A rub differs from a scratch in having appreciable width.

Scratches - Any marking or tearing of the surface appearing as though it had been done by either a sharp or rough instrument. Scratches occur on glass in all degrees from various accidental causes. A sleek is a hairline scratch. A crush or rub is a surface scratch or series of small scratches generally caused by handling.

Seeds - Minute bubble less than 1.0 mm in diameter. Fine seeds are visible only upon close inspection, usually appearing as small specks, and are an inherent defect in the best quality of plate glass. Seeds about 1.0 mm in diameter are usually considered coarse seeds.

Squareness - The difference between the two corner-to-corner diagonals of a square or rectangular shape.

Stones - Any opaque or partially melted particle of rock, clay or batch ingredient embedded in the glass.

Strings (see Ream) - Wavy, transparent lines appearing as though a thread of glass has been incorporated into the sheet.

Total Solar Transmittance - The calculated transmittance for solar energy derived from the measured value of the spectral transmittance of the glass and using the values for the spectral distribution of solar energy received at sea level by a surface perpendicular to the sun's rays through an air mass of 2. (See Parry Moon, "Proposed Standard Solar - Radiation Curves for Engineering Use," Journal Franklin Institute, Volume 230, Page 704, Table III, 1940.)

Vee-Chip - Deep "V" shaped chip at glass edge causing area of high stress.

Visual Interference Angle (VIA) - The angle of orientation of the glass light with respect to the observer.

Wave - Defects resulting from irregularities of the surfaces of glass making object viewed at varying angles appear wavy or bent.

**Environmental Conditions
Barstow, California**

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- 1. **General**
- 1.1 Scope
- This document lists the environmental conditions for the
 10 MWe Solar Central Receiver Pilot Plant to be located
 the Southern California Edison (SCE) Cool Water Site near
 Barstow, California.
- 2. **Documents**
- The following form a part of this document to the extent
 stated herein:

MIL-STD-810B Environmental Test Methods
Uniform Building Code - 1976 Edison, Volume I, by
International Conference of Building Officials

3. **Environments**

Environmental conditions include winds and gusts, temperature extremes, rain, sleet, hail, snow, earthquake and soil conditions as follows:

3.1 **Wind**

The wind speed specifications at a reference height of 10 m (30 ft) shall be:

3.1.1 **Speed Frequency**

Speed, m/s (mph)		Frequency, Percent
0-2	(0-4.5)	29
2-4	(4.5-9.0)	21
4-6	(9.0-13.5)	19
6-8	(13.4-18.0)	14
6-10	(18.0-22.5)	8
12-14	(27.0-31.5)	3
14-	(31.5-)	Less than 1

For the calculation of wind speed at other elevations, assume the following model:

$$V_H = V_1 \left(\frac{H}{H_1} \right)^c$$

Where: V_H = wind velocity at height H

V_1 = reference wind velocity

H_1 = reference height (assume 10 m, 30 ft)

$c = 0.15$

3.1.2 **Wind Rise Rate.** A maximum wind rise rate of 0.01 m/s² (0.02 mph/s²). A maximum wind of 25 m/s (55 mph) from any direction may occur resulting from unusual rapid wind rise rate, such as severe thunderstorm gust fronts.

3.1.3 **Survival Wind.** A maximum wind speed, including gusts, of 40 m/s (90 mph).

3.1.4 **Dust Devils.** Dust devils with wind speeds up to 17 m/s (38 mph).

3.1.4 **Sandstorm Environment.** Sandstorm limits within tests per MIL-STD-810B, Method 510.

3.2 **Temperature**

Ambient air temperatures range from -30°C to +40°C (-20°F to +120°F).

3.3 Precipitation

3.3.1 Rain - Average annual: 750 mm (30 in) Maximum 24-hour rate: 75 mm (3 in)

3.3.2 Ice - Freezing rain and ice deposits in a layer up to 50 mm (2 in) thick.

3.3.3 Hail -

Diameter	25 mm (1 in)
Specific Gravity	0.9
Terminal Velocity	23 m/s (75 ft/s)

3.3.4 Snow - Maximum 24-hour rate: 0.3m (1 ft); maximum loading: 250 Pa (5 lbs/ft²).

3.4 Insolation

3.4.1 Maximum Flux. Direct normal nominal insolation of 1100 watts/square metre maximum at the plant site.

3.4.2 Rate of Change. The maximum rate of change of incident flux shall be assumed as that which would result from the passage of an opaque cloud across an otherwise clear sky where the sharp leading or trailing edges of the shadow move across the Pilot Plant site at a velocity of 20 m/s (45 mph).

3.5 Earthquake

Seismic zone 3 (uniform Bldg. Code).

3.6 Soil Properties

The surface deposits of silty sand, which extends to depths of from 0.3m to 1.5m (1 ft to 5 ft), are only moderately firm and become weaker when wet. The sand below a depth of about 1.5m (5 ft) is firm but contains thin layers of relatively soft silt. In general, the sand is firmer below 3m (10 ft) and layers of soft silt were not encountered.

3.6.1 G. Shear Modulus, and E, Secant Modulus

$$\text{Shear Modulus} = G = \frac{B(h+z)}{2(1+u)} \simeq \frac{By}{2.6}$$

$$\text{Secant Modulus} = E = B(h+z) \simeq By$$

Where B = function of soil depth (see chart)

h = depth of burden

z = depth from burden

u = constant = 0.3

y = depth from surface

Soil Depth (y)		Density		B		Secant Modulus at the free surface	
(m)	(ft)	(kg/m ³)	(Lb/ft ³)	(MPa/m)	(psi/ft)	(MPa)	(psi)
0-1.5	(0-5)	1600	(100)	1.7	(75)	0.7	(100)
1.5-3.0	(5-10)	1840	(115)	2.5	(110)	1.4	(200)
3.0-	(10-)	1920	(120)	3.4	(150)	2.1	(300)

At depth of 1.5 m (5ft) $G = 10$ MPa, (1500 psi)

$E = 28$ MPa (4000 psi)

At depth of 3.0 m (10 ft) $G = 32$ MPa, (4600 psi)

$E = 83$ MPa (12,000 psi)

Geophysical data (from seismic refraction investigation) indicates a shear modulus at a strain rate of 10^{-4} m/m (in/in) of between 100 to 140 MPa (15,000 to 20,000 psi) at a depth of 3 m (10 ft).

3.6.2 Bearing Capacity (allowable for standard spread or mat-type foundations).

Depth,m (ft)	Load kPa (psf)
0.6 (2)	70 (1,500)
1.5 (5)	240 (5,000)
3.0 (10)	480 (10,000)

3.6.3 Penetration Data. The number of blows required to drive a materials sampler 300 mm (12 in) was recorded for a number of borings. To a depth of 7.5 m (25 ft) a weight of 725 kg (1600 lb) (Kelly weight) falling a distance of 0.3 m (1 ft) was used to drive the 76 mm (3 in) diameter sampler.

Number of Blows to Drive an LC/A Sampler 300 mm (12 in)

Depth (m)	(ft)	Average	Range	No. of Samples
0 - 1.5	(0 - 5)	2.6	0 - 9	74
1.5 - 3.0	(5 - 10)	4.2	1 - 10	42
3.0 - 4.5	(10 - 15)	5.9	2 - 11	31
4.5 - 6.0	(15 - 20)	8.0	4 - 15	19
6.0 - 7.5	(10 - 25)	9.0	5 - 20	17

Note: There does not appear to be a direct conversion between these data and a standard penetration test, so the results are qualitative in nature.

3.6.4 Water Table. Below 30 m (100 ft)

APPENDIX II

HELIOSTAT DESIGN DESCRIPTION FOR THE 10 MW_e SOLAR THERMAL CENTRAL RECEIVER PILOT PLANT

Introduction

Development of a heliostat for the Pilot Plant began in 1975, with Department of Energy (DOE) (ERDA in 1975) contracts at Boeing Engineering and Construction, Honeywell, Inc., Martin Marietta Corporation, and McDonnell Douglas Astronautics Company. Several prototypes of each heliostat were built and tested (References 1-10). An evaluation of each design was made by Sandia National Laboratories Livermore (SNLL) and a design concept for the plant was selected and recommended to DOE (References 11,12). McDonnell Douglas's commercial open loop, single pedestal (with elevated drive mechanisms) design concept was technically and economically superior to the other designs.

In September 1978, the DOE and the San Francisco Operations Office of the DOE initiated a one-year competitive heliostat design program on the generic glass/metal single-pedestal design concept recommended by SNLL for the Pilot Plant. Martin Marietta Corporation of Denver, Colorado, and McDonnell Douglas Astronautics Company of Huntington Beach, California, were the competitively selected contractors. These competitive contracts, designated as Phase I Preproduction Activity, covered the detail design, development, and fabrication of prototype test heliostats. The outcome became part of the basis for the DOE's evaluation and ultimate contractor selection for production of the Pilot Plant heliostats.

SNLL, in support of the DOE/Solar Ten Megawatt Project Office (STMPO) in El Monte, California, was responsible for defining and executing the heliostat test and evaluation program. The program began in June 1979, and with some exception, was completed in October 1979. The test and evaluation results were reported in Reference 13.

Although the results of the heliostat evaluation program were a major factor in selecting the heliostat production contractor, they were not the sole basis for judging the two competitive designs. Other considerations, such as contractor performance, operations and maintenance evaluations, and quoted costs, all determined the ultimate selection of Martin Marietta as the heliostat production contractor for the Pilot Plant (see Reference 13). Martin Marietta made some design improvements based on the test program then produced and installed the 1,818

heliostats. An additional 93 were produced and installed at the International Energy Agency's solar plant in Spain. A brief design description of the heliosat assembly and of each of the major subassemblies follows:

Design Descriptions

Heliostat Assembly

A photograph of the front and back of the heliostat is shown in Figure AII-1. The more significant design features are shown in Table AII-I. A more detailed description is contained in later paragraphs. Each heliostat has 12 mirror modules which are attached at 3 points to the open welded/steel trusses. The single mirror attachment point is on the outboard truss. There is a dimensional offset of the torque-tube with regard to the centerline of the mirror assembly, thus minimizing the mass/center of gravity offset of the total reflective assembly with regard to the elevation axis of the drive mechanism. Therefore, the load on the elevation drive mechanism due to gravity and wind is reduced. The weights and weight per unit mirror area are shown in Table AII-II, where the actual reflective area of 39.1 m^2 is used to calculate the weight per unit area.

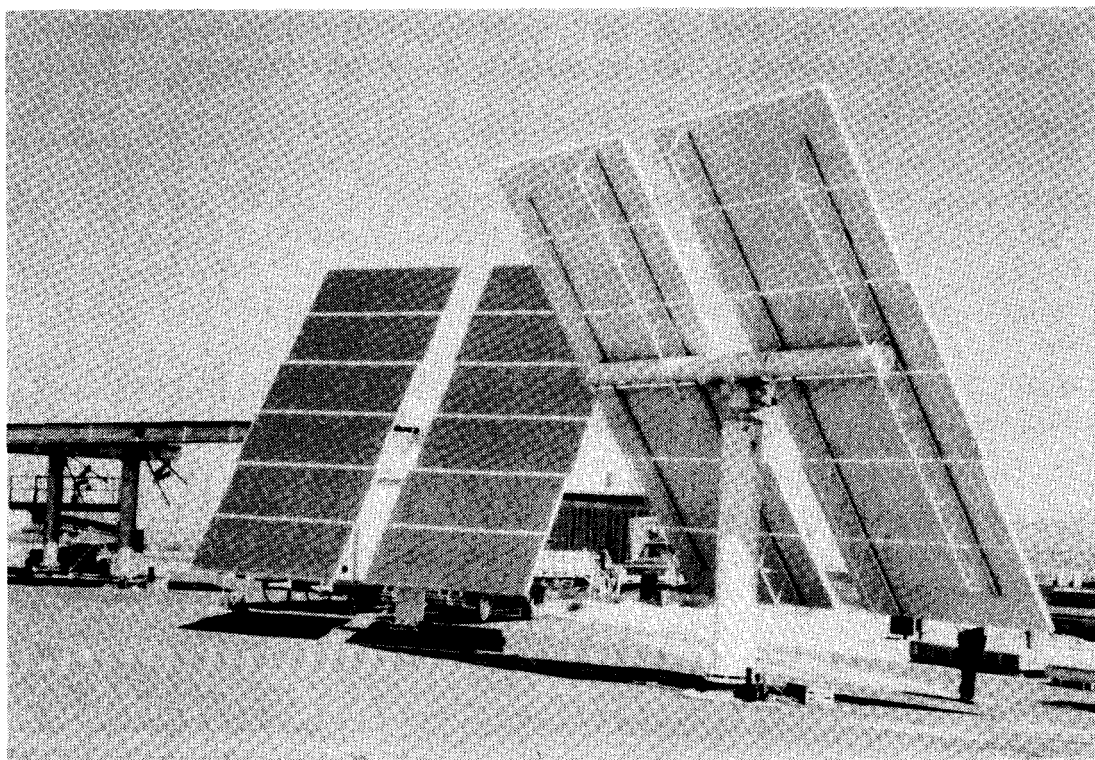


Figure AII-1. Pilot Plant Heliostats

TABLE AII-I
HELIOSTAT DESIGN FEATURES

<u>Mirror Module Assemblies:</u> • 39.1 m² total reflective area • Glass-3.2 mm x 1.092 x 3.05 m • Reflectivity: 91% • Aluminum Honeycomb core 6.5 cm thick • 3-point mount, flush plate mounts • 1-piece formed pan backing • High temperature epoxy adhesive • "Spherical" (2-axis) curvature • Edge seal • Painted finish	<u>AZ-EL Drive Mechanisms:</u> • Combined AZ-EL drives single housing; totally sealed unit • Azimuth drive: 1st Stage reduction (input)-worm gear; 2nd stage reduction (output)-helical pinion gear • Elevation drive: same internal drive as azimuth, with external connecting arms to torque tube • Motors: two, each requiring 18 Vdc for tracking and 120 Vdc for slewing • Separate azimuth drive-to-pedestal adapter
<u>Mirror Support Structure:</u> • Cross beams: 35.6 cm deep welded steel truss members • Torque tube: 30.5 cm dia., .48 cm wall steel cylinder • Weight: 588 kg (torque tube and cross beams) • Joints (cross beam/torque tube: bolted mech./friction joint, weld beads added for tested units • Finish: painted	<u>Pedestal Structures:</u> • 3.1 m long, .51 m dia., .64 cm wall • Base flange: 2.5 cm thick Finish: painted
<u>Total Weight: 1878 kg</u>	

TABLE AII-II
HELIOSTAT WEIGHTS

Component	Kg.	lb	Component Weight	
			Kg/m ²	lb/ft ²
Drive Mechanism	341	751	8.72	1.78
Mirror Support Structure (torque tube and Trusses)	588	1294	15.04	3.07
Mirror Module				
Each Module	50	110	15.35	3.14
All Modules	600	1320	15.35	3.14
Pedestal	349	767	8.93	1.82
 Total	 1878	 4132	 48.03	 9.82
Reflective Area = 39.1 m ² (420.94 ft ²)				

Mirror Module

The Pilot Plant heliostat mirror modules are all the same size and have the same focal length 366 m (1200 ft). A mirror module assembly drawing is shown in Figure AII-2. The module is a bonded (high temperature epoxy) sandwich design with an aluminum honeycomb core sandwiched between the glass mirror and a formed steel pan. The entire module is sealed against water penetration with polyisobutural (PIB) and silicone. These sealants are contained within a steel "C" shaped edge cap as shown in the figure. The aluminum honeycomb core is 6.4 cm (2.5 inch) thick and has perforations in the cell walls to allow free air circulation which prevents a build-up of air pressure between the pan and the mirror, since there is a small vent tube in one end of the pan. Each module has three mounting points which consist of a nut in a doubler plate which is bonded to the outside of the steel pan.

The mirror is made using low iron float glass which has an average solar transmittance of 0.890. The air-mass 1.5 solar reflectivity is nominally 91%. The glass thickness is 3.2 mm (.125 inch) and the width and length is 1.092 x 3.05 m (43 x 120 inches) respectively. The reflective area is 3.259 m² (35.078 ft² which is less than the size of the glass due to the edge seal. The mirror material is silver which is protected by a thin layer of copper and two layers of paint as shown in Figure AII-3. The second layer of paint was added to delay water penetration to the copper.

The glass for the mirrors was characterized by Pacific Northwest Laboratory and is reported in Reference 18. This report describes the optical properties, durability, and mirroring properties for this special run of low iron float glass. The glass exceeds all specifications for optical transmittance, and durability and there was no apparent difficulty in silvering the glass.

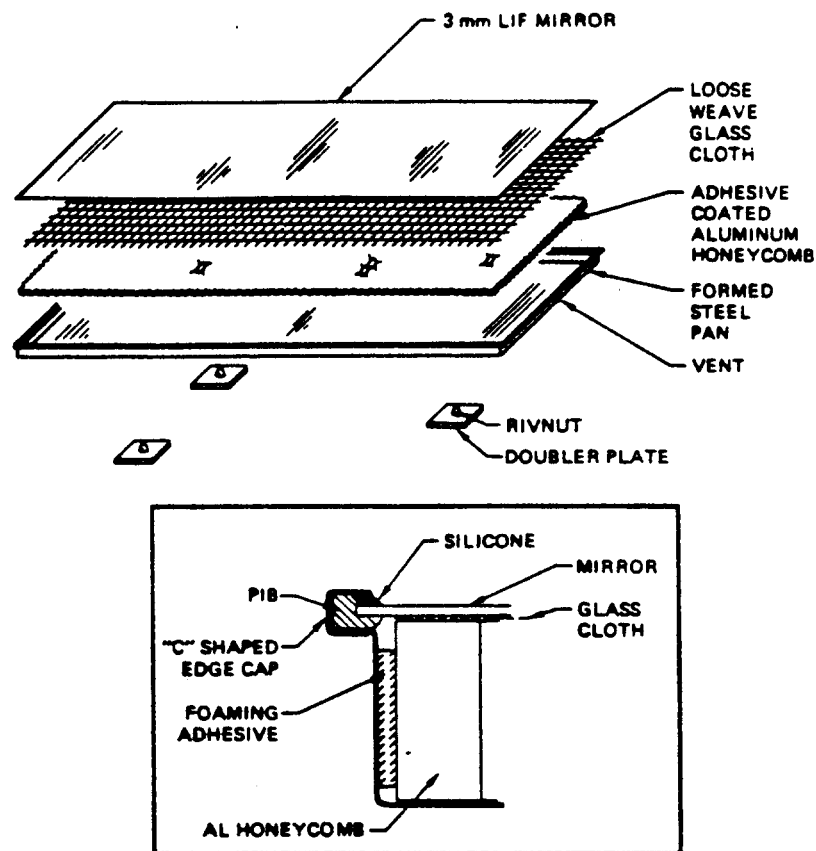


Figure AII-2. Barstow Mirror Module

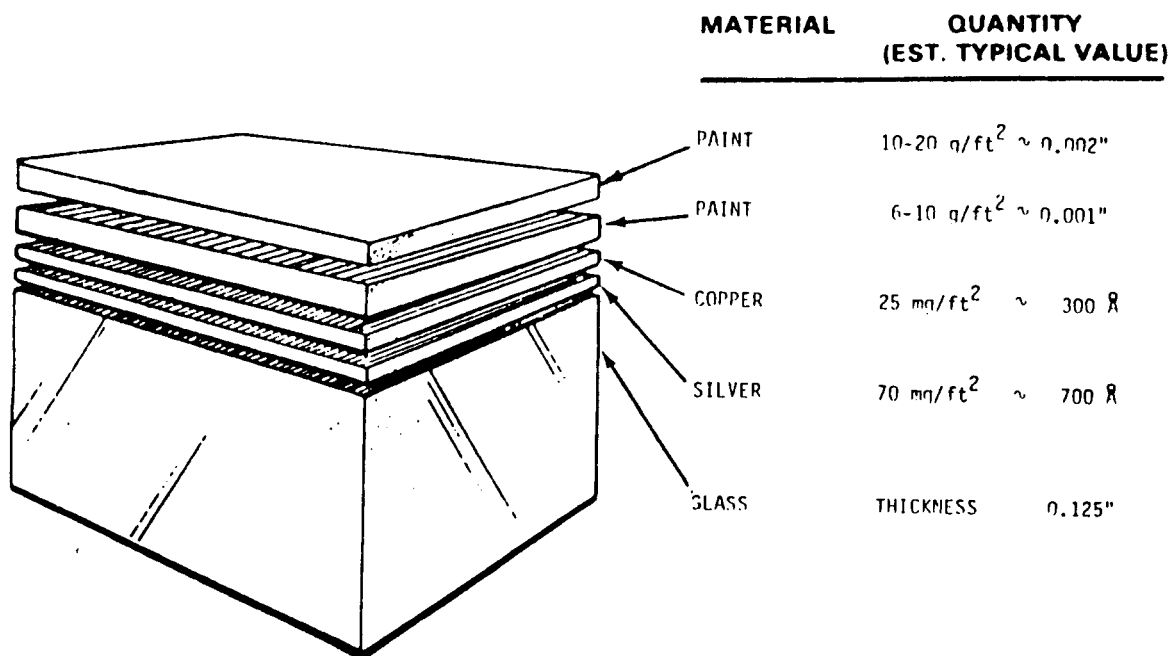


Figure AII-3. Structure of Pilot Plant Mirrors

Mirror Assembly Support Structure – The mirror support structure consists of a torque tube and four cross beams as shown in Figure AII-1. The cross beams are 35.56 cm (14 inch) deep welded steel truss members and the steel torque tube diameter is 30.48 cm (12 inch) with a 0.478 cm (.188 inch) wall thickness. The entire assembly is painted and weighs 588.2 Kg (1294 lbs).

Drive Mechanism – Figure AII-4 shows an external view of the drive assembly complete with the connecting arms for the torque tube, motors, limit switches, optical encoders and pedestal adapter. The heliostat azimuth and elevation drive gear trains are both contained in the single housing. Both of the drive trains employ identical first stage worm/gear reduction and intermediate helical pinion shafts. It is only in the helical output gearing and drive shafts that the two systems differ. The three shafts of the gear box are all double sealed, and “thermal pumping” past the seals is prevented by an equalizing pressure diaphragm. The motors are 1/6 HP and they operate on 18 Vdc for tracking and 120 Vdc for slewing. A 13-bit incremental encoder is used on both the azimuth and elevation output shafts to provide axis position data.

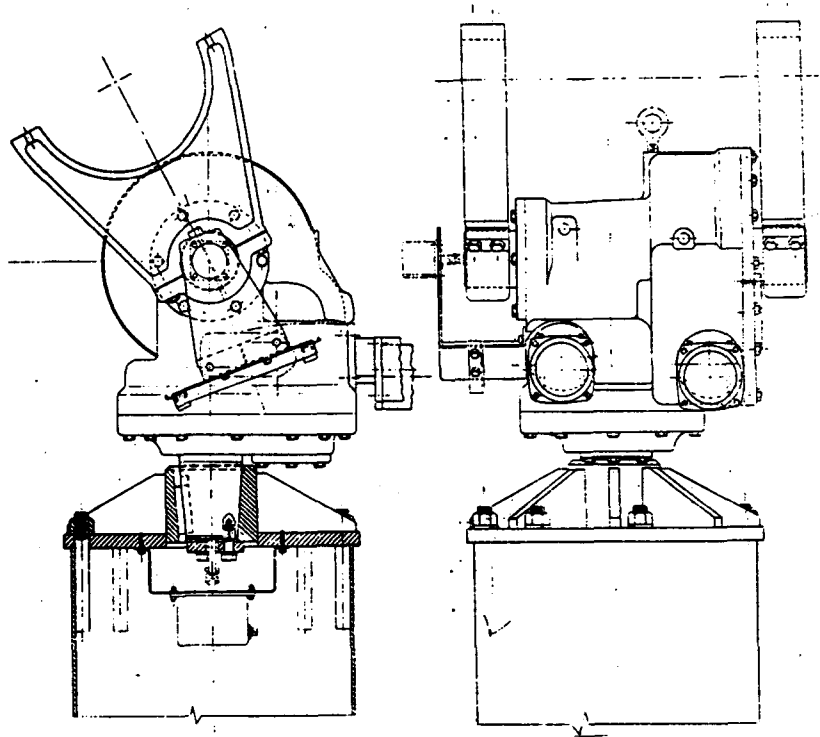


Figure AII-4. MMC 10 MW_e Solar Power Plant Drive Mechanism Assembly

Pedestal – The steel cylindrical pedestal is 3.086 m (121.5 inch) long, 0.508 m (20 inch) in diameter, with a 6.35 mm (0.25 inch) thick wall. A 2.54 cm (1 inch) thick steel flange is used to connect the pedestal to the foundation bolts. There is a cutout with a cover near the center of the pedestal where the heliostat control box is inserted and another cutout near the top to allow access to the azimuth encoder and limit switches. The pedestal is finished with paint.

Foundation – A drilled pier foundation made of reinforced concrete is used to support the heliostat. The foundation is 3.05 m (10 ft) deep and 0.91 m (3 ft) in diameter with 8 top-exposed pedestal attachment bolts.

Heliostat Control – The heliostat field control system consists of a micro-processor based controller inside of each heliostat pedestal and Heliostat Field Controllers (HFC) for control of groups of up to 32 heliostats which are also located inside of a pedestal, and a central computer called a Heliostat Array Controller, for control of the entire field. The heliostats can be controlled individually or by groups in either manual or automatic modes through the Heliostat Array Controller which is located in the central control room. The computational requirements are shared by the Heliostat Array Controller (HAC) and the individual Heliostat Controllers (HC). The HAC calculates the sun position and sends this information via the HFC to the HC. The HC uses the sun position to calculate the required position for heliostat azimuth and elevation axis. The required position is compared to the actual position from the incremental encoders and the motors are turned on as needed to reach the desired position. The encoders have a 13-bit or 0.76 mr resolution. The heliostat absolute orientation is determined from a separate, single-encoder bit. This bit or mark is located a few degrees from the heliostat face-down stow position. The absolute position is corrected when the heliostat encounters this bit.

Microswitch limit switches on each axis interrupt motor current and prevent mechanical damage in the event of control or operator error. Power to the heliostat is 120 volts a.c. single phase and a heliostat uses about 380 watt-hours of energy in a typical 10-hour day. Rectifiers in each HC provide the d.c. power to run the heliostat motors and electronics.

Drawing List

Drawing numbers for the Martin Marietta drawings, which provide the heliostat design description, are as shown in Tables AII-III through AII-XI.

TABLE AII-III
HELIOSTAT ASSEMBLY DRAWINGS

Nomenclature	Part Number
Heliostat Assembly	40M5005132720-010
*Installation Instructions-Mechanical	40M5001I
*Assembly Canting Procedure	40M50002M
Drive Mechanism Assembly	40M5005132721-010
*Drive Mechanism Assembly	40M50009M
*Transpsorting Procedure	40M50007M
*Check-out Procedure	40M50026M
(See Table AII-IV)	
Pedestal Assembly	40M5005132725-029
(See Table AII-V)	
Reflective Assembly	40M5005132730-010
*Reflective Assembly procedure	40M50006M
*Loading and Transport Procedure	40M50008M
*Rack Assembly Procedure	40M50004M
*Mirror Assembly Procedure	40M50009M
*Mirror Cleaning/Inspection	40M50010M
*Details - Pan Assembly	40M50011M
*Corner Clip Detail	40M50012M
*Pan Assembly	40M50013M
*Mirror Module Bondment Assembly	40M50014M
*Contour Check	40M50016M
*Rivnut/Doubler Assembly	40M50016M
*Accelerator/Spacer Tape Assembly	40M50017M
*Doubler Bond Assembly	40M50018M
*Final Sealant	40M50019M
*Pack, Ship and Transportation	40M50020M
(See Table AII-VI)	
Electrical Installation	40E5005132735-009
* Installation Instructions-Electrical	40M50031
*Power Cord Assembly	40E5005132740-C01
*HC-HC/HFC Mechanical Assembly	40E5005132740-M01
*Cable Assembly	40E5005132745-CXX
*Plug Assembly	40E5005132745-J03
*Wire Assembly	40E5005132745-W01
(See Table AII-VII)	
*Manufacturing Procedures and Instructions	

TABLE AII-IV
10 MWe PHASE II INDENTURED PARTS LIST
Drive Mechanism Assembly

Nomenclature	Part Number
Drive Mechanism Assembly	40M5005132721-010
Drive Mechanism (Vendor Supplied)	40M5001132711-010
Gear Motor (Vendor Supplied)	40E5001132712-019
Encoder (Vendor Supplied)	40E5001132712-020
Encoder (Vendor Supplied)	40E5001132713-019
Peestal Interface Adapter	40M5005132722-003
Ring - Tie Down	40M5005132722-004
Control Arm	40M5005132723-009
Encoder Cover	40M5005132727-014
Mounting Plate	40M5005132727-015
Bracket	40M5005132727-016
Spring	40M5005132727-017
Mounting Plate	40M5005132727-018
Arm Assembly	40M5005132727-019
Arm Assembly	40M5005132727-020
Bracket - Adjustable	40M5005132727-021
Bracket	40M5005132727-022
Arm	40M5005132727-023
Bracket	40M5005132727-024

TABLE AII-V
PEDESTAL ASSEMBLY DRAWINGS

Nomenclature	Part Number
Pedestal Asssembly	40M5005132725-029
Flange - Base	40M5005132725-002
Stud	40M5005132725-003
Strap	40M5005132725-007
Pedestal	40M5005132725-013
Access Shroud	40M5005132725-017
Plate	40M5005132725-18
Access Caover Assembly - Large	40M5005132725-019
Access Cover - Large	40M5005132725-004
Tab	40M5005132725-006
Strap	40M5005132725-022

TABLE AII-VI
REFLECTIVE ASSEMBLY DRAWINGS

Nomenclature	Part Number
Reflective Assembly	40M5005132730-010
Rack Assembly	40M5005132732-040
Bar Joist Assembly	40M5005132732-049
Bar Joist	40M5005132733-009
Angle	40M5005132733-001
Rod	40M5005132733-002
Web	40M5005132733-003
Web	40M5005132733-004
Tab	40M500513272732-007
Tab	40M500513272732-013
Bar Joist Assembly	40M5005132732-050
Bar Joist	40M5005132733-009
Angle	40M5005132733-001
Rod	40M5005132733-002
Web	40M5005132733-003
Web	40M5005132733-004
Tab	40M5005132732-007
Tab	40M5005132732-013
Bar Joist Assembly	40M5005132732-059
Bar Joist	40M5005132722-019
Angle	40M5005132722-005
Rod	40M5005132733-006
Web	40M5005132733-007
Web	40M5005132722-008
Tab	40M5005132732-007
Tab	40M5005132732-013
Bar Joist Assembly	40M5005132732-060
Bar Joist	40M5005132722-019
Angle	40M5005132733-005
Rod	40M5005132733-006
Web	40M5005132733-007
Web	40M5005132733-008
Tab	40M5005132732-007
Tab	40M5005132732-013
Elevation Beam	40M5005132732-069
Tube	40M5005132732-001
Lug	40M5005132732-002
Gusset	40M5005132732-003
Lug	40M5005132732-012
Angle	40M5005132732-014
Mirror Assembly	40M5005132719-009
Mirror	40M5005132718-009
Pan	40M5005132719-001
Inside Corner Clip	40M5005132719-003
Edge Clip	40M5005132719-004
Outside Corner Clip	40M5005132719-005
Edge Clip	40M5005132719-006
Capillary Cap	40M5005132719-007
Capillary Tube	40M5005132719-008
Plate Assembly	40M5005132719-010
Plate	40M5005132719-002

TABLE AII-VII
ELECTRICAL INSTALLATION DRAWINGS

Nomenclature	Part Number
Installation Assembly	40E5005132735-009
Wiring Harness	40E5005132739-009
Cable	40E5005132739-001
Limit Switch Assembly, Azimuth	40E5005132729-010
Limit Switch Assembly, Elevation	40E5005132739-019
Data Cable	40E5005132739-020
Data Cable	40E5005132739-029
Data Cable	40E5005132739-030
Data Cable	40E5005132739-039
Data Cable	40E5005132739-040
Data Cable	40E5005132739-049
*HC Electrical Unit	40E5005132740-029
*HC Electrical Subassembly	40E5005132740-039
Mounting Plate	40E5005132741-004
Wiring Harness	40E5005132745-040
*Card Assembly, HC	40E5005132747-010
Card, Printed Wiring	40E5005132742-002
Housing, Louvered	40E5005132741-001
Cable	40E5005132745-029
Cable	40E5005132745-030
Warning Tag	40E5005132746-002
Identification Plate	40E5005132746-003
Reference Designator Set	40E5005132746-005
*HC/HFC Electrical Unit	40E5005132740-030
*HFC Electrical Subassembly	40E5005132740-040
HC Electrical Subassembly	40E5005132740-039
Mounting Plate	40E5005132741-004
Wiring Harness	40E5005132745-040
*Card Assembly, HC	40E5005132747-010
Card, Printed Wiring	40E5005132742-002
*Cable	40E5005132745-039
*Jumper, Power Cable	40E5005132745-049
*Card Assembly, HFC	40E5005132748-010
Card, Printed Wiring	40E5005132743-002
Housing, Louvered	40E5005132741-001
Cable	40E5005132745-029
Cable	40E5005132745-030
Warning Tag	40E5005132746-002
Identification Plate	40E5005132746-004
Reference Designator Set	40E5005132746-005
*Manufacturing procedures and instructions as well as component drawing.	

TABLE AII-VIII
HAC TO HFC INTERFACE DRAWINGS

Nomenclature	Part Number
HAC to HFC Interface	40E5005132751-030
Card Assembly	40E5005132751-039
Card Assembly	40E5005132751-040
Cable Assembly	40E5005132751-049

TABLE AII-IX
FABRICATION EQUIPMENT DRAWINGS

Nomenclature	Part Number
Fabrication Equipment	40M500132760
Assembly Canting Tool	40M5005132761
Drive Mechanism Assembly Fixture	40M5005132762
Drive Mechanism Lifting Device	40M5005132763
Rock/Reflective Assembly Fixture	40M45005132764
Adapter Plate - Talyrel	40M5005132766
Mirror Assembly Dolly	40M5005132767
Reflective Assembly Handling Sling	40M5005132768

TABLE AII-X
INSTALLATION MAINTENANCE EQUIPMENT DRAWINGS

Nomenclature	Part Number
Installation Maintenance Equipment	40M500132770
Field Canting Tool	40M5005132771
Protective Cover-Mirror	40M5005132772
Transporter Rack-Reflective Assembly	40M5005132773
Manual Control Box	40M5005132774
HC/HFC Stimulator	40M5005132775
Drive Unit Checkout Console	40M5005132776
Transporter Rack-Drive Units	40M5005132777
Lifting Adapter-Pedestal	40M5005132779
Encoder Bias Measurement System	40M5005132781
Encoder Zero Set Indicator	40M5005132782
Field Inst. Adapter Reflective Assembly	40M5005132783
Motor Drive Tool	40M5005132784

TABLE AII-XI
DOCUMENTATION DRAWINGS

Nomenclature	Part Number
Drawing Tree	40M5005132701
Windloading Analysis	MCR-78-1333
Foundation Requirements	40M5002S
Collector Control Software	40I5001S
Design Specification	
Quality Assurance Plan - Phase II	MCR-79-1352
Manufacturing Plan - Phase II	4005002P
O & M Equipment - Phase II	4005004P
Acceptance Plan - Phase II	4005005P
O & M Manuals - Phase II	4005007P
O & M Facilities Requirements - Phase II	4005008P
Phase II Planning	400500GP

APPENDIX III

BEAM CHARACTERIZATION SYSTEM DESIGN DESCRIPTION FOR THE 10 MW_e SOLAR THERMAL CENTRAL RECEIVER PILOT PLANT

General Description

The Beam Characterization System (Reference 34), (BCS), includes the hardware and software required to permit rapid and automatic characterization of the reflected beams directed to the receiver by any single heliostat and simultaneous measurements of sun shape. A block diagram is shown in Figure AIII-1. The data available from the BCS includes beam size and shape, beam centroid, flux distribution, total beam power, and as required, the radial radiance distribution of the sun. BCS beam data are gathered by four vidicon cameras (each dedicated to a separate target) which view tower-mounted targets located below the receiver. Incident irradiance data are obtained by radiometers located on each target. The cameras are located as shown in Figure AIII-2 to be near-perpendicular to their respective targets. The physical characteristics of targets are shown in Figure AIII-3 along with the locations of the radiometers.

Data gathered by the BCS equipment are digitized, calibrated, processed to characterize the image, and stored. These data can then be used to align and evaluate the heliostats during plant operation. The system is designed to sequentially evaluate reflected images on an individual heliostat basis. Simultaneous operation of the 4 targets and cameras for the calibration of individual heliostats is possible. However, to eliminate stray beams crossing a target during data acquisition opposite targets (N-S or E-W), are normally run simultaneously.

The major BCS hardware elements are the video equipment, the data processing and control equipment, the target, and the sunshape camera. Detailed descriptions of each of these elements are presented in the following four sections.

1. BCS Video Equipment The BCS video equipment consists of:

- Four self-contained video cameras with camera lenses and sunshields, installed as shown in Figure AIII-2.
- Remote camera control system with interconnecting cables to the video switching system and the computer and a remote control panel.

- Video switching system
- Video monitors
- Mounting bases for the video cameras with sunshields.
- A separate suntracking camera mounted on the roof of the control building.

A. Video Cameras. The BCS video cameras are self-contained, low-light-level television cameras enclosed in environment-resistant housings and equipped with silicon vidicon tubes. Although designed for operation between -40° to 60°C (-40°F to 140°F), certain modifications are provided to minimize camera dark current variations with temperature. Additionally, all video automatic gain control circuits are disabled so that the cameras can operate as radiometers.

The cameras are designed for reliable, unattended, continuous-duty operation in day and night monitoring or surveillance applications and are, therefore, satisfactory for use as BCS field cameras requiring minimum maintenance. The cameras can operate automatically in light levels ranging from bright sunlight to moonlight.

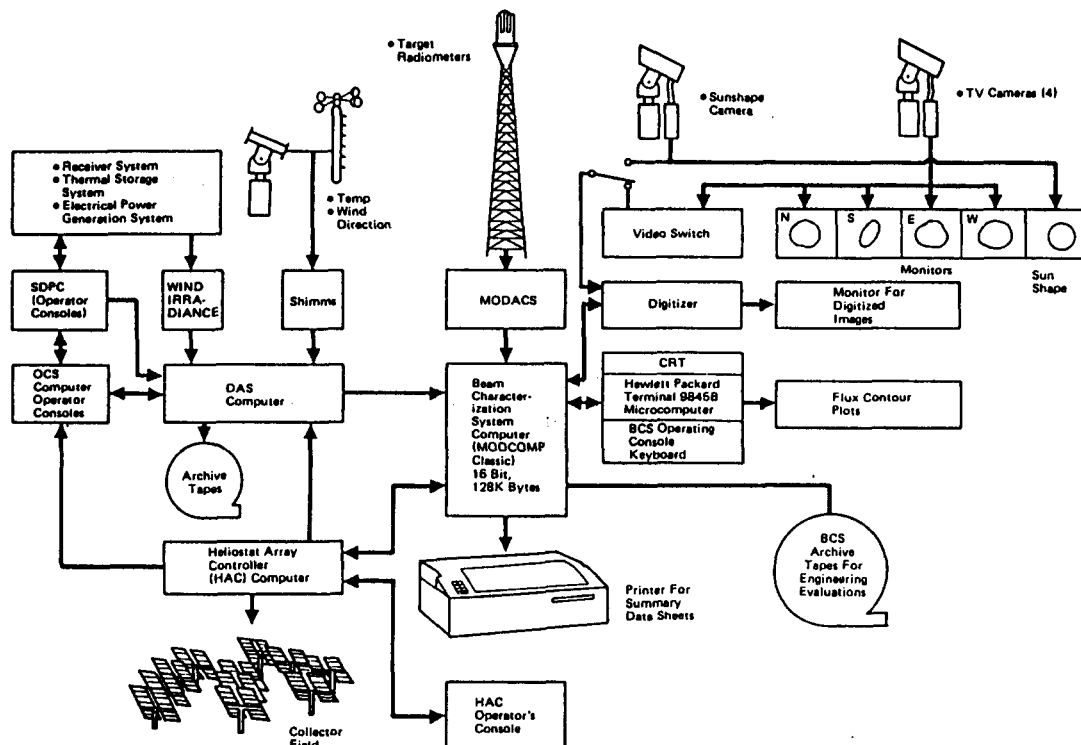


Figure AIII-1. BCS Interface Block Flow Diagram Landscape

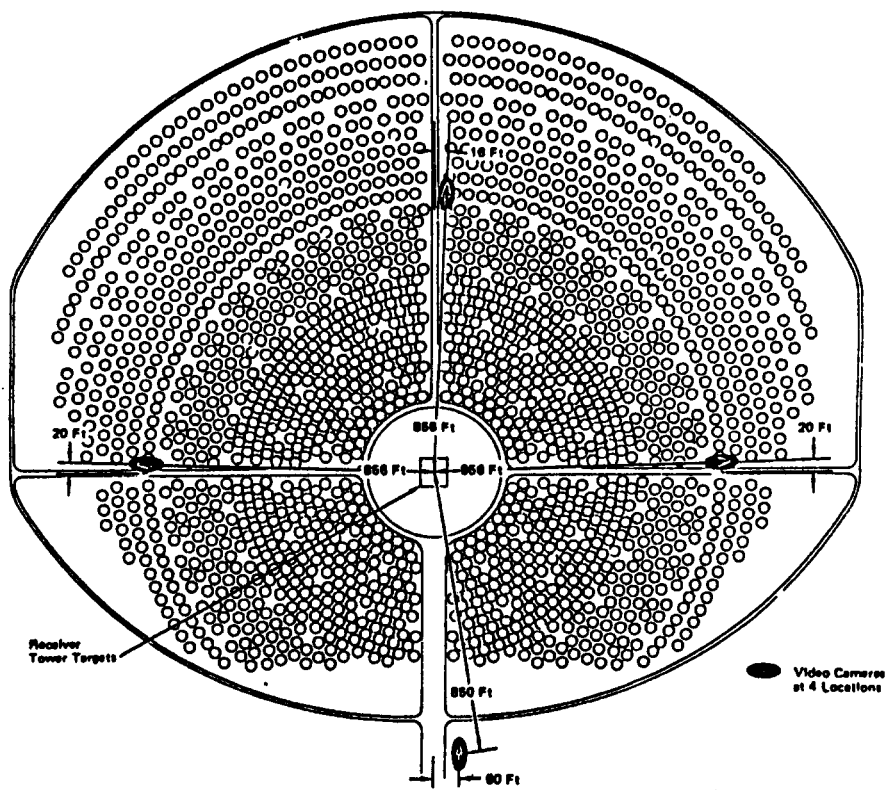


Figure AIII-2. BCS Camera Locations

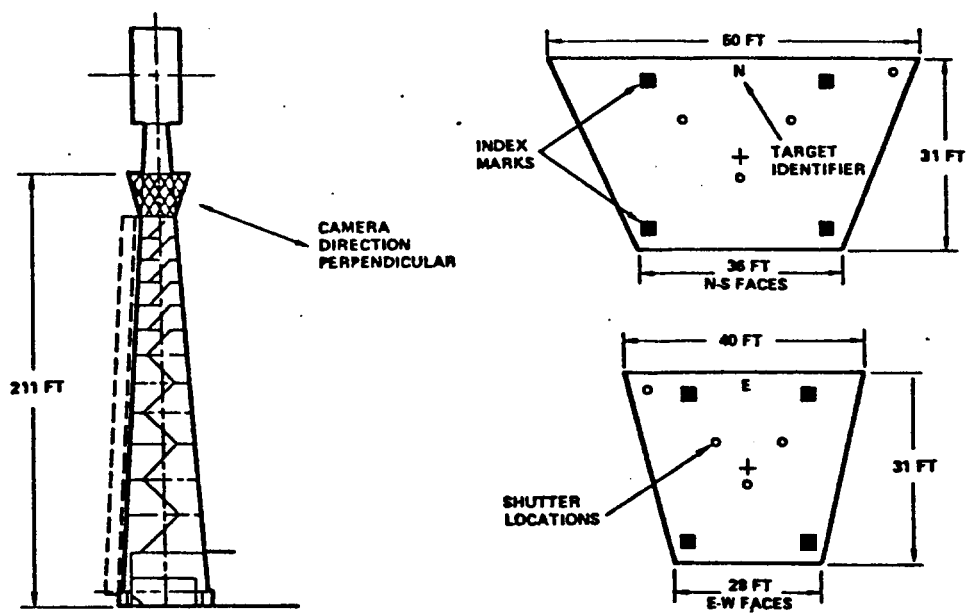


Figure AIII-3. BCS Targets

A bright light limiter circuit allows full camera performance under conditions where blooming from intense scene highlights would otherwise make the picture unsatisfactory. The level and amount of scene highlights affected are adjustable. Highlight level can be set from black to maximum white for best contrast and resolution.

Video Camera. The video camera is a model 2850C-207 low light television camera manufactured by COHU, Inc. Electronics Division. The camera is equipped with an RCA model 4532 B/H silicon diode array vidicon tube and a COHU model 2820 C-204 10:1 zoom lens with a 2X extender. Features include remote or automatic iris and zoom control, antiglare shields, sealed environmental housing, Dual Tone Modulated Frequency (DTMF) control from the BCS computer interface, and stable platform to minimize camera movement and wind induced vibration (see Figure AIII-4).

The antiglare shields eliminate stray light from clouds, receiver, sun, etc., which could cause erroneous measurements. The shields are formed to match the shape of the target and two or three are used as multiple light baffles.

B. Remote Camera Control System The remote camera control system provides a means to remotely control the operation of the four (4) video cameras located in the collector field. The following functions are controlled by the camera control unit from the local control panel or the BCS computer:

- Iris
- Focus
- Camera switching
- Camera power

The basic system consists of a transmitter at the control station, with the capability of 40 different commands, and a receiver at each television camera location. The system includes: 1) a computer interface unit with a remote control interlock and remote status feedback; 2) a switcher control; 3) pre-select automatic standby or automatic off. Communications between the transmitter and each receiver are over a standard twisted-pair wire.

Dual Tone Multifrequency (DTMF) Camera Control System. Camera selection and light control are accomplished by a noise resistant tone command system composed of a transmitter in the camera control rack and a remote receiver near each camera.

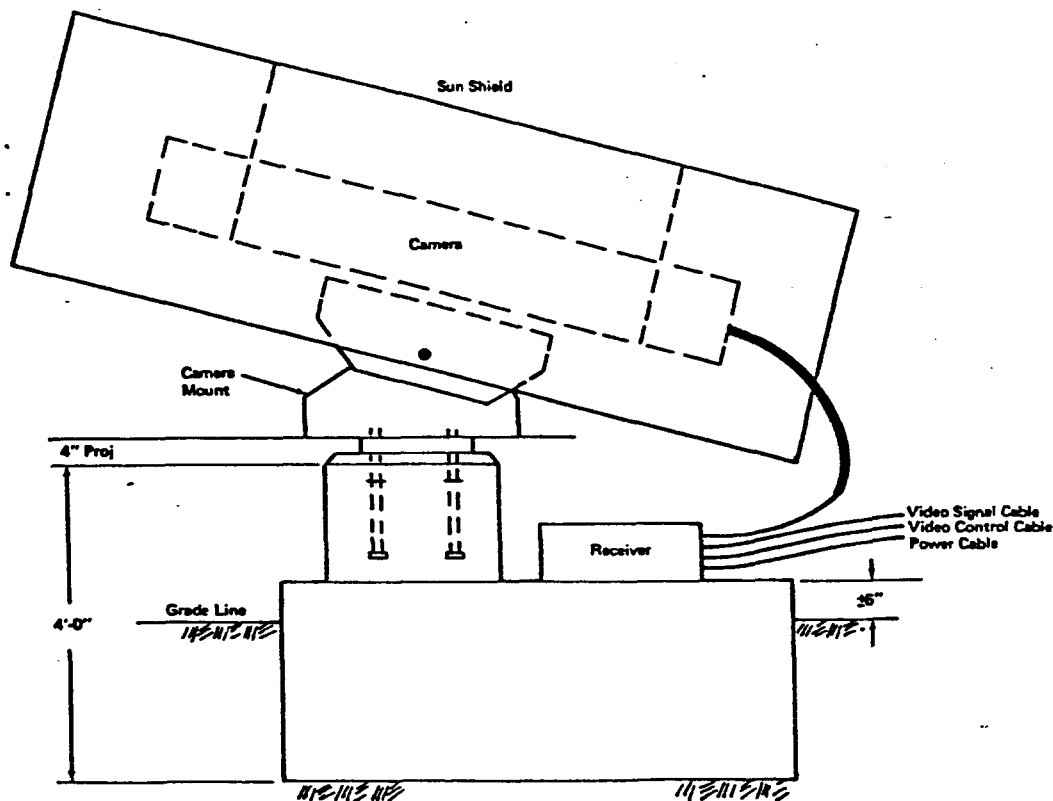


Figure AIII-4. BCS Camera and Foundation

The transmitter is a COHU model DTMF 100 modified for the Solar One application. Integral manual control switches are provided to select the desired camera, apply power, and control the iris or place it in automatic mode. Reed relay outputs from the BCS computer provide programmable camera selection and iris control. Camera control commands are encoded to digital form and transmitted to the selected receiver over standard twisted pair wires using audio tones to represent the digital information. The transmitter also sends camera select commands to route the desired video input through the video switch to the digitizer.

The COHU model DTMF 200 receiver decodes the command data from the transmitter and provides power and iris control commands to its associated video camera.

C. Video Switching System The video switching system provides a means for connecting the four BCS video camera inputs and the sunshape camera input to a single video digitizer and four video monitors. This device will provide for up to seven camera inputs to be switched to up to five output devices (i.e., the video digitizer and four video monitors are the outputs required).

The unit consists of a standard 19-inch, rack mountable chassis which includes an integral power supply. Each unit is equipped with a circuit interconnection board; wiring; connectors; and plug-in, etched-circuit cards as required to perform the specified functions.

The video switch is a Pelco Model VS504R switching matrix which routes the selected video input (North, South, East, West, or Sunshape camera) to the video digitizer.

D. Video Monitors Six 9-inch video monitors are provided for use with the field camera. One is located in the BCS cabinet in the equipment room. Four BCS monitors are located in the Data Acquisition System (DAS) room, and the fifth is located in the control room. The video monitors connect to the video digitizer or the video switcher. A sixth monitor is located in the DAS room, connected directly to the sunshape camera. The four BCS monitors display images of the targets and of the sun during data acquisition.

E. Video Camera Foundations and Mounts The BCS video cameras are mounted in the field in the orientation shown in Figure AIII-2. An adjustable camera mount bolted to a reinforced concrete pedestal and mounting plate form the camera mount.

The mount is of a adjustable pan and tilt design which can be adjusted manually. It can be installed in any orientation on a flat surface with a single bolt.

The camera can be locked in any desired panning orientation (360° by tightening the 5/16 inch panning bolt; it can be tilted $\pm 50^\circ$ as required and locked in position by tightening the tilt axis socket head bolt.

2. Data Processing and Control Equipment

The data processing and control equipment consist of:

- Video digitizer
- BCS computer interface
- CRT/keyboard terminal

A. Video Digitizer System

The video digitizer system: 1) accepts the video signal from the video camera; 2) converts the signal to a digital form; 3) stores the digital data; and 4) transmits these data to the BCS computer upon demand.

The video digitizer system is a Quantex Model DS-12 digital image memory/processor. This system: 1) accepts the video signal from the video camera (conforming to the IEA RS-170 standard), 2) converts the signal to a digital

form, 3) stores the digital data, and 4) transmits the data to the BCS computer upon command over an IEEE 488 interface.

Incoming composite video is stripped of sync and applied to a high speed A/D converter. Data from the A/D passes through the arithmetic processor where it may be combined with memory data through hardwired arithmetic processes which include summation with data already in memory, averaging, and subtraction. The resulting data is then stored in memory.

The IEEE Standard 488 interface connects the digital memory port and the system control microprocessor to the BCS computer. This interface connects the digitizer to a direct memory access channel of the BCS computer and allows block transfer of image data and program control of the digitizer functions.

A standard IEA RS-170 video output is routed to the BCS monitor CRT in the receiver console in the control room. Processed data is routed through a D/A converter to the digitizer or unprocessed data may be selected.

B. BCS Computer Interface

The video digitizer interfaces with the BCS computer through an IEEE 488 bus controller interface. This interface connects the digitizer to a direct memory access channel of the computer and allows block data transfers.

C. CRT/Keyboard Terminal

A CRT/keyboard terminal with integral hard copy capability is provided with the BCS and connected to the BCS computer to: 1) view data processed by the BCS software, and 2) allow the operator to enter data and control the BCS activities via the keyboard. This equipment is a black and white storage tube type display table mounted and located in the data evaluation room.

3. BCS Targets

The target equipment consists of the:

- Four targets
- Radiometers
- Target shutters

A. BCS Targets Each target consists of 20 individual panels hoisted and assembled in place on each side of the tower. Accurately located horizontal frames are permanently attached to the side of the tower. The panels are of 6061-T6 aluminum and 3.2 mm (0.125 inch) thick. Panel flatness criteria is established at ± 2.54 cm (1 inch) per 3.05 m (10 feet).

B. Radiometers Four radiometers are located on each target in the patterns as shown in Figure AIII-5. The radiometers measure the reflected beam irradiance incident on the surface of the sensor and provide an analog signal proportional to this irradiance to the MODCOMP MODACS Analog Input Circuitry. The measurements are digitized and subsequently transmitted to the BCS computer where the values are used in beam characterization computations.

The diagram shows two trapezoidal structures representing the North and East elevations of a target. The North Elevation is on the left, and the East Elevation is on the right. Both are labeled with dimensions and sensor locations.

North Elevation - 1/8" = 1'-0"

- Sensors:**
 - Top Left: 15'-10" from the left edge, 4" from the top edge.
 - Top Center: 18'-10" from the left edge, 8" from the top edge.
 - Top Right: 18'-10" from the left edge, 8" from the top edge.
 - Bottom Left: 15'-10" from the left edge, 1'-4" from the bottom edge.
 - Bottom Center: 18'-10" from the left edge, 1'-4" from the bottom edge.
 - Bottom Right: 18'-10" from the left edge, 1'-4" from the bottom edge.
- Targets:**
 - Top BCS Target: 8" x 8" Flat Black Point (Typ) located 8'-10 1/2" from the left edge and 7'-10 1/2" from the top edge.
 - Bottom BCS Target: Located 18'-10" from the left edge and 1'-4" from the bottom edge.
- Other Dimensions:**
 - Top width: 18'-10"
 - Bottom width: 18'-10"
 - Height: 2'-0"

East Elevation - 1/8" = 1'-0"

- Sensors:**
 - Top Left: 11'-10" from the left edge, 4'-8" from the top edge.
 - Top Center: 11'-10" from the left edge, 4'-8" from the top edge.
 - Top Right: 11'-10" from the left edge, 4'-8" from the top edge.
 - Bottom Left: 11'-10" from the left edge, 1'-4" from the bottom edge.
 - Bottom Center: 11'-10" from the left edge, 1'-4" from the bottom edge.
 - Bottom Right: 11'-10" from the left edge, 1'-4" from the bottom edge.
- Targets:**
 - Top BCS Target: 8" x 8" Flat Black Point (Typ) located 11'-10" from the left edge and 5'-8" from the top edge.
 - Bottom BCS Target: Located 11'-10" from the left edge and 1'-4" from the bottom edge.
- Other Dimensions:**
 - Top width: 11'-10"
 - Bottom width: 11'-10"
 - Height: 2'-0"

C. Target Shutters Three target shutters are provided on each target. The shutters allow the total blocking of the light source impinging at the radiometer apertures located closest to the target center. The three shutters on each target are pneumatically controlled by a single solenoid operated valve that is activated from the MODACS digital output circuitry. The location of the shutters are shown in Figure AIII-5. Originally, the shutters were used to provide a nearly uniform reflecting surface during the video “image grab” portion of the BCS data acquisition. However, this procedure was modified so that the shutters are always open to obtain more nearly simultaneous measurements of the beam and the radiometer readings since beam motion was excessive for certain conditions, and the

time delay required for shutter opening and closing caused inaccuracies in power measurements.

4. Sunshape Camera

The sunshape camera shown in Figure AIII-6 is located on the Control Building roof adjacent to an Epply Normal Incident Pyrheliometer. The sunshape camera tracks the sun during BCS data acquisition and measures the solar radiance distribution an instant after the beam data is obtained for each heliostat. All of these data are stored on tape for engineering evaluation purposes, such as comparisons of the actual and ideal beam irradiance distributions, determination of effects of atmospheric scattering and clouds on solar radiance, and calculations of the solar irradiance which could be redirected to the receiver by an ideal heliostat. These evaluations are needed in the determination of the nature and magnitude of energy losses.

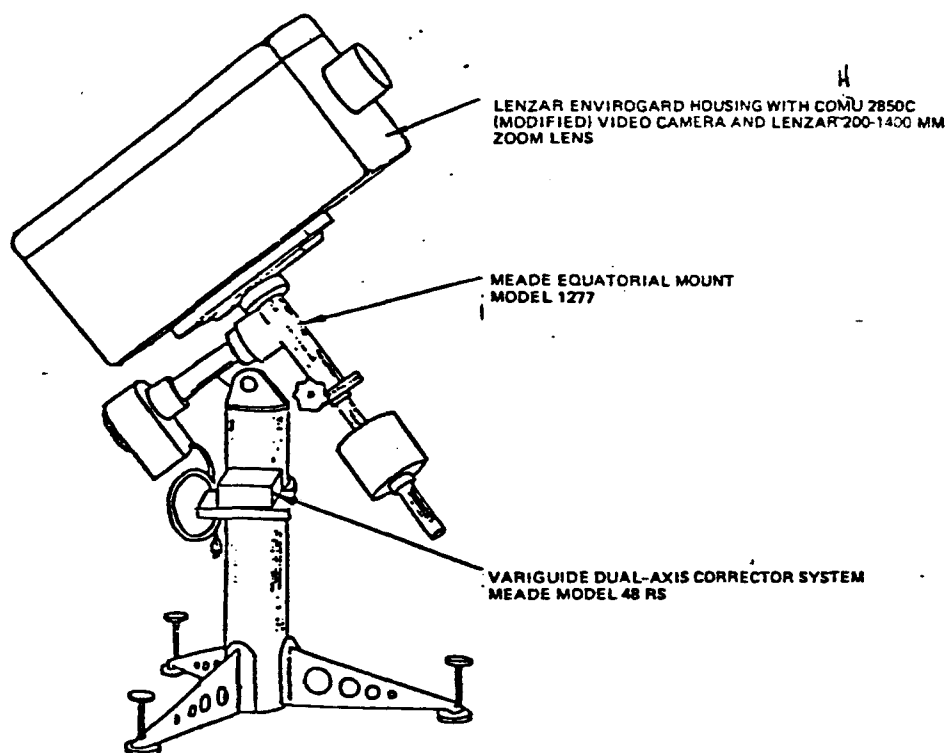


Figure AIII-6. Sun Shape Camera

The basic video camera is identical to the BCS field cameras except for the optics, vidicon tube, environmental enclosure, and filters. Camera modifications for elimination of AGC and black level control are identical, and shading corrections are made in the same manner. The camera is cooled to a constant temperature of 10°C (50°F) to provide a constant dark current.

A Hamamatsu IR vidicon (N214) is used, having a spectral response from 400 to 2000 nm, with excellent sensitivity in the far red range.

The spectral response characteristics of the Hamamatsu N214 tube shows a high peak in the visible and decrease out to about 2000 nm. However, the sun's radiance has a spectral dependence that depends on radius from the sun's center. Therefore, to obtain a valid radiance distribution for the total sun's radiance over all wavelengths, the tube's spectral response must be corrected by filters to obtain at least a reasonably constant output over its spectral range. A wide variety of off-the-shelf filters were investigated to obtain a set which provided reasonable flatness to the spectral response curve. The filters selected and the response are shown in Figure AIII-7.

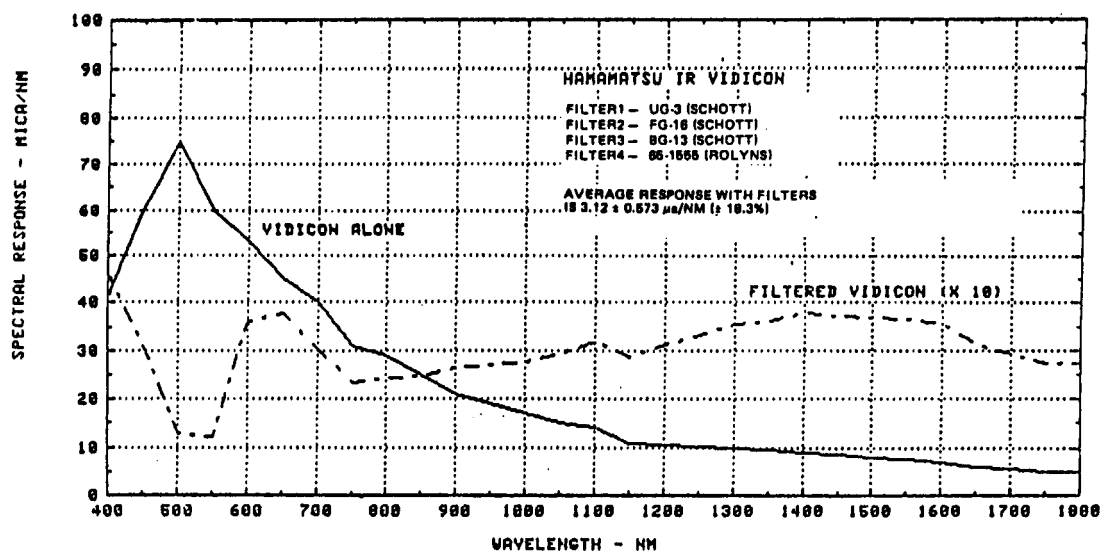


Figure AIII-7. Corrected Camera Response with Selected Filters

The camera and optics are enclosed in a Lenzar Optics Envirograd housing which uses solid state (Peltier effect) cooling to maintain the enclosure temperature at approximately 10°C (50°F). A Lenzar Optics 200 to 1400 mm manual control zoom lenses is used so that wide range of magnifications can be obtained.

The camera is mounted on a Meade tracker. Dual-axis corrector controls located at the BCS console allow the operator to position the camera as required for continuous sun tracking. Initial alignment is required each morning of the test day. This simply involves swinging the camera to point at the sun and turning on the tracker. A timer shuts off the tracker late in the afternoon.

Sunshape camera calibration is obtained by comparing the sum of the net direct image radiometer values to the irradiance, over the solid angle corresponding to the Epply Normal Incident Pyrheliometer.

These results over the entire face of the sun involve as many as 65,000 radiance values. Rather than use these in the computer analysis of the ideal beam shape, a radial distribution is developed and stored on magnetic tape with each heliostat beam scan. Tests of the four radial distributions (right, left, top, and bottom) are conducted to assure that the sun shape is symmetrical and not distorted by clouds.

5. BCS Operation

The BCS is used to measure the beam produced by an individual heliostat. The measurement information is used in heliostat performance evaluation and to make corrections in the pointing of the heliostat. The pointing error is determined by the BCS and the Heliostat Array Controller (HAC) uses this information to make changes to the "biases" in each heliostat. The bias is a number used to correct the encoder relative position to an absolute position.

The BCS operates in conjunction with the HAC in performing the measurement and bias updates.

There are five phases of operation of the BCS/HAC:

A. Initialization and Calibration. This phase includes setup of the equipment, location of the target registration marks and initialization of the BCS.

BCS initialization is required any time the BCS computer, the MODACS or other equipment is restarted. This phase gets the BCS into a state where the other phases can be performed.

The target registration marks are the black squares on each BCS target. These marks are used as a reference in the centroid measurement. Registration mark calibration is done at least once a week or anytime maintenance is done on the cameras or after high winds.

B. Candidate List Generation. This list is the list of heliostats to be measured. This step must be performed the day before BCS measurements because the program uses the date in the list generation. The candidate list can be automatically generated or the operator can select particular heliostats to be measured. Up to 60 heliostats can be put on the list. There are actually three identical lists generated to correspond with the three measurement periods: morning, noon, and afternoon.

When heliostats are automatically selected the "oldest" ones are selected first. A heliostat with a bias update six months ago would be selected before one updated yesterday. It is recommended that some heliostats be measured again the day after a bias update. This is especially true of any questionable ones or heliostats with beams partially off the target. Any heliostat which has an encoder replaced or adjusted should be scheduled for measurement as soon as possible.

C. BCS Measurement. This is the "auto-BCS" operation. The HAC automatically directs heliostats from standby or track to a BCS target for measurement by the BCS. Heliostats which may block or shadow the measured heliostat beam are moved to face up stow. The candidate list generated above contains the heliostats to be measured and the blocking heliostats to be moved. Once the measurement is complete the heliostats are returned to their previous mode.

Measurements are scheduled at three periods in the day. The object is to get a mid-morning, noon, and mid-afternoon measurement. Measurements too close together, very late in the day or early in the day, could reduce the measurement accuracy and the effectiveness of the bias update.

This phase requires BCS initialization and then starting BCS at the HAC console. Once a measurement list has been started, it proceeds automatically. The operator need only schedule each of the three sets of measurements. A list of 60 measurements takes about one hour. The actual time depends on how many heliostats are in the correct mode for measurement and their position in the field. Heliostats near the singularity point may take several minutes to move between track/standby to the BCS target.

D. Bias Update. Once the three measurements have been completed, the bias update can be performed. The object is to correct the pointing of heliostats.

The update is done by operating both the BCS and the HAC. The HAC uses the same candidate list used for measurement and obtains the centroid error information from the BCS. A new bias is calculated and the operator is asked if a change is to be made. If a change is made, it is incorporated in the HAC data base, but the heliostat is not updated until a load is performed. The update is also flagged in the BCS data base so that this heliostat will not be reselected for measurement when the next candidate list is generated.

APPENDIX IV

Solar One Wind Speed Data

List of Figures:

Wind speed plot with average wind speed -	west station, day 329 tower 4, day 329 tower 5 at 20 ft., day 317
Wind speed plots at 32.8 ft., 20 ft., and 10 ft. -	tower 3, day 101 tower 1, day 110 tower 4, day 356
Effect of height on average wind speed -	tower 1, day 356 tower 2, day 317 tower 3, day 358
Effect of location in field on average wind speed -	day 317 day 329 day 356 day 358

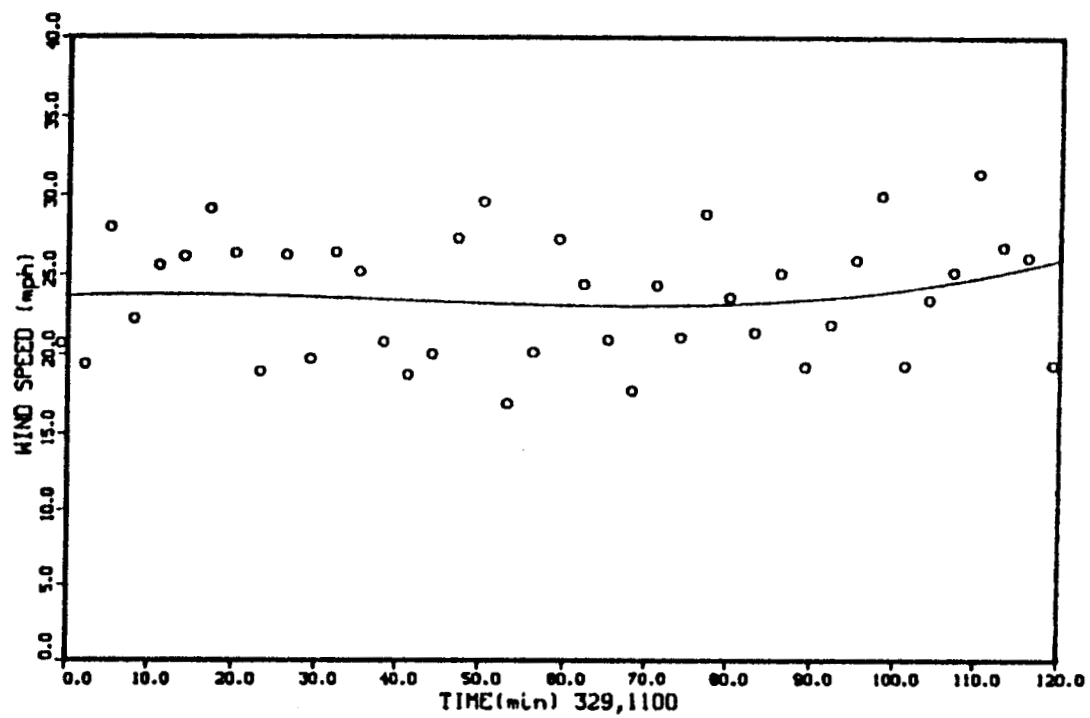


Figure AIV-1. Wind Speed Plot with Average Wind Speed, West Station, Day 329

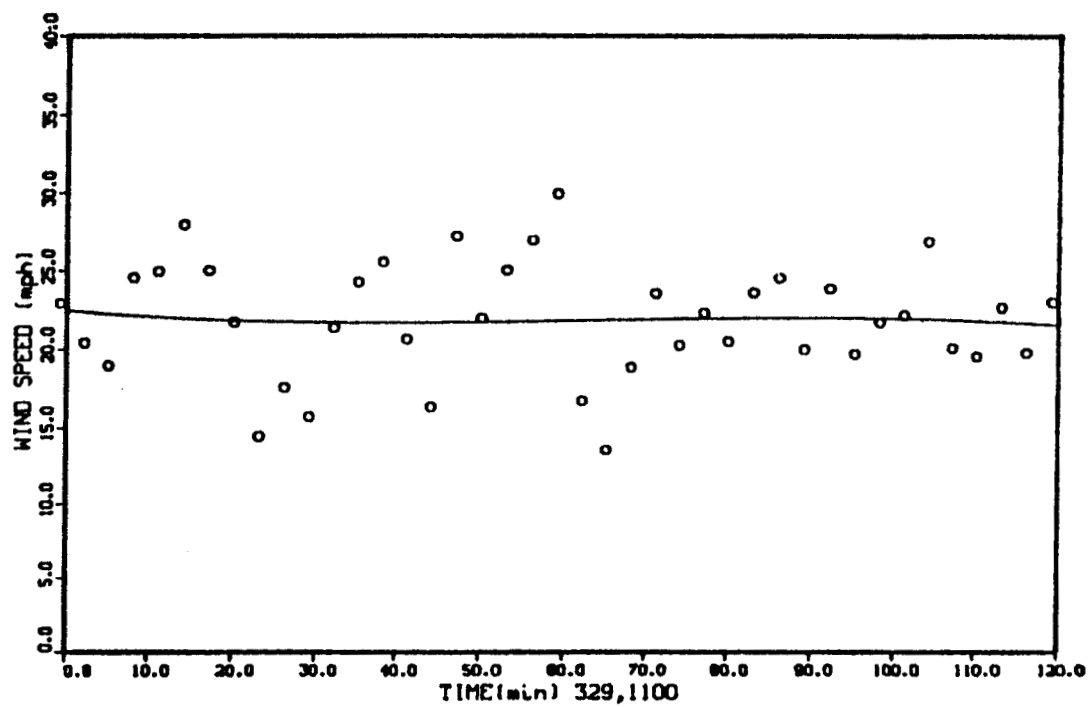


Figure AIV-2. Wind Speed Plot with Average Wind Speed, Tower 4, Day 329

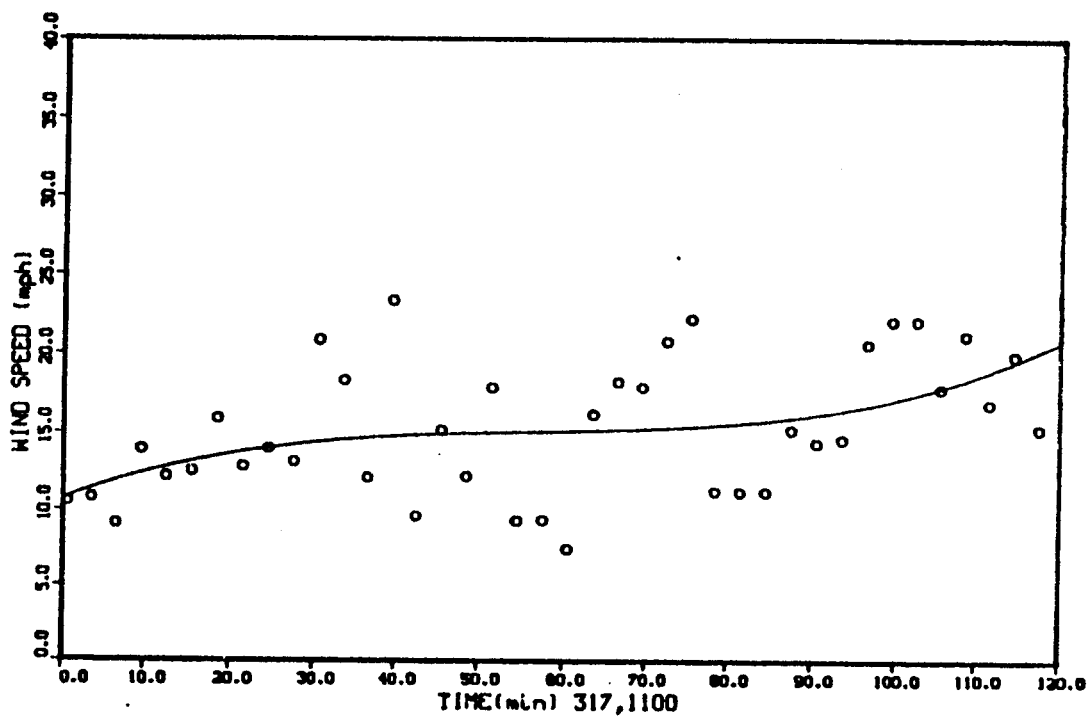


Figure AIV-3. Wind Speed Plot with Average Wind Speed, Tower 5 at 20 ft., Day 317

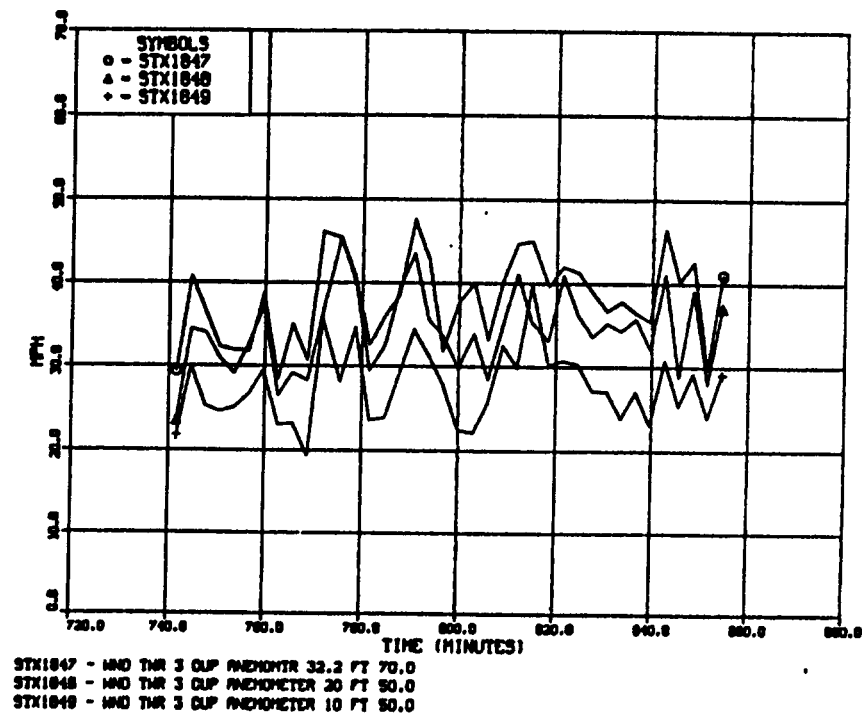


Figure AIV-4. Wind Speed Plot at 32.8 ft., 20ft., and 10 ft., Tower 3, Day 101

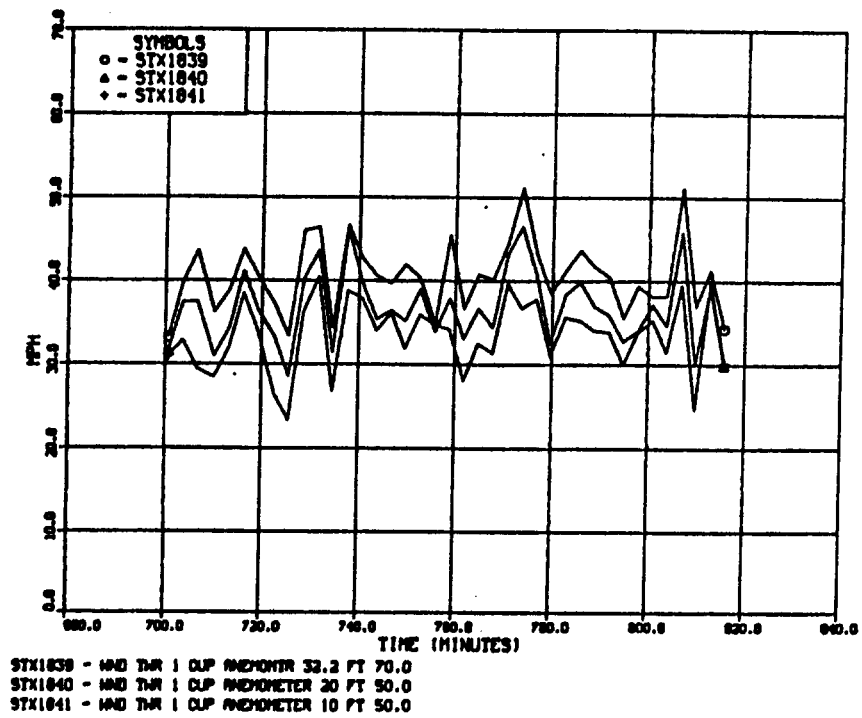


Figure AIV-5. Wind Speed Plot at 32.8 ft., 20ft., and 10 ft., Tower 1, Day 110

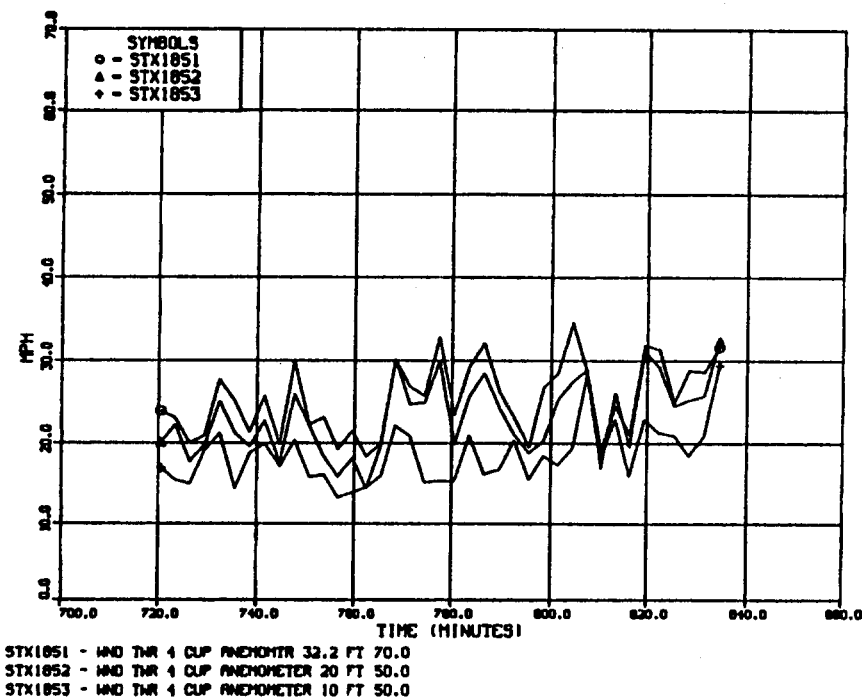


Figure AIV-6. Wind Speed Plot at 32.8 ft., 20ft., and 10 ft., Tower 4, Day 356

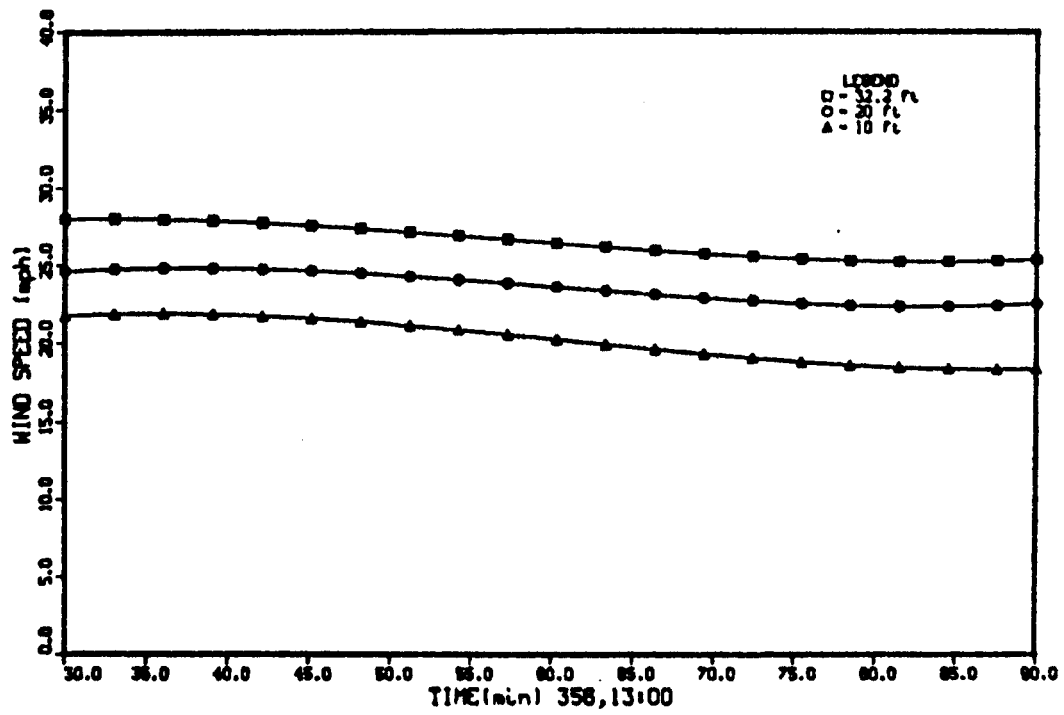


Figure AIV-7. Effect of Height on Average Wind Speed, Tower 1, Day 356

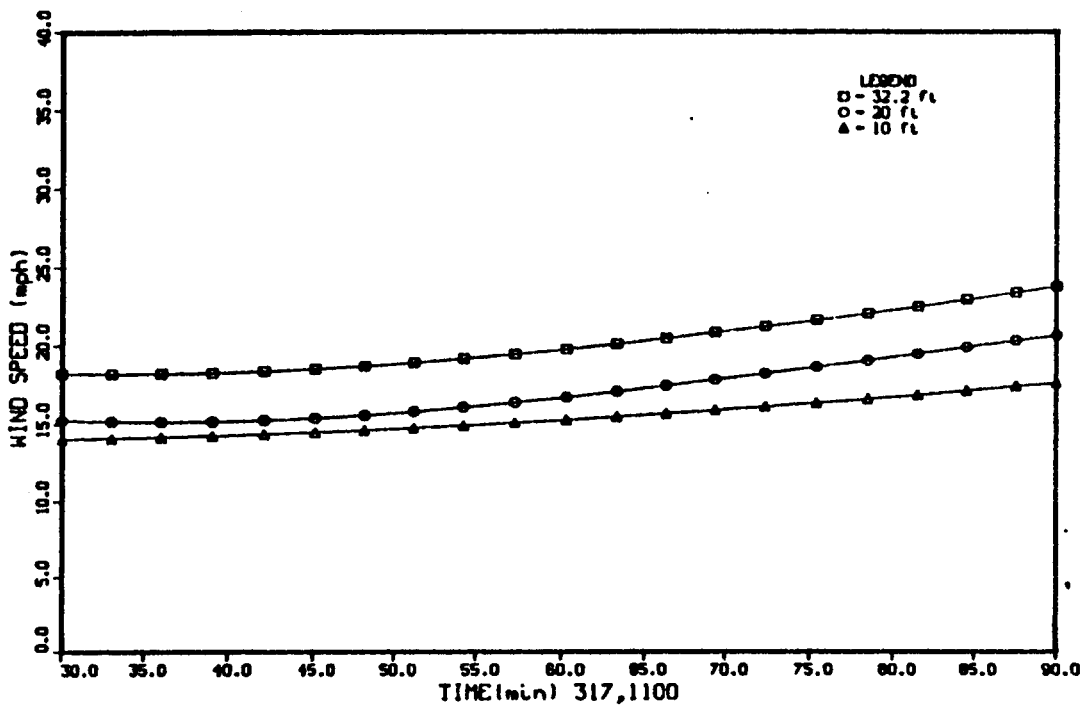


Figure AIV-8. Effect of Height on Average Wind Speed, Tower 2, Day 317

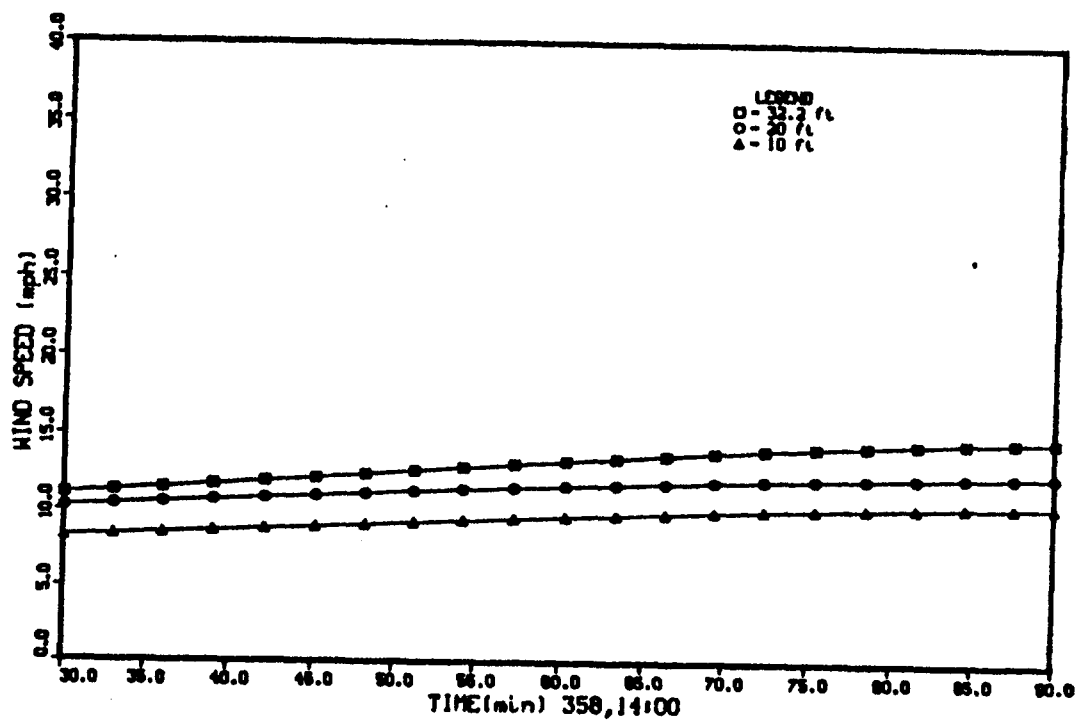


Figure AIV-9. Effect of Height on Average Wind Speed, Tower 3, Day 358

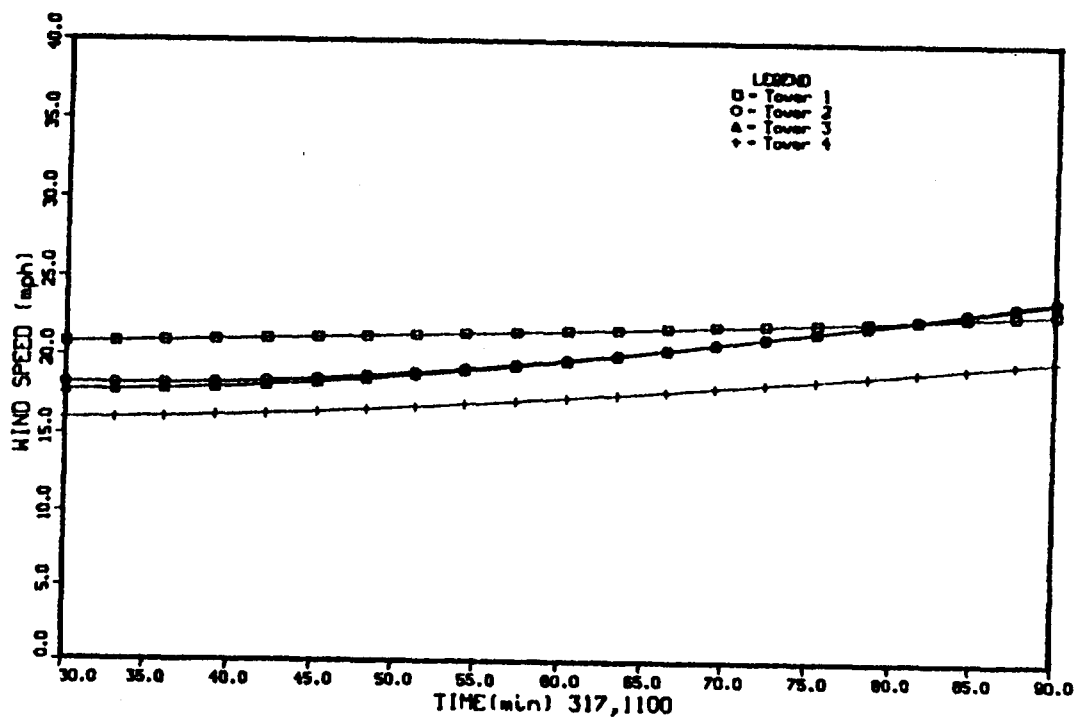


Figure AIV-10. Effect of Location in Field on Average Wind Speed, Day 317

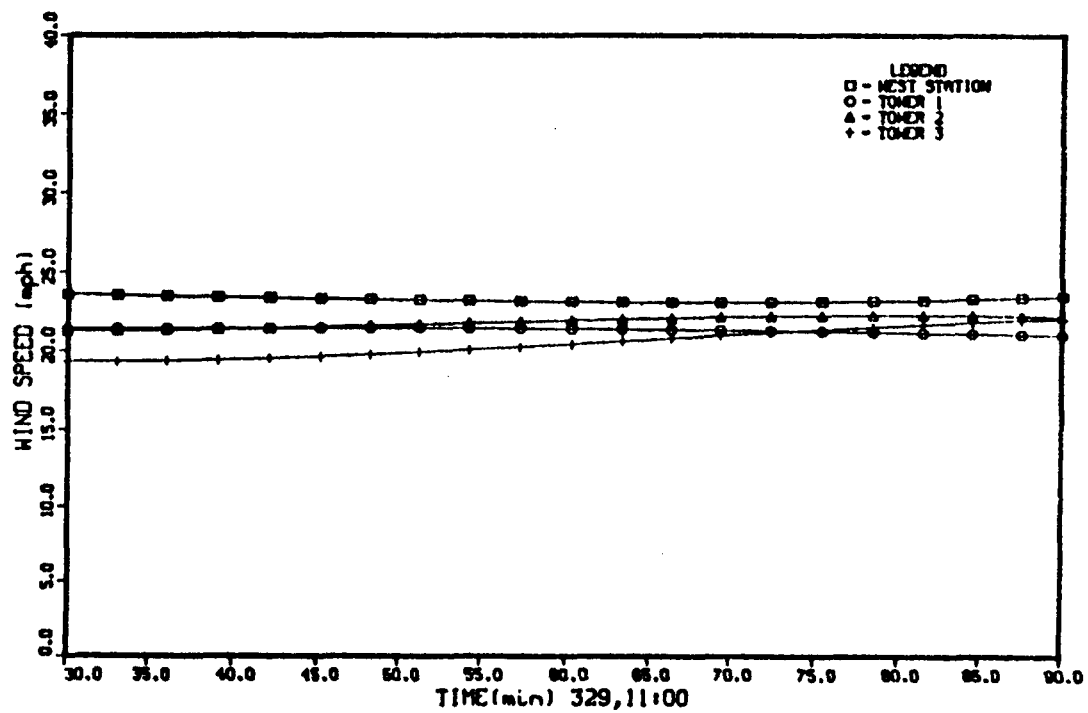


Figure AIV-11. Effect of Location in Field on Average Wind Speed, Day 329

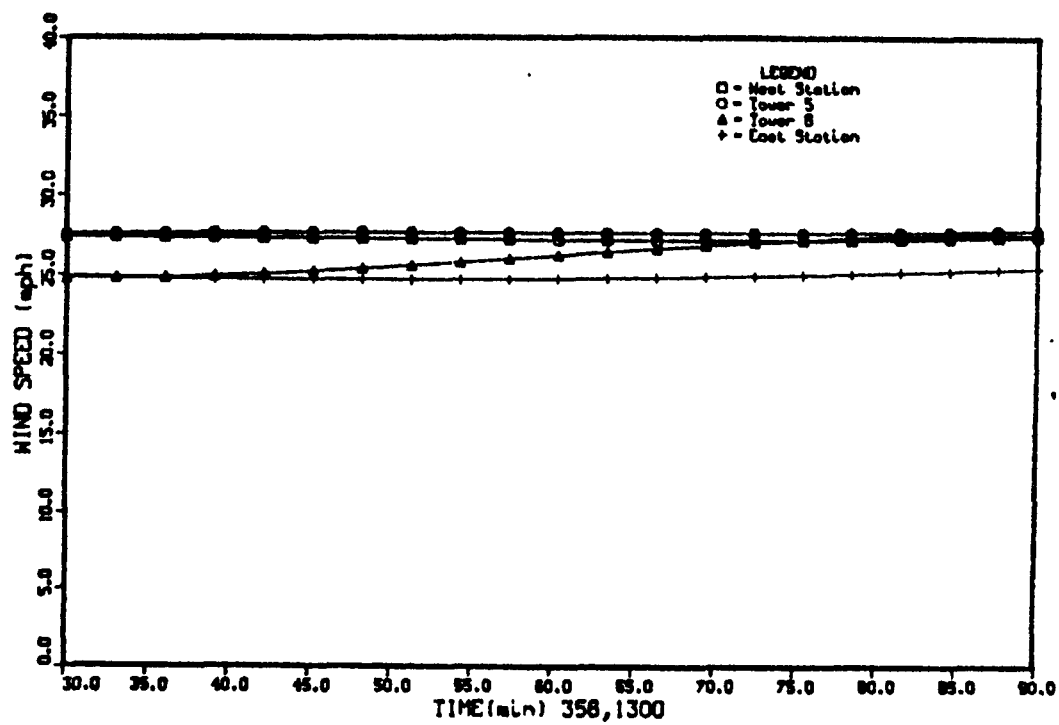


Figure AIV-12. Effect of Location in Field on Average Wind Speed, Day 356

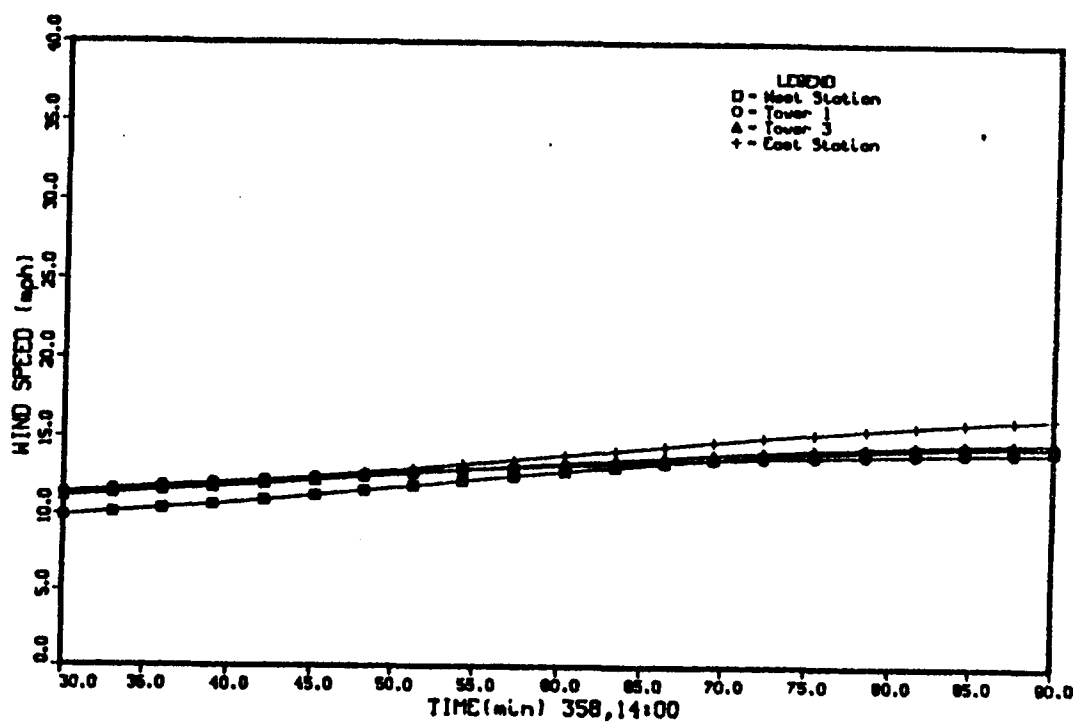


Figure AIV-13. Effect of Location in Field on Average Wind Speed, Day 358

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