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Performance of the Solar One Power Plant as Simulated by the SOLERGY Computer Code

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ABSTRACT

The SOLERGY computer code is a valuable tool for the commercialization of solar central receiver power plants. SOLERGY predicts the annual energy produced by a plant and can be used in design optimization studies to evaluate alternative plant designs or operating strategies. This report validates SOLERGY by comparing its prediction of annual energy with the actual performance of the Solar One power plant during 1985. SOLERGY reliably estimates annual energy production, provided good estimates of user-supplied parameters on the plant's operation are available. The code's predictions of plant performance on clear days agree well with the actual performance. However, the code tends to overestimate the performance on partly cloudy days because of the use of 15-minute average insolation data and its failure to account for actions taken by the plant's operators. Possible applications of the code and a discussion of the sensitivity of results to uncertainty in key input parameters are presented.

Acknowledgments

The authors would like to acknowledge the help of Mary Claire Stoddard in preparing the SOLERGY code for use with the Solar One operating system. Hal Norris, Al Baker, Duncan Tanner, and Scott Faas provided assistance in the collection of data used as input to SOLERGY. The efforts of Charles Randall to resurrect the 1976 and 1977 insolation data for Barstow are appreciated. At Solar One, Chuck Lopez and Anita Snedeker provided invaluable support in the collection of the data on the plant's actual performance. The many useful suggestions on the contents of this report provided by Lee Radosevich, David Menicucci, and Anne Poore are also gratefully acknowledged.

FOREWORD

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

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

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

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

Reliable predictions of the energy a solar plant can be expected to produce are vital to the commercialization of solar technologies. Potential purchasers or investors will consider investing in a new technology only when they can be assured that estimates of promised energy production are realistic. Thus, computer codes are needed that can be used to predict energy production as part of the conceptual development of a project. Such codes are also valuable tools in design-optimization studies to evaluate alternative plant designs or operating strategies. Recently, the SOLERGY computer code (Stoddard et al. 1987) for calculating the annual energy production of solar central-receiver power plants was completed by Sandia National Laboratories, Livermore. SOLERGY is becoming widely used; however, the accuracy of the code's energy predictions had never been verified. This report validates SOLERGY by comparing its predictions with the actual plant performance of the Solar One power plant.

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Chapter 1

Introduction

Reliable predictions of the energy a solar power plant can be expected to produce are vital to the commercialization of solar technologies. Potential purchasers or investors will consider investing in a new technology only when they can be assured that estimates of promised energy production are realistic. Thus, computer codes are needed that can be used to predict energy production as part of the conceptual development of a project. Such codes are also valuable tools in design-optimization studies to evaluate alternative plant designs or operating strategies. Recently, the SOLERGY computer code (Stoddard et al. 1987) for calculating the annual energy production of solar central-receiver power plants was completed by Sandia National Laboratories, Livermore. SOLERGY was developed as part of a study to evaluate conceptual central receiver designs. The results of that study are documented in A Handbook for Solar Central Receiver Design (Falcone 1986). SOLERGY is currently used at Sandia National Laboratories, Albuquerque, and at the Solar Energy Research Institute (Anderson et al. 1987). It was also used in the DOE/Utilities Joint Studies of Central Receiver Technology (Hillesland and Weber 1988). Though SOLERGY is becoming widely used, the accuracy of the code's energy predictions had never been verified. This report validates SOLERGY by comparing its predictions with the actual plant performance of the Solar One power plant.

Solar One is a good choice for this comparison because it is heavily instrumented, and extensive data have been collected during the more than five years the plant has operated. Data from calendar year 1985 were chosen for the validation because the plant was operated to maximize energy production during this period.

Estimates of Solar One's annual performance made during the plant's design proved to be overly optimistic (Aerospace Corp. 1981 and Radosevich 1987). One important reason for the poor predictions was the lack of *a priori* knowledge about the way a central receiver plant would operate. The importance of a number of plant features had not been anticipated before the plant was built and operated. Examples of these features include accounting for the daily parasitic load of the plant for a full 24 hours, the availability of the plant, and the importance of cloud transients to plant operation. The models used to predict the plant's annual performance did not properly account for many of these effects. In the more than five years that Solar One has been operated, a great deal of knowledge has been gained about the operation of a central receiver power plant. With this *a posteriori* knowledge, it is possible to write a code like SOLERGY that properly accounts for all the important features of a central receiver power plant.

SOLERGY simulates the operation of a solar central receiver power plant using an insolation record recorded at 15-minute intervals. The relatively short intervals are needed to model plant start up and the effects of cloud transients. The code has subroutines for each major plant system i.e., heliostat field, receiver, thermal-energy storage, and turbine/generator. A program flow diagram is shown in Figure 1-1. For each 15-minute time step, SOLERGY determines the plant's operational state (shut down, starting up, etc.) and calculates steady-state power flows through each plant system. Annual plant performance is found by summing the performance at every 15-minute time step.

SOLERGY's computational algorithms are based on simple conservation of energy. There are no detailed thermodynamic calculations - no tracking of pressures and temperatures throughout the plant. Such detailed calculations are necessary for the design and analysis of the performance over short periods but are not practical for an analysis of annual-energy performance. (Such calculations, however, could be an important source of the data used as input to SOLERGY.) In SOLERGY, user-specified plant operational parameters, including the time or energy required to start up and operate a system, the parasitic load of major systems, and the performance of individual components (e.g., receiver thermal losses or turbine heat rate) are used to determine the plant's operation and performance during each time step. For an operating plant like Solar One, these data can be developed from the records of plant performance. For a plant in the design stage, fairly detailed analyses are required to develop the necessary input data.

SOLERGY was written to analyze plant designs slightly different from Solar One's. The principal design difference is that SOLERGY plants use an intermediate heat-transfer fluid (e.g., liquid sodium or salt) in the receiver; the heat-transfer fluid is used to produce steam to drive a turbine. Solar One, however, produces steam directly in the receiver. (Details of Solar One's design and operation are presented in Chapter 2.) Thus, validation of SOLERGY using data from Solar One required a number of changes to the code. The principal change in SOLERGY, needed to simulate direct receiver-to-turbine operation, was the removal of SOLERGY's energy-dispatch strategy (subroutine GONOGO). In GONOGO, the algorithm determines if there is sufficient energy in the thermal storage tank to operate the turbine. In SOLERGY, the decision to operate the turbine can be made so as to either maximize the amount of energy produced or to maximize the value of the energy by using thermal energy storage to delay power generation to periods of higher value. The revised program flow model for modeling Solar One is shown in Figure 1-2. In addition, SOLERGY's generic parasitic-power model was replaced with a model appropriate for Solar One. Details of the revised parasitic model are described in Section 3.3. Most of the other changes to SOLERGY were minor and arose from our use of time-varying values for some parameters, such as heliostat reflectivity, where SOLERGY normally uses an average parameter (see Chapter 3).

One of the more important tasks in the validation of SOLERGY was the development of appropriate values to use as input to the code. The derivation of input data from the Solar One data base is described in Chapter 3. Chapter 4 presents a comparison of SOLERGY predictions and actual plant performance for clear and partly cloudy days. Chapter 5 presents the calculated versus actual plant performance for one full year. The conclusions of the study, the results of a sensitivity analysis, and a discussion of the implications of the results for improving plant design and performance are given in Chapter 6.

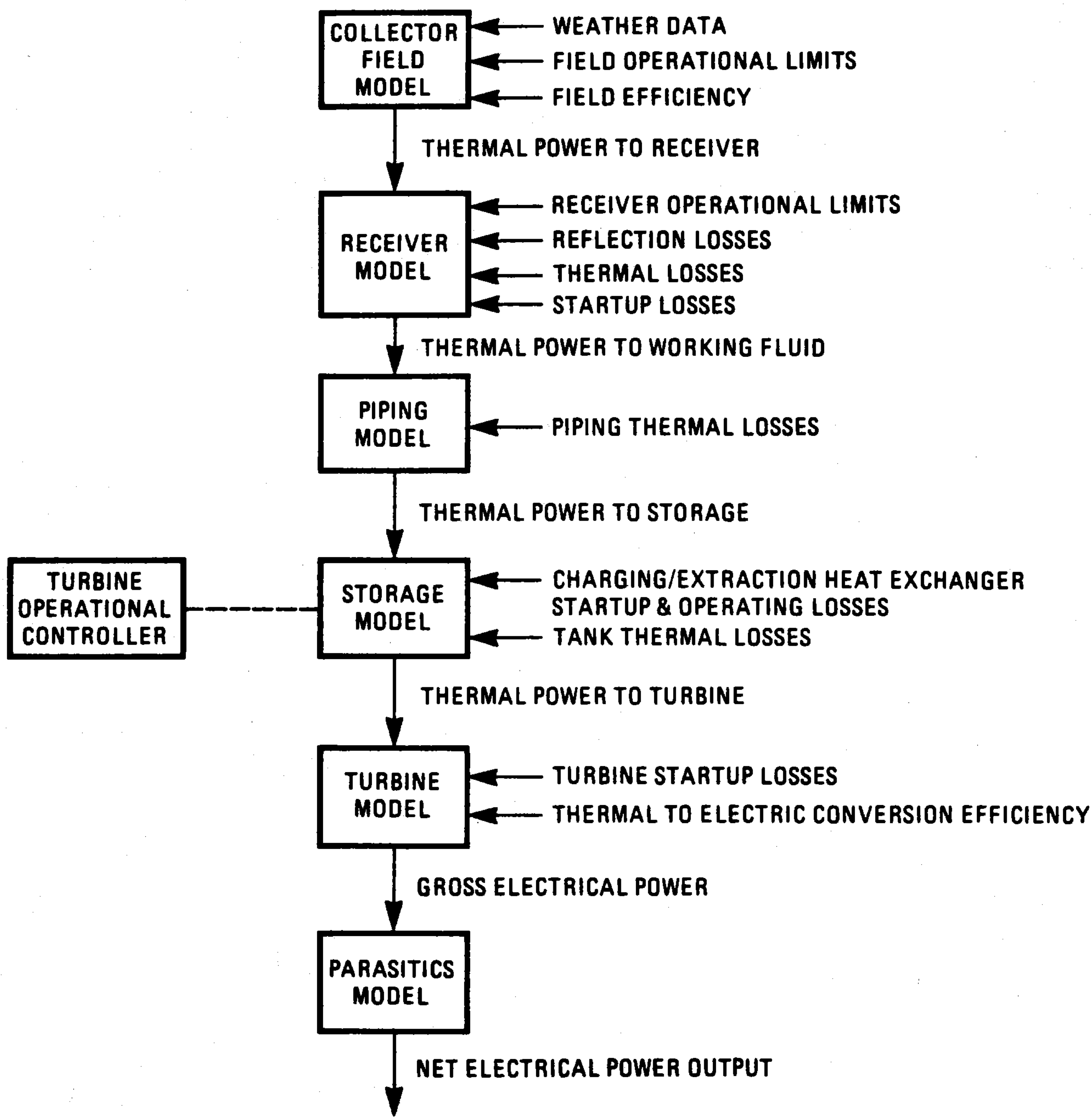


Figure 1-1. Program Flow Diagram for the SOLERGY Computer Code (Stoddard et al. 1987).

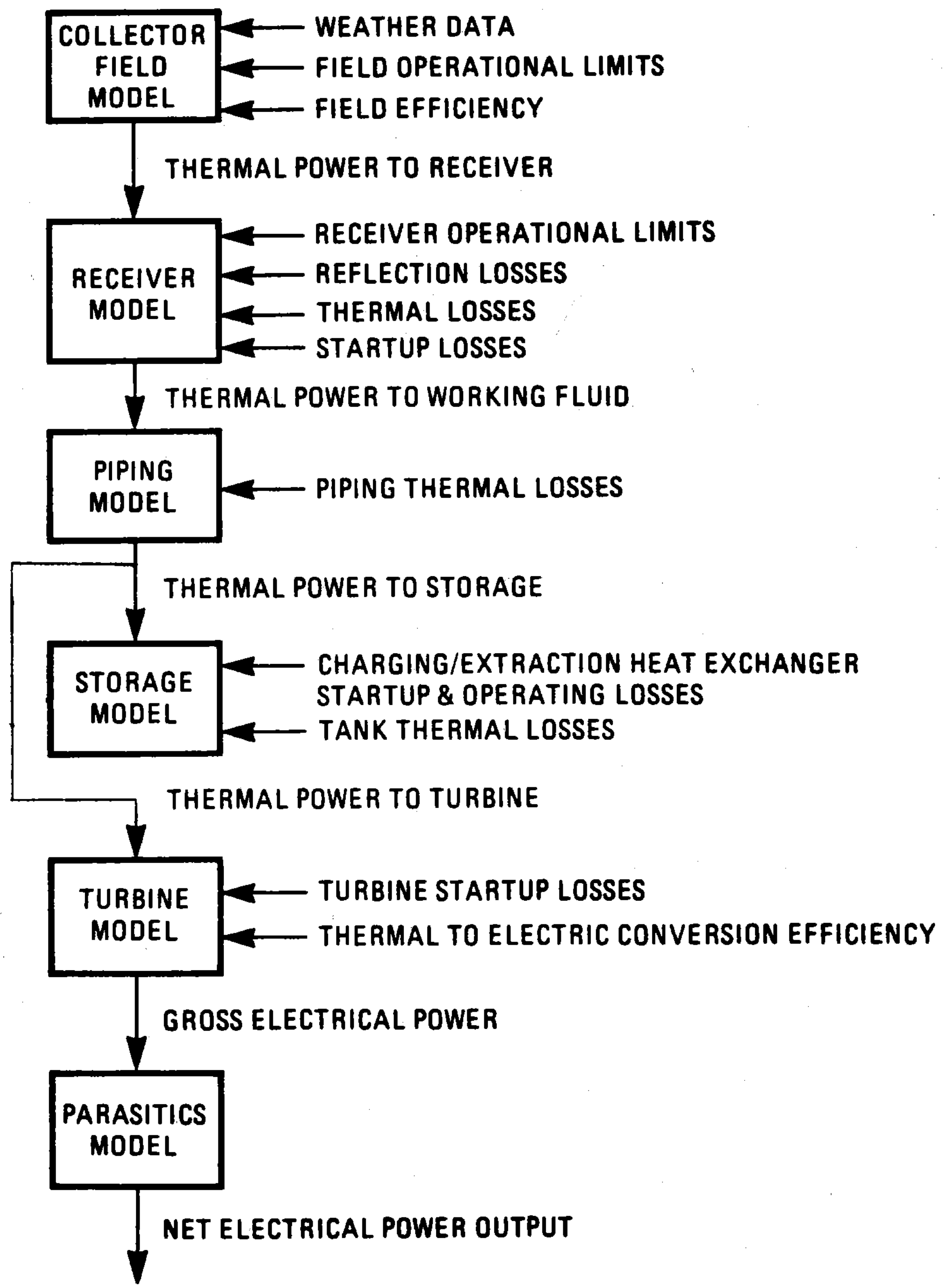


Figure 1-2. Revised Program Flow Diagram for SOLERGY Used to Model the Solar One Pilot Plant.

Chapter 2

Description of the Solar One Plant

A brief overview of the design and operation of the Solar One plant is in this chapter. This background information is required to understand the terminology used in subsequent chapters. The discussion focuses on those design and operational features that are important to annual energy calculations. Overviews of the plant design and operation are described in Sections 2.1 and 2.2 respectively. A more detailed discussion of these topics can be found in Radosevich (1985) and US DOE (1982).

2.1 Design of the Solar One Plant

Site and General Design Data

The pilot plant is located in the Mojave Desert and is about 12 miles east of Barstow, California, near Daggett. The site is on 130 acres of land, directly adjacent to SCE's Cool Water Generating Station. Figure 2-1 shows the pilot plant with Cool Water's evaporation ponds in the background.

The plant is designed to produce at least 10 MW_e net for a period of 7.8 hours on the plant's best design day (summer solstice) and for a period of 4 hours on the plant's worst design day (winter solstice). The plant is also designed to produce 7 MW_e net for a period of 4 hours when operating from thermal storage.

Systems Within the Plant

The pilot plant, which is based on the central receiver concept, uses a large number of computer-guided tracking mirrors, called heliostats, that reflect the sun's energy to a receiver mounted on top of a tower. The receiver absorbs the solar energy in water that is boiled and converted to high-pressure steam. This steam powers a turbine-generator, which generates electricity. Steam from the receiver, in excess of the energy required to generate 10 MW_e net power to the utility grid, is diverted to thermal storage to use when output from the receiver is less than needed for rated electrical power. The plant consists of the major systems listed below (see Figure 2-2):

- the <u>collector system</u>, including 1,818 heliostats that reflect solar energy onto the receiver;
- the <u>receiver system</u>, consisting of tubes welded into twenty-four panels mounted on a central tower. The receiver is analogous to a boiler in a conventional steam power plant;

- the thermal storage system, which stores energy as sensible heat in a bed of heat-transfer oil, sand, and gravel;

- the plant control system, including computers that monitor and control the plant;

- the electric power generation system, including the turbine-generator and its auxiliaries; and

- the plant support system, consisting of site structures, buildings, and facility services, such as raw water, fire protection, demineralized water, bearing cooling water, nitrogen, compressed air, oil supply, liquid waste, and electrical distribution equipment.

Collector System

Each of the 1818 heliostats has a reflective surface area of 39.1 m^2. The heliostat field, which has a total reflective area of 71130 m^2 surrounds the central receiver tower, with 1240 of the heliostats in the north portion of the field and 578 in the south portion. The mirrors have an average clean reflectivity of 0.903; this average is area weighted for the mixture of low- and high-iron glass used in the field. Each mirror assembly is attached to a geared drive unit for azimuth and elevation control. The drive unit is mounted on a fixed pedestal. The entire heliostat unit is designed to track the sun in winds up to 45 miles/hr.

The locations of the heliostats in the field were determined by computer codes the University of Houston developed0 These locations produce optimum field performance on an annual basis. The field redirects approximately 70% of the annual incident solar energy to the receiver. The 30% losses are primarily due to cosine, shading, blocking, and spillage inefficiencies. Cosine losses are due to the fact that the heliostats are not pointed directly at the sun; the energy reflected to the receiver is thus reduced by the cosine of the angle defined by the sun's location and a vector which is normal to the mirror. Shading losses occur when a neighboring heliostat casts a shadow on another heliostat in the field. Blocking losses occur when the backside of a neighboring heliostat intercepts a portion of a heliostat beam. And finally, spillage losses result because the heliostat is not perfectly focused and a portion of its beam misses the receiver target.

Receiver System

The receiver system consists of a single-pass-to-superheat boiler with external tubing, support tower, valves, piping, and controls necessary to provide the required amount of steam to the turbine. The receiver is approximately 13.7 m high, 7 m in diameter and is located approximately 90 m above the ground. It produces approximately 40 MWt of 800 °F superheated steam at rated conditions and is capable of operating at a turndown ratio of 10 to 1, i.e., 4 MWt of superheated steam can also be produced at low load conditions. The external tubing is coated with a special black paint (Pyromark) to increase energy absorption. The absorptance of a new coat of paint is approximately 0.97.

The Solar One receiver converts approximately 70% of the annual incident solar energy to process steam. The 30% losses are primarily due to absorptance, thermal, and start-up inefficiencies. Absorptance losses occur because the Pyromark does not absorb all the incident energy. Thermal losses are caused by radiation and convection heat transfer between the receiver and the environment. During start-up several MWt of energy must be absorbed and lost to the receiver structure in order to produce rated steam conditions.

Thermal Storage System

The thermal storage system at Solar One is no longer in use. On August 30, 1986 the system was damaged by a fire. Because the analysis contained in this report is based on Solar One data when the thermal storage system was functional, a description of the system is included.

The thermal storage system consists of a tank, a thermal charging loop, and a thermal discharging loop. The tank contains a packed bed of rock/sand and Caloria HT-43 heat transfer oil, which flows through the bed to deposit or withdraw energy. The system was designed to store solar energy to extend the plant's electrical power generating capability into nighttime or periods of cloud cover. The system is sized to provide 7 MWe net for a period of four hours. It also provides steam to keep selected portions of the plant warm during non-operating hours and during start up of the plant.

Control System

The control system integrates several independent controllers contained within the collector, receiver, thermal storage, electric power generation, and plant support systems. Operating commands can be initiated either by the operator or directly from plant operating software contained in the operational control system's computer.

The data acquisition system is a subsystem used to record up to 2000 channels of control and monitoring data. It provided the majority of the necessary plant performance and weather data for the analysis presented in this report.

Electric Power Generation System

The electric power generation system consists of Rankine-cycle power plant equipment including the turbine-generator, condensate and feedwater equipment, circulating and cooling water systems, auxiliary steam system, condensate polishing system, chemical analysis/feed system, compressed air system, sampling system, and electrical distribution network. The principal process flow paths and major process interfaces with the system are shown in Figure 2-3.

The turbine can produce 12.5 MWe when operating on receiver generated steam at rated conditions with a gross turbine-generator efficiency of approximately 33%. The turbine can produce 7 MWe when operating from storage system steam with a gross turbine-generator efficiency of approximately 24%. On an annual basis, the turbine-generator operates at an efficiency of approximately 30% when operating solely on receiver steam. The annual efficiency is lower than the design point value because additional losses are incurred when warming the turbine during daily start-up and during part load operation.

Support System

The support system consists of the balance-of-plant system hardware and includes all site structures. The hardware consists of compressed air, raw water, fire protection, demineralized water, cooling water, nitrogen, liquid waste, oil supply, and lightning protection.

The support system's equipment and buildings, as well as hardware included in other systems, require a significant amount of electric power to operate. The energy consumed by this equipment, known as parasitic power, reduces the net amount of electricity delivered by Solar One to the utility grid. On an annual basis, parasitic power consumption has been running about 33% of the gross electricity produced by the turbine-generator. Parasitic consumption is high because Solar One is a small plant. A larger plant, say 100 MWe, would have a much smaller parasitic loss fraction because it would use nearly the same size buildings and equipment that Solar One uses, yet would produce much more electric power.

2.2 Operation of Solar One Plant

The plant can be operated in eight steady-state modes, each characterized by different process flow paths between the plant's collector, receiver, thermal storage, and electric power generation systems (see Figure 2-4). The modes are

Mode 1 - Turbine Direct

In the turbine direct mode, all steam generated by the receiver passes directly to the turbine-generator and the thermal storage system is bypassed. The turbine direct mode is the most efficient for power production and is used on clear days when charging the thermal storage unit is not required.

Mode 2 - Turbine Direct and Charging

In this mode, steam from the receiver is directed simultaneously to the turbine-generator and to the thermal storage system. This operating mode would be used at midday on a clear day when the available solar energy exceeds the maximum capability of the turbine.

Mode 3 - Storage-Boosted

Steam generated by the thermal storage system is used to supplement steam generated in the receiver. This mode could be used on a clear day during early morning and late afternoon, when the available solar energy is less than the maximum capability of the turbine.

Mode 4 - In-Line Flow

Here, steam from the receiver is used to charge the thermal storage system, which then generates steam for the turbine-generator. When operating in this mode, the unit's tolerance of cloud transients is enhanced. Due to limitations on the temperature of the heat transfer oil and the temperature differences across the heat exchangers, plant efficiency and maximum power output are less than for Mode 1.

Mode 5 - Storage Charging

In this mode, the turbine-generator is not operating and all steam generated in the receiver is delivered to the thermal storage system.

Mode 6 - Storage Discharging

Here, the heliostats and receiver are not operating and the thermal storage system generates steam for use in the turbine-generator. This mode would be used on overcast days or at night.

Mode 7 - Dual Flow

In this mode, steam from the receiver is delivered to both the turbine-generator and the thermal storage system. Simultaneously, steam from the thermal storage system is directed to the turbine-generator. This mode could be used on cloudy days since it allows the thermal storage system to dampen transients caused by passing clouds.

Mode 8 - Inactive

None of the major plant systems are in use in this mode; only a portion of the plant's support systems is in operation. The support systems are used to generate auxiliary steam, building heating and ventilation, and other plant support functions.

Even though the plant could operate in the eight modes described above, only three were routinely used before the storage fire. They were Modes 1, 5, and 8.

Mode 2 was not used because the heliostat field was not large enough to supply full power to the turbine and the storage simultaneously. The size of the heliostat field was reduced just before the plant was built to reduce costs. The remaining modes were not routinely used because of control difficulties and/or because the plant ran more efficiently in Mode 1.

Before the fire, the storage tank was charged approximately every ten days (Mode 5). The energy stored in the tank was used to provide auxiliary steam during start up and at other times. If this had not been done, auxiliary steam would have been provided by an electric boiler. Charging storage every ten days, rather than operating the turbine, was believed to be a more efficient way of operating the plant. It was felt that on an annual basis the additional energy generated on those days would not offset the additional parasitic energy consumed by the electric boiler. In Chapter 5 we show that Solar One would have produced more net energy in 1985 if thermal storage had <u>not</u> been used and service steam had been provided instead by the electric boiler.

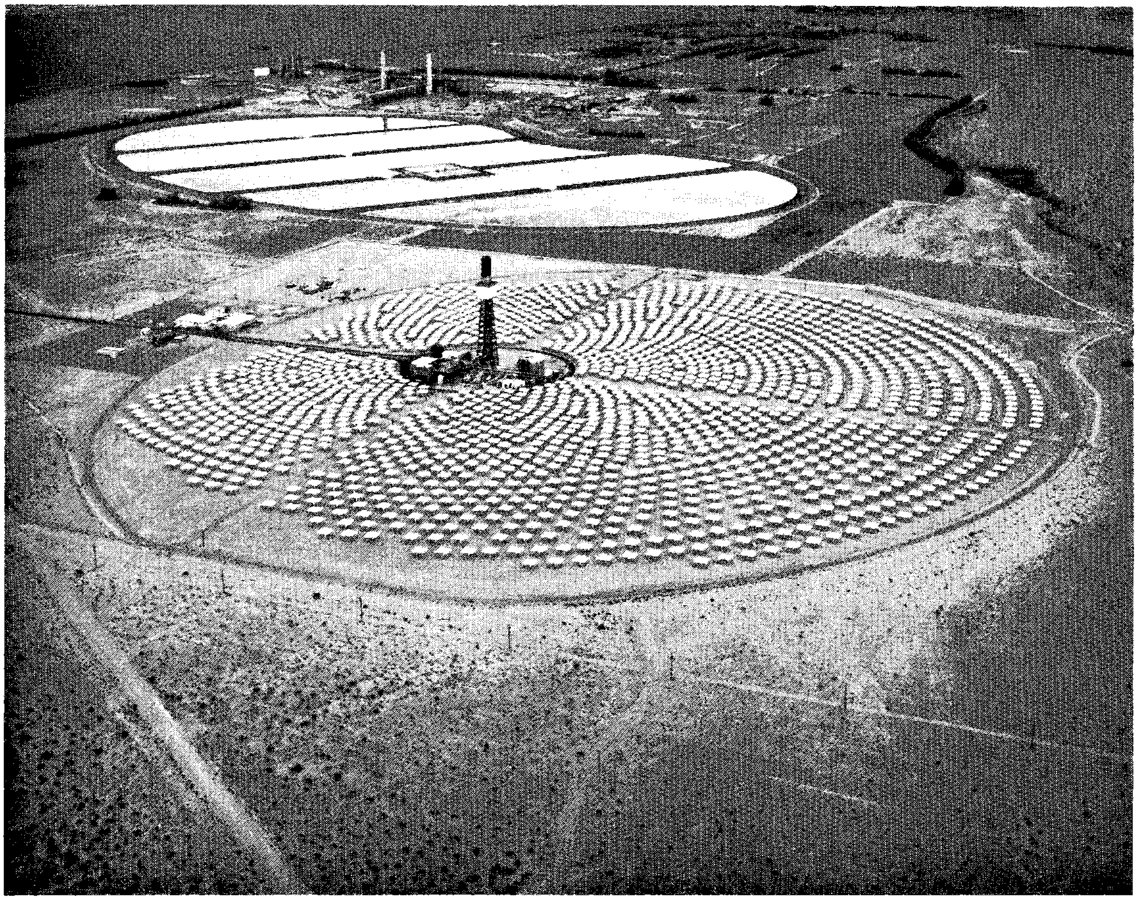


Figure 2-1 Overview of the Pilot Plant

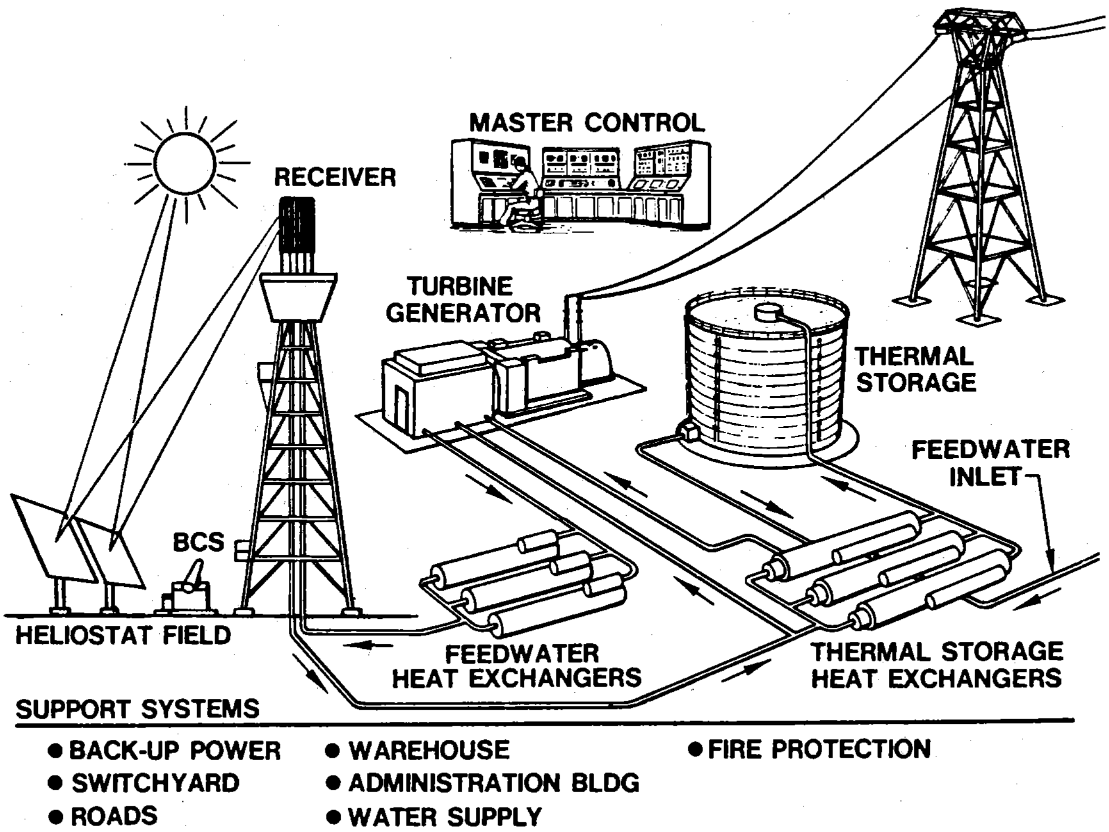


Figure 2-2 Schematic of the Pilot Plant

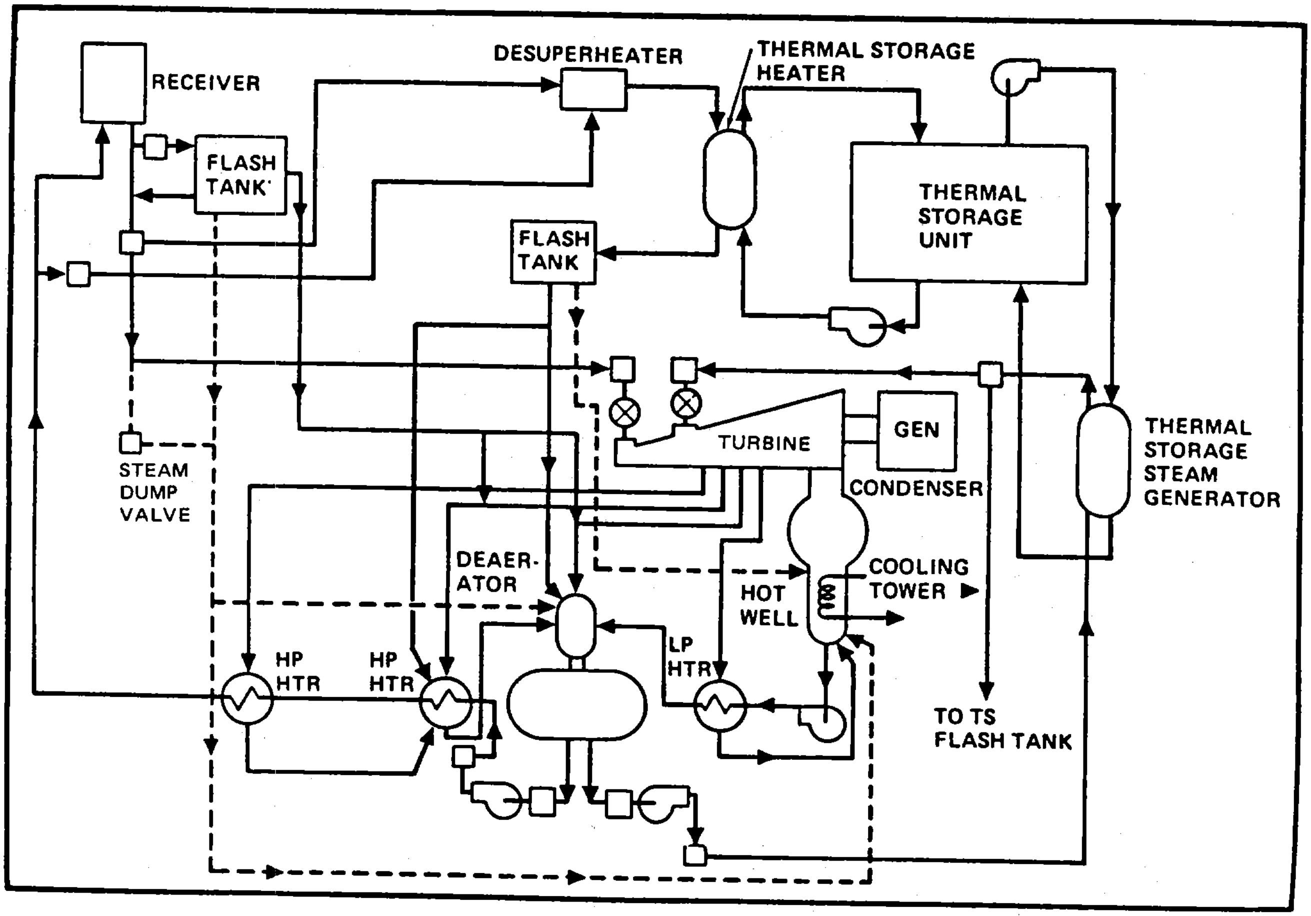
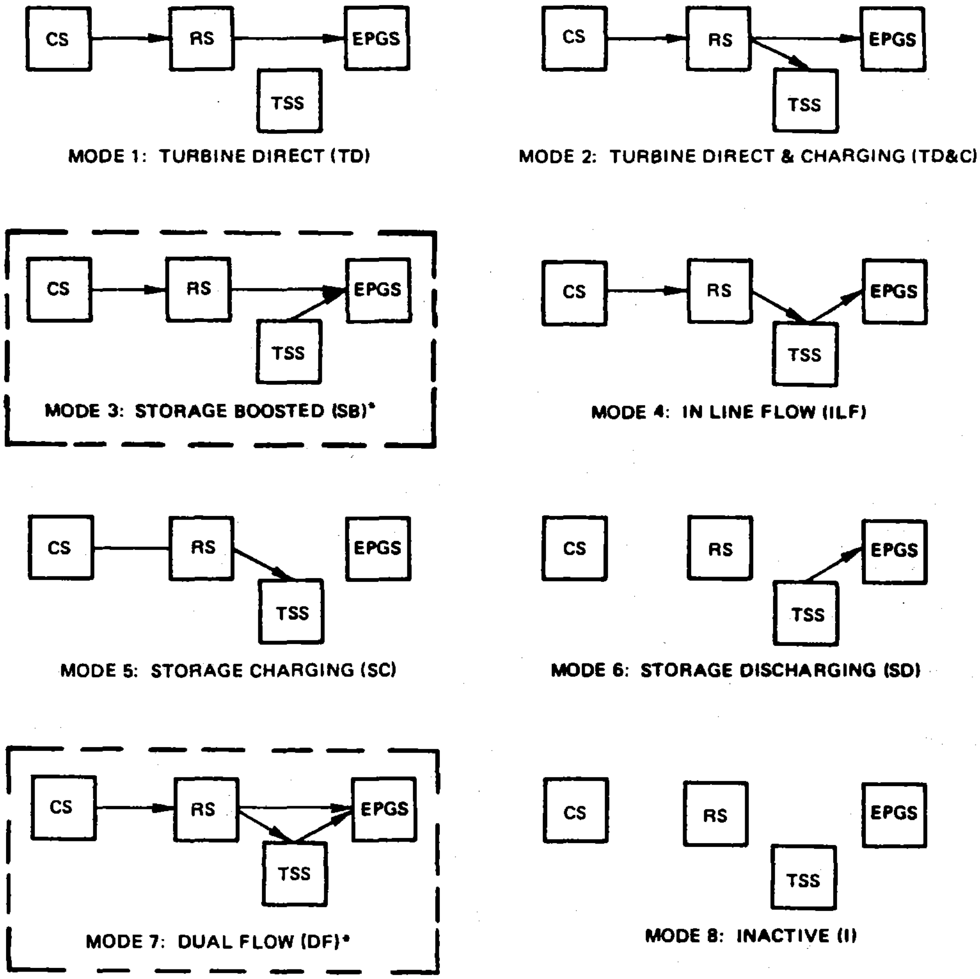


Figure 2-3 Schematic of Major Plant Systems



Mode 1	Turbine Direct:	Receiver-generated steam directly powers the turbine.
Mode 2	Turbine Direct and Charging:	Receiver-generated steam powers the turbine and charges storage.
Mode 3	Storage Boosted:	Steam from the receiver and storage powers the turbine.
Mode 4	In-Line Flow:	Receiver steam charges storage, while storage steam is stimultaneously discharged powering the turbine.
Mode 5	Storage Charging:	Receiver steam charges the storage system.
Mode 6	Storage Discharging:	Steam generated by the storage system is used to power the turbine.
Mode 7	Dual Flow	A combination of Modes 2 and 3 (probably only achieved during transitions).
Mode 8	Inactive	Major systems are standing by for operation.

*Engineering Test and Transitory Modes

Figure 2-4 Operating Modes

Chapter 3

Estimation of the Solar One Parameters Required by the SOLERGY Computer Code

3.1 Overview

The SOLERGY computer code can simulate how many different types and sizes of central receiver power plants can perform. Simulation of a particular central receiver design requires the user of the code to input design-specific values for each of the plant's subsystems, i.e., the receiver, collector field, thermal storage, and power conversion system. The location of the plant, its daily availability, and the simulation time step must also be supplied. The SOLERGY input parameters are listed in Table 3-1. In Section 3-1 we discuss the methods and data used to estimate the parameter values for Solar One listed in the table. The changes made to the SOLERGY parasitic model to mimic Solar One are discussed in Section 3.2. Before proceeding with these discussions, it is appropriate to describe our philosophy of estimating parameters.

Analysts use three basic approaches to estimate input parameters. In order of preference they are 1) to obtain estimates from curve fits to experimental data, 2) to use analytical models to calculate them, or 3) to make a reasonable guess. Since Solar One has been operating for a number of years, we were fortunate to have a large experimental data base at our disposal, which allowed us to estimate most of the SOLERGY parameters by the first approach. The second approach was not used in the work presented in this report. The third approach was only used for a few parameters for which data were unavailable and were deemed to have an insignificant impact on the results of our study. SOLERGY analyses of a plant that has not yet been built would have to utilize the second and third approaches, since little or no experimental data are available. For example, in our analyses of central receiver plants that use molten-nitrate salt, we use results from dynamic-simulation models to estimate many of the SOLERGY parameters (ESSCOR 1988; Kolb, Greenlee, and Ringham 1987).

3.2 Estimation of the SOLERGY Parameter Values Listed in Table 3-1

The parameters in Table 3-1 have been categorized according to the input-name-list groups defined in the SOLERGY user's manual. The discussion below is organized in this manner.

<u>Collector-Field Parameters (NMLCOLF)</u>

This group addresses the availability and performance of the heliostats in the collector field. Factors that impact heliostat availability are hardware failures and exceeding operating limits. Factors that impact heliostat performance are reflectivity, start-up angle, and wind speed effects.

Hardware failures were estimated using heliostat availability data collected at the plant during 1985. These data are presented in Table 3-2. The available field size (FS) is the size of the full field (71130 m^2) reduced by an availability factor (AFAC):

$$FS = 71130 * AFAC \quad . \qquad (3-1)$$

An FS based on an annual average is normally input. However, since we had access to time-dependent availability data, we preserved this information by inserting a few equations, like Equation (3-1), into SOLERGY.

Manufacturers of heliostats recommend they be stowed (i.e., placed out of service) if the wind-speed limit (WSLIM) or temperature limits (TLIML, TLIMU) are exceeded. Discussions with knowledgeable personnel indicated that this was rarely done at Solar One, given sunny skies. These parameter values were therefore not used, by setting them to values which would not be exceeded during the 1985 weather year.

The reflectivity of the entire heliostat field was estimated using data collected from a small subset of the field. Cleanliness data are plotted in Figure 3-1. (During 1985, heliostats were only cleaned by rainfall; these data are also depicted in the figure.) The field's reflectivity (RFLCTY) is the clean reflectivity (0.905) reduced by a cleanliness factor (CFAC):

$$RFLCTY = 0.905 * CFAC \quad . \qquad (3-2)$$

An average reflectivity based upon an annual average is typically input. However, since we had access to time-dependent cleanliness data, we preserved this information by making CFAC in Equation (3-2) a function of time. This was done by curve fitting the data presented in the figure. These curve fit equations were inserted into the INPUT2 subroutine.

At Solar One the heliostats start tracking the receiver at sunrise. The value of ELIM was thus set to zero.

Wind can cause heliostats to vibrate and to experience mirror deflections. These wind effects cause focusing problems, which can increase receiver spillage. Information was not available in this area and we assumed heliostat performance was not affected by wind. This is probably a reasonable assumption since the receiver at Solar One is oversized relative to the field size; it is therefore likely that slightly mis-aimed heliostat beams would still be intercepted by the receiver. Parameters NEFWS, WSX, and WSEF were therefore not used.

Receiver Parameters (NMLRCVR)

This name-list group addresses the performance of the receiver during start up, shutdown, and steady-state operation.

Start up of the Solar One receiver is not considered to be complete until rated steam conditions (800 °F superheated steam) are achieved at the receiver downcomer valve. From cold conditions, the solar power incident on the receiver must exceed that required for stable flow conditions [i.e., design specifications dictate that the receiver's minimum flow fraction (RMF) must exceed 10% of the 50-MW_t thermal rating (RS)]. Once minimum flow has been achieved, additional solar energy must be absorbed by the receiver (EREQD) in order to achieve rated steam conditions. The value for the EREQD parameter was obtained by comparing turbine on-line times predicted by SOLERGY with actual on-line times for several clear weather days throughout 1985. A value of 1.7 MWh_t was found to give a good comparison. (In this calculation, the time between rated conditions at the downcomer and turbine on-line time was 40 minutes. See the Turbine Parameter section of this chapter). Displayed in Table 3-3 is a comparison of the SOLERGY and actual start-up times using an EREQD equal to 1.7 MWh_t.

The absorptance of the Pyromark paint covering the receiver tubes is 0.96 soon after it is applied. Exposure to the solar flux and the weather causes the absorptance to degrade over time. The absorptance of the receiver paint was measured at the end of 1984 to be 0.88. During November of 1985 it was found to be 0.86. The receiver was repainted in December 1985 and restored to 0.96. An average value of receiver absorptance (EPS) is typically input to SOLERGY. However, since we had access to time-dependent data, we developed a time-dependent equation for the absorptance. A linear equation with a slope of -0.02/year and an intercept of 0.88 was used between 1/1/85 and 12/18/85. Between 12/19/85 and the end of the year a value of 0.96 was used. These curve-fit equations were inserted into SOLERGY.

A portion of the thermal power incident on the receiver is lost to the environment by convection and radiation. Thermal losses at the Solar One receiver have been extensively evaluated (Stoddard 1986; Baker and Atwood 1985). Stoddard (1986) showed that a heat loss correlation developed by Siebers and Kraabel (1984) gave a good approximation to the actual overall thermal losses at various wind speeds. Displayed in Figure 3-2 is a curve taken from Stoddard (1986), which relates receiver efficiency vs. wind speed using the Siebers and Kraabel correlation. The points on this curve also satisfy the following equation:

$$EFF_{rec} = EPS - (PLXLR/PTR) \qquad (3\text{-}3)$$

where,

EFF_{rec} = receiver efficiency,
EPS = absorptance,

PLXLR = thermal power lost from receiver (MW_t), and
PTR = power to receiver.

All terms in Equation (3-3) are given in Figure 3-2 except PLXLR. Figure 3-2 and Equation (3-3) can therefore be combined to determine PLXLR as a function of wind speed. This analysis produced the values presented in Table 3-4.

Solar One's receiver may trip off during a cloud transient. In a tripped state, the heliostats are pulled off the receiver and the downcomer valve is closed; the receiver gradually cools toward the ambient temperature. These events are displayed in Figure 3-3. This figure was used to estimate the receiver cool down parameter (ALPHAR). The temperature decay that commenced at approximately 800 minutes was fit with the following equation described in the SOLERGY manual:

$$T(t) - T_{amb} = (T_o - T_{amb}) * e^{-t*ALPHAR} \qquad (3-4)$$

where,

$T(t)$ = receiver temperature as a function of time (°F),
T_{amb} = ambient temperature (°F),
T_o = initial receiver temperature (°F),
t = time.

This analysis produced a cool-down parameter (i.e., inverse time constant) of 0.26 $hours^{-1}$.

Turbine-Generator Parameters (NMLTRBN)

This name-list group addresses the performance of the turbine-generator during start up and steady-state operation.

When the receiver has been started up, the operators begin start up of the turbine-generator. The downcomer valve is opened and steam begins to warm the turbine and its inlet piping. Following warm up, the turbine is synchronized to the grid. Plant data indicate that it takes an average of 40 minutes after an overnight shutdown to warm the turbine and synchronize it to the grid. This is the time we used for parameters SDC, SDW, and SDH. We did not attempt to determine different start-up times depending on whether the turbine was cold (SDC), warm (SDW), or hot (SDH) before start up; examination of the data revealed that possible differences in these times were small compared to other timing uncertainties in our analysis.

Following synchronization, the operator ramps the output power up to the level that matches the thermal power produced by the receiver. Plant data indicate that it takes approximately 15 minutes to perform this ramping action and we used the time for parameters RDC, RDW, and RDH. We did not attempt to determine different ramp times depending on whether the turbine was cold (RDC), warm (RDW), or hot (RDH) before start up for the same reason as given above.

The thermal-to-electric conversion efficiency of the turbine-generator, when operating on receiver steam, was measured by McDonnel Douglas Corporation (1984). A curve taken from that report is displayed in Figure 3-4. This curve displays the turbine-generator's gross efficiency (expressed in terms of heat rate units) vs. the turbine's output power. Values from this curve were used to estimate the turbine-generator's efficiency as a function of its inlet thermal power (i.e., the relationship required by SOLERGY). To do this, the abscissa must be converted to input thermal power by the relationship (gross input thermal power)=(gross output electric power)/(gross thermal-to-electric conversion efficiency). Displayed in the first column of Table 3-5 is the REPSS vector and in the second column, the corresponding FEPSS vector. The SOLERGY code also allows the turbine-generator efficiency to be dependent on the wet bulb temperature. This effect was deemed to be small compared to other uncertainties in our analysis; we therefore did not include this dependency.

When operating at rated conditions, the turbine-generator converts 38 MW_t of receiver steam (parameter TPFSL) at an efficiency of 33% to produce 12.5 MW_e of gross electrical power. Just prior to shutdown at the end of the day or during periods of low insolation, the turbine-generator converts 15% (parameter TMFS) of the rated thermal power (38 MW_t) at an efficiency of 17% to produce 1 MW_e of gross electrical energy. The turbine is shut down near this point because the plant no longer produces net electric power; operating parasitic loads at the plant are approximately 1 MW_e.

Parameters Common to the Collector Field and Receiver (NMLCOEF)

The efficiency of converting direct normal insolation to power on the receiver (EFF_{total}) can be expressed by the following equation:

$$EFF_{total}=EFF_{ref}*EFF_{cos}*EFF_{sh}*EFF_{bl}*EFF_{sp} \quad (3-5)$$

where,

EFF_{ref} = field reflectivity efficiency,
EFF_{cos} = field cosine efficiency,
EFF_{sh} = field shadowing efficiency,
EFF_{bl} = field blocking efficiency,
EFF_{sp} = field to receiver spillage efficiency.

These terms are defined in Section 2.1.

The total efficiency is a function of various plant design specifications such as the tower height, receiver size, heliostat focusing accuracy, heliostat layout pattern, as well as the position of the sun in the sky. This complex calculation is typically performed by computer codes like DELSOL (Kistler 1986), MIRVAL (Leary and Hankins 1979), or NS (Lipps and

Vant-Hull 1980). We used the MIRVAL code. SOLERGY requires the user to input this total efficiency as a function of sun position. The MIRVAL code produced the relationship displayed in Table 3-6. All numbers in this table are based on an EFF_{ref} equal to unity. The field reflectivity was treated separately. (See the Collector Field Parameters section.) The information presented in Table 3-6 was used to define the parameters NX, NY, AZR, ELR, and FR listed in Table 3-1.

Parameters Related to Simulation Time Step and Outage Days (NMLGEN)

The SOLERGY code is traditionally operated using 15 minute time steps. The reasons for this are: 1) several tapes with 15 minute interval weather information are available, and 2) the CPU time required to run SOLERGY for an entire weather year is reasonable (e.g. a few minutes on a VAX 8650). Most of the results presented in this report were also obtained using a 15-minute time step (DELT was set to .25 hours). In general, we found that use of this time step adequately captured the dynamics of the Solar One plant. However, we show in Chapter 4 that a 3-minute time step allows SOLERGY to predict the plant dynamics more accurately during intermittently cloudy weather.

Given good weather, there were three reasons the plant did not deliver power to the grid during 1985: 1) equipment failures caused an unscheduled outage, 2) the plant was shut down to perform scheduled maintenance activities, 3) the oil in the storage tank was heated with receiver steam. Outage times ranged from less than an hour to several days. In our SOLERGY simulations we chose the same forced (IFOUT), scheduled (ISCHED), and storage-charging (ICOUT) outage days that occurred at Solar One during 1985. We also combined the partial outage days to yield equivalent full outage days. For example, an equivalent full outage day was chosen if there were three instances in which Solar One was down for 1/3 of a day. We chose equivalent outage days because SOLERGY is currently set up to treat full outage days only. The outage days we chose are listed below:

IFOUT - 16,31,38,76,89,145,176,189,190,196,197,198,315,316,317, 318,319,320,321,322,323,324,1,81,91,106,131,135,149, 165,201,221,232,274,364,

ISCHED - 41,42,43,44,45,46,47,48,49,50,51,52,53,54,55,56,57,58, 59,60,61,62,63,64,65,66,67,68,69,70,71,211,336,337, 338,339,340,341,342,343,344,345,346,347,348,349,350, 351,3,72,252,266,

ICOUT - 9,34,36,37,72,75,85,105,109,129,175,202,257,278,302, 313,314,334,335,356,362,19,78,116,140,157,225,244,285.

The equivalent full outage days are those listed in the second sequence (e.g., 3, 72, 252, and 266 in the ISCHED list). And finally, it should be noted that the plant was also unable to operate during all or portions of several of the outage days because of poor weather. For example, it is standard practice at Solar One to perform scheduled maintenance activities when the skies are completely overcast.

Plant Location Parameters (NMLLOC)

The position of the sun in the sky as a function of local clock time can be calculated by SOLERGY given that parameters related to plant location and time zone are provided. These parameters and the values applicable to Solar One are presented in Table 3-1.

Piping Parameters (NMLPIPE)

The piping parameters and model in SOLERGY define the energy lost from the working fluid between the receiver and the turbine-generator as a function of ambient temperature. This loss is typically quite small. We therefore did not develop plant-specific parameters; the default values presented in the SOLERGY manual were used.

Storage Parameters (NMLSTRG)

As described in Chapter 2, the function of Solar One's storage system during 1985 was to provide auxiliary steam for plant start up. The goal of using storage in this manner was to lessen the reliance on the electric boiler, to reduce parasitic power consumption, and to gain experience with the thermal storage system. The parasitic models described in Section 3.2 include the effect of operating storage in this manner. The reader should refer to that section for a discussion of this topic.

The SOLERGY storage model and parameters are intended to be used for a situation in which the stored energy supplies the turbine-generator. The storage model was therefore not used in our simulations.

3.3 Solar One Parasitic-Power Model

The parasitic power models used in SOLERGY are generic in nature and intended to be valid for any commercial-scale power plant. However, the models are not appropriate for a pilot plant such as Solar One. Therefore, the parasitic power models were completely replaced for this study.

A study was performed to measure the actual parasitic power use of the plant (Ege and Lehman, draft). It examined the power rating of every piece of equipment in use during each plant condition (e.g., online, standby, nighttime, etc.). Table 3-7 lists the equipment and conditions. These data, combined with an estimate of the duty cycle of each component, can be used to estimate the total parasitic load. However, because data on the daily use of each piece of equipment are not available, the values in Table 3-1 were not used in the present study. Rather, we developed new models using the actual parasitic-power data recorded at the plant. The data recorded at the plant include: total daily parasitics, total daily online parasitic energy, daily gross energy produced, daily hours of charging storage, and daily hours of turbine operation. The results of the study by Ege and Lehman served as a plausibility check in the present study.

We developed the new models using simple linear regression fits to 77 days (11 weeks) of plant data. The full range of operating conditions is represented in the selected days. The data and a brief discussion of the regression analyses are provided in Appendix A. Because of the limited amount of available data, we developed parasitic-power models for only four plant conditions: online, offline, charging storage, and shutdown. The shutdown condition was assumed for days the plant did not operate. We did not try to differentiate days the plant was shut down due to weather outages, forced outages, or scheduled outages. Shutdown parasitics were not fit with a regression model; rather, we calculated an average of the parasitic energy used on days the plant did not operate. The offline load applies only on days the plant operated and includes nighttime, pre-dawn startup and standby periods. The online load was estimated both as a total parasitic power and as a fraction of the daily gross turbine energy. The parasitic-power models developed from the regression analyses are given in Table 3-8. The standard errors of the regression fits are on the order of +/- 10% of the listed value. The standard deviation of the shutdown parasitics is 40 kW. The parasitic powers in Table 3-8 agree reasonably well with the values estimated by Ege and Lehman.

We incorporated the parasitic models for each plant state into SOLERGY with simple linear relationships of the form:

$$\text{Daily Parasitics (kWh)} = (\text{Hours in a plant state}) * (\text{Parasitic Power, kW})$$

The total daily parasitics are the sum of the daily parasitics for each plant state. For the second online parasitic model, the following equation was used:

$$\text{Daily Parasitics (kWh)} = 0.11 * (\text{Daily Gross Energy Produced, kWh})$$

We performed daily and annual SOLERGY calculations with both online parasitic models and concluded that the fraction of gross daily energy gave better agreement with the measured values. In the next chapter, we present comparisons of the measured daily parasitic energy with predictions by SOLERGY using the above models.

As mentioned in Chapter 2, Solar One's thermal storage system was used in 1985 only to provide auxiliary steam for the plant. If the storage system had not been used, additional energy could have been generated and auxiliary steam provided by an electric boiler. Thus, energy put into storage should be included as parasitic energy.

3.4 Insolation Data

One of the more important pieces of data used as input to SOLERGY is a record of direct normal insolation (DNI). The data used in our study were collected using a normal incidence pyroheliometer (NIP) mounted on the roof of Solar One's control building. At Solar One, recordings of insolation and meteorological parameters, along with other plant parameters, are made at three minute intervals for archival purposes. These data formed the basis for the 15-minute averaged data used with SOLERGY. The 1985 insolation record used in this study was prepared by Sandia Laboratories, Livermore (Baker and Faas 1986). The total measured insolation at Solar One in 1985 was 2.5 MWh per square meter. The insolation record also contains 15-minute average values of wind direction, wind speed, temperature, and dew-point temperature. A copy of the file is available from the authors.

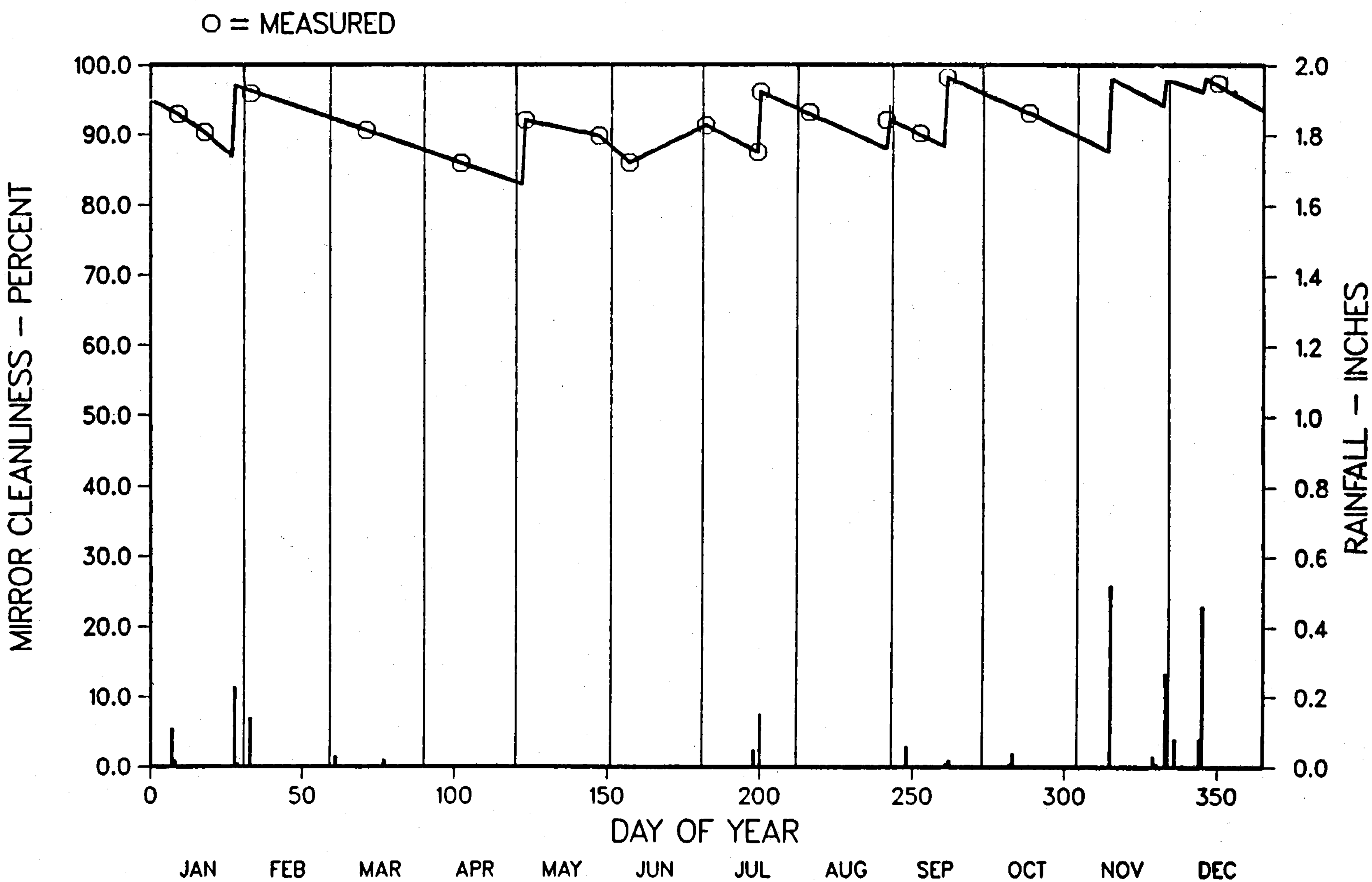


Figure 3-1 Cleanliness of the Solar One Heliostat Field During 1985

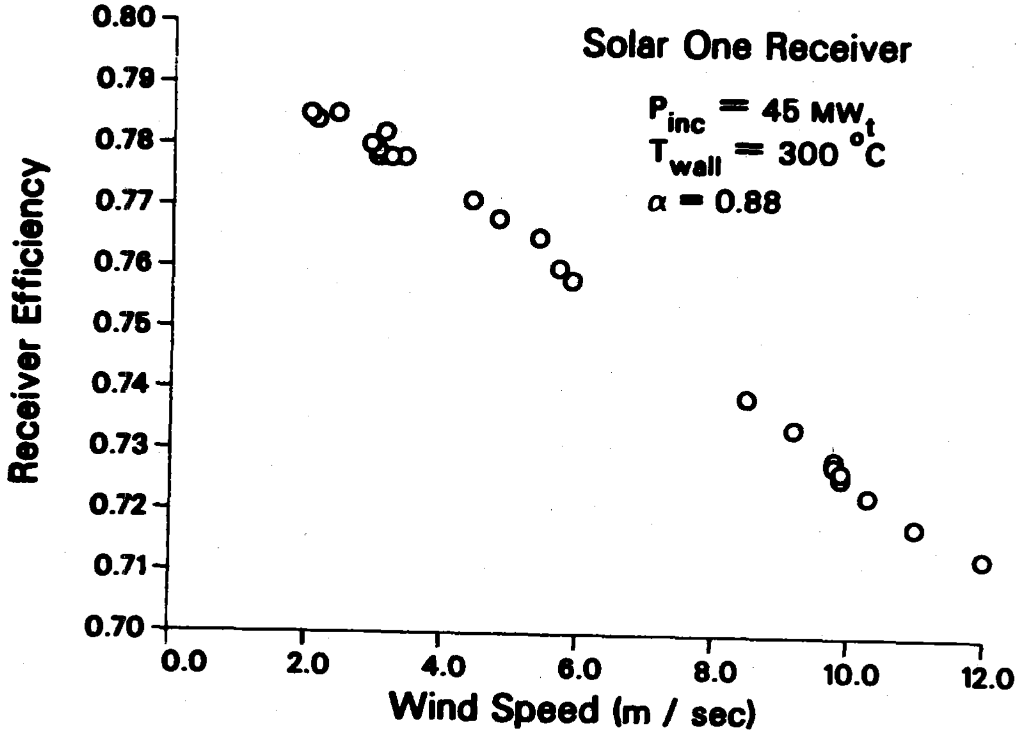


Figure 3-2 Wind Speed versus Receiver Efficiency at Solar One (Stoddard 1986)

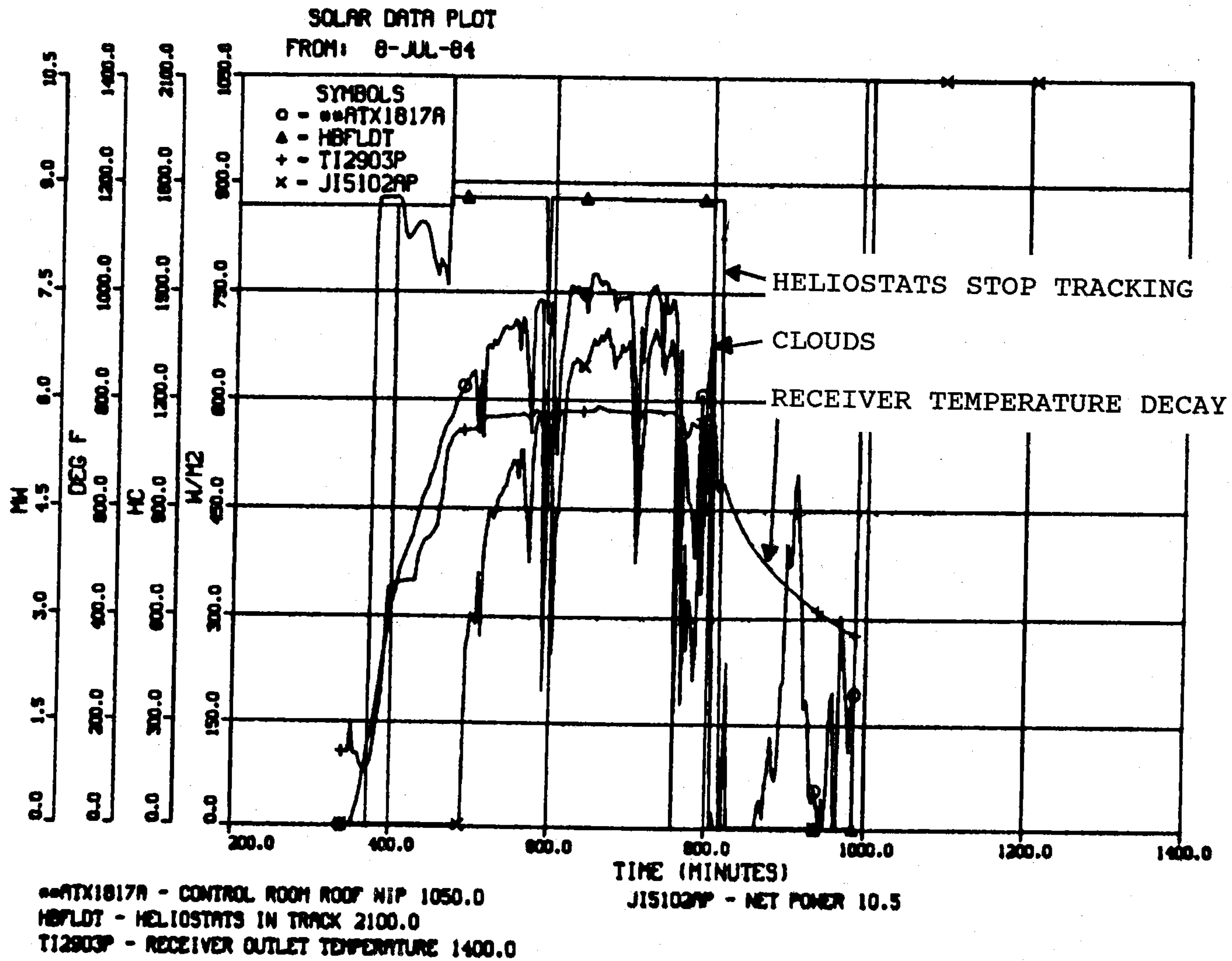


Figure 3-3 Trip of the Solar One Receiver During a Cloud Transient

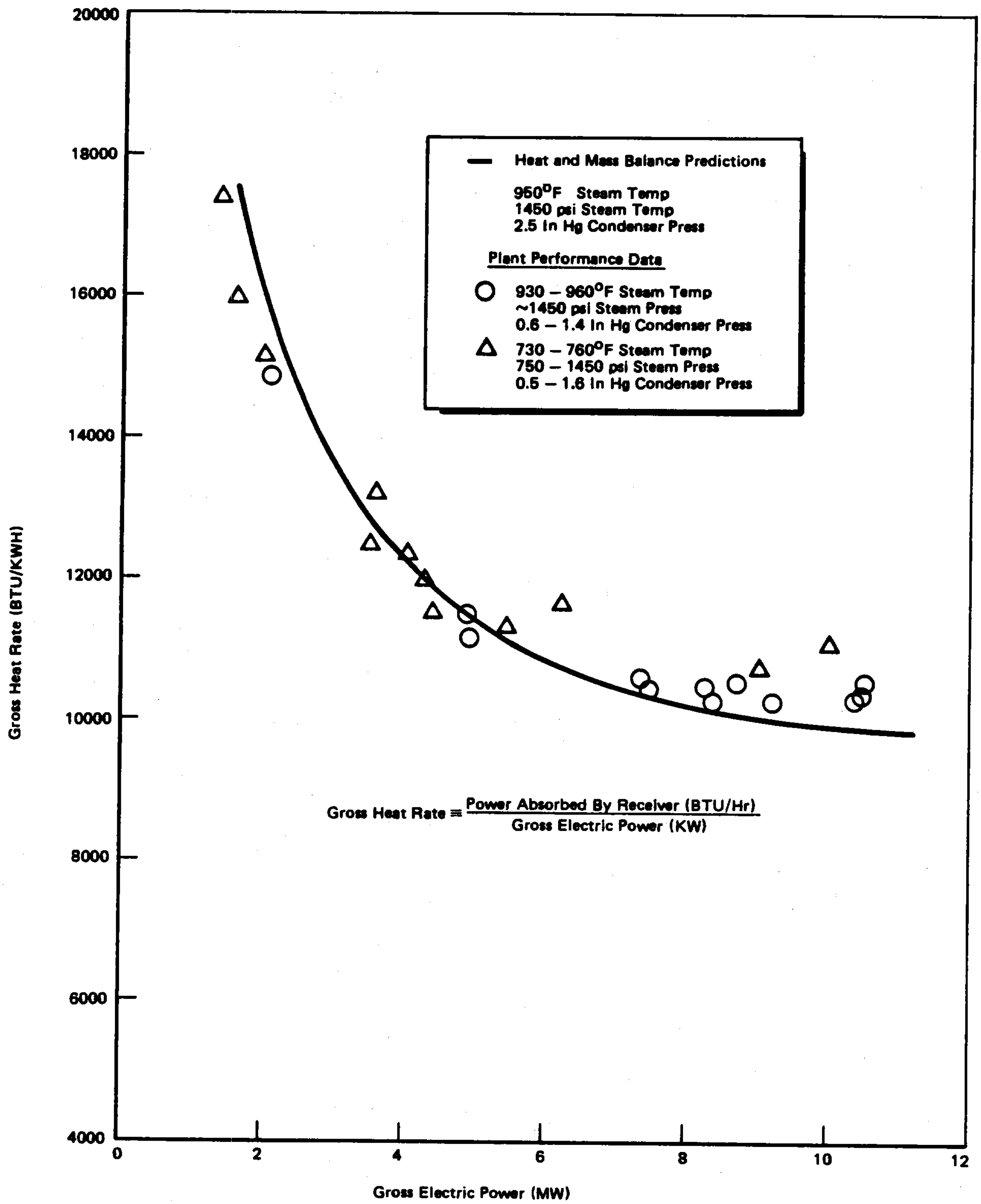


Figure 3-4 Gross Heat Rate for Solar One Turbine-Generator Operating on Receiver Steam. Steam Temperature Was Approximately 800 °F During 1985. (McDonnel Douglas Aeronautics Company 1984)

Table 3-1 SOLERGY INPUT PARAMETERS

Value(s)	Parameter	Description	Namelist
71130*AFAC	FS	- Collector field reflective area (m2)	NMLCOLF
not used	TLIML	- Lower collector field operating temperature limit (RF)	NMLCOLF
not used	TLIMU	- Upper collector field operating temperature limit (RF)	NMLCOLF
not used	WSLIM	- Maximum wind speed for field operation (m/s)	NMLCOLF
0.0	ELIM	- Minimum solar elevation angle for collector field operation (degrees)	NMLCOLF
0.905*CFAC	RFLCTY	- Heliostat reflectivity, if not included in FR	NMLCOLF
not used	NEFWS	- Number of elements in the wind speed efficiency array	NMLCOLF
not used	WSX	- Wind speed values for spline fit (m/s)	NMLCOLF
not used	WSEF	- Wind speed efficiency vector	NMLCOLF
+	EPS	- Receiver absorptance	NMLRCVR
50.	RS	- Receiver thermal rating (MWt)	NMLRCVR
0.26	ALPHAR	- Receiver cool down parameter (hours-1)	NMLRCVR
--	TREQD	- Time delay for receiver startup (hours)	NMLRCVR
1.7	EREQD	- Energy required for receiver startup (MWthr)	NMLRCVR
0.1	RMF	- Receiver minimum flow fraction	NMLRCVR
2 (no door)	IFILL	- Receiver door flag	NMLRCVR
7	NXLR	- Number of elements in wind vector	NMLRCVR
+	WXLR	- Vector of wind speed points for spline fit, in ascending order (m/sec)	NMLRCVR
+	PLXLR	- Vector of corresponding heat losses (MWt)	NMLRCVR
not used	TBHWS	- Time between hot and warm startup (hr)	NMLTRBN
not used	TBWCS	- Time between warm and cold startup (hr)	NMLTRBN
.66	SDH	- Hot turbine synchronization delay (hr)	NMLTRBN
.66	SDW	- Warm turbine synchronization delay (hr)	NMLTRBN
.66	SDC	- Cold turbine synchronization delay (hr)	NMLTRBN
.25	RDH	- Hot turbine ramp delay (hr)	NMLTRBN
.25	RDW	- Warm turbine ramp delay (hr)	NMLTRBN
.25	RDC	- Cold turbine ramp delay (hr)	NMLTRBN
38.1	TPFSL	- Thermal power for rated turbine operation (MWt)	NMLTRBN
0.15	TMFS	- Minimum turbine flow fraction (0.0 to 1.0)	NMLTRBN
not used	ESMIN1	- Minimum storage energy level for turbine start, peak period, receiver operating (MWthr)	NMLTRBN

\+ - See Text

Table 3-1 (continued)

Value(s)	Parameter	Description	Namelist
not used	ESMIN2	- Minimum storage energy level for turbine start, peak period, receiver not operating (MWthr)	NMLTRBN
not used	ESMAX1	- Storage level at which turbine must be started, receiver operating (MWthr)	NMLTRBN
not used	NREPSS	- Number of rows in FEPSS matrix (no. of wet bulb temperatures)	NMLTRBN
7	NCEPSS	- Number of columns in FEPSS matrix (no. of fractions of rated power)	NMLTRBN
6	REPSS	- Row vector of fractions of rated power for bicubic spline (0.0 to 1.0). Must be NCEPSS values in ascending order.	NMLTRBN
7	CEPSS	- Column vector of wet bulb temperature values (RC) for bicubic spline. Must be NREPSS values in ascending order.	NMLTRBN
+	FEPSS	- Matrix values for thermal to electric conversion efficiency (0.0 to 1.0). Order is important: all values in column 1, followed by all values in column two, etc. (NCEPSS by NREPSS)	NMLTRBN
7	NX	- Number of rows in the FR array (number of EL angles)	NMLCOEF
7	NY	- Number of columns in the FR array (number of AZ angles)	NMLCOEF
+	AZR	- Row vector of azimuth angles: NY values in ascending order	NMLCOEF
+	ELR	- Column vector of elevation angles: NX values in ascending order	NMLCOEF
+	FR	- Field efficiency matrix (NY by NM)	NMLCOEF
.25	DELT	- SOLERGY time step, hrs	NMLGEN
29 days	ICOVT	- Julian dates of the storage charging outage days	NMLGEN
35 days	IFOUT	- Julian dates of the forced outage days	NMLGEN
51 days	ISCHED	- Julian dates of the scheduled outage days	NMLGEN
34.9	ALAT	- Local latitude (degrees	NMLLOC
117.0	ALONG	- Local longitude (degrees west of Greenwich)	NMLLOC
8.(Pacific)	ZONE	- Local international time zone	NMLLOC

+ - See Text

Table 3-1 (continued)

Value(s)	Parameter	Description	Namelist
default	NXLP	- Number of elements in the temperature vector	NMLPIPE
default	TXLP	- Vector of ambient temperature points for spline fit, in ascending order (RC)	NMLPIPE
default	YXLP	- Vector of corresponding loss coefficients	NMLPIPE
not used	PTSMAX	- Maximum charging rate (MWt)	NMLSTRG
not used	PFSMAX	- Maximum discharge rate (MWt)	NMLSTRG
not used	PTSMIN	- Minimum charging rate (MWt)	NMLSTRG
not used	PFSMIN	- Minimum discharge rate (MWt)	NMLSTRG
not used	EMAX	- Maximum value of the stored energy (MWthr)	NMLSTRG
not used	EMIN	- Minimum value of the stored energy (MWthr)	NMLSTRG
not used	ES	- Energy in storage (MWthr)	NMLSTRG
not used	A(*)	- Thermocline degradation coefficients (unitless)	NMLSTRG
not used	CLF	- Charging loss factor (MW)	NMLSTRG
not used	DLF	- Discharging loss factor (MW)	NMLSTRG
not used	TNKLF	- Tankage loss factor (MWt or hr)	NMLSTRG
not used	LS	- Storage flag	NMLSTRG
not used	REFPC	- Reference power for heat exchanger thermal losses (MWt)	NMLSTRG
not used	TSTCR	- Minimum time delay for storage charging startup (hr)	NMLSTRG
not used	ESTCR	- Energy penalty for storage charging startup (MWht)	NMLSTRG
not used	TSTDR	- Minimum time delay for storage discharging startup (hr)	NMLSTRG
not used	ESTDR	- Energy penalty for storage discharging startup (MWthr)	NMLSTRG
not used	PWARMC	- Maximum charging rate during charging startup (MWt)	NMLSTRG
not used	PWARMD	- Maximum extraction rate during extraction startup (MWt)	

Table 3-2

Availability of the Heliostats at Solar One During 1985

Time Period	Average Number of Heliostats Available	Percent Availability
January - May	1725	0.95
June - November 10	1800 - 1815	0.99 - 0.998
November 11 - 19	0	0.0
Nov 20 - Dec 16	1350 - 1850	0.74 - 0.99
December 17 - 31	1760 - 1815	0.97 - 0.998

Table 3-3

Comparison of Solar One and SOLERGY
Turbine On-Line Times

Date	Solar One On-Line Time	SOLERGY On-Line Time
1/17/85	9:11 a.m.	9:00 a.m.
1/20/85	9:12 a.m.	9:00 a.m.
4/11/85	7:23 a.m.	7:45 a.m.
5/13/85	8:08 a.m.	8:00 a.m.
7/22/85	8:13 a.m.	8:15 a.m.
10/15/85	8:53 a.m.	9:00 a.m.
12/19/85	8:41 a.m.	9:00 a.m.

Table 3-4

Thermal Losses from the Solar One Receiver
as a Function of Wind Speed

Wind Speed (m/sec)	Thermal Losses (MWt)
0.0	3.6
2.0	4.2
4.0	4.8
6.0	5.4
8.0	6.1
10.0	6.8
12.0	7.5

Table 3-5

Gross Thermal-to-Electric Conversion Efficiency of the Solar One Turbine-Generator as a Function of Load

Percent of Full Load	Efficiency
0.15	0.17
0.18	0.20
0.24	0.23
0.38	0.28
0.46	0.31
0.66	0.33
1.00	0.33

Table 3-6

Solar One Field and Receiver Interception Efficiency as a Function of Sun Location

		AZIMUTH ANGLE						
		0.	30.	60.	75.	90.	110.	130.
ELEVATION ANGLE	0.	0.	0.	0.	0.	0.	0.	0.
	5.	.30	.29	.28	.27	.27	.26	.26
	15.	.60	.58	.55	.54	.53	.50	.48
	25.	.72	.70	.67	.66	.64	.61	.59
	45.	.78	.76	.74	.74	.72	.70	.68
	65.	.78	.77	.77	.75	.75	.74	.72
	90.	.76	.76	.76	.77	.76	.76	.76

Table 3-7. Solar One Parasitics (from Ege and Lehman, draft)

Equipment	Load (kW)	Extended Shutdown	Pre-Dawn Start-up	Night	Storage Charge	Online
Air Conditioning	125	x	x	x	x	x
Main/Aux Transformers	37	x	x	x	x	x
Heliostat Transformers	8	x	x	x	x	x
Lighting	50	x	x	x	x	x
Heat Trace	3	x		x		
Turbine Lube Oil Pump	6	x	x	x	x	x
Heliostats	54				x	x
Electrohydraulic Control Pump	6		x		x	x
Compressed Air Driers	7	x	x	x	x	x
Service Water Jockey Pump	4	x	x	x	x	x
Condenser Hotwell Pump	56		x			x
Condenser Vacuum Pump	30		x			x
Circulating Water Pump	150	*	x	*		x
Receiver Feedwater Pump	500		x		x	x
Charging Oil Pumps	300				x	
Electric Boiler	45-1000					
Other Online Loads	130					x
Other Offline Loads	53	x	x	x	x	
Total (kW)		293	1032	293	1150	1157

* intermittent operation for bearing cooling

Table 3-8

Parasitic Power Models Developed by Regression Fit to Solar One Data

Plant State	Parasitic Power
Shutdown	370 kW (for 24 hours)
Turbine Offline	470 kW
Charging Storage	830 kW
Turbine Online	925 kW
Turbine Online	11% of daily gross turbine energy

Chapter 4

Comparison of Daily Performance

In this chapter we compare the actual performance of Solar One with SOLERGY predictions during several typical weather days. The SOLERGY predictions used the code input parameters described in Chapter 3. Comparisons on clear-sky weather days are presented in Section 4.1. In Section 4.2, we compare performance during differing types of cloudy weather. Finally, in Section 4.3, we summarize the comparison for 153 days during 1985.

4.1 Comparison of Performance on Clear Weather Days

Performance was first compared on several clear weather days during 1985. Clear days were studied first in order to reduce uncertainties associated with operator actions. Operator actions on cloudy days will be discussed in Section 4.2.

Displayed in Figures 4-1 and 4-2 are the gross turbine power produced at Solar One on July 22, 1985, and the SOLERGY prediction for the same day. The Solar One data were recorded at 3-minute intervals, whereas the SOLERGY predictions were made every 15 minutes. It can be seen that SOLERGY provides an excellent prediction of the gross turbine power throughout the day, i.e., the turbine on-line and off-line times are very close, and so are the peak turbine power and general shape of the curve. The SOLERGY prediction used the parameter values described in Chapter 3 and a direct-normal-insolation (DNI) curve based upon a 15-minute average (Figure 4-3). This average curve was developed from instantaneous DNI recorded at Solar One every three minutes (Figure 4-1). The gross energy produced on this day is obtained by integration of Figure 4-1; Solar One produced 91.6 MWh_e and SOLERGY predicted 89.7 MWh_e.

Performance on July 22 and on other clear days throughout 1985 is compared in Table 4-1. In this table we compare on-line time, off-line time, daily gross turbine energy, and daily net energy. The daily net energy includes the effect of the electrical parasitics that were consumed throughout the full 24 hours of the day. As can be seen, the SOLERGY code provides an excellent prediction of the actual plant performance on clear days throughout the entire calendar year. The errors in the SOLERGY prediction appear to be random in nature. For example, on some days SOLERGY slightly overpredicts the net energy while on other days the code underpredicts it. This is an indication that the SOLERGY model and parameters are not biased.

4.2 Comparison of Performance on Cloudy Weather Days

Prediction of clear-day performance is easier than for cloudy days primarily because operator actions are known with more certainty on clear days. For example, on a clear day the operators typically have the heliostats tracking the receiver at sunrise and take the heliostats off the receiver near sundown. Operator actions are very predictable on clear weather days and the power produced by the plant is directly proportional to the DNI curve. However, on cloudy days the power produced by the plant is not always proportional to the insolation curve because the operator may not decide to operate the plant during a portion or all of the day. The operator visually observes the local weather conditions and consults weather satellite information when making this decision. The operator then makes an educated guess at the amount of energy the plant may produce and compares this with the amount of parasitic energy required to start the plant and maintain the plant in hot standby status during plant trips caused by intermittent clouds. If the estimated amount of parasitic energy is greater than the production amount, the operator will probably decide not to start the plant even when the skies are temporarily sunny. The SOLERGY code does not model operator actions; the code will attempt to start and run the plant whenever DNI is available.

For purposes of discussion, we have categorized cloudy weather into three different groups. Each group is characterized by a different cloud pattern and different uncertainties associated with operator actions (group 1 has the lowest uncertainty and group 3 the highest).

1. Translucent clouds or haze cause a reduction in the DNI upon the heliostat field to a value below the clear-sky value.

2. Large opaque clouds cover the entire field and reduce the DNI to near zero for an extended period. These types of clouds are characteristic during a passing weather front.

3. Small opaque clouds cross the field in an intermittent fashion. These types of clouds cause the DNI to drop to near zero for a few minutes followed by a rapid return to full sun conditions.

The above groups were formed in order to characterize different cloud patterns as well as the expected differences in operator actions in response to the clouds. The ability of SOLERGY to predict the performance of Solar One during each of these types of clouds is discussed in the following paragraphs.

Translucent Clouds or Haze

SOLERGY predicts well the Solar One performance during the first type of cloudy weather. Though reduced, the insolation remains high enough to avoid a plant trip. The operator continues to maintain the plant in operation throughout the day. Plant performance is similar during this type of weather to that on clear days, except the output power is lower because the insolation is lower.

Large Fronts of Opaque Clouds

The SOLERGY code also provides a good prediction of performance during cloudy weather of the second type. On these days, opaque clouds typically cover the field for one or more hours during the early morning or late afternoon. During the remaining hours of the day the weather is clear and several hours are available to run the plant. Operator actions are fairly well understood on these days because the weather front is clearly visible and weather prediction becomes a fairly easy task.

Displayed in Figure 4-4 are the gross turbine power and DNI recorded at Solar One on July 26, 1985. The weather on this day was predominantly clear until 1554 (954 minutes) At that time a large front moved across the field and shut down the plant. (Prior to this time, two large dips in the turbine power can be seen. This probably means that two very short cloud transients occurred. The first cloud transient lasted less than 3 minutes, since it is not visible on the DNI curve.)

Displayed in Figure 4-5 is the DNI curve employed in the SOLERGY simulation of this day. This curve is plotted at 15-minute intervals and represents the 15-minute average of the 3-minute instantaneous DNI values plotted in Figure 4-4. The averaging has little effect on the shape of the DNI curve during clear-sky conditions. However, the averaging has a very noticeable effect during short-term transients. For example, the 3 minute instantaneous curve shows the insolation dropping to zero at 954 minutes and then oscillating between low and high values as the cloud front covers the field. The 15-minute average curve, on the other hand, shows only one major oscillation between 900 and 960 minutes, followed by a very rapid drop in the DNI when the front covers the field.

The insolation averaging in the DNI file used by SOLERGY impacts the ability of the code to predict performance during short-term transients. Displayed in Figure 4-6 is the SOLERGY prediction of the gross turbine power on July 26. SOLERGY is seen to give a good prediction of the output power up until the cloud transient at 954 minutes. In response to this transient, SOLERGY predicted a rapid drop in turbine power; the turbine remained on-line, however, because the DNI file did not drop to a low enough value to cause a trip. SOLERGY allowed the turbine to remain on-line until the cloud front fully covered the field at 1020 minutes. At Solar One, the turbine tripped at 954 minutes because the insolation dropped to zero for a few minutes. The operators saw the impending cloud front and decided not to restart the plant. Because SOLERGY allowed the turbine to remain on-line longer during the cloud front, it overpredicted the gross power produced by the turbine. On this day Solar One produced 63 MWh_e and SOLERGY predicted 72 MWh_e.

Based on the above discussion it can be concluded that SOLERGY produces a reasonable estimate of plant performance on days involving large cloud fronts. The code will probably overpredict the power produced by the turbine during the interval in which the front is covering the field because the 15-minute average DNI file does not capture very short transients in which the DNI drops below the turbine's trip level. If the SOLERGY simulation of this day had used instantaneous DNI data, the code would have predicted a turbine trip at nearly the same time as it actually occurred at Solar One. Use of instantaneous data within SOLERGY is discussed further in the next section.

Intermittent Clouds

In the introduction of Section 4.2 we state that prediction of cloudy day performance is difficult because of the uncertainties associated with operator actions. As discussed above, this task becomes even more difficult when the DNI file does not contain enough detail to distinguish short-term transients. We show in this section that SOLERGY consistently overpredicts plant performance on intermittently cloudy days because of these two problems. We also show that the overprediction can be mitigated somewhat by using a DNI file containing more detail.

Displayed in Figure 4-7 are plots of DNI on an intermittently cloudy day (Day 8). The upper plot shows the 3-minute instantaneous values recorded by the data acquisition system at Solar One. The lower plot is the 15-minute average of the 3-minute values. The 15-minute averaging is seen to have a significant impact on the shape of the DNI curve, as discussed previously.

A SOLERGY simulation utilizing the 15-minute average curve predicted that the turbine was on-line at 0900 and off-line at 1600. These times are compared in the first entry of Table 4-2 with the actual times recorded at the plant (on-line at 0945, off-line at 1023) and with other SOLERGY predicted times using the 3-minute instantaneous DNI file (on-line at 0848, off-line at 1021, on-line again at 1206, off-line again at 1336). SOLERGY did not predict a turbine trip during the intermittent cloud transients when using the 15-minute average file because the averaging process did not allow the DNI to drop to a value low enough to cause turbine trip. Use of the 3-minute DNI file, on the other hand, predicted a turbine trip at approximately the same time (1021) as it actually occurred at Solar One. At this time, the insolation momentarily dropped to zero due to a passing cloud (see Figure 4-7). The plant did not operate for the rest of the day after this cloud transient. The SOLERGY code, however, predicted that the plant could have run for another 1.5 hours during the clear-sky period ("operating window") between 1130 and 1330. The reason the plant did not operate during this period is unknown. A reasonable guess is that following the trip at 1021 the operators made a weather prediction that an operating window would not occur for the rest of the day; they then placed the plant in cold shutdown to conserve parasitic power consumption.

Examples of the DNI on other intermittently cloudy days during 1985 are displayed in Figure 4-8. These plots represent 15-minute averages. (Examination of the 3-minute instantaneous curves indicated that several of the troughs in the 15-minute curves actually dropped to near zero.) Solar One did not operate on day 26 because the insolation was too erratic. The plant operated during a portion of the remaining days. The actual turbine on-line and off-line times are compared with the SOLERGY predictions for these days in Table 4-2. It can be noted that SOLERGY more closely predicts the actual times when using the 3-minute DNI file. The difference between these SOLERGY predictions and the actual is most likely attributed to the inability of the operators to accurately predict operating windows. Another plausible reason is that a turbine trip resulted from a cloud transient lasting less than 3 minutes. Since the data acquisition system logged DNI at 3-minute intervals, it is possible that a very short cloud transient was not recorded. This is what most likely occurred on day 242 at 1227.

4.3 Comparison of Performance on 153 Days During 1985

The ability of the SOLERGY code to predict performance was tested further by comparing actual Solar One performance with SOLERGY predictions on 153 individual days scattered throughout 1985. A day was selected if all of the following criteria were met:

1. there were no scheduled or forced outages,

2. thermal storage was not charged during the day, and

3. the Solar One data acquisition system was available during the daytime.

The first two criteria ensure that, given good weather, the plant was available for power production. The third criterion ensures that an actual DNI file was produced on that day. (It should be noted that the data acquisition system was unavailable during portions of several days during 1985. On these days the gaps in the DNI file were filled with educated guesses of the actual DNI).

The weather at Solar One on these 153 days covered a broad range of possibilities: clear skies, hazy skies, various types of partly cloudy weather, completely overcast days, combined with a variety of wind velocities.

Displayed in Figures 4-9 through 4-11 are scatter plots relating the actual performance at Solar One on these 153 days to the SOLERGY prediction. In these plots we compare gross daily turbine energy production, total daily parasitics, and daily net energy production, respectively. The SOLERGY calculations were based on the 15-minute average DNI files described previously. It can be noted that SOLERGY produced a very reasonable prediction of the actual performance for the majority (approximately 88%) of the 153 days. For the remaining days, SOLERGY significantly overpredicted energy production.

We reviewed the detailed calculations for those days for which the SOLERGY prediction was poor. We found that intermittently cloudy weather occurred on all of these days. The reasons for the overprediction was due to unpredictable operator actions and use of a 15-minute average DNI file. This topic is discussed in detail in Section 4.2.

Table 4-3 shows the summary statistics associated with these 153 days. The statistics indicate that SOLERGY produced a very reasonable estimate of performance; all predictions were within approximately 10% of the actual.

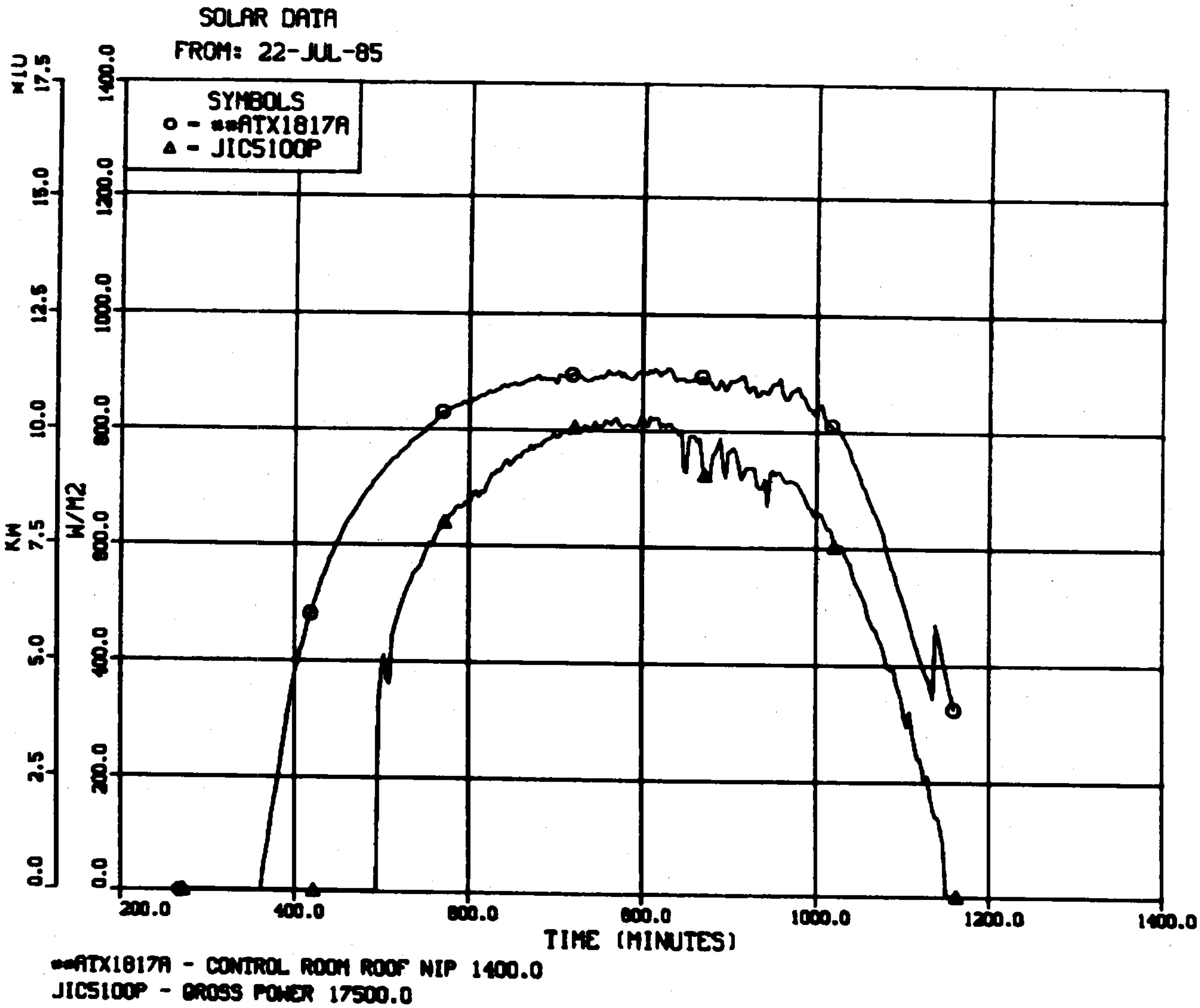


Figure 4-1 Gross Turbine Power and Direct Normal Insolation Data (3 minute instantaneous) Recorded at Solar One on July 22, 1985

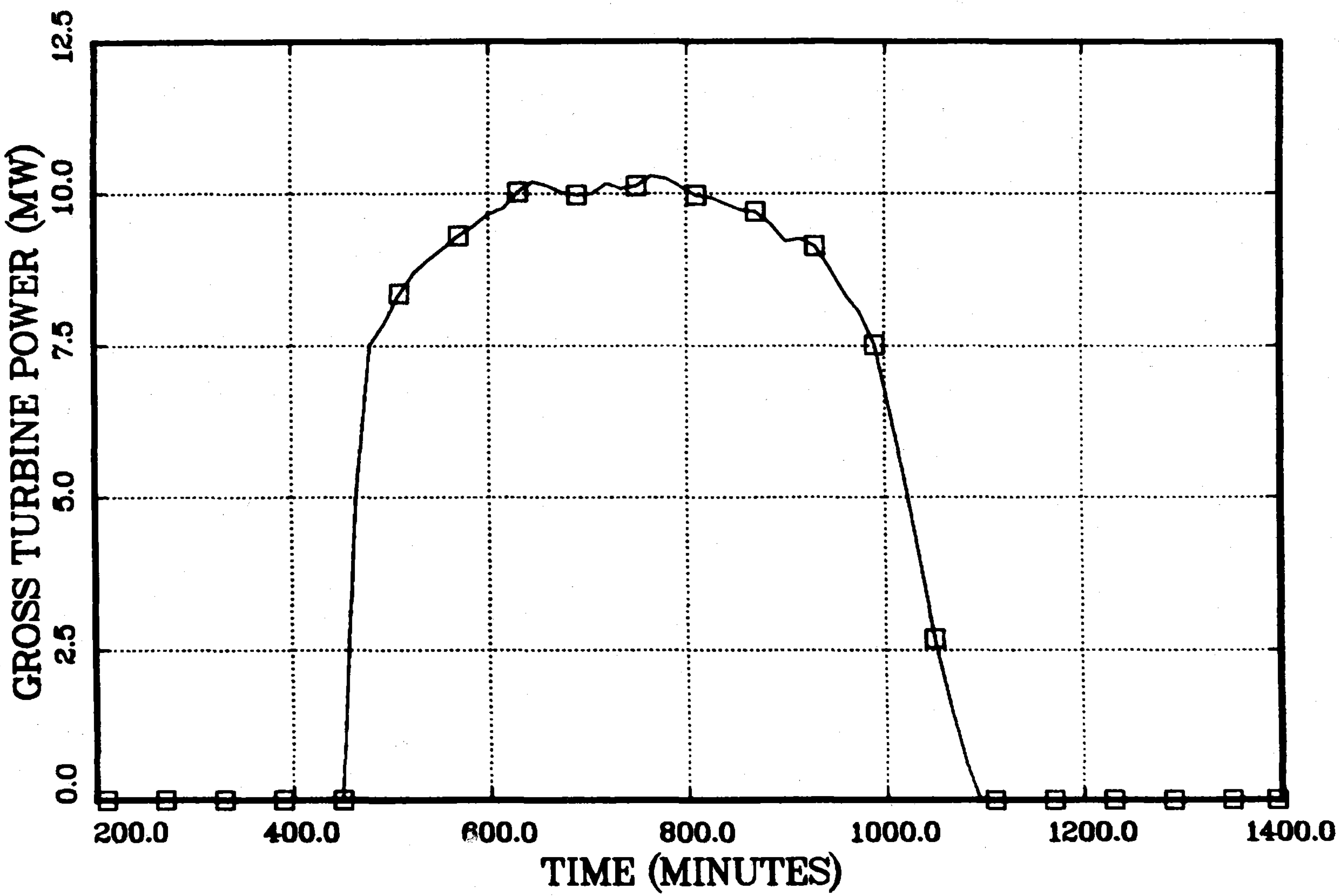


Figure 4-2 Prediction of the Gross Turbine Power at Solar One on July 22, 1985 by the SOLERGY Computer Code

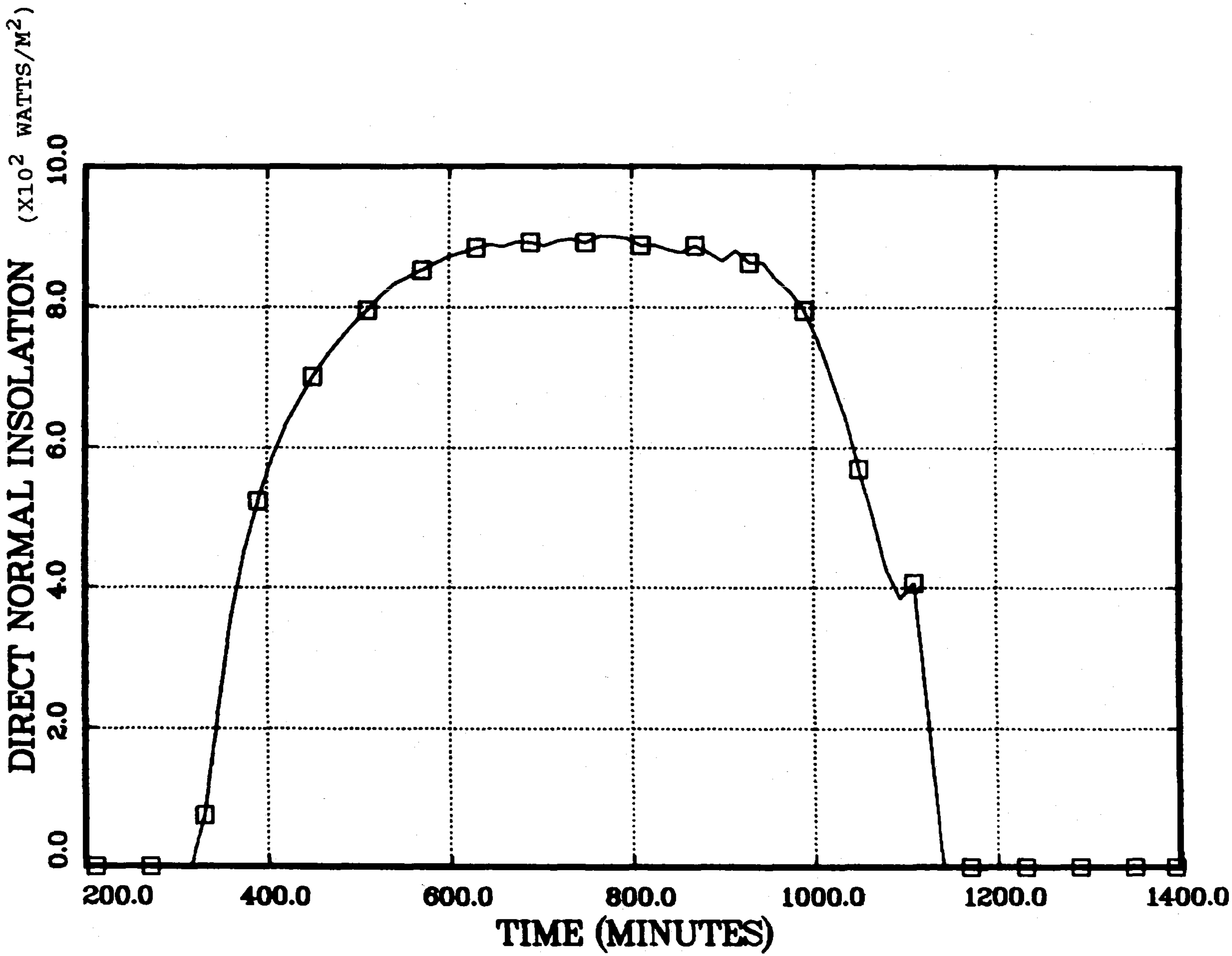


Figure 4-3 Direct Normal Insolation at Solar One on July 22, 1985 (15 Minute Average)

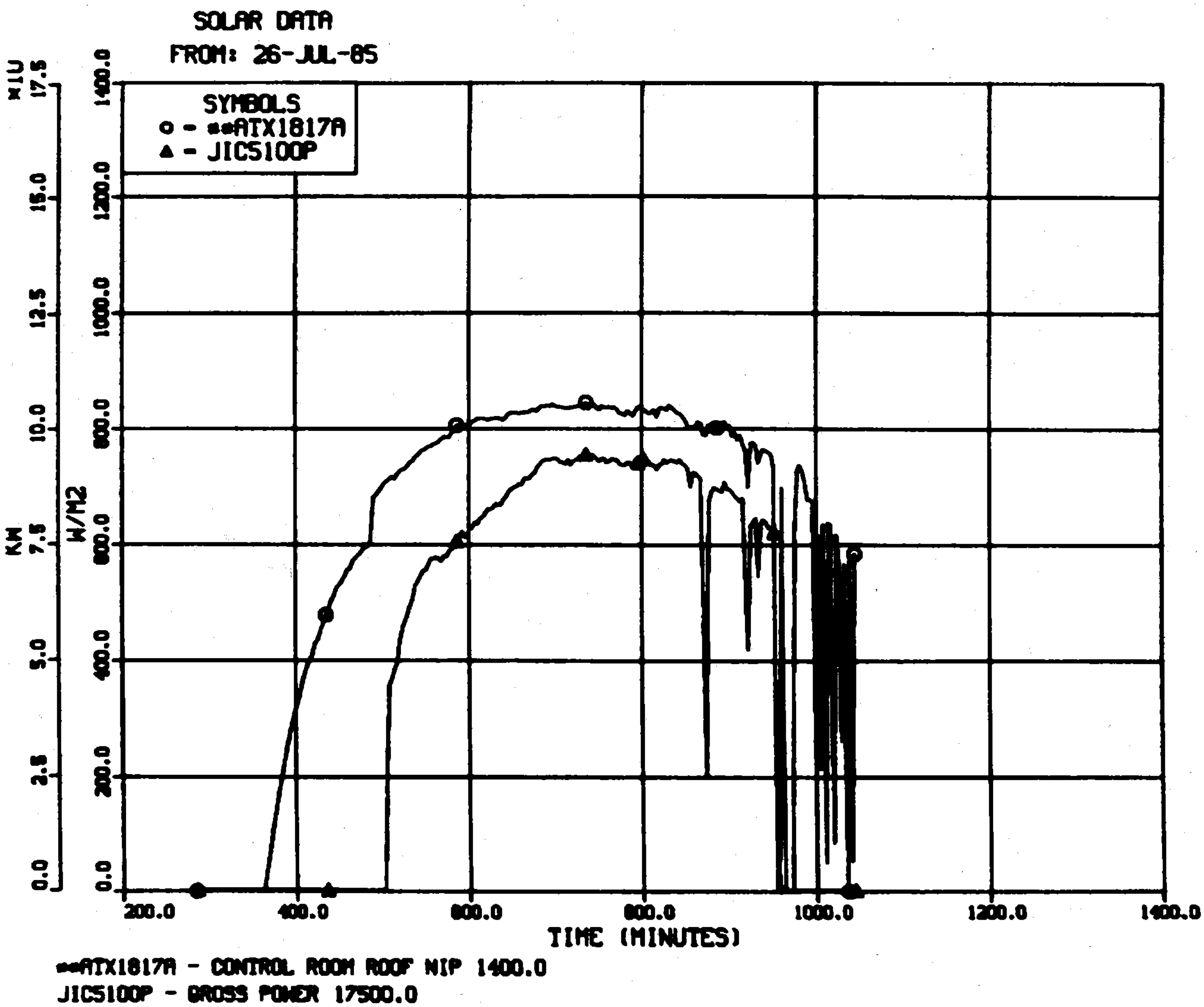


Figure 4-4 Gross Turbine Power and Direct Normal Insolation Data (3 minute instantaneous) Recorded at Solar One on July 26, 1985

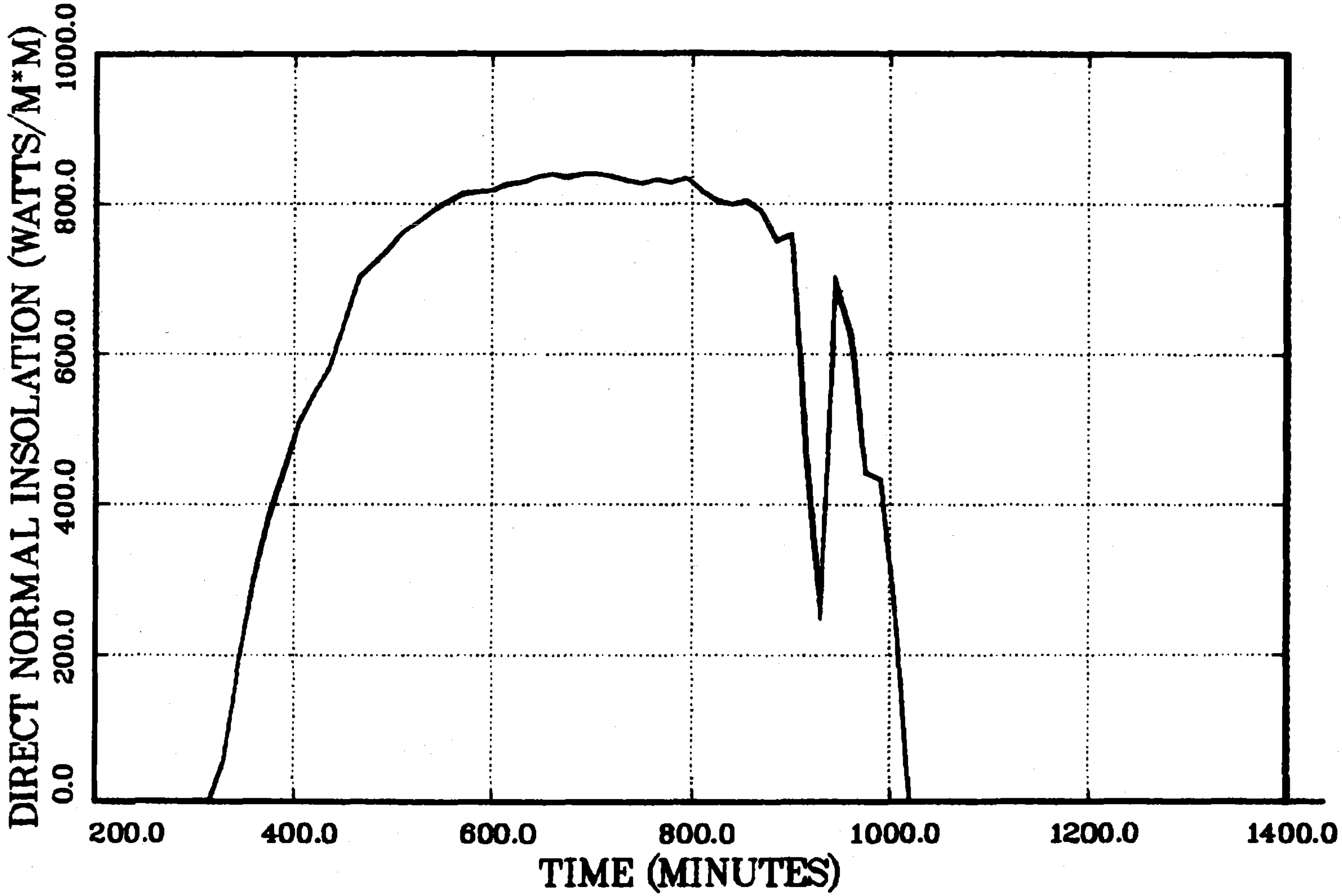


Figure 4-5 Direct Normal Insolation at Solar One on July 26, 1985 (15 Minute Average)

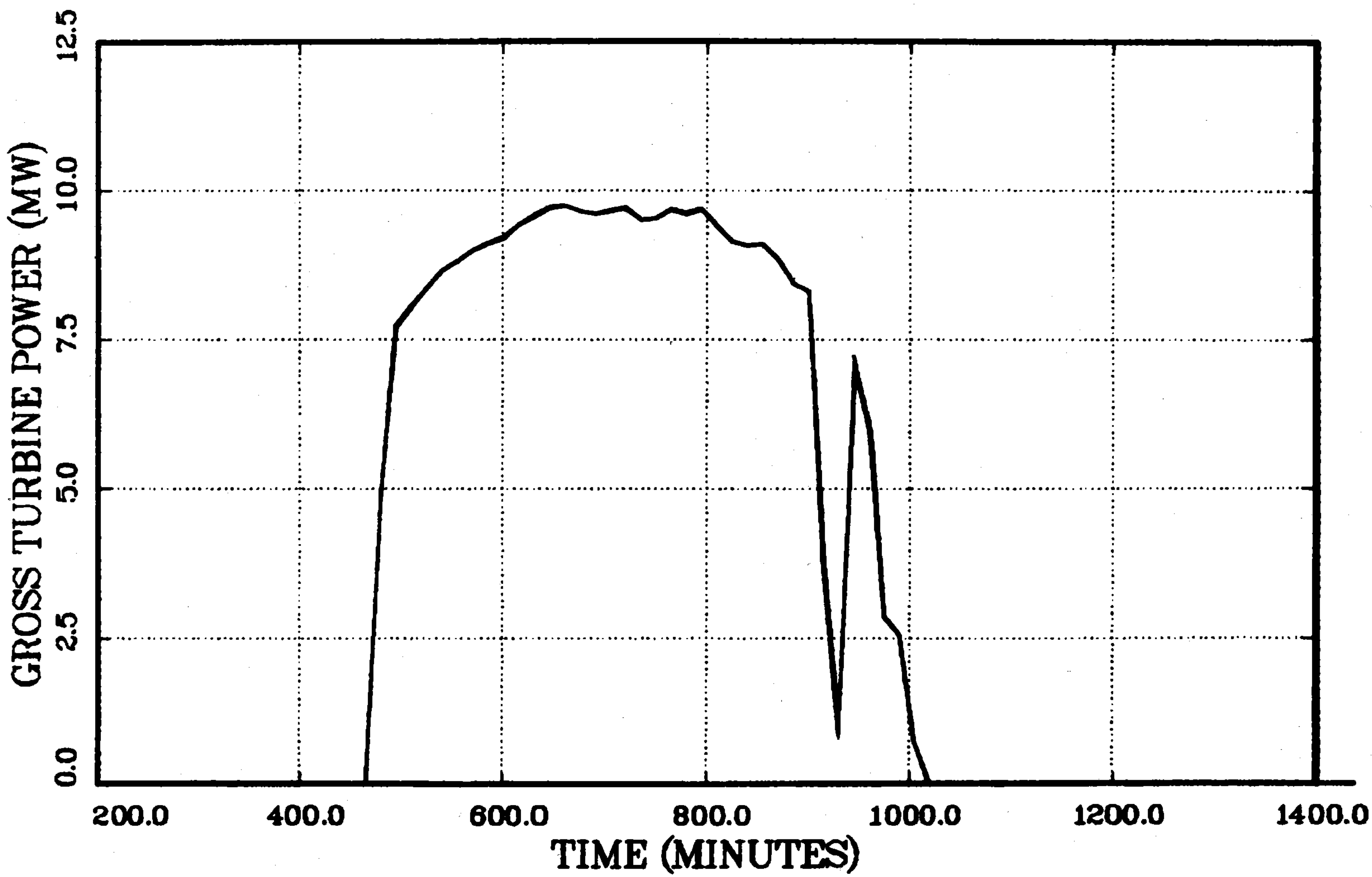


Figure 4-6 Prediction of the Gross Turbine Power at Solar One on July 26, 1985 by the SOLERGY Computer Code

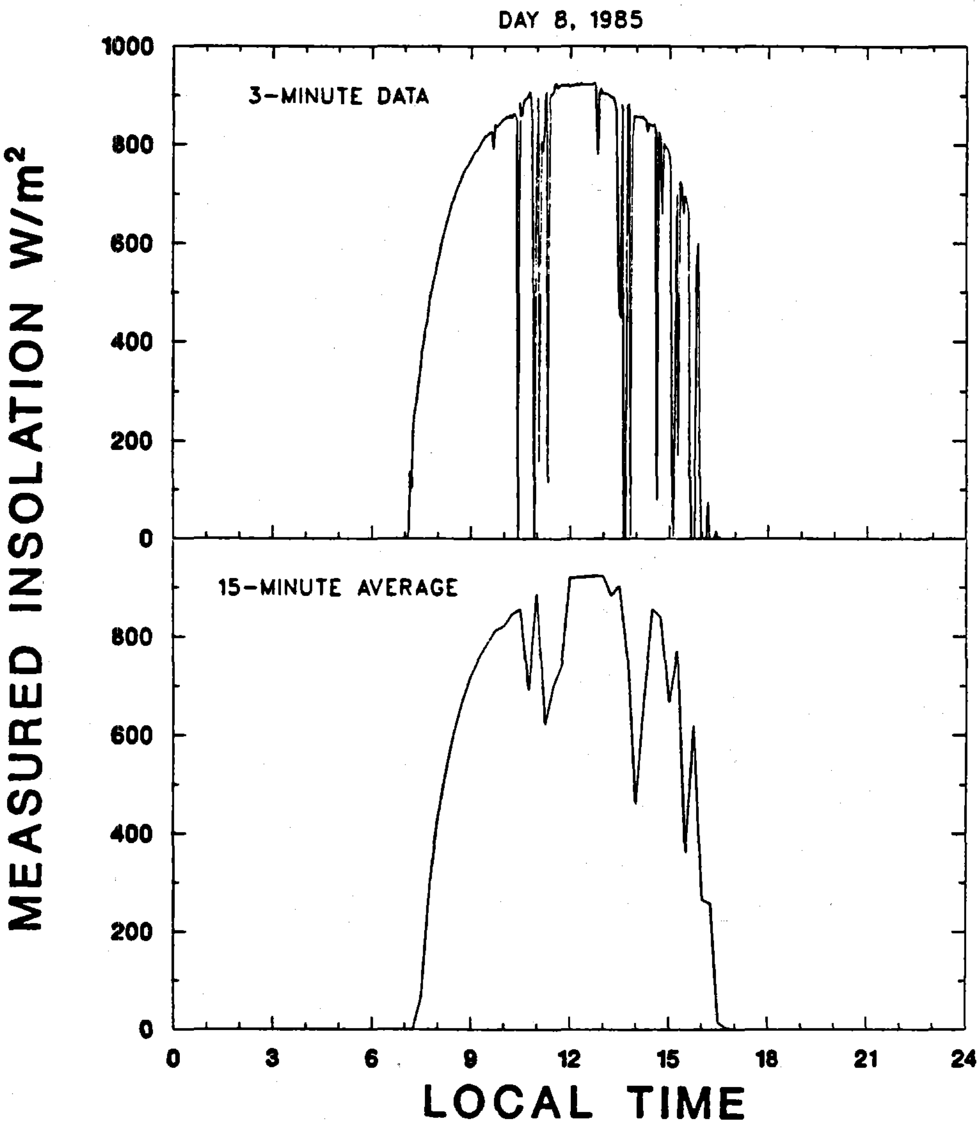


Figure 4-7 Comparison of Direct-Normal-Insolation Data

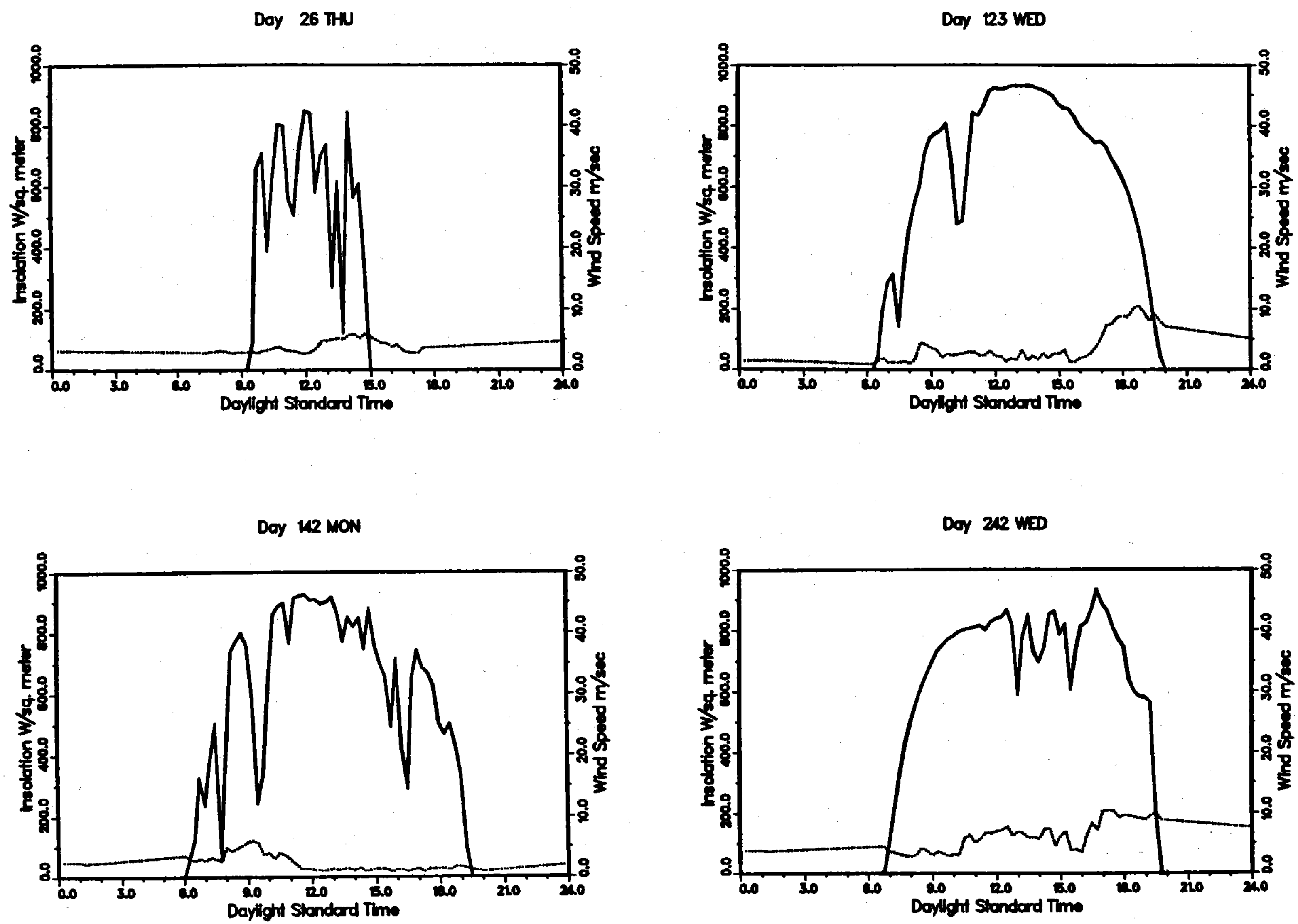


Figure 4-8 Direct Normal Insolation Data Averaged Over 15-Minute Intervals for Several Days in 1985

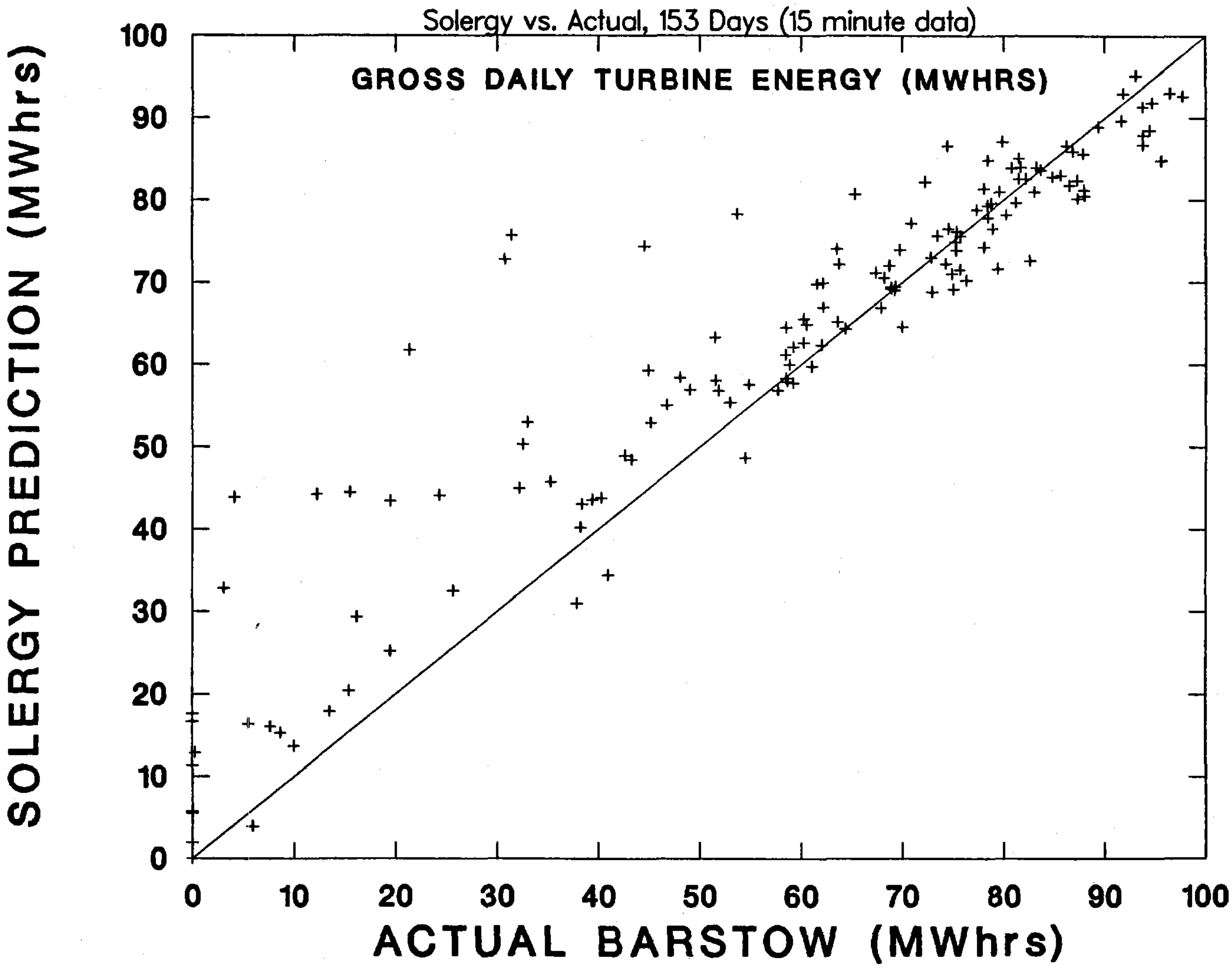


Figure 4-9 Comparison of the Actual Gross Daily Turbine Energies Produced at Solar One with the SOLERGY Predictions

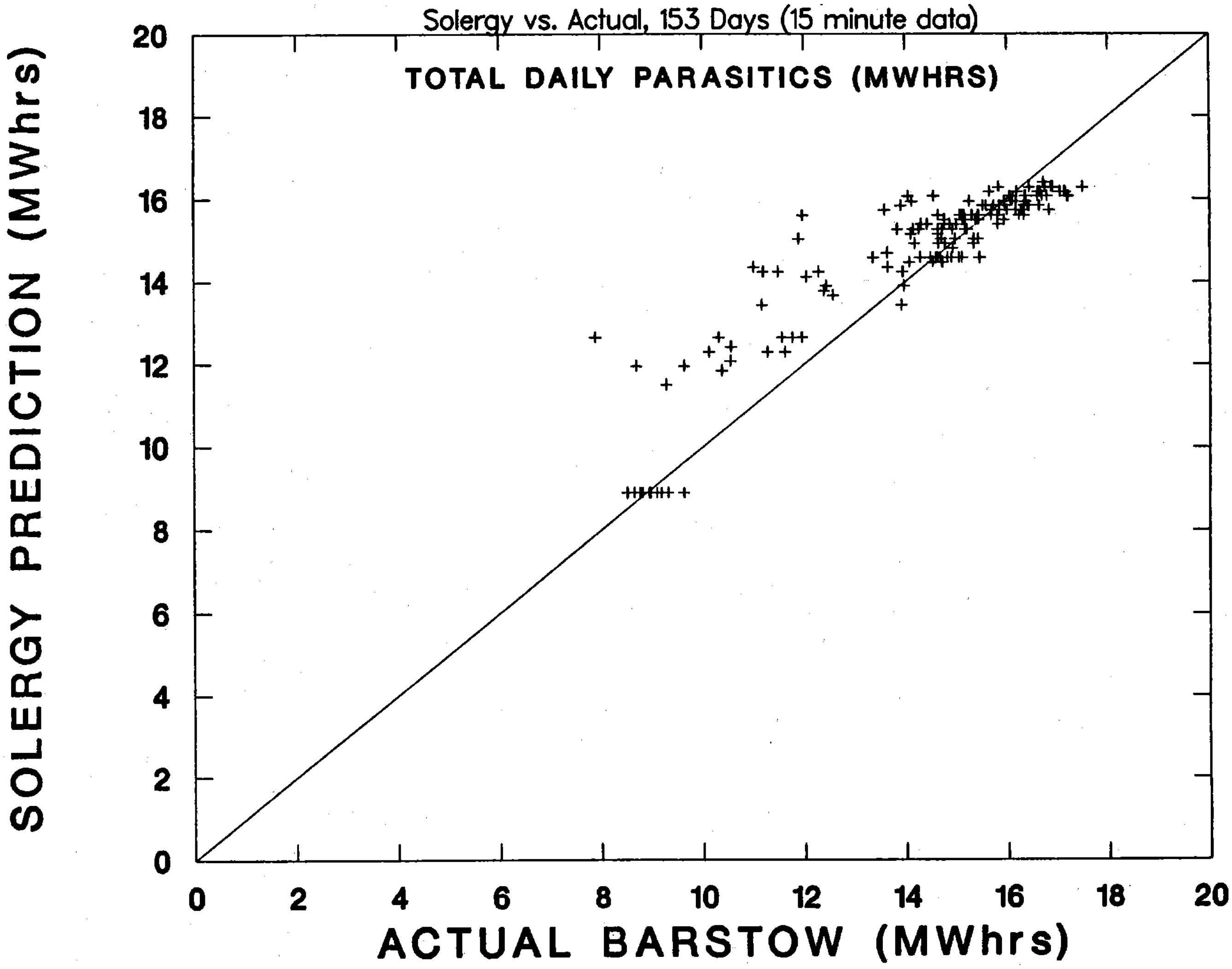


Figure 4-10 Comparison of the Actual Daily Parasitic Energies Consumed at Solar One with the SOLERGY Predictions

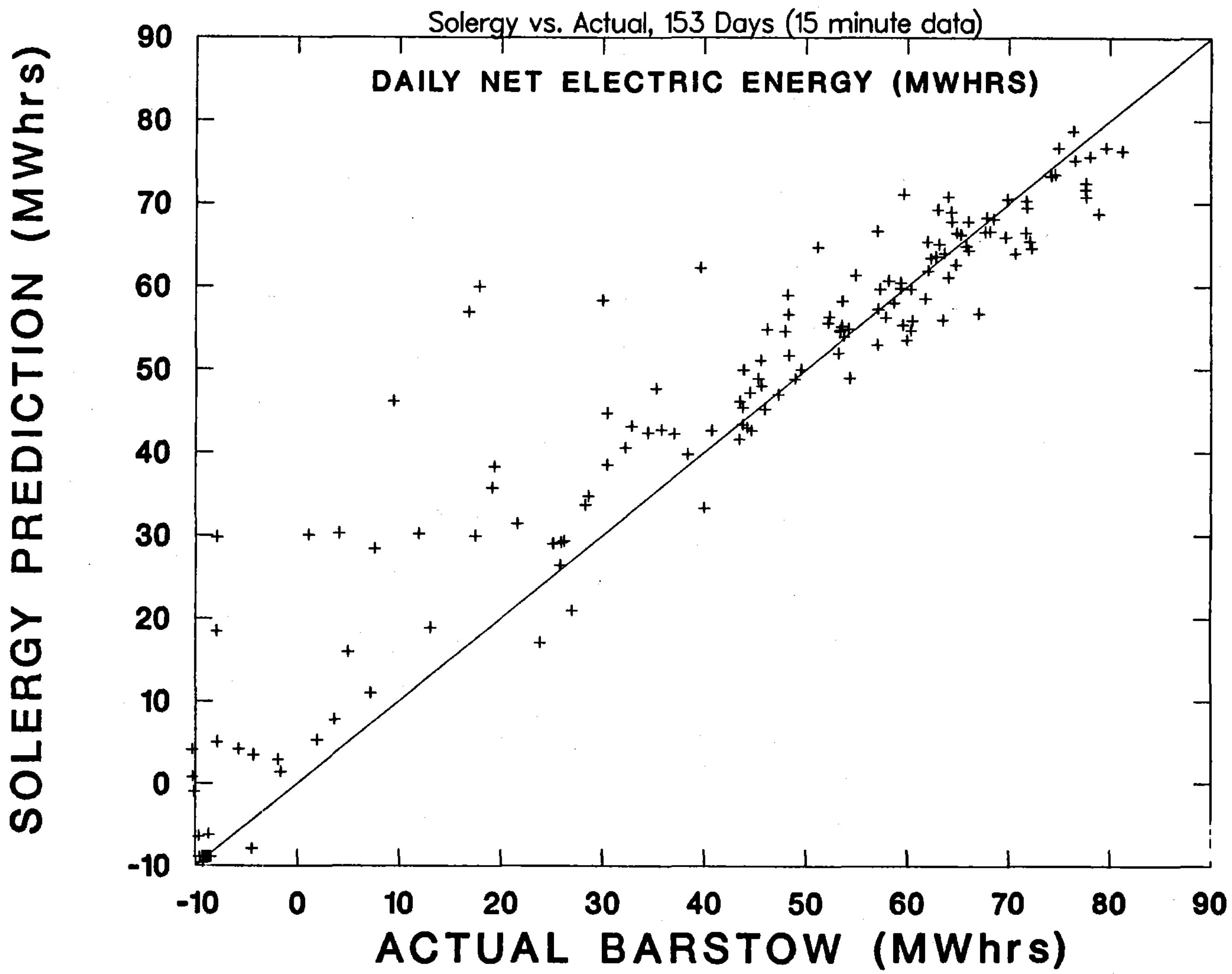


Figure 4-11 Comparison of the Actual Daily Net Energies Produced at Solar One with the SOLERGY Predictions

Table 4-1

Comparison of SOLERGY Predictions with Actual Performance at Solar One On Several Clear-Weather Days During 1985

Date	On-Line Time		Off-line Time		Gross Turbine Energy (MWhe)		Net Daily Energy (MWhe)	
	Data	SOLERGY	Data	SOLERGY	Data	SOLERGY	Data	SOLERGY
1/17	0911	0900	1629	1615	61.1	59.8	46.0	45.3
1/20	0912	0900	1632	1615	58.7	57.9	43.8	43.4
4/11	0723	0745	1736	1745	75.7	75.7	59.6	59.4
5/13	0808	0800	1903	1915	93.1	95.2	76.4	78.5
7/22	0813	0815	1910	1900	91.6	89.7	74.6	73.3
10/15	0853	0900	1744	1745	81.2	79.7	66.0	64.3
12/19	0841	0900	1612	1615	68.9	69.2	53.4	54.9

Table 4-2

A Comparison of Turbine On-line and Off-line Times During Several Intermittently Cloudy Weather Days

Day Number	Solar One Data		SOLERGY Prediction			
			Three Minute Data		Fifteen Minute Data	
	Turbine On-line Time	Turbine Off-line Time	Turbine On-line Time	Turbine Off-line Time	Turbine On-line Time	Turbine Off-line Time
8	0945	1023	0848 1206	1021 1336	0900	1600
26	DID NOT OPERATE		1048 1157	1109 1215	1045	1345
123	1344	1833	0827 1051	0954 1824	0845	1845
142	1119 1615	1606 1848	0824 1009 1654	0857 1600 1833	0900	1900
242	0839	1227	0821 1557	1509 1830	0845	1845

Table 4-3

Results From Comparing 153 Days in 1985

	SOLERGY	Solar One	
Gross Turbine Energy Production (MWh_e)	9070.	8313.	+9.1%
Total Parasitic Consumption (MWh_e)	2161.	2174.	-0.6%
Net Plant Energy Production (MWh_e)	6909.	6140.	+12.0%

Chapter 5

Performance Comparison for a Full Year

The final validation of SOLERGY was a comparison of the plant performance for one full year. Again, the comparison was for calendar year 1985. To perform an annual simulation, SOLERGY requires an insolation record at 15-minute intervals for a full year. One difficulty we encountered was missing data in the insolation record. There were over 100 days for which at least part of the necessary insolation record was missing; the missing data included most of the months of February and June. Missing data generally correspond to periods the plant did not operate. Holes in the insolation record were filled with days having similar total insolation from either the 1984 insolation file or similar days in the 1985 record (Baker and Faas 1986).

We used the actual plant records for forced and scheduled outages as input to the code along with the days that the storage system was charged. We had to make one simplifying assumption because SOLERGY considers plant outages, but only for full days. Since the duration of plant outages at Solar One is often less than a full day, we combined days with partial outages into an equivalent number of full days. Partial days during which thermal storage was charged were also combined into equivalent full days. There is some error associated with this simplification since the insolation during the actual outage period may differ from that used in our calculations.

Figure 5-1 summarizes the annual energy flows calculated by SOLERGY for 1985. The left side of the figure shows the calculated efficiencies for each of the major plant systems. On the right side are the energy losses for each system. In a recent report, Radosevich (1988) reported system efficiencies for the three years of Solar One's power production phase (August 1984 to July 1987); his efficiencies are based either on direct measurements or on detailed calculations. Table 5-1 compares Radosevich's annual efficiencies for the first and second years of power production (August 1984 through July 1986) with the values calculated with SOLERGY for calendar year 1985. The SOLERGY-calculated values should be roughly the average of the first and second years of the power production phase. The agreement is very good for most of the plant's systems. Slight differences in annual efficiencies are in part because SOLERGY uses a different definition for a system than that used by Radosevich. The difference in receiver absorptance is because the receiver was repainted in December 1985 which increased absorptance from 0.88 to 0.96 (see Section 3.2). The calculated value for receiver efficiency also agrees well with the value reported by Baker and Atwood (1985) using data collected during 1983.

Table 5-2 compares the actual performance of Solar One in 1985 with that predicted by SOLERGY. The overall performance predicted by SOLERGY agrees reasonably well with the actual performance. Despite the large amount of simulated insolation data, the total insolation in the file used as input to SOLERGY agrees with the actual observation. The SOLERGY simulation produces 16% more gross and net energy. In Chapter 4, we estimate that SOLERGY overpredicts annual energy by about 12% because it does not account for decisions made by the operators and because it uses 15-minute average insolation data. The additional 4% overprediction seen in the annual calculations is due to our combining of partial outage days into full outage days. Figure 5-2 shows the simulated annual performance for each of the plant systems in waterfall form. Plant outages account for a 20% loss in the incident insolation. Leaks in the receiver tubes were the major cause of unscheduled plant outages (Radosevich 1988). Plant parasitics amount to 32% (68% efficient) of the gross energy produced; if the additional efficiency factor of 90%, corresponding to the use of the thermal storage system, is included, the combined parasitics total 39% of the gross annual energy.

One use for a code such as SOLERGY is to evaluate alternative plant designs or operational strategies. To demonstrate this capability, we used SOLERGY to determine the efficacy of charging Solar One's thermal storage system to provide auxiliary steam instead of generating auxiliary steam with the electric boiler. Only one change was necessary to perform this calculation; a plant parasitic-power model that reflected the use of the auxiliary boiler was needed. Solar One's storage system was damaged in August 1986 and has not been used since; in its place, auxiliary steam has been provided by an electric boiler. We obtained 103 days of daily plant performance data from 1987 and repeated the simple regression analyses described in Section 3.3. The revised plant parasitic models are shown in Table 5-3. The standard errors in the regression fits are on the order of 10%. The standard deviation of the shutdown value is 40 kW. The use of the auxiliary boiler to provide service steam is reflected in the nearly 100 kW increase in the offline parasitic power.

Using the revised parasitic model, we repeated the annual calculations assuming the turbine had been operated on the days in 1985 when thermal storage was charged. All other assumptions and input data were unchanged. The theoretical performance without the storage system is compared in Table 5-4 with the SOLERGY-predicted plant performance from Table 5-2. The slight reduction in shutdown parasitics reflects the successful efforts of SCE to reduce the parasitic load when the plant is not in operation. Though the total parasitics would have been 8% greater if the thermal storage system had not been used, an additional 1200 MWh net energy could have been produced - equal to an 11% increase in annual energy efficiency. Thus, it was inefficient to use Solar One's thermal storage system solely as a source of auxiliary steam. Of course, using thermal storage to act as a buffer between the receiver and the turbine or to shift electrical generation to high-value periods have been shown to be cost effective (Falcone 1986). The use of thermal storage in this manner was successfully demonstrated at Solar One (Faas et al. 1986).

```
1985 SOLAR ONE  INCLUDES CHARGING STORAGE

     PLANT SUMMARY - DAYS   1 TO 365 YEAR 1985

  EFFICIENCY          (MWHRS)              ENERGY LOSSES
              I--------------------------I   (MWHRS)
              I     TOTAL INSOLATION     I
              I       178380.47          I
              I--------------------------I
                          V
              I--------------------------I OUTAGE LOSSES
     0.804    I     AVAILABLE ENERGY     I   16060.49 FORCED
              I       140147.67          I   18814.01 SCHEDULED
     0.977    I--------------------------I    3338.30 HELIOSTATS
                          V
              I--------------------------I FIELD LOSSES
     0.818    I    REDIRECTED ENERGY     I   25504.58 REFLECTIVITY LOSS
     0.698    I        79996.11          I   34646.99 COSINE, SHADOWING, BLOCKING,
              I--------------------------I               SPILLAGE, TRANSMISION AND OPERATION LIMITS
                          V
              I--------------------------I STORAGE FULL OR  CHARGING HX IN STARTUP
     0.998    I  RCVR INCIDENT ENERGY    I      155.63 DEFOCUS HELIOSTATS (YSUPTR)
              I        79840.47          I
              I--------------------------I
                          V
              I--------------------------I RECEIVER LOSSES
              I        RECEIVER          I    2533.76 RCVR MIN FLOW (YPLRMF)
              I     ABSORBED ENERGY      I       0.00 SURPLUS ENERGY TO  RECEIVER, PTR>RS, DEFOCUS HELIOSTATS (YSPTR)
     0.687    I                          I    9805.35 ABSORPTANCE
              I        54861.16          I   11586.34 THERMAL LOSS (RADIATION AND CONVECTION)
              I--------------------------I    1053.85 RCVR STARTUP (YRSTRT)
                          V
              I--------------------------I PIPING LOSSES
     0.995    I    ENERGY TRANSPORT      I      270.16
              I       54591.00           I
              I--------------------------I
                          V
                          V
              I--------------------------I  ENERGY TO STORAGE
              I        ENERGY TO         I    5279.51 (INCLUDES STARTUP)
     0.903    I         TURBINE          I
              I        49310.24          I
              I--------------------------I
                          V
                          V
              I--------------------------I EPGS LOSSES
              I                          I    2810.13 STARTUP
     0.301    I      GROSS ENERGY        I     631.86 TURBINE SYNC LOSS (YTSTRT)
              I        14746.75          I   31120.28 RANKINE LOSS (APPROX)
              I--------------------------I       1.22 OTHER
                          V
              I--------------------------I AUXILIARY ENERGY
              I       NET ENERGY         I    1592.65 OPERATIONAL PARASITICS
     0.681    I         OUTPUT           I    2134.62 OFFLINE PARASITICS
              I                          I     205.91 CHARGING STORAGE
              I      10048.16 MWHe       I     765.40 SHUTDOWN PARASITICS
              I--------------------------I (  4698.58 TOTAL AUX ENERGY (YPARN))
     0.057

     0.057 OVERALL PLANT EFFICIENCY (TOTAL NET ELECTRICITY/TOTAL DNI ON FIELD
```

Figure 5-1. The Summary of Annual Energy Flows as Calculated by SOLERGY for Calendar Year 1985. This is a Reproduction of the Output Produced by SOLERGY - Not all the Significant Digits are Significant.

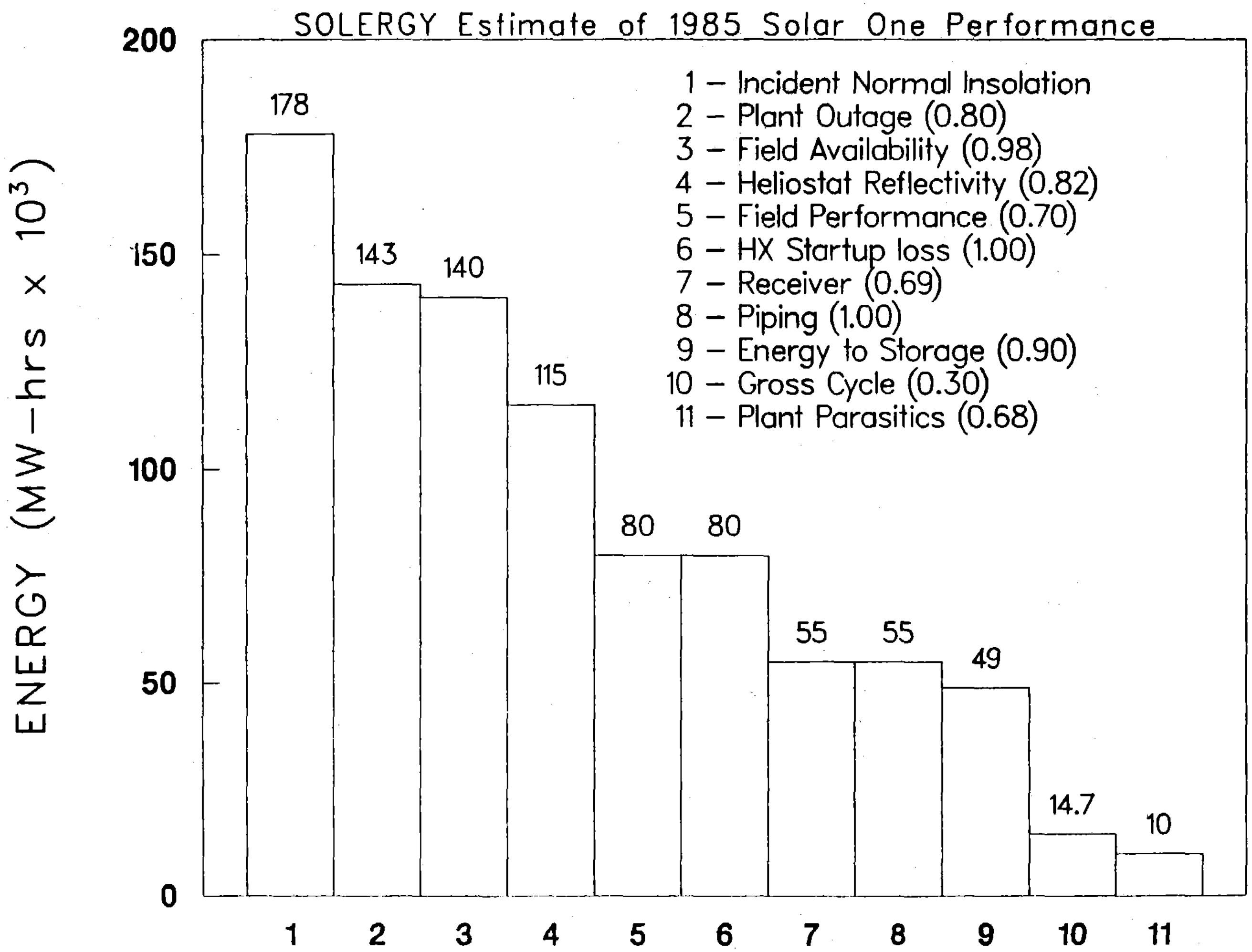


Figure 5-2. Waterfall Diagram for Solar One During 1985 Calculated Using SOLERGY.

Table 5-1

Comparison of Annual System Efficiencies Estimated by Radosevich (1988) for The First and Second Years of the Power Production Phase (August 1984 to July 1986) with SOLERGY Predictions for CY 1985

System	First Year (Radosevich 1988)	Second Year (Radosevich 1988)	SOLERGY 1985
Plant Availability	0.800	0.830	0.80
Heliostat Availability	0.967	0.982	0.98
Field Performance			
Cosine	0.786	0.786	n/c
Blocking & Shadowing	0.967	0.967	n/c
Atmospheric Attention	0.966	0.966	n/c
Spillage	0.979	0.979	n/c
Total	0.717	0.717	0.70
Heliostat Reflectance	0.808	0.840	0.82
Field Operation	0.900	0.900	n/c
Receiver Operation	0.840	0.840	0.97
Receiver Startup	n/c	n/c	0.98
Receiver Absorptance	0.880	0.910	0.87
Radiation and Convection	0.803	0.812	0.83
Piping	0.996	0.996	0.995
Energy to Storage	0.886	0.909	0.90
Startup of Storage	n/c	n/c	0.998
Turbine Startup	n/c	n/c	0.93
Gross Conversion	0.328	0.335	0.32
Plant parasitics	0.600	0.676	0.68
Overall	0.042	0.056	0.056

n/c means not calculated

Table 5-2

Comparison of Actual Solar One Performance in 1985
With that Predicted using SOLERGY

	Barstow	Solergy	Difference
Total Insolation (GWh)	178	178	0
Hours of Turbine Operation	1726	1904	+10%
Gross Energy (MWh)	13363	14747	+10%
Operating Parasitics (MWh)	1460	1592	+9%
Total Parasitics (MWH)	4737	4698	-1%
Net Energy (MWH)	8625	10048	+16%
Annual Energy Efficiency	4.8%	5.6%	+16%

Table 5-3

Parasitic Power Models Developed by Regression Fit to Solar One Data After the Storage Tank Fire

Plant State	Parasitic Power
Shut Down	350 kW (for 24 hours)
Turbine Offline	560 kW
Turbine Online	11% of gross daily energy

Table 5-4

Comparison of SOLERGY-Predicted Theoretical Performance of Solar One With and Without the Thermal Storage System Providing Auxiliary Steam

	SOLERGY Prediction for 1985		
	Without Storage	With Storage	Difference
Hours of Turbine Operation	2114	1904	+10%
Gross Energy (MWH)	16349	14747	+10%
Offline Parasitics (MWH)	2547	2134	+16%
Operating Parasitics (MWH)	1814	1592	+12%
Shutdown Parasitics (MWH)	722	765	-6%
Total Parasitics (MWH)	5085	4698	+8%
Net Energy (MWH)	11265	10048	+11%
Annual Energy Efficiency	6.3%	5.6%	+11%

Chapter 6

Conclusions and Summary

In this chapter we summarize the conclusions of the SOLERGY validation effort, describe a simple sensitivity study of three key parameters, and present recommendations for possible improvements to the code and for its future application.

The major conclusions of this study include:

- SOLERGY reliably estimates the annual energy production of a solar central receiver power plant. The annual performance has been validated against actual plant data and against previously published evaluations.

- Turbine startup times for Solar One are more accurately predicted if instantaneous insolation data at 3-minute intervals are used instead of recordings of 15-minute averaged insolation.

- SOLERGY overpredicts plant performance on partly cloudy days due to the use of 15-minute average insolation and because it does not account for decisions by the operator as to whether or not to start up the plant. We estimate this only leads to a 12% overprediction in annual energy.

- Use of the thermal storage system at Solar One in 1985 only to provide auxiliary steam was not cost effective; we estimate that the net energy for 1985 would have been 11% greater if the turbine had been operated instead of charging storage. However, thermal storage has been shown elsewhere (Falcone 1986) to be cost effective as a buffer between the receiver and turbine or to shift power generation.

6.1 Discussion

For the first time a method exists to reliably estimate the annual energy production of a solar central receiver power plant. The SOLERGY computer code is a valuable tool for optimizing plant designs and operational strategies to maximize the value of the energy produced. We have described a validation of SOLERGY using performance data from the Solar One power plant. On clear days, we find SOLERGY gives excellent agreement with the actual performance of Solar One. There is also good agreement on days with a sun-obscuring cloud front. SOLERGY tends to overpredict energy on partly cloudy days; however, these days contribute only a small part to the total annual energy. Two main reasons for the poor agreement on partly-cloudy days are SOLERGY's use of 15-minute average insolation data and SOLERGY's failure to account for the actions of the plant operators in response to intermittent clouds. SOLERGY calculations using insolation data at 3-minute intervals gave slightly better agreement; however, the additional computational expense is too large to justify using 3-minute data. Thus, we conclude that 15-minute time steps should continue to be used.

We suggest exploring two possible changes to improve the code's predictions on partly cloudy days. First, instead of averaging the observations of insolation over a 15-minute time step, the lowest observed insolation value should be applied to the full time step. Thus, short-duration dips in insolation caused by a passing cloud as shown in Figure 4-7 would not be obscured by averaging. The second is to try to incorporate possible actions taken by an operator in deciding if the future insolation will be sufficient to justify operating the receiver. For example, looking ahead in the insolation record would give the same effect as the operator looking out a window or consulting a weather forecast. One disadvantage to this is that, unlike reality, there would be no uncertainty in such an insolation "prediction."

Overall we conclude that SOLERGY gives good predictions of total annual energy. The systematic overprediction of about 16% we observed in net energy is in part (12%) due to not incorporating the decisions of the plant operator as to whether or not to operate the plant in partly cloudy conditions. We estimate that the use of an equivalent number of full days to account for days of partial plant outage or storage charging resulted in a 4% overprediction. We feel the key to obtaining good predictions from SOLERGY is the use of good data as input to the code. The sensitivity of predicted annual energy to uncertainties in three key parameters is described in the next section. The failure of previous efforts to accurately predict the annual performance of Solar One can be tied to a lack of knowledge of plant operating data and parameters. Development of these data for a plant on the drawing board is not an easy task, but it is crucial to the credibility of the energy predictions. The authors appreciate the wealth of data that has been collected at Solar One; without these data, studies such as ours would not be possible. Development and distribution of good input data for use with current plant designs should be a priority in the central-receiver program. Such a data base would be a valuable resource for the industry.

One use for SOLERGY will be the evaluation of alternative design or operation strategies for solar central receiver power plants. For example, as part of this study we examined the efficacy of charging Solar One's thermal storage system every 10 days to provide the plant with auxiliary steam. Using SOLERGY we concluded that use of the thermal storage system at Solar One only to provide auxiliary steam was not cost effective; net energy for 1985 would have been 11% greater if the turbine had been operated instead of charging storage. Thermal storage has been shown to be cost effective as a buffer between the receiver and turbine or to shift power generation (Falcone 1986).

6.2 Sensitivity Analysis

The SOLERGY predictions presented thus far are based on the assumptions and parameters described in Chapter 3. These calculations represent our "base case" analysis. In addition, we performed a sensitivity analysis to determine how these predictions might change if other plausible assumptions were made. To keep the study tractable, we used engineering judgement to identify the parameters in Chapter 3 that are the most uncertain and known to have a strong influence on the results. There were three groups of parameters that met these criteria: 1) the direct-normal-insolation file, 2) the turbine's thermal efficiency parameters, and 3) parameters related to convective losses from the receiver. We first describe the uncertainty associated with each of these groups of parameters. This is followed by a discussion of the impact of uncertainty in these parameters on predicted annual energy.

Uncertainty in the Direct-Normal-Insolation File

Since operation of Solar One began in 1982, the amount of direct normal insolation measured at the site has been consistently less than the long-term average values used to size the plant (Radosevich 1988). The decrease in observed insolation is in part due to the effects of Mexican volcanos, nearby agricultural activity, and increased air pollution. Sandia recently inspected the insolation monitoring equipment at Solar One and concluded that the normal incidence pyroheliometer (NIP) used at the plant underestimates insolation (Menicucci 1988a). Insolation measurements may be low by as much as 15%. A comparison of daily-average, direct-normal insolation for five years at Solar One (Radosevich 1985, 1988 and Kolb 1988) with other nearby measurements is shown in Figure 6-1. The nearby data include measurements from: the revised 25-year SOLMET/ERSATZ data for Daggett* (Menicucci 1988b), measurements by The West Associates at Barstow and Victorville, CA (Yinger 1982), data prepared by Randall using the measurements of West Associates (Randall 1978), measurements from the Lugo photovoltaic plant near Victorville (Menicucci 1988c), and measurements from Solar One. The 1985 insolation record from Solar One used in the present study is below the long-term average by about 11%. To assess the effect of uncertainty in insolation data on

* SOLMET/ERSATZ data are estimates based on hourly observations of cloud cover at the Daggett airport near Solar One (Menicucci 1988b).

predicted annual energy, we repeated our SOLERGY calculations with the insolation during each time step arbitrarily increased by 11%.

Uncertainty in the Turbine's Heat-Rate Curve

The turbine's heat-rate curve for Solar One is presented in Figure 6-2 (McDonnell Douglas Corporation 1984). The circles and triangles represent actual measurements for steam temperatures of approximately 945 degrees F and 745 degrees F, respectively. Our base case analysis employed a heat-rate curve defined by the solid hexagons. Due to the scatter in the measured data, our base case curve was believed to be plausible. The curve we chose tends to minimize heat rate (maximizes conversion efficiency). From the data in Figure 6-2, it is clear that other plausible curves can be drawn. For example, a curve that maximizes heat rate (minimizes conversion efficiency) is represented by the solid rectangles.

In our sensitivity analysis we used two heat-rate curves represented by the solid hexagons (base case) and the solid rectangles (high heat rate).

Uncertainty in the Convective Losses From the Receiver

As discussed in Chapter 3, others have extensively evaluated the thermal losses from Solar One's receiver. Displayed in Figure 6-3 are the convective losses, and associated uncertainty interval, for the Solar One receiver (Siebers and Kraabel 1984). The highest curve (A) represents the total thermal losses employed in our base case analysis. Our curve is higher because it includes convective and radiative losses; the convective portion of curve A is curve C and the radiative part is the difference between the two curves.

From Figure 6-3, it is clear that there is considerable uncertainty in Siebers and Kraabel's convective loss estimates. In our sensitivity analysis, we used three convective loss curves. High convective losses (HI) were characterized by curve B, the base case by curve C, and low losses by D (LO). In the analysis we assumed that uncertainties associated with convective losses were much greater than for radiative losses and therefore ignored the latter uncertainties.

Results of the Sensitivity Analysis

Table 6-1 shows the variation from the base case in SOLERGY-predicted annual gross energy for eight different combinations of the three uncertain parameters. The predicted annual energies range from near agreement with the actual up to a 29% overprediction. In cases 2, 3, 4, and 6 we have changed only a single parameter from the base case.

Clearly, the single most important parameter is the direct normal insolation. Figure 6-4 shows scatter plots of predicted and actual daily gross electrical energy for the base case and eight cases from our sensitivity study. The base case and cases 7 and 8 all show a reasonably unbiased prediction of daily gross energy. Since SOLERGY uses fairly simple models for each plant component, a systematic error in one parameter can be cancelled by an error in another parameter. Moreover, there are few synergistic effects between the models for individual components. In our study for 1985, it is likely that the insolation data used in the base case are too low; however, reasonable agreement with actual data can still be obtained using values for other parameters that are within uncertainty bounds.

This simple sensitivity analysis demonstrates the importance of obtaining correct data to be used as input to SOLERGY. A similar estimate of annual energy can be obtained from an infinite number of plausible input values. Therefore, we recommend that when using the code to predict annual energy, users perform sensitivity studies on all parameters to help understand the magnitude of uncertainty in annual energy predictions.

6.3 Summary and Recommendations

The goal of DOE's development program is to improve the reliability and performance while reducing the cost of solar central receiver power plants. DOE's long-term goal for overall plant efficiency is 22% (USDOE 1986). Recent studies indicate that current central receiver technology using molten salt or sodium as the heat-transfer fluid would provide an overall efficiency of only 15% (Falcone 1986; Hillesland and Weber 1988).

SOLERGY can help in achieving the long-term goals. It can be used to develop plant-operation strategies that will maximize a plant's net revenue. For example, the size of a plant's thermal storage system determines the extent that power generation can be shifted to periods of highest energy value. Using SOLERGY, the optimal storage capacity can be found considering a utility's time-of-day energy value. Such a study was undertaken as part of the recent Utility Study of Central Receiver Plants (Hillesland and Weber 1988).

Another potential use for a code such as SOLERGY is to identify where improvements in the performance of individual components are needed and to evaluate the efficacy of improved component designs. For example, Table 6-2 shows the SOLERGY-calculated efficiencies of Solar One plant components in 1985 versus the efficiencies in DOE's long-term goals for central receivers. The goals for field performance (cosine, spillage, shadowing, etc.) and the transport system have been met at Solar One. However, because this is only a pilot plant with a fairly small heliostat field and large receiver, its field performance is somewhat better than would be expected from a commercial-scale plant (100 MWe or more).

There are a number of possible design and operation approaches that could be taken to improve overall efficiency. For example, the performance of the heliostats at Solar One could be increased by using mirrors with higher reflectance such as thin, low-iron glass (Radosevich 1988). Reflectivity can also be increased by cleaning the heliostats on a regular basis. Since heliostat cleaning was implemented on a regular basis at Solar One, the average reflectivity has been increased to 88% (Radosevich 1987). Plant availability is a concern at Solar One. Future plants will use a molten salt heat-transfer fluid in the receiver that should be more reliable than the water/steam receiver used at Solar One. Receivers using molten salt will have a higher thermal efficiency because they use higher average fluxes and thus can be smaller. The smaller size reduces the fraction of energy lost due to radiation and convection. In addition, the current receiver absorptance is above 94% (Radosevich 1987) compared to an average of 87% in 1985, indicating that much has been learned at Solar One about the application of absorptive coatings. The development of a falling-film, direct-absorption receiver will further increase the receiver's performance by reducing startup losses. The turbine's efficiency at Solar One, which includes losses from startup, is close to the expected gross-cycle efficiency of 33% (Radosevich 1987). Increased turbine efficiency would follow directly from an increased plant size, since larger turbines with the capability for reheat have efficiencies near 40%. In addition, the use of thermal energy storage using molten salt decouples the receiver from the turbine, reducing energy losses during turbine startup and eliminating the need for multiple startups in response to cloud transients. Finally, increased plant size would significantly increase the efficiency of a plant's auxiliary systems and reduce the portion of energy output taken by parasitics.

We will be exploring in detail each of these areas as part of Sandia's Annual Energy Improvement Study. Based on the operation of Solar One, we see three key areas, in addition to the need for an improved receiver design, in which improved performance is crucial to meeting the long-term goals. They are reliability, parasitics, and cleanliness of the heliostats' mirrors. The first task in the Annual Energy Improvement Study was the validation of SOLERGY, which is described in this report. The remaining tasks in the study are the following:

1) SOLERGY will be used to examine the sensitivity of Solar One's performance to changes in design or operation of individual plant components. The changes in design will

be based on current central receiver technology.

2) A conceptual design of a central receiver plant will be developed based on current technology. The design will be studied with SOLERGY to identify issues of the plant's design or operation that could increase annual energy production.

3) A cost/benefit analysis will be performed to determine the relative value of the issues identified in Task 2.

The study will help direct current research and development efforts by identifying where improvements in current technology are necessary to approach DOE's long-term goal of 22% annual efficiency. SOLERGY will be a key tool in the study. It can be used to assess the value of changing a plant's maintenance schedule. For example, the appropriate frequency for cleaning each heliostat can be easily evaluated. SOLERGY's energy predictions for each cleaning frequency, combined with an estimate of the cost of cleaning, provides a direct assesment of the value of cleaning heliostats. SOLERGY can also be used to evaluate alternative plant components. For example, the performance of a salt-in-tubes receiver can be compared with that of a falling-film, direct-absorption receiver (Anderson et al. 1987). SOLERGY can be used to explore ways to improve reliability. For example, the value of having redundant plant systems can be determined by using the data base on component reliability from Solar One and elsewhere to estimate failure frequencies. The value of a redundant system can be found by comparing the cost of the system with the SOLERGY-predicted value of the increased energy production from avoiding plant outages. The remaining tasks of the Annual Energy Improvement Study will be documented in subsequent reports.

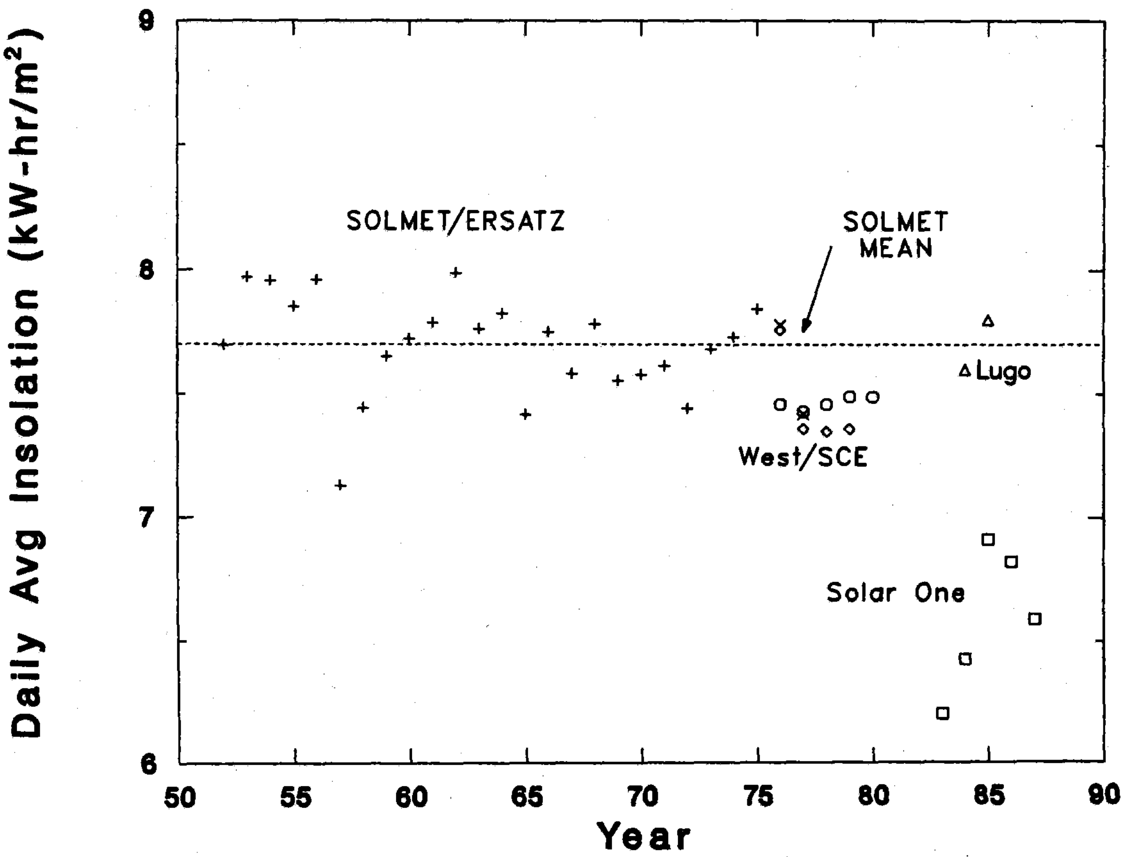


Figure 6-1. Thirty years of daily-average insolation data measured at sites near Solar One. Improved SOLMET data are shown with a +; the West Associates data for Barstow are circles and diamonds for Victorville; Randall's reevaluation of West Associates' Barstow data are shown with an X; Lugo PV data with triangles; and Solar One with squares. The average of the 5 years of Solar One data is nearly 15% below the average of the other measurements.

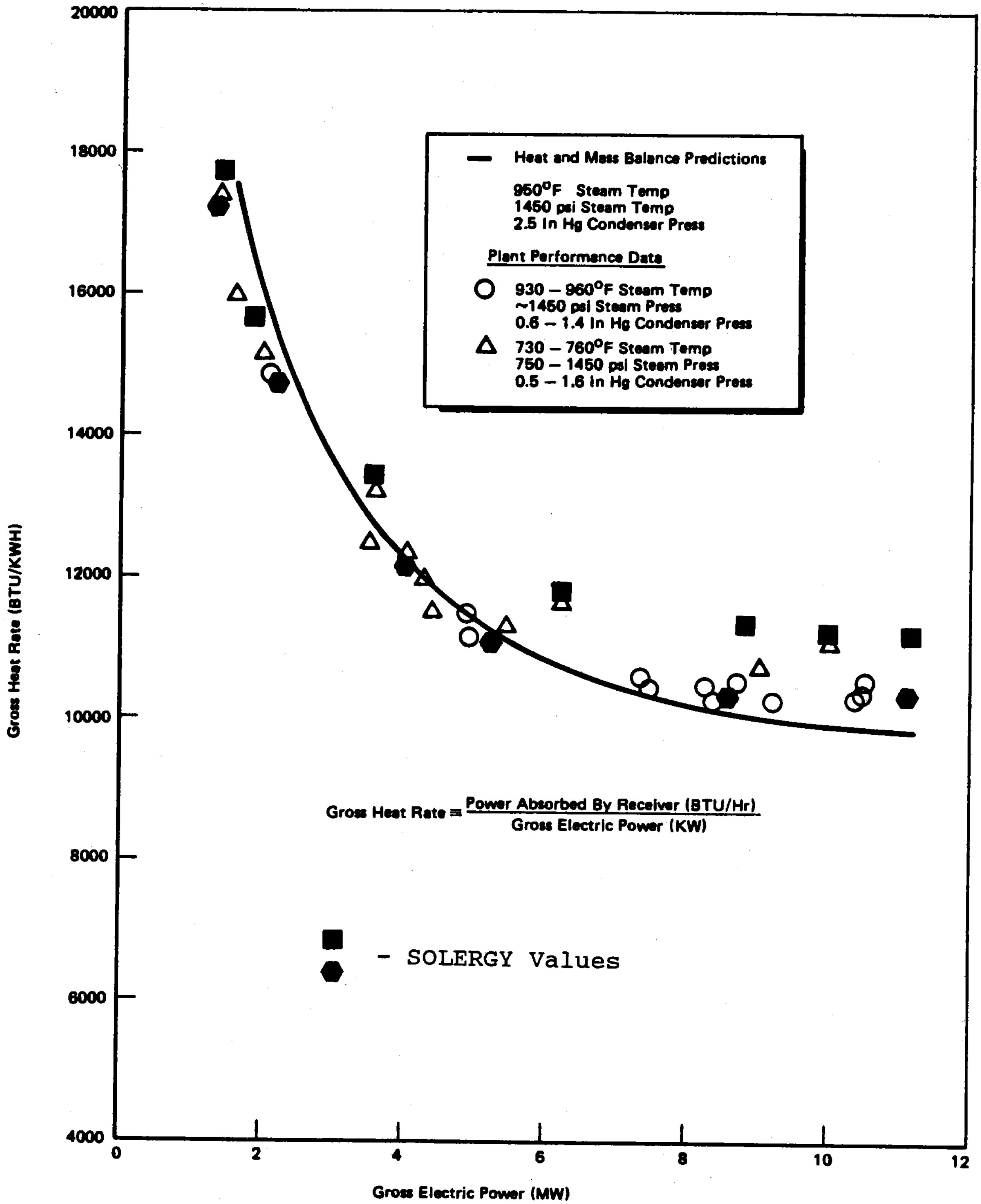


Figure 6-2. Gross Heat-Rate for the Solar One Turbine-Generator (data from McDonnell Douglas Corporation 1984). Our base case is shown with hexagons and the high heat-rate case with squares.

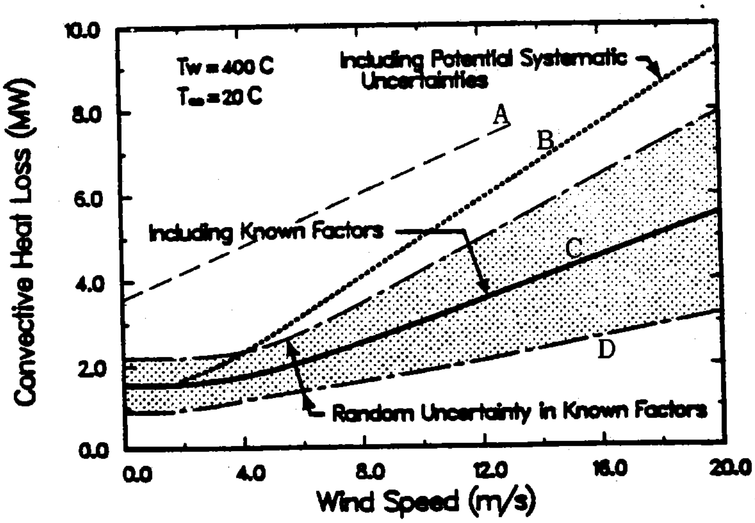
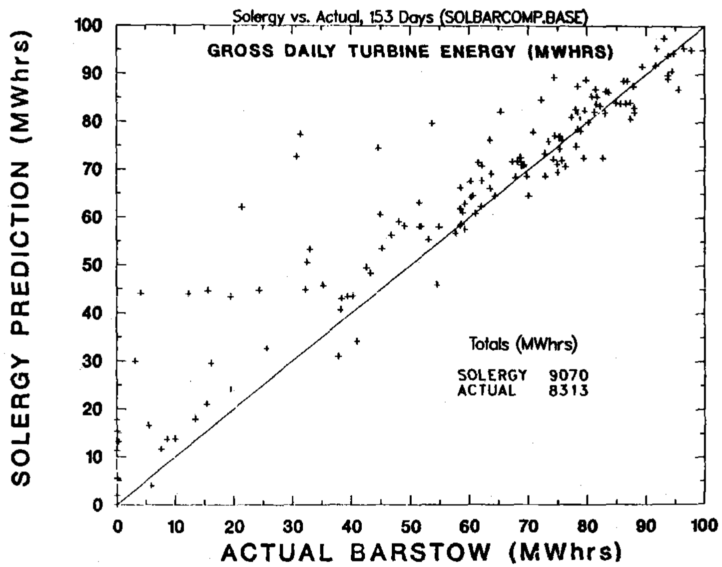
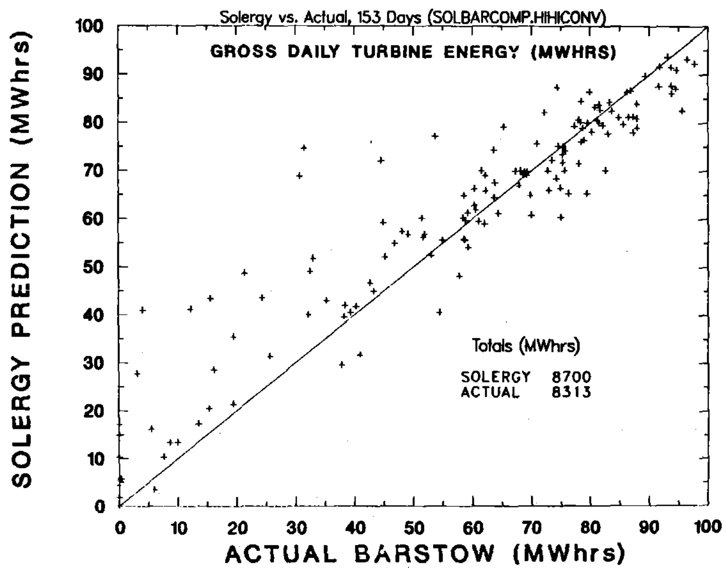


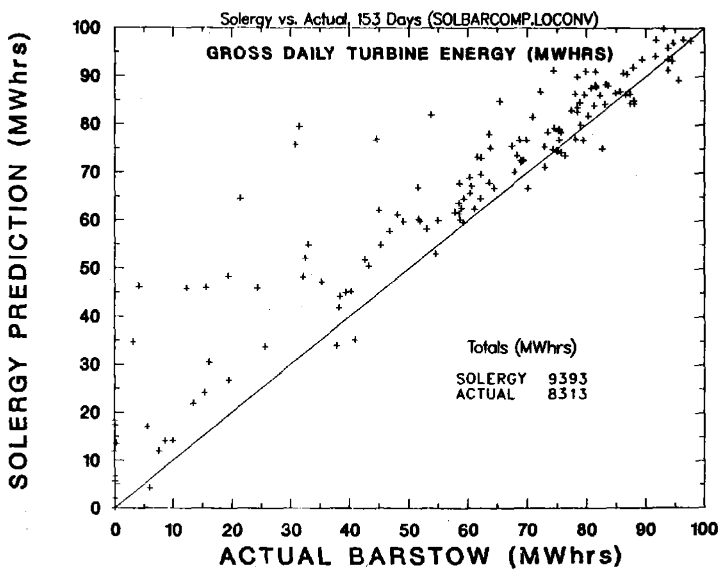
Figure 6-3. Convective Losses from the Solar One Receiver (Siebers and Kraabel 1984). Total thermal losses from both convection and radiation for the base case are represented by curve A. The base case thermal losses are curve C. Curves B and D are, respectively, the high and low cases in our sensitivity study.



Base Case

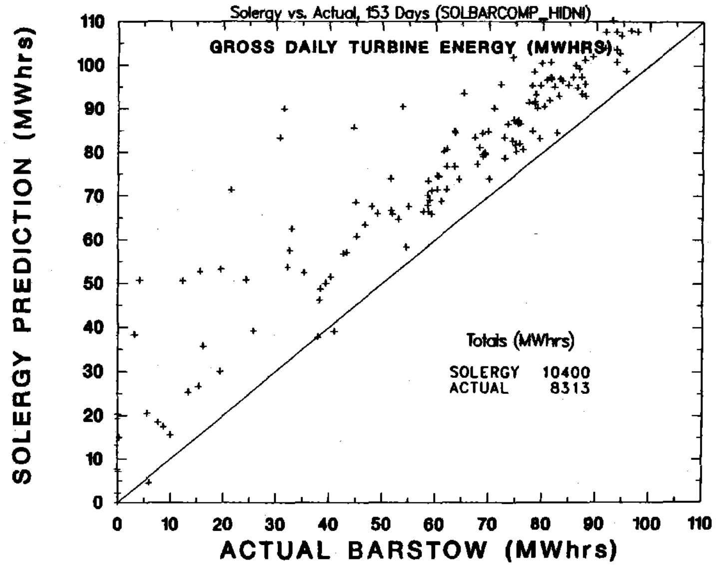


Case 2

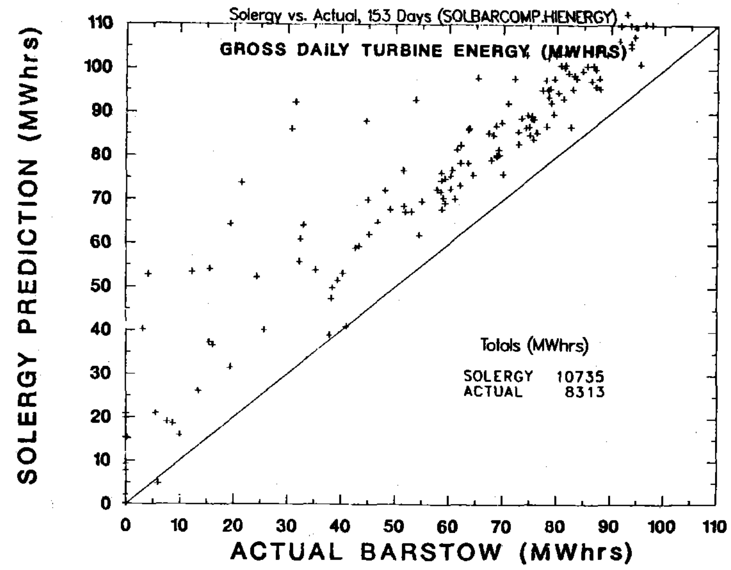


Case 3

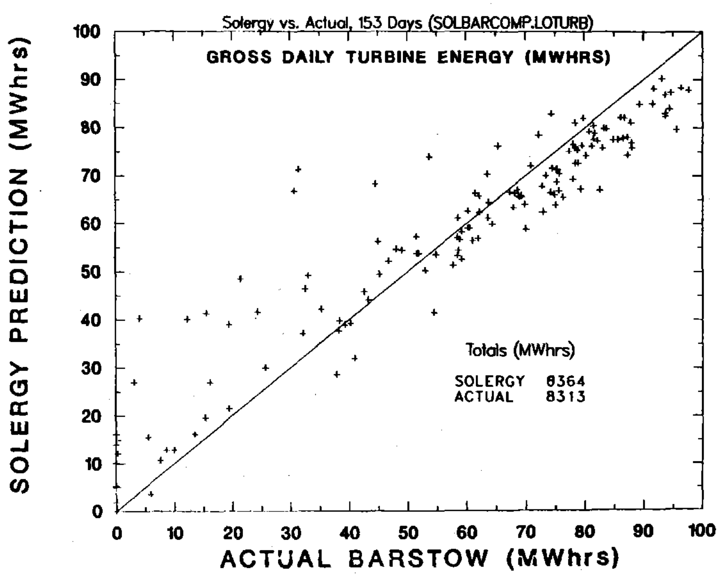
Figure 6-4. Scatter plots comparing actual and SOLERGY-predicted daily gross energy production for the base case and 8 cases from our sensitivity study. Only predictions for the 153 days described in Chapter 4 are presented.



Case 4

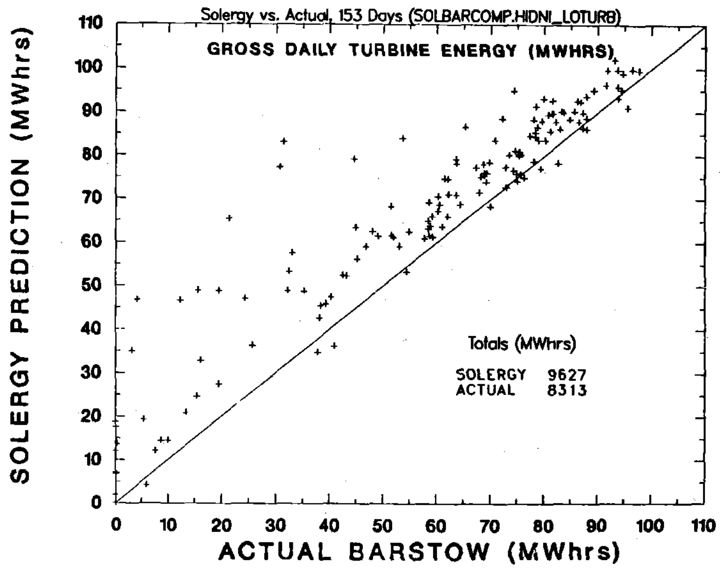


Case 5

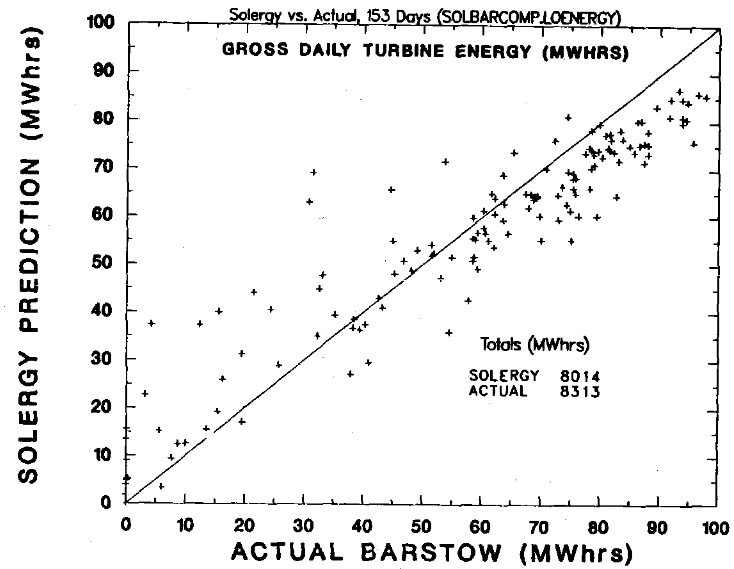


Case 6

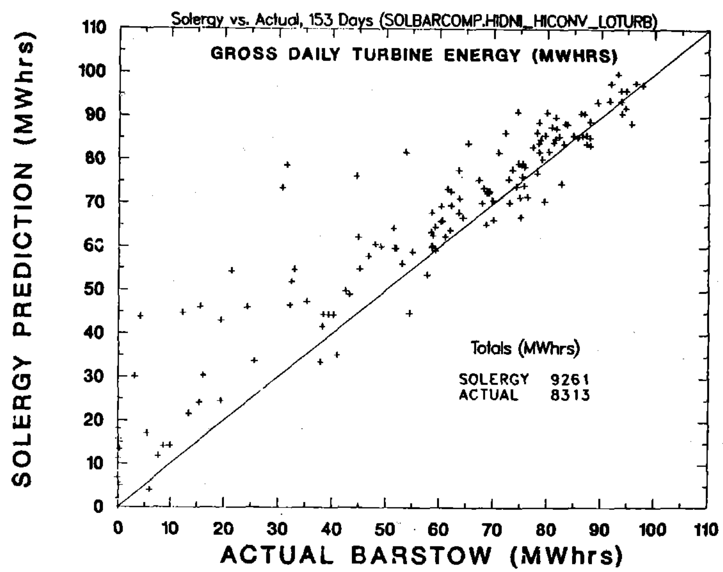
Figure 6-4. Continued



Case 7



Case 9



Case 8

Figure 6-4. Continued

Table 6-1
Results of the Sensitivity Analysis*

Case	Turbine Heat Rate		Convective Losses			DNI		Gross Daily Energy	
	BC	Hi	Hi	BC	Lo	Hi	BC	Change From Base Case	Difference From Actual
Base	X			X			X	-	9.1%
2	X		X				X	-4.1%	4.6%
3	X				X		X	3.6%	13.0%
4	X			X		X		15%	25.1%
5	X				X	X		18%	29.1%
6		X		X			X	-8.0%	0.6%
7		X		X		X		6.0%	15.8%
8		X	X			X		2.0%	11.4%
9		X	X				X	-12%	-3.6%

BC refers to Base Case, DNI stands for direct normal insolation

Table 6-2
Annual Efficiencies of Solar One Plant Components
in 1985 versus DOE's Long-Term Goals (U.S. D.O.E. 1986).

	SOLERGY (1985)	DOE Long-Term Goal
Plant Availability	0.80	0.94 *
Heliostats	0.80	0.92
Field	0.70	0.68 *
Receiver	0.69	0.90
Transport	0.995	0.99
Turbine	0.30	0.41 *
Auxiliaries (with storage)	0.61	0.95 *
Product	0.056	0.22

* inferred from information in the plan

Appendix A

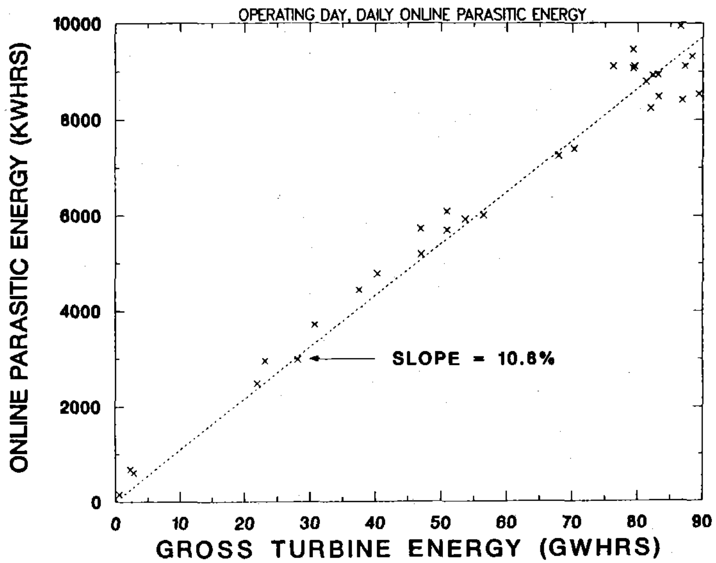
Regression Fit for Daily Parasitic Energy Use

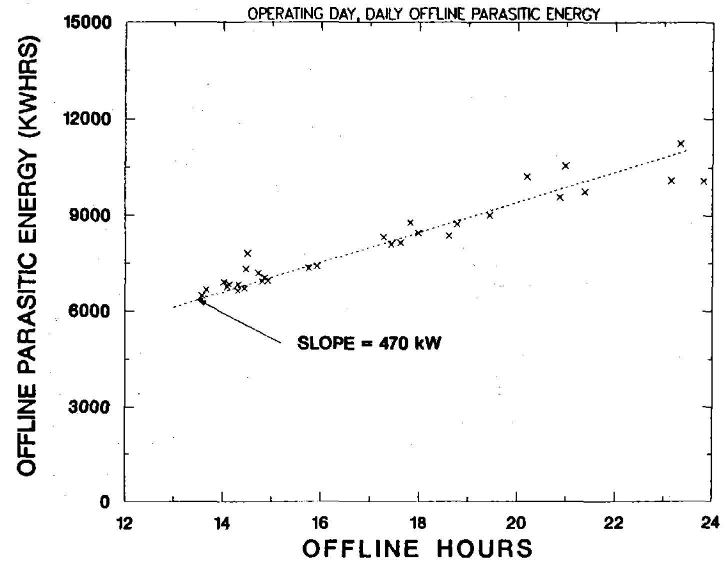
Models for daily parasitic energy use were developed using simple linear regression models. The models were of the form: Y = m * X where X is a measured (independent) variable, Y is the daily parasitic energy use (the dependent variable), and m is the desired regression coefficient. Regression models without a Y-intercept were used because the regression fits should pass through the origin. Regression models were developed for three plant states: turbine offline, online and charging storage. Table A-1 lists the independent and dependent variables for the three plant states fit with regression models. As described in Section 3.3, two separate parasitic models were developed for online operation. The fourth plant state, shutdown, was not fit with a regression model; rather, a simple average of parasitic energy use was calculated for days the plant did not operate. We did not try to differentiate days the plant was shut down due to weather outages, forced outages, or scheduled outages. The data for the 77 selected days (11 weeks) used in the regression analyses are given in Table A-2; a full range of operating conditions is represented. Figure A-1 shows the three regression models plotted against the 77 actual days.

Table A-1

Independent and Dependent Variables For the Three Plant States Fit with Regression Models

Plant State	Dependent Variable (kWh)	Independent Variable	Regression Coefficient
Turbine Offline	Offline Parasitic Energy	Hours Offline	Parasitic Power (kW)
Charging Storage	Charging Parasitic Energy	Hours Charging	Parasitic Power (kW)
Turbine Online	Online Parasitic Energy	Hours Online	Parasitic Power (kw)
same	Online Parasitic Energy	Gross Power Produced (kWh)	Fraction of Gross Power





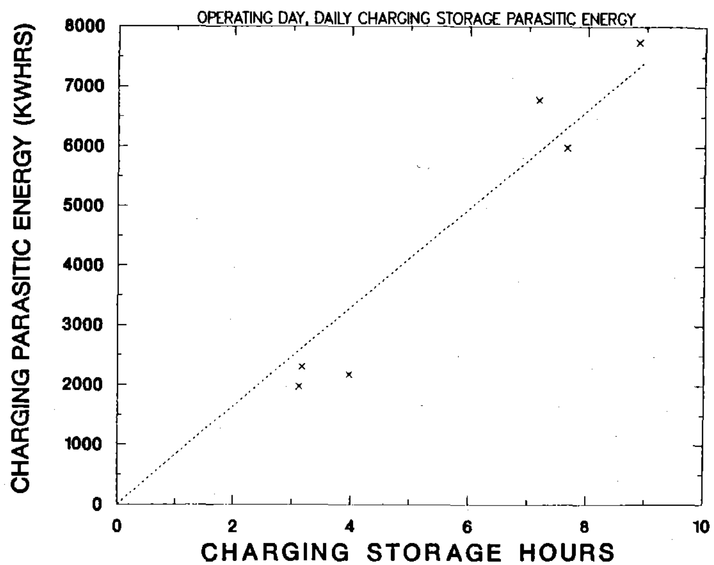


Figure A-1. Regression models (dotted lines) for online, offline, and charging storage parasitics versus actual data for 77 days (shown with x's).

Table A-2.
77 Days of Data Used in the Regression Analyses

Daily Offline Parasitic Energy (kWh)	Daily Charging Storage Hours	Daily Online Hours	Daily Total Parasitic Energy (kWh)	Daily Gross Energy (kWh)
8/7/84				
8137.	0.	6.38	14053.	53696.
7185.	0.	9.28	15974.	81362.
8089.	0.	6.57	14171.	50950.
6657.	0.	10.33	15970.	88376.
6470.	0.	10.42	15579.	87264.
7305.	0.	9.53	16229.	82305.
15148.	7.58	1.89	16811.	8835.
11/13/84				
9046.	0.	0.	9046.	0.
8712.	0.	0.	8712.	0.
7836.	0.	0.	7836.	0.
5582.	0.	0.	5582.	0.
8265.	0.	0.	8265.	0.
8890.	0.	0.	8890.	0.
10169.	0.	0.	10169.	0.
8/28/84				
7793.	0.	9.5	17244.	79365.
6896.	0.	9.98	16835.	86517.
10202.	0.	3.8	13913.	30758.
6825.	0.	9.87	15935.	76306.
13130.	5.6	3.23	16118.	20606.
6753.	0.	9.90	15817.	79387.
6822.	0.	9.68	15928.	79575.
9/18/84				
7774.	0.	0.	7774.	0.
7831.	0.	0.	7831.	0.
7030.	0.	9.15	15273.	81993.
6625.	0.	9.68	15157.	89354.
6699.	0.	9.55	15104.	86821.
8724.	0.	0.	8724.	0.
6944.	0.	9.08	15420.	83242.

Table A-2 continued

Daily Offline Parasitic Energy (kWh)	Daily Charging Storage Hours	Daily Online Hours	Daily Total Parasitic Energy (kWh)	Daily Gross Energy (kWh)
11/27/84				
9642.	0.	0.	9642.	0.
8704.	0.	0.	8704.	0.
10342.	0.65	0.	10342.	0.
13670.	7.65	0.	13670.	0.
11591.	3.97	0.	11591.	0.
9196.	0.	0.	9196.	0.
9165.	0.	0.	9165.	0.
3/5/85				
6916.	0.	9.20	15847.	83178.
8358.	0.	5.40	13547.	46996.
8541.	0.	0.	8541.	0.
7830.	0.	0.	7830.	0.
10070.	0.	0.18	10227.	620.
9055.	0.	0.	9055.	0.
9721.	0.	2.62	12204.	21919.
12/4/84				
8999.	0.	0.	8999.	0.
8922.	0.	0.	8922.	0.
8950.	0.	0.	8950.	0.
8705.	0.	0.	8705.	0.
8870.	0.	0.	8870.	0.
9175.	0.	0.	9175.	0.
9177.	0.	0.	9177.	0.
2/12/85				
8904.	0.	0.	8904.	0.
9143.	0.	0.	9143.	0.
8899.	0.	0.	8899.	0.
8567.	0.	0.	8567.	0.
10353.	0.	0.	10353.	0.
10338.	0.	0.	10338.	0.
9258.	10.	0.	9258.	0.

Table A-2 continued

Daily Offline Parasitic Energy (kWh)	Daily Charging Storage Hours	Daily Online Hours	Daily Total Parasitic Energy (kWh)	Daily Gross Energy (kWh)
1/15/85				
11791.	3.12	0.	11791.	0.
12095.	3.17	0.	12095.	0.
11239.	0.	0.67	11843.	2844.
14681.	7.17	0.	14681.	0.
8314.	0.	6.72	14317.	56503.
10086.	0.	0.85	10758.	2276.
9258.	0.	0.	9258.	0.
2/5/85				
10541.	0.	3.02	13527.	28179.
9460.	0.	0.	9460.	0.
9794.	0.	0.	9794.	0.
8686.	0.	0.	8686.	0.
14851.	8.87	0.	14851.	0.
8998.	0.	4.57	13442.	37570.
10419.	0.	0.	10419.	0.
10/3/84				
9556.	0.	3.13	12509.	23151.
8714.	0.	5.23	13496.	40312.
8766.	0.	6.18	14460.	50912.
7339.	0.	8.25	14730.	70299.
7401.	0.	8.08	14646.	67875.
9031.	0.	0.	9031.	0.
8439.	0.	6.02	14162.	46971.

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