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Monograph Series No. 2: 10 MWe Solar Thermal Central Receiver Pilot Plant and Receiver Performance Evaluation

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MONOGRAPH SERIES NO. 2: 10 MWe SOLAR THERMAL CENTRAL RECEIVER PILOT PLANT AND RECEIVER PERFORMANCE EVALUATION

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ABSTRACT

The plant and receiver performances of the 10 MWe Solar Thermal Central Receiver Pilot Plant located in Barstow, California, are evaluated based on measured and calculated data. An extended data base is used to update the receiver performance reported in March 1983. Full and part load results and trends in receiver performance when operating at varying outlet temperatures and pressures are provided. The plant and receiver performances are compared to design predictions. Data are included for both points in time and average values of performance.

FOREWORD

The research and development described in this report was conducted within the U.S. Department of Energy's (DOE) Solar Thermal Technology Program. The Solar Thermal Technology Program directs efforts to advance solar thermal technologies through research and development of solar thermal materials, components, and subsystems, and through testing and evaluation of solar thermal systems. These efforts are carried out through DOE and its network of national laboratories who work with private industry. Together they have established a goal-directed program for providing technically proven and economically competitve options for incorporation into the Nation's energy supply.

The two primary solar thermal technologies, central receivers and distributed receivers, use various point and line-focus optics to concentrate sunlight onto receivers where the solar energy is absorbed as heat and converted to electricity or used as process heat. In central receiver systems, which this report will consider, fields of heliostats (two-axis tracking mirrors) focus sunlight onto a single receiver mounted on a tower. The concentrated sunlight is transformed into high temperature thermal energy in a circulating working fluid. Receiver temperatures can reach 1500^{o}C.

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EXECUTIVE SUMMARY

In this report the plant and receiver performances of the 10 MWe Solar Thermal Central Receiver Pilot Plant located at Barstow, California, receiver are evaluated. The results of these evaluations are compared to design predictions. Three different types of data bases, dependent on how the incident power on the receiver is calculated, are used for the evaluation. Except for the receiver incident power, other data is either measured data or calculated from measured data. The three data bases are: (1) performance data base, (2) trend data base, and (3) operations data base. The performance data base, which uses the best available information and accounts for changes in the mirror focal lengths as a function of temperature and the exact heliostat tracking the receiver, is believed to be the most accurate. The trend and operations data base which uses a table look-up for the heliostat field performance value is less accurate but is used to calculate the receiver incident power when many times during the day and days are being considered. With the performance data base, predictions of the receiver, turbine/generator, and plant performance are calculated and compared to those which were previously reported in March 1983 and with those which were predicted during the design phase of the program. The trend data base is used to compare the receiver, turbine/generator, and plant outputs when changes in the operating conditions of the receiver, i.e. outlet temperatures and pressures, are made. Operations data is used to calculate the average performance of the the receiver, turbine/generator, and plant after many days of operations.

From performance equations for the receiver and turbine/generator developed from the performance data base, an assessment of the plants capabilities to meet its design requirement is made. These equations result from a least-square polynomial fit of the data for the two parameters being evaluated. From the performance data base, data fit equations for the receiver absorbed power given the receiver incident power, gross electric power given the receiver absorbed power, net electric power given the gross electric power, and the net electric power given the receiver incident power were developed. Similar data fit equations were developed and reported in March 1983. In each case it was found that at power levels which would be necessary for the plant to produce 10 MWe net the current data fit equations did not differ from those reported in March 1983 by as much as 1%. When the current data fit equations were evaluated at power levels predicted during the design phase and then compared with those design phase predictions differences did occur. The following highlight those differences:

1. It was found that the receiver absorbed power at a design level incident power was 5.6% less than that predicted during the design. This results in a receiver efficiency of about 77% compared to the design prediction of about 81%.

2. At a design level receiver absorbed power, the current data fit equation results for gross electric power was 8.1% less than that predicted during the design.

3. The net electric power from the data fit equation was 7.3% more than was predicted during the design phase for a design level gross electric power.

4. When the data fit equation for the plant net electric power at a design level of receiver incident power was compared to that predicted during the design, the current value is about 9% less than that which was predicted.

If these comparisons would have been made at lower power levels (not all design values are available at lower levels) then the differences between the current data fit equation results and design predicted values would have been less.

The trend data base was used to investigate how the receiver, turbine/ generator, and plant would perform if the receiver outlet operating temperature and pressure were changed. It was found that at an outlet pressure above 1400 PSI, changing the receiver outlet temperature from 925-950^{o}F to 775-800^{o}F would result in a slight increase in receiver absorbed power for a given receiver incident power, a decrease in the gross electric power for a given receiver absorbed power, no change in net electric power for a given gross electric power, and a slight overall increase in the net electric power for a given receiver incident power. There was considerable scatter in the data and only by doing a statistical test on each data set and the combined data and then comparing the plots of the data fits for each data set could the differences be seen. At a fixed receiver outlet temperature of 775-800^{o}F it was found that the receiver absorbed power for a given receiver incident power decreased as the receiver outlet pressure was decreased from above 1400 PSI to less that 1000 PSI.

The receiver efficiency (receiver absorbed power/receiver incident power) was calculated using the trend data base and changes in this efficiency were plotted versus wind speed and the difference in the receiver outlet temperature raised to the forth power minus the ambient temperature raised to the fourth power. These two plots showed that with increasing wind speeds there was a slight decrease in the receiver efficiency up to the limit of the data (20 MPH) and with decreasing temperature differences the receiver efficiency increased slightly.

Operations data covered a time period between December 1, 1982 and December 31, 1983. Of these 396 days, about 57% of the calculated time between sunrise and sunset are accounted for in the data while about 70% of the days (277 days) have some data. For these days the total amount of power available to the heliostat field (mirror area times direct normal insolation), receiver incident power, receiver absorbed power, net electric power produced in any operating mode, and net electric power produced in the turbine direct mode was calculated. Within these 277 days there were 44 "good" days when there was measured insolation for all but one hour during the day, the average insolation was at or above 500 watts/m2, heliostat tracking of the receiver started within one hour of sunrise, and the receiver operated for all but three hours during the day. From this data it was found that the average receiver efficiency (receiver absorbed energy/receiver incident energy) times 100 was 68-70%. When the plant operated in any mode, the plant efficiency (plant net electric energy/energy available in the heliostat field) times 100 was about 6.5%. Of these 44 "good" days 18 were for the plant operating in the turbine direct mode and the resulting plant efficiency was 9.3%.

The only operational requirement for the Pilot Plant was that it would produce 10 MWe net in the turbine direct mode for 7.8 hours on the design "best day" and for 4.0 hours on the design "worst day". These design days were defined as June 21 and December 21 with a specified insolation curve for those days. Since the specified insolation for the design days has not occurred at the site and the design was for "all" heliostats tracking the receiver and for clean mirrors which also has not occurred, an assessment was performed to see if the plant would meet these design requirements. The data fit equations developed from the performance data base, all heliostats tracking the receiver, clean mirrors and the design insolation were used for this assessment. It was found based on this data and equations that the plant could not meet its design requirement. However, it would produce over 9 MWe net for the times required and would produce 10 MWe net nearer to solar noon on the two design days.

MONOGRAPH SERIES, NO. 2
10 MWe SOLAR THERMAL CENTRAL RECEIVER
PILOT PLANT AND RECEIVER PEFORMANCE EVALUATION

Introduction

In the "10 MWe Solar Thermal Central Receiver Pilot Plant Receiver Steam Generation (Test 1030) Evaluation Report" (Ref. 1) issued in March 1983, performance predictions for the receiver and turbine/generator were presented. These results were calculated for points in time based on data from selected days and times (14 Cases) between May 1982 and June 1982. That performance data base has been expanded to now include selected days and times (64 cases) through December 1983. Using calculated values of the incident power on the receiver and measured data to determine the receiver absorbed power, new predictions are made of the receiver performance. The expanded data base includes additional measured data for the turbine/generator. These new performance results will be compared to those presented in March 1983.

A description of the receiver at the 10 MWe Solar Thermal Central Receiver Pilot Plant can be found in Reference 1. Also included in Reference 1 is information on the receiver instrumentation, the heliostat field, and heliostat field aimpoints.

For the period between December 1982 and December 1983, a point in time steady state operations trend data base has been developed. This trend data base uses a less accurate technique to calculate the receiver incident power than that used for the performance data base and measured data from the receiver and turbine/generator. The trend data base (1150 Cases) is used to compare the trend in the receiver performance when operating at various steady state outlet temperatures and pressures.

Over the thirteen months between December 1, 1982 and December 31, 1983 operational data from the receiver and the plant has been evaluated using an operations data base. The results of this evaluation include average values of performance, time it takes to start-up the plant, average times of operation, and overall efficiencies. The procedure to calculate the receiver incident power every few minutes during the day for the operations data base used for this evaluation was the same as that used for the trend data base.

Since the plant has yet to operate on an "ideal day" as defined during the design phase, and has only made 10 MWe (net) on a few occasions, the question of whether the plant will meet its design requirement has yet to be answered. Using the performance predictions from the performance data base, the ideal day insolation and all heliostats tracking the receiver with clean mirrors, estimates of the "best" and "worst" day power output are made. The calculation of the receiver incident power every few minutes during the ideal day was the same as that used for the trend data.

The data used in these evaluations is all measured data except the receiver incident power. The measured data was recorded on the plant's Data Acquisition System (DAS). Such data as the direct normal insolation, wind speed, ambient temperature, receiver flow, receiver inlet and outlet temperature and pressure, and electric power production are recorded on the DAS. However, even after a year of operations, many of these measurements are just now being calibrated. Those that have been calibrated have been reasonable so the data used are believed to represent the Pilot Plant. The incident power on the receiver from the heliostat field is calculated for the performance data base using the MIRVAL heliostat field performance code developed at Sandia. Input to that code for each case in the performance data base includes such data as heliostat beam pointing error, beam quality error, mirror module focal length as a function of temperature, location of heliostats out of service, mirror reflectivity, insolation, time of day, and sunshape among others. The beam characterization system at the Pilot Plant to measure the beam pointing errors, beam quality errors, and sunshape has not yet began routine operations. Thus, best estimates of these inputs based on earlier measurements other than at the Pilot Plant have been used in MIRVAL. The incident power on the receiver for the trend data base uses a "field performance value" and measured insolation, mirror reflectivity, and actual numbers of heliostats tracking the receiver. The field performance value is an output from MIRVAL for a given set of input variables. By running MIRVAL for different sun positions i.e., sun elevation and azimuthal angles, a matrix of field performance values is created. This matrix is used to find the field performance value for any sun position, i.e., time of day, when the receiver incident power is to be calculated for the trend and operations data bases.

The measured data used in this report has been taken almost entirely from "Summary Data Tapes" which are developed from the data tapes produced by the plant DAS. These summary data tapes contain data at three (3) minute intervals as compared to the DAS data tapes which have data at less than one second intervals. It is recognized that by using the summary data tapes there are times when the plant is operating and data is not recorded by the DAS and is thus not available on the data tapes. Also, there are times when the measured values used in this report are not recorded even though the DAS is operating, there are times when the DAS is not started until after the plant is operating, and there are times when the DAS is stopped before the plant is shut down. All of these conditions can have some influence on the performance reported for trends and operations data bases. However, the performance data base used data only on those days and times of day when the DAS is operating and the data needed is being recorded.

Performance Update

In Reference 1 a collection of point-in-time data was presented for the receiver absorbed power versus receiver incident power, generator gross electric power versus receiver absorbed power, and plant net electric power versus gross electric power. Input for each of these comparisons was based on a limited amount of point-in-time data. The data base for these comparisons has been expanded and new equations have been developed by fitting a least-squares polynomial through the data. Table I lists the date, day of the year, and solar time for each case which is included in the performance data base. Solar time is define such that at solar noon (12.000 hr) the sun's azimuthal angle is zero. The first fourteen cases listed in Table I made up the cases for the performance data base used in Reference 1. For each day and time listed in Table I the incident power on the receiver was calculated using the MIRVAL heliostat field performance code. The measured site insolation, heliostat mirror reflectivity, ambient temperature, and the actual heliostats tracking the receiver were input to the code. The heliostat beam pointing error and beam quality error used in the code were the best available at the time of each run. Other than the calculations of incident power on the receiver, measured data has been used for all other parameters. When ever possible redundant measurements of each parameter were compared in order to determine if the measured value was reasonable. The data in this section is point-in-time data, i.e., at the times listed in Table I data was collected, and this collection of point-in-time data is used for performance evaluation.

The operating conditions which make up the cases listed in Table I include operations at both full and part load and both design and off design receiver outlet temperatures and pressure. However, most of the data is for the design receiver outlet temperature of about 950°F. Differences in the plants performance at various operating conditions is covered in the Trends Data section of this report.

Figure 1 is a plot of the receiver absorbed power versus the receiver incident power. The line through the data is the result of a least-squares fit of the data. As was the case in Reference 1 a first order polynomial, i.e., a straight line, had the smallest one sigma variation for the data used. The two points in Figure 1 represented by the "X" are values of the receiver incident and corresponding absorbed powers reported in Reference 2 and were calculated values during the design phase. There were no design requirements for receiver absorbed power and thus documented design values of receiver incident and absorbed power shown in Figure 1 are from "Pilot Plant Power Flow Waterfall Charts" from Reference 2. In Reference 1 the equation reported for the receiver absorbed power was:

$$\text{Absorbed Power} = 0.84884(\text{Incident Power}) - 3.4060 \quad \text{(MWt)}$$

TABLE I

Date	Day	Solar Time (Hour)	Date	Day	Solar Time (Hour)
05/19/82	139	11.272	04/08/83	98	11.095
		12.272			11.596
05/24/82	144	11.265			12.113
		11.848			12.746
		12.432			13/563
05/28/82	148	11.758			13.929
		12.757	04/18/83	108	10.621
		13.757			11.138
		14.757			11.638
		15.757			12.305
		16.757			12.888
06/07/82	158	10.031	07/07/83	188	10.048
		11.231			10.548
		14.431			11.048
10/10/82	283	13.178			11.564
		14.178			12.381
		15.179			12.880
		16.179			13.381
01/17/83	17	12.043			13.881
		14.042	07/17/83	198	8.873
		16.042			11.124
02/01/83	32	11.984			13.626
		12.484	08/24/83	236	11.153
		14.484			13.655
		16.484	10/14/83	287	10.953
02/14/83	45	11.974			14.957
		13.974	11/06/83	310	11.478
03/12/83	71	9.547			14.229
		10.664	12/28/83	362	9.665
		13.298			12.166
		14.298			15.168
		15.298			
		16.298			

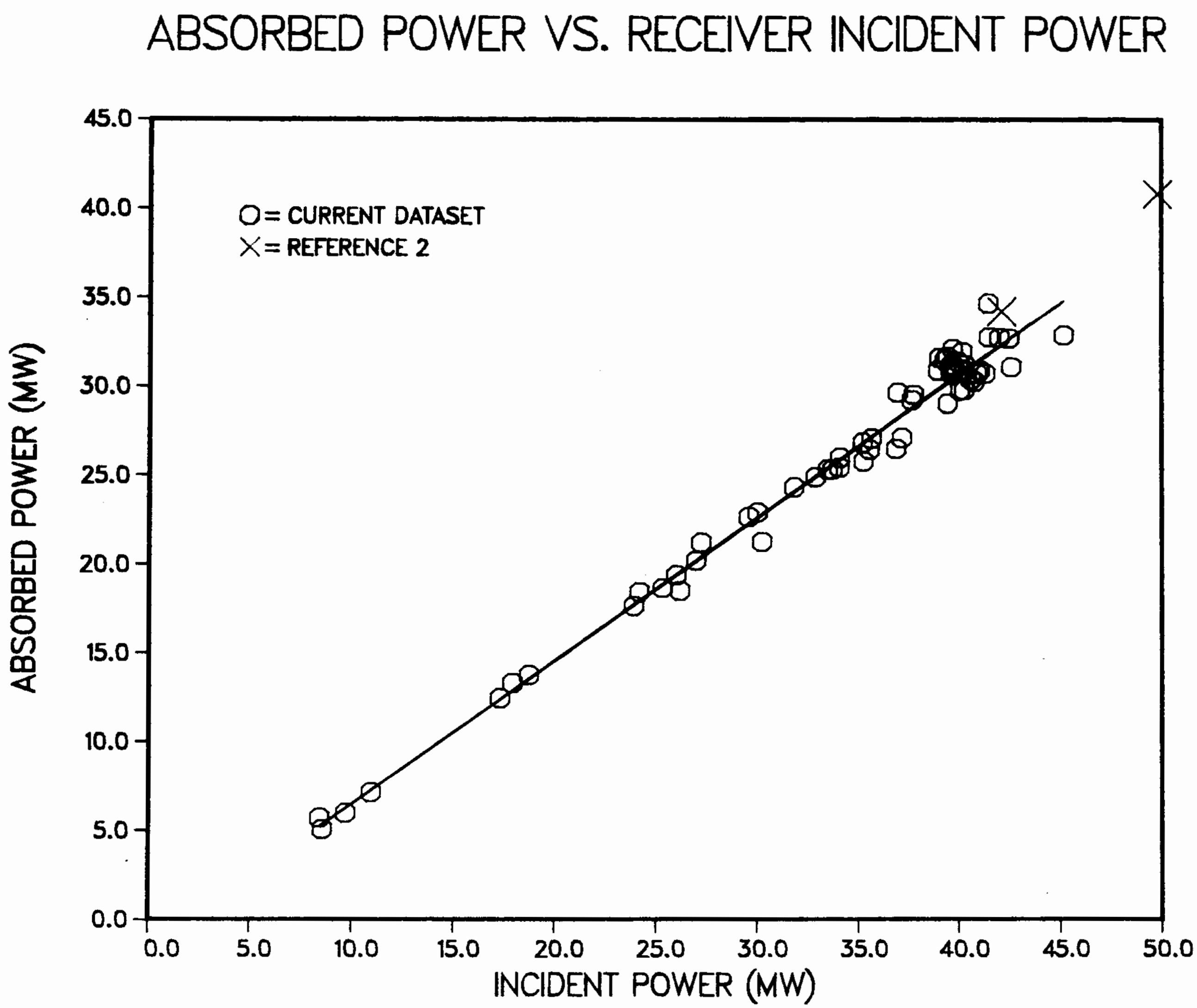

Figure 1. MIRVAL calculated receiver incident power and the corresponding calculated receiver absorbed power base on measured parameters from the performance data base. The design values from Reference 2 are shown as the "X".

The equation determined from the current extended performance data base is:

Absorbed Power = 0.8056(Incident Power) - 1.5690 (MWt)

At a nominal value for the receiver incident power of 40.0 MWt the Reference 1 absorbed power equation yields a value of 30.5 MWt while the current equation yields a value of 30.7 MWt. For the same receiver incident power as one of the design values in Reference 2, i.e., 42.1 MWt, the current equation results in a receiver absorbed power of 32.3 MWt compared to the design value of 34.2 MWt. For this receiver incident power (42.1 MWt) the value from the data fit curve is 5.5% less than the design value where the difference is defined as (design value - data fit value)/ design value times 100.

Another approach is to calculate the receiver incident power from the data fit equation for a given receiver absorbed power. The design prediction with the receiver incident power of 42.1 MWt was that the receiver absorbed power would be 34.2 MWt. For this predicted receiver absorbed power the data fit equation was solved for the receiver incident power which was 44.4 MWt. The receiver incident power calculated from the data fit equation is 5.2% higher than the design value of 42.1 MWt for the same receiver absorbed power. Thus, either the actual absorbed power from the receiver for a given receiver incident power is less than expected by 5.6% or the calculated receiver incident power is higher than the real receiver incident power by 5.2%. Both of these conditions are possible for a variety of reasons. In either case the difference between the design and current prediction is about 5%. Further discussions on one possible reasons for this difference will be addressed later.

A second comparison made in Reference 1 was that of plant gross electric power produced versus receiver absorbed power when operating in the turbine direct mode. These same parameters are compared with the current data base. In this case only measured data is used. Figure 2 shows a plot of the plant gross electric power versus receiver absorbed power. The line represent a fit of the data using a first order least-squares polynomial and the "X" are data from Reference 3 which are design values. The equation of the data fit reported in Reference 1 was:

Gross Electric = 0.33372(Absorbed Power) - 0.70071 (MWe)

The fit of the current extended data base resulted in the following equation:

Gross Electric = 0.3391(Absorbed Power) - 0.8497 (MWe)

For a receiver absorbed power of 30.0 MWt, the Reference 1 equation yields a value of plant gross electric power of 9.31 MWe and the current equation yields a value of 9.32 MWe. Using a design value for receiver absorbed power of 34.2 MWt from Reference 2, the current data fit

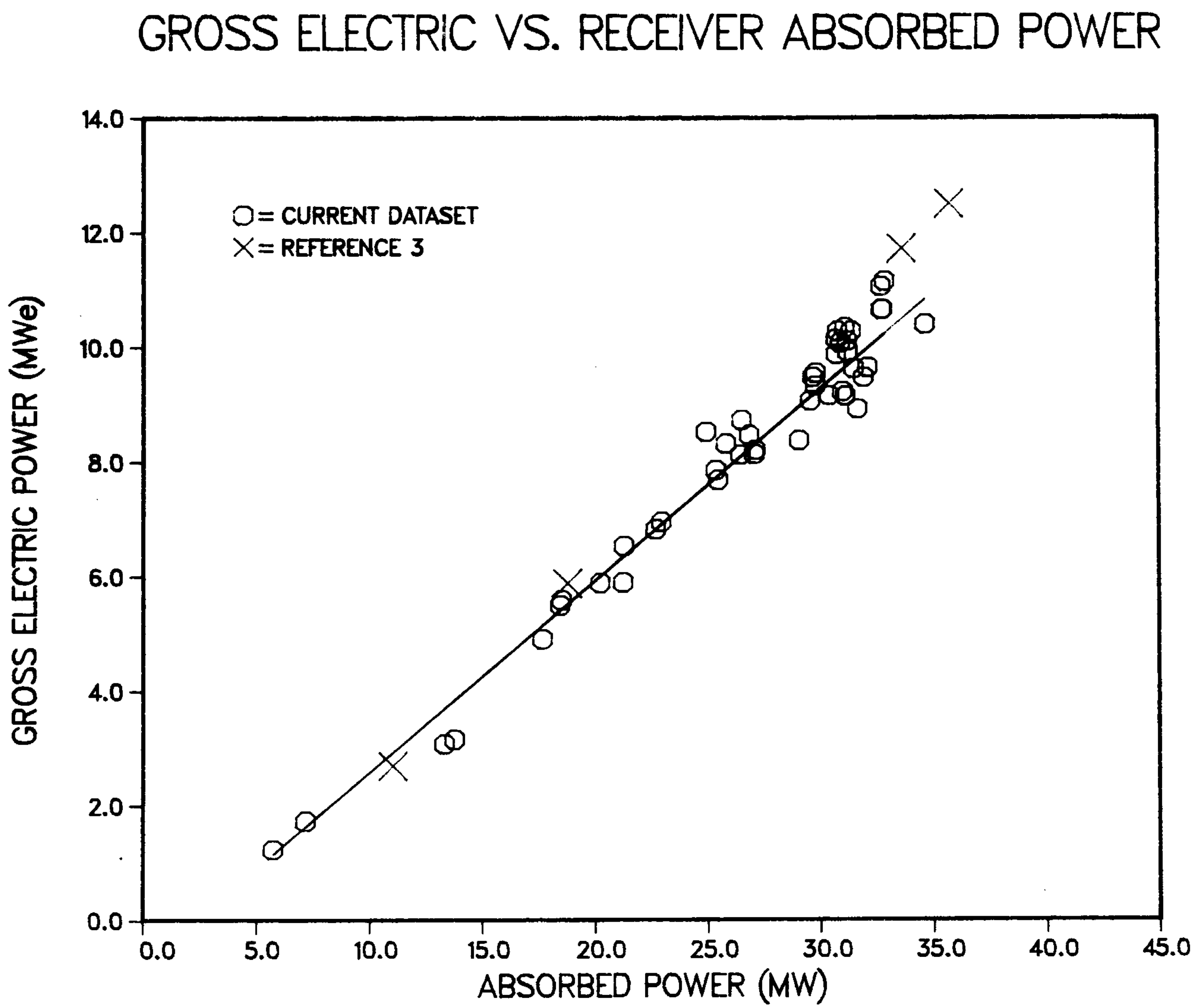

Figure 2. Calculated receiver absorbed power using measured data and the corresponding measured gross electric power produced by the plant operating in the turbine direct mode. The design values from Reference 3 are shown as the "X".

equation results in a plant gross electric power of 10.75 MWe which is less than the design value of 11.7 MWe for the same absorbed power. For this value of the receiver absorbed power the data fit gross electric power is 8.12% less than the design value. The 8.1% difference between design and data fit represents the nonsolar portion of the plant where receiver thermal power is converted to electrical power. This less than predicted output of the turbine/generator indicates that either the turbine/generator is less efficient than expected or there are losses of thermal energy between the receiver and turbine/generator by heat losses or steam leaks.

The third comparison made in Reference 1 was for the plant net electric power delivered to the grid versus gross electric power produced. As was the case of the comparison of plant gross electric power to receiver absorbed power, only measured data is used to plot plant net versus gross electric power. Figure 3 shows the plot of plant net electric power versus gross electric power and the least-squares polynomial fit of the data. Again the plant was operating in the turbine direct mode. The "X" data values shown in the figure are design values from Reference 2 and Reference 3. In Reference 1 the data fit equation was:

$$\text{Net Electric Power} = 0.98818(\text{Gross Electric Power}) - 0.91356 \qquad (\text{MWe})$$

The data fit equation of the extended performance data base is:

$$\text{Net Electric Power} = 0.9909(\text{Gross Electric Power}) - .8606 \qquad (\text{MWe})$$

For a nominal value of the plant gross electric power of 10.5 MWe the Reference 1 equation yields a net electric power of 9.46 MWe while the current data fit equation yields a value of 9.54 MWe. A design plant gross electric power of 11.7 MWe in Reference 2 was to result in a net electric power of 10.0 MWe while the current data fit equation shows a net electric power of 10.73 MWe for this gross electric power. The difference between the design and current data fit is -7.3%. Thus the plant produces 7.3% more net electrical power at this gross electric power than was predicted during the design phase. This increase in net electric power for a given gross electric power indicates the plant parasitic power is less than was expected.

Figures 1, 2, and 3 have shown the accumulation of point-in-time data and the data fit equations for the receiver, turbine/generator, and electric consuming components with a comparison to the design predictions. Using the current data fit equations to represent these components and by substituting design values into these equations a comparison of component performance to predictions was made. The following summarizes those results:

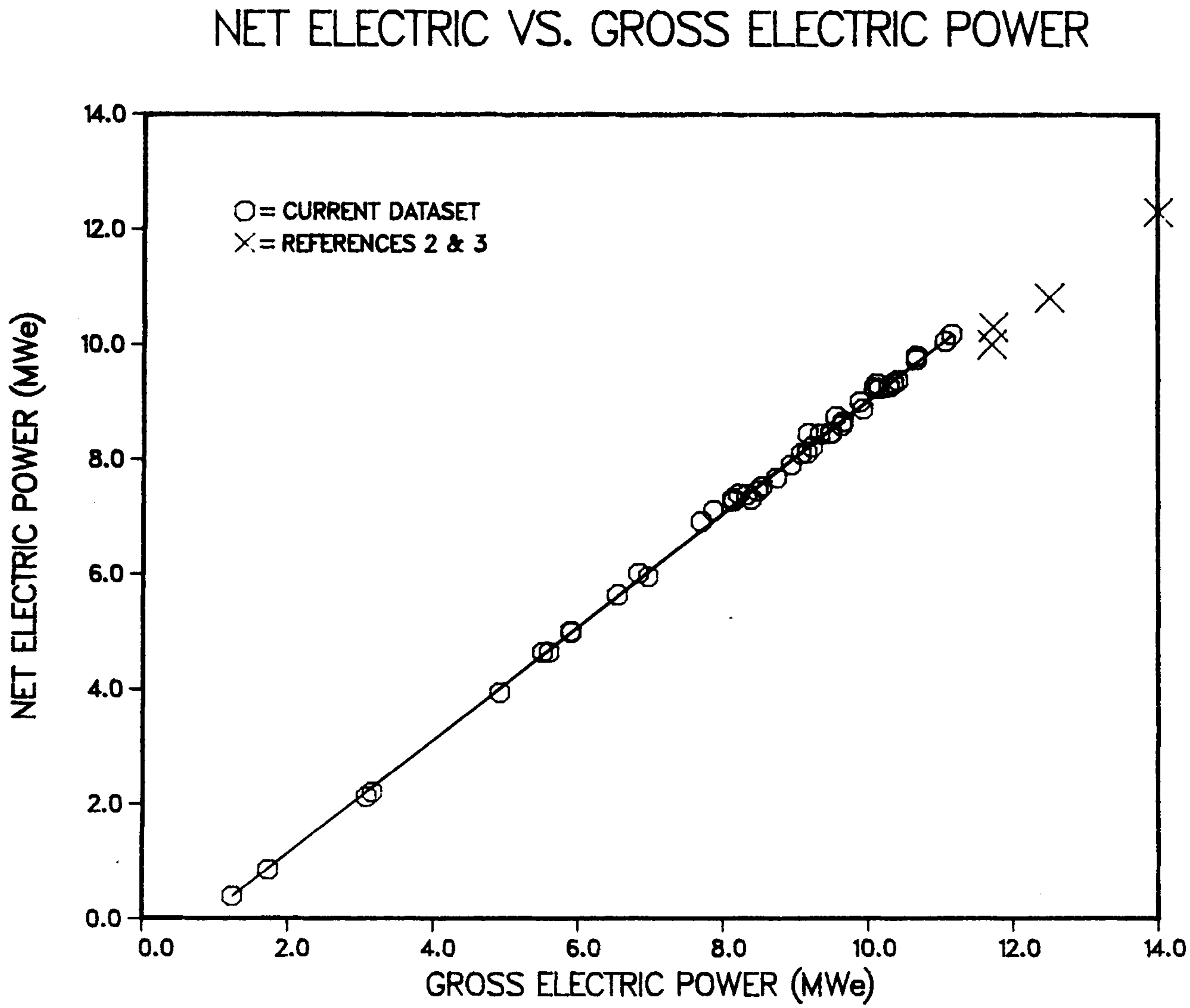

Figure 3. Measured plant gross and net electric power produced in the turbine direct mode. Design values from Reference 2 and 3 are shown as the "X".

Design Input	Design predicted output (Ref. 2)	Data fit eq. output	Difference
Power available to the heliostat field --66.6 MWt	incident power 42.1 MWt	-----	
Receiver incident power--42.1 MWt	Absorbed power 34.2 MWt	Absorbed power 32.3 MWt	5.6 %
Receiver absorbed power--34.2 MWt	Gross electric 11.70 MWe	Gross electric 10.75 MWe	8.1 %
Gross electric power--11.70 MWe	Net electric 10.0 MWe	Net electric 10.73 MWe	-7.3 %

It should be noted that, even with the limited amount of design data used in these comparison of design versus current data fits, there is a difference in the slopes of the curves. At lower values of receiver incident power, receiver absorbed power, and plant gross electric power the differences between design and data fit values would be less than those reported at higher values of these parameters. These comparisons have been made at levels which would be necessary for the plant to produce 10 MWe for several hours which was the design requirement.

In Reference 2, a value of .95 was used for the average receiver active surface absorptivity. Thus about 5% of the receiver incident power is reflected from the receiver. Measurements of the absorptivity for each panel on the receiver and the two spare panels were made in November 1982 and November 1983. From the measurements on the receiver panels an average value of the receiver absorptivity was calculated. Figure 4 shows the results of those measurements where panels 1 through 24 are the receiver panels, panels 25 and 26 are the spare panels, and REC is the calculated average value for the receiver. Panels 1, 2, and 3 are the low temperature preheat panels and panels 22, 23, and 24 are the high temperature preheat panels. Panels 4 through 21 are the receiver boiler panels. In November 1982 the calculated average receiver absorptivity was .92 and in November 1983 the receiver average absorptivity was calculated to be .90. Using an average value for the receiver absorptivity of .91, the difference between the value used during the design and this average is 4.2% lower than the design value. Thus about 4.2% less of the receiver incident power is absorbed on the receiver surface than was expected. This would account in part for the less than design receiver absorbed power for a given value of the receiver incident power. The difference between the design and measured receiver absorptivity accounts for almost all of the difference between the measured and design values of receiver absorbed power shown in Figure 1.

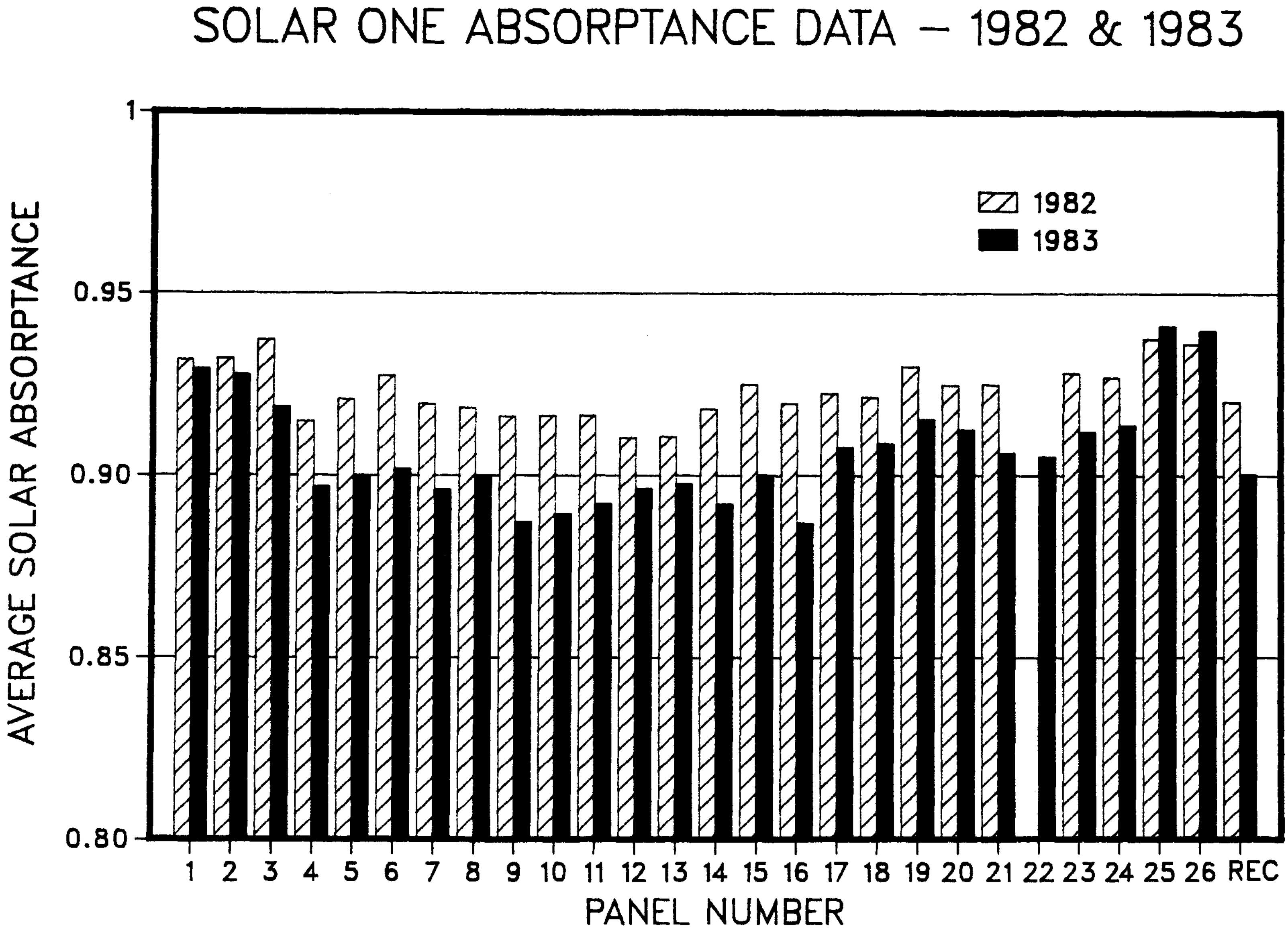

Figure 4. Measured receiver panel absorptivity for each of the 24 receiver panels, two spare panels (panel 25 and 26), and the calculated average receiver absorptivity. The data was taken in November of 1982 and 1983.

As was noted earlier almost all of the data in the performance data base is for the receiver operating at its rated outlet temperature and pressure. One of several exceptions is the data for July 7, 1983 (day 188) in Table I. Operations of the receiver and plant on this day were changed so that part load data could be taken at both rated, i.e., 950^{o}F and 1450 PSI outlet conditions, and derated, i.e., 775^{o}F and 1450 PSI outlet conditions. Part load levels were accomplished by reducing the number of heliostats tracking the receiver. The test was run by having the plant producing its maximum power at about 2 hours before solar noon at rated conditions. The number of heliostats tracking the receiver was reduced to achieve a nominal plant net electric power of 7.5 MWe, 5.0 MWe, and 2.0 MWe. While at the 2.0 MWe output the receiver outlet temperature was reduced to about 775^{o}F. Then the number of heliostats tracking the receiver were increased in exactly the same order they had been reduced. The rated condition tests were run before solar noon and the derated condition tests were run after solar noon. The results of this part load test are shown in Table II. All the data in Table II is measured or was calculated from measured data. It can be seen at each power level that the number of heliostats tracking the receiver was the same. There was some slight changes in the insolation and the tests at similar power levels were not exactly symmetric around solar noon, i.e., there was about a 4 minute difference in time from solar noon. Even though there were no changes in the operating conditions of the receiver some natural changes did occur. At low output power the receiver inlet temperature decreased since at low flow the plant inline heaters are not as effective. In this part load test there was almost no change in the receiver absorbed power, gross electric power, and net electric power at the two outlet temperatures for the same power level. For completeness it should be noted that there was an increase in the wind speed at the site from about 5 mph to about 15 mph during the derated temperature tests at the 7.5 MWe and Max power levels. These higher winds could reduce the receiver absorbed power which would then reduce the gross and net electric output of the plant for these power levels. The effects of wind speed on receiver performance are covered in the Trend Data section of this report.

A final comparison made between design and current data which was not made in Reference 1 is evaluating plant net electric power versus receiver incident power. Figure 5 shows a plot of the data for net electric power produced by the plant versus receiver incident power when operating in the turbine direct mode. The line is the least-squares polynomial fit of the data and the "X" is the design values reported in Reference 2. The data fit equation for this plot is:

$$\text{Net Electric Power} = 0.2644\ (\text{Incident Power}) - 2.032 \qquad (\text{MWe})$$

Using the lower value of the receiver incident power from Reference 2 of 42.1 MWt where 10.0 MWe net were to be produced and comparing the data fit equation value of 9.1 MWe for this receiver incident power the difference is 9.1%. This indicates the plant produces 9.1% less net electrical power than was predicted during the design phase.

PART LOAD TEST (7/7/83) DAY 188

NET LOAD (MWe)	MAX		7.5		5.0		2.0	
RECEIVER CONDITIONS	Rated	Derated	Rated	Derated	Rated	Derated	Rated	Derated
INLET TEMP (°F)	320	375	311	313	295	296	267.5	268
INLET PRESS (PSI)	1717	1795	1668	1711	1610	1630	1560	1567
FLOW (KLB/HR)	87.5	101.9	77.0	86.9	58.1	67.0	37.4	42.4
OUTLET TEMP (°F)	944	778	942	778	942	778	941	774
OUTLET PRESS (PSI)	1502	1506	1489	1488	1472	1472	1456	1456
ABS POWER (MW)	29.79	29.78	26.45	27.06	20.21	21.23	13.31	13.76
NO HELIO	1797	1797	1580	1580	1209	1209	825	825
INSOLATION (W/m2)	904	898	902	905	898	892	888	898
GENERATOR CONDITIONS								
GROSS ELECT (MW)	9.55	9.33	8.13	8.14	5.89	5.90	3.08	3.16
NET ELECT (MW)	8.75	8.44	7.32	7.28	5.01	4.99	2.12	2.20
SOLAR TIME (HRS)	10.05	13.88	10.55	13.38	11.05	12.88	11.55	12.38
TIME FROM SOLAR NOON (HRS)	1.95	1.88	1.45	1.38	.95	.88	.45	.38

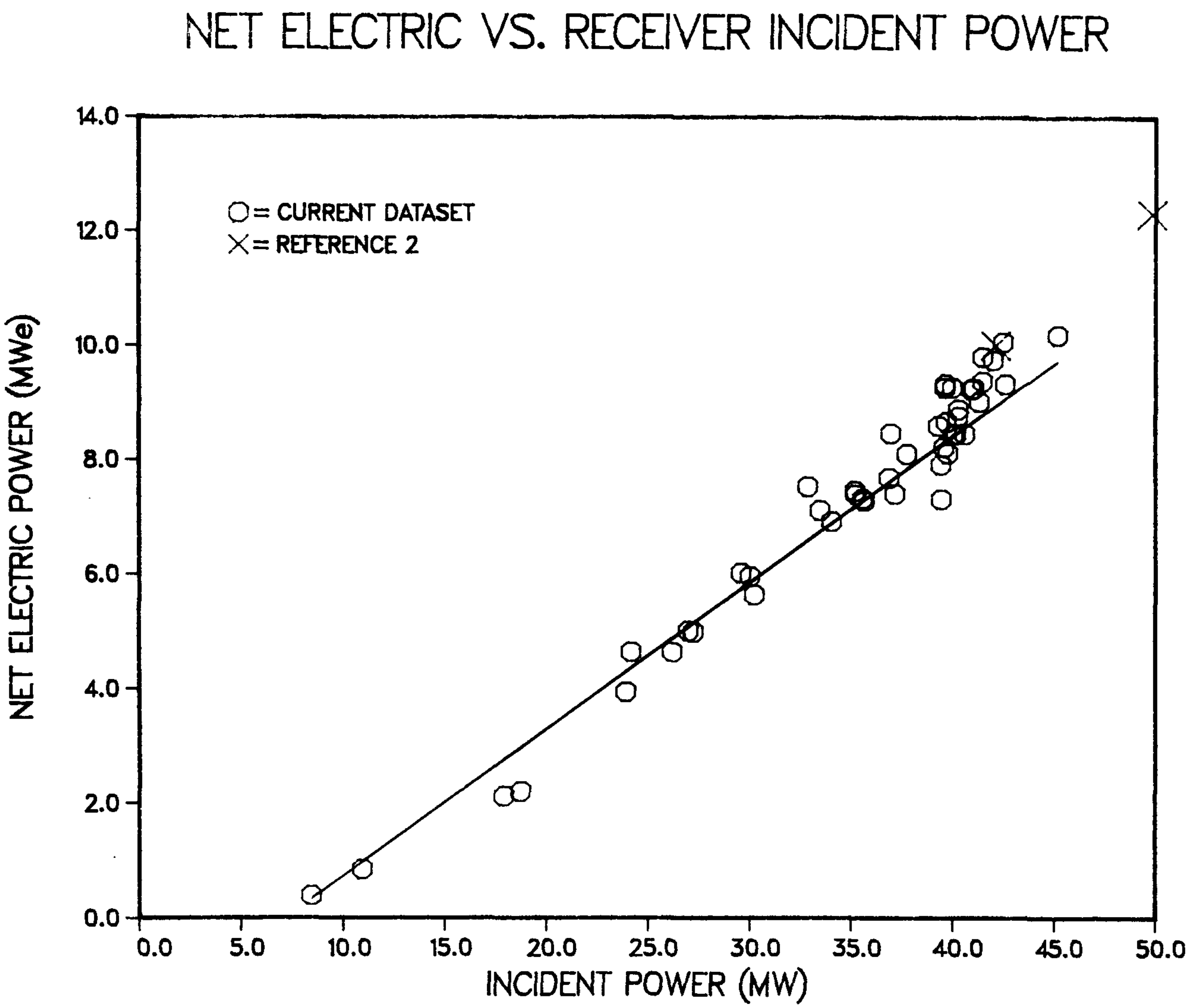

Figure 5. MIRVAL calculated receiver incident power and the corresponding measured net electric power delivered to the grid when operating in the turbine direct mode. Design values from Reference 2 are shown as the "X".

It has been shown that this reduced net electrical power production for a given high value of receiver incident power compared to the design predictions is made up in part of the 5.6% over estimate of receiver absorbed power, a 8.1% over estimate of plant gross electric power from the higher values of receiver absorbed power, and an under estimate of 7.3% of the net electrical power produce from the higher values of plant gross electric power. At lower power levels these difference would be less until at less than about 20 MWt receiver incident power where the data indicates the plant would produce more net electrical power than was predicted during the design. However, the design requirement was that the plant would produce 10 MWe net for at least 7.8 hours on the best design day and for at least 4.0 hours on the worst design day and 10 MWe net is considered high power operations. To evaluate efficiencies of the receiver and the plant the following definitions are used:

System Thermal Efficiency = (Receiver Absorbed Power/Receiver Incident Power) x 100.

and

System Electric Efficiency = (Net Electric Power/Receiver Incident Power) x 100.

Figure 6 shows these two efficiencies plotted versus receiver incident power. For the system electric efficiency the plant was operating in the turbine direct mode. Again the lines represent a least-squares polynomial fit of the data and the "X" are the efficiencies calculated from the two data points in Reference 2. At a receiver incident power of 42.1 MWt from Reference 2, the design thermal efficiency was predicted to be about 81% compared to the current data fit value of 77%. At this same receiver incident power, the design system electric efficiency was to be about 24% compared to the current data fit value of 22%. It can be seen as the receiver incident power is decreased from high levels to moderate levels both efficiencies decrease slightly. However, both efficiencies show a marked reduction at low receiver incident power levels.

To compare the performance of the plant as predicted using the current data fit equations and those predicted during the design phase the case in Reference 2 for the plant to produce 10 MWe net was selected. This case in Reference 2 is for a single point-in-time, i.e. December 21 at 2:00 pm. The data fit equations are a fit of data taken at many different points-in-time as listed in Table I. The following summarizes the data from Reference 2 and the results from the data fit equations with receiver incident power as the common input and where the results from each data fit equation are used as the input to the next data fit equation:

SYSTEM EFFICIENCIES

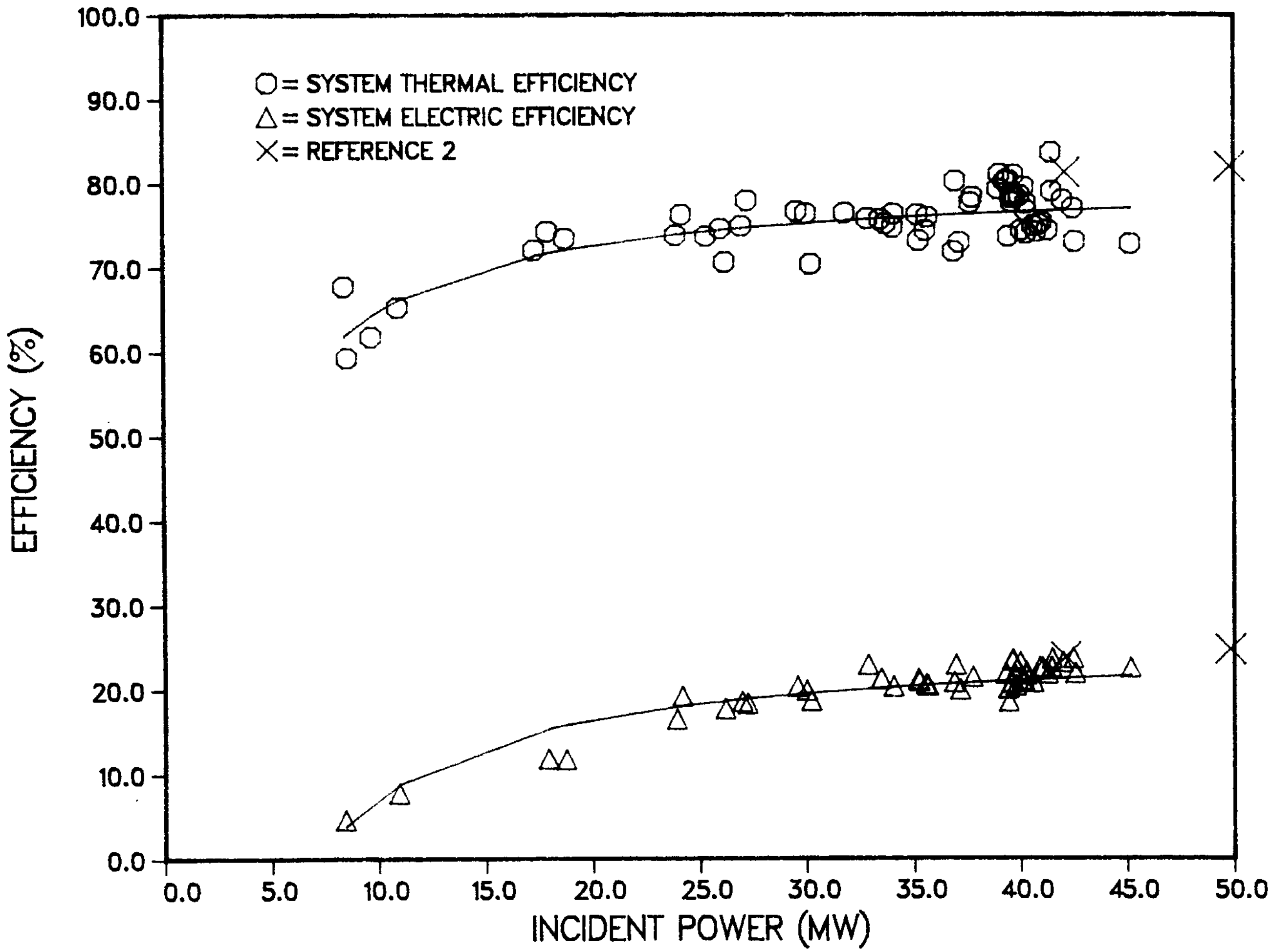

Figure 6. MIRVAL calculated receiver incident power and the corresponding calculated System Thermal Efficiency (receiver absorbed power/receiver incident power) and System Electric Efficiency (net electric power/receiver incident power). System electric efficiency is for the turbine direct mode. Design values from Reference 2 are shown as the "X".

Parameter	Reference 2 data	Data fit equations
Power available to the heliostat field	66.6 MWt	----
Receiver incident power	42.1 MWt	42.1 MWt
Receiver absorbed power	34.2 MWt	32.35 MWt
System gross electric power	11.7 MWe	10.12 MWe
System net electric power	10.0 MWe	9.17 MWe.

Recall that the data fit equation for net electric power produced given the receiver incident power resulted in 9.1 MWe net electric power for a 42.1 MWt receiver incident power. Using the above receiver incident power as the bases to calculate efficiencies for these point-in-time data the following efficiencies result:

Parameter	Reference 2 data	Current equations
Receiver incident power/incident power	100.0 %	100.0 %
Receiver absorbed power/incident power	81.2 %	76.8 %
System gross electric power/incident power	27.8 %	24.0 %
System net electric power/incident power	23.7 %	21.7 %.

Figure 6 shows a plot of the receiver absorbed power/receiver incident power and system net electric power/receiver incident power for other values of the receiver incident power than that used in the comparison. These two efficiencies were defined as the System Thermal Efficiency and System Electric Efficiency. The System Thermal efficiency as defined can also be considered as the receiver efficiency.

Trend Data

To investigate how the receiver and plant perform when operating at different receiver outlet temperature and pressure levels steady state trend data has been calculated. The data is considered trend data rather than performance data since the calculation of the receiver incident power is done by a method which is less accurate than that used for the performance data. However, the data is point-in-time data since for each point-in-time the receiver incident power or other values were calculated at that instant in time. Data other than the receiver incident power is measured data. The trend data receiver incident power is calculated by using actual measured solar insolation, heliostat mirror reflectivity, and number of heliostats tracking the receiver and a "look up table" for heliostat field performance values. The plant was considered to be at steady state if selected measured parameters did not change values within specified limits for a period of twenty one minutes (seven consecutive data time steps on the summary data tapes). The trend data is used to evaluate the same parameters that were discussed in the Performance Update section except the receiver operating conditions for a given set of parameters are changed and the results are compared to see the effect on the parameters. With this larger data base the steady state trend data was used to evaluate the trend in the receiver efficiency or System Thermal Efficiency (defined as receiver absorbed power/receiver incident power) for various wind speeds and outlet temperatures.

To compare the receiver performance when operating at different outlet temperatures and at pressures above 1400 PSI with wind speed less than 10 mph two temperature ranges were selected. The low temperature range was 775°F to 800°F and the high temperature range was 925°F to 950°F. Figure 7 shows the results of this comparison. With so much scatter in the data a statistical test was performed on each data set and the combined data from both sets. This statistical test showed that there was a difference between the two sets of data. As can be seen in Figure 7 the receiver performs slightly better, i.e., more receiver absorbed power for a given receiver incident power, when operating between 775-800°F than at 925-950°F. This small change in receiver performance with a 150°F change in receiver outlet temperature is due in part to the relative small amount of area on the receiver affected by the temperature reduction. Of the 24 panels on the receiver 6 are preheaters which are not affected by the receiver outlet temperature reduction. The preheaters represent 25% of the total receiver surface area. At a fixed pressure the boiling temperature of the water flowing through the boiler panels is not changed so only the superheated area of the boiler panels is affected by the temperature change of the outlet steam temperature. The superheated part of the boiler panel represents about one third of a total panel area. Thus, of the 75% of the total receiver area which might be affected by a temperature change only one third of that, i.e., 25%, is actually affected by the receiver outlet temperature change.

To compare the operations of the receiver at a fixed outlet temperature with different outlet pressures a temperature range of 775-800°F was selected. This selection was necessary since most operations of the receiver occur at pressures above 1400 PSI at steady state with lower pressures occurring at start-up and shut-down. Figure 8 shows the comparison of receiver performance when operating below 1000 PSI and above 1400 PSI with the outlet temperature between 775-800°F. The statistical test of the data did show there was a difference between the two data sets. As can be seen in Figure 8 there is a slight advantage in operating the receiver at higher outlet pressures. The reason for this slight advantage when operating at higher pressure is similar to that for the temperature change, i.e., a small part of the total receiver surface is affected. At lower pressures the boiling temperature of the water flowing through the boiler panels is reduced so the superheated area is slightly increased.

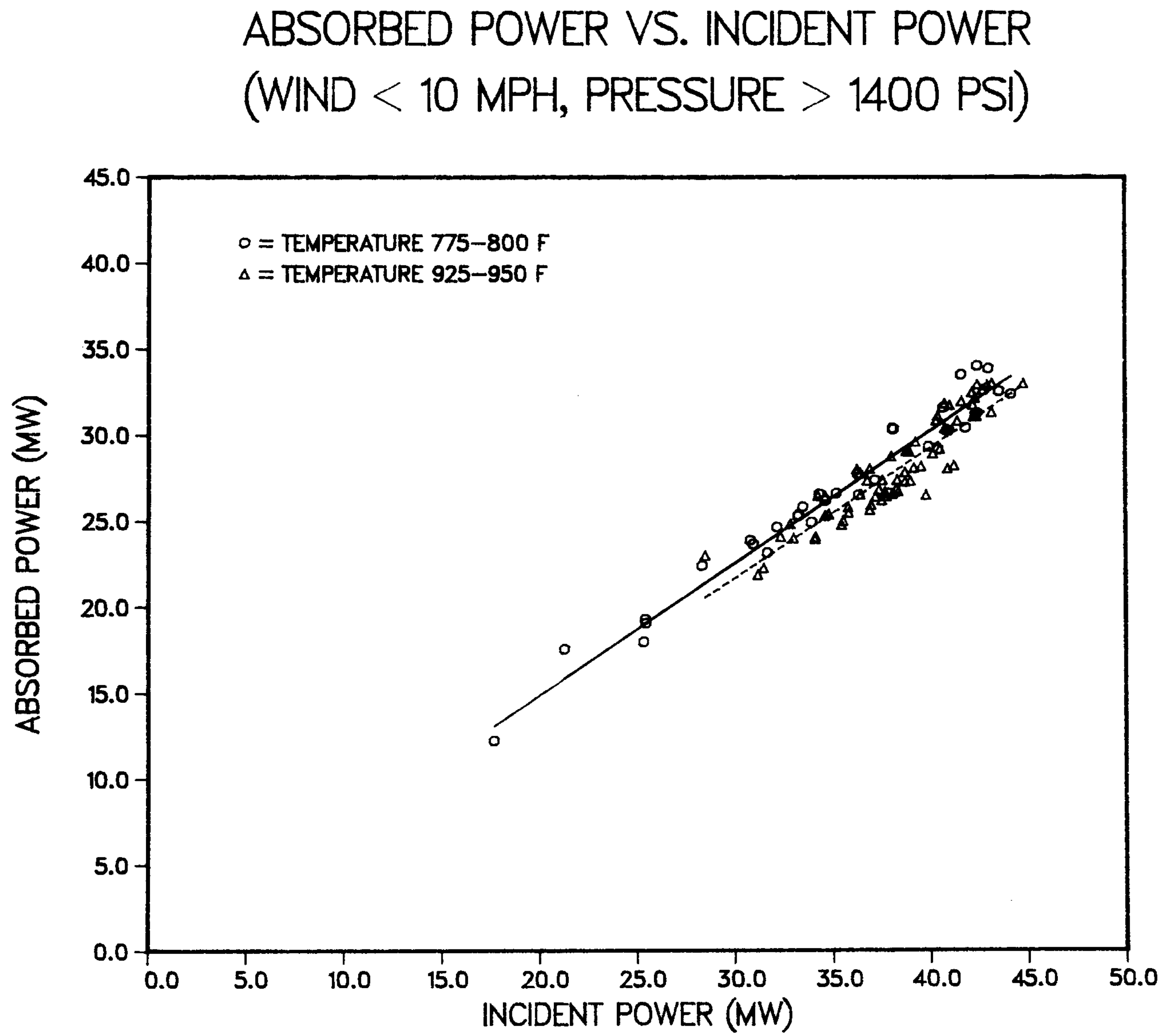

Figure 7. Trend data receiver absorbed power versus receiver incident power when operating at an outlet temperature between 775-800^{o}F and 925-950^{o}F with an outlet pressure above 1400 PSI and wind speeds less than 10 mph. The data shows a slight advantage in operating the receiver at lower outlet temperatures.

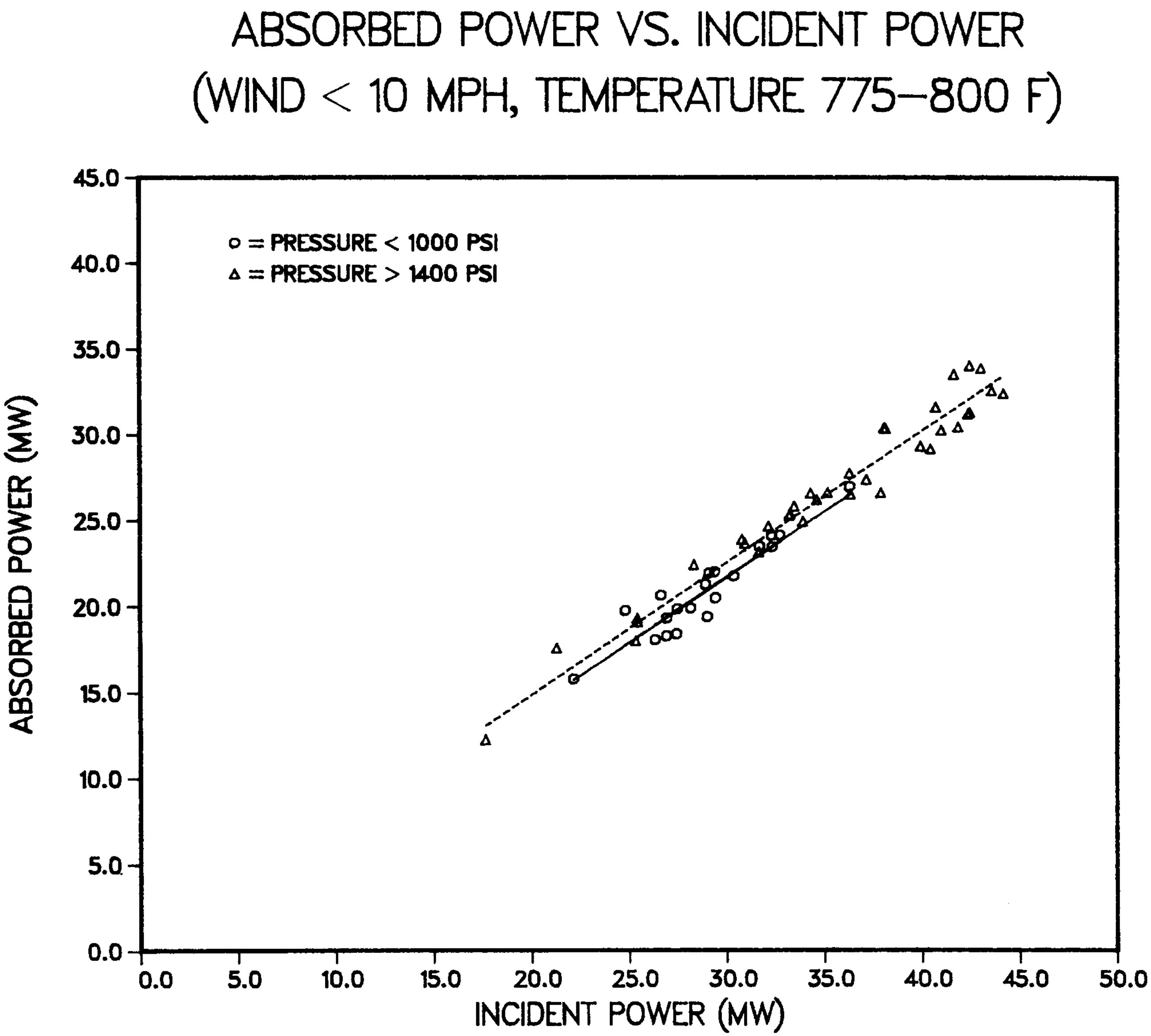

Figure 8. Trend data receiver absorbed power versus receiver incident power when operating at an outlet pressure below 1000 PSI and above 1400 PSI within an outlet temperature range of 775-800^{0}F with wind speed below 10 mph. There is a slight advantage in operating the receiver at higher outlet pressures.

The gross electric power produced by the plant in the turbine direct mode when the receiver outlet temperature was varied is shown in Figure 9. The receiver outlet pressure was above 1400 PSI. For the same receiver absorbed power at lower temperatures the water/steam flow through the receiver is increased. The data in Figure 9 indicates the turbine/generator produces more electricity with higher temperatures and lower flows than with lower temperatures and higher flows for pressures above 1400 PSI. Again the change is slight and there is a lot of scatter in the trend data. Evaluation of the data using a statistical test showed that there was a difference between the data sets.

There was almost no change in the net electric power delivered to the grid for a given amount of gross electric power produced with a receiver outlet temperature between 775-800^{o}F and 925-950^{o}F and the receiver outlet pressure above 1400 PSI. Figure 10 shows this comparison where there is very little scatter in the data. For a fixed receiver outlet pressure the only difference for these two temperature ranges is the flow through the receiver. At the lower outlet temperature the flow through the receiver is higher than for the high outlet temperature.

The receiver outlet temperature was varied with the pressure fixed at above 1400 PSI and wind speeds less than 10 mph to evaluate the change in net electric power for the turbine direct mode of operations versus receiver incident power. As before the two temperature ranges of 775-800^{o}F and 925-950^{o}F were used for the comparison. Figure 11 shows the results of this comparison. Because of the scatter in the data the statistical test was performed and the results show that there is a difference between the two sets of data. From Figure 11 it can be seen that there is a slight advantage in operating the plant at temperatures between 775-800^{o}F over the temperature range of 925-950^{o}F based on the comparison of the polynomial fits of the data. The difference between these two operating temperatures on any given day may or may not be seen as was the case on the part load test day of July 7, 1983. An analysis of the data fit equations shows that the differences between the curves is smallest at high values of the receiver incident power and increases as the receiver incident power is decreased.

For each set of parameters evaluated with different receiver operating conditions the differences were small. Because of the scatter in the data statistical tests were performed on the data sets to see that they were different. Only by comparing the data fit equations and their plots could differences be determined. Based on the trend data used there did not seem to be a set of operating conditions which would warrant changing normal operations of the plant. However, slight advantages were seen in operating the receiver at temperatures around 800^{o}F and at pressures above 1400 PSI. Given the uncertainty in the trend data receiver incident power calculation it is believed that the performance equations presented in the Performance Update section provide a reasonable representation of the receiver, turbine/generator, and plant.

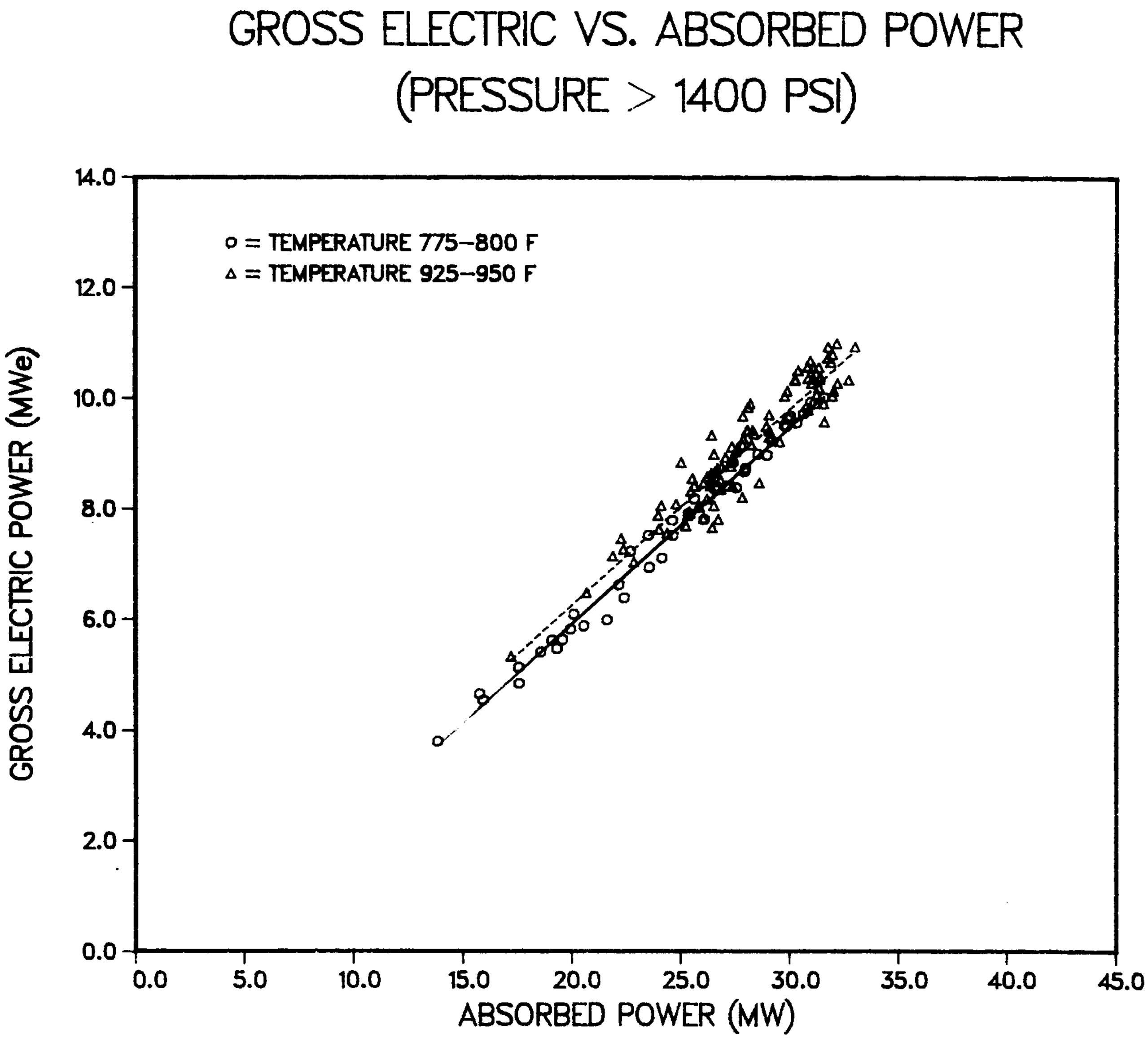

Figure 9. Trend data turbine/generator gross electricity produced versus receiver absorbed power for pressures above 1400 PSI and different absorbed power temperature ranges. Higher temperature operations show a slight advantage over lower temperature operation.

NET ELECTRIC VS. GROSS ELECTRIC POWER
(PRESSURE > 1400 PSI)

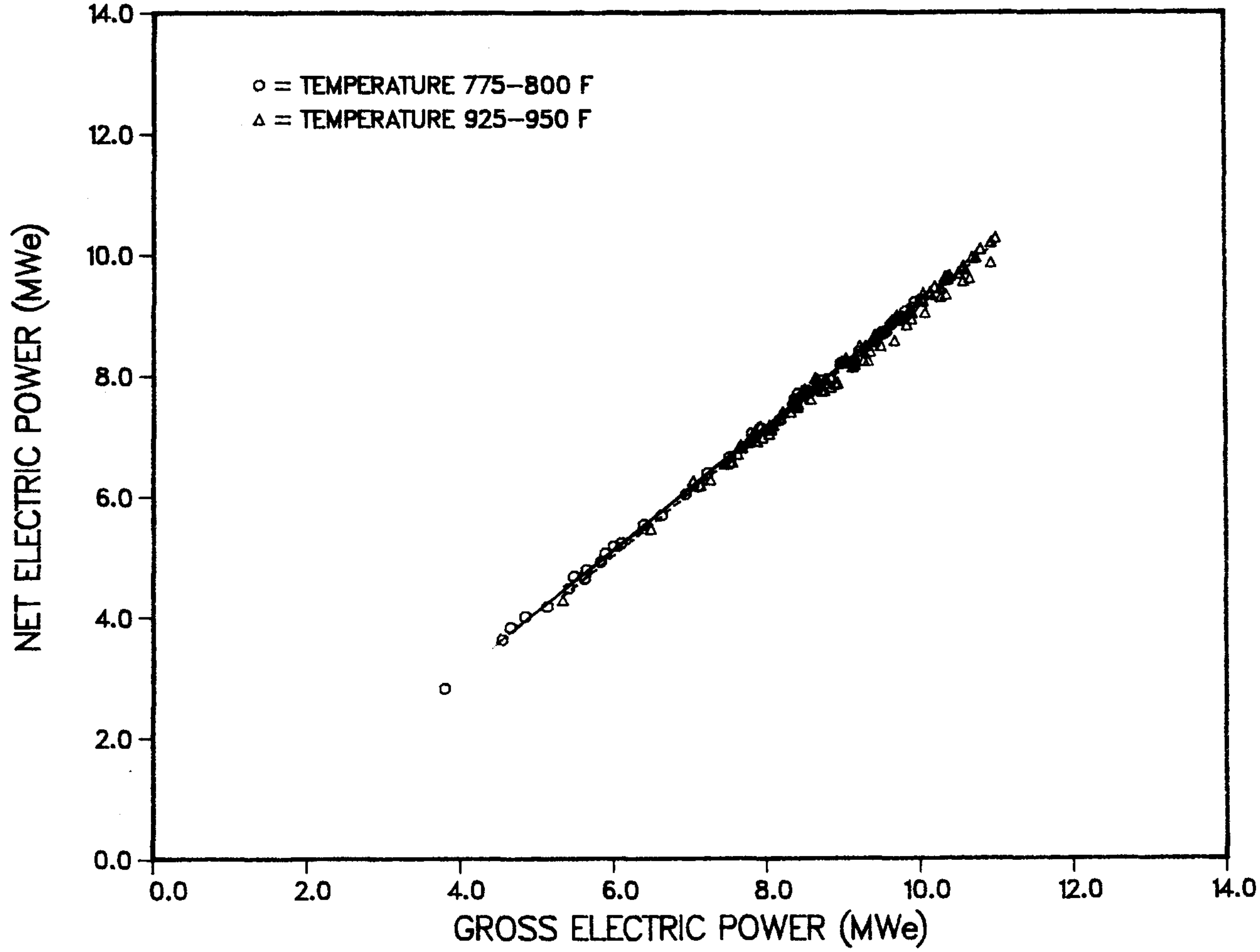

Figure 10. Trend data turbine/generator net electric power versus gross electric power with the receiver outlet temperature between 775-800^{o}F and 925-950^{o}F and the receiver outlet pressure above 1400 PSI. There is almost no difference between net electric power for these receiver outlet temperature ranges.

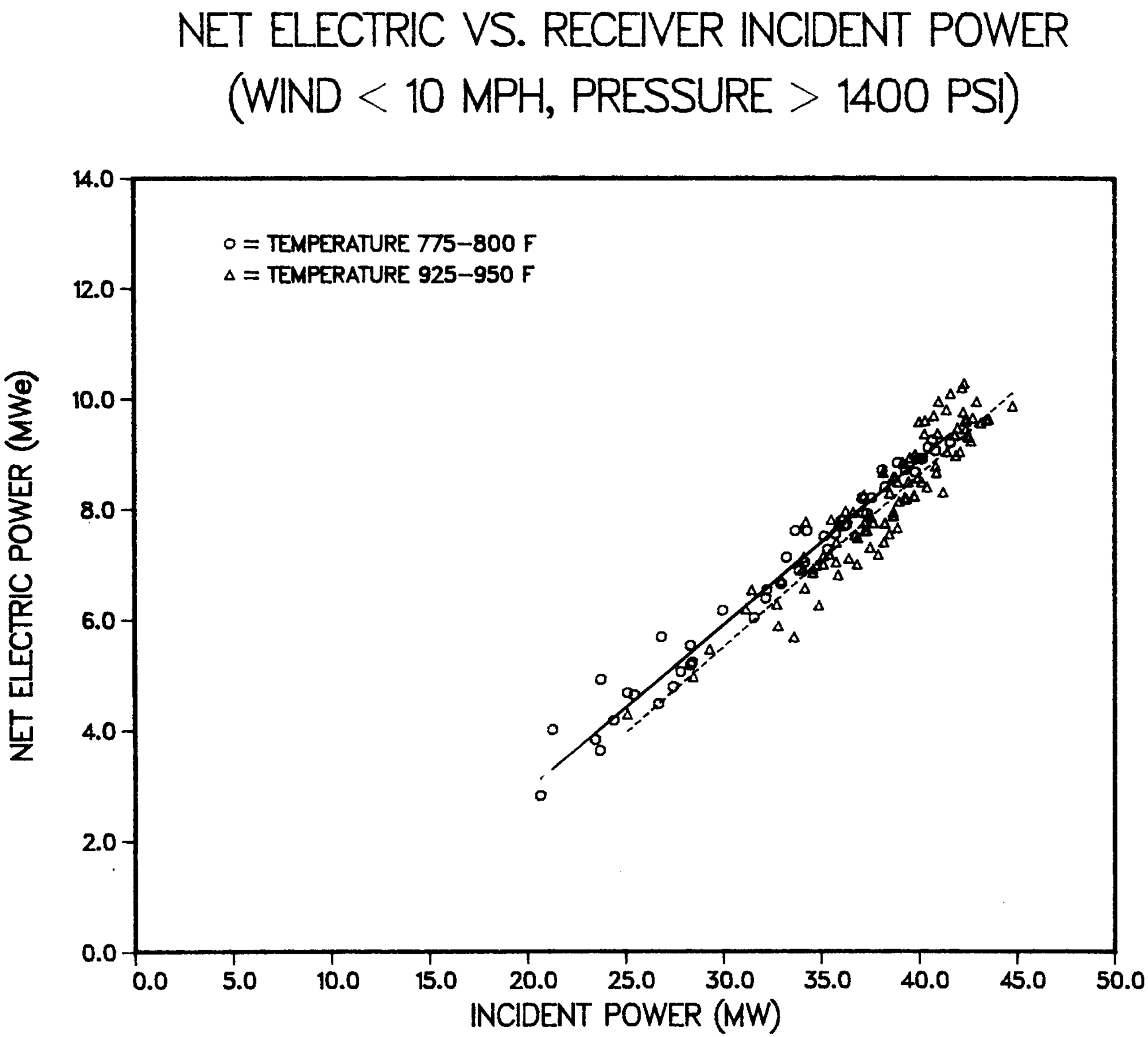

Figure 11. Trend data net electric power produced versus receiver incident power by the plant in turbine direct operations with the receiver outlet temperature between 775-800^{0}F and 925-950^{0}F and the receiver outlet pressure above 1400 PSI. There is a slight advantage in operating the receiver at lower outlet temperatures with the advantage increasing as the receiver incident power decreases.

The MIRVAL and trend data receiver incident power calculations do not take into consideration the wind speed. Thus, for a given set of heliostat field conditions the same receiver incident power would be calculated independent of wind speed. If the receiver absorbed power is reduced by increasing wind then this effect would be accentuated if the receiver efficiency (receiver absorbed power/receiver incident power) were plotted versus wind speed. Figure 12 is a plot of receiver efficiency versus wind speed for the receiver operating in the temperature range of 825-850°F with the pressure above 1400 PSI. It can be seen in Figure 12 that for wind speeds up to 20 mph there is a very slight decrease in receiver efficiency. An implication of the results in Figure 12 is that for this receiver forced convection heat losses are not an important factor for wind speeds up to 20 mph. This statement may be true for the entire receiver but an individual panel may have significant changes in its convective losses with changing wind speeds depending on its location relative to the wind direction.

Another receiver loss mechanism is that of radiation. In general radiation losses are a function of the receiver surface temperature to the fourth power minus the ambient temperature to the fourth power. If it is assumed that the receiver outlet steam temperature is related to the receiver surface temperature then a plot of the receiver outlet temperature to the fourth power minus the ambient temperature to the fourth power versus receiver efficiency would indicate a trend in radiation losses. Figure 13 is a plot of these absolute temperatures to the fourth power differences (TEMPERATURE DIFFERENCE (R4)) versus receiver efficiency. The trend data for this plot was for the cases in the trend data base when the receiver incident power was between 37 and 41 MWt, the wind speed less than 10 mph, and the receiver outlet pressure above 1400 PSI. It can be seen in Figure 13 that as the receiver outlet temperature increases there is a slight decrease in the receiver efficiency assuming a constant ambient temperature. A single panel could have greater changes in its efficiency as its outlet temperature is changed since a larger portion of its total area would be influenced by an outlet temperature change as compared to the entire receiver. These results agree with the trend found in Figure 7 where there was a slight advantage in receiver performance when operating in the temperature range of 775-800°F over that of 925-950°F.

System Operations Data

For each day between December 1, 1982 and December 31, 1983 when there is data on the summary data tapes selected data has been integrated to find its total value for the entire day, i.e. the times during the day when data exist on the summary data tape. For example the direct normal insolation, power available to the heliostat field (mirror area times insolation), receiver absorbed power and electric power produced have been integrated to determine corresponding energies. To find the total daily solar energy incident on the receiver the

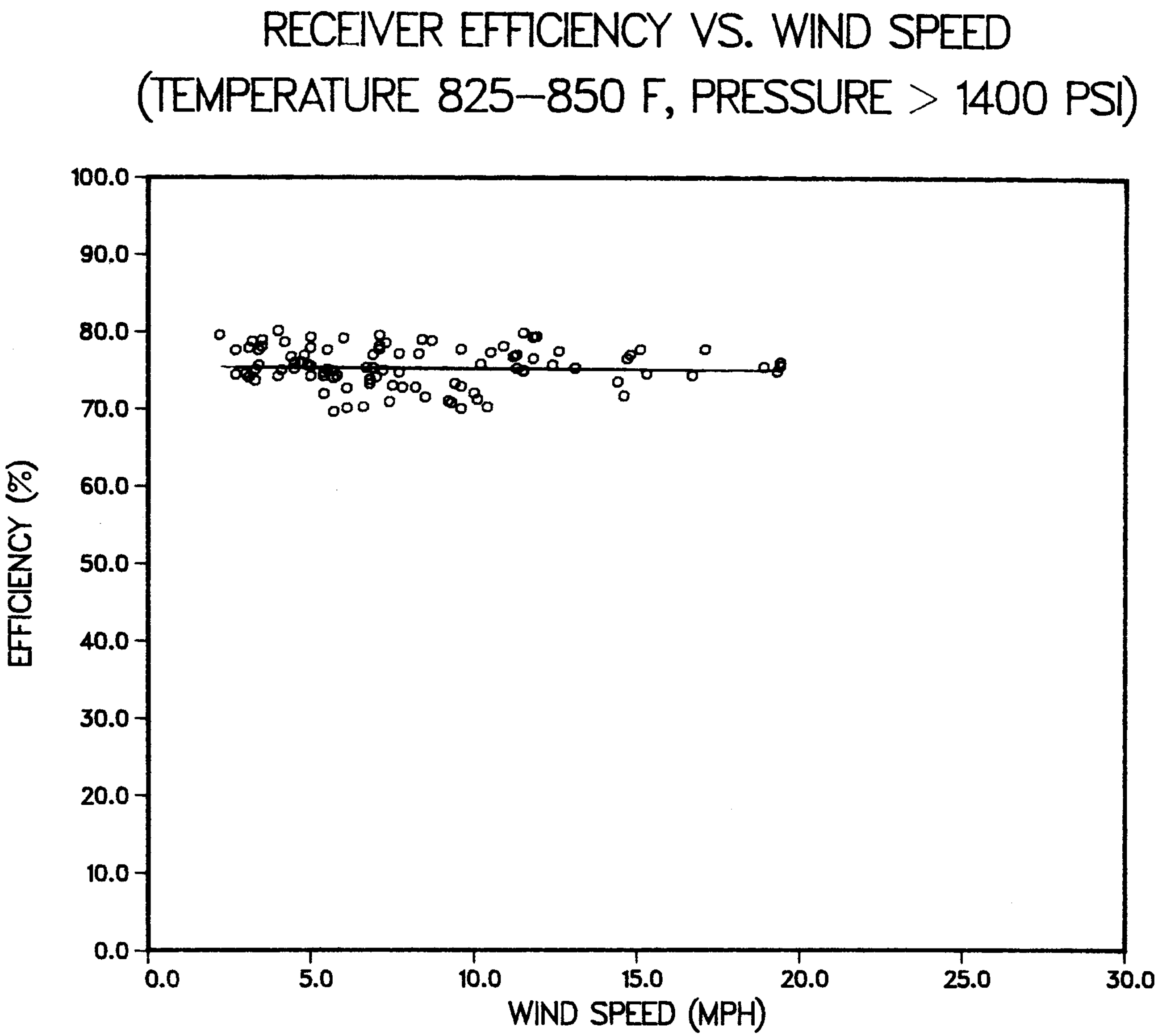

Figure 12. Receiver efficiency (receiver absorbed power/receiver incident power) versus wind speed. The calculation of the receiver incident power is independent of wind speed.

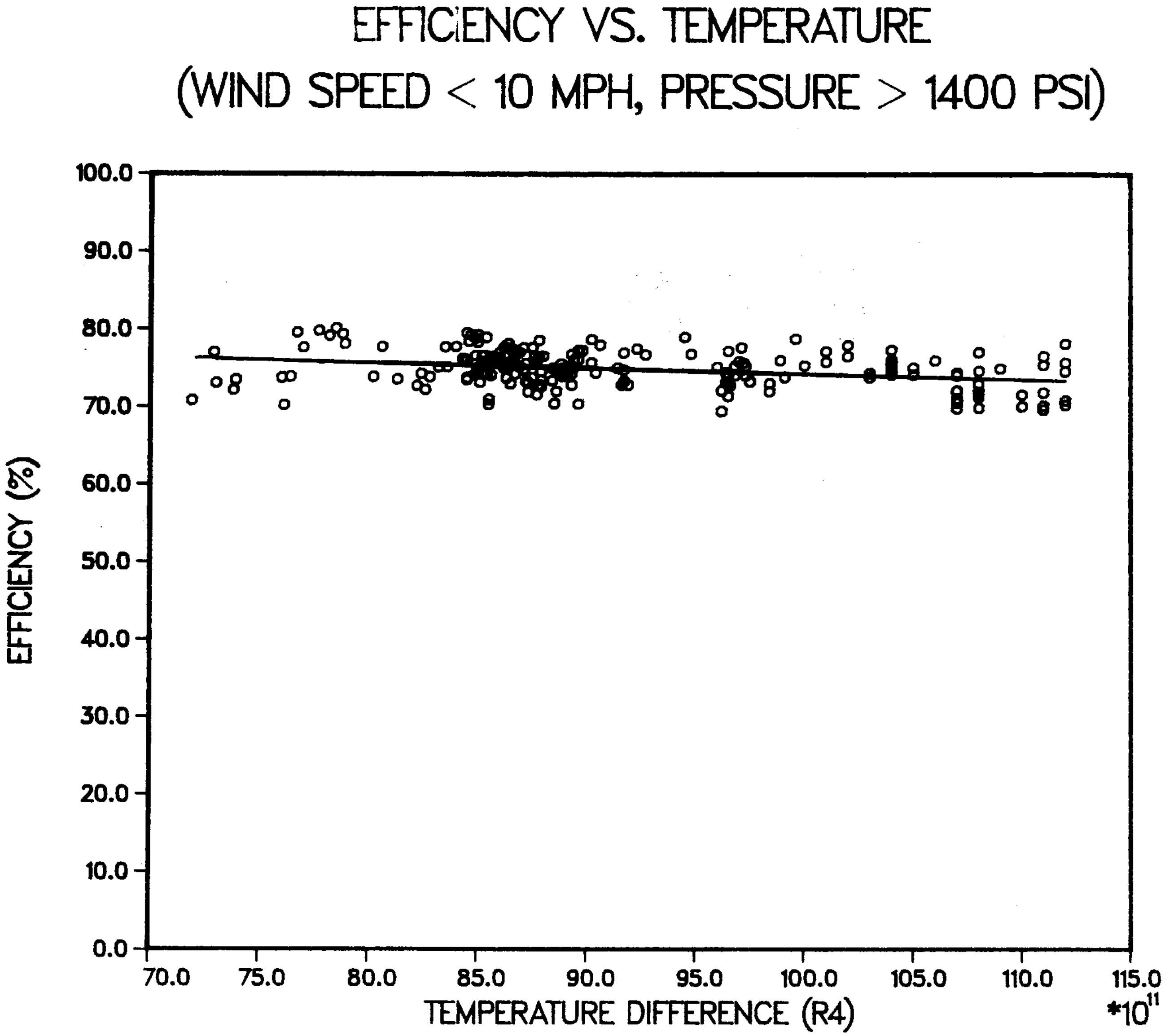

Figure 13. TEMPERATURE DIFFERENCE (R4) is defined as the absolute values of the receiver outlet steam temperature to the fourth power minus the ambient temperature to the fourth power. Data in this plot is for the receiver incident power between 37 and 41 MWt, wind speed less than 10 mph, and receiver outlet pressure above 1400 PSI. Efficiency is receiver absorbed power/receiver incident power.

incident power was calculated at each time step on the summary data tape using the method for the trend data base and then these calculated values were integrated. As before, except for the incident power on the receiver all other data used to report system operations average performance are based on measured data.

The operations of the pilot plant during the 13 months which are being evaluated for system average performance were part of the "Test and Evaluation Phase". The next phase is the "Power Production Phase" where the plant will be operated in a power production mode. During the test and evaluation phase the plant was not necessarily always run in a mode which would maximize electrical power production. However, the test and evaluation activities were performed during the week (Monday through Friday) and the plant was operated for power production on the weekends. Also, when there were no test and evaluation activities occurring during the week the plant was run in a power production mode.

Between December 1, 1982 and December 31, 1983 there are 396 days. Of these, 391 days are accounted for on the summary data tapes. The five missing days occurred at either at the start or end of a month when no data was recorded and the day was omitted from the summary data tape. During these 391 days there were 4,624.0 hours of time calculated between sunrise and sunset for an average value of 11.8 hours per day. There were 277 days on the data tapes which had "some" amount of measured direct normal solar insolation. This measured insolation accounted for a total of 2,639.0 hours and an average value of 9.5 hours per day. Thus about 58% of the total calculated time between sunrise and sunset are accounted for on the summary data tapes. The total measured direct normal insolation was 1,676.0 kw-hr/m2 with an average value of 6.1 kw-hr/m2 per day based on 277 days. Figure 14 shows both the daily and cumulative values of the measured direct normal solar insolation at the pilot plant. As can be seen from Figure 14 there were times when the insolation was not measured. These times usually occurred when the plant was shut down for either a scheduled or unscheduled outage. The seasonal trend in the length of the day is seen in Figure 14 with the days being short in the winter and longer in the summer.

The summary data tapes contained 237 days when thermal power was collected by the receiver at a temperature above $500^{O}F$. A total of 36,578.9 MWt-hr of power was collected with an average value 154.3 MWt-hr per day. Figure 15 shows the daily and cumulative thermal power production of the receiver. There were 174 days on the data tapes when the plant produced electricity either from thermal storage and/or directly from the receiver and 153 days when electricity was produced only directly from the receiver (Mode 1). Figure 16 shows the daily and cumulative total net electricity production from thermal storage and/or directly from the receiver. The values shown in Figure 16 are slightly different from those which have been reported elsewhere since the others are meter readings taken manually at the plant and those in Figure 16 were taken from the summary data tape.

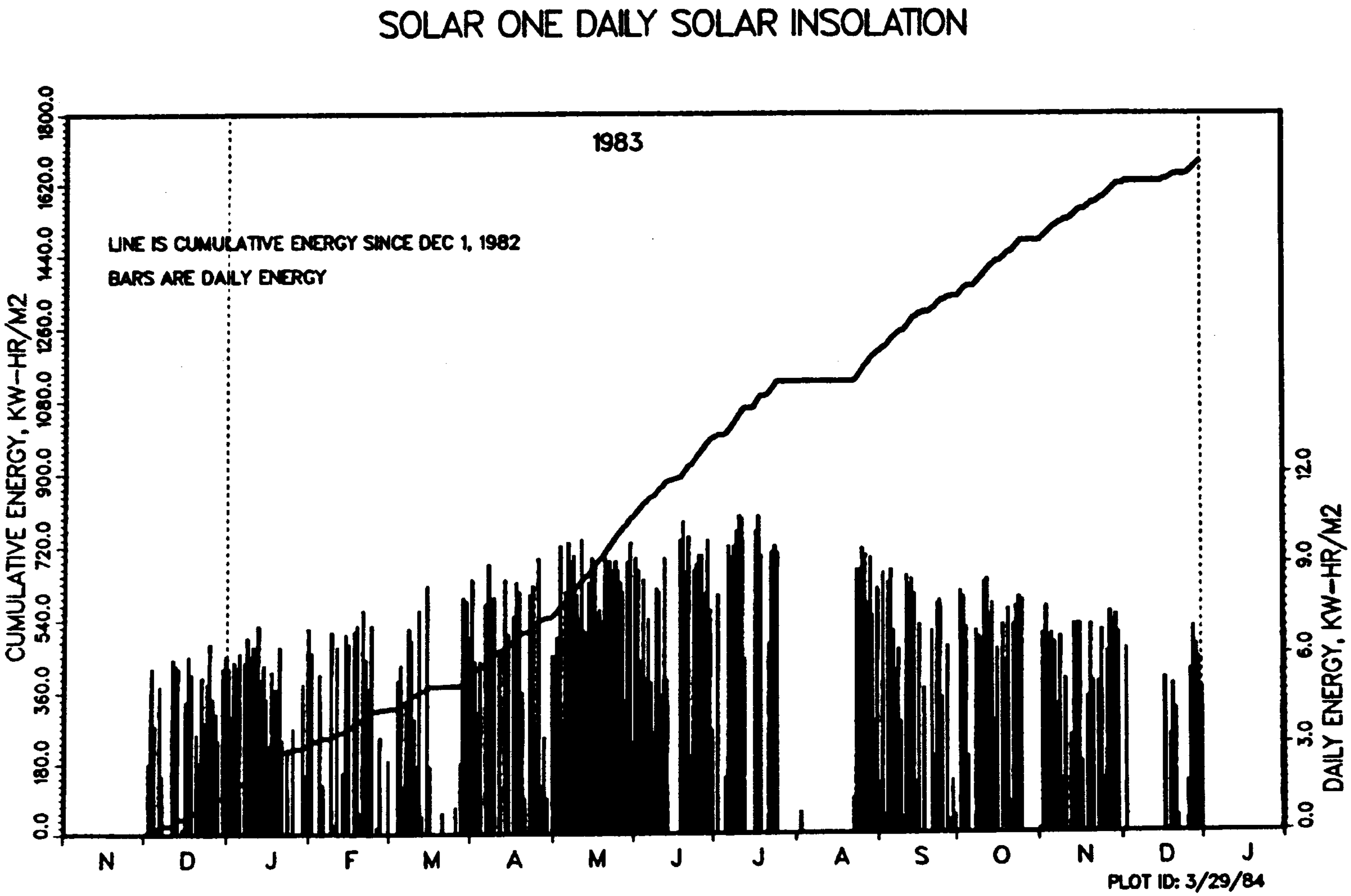

Figure 14. The daily measured direct normal insolation and cumulative values for 278 days at the plant from the summary data tapes. The data covers the time period between December 1, 1982 and December 31, 1983. No data occurs when the plant is shut down for scheduled or unscheduled outage.

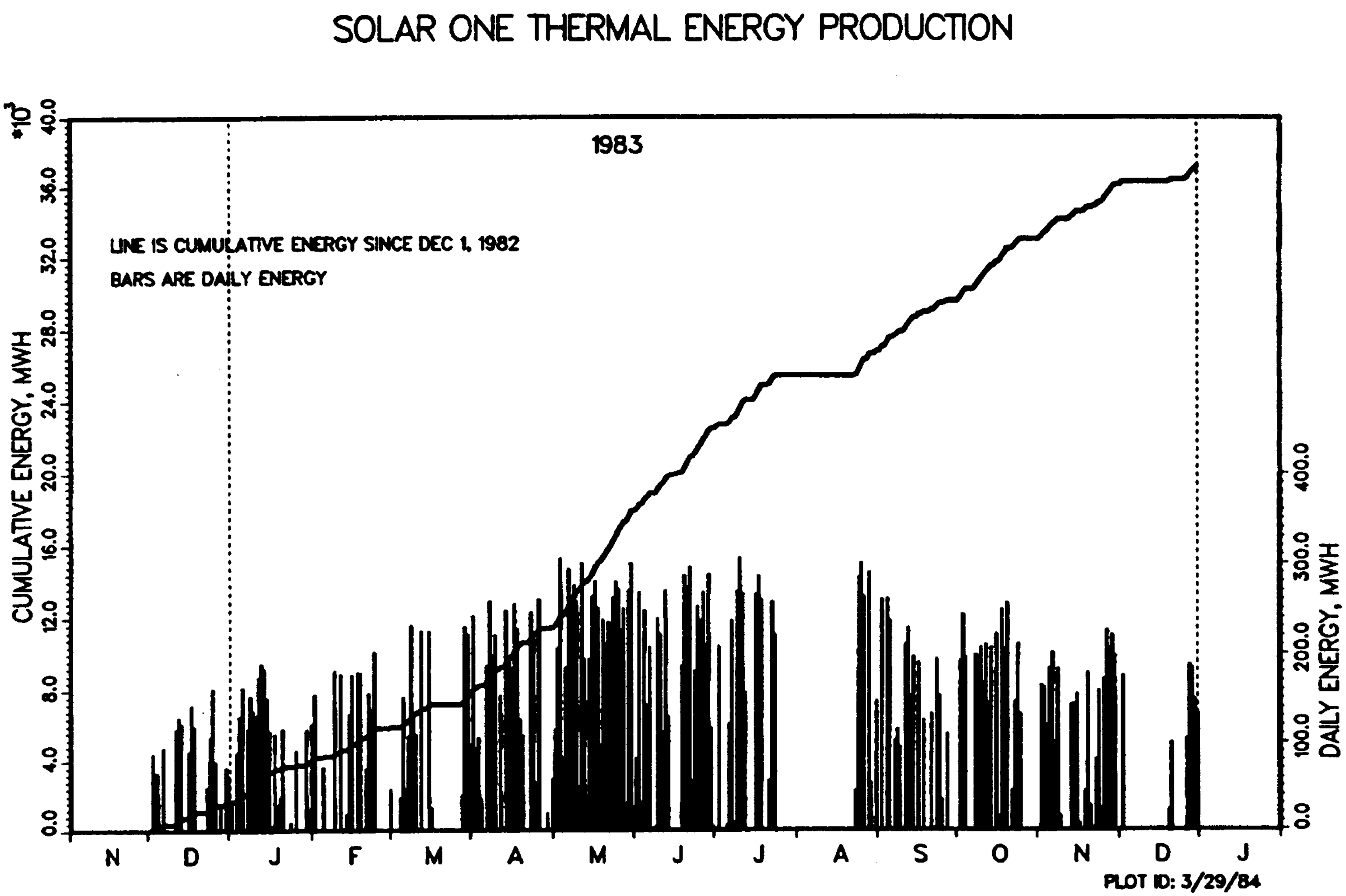

Figure 15. The daily calculated thermal power based on measured data for the receiver at steam outlet temperatures above 500°F and the cumulative values. The data is for 237 days between December 1, 1982 and December 31, 1983 from the summary data tapes.

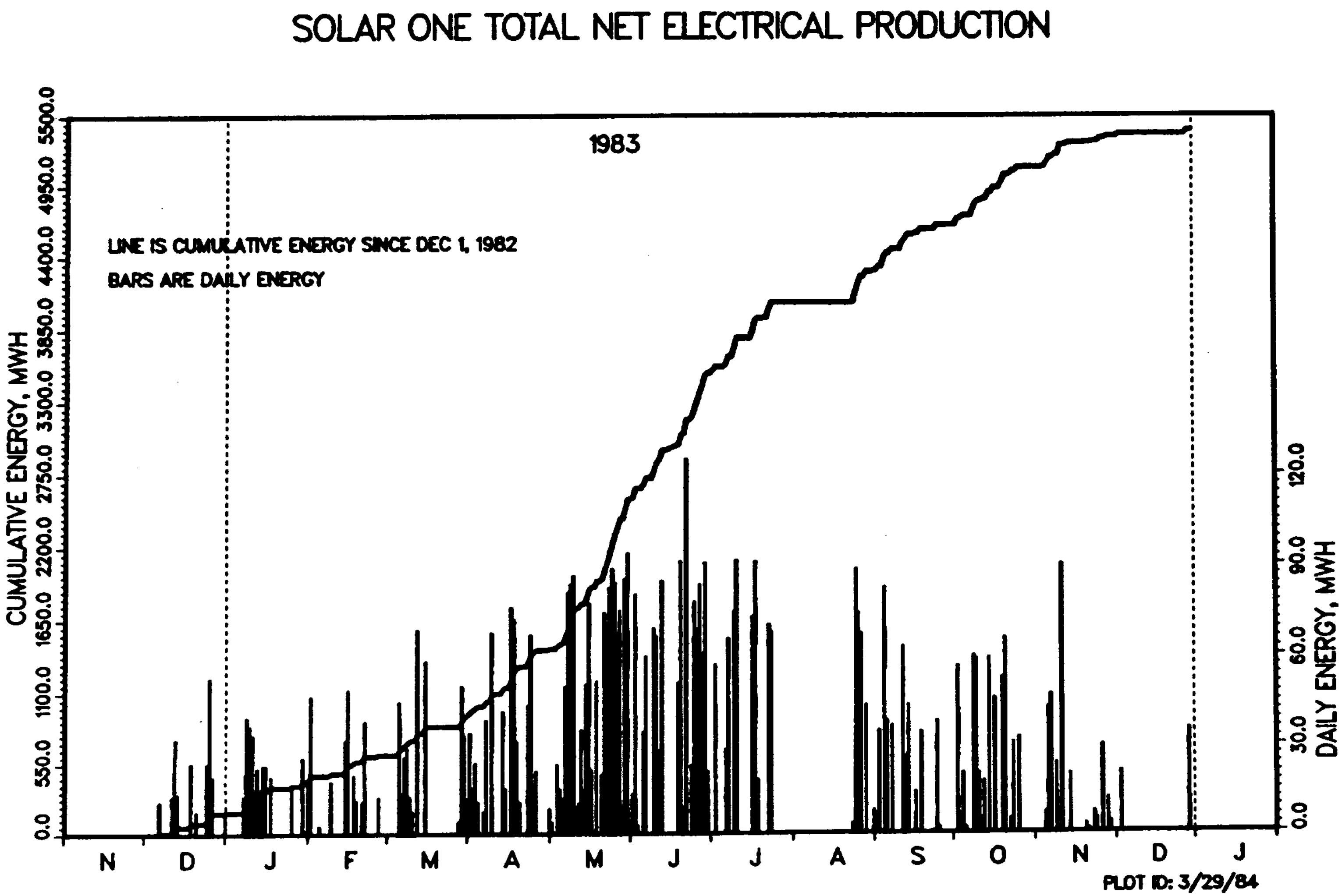

Figure 16. The daily measured net electrical power produced in any operating mode and cumulative values for the plant from the summary data tapes. The data is for 174 days during the period of December 1, 1982 to December 31, 1983.

The major design requirement for the pilot plant was that it would produce 10 MWe net for at least 7.8 hours on the design "best day" and for at least 4.0 hours on the design "worst day" when operating with steam from the receiver directly to the turbine (Mode 1). The summary data tapes show that the plant has produced 10 MWe net when operating in mode 1 on four (4) separate days. The total time at 10 MWe net for these four days is 2.4 hours with the longest time being 1.4 hours. Figures 17 and 18 show the daily hours and cumulative hours of mode 1 electrical production at or greater than 6.0 MWe net and 8.0 MWe net, respectively. In Figure 17 it can be seen that the plant has produced at least 6.0 MWe net for over 4.0 hours during the day in the winter months (worst days) and for over 7.8 hours during the day in the summer months days). However, in Figure 18 for mode 1 operations above 8.0 MWe net the plant produced 8.0 MWe net for about 3.0 hours during the day in the winter and for about 6.0 hours during day in the summer. The data from the summary data tapes during the time period being evaluated indicates that the pilot plant has not met its design requirement to produce 10 MWe net for a minimum of 4.0 hours on any day.

There are 210 days on the data tapes when there was enough information to calculate the incident power on the receiver and there was measured data to calculate the receiver absorbed power. However, of these 210 days electrical power production only occurred on 145 days. These 210 days include plant operations when thermal storage was being charged and discharged as well as Mode 1 operations. The following average performance values have been calculated:

Heliostat field efficiency (receiver incident energy/ energy available to the heliostat field)	47.1%
Receiver efficiency (receiver absorbed energy/ receiver incident energy)	68.9%
Plant thermal efficiency (receiver absorbed energy/ energy available to the heliostat field)	32.5%
System electric efficiency (net electrical energy/ receiver incident energy)	9.7%
Plant net electric efficiency (total net electrical energy/energy available to the heliostat field)	4.6%

Several points should be made about the data used for the above efficiencies:

1. The net electric energy is for only those times when the turbine/generator is in operation and does not include electricity consumption when the plant is operating without the turbine/generator or at night when the plant is not operating.

2. The energy available to the heliostat field is the product of the direct normal insolation and the normal area of the total heliostat field reflecting surfaces independent of the number of heliostats out of service, i.e. all heliostats are included.

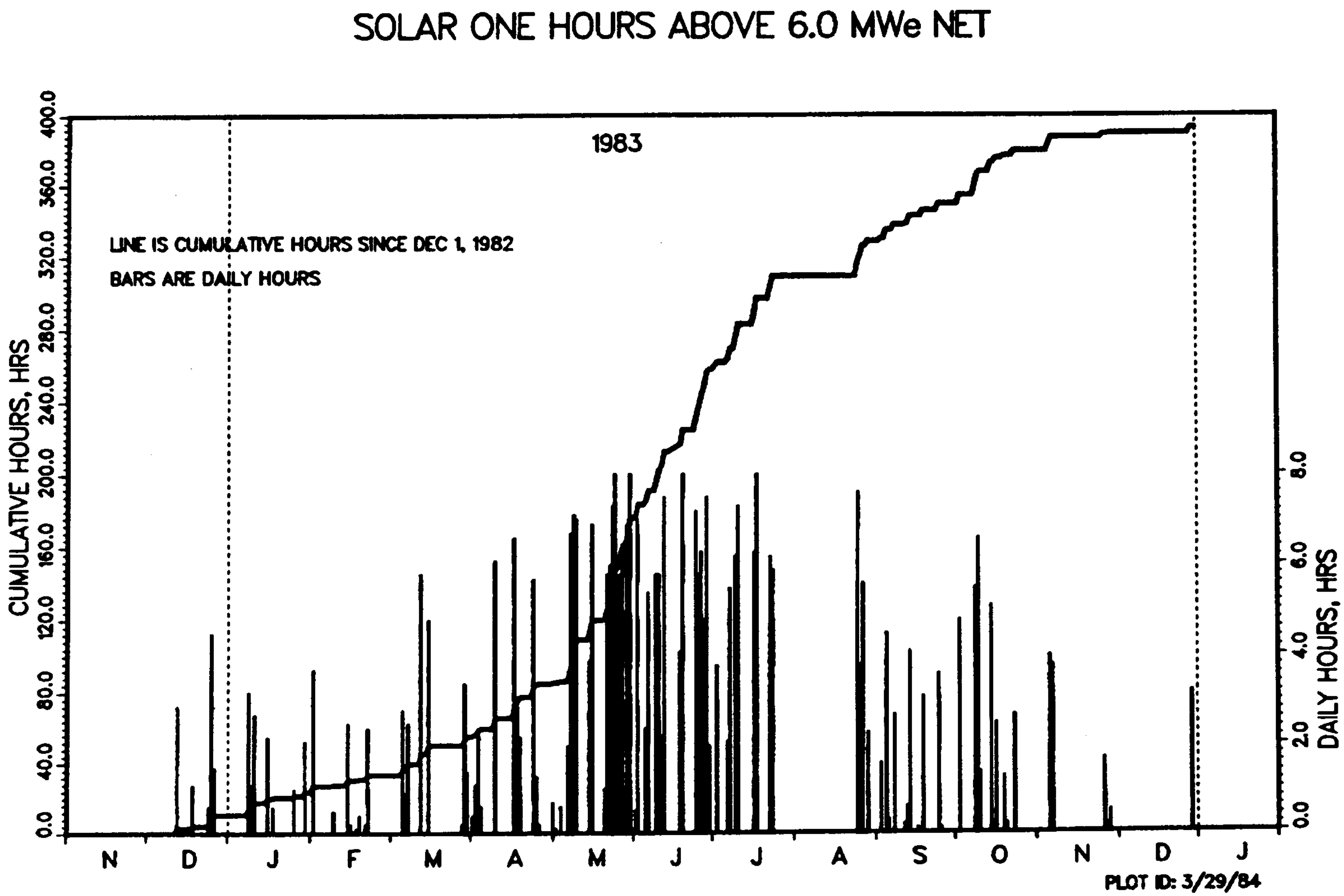

Figure 17. The daily hours of turbine direct net electrical power production at or above 6.0 MWe and the cumulative hours. The plant has produced 6.0 MWe net for over 4.0 hours in the winter and 7.8 hours in the summer.

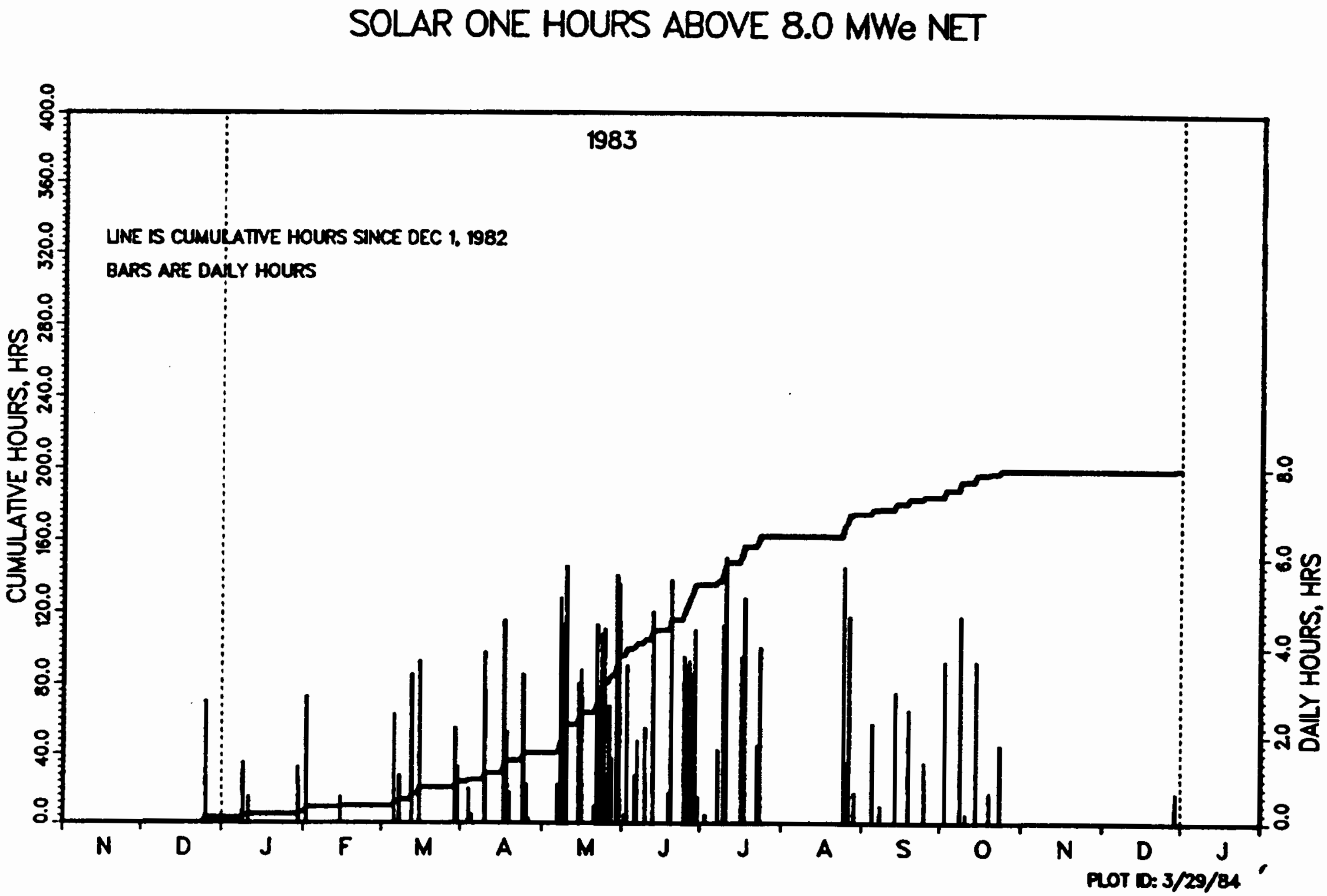

Figure 18. The daily hours of turbine direct net electrical power production at or above 8.0 MWe and the cumulative hours. The plant has produced 8.0 MWe net for about 3.0 hours in the winter and 6.0 hours in the summer.

3. The maximum possible value for the heliostat field efficiency is the field average clean mirror reflectivity. This value is reduced by heliostat shadowing and blocking, heliostats out of service, cosine effects, and dirty mirrors.

4. The system electric and plant net electric efficiencies are for 145 days of electric power production in any operating mode sometime during the day within 210 days the plant was operating.

Of these 210 days there were 81 days when there was information to calculate available energy to the heliostat field, incident power on the receiver, absorbed power by the receiver, and each day had electric power production in the turbine direct mode (Mode 1) sometime during the day. For these 81 days the plant was operated without thermal storage charging or discharging. For these days the average performances were:

Heliostat field efficiency (receiver incident energy/energy available to the heliostat field)	47.9%
Receiver efficiency (receiver absorbed energy/ receiver incident energy)	67.9%
Plant thermal efficiency (receiver absorbed energy/ energy available to the heliostat field)	32.5%
System electric efficiency (net electrical energy/ receiver incident energy)	15.4%
Mode 1 Plant net electric efficiency (net electrical energy/energy available to the heliostat field)	7.4%

There were 44 days when insolation was measured for all but one hour during the day between sunrise and sunset, the average insolation was above 500 watts/m2, heliostat tracking started within one hour of sunrise, and the receiver operated for all but three hours during the day. The plant was operated in any mode, i.e. charging storage, discharging storage, and/or mode 1. The average performances for these days were:

Heliostat field efficiency (receiver incident energy/ energy available to the heliostat field)	55.8%
Receiver efficiency (receiver incident energy/ receiver absorbed energy)	69.8%
Plant thermal efficiency (receiver absorbed energy/ energy available to the heliostat field)	38.9%
System electric efficiency (net electric energy/ receiver incident energy)	11.6%
Plant net electric efficiency (net electric energy/ energy available to the heliostat field)	6.5%

For these 44 days the average time to get steam in the downcomer, i.e. superheated steam from the tower, was 1.9 hours, the average time to get all available heliostats to track the receiver even though some heliostats started tracking the receiver earlier was 2.5 hours, and the average time to start producing electricity in mode 1 (steam direct from the receiver) was 3.9 hours. There were 18 days included in the 44 days where the plant was run only in Mode 1. For those 18 days of Mode 1 operation the average performances were:

Heliostat field efficiency (receiver incident energy/ energy available to the heliostat field)	55.7%
Receiver efficiency (receiver absorbed energy/ receiver incident energy)	68.7%
Plant thermal efficiency (receiver absorbed energy/ energy available to the heliostat field)	38.2%
System electric efficiency (net electric energy/ receiver incident energy)	16.7%
Mode 1 Plant net electric efficiency (Mode 1 net electric energy/energy available to the heliostat field)	9.3%

Comparing the average performances for the case of 44 days of operations in any mode, i.e. electric power production from either thermal energy storage or turbine direct, with those for the 18 days of operations in the turbine direct mode shows the effect of the loss of energy going through thermal energy storage. Even though the heliostat field, receiver, and plant thermal efficiencies are about the same there is a decrease in the system electric and plant net electric efficiencies. The differences between the average performances for the 81 days of turbine direct operations and those for the 18 "good" days of turbine direct operations show in part the effect of not getting all the working heliostats tracking the receiver as early as possible, i.e. heliostat field efficiency of 47.9% versus 55.7%. This can also be seen in the difference between the Mode 1 plant net electric efficiency of 7.4% for the 81 days case and 9.3% for the 18 "good" days while the system electric efficiencies are about the same, i.e. 15.4% versus 16.7%.

The data which has been included in this "System Operations Data" section is for average performances based on energy where the "Performance Update" section was for point-in-time data based on power. Two different definitions have been used to define efficiencies, i.e., (1) receiver incident power or energy as the bases and (2) power or energy available to the heliostat field as the bases. When the receiver incident power (energy) is used then the efficiencies are for the actual calculated power (energy) into the system. The power (energy) available to the heliostat field efficiencies are based on the maximum possible power (energy) available and not on any actual power (energy) to the plant. A comparison of point-in-time performance using receiver incident power and average performances using the receiver incident energy as the bases is as follows:

	Point-in-time		Average values	
	Design Point Dec. 21 @ 2:00 pm	Data Fit Equations	81 Days	18 "good" Days
Receiver	81.2%	76.8%	67.9%	68.7%
Net electric	23.7%	21.7%	15.4%	16.7%.

A similar comparison using the power or energy available to the heliostat field as the bases results in the following:

	Point-in-time Dec 21 @ 2:00 pm	Average values 81 days	18 "good" days
Heliostat field	63.7%	47.9%	55.7%
Receiver	51.4%	32.5%	38.2%
Net electric	15.0%	7.4%	9.3%.

The comparison of point-in-time data at near maximum plant output levels as is the case here and average performances over many days using the receiver incident power (energy) as bases shows the effects of operating the plant at less than rated power. Figure 6 showed that both the receiver and net electric efficiencies decrease as the level of the receiver incident power decreases. When the power (energy) available to the heliostat field is used for the comparison between the design point and average values the influence of not having all the heliostats in service, dirty mirrors, daily average cosine effects, daily average shadowing and blocking, and operating at less than rated conditions are apparent.

Operational Requirements

To assess if the pilot plant would meet its design requirement of producing 10 MWe net for 7.8 hours on the design "best day" defined as June 21 and for 4.0 hours on the design "worst day" defined as December 21 the equations developed in the Performance Update section are used. This assessment will use the "look up table" for the heliostat field performance with all the heliostats, i.e., 1818, tracking the receiver, clean mirror reflectivity (.906 field average), and the insolation data specified during the design phase for the two design days.

Assuming that the 7.8 hours and 4.0 hours of operation are symmetric around solar noon the following data for the two design days has been calculated (times are in local standard time (LST):

	June 21	December 21
Sunrise	4:37	6:55
Operation start to meet req.	7:55	9:45
Solar noon	11:47	11:45
Operation stop to meet req.	15:43	13:45
Sunset	18:56	16:35
Time available for start-up (sunrise to operation start)	3:18	2:50

The operation start times to meet the operational requirement are with all heliostats tracking the receiver and the turbine/generator online in the turbine direct mode of operation. A review of the operations data from the summary data tapes shows that in the past it has not been routine to have the plant producing electricity in the turbine direct mode within 2:50 from sunrise with all available heliostats tracking the receiver. However, recent data for the first two months of 1984 shows that this has been possible on several occasions. Thus, the design requirement start-up can be meet by the plant.

The following insolation values were taken from the insolation curves for the two design days:

Time	June 21	December 21
Operation start time	920 w/m2	920 w/m2
Solar noon	990 w/m2	960 w/m2
Operation stop time	920 w/m2	920 w/m2

Using the current performance equations developed in the Performance Update section of this report, operation start times, solar noon times, operation stop times, and design values of insolation the following results were obtained:

Item	June 21	December 21
Operation start		
Heliostat field performance (%)	71.	72.
Receiver incident power (MWt)	42.14	42.72
Receiver absorbed power (MWt)	32.38	32.85
Gross electric power (MWe)	10.13	10.29
Net electric power (MWe)	9.18	9.33
Solar noon		
Heliostat field performance (%)	80.	77.
Receiver incident power (MWt)	50.97	47.61
Receiver absorbed power (MWt)	39.49	36.79
Gross electric power (MWe)	12.54	11.63
Net electric power (MWe)	11.57	10.66
Operation stop		
Heliostat field performance (%)	71.	72.
Receiver incident power (MWt)	42.14	42.76
Receiver absorbed power (MWt)	32.38	32.88
Gross electric power (MWe)	10.13	10.30
Net electric power (MWe)	9.18	9.35

As can be seen from the above data used for this assessment the plant would not produce 10 MWe net for 7.8 hours on June 21 or for 4.0 hours on December 21 with 1818 heliostats tracking the receiver, clean mirrors, and design insolation. However, on both design days at solar noon the plant would produce 10 MWe net in the turbine direct mode for the design conditions. As had been noted several times in this report questions still exist as to the actual incident power on the receiver and these questions are being addressed during the balance of the test and evaluation phase of the program. Also, investigations of receiver absorptivity and thermal losses between the receiver and turbine/generator will continue. Other than the receiver incident power, measured data has been used for this operational requirement assessment. It is known that to date the plant has not met the design requirement.

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3. "10 MWe Solar Thermal Central Receiver Pilot Plant Solar Facilities Design Integration Heat and Mass Balance Design Analysis (RADL ITEM 2-15)", SAN/0499-47, MDC G8255, Revised February 1980.

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