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# Monograph Series No. 3: 10 MWe Solar Thermal Central Receiver Pilot Plant Receiver Solar Absorptance Measurements and Results

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# MONOGRAPH SERIES NO. 3: 10 MWe SOLAR THERMAL CENTRAL RECEIVER PILOT PLANT RECEIVER SOLAR ABSORPTANCE MEASUREMENTS AND RESULTS

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## ABSTRACT

Solar absorptance data on Pyromark painted receiver panels at the 10 MWe Solar Thermal Central Receiver Pilot Plant located near Barstow, California are reported. Measurements were made in 1982, 1983, and 1984. Selected measurements were made in 1985 after one receiver panel was repainted with Pyromark. The results show a linear decrease in the solar absorptance with time from an original average value of 0.92 to 0.88 after 663 days. The decrease in solar absorptance correlated with the higher incident solar flux levels on the receiver panels and not with the operating temperature of the panels. Repainting of one receiver panel successfully increased the solar absorptance to a value above 0.96.

## SOLAR THERMAL TECHNOLOGY
## 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 or Fresnel lenses 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 100$^{o}$C in low-temperature troughs to over 1500$^{o}$C 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.

To meet the performance targets developed for central receiver systems, the performance of currently operating systems needs to be understood. Since the amount of concentrated radiant energy absorbed by the solar thermal receiver is directly affected by the solar absorptance of the receiver surface, this material property needs to be measured and its change, if any over a period of time, evaluated. This report gives the results of the measurements of the receiver solar absorptance at the 10 $MW_e$ Solar Thermal Central Receiver Pilot Plant located near Barstow, California over several years.

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## SUMMARY

The receiver panels on the 10 MWe Solar Thermal Central Receiver Pilot Plant near Barstow, California, are painted with Pyromark (Ref 1), a high temperature, nonselective black paint. The Pyromark paint was applied in early 1981 and cured after the panels were installed on the central receiver tower at the site in early 1982. The cure was accomplished using the sun's energy reflected from the heliostat field to heat the panels. Nominal recommended cure temperatures and times were used to cure the panels except for the final temperature-time of 535°C (1000°F) for twenty-four hours. The maximum temperature over most of the panels even when operating at the design superheated steam outlet temperature for the cure was below 385°C (725°F). Only the top of the boiler panels experienced temperatures near the recommended final cure temperature.

The solar absorptance measurements were made using a solar spectrum reflectometer manufactured by Devices and Services Co. of Dallas, TX. For flat samples, the instrument is accurate to +/- 0.01 absorptance units; the necessity of generating correction factors for measurements on the small tubes reduces the accuracy to about +/- 0.02 absorptance. The instrument measures the solar spectrum reflectance and the absorptance is calculated as one minus the correction factor times the measured reflectance. In most cases the number of measurements made was such that the 90% confidence interval on the panel average solar absorptance was +/-0.005 absorptance units.

The average solar absorptance for the receiver was calculated using the individual panel averages but each panel average value was weighted based on a representative noon time distribution of solar energy incident on the receiver. Thus, more weight was given to the average solar absorptance of the panels which have the most incident solar energy and less to panels with less incident solar energy. The results from the measurements and calculations for the receiver are:

| YEAR | WEIGHTED AVERAGE RECEIVER SOLAR ABSORPTANCE |
|---|---|
| 1982 | 0.92 |
| 1983 | 0.90 |
| 1984 | 0.88 |

In general, the trend in the individual panel average solar absorptance and the vertical distribution on selected panels changed from year to year. In 1982 the water preheat panels had higher solar absorptance than the boiler panels. The range in the boiler panel average solar absorptance was from about 0.91 to 0.93. The vertical distribution of the selected panels examined was fairly uniform. By 1983 the three low temperature water preheat panels had higher average

solar absorptance than the high temperature water preheat panels and the boiler panels. Several boiler panels had higher average solar absorptance than the three high temperature water preheat panels. The vertical distribution of the solar absorptance on selected boiler panels showed a relative increase from the bottom (low temperature end) to the top (high temperature end). In 1984 the three low temperature water preheat panels still had the highest average solar absorptance but their values decreased as the incident solar flux increased from panel to panel. As in 1983 the three high temperature water preheat panels had lower average solar absorptance than several boiler panels. The range in the boiler panel average solar absorptance was from about 0.87 to 0.90. The vertical distribution of the solar absorptance on the examined boiler panels was lowest at the bottom, fairly uniform in the middle, and highest near the top.

Data from the one panel which was repainted with Pyromark and cured as the original panels showed an improvement in its average solar absorptance from 0.87 to about 0.97. There were a couple of areas where the Pyromark paint could be wiped off the tubes or the panel had the same appearance as when the paint was wiped off where the measured solar absorptance was about 0.94 to 0.95. This may indicate that further improvements are needed in the panel cleaning and/or painting techniques.

Data over the measurement period shows that the individual panel average solar absorptance and the weighted average receiver solar absorptance have decreased. The receiver panels with the lowest operating temperature had the highest measured solar absorptance. The panel to panel variation of the solar absorptance within the group of low temperature water preheat panels, high temperature water preheat panels, and boiler panels which all operate within their group with about the same temperature distribution and outlet temperatures show a decrease in average solar absorptance with an increase in incident solar flux. The vertical solar absorptance distribution on the boiler panels by the last measurement period shows the lowest solar absorptance near the bottom of the panel (low temperature and low incident solar flux) and in the middle of the panels (moderate temperature and highest incident solar flux). The highest solar absorptance usually occurred at the top of the boiler panels (high temperature and low incident solar flux). Over the solar absorptance measurement time period the two spare panels showed very little change in their average solar absorptance compared to the panels on the receiver.

# MONOGRAPH SERIES NO. 3: 10 MWe SOLAR THERMAL CENTRAL RECEIVER PILOT PLANT RECEIVER SOLAR ABSORPTANCE MEASUREMENTS AND RESULTS

## Introduction

The receiver at the 10 MWe Solar Thermal Central Receiver Pilot Plant located near Barstow, California, is shaped as a right circular cylinder with the axis of rotation of the cylinder as the receiver vertical axis. Subcooled water enters the receiver and exits as superheated steam. The receiver is 7.01 m (23 ft) in diameter and 13.7 m (45 ft) in height. It consists of twenty-four panels, six are water preheat panels and eighteen are water-to-steam boiler panels. Water enters the receiver where it flows in parallel through the three low temperature water preheat panels, then flows in parallel through the three high temperature water preheat panels, and finally water flows in parallel through the eighteen boiler panels where it exits as superheated steam. For all panels, the inlet is at the panel bottom and the outlet at the top. Each panel has seventy parallel tubes welded together on the back of the panel. The tubes, made of Incoloy 800, are 1.27 cm (0.5 inch) outside diameter with a 0.3175 cm (0.125 inch) wall thickness. The receiver is designed to operate with an inlet water temperature to the first preheat panels of about 175$^{o}$C (350$^{o}$F) and an outlet superheated steam temperature from all of the boiler panels of about 510$^{o}$C (950$^{o}$F). The water inlet pressure is about 10.7 MPa (1550 psia) and the outlet superheated steam pressure is about 10.0 MPa (1450 psia). The receiver panels are painted with Pyromark, a high temperature, nonselective black paint.

After the receiver panels were coated with the Pyromark paint they were to be cured following a recommended cure temperature-time cycle. The final recommended cure temperature-time is 535$^{o}$C (1000$^{o}$F) for twenty-four hours. However, because of the size of the panels, they were not cured following the recommended cycle but were cured after the panels were installed on the tower at the Pilot Plant using the sun's energy reflected from the heliostat field to heat the panels. The panels were painted with Pyromark in early 1981 and the paint was cured in early 1982. Due to weather and mechanical problems this curing cycle extended over several days. The receiver was first exposed to solar radiation from the heliostat field in February 1982. The Pyromark paint curing at superheated steam temperatures was completed by the end of February 1982. Two spare receiver panels which are located painted side up, on the ground were not cured. Nominal recommended cure temperatures and times were used to cure the panels except for the final temperature. The maximum temperature over most of the panels even when operating at the design superheated steam outlet temperature for the cure was below

385°C (725°F). Only the top of the boiler panels experienced temperatures near the recommended final cure temperature. When heating the panels after they are installed, there is a temperature gradient from the bottom to the top of the panels. The bottom of the panels are at a lower temperature than the top of the panels.

After the Pyromark paint curing, the receiver was operated whenever possible while various systems were activated. This process included receiver operations at rated and derated receiver steam outlet temperatures. The first receiver panel Pyromark paint solar absorptance measurements were made in November 1982. Further solar absorptance measurements were made in December 1983 and September 1984. One receiver panel and some small samples were repainted in March 1985. The small samples were attached to a panel next to the repainted panel at several vertical locations. Solar absorptance measurements were made on the repainted panel, small samples, and the neighboring panels in April 1985.

This report describes the solar absorptance measurement technique and results. Trends in absorptance variations among panels with different temperature and incident solar flux levels are assessed. A method of repainting the receiver has been developed; a single boiler panel has been repainted. Both the repainting method and subsequent absorptance measurements on the repainted panel are described.

## Solar Absorptance Measurements

The solar absorptance measurements were made using a solar spectrum reflectometer manufactured by Devices and Services Co. of Dallas, TX. For flat samples, the instrument is accurate to +/- 0.01 absorptance units; the necessity of generating correction factors for measurements on the small tubes reduces the accuracy to about +/- 0.02 absorptance (Ref 2). The instrument measures the solar reflectance and the absorptance is calculated as one minus the correction factor times the measured reflectance.

For each solar reflectance value measured, the solar spectrum absorptance was calculated using the following equation:

Absorptance = 1 - (Correction Factor) * (Measured Reflectance).

The correction factor takes into account that the measurements are being made at the crown of a round tube rather than on a flat sample. Each corrected solar absorptance value is accurate to about +/- 0.02 absorptance units. It is assumed that the solar absorptance values measured on the panels are normally distributed. When dealing with normally distributed random data with an unknown standard deviation, Student's t distribution is used to set confidence limits. A 90% confidence interval was used to evaluate this solar absorptance data. Based on this confidence interval the number of data points taken on each panel exceeded the number required to keep the magnitude of the sampling error below the measurement error. The magnitude of the sampling error calculated for this data was based on the following equation:

Error = (t(n-1,0.05) * s)/SQRT(n)

where t(n-1,0.05) is a constant determined from tables of the t distribution, s is the estimate of the standard deviation calculated from n measurements. In most cases the number of measurements made was such that the 90% confidence interval on the panel average solar absorptance was +/- 0.005 absorptance units. The average for the receiver was calculated three different ways. The first simply used all the data measured to find the average. The second used individual panel averages to calculate the average. The third used the individual panel averages but each panel average value was weighted based on a representative noon time distribution of solar energy incident on the receiver. Thus, more weight was given to the average solar absorptance of the panels which have the most incident solar energy and less to panels with less incident solar energy. The difference between these three values was small. In this report the third method will be used for the receiver and is called the "weighted average receiver solar absorptance".

Each receiver panel has three flux gages located in the middle of the panel at different elevations from the bottom. These flux gages were used as references to locate the vertical elevation where solar absorptance mesurements were made. Flux gage "A" is the highest on the panel at 9.9 m (32.5 ft) from the bottom of the panels. Flux gage "B" is at 6.4 m (20.9 ft) and flux gage "C" is at 3.9 m (13.0 ft) from the bottom of the panels. Figure 1 shows the predicted tube crown temperature distribution for a panel, i.e. Panel 12 at noon in June, when operating with an outlet steam temperature of 505$^{o}$C (940$^{o}$F), predicted incident flux distribution, and the vertical location of the flux gages A, B, and C. These temperatures were predicted using the computer code, PARFLO developed by Sandia, which models the thermal and hydraulic behavior of a single panel. Incident flux distribution was predicted using the computer code MIRVAL also developed by Sandia. From Figure 1 it can be seen that only the top part of the panel has crown temperatures above the recommended final cure temperature of 530$^{o}$C (1000$^{o}$F). Other vertical locations where solar absorptance measurements were routinely made are also shown in Figure 1 as unlabeled open triangles. These locations were found by measuring above or below one of the flux gages, e.g. "A" plus 6 feet. The horizontal location of the solar absorptance measurements was determined by tube number from the right side of each panel. Measurements were made on Tubes 5, 20, 35, 50, and 65. Tube 35 is the middle of the panel. Each time the solar absorptance measurements were made, the same general location on the panels was used.

Whenever solar absorptance measurements were made on the receiver they were also made on the two spare panels. These spare panels are at the Pilot Plant and are laying horizontal with the Pyromark surface facing up, uncovered. The Pyromark paint on these panels has not been cured and has not been exposed to high solar flux or temperature, but has been exposed to the normal weather at the site. On the receiver, each panel is numbered. Figure 2 shows the panel numbering system on the receiver. Panels 25 and 26 are the two spare panels. Panels 1, 2, and 3 are the low temperature water preheat panels. Panels 22, 23, and 24 are the high temperature water preheat panels. Water enters the receiver flowing first in parallel through Panels 1, 2, and 3 then flowing in parallel through Panels 22, 23, and 24. Panels 4 through 21 are the receiver boiler panels. After the water exits Panels 22, 23, and 24 it enters a common ring header which feeds water to all of the boiler panels. South is between Panels 1 and 24 and north is between Panels 12 and 13. The north panels receive the highest incident solar fluxes and the south panels the lowest. Each boiler panel is controlled to have the same superheated steam outlet temperature. Thus each boiler panel has experienced about the same temperature distributions but with different incident solar fluxes. The peak incident flux ranges from a low of 100 kw/m2 on Panels 1 and 24 to a high of about 300 kw/m2 on Panels 12 and 13. The incident flux distribution is nearly the same on all of the panels and only the peak values change.

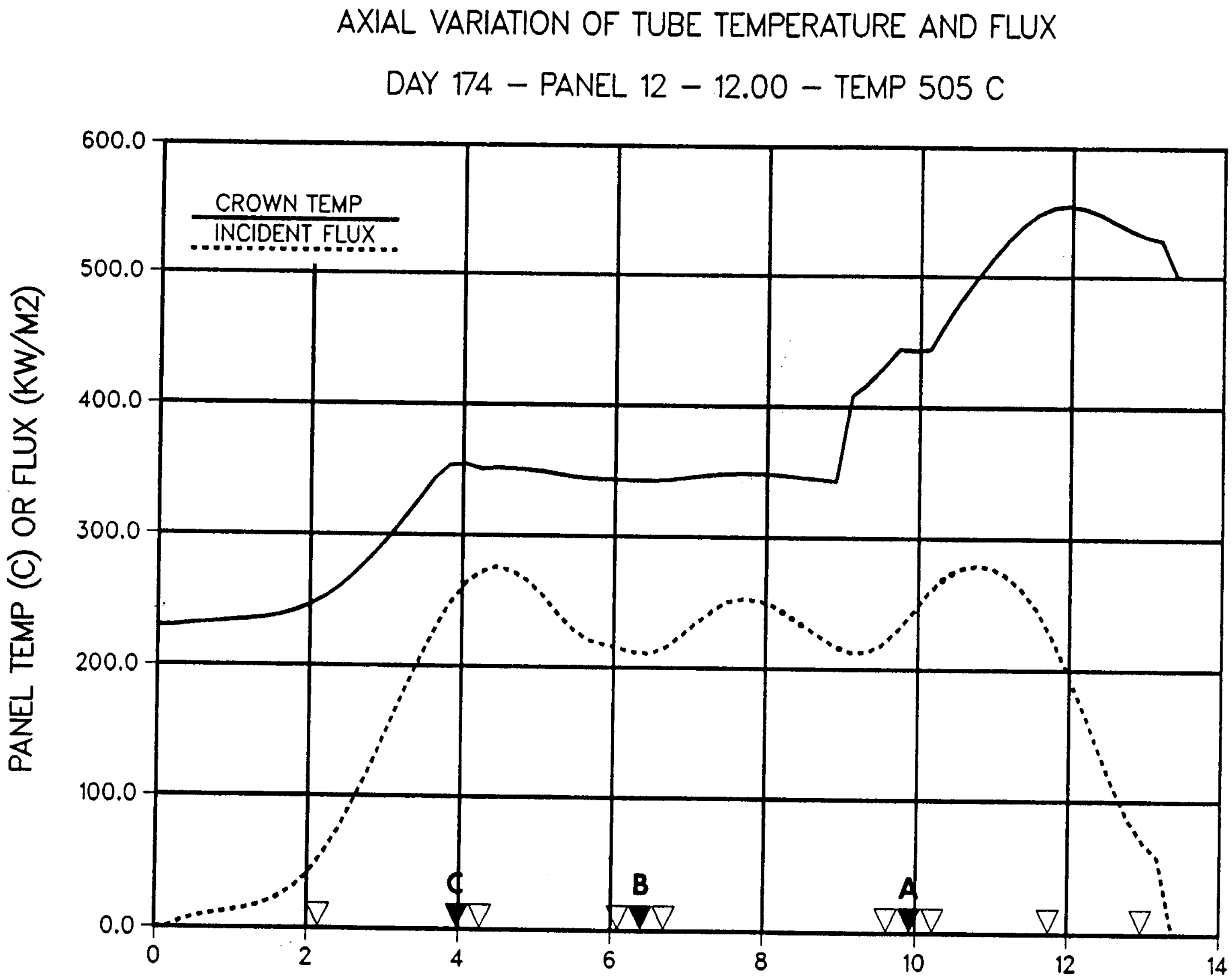


Figure 1. The predicted crown and back surface tube temperature distribution for a panel when operating with an outlet steam temperature of 515°C (960°F). The triangles are the vertical locations of the panel flux gages (A, B, and C) and where routine solar absorptance measurements were made.

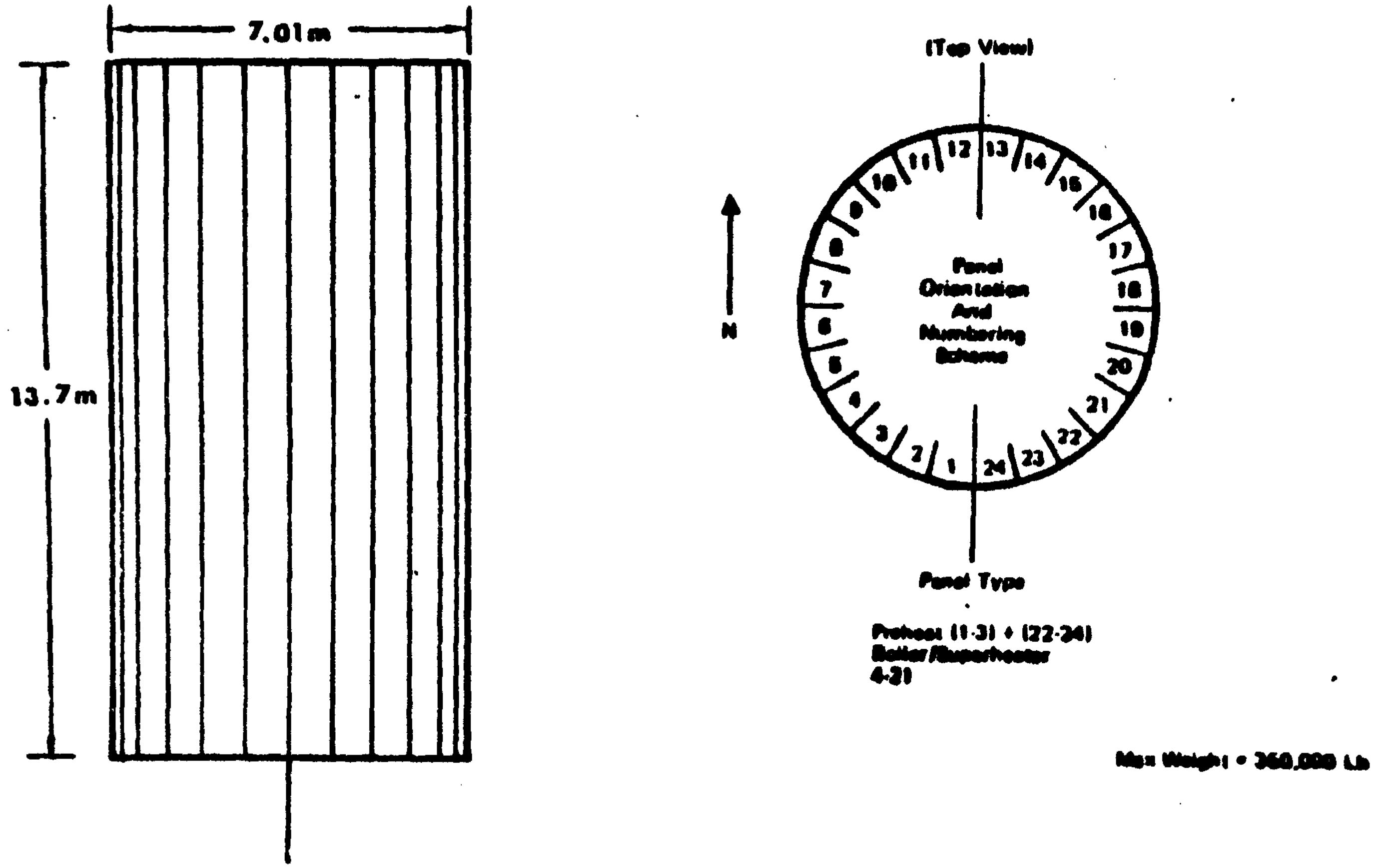


Figure 2. The panel numbering system on the receiver. Panels 25 and 26 are the two spare panels not shown.

## Solar Absorptance Measurement Results

### 1982 Results

The first measurements of the Pyromark paint solar absorptance on the Pilot Plant receiver panels were made between November 17, 1982, and November 23, 1982. This was about a week after the last measurable rain fall at the site. Solar absorptance measurements were made on all panels except Panel 22. Appendix A contains the measured reflectance data, calculated absorptance data, and average data for the individual panels and the receiver. The weighted average receiver solar absorptance based on data from twenty-three panels was found to be 0.92. The average panel values range from a high of 0.937 on Panel 3 (a low incident solar flux, low temperature water preheat panel) to a low of 0.911 on Panels 12 and 13 (high incident solar flux boiler panels). The two spare panels (Panels 25 and 26) had average solar absorptance values of 0.938 and 0.936. Figure 3 shows the average panel solar absorptance for each panel and the weighted average receiver solar absorptance (REC) in 1982. Also shown are the two spare panels. Recall that Panels 1, 2, and 3 are the low temperature water preheat panels and Panels 22, 23, and 24 are the high temperature water preheat panels. Panels 4 through 21 are the boiler panels and all have about the same temperature distribution. The incident solar flux for the boiler panels is lowest on Panel 4 and increases to Panel 12. The flux then decreases from Panel 13 to about the same value as on Panel 4 at Panel 21. As can be seen the solar absorptance is highest on the low incident solar flux low temperature preheat panels and then decreases on the boiler panels. The lowest solar absorptance values were on the high incident solar flux boiler panels.

Figure 4 shows the vertical solar absorptance distribution for eight panels in 1982. Panels 1 and 24 are low incident solar flux preheat panels, Panels 6 and 17 are boiler panels which have medium incident flux levels, and Panels 11, 12, 13, and 14 are boiler which have the highest incident flux levels. The average at each panel elevation was calculated based on measurements on Tubes 5, 20, 35, 50, and 65 at each elevation. In general the panel solar absorptance was nearly uniform over the entire length of the panels. For these eight panels the solar absorptance at the bottom of the panels (low temperature and low incident flux) was slightly higher than at the top (high temperature and low incident flux). The lowest solar absorptance appears to be near the middle on Panels 11, 13, and 14 (moderate temperature and high incident flux). These differences are small and could be within the accuracy of the measurement equipment.

Solar absorptance data was taken on the McDonnell Douglas receiver panel tested at the Central Receiver Test Facility in Albuquerque, New Mexico between February 1979 and March 1980 (Ref 3). It was reported that the post test range in that solar absorptance data was from about 0.91 to 0.95. The vertical distribution of the solar absorptance on that test panel was fairly uniform from the bottom to the top.

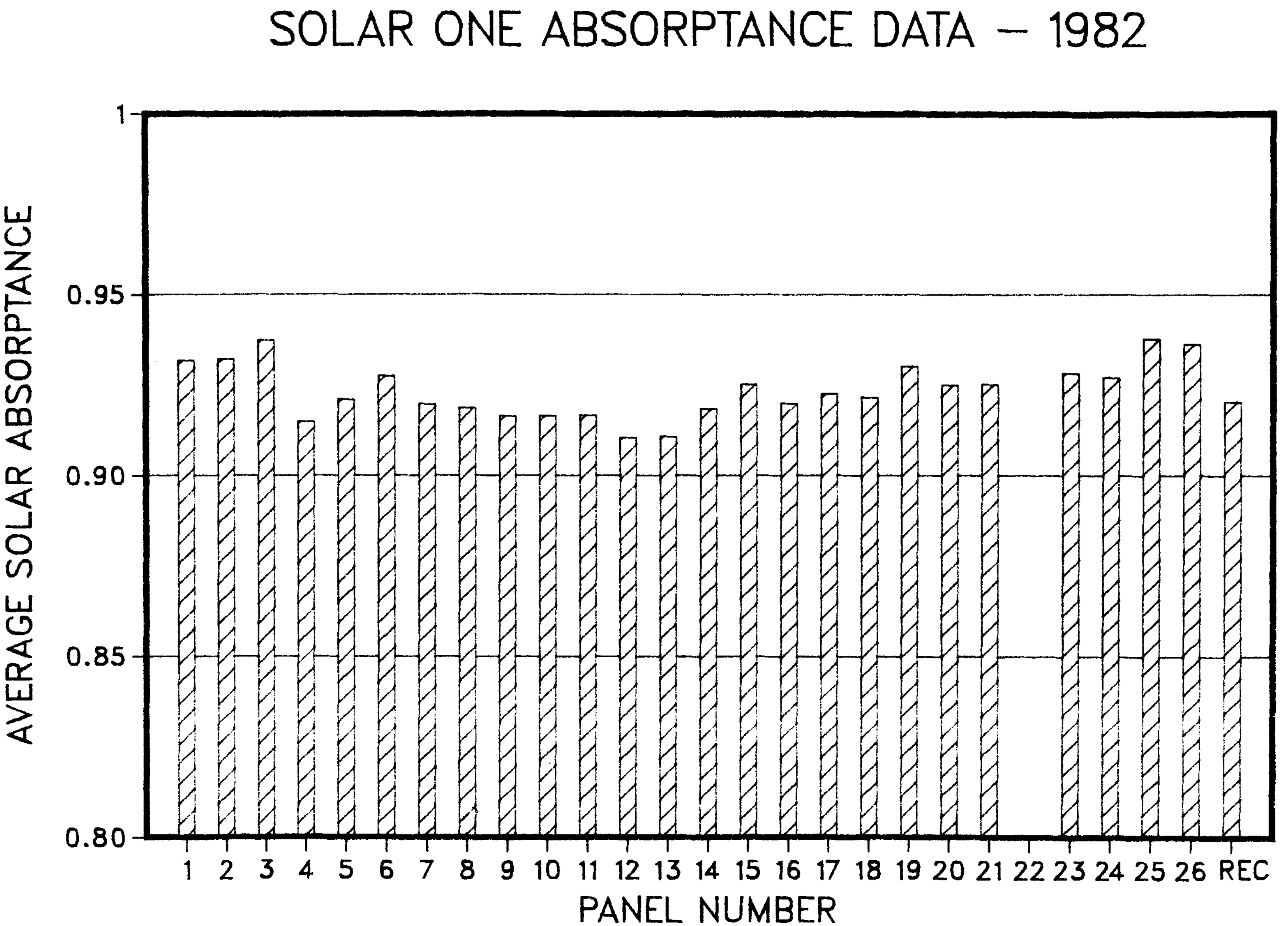


Figure 3. The average panel solar absorptance for each panel and the weighted average receiver solar absorptance (REC) in 1982. Also shown are the two spare panels, Panels 25 and 26.

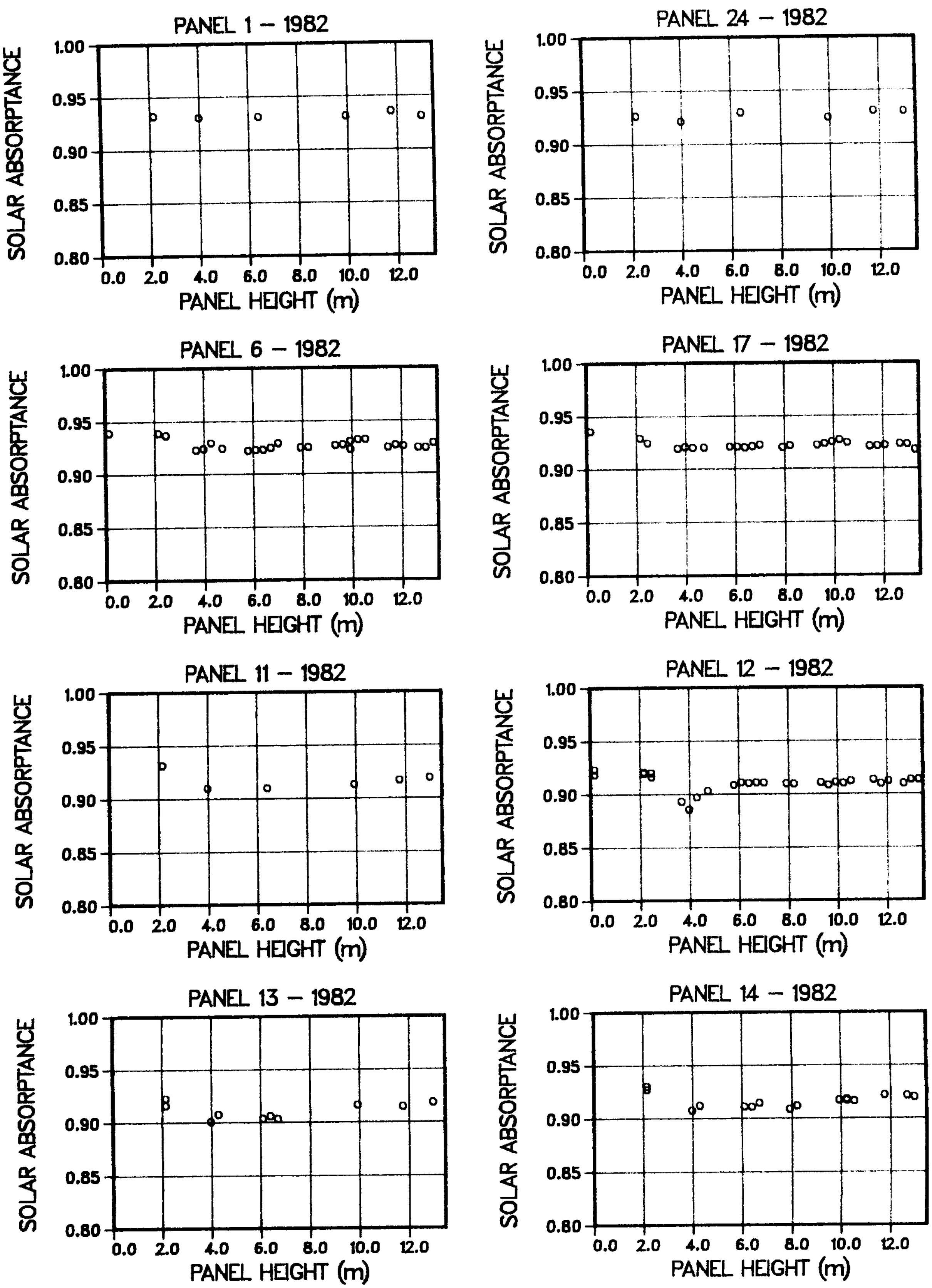


Figure 4. The vertical solar absorptance distribution for eight panels in 1982. The average at each elevation was calculated based on five measurements.

## 1983 Results

The second solar absorptance measurements on the receiver panels were taken between December 5, 1983, and December 11, 1983. There had not been any measurable rain for about two months at the site. Solar absorptance measurements were made on all receiver panels and the two spare panels. Appendix B contains the measured reflectance data, calculated absorptance data, and average data for the individual panels and the receiver. The weighted average receiver solar absorptance from these measurements was 0.90, a drop from 0.92 in 1982. Figure 5 shows the average panel solar absorptance for each panel and the weighted average receiver solar absorptance (REC) in 1983. Also shown are the two spare panels. The range in panel average solar absorptance values was from a high of 0.929 on Panel 1 to a low of 0.887 on Panels 9 and 16. Panels 12 and 13 had values of 0.897 and 0.898. The two spare panels (Panels 25 and 26) had solar absorptance values of 0.941 and 0.940. These are slightly higher than those measured in 1982 (0.938 and 0.936) for the spare panels, but are well within the sample and measurement errors. Unlike 1982 data, some of the boiler panels, e.g. Panels 17, 18, 19, 20, and 21, had solar absorptance values near those of the high temperature water preheat Panels 22, 23, and 24. The panels on the west side of the receiver (Panels 4 through 12) appear to have lower solar absorptance values than those on the east side. The predominant winds at the site are from the west to the east. It is possible that since it had not rained for a couple of months, the west panels were dirty compared to the east side. No attempt to clean the panels is made before the measurements are made.

Figure 6 shows the vertical solar absorptance distribution for the same eight panels as in Figure 4 for 1983. As was the case in 1982, Panel 1 vertical distribution is uniform from bottom to top. Panel 24 solar absorptance seems to decrease from the bottom toward the top with a slight increase at the very top. In general, the six boiler panels show an increase in relative solar absorptance proceeding from near the bottom to the top. However, at the very bottom of Panels 11, 12, and 13 the solar absorptance is higher than the rest of the panel. The lowest solar absorptance on the boiler panels occurs between 2 and 8 meters from the panel bottom, areas of low to moderate temperatures and highest solar flux. This trend although not as pronounced was also seen in the data from 1982 (Figure 4). Recall from Figure 1 that the temperature at the top of the boiler panels is higher than the rest of the panel and the incident flux is highest in the middle of the panel (from 4 to 11 meters). This was also true during the paint curing cycle with the top of the panels being near the final recommended cure temperature of 530$^{o}$C (1000$^{o}$F) and the rest of the panel being lower. Panels 1 and 24 received only a low temperature cure of about 175$^{o}$C (350$^{o}$F) to 260$^{o}$C (500$^{o}$F). These lower than recommended cure temperatures may in part explain the lower solar absorptance in the middle of the panels relative to the top. Yet, the low temperature and low flux preheat panels do have an overall average solar absorptance higher than the boiler panels.

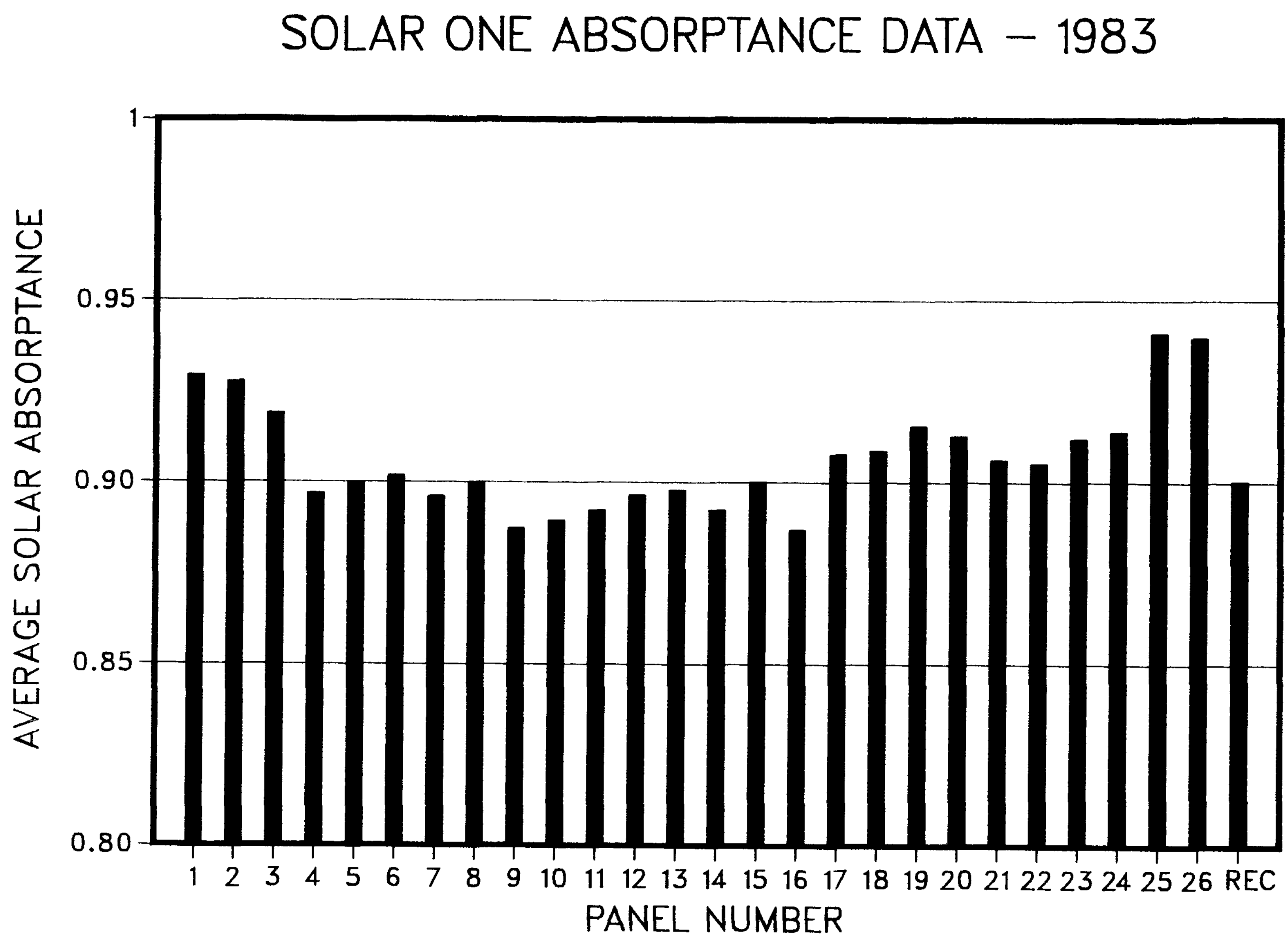


Figure 5. The average panel solar absorptance for each panel and the weighted average receiver solar absorptance (REC) in 1983. Also shown are the two spare panels, Panels 25 and 26.

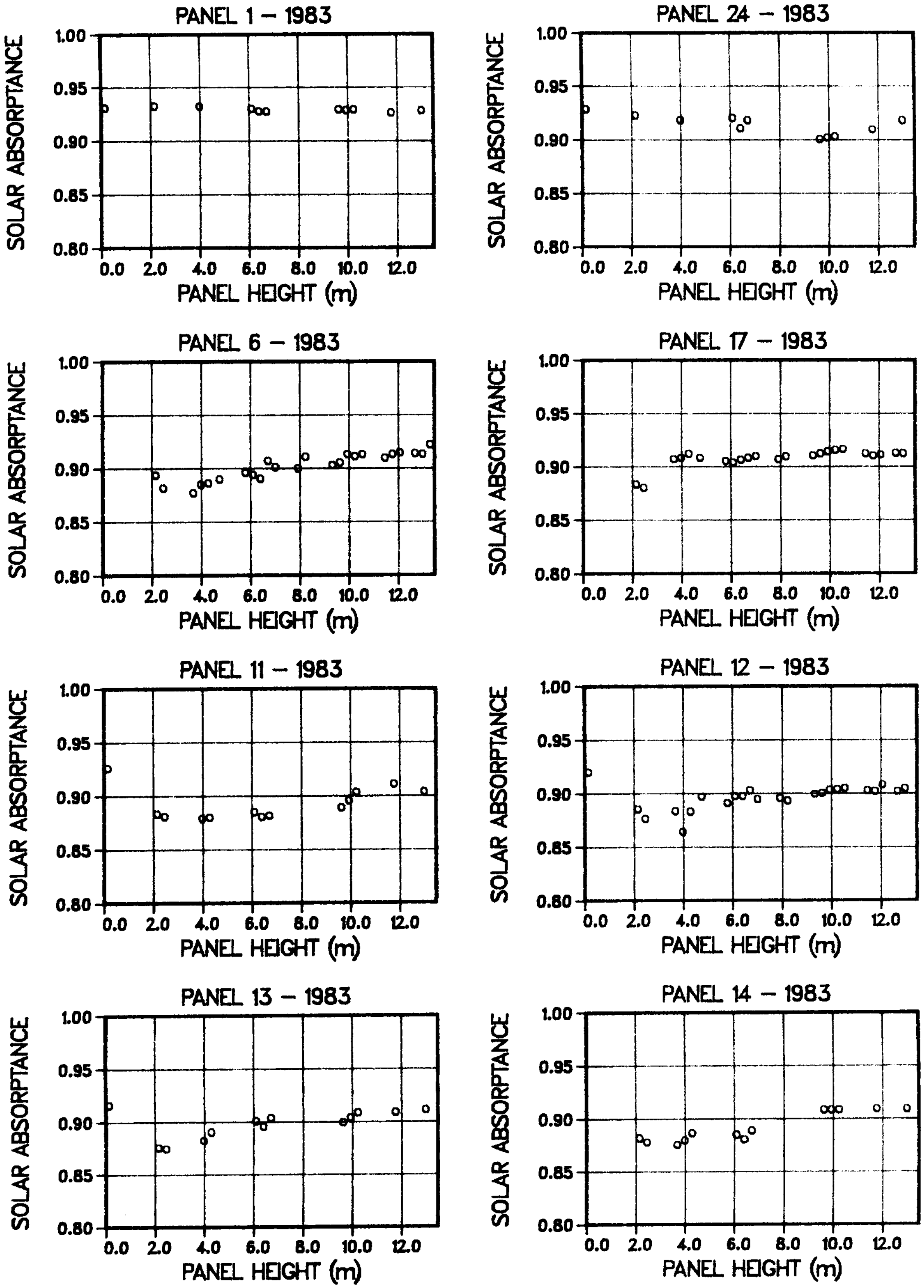


Figure 6. The vertical solar absorptance distribution for eight panels in 1983. The average at each elevation was calculated based on five measurements.

Figure 7 compares the average panel and receiver solar absorptance between 1982 and 1983. Very little change occurred on Panels 1 and 2 and the spare Panels 25 and 26. The high temperature water preheat panels (Panels 23 and 24) showed a larger change than the low temperature water preheat panels (Panels 1 and 2). The east side of the receiver (Panels 17 through 21) had a smaller change than the west side (Panels 4 through 11). The change in Panel 12 was from 0.911 to 0.897 or 0.014 absorptance units. This value is less than the instrument error. However, 120 measurements were made on this panel and the 90% confidence interval for this mean value is about +/- 0.002 absorptance units.

## 1984 Results

The last solar absorptance measurements on all of the receiver panels were made between September 11, 1984 and September 14, 1984. Solar absorptance measurements were made on all receiver panels and the two spare panels. The last measurable rain occurred three days before the measurements began. In addition to the "standard" measurements, small portion of several panels were washed with mild soap and rinsed with water. Both before and after washing, data were taken. Also, attempts were made to measure the panel Pyromark paint emissivity using a different instrument. Appendix C contains the measured reflectance data, calculated absorptance data, and average data for the individual panels and the receiver. Also in Appendix C is the washed and unwashed data and the emissivity data. The weighted average receiver solar absorptance from the "standard" measurements for 1984 was 0.88. Thus, since 1982 the weighted average receiver solar absorptance has decreased from 0.92 to 0.88.

Figure 8 shows the average panel solar absorptance for each panel and the average receiver solar absorptance (REC) in 1984. Also shown are the two spare panels. The range in panel average solar absorptance values was from a high of 0.920 on Panel 1 to a low of 0.870 on Panels 11 and 12. The two spare Panels (25 and 26) had solar absorptance values of 0.933 and 0.932. As seen in Figure 8 the three low temperature water preheat panels (Panels 1, 2, and 3) have the highest average panel solar absorptance compared to the other panels. Their values decrease as the incident solar flux increases. As was the case in 1983 the three high temperature water preheat panels (Panels 22, 23, and 24) have average solar absorptance lower than several boiler panels, e.g. Panels 4, 5, 6, 20, and 21. Their values also decrease as the incident solar flux increases but not as clearly as the low temperature water preheat panels. Unlike 1983 the boiler panels on the east side of the receiver, i.e. Panels 16 through 19, have lower solar absorptance than the west side, i.e. Panels 6 through 9. The reverse was true in 1983 and was thought to have been caused by dirt on the west panels. In general, the boiler panels with the lowest incident solar flux have the highest average solar absorptance compared to the other boiler panels, i.e. Panels 4 and 21 are higher than Panels 12 and 13. Yet, all the boiler panels operate with about the same temperature distribution and outlet steam temperatures.

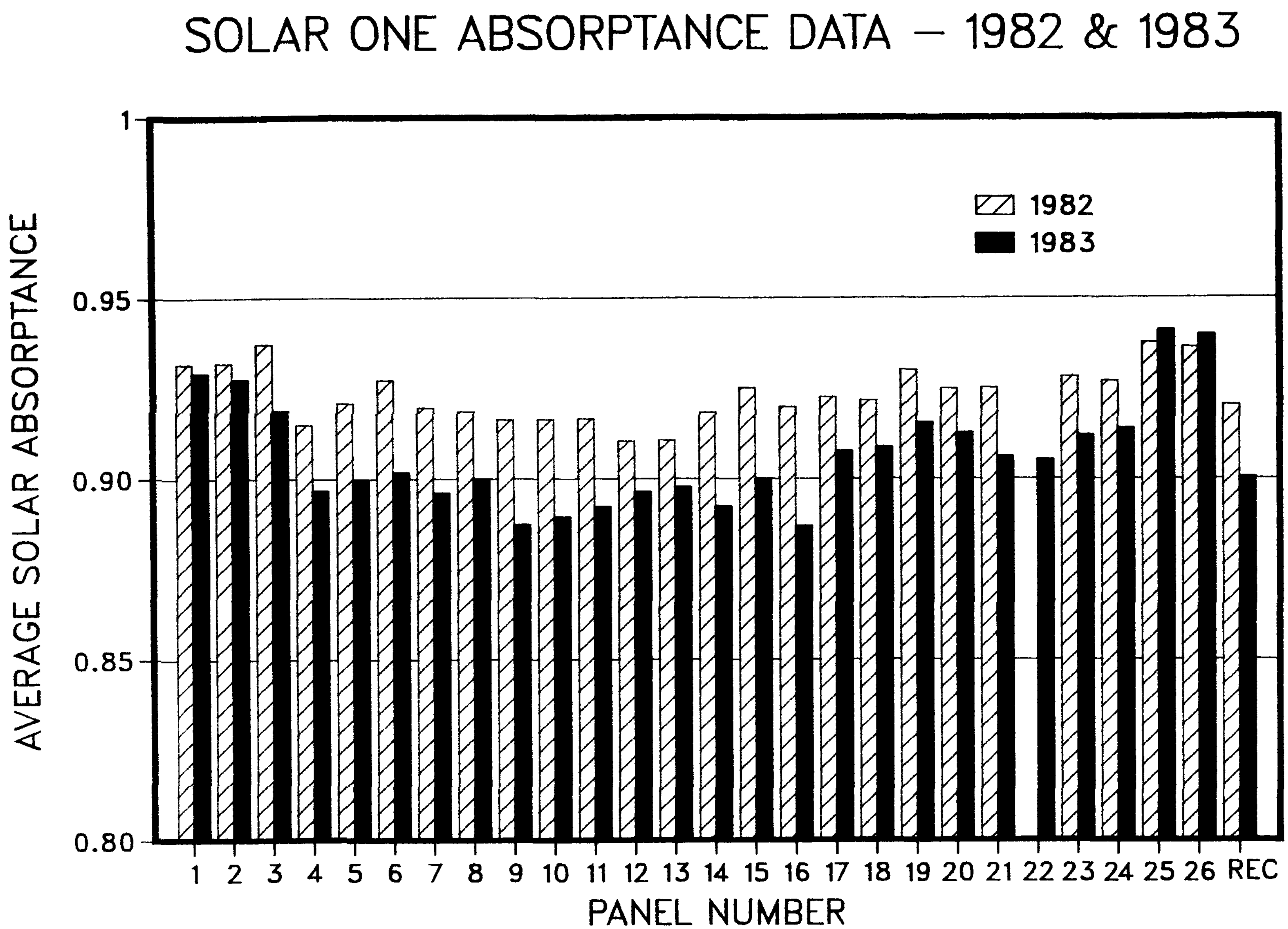


Figure 7. A comparison of the average panel and receiver solar absorptance between 1982 and 1983. No measurement was made on Panel 22 in 1982 and Panels 25 and 26 are the two spare panels.

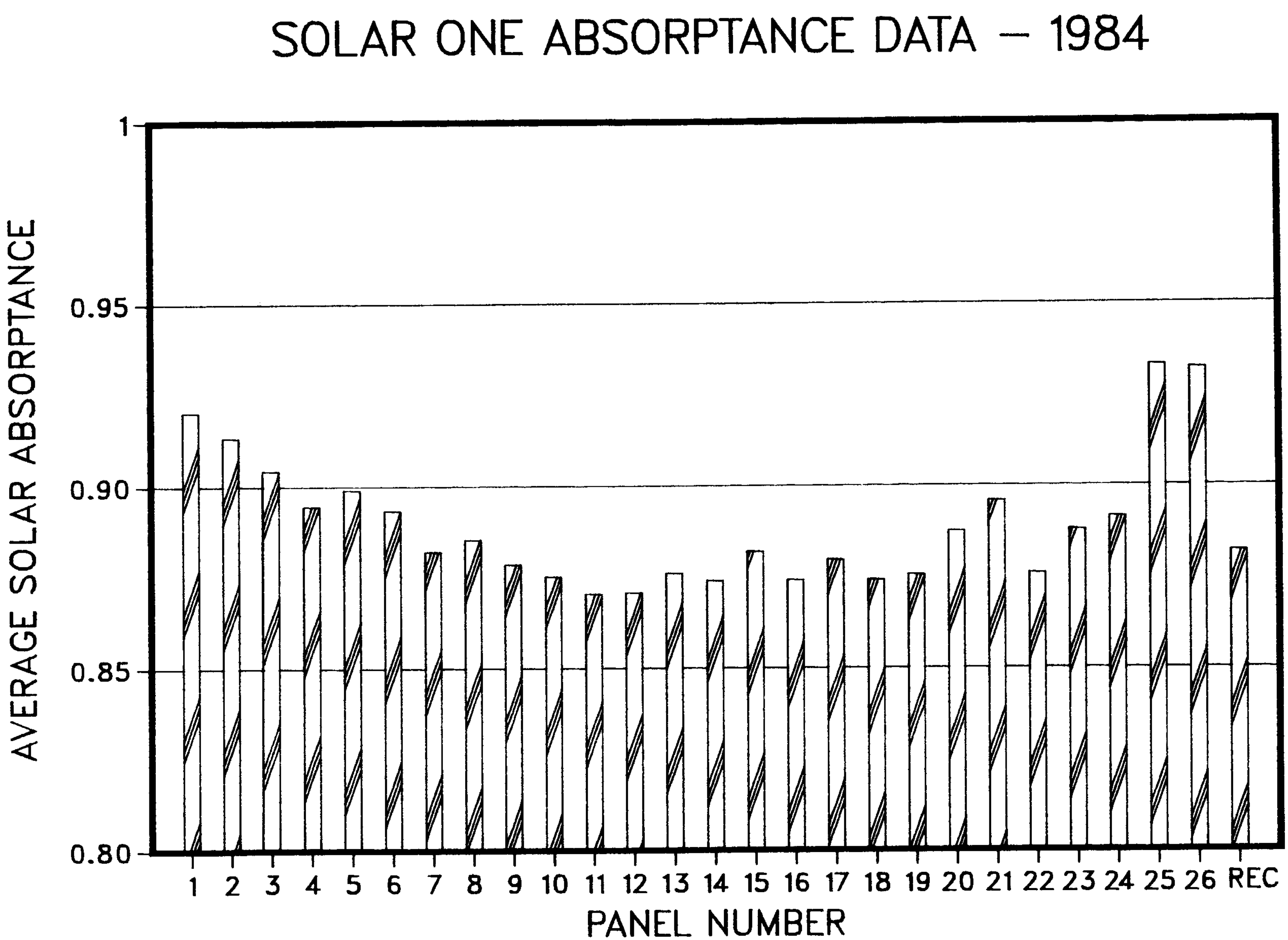


Figure 8. The average panel solar absorptance for each panel and the weighted average receiver solar absorptance (REC) in 1984. Also shown are the two spare panels, Panels 25 and 26.

Figure 9 shows the vertical solar absorptance distributions for the eight panels as Figures 4 and 6. Now there appears to be a slight decrease in the solar absorptance on Panel 1 from bottom to top. Panel 24 also to shows a similar decrease from bottom to top as in 1983. The six boiler panels show the same relative increase in solar absorptance from bottom to top as they did in 1983. Except for Panel 17, the solar absorptance on all the boiler panels in Figure 9 is highest at the top of each panel. This is the high temperature and low incident solar flux portion of the panels and was also cured near the recommended cure temperature. The bottom of the boiler panels (low temperature and low incident solar flux) and the middle portion of the boiler panels (moderate temperature and high incident solar flux) continues to show the lowest measured solar absorptance. The panel top solar absorptance values range from a low of 0.895 on Panel 12 to a high of 0.914 on Panel 6.

An experiment was performed to determine if the panels were dirty by washing a small area on eleven panels at the flux gage "B" level. After washing, reflectance measurements were taken on five tubes (Tubes 5, 20, 35, 50, and 65) where all other measurements had been made. Data from the original 1984 measurements at these same locations were compared to those after washing. Figure 10 shows the comparison between "clean" and "dirty" average values of the five measurements at flux gage B. In each case there was a slight increase in the measured solar absorptance after washing. Panel 13 showed the greatest improvement. The measurement equipment only measures the solar absorptance near the crown of the tube. Even though the washed area look visibly cleaner after washing the data showed only a slight improvement in solar absorptance. Even though some improvements were obtained by washing, dirt does not appear to be a significant cause of the loss in solar absorptance.

To get an indication of the Pyromark paint emissivity on the Pilot Plant receiver panels a "laboratory" type instrument, Gier-Dunkle Infrared Reflectometer, Model DB-100, was used to make measurements on seven receiver panels and one of the spare panels. A filter to limit the wavelength to 8 - 12 microns was installed in the instrument. The seven receiver panels included one preheat panel and six boiler panels. This instrument was found to be difficult to use in a "field" environment. Only the trend in the data was considered important. Measurements were made on Tubes 5, 20, 35, 50, and 65 at the "B" flux gage level on the seven panels and at the "A" flux gage level on four panels. There was no clear difference between the emissivity measurements at flux gage "B" and "A". Figure 11 shows the comparison for the average value of the emissivity on those seven panels and an average for the receiver based on those seven panels. Also shown is the average value for the spare panel (Panel 25). These results are within those published by others at room temperature.

Figure 12 compares the panel and receiver average solar absorptance for the three measurement years of 1982, 1983, and 1984. Several observations can be made from the data:

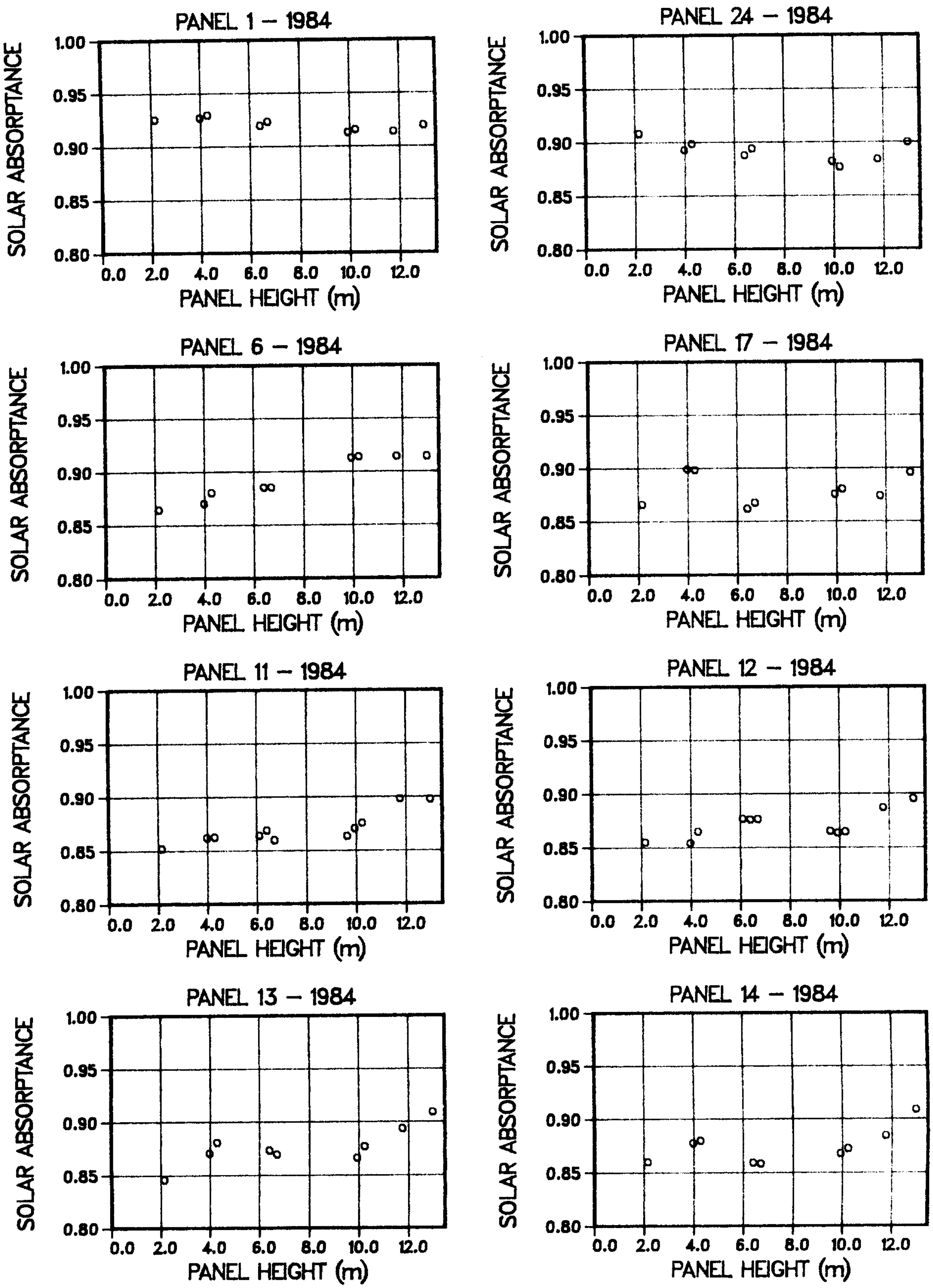


Figure 9. The vertical solar absorptance distribution for eight panels in 1984. The average at each elevation was calculated based on five measurements.

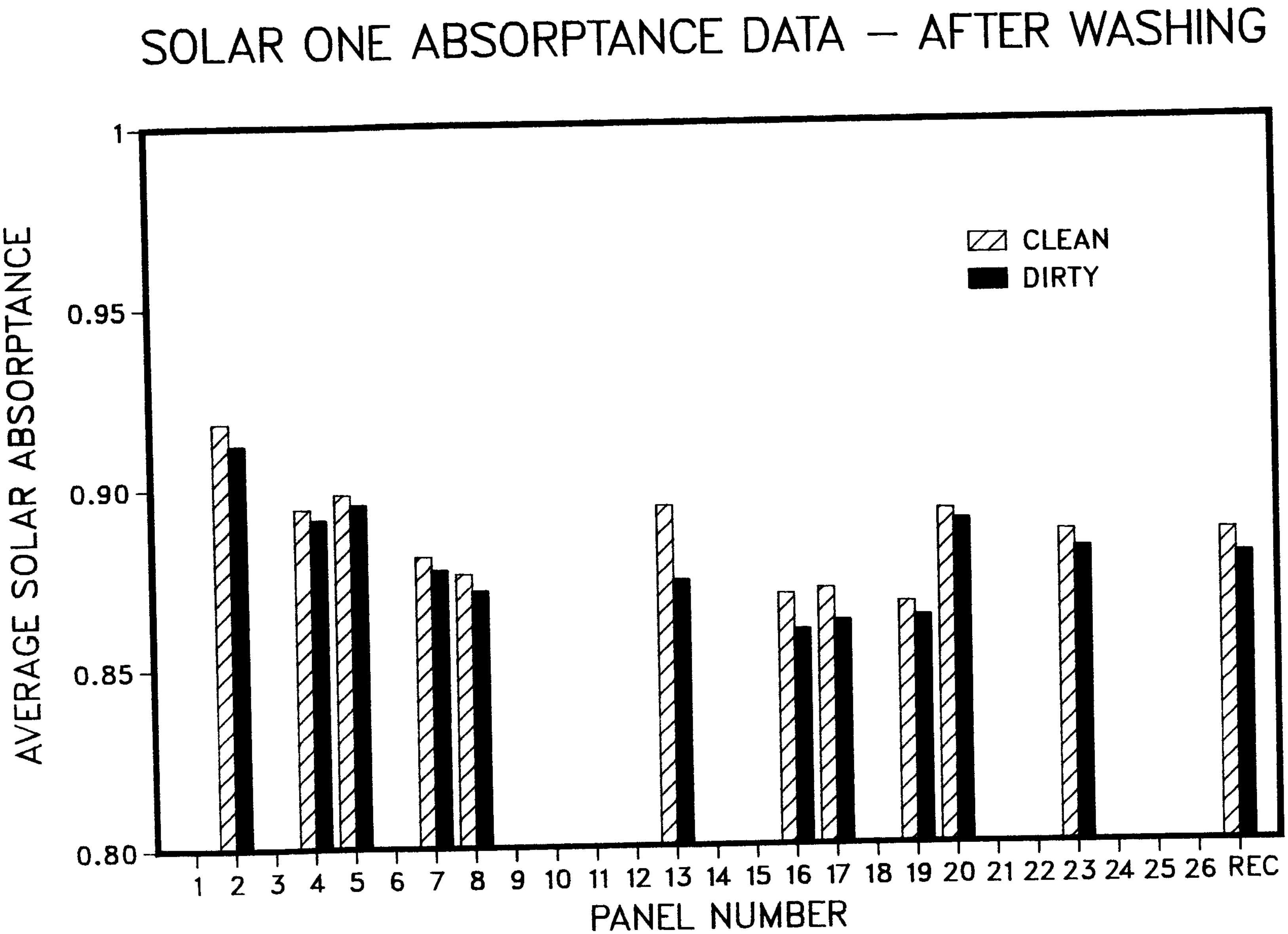


Figure 10. Comparison between "clean" and "dirty" average values of the five measurements at flux gage B for eleven panels. The receiver average (REC) was calculated based on those eleven values.

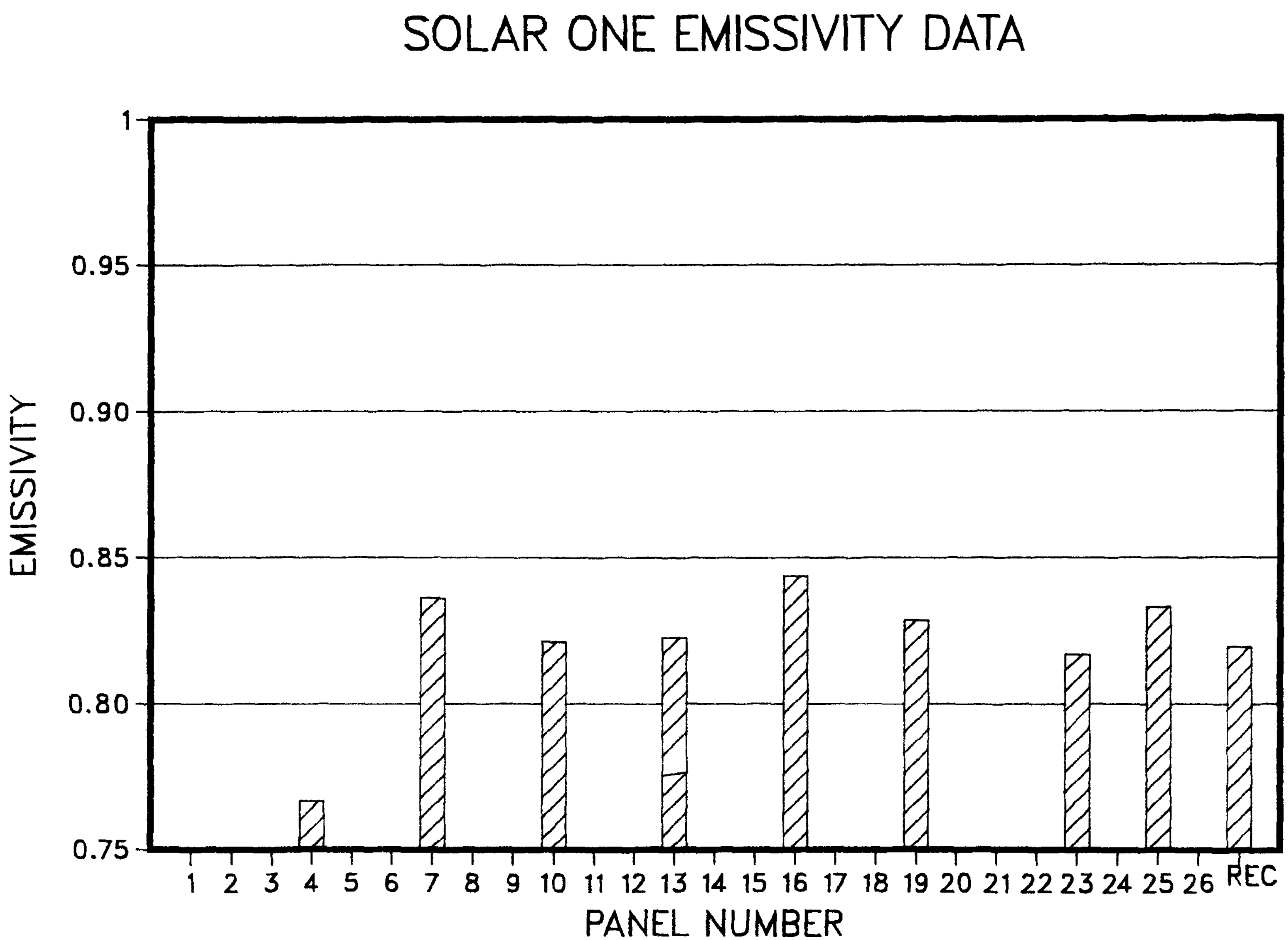


Figure 11. The average value of the emissivity on seven panels and an average for the receiver based on those seven panels. Also shown is the average value for the spare panel (Panel 25).

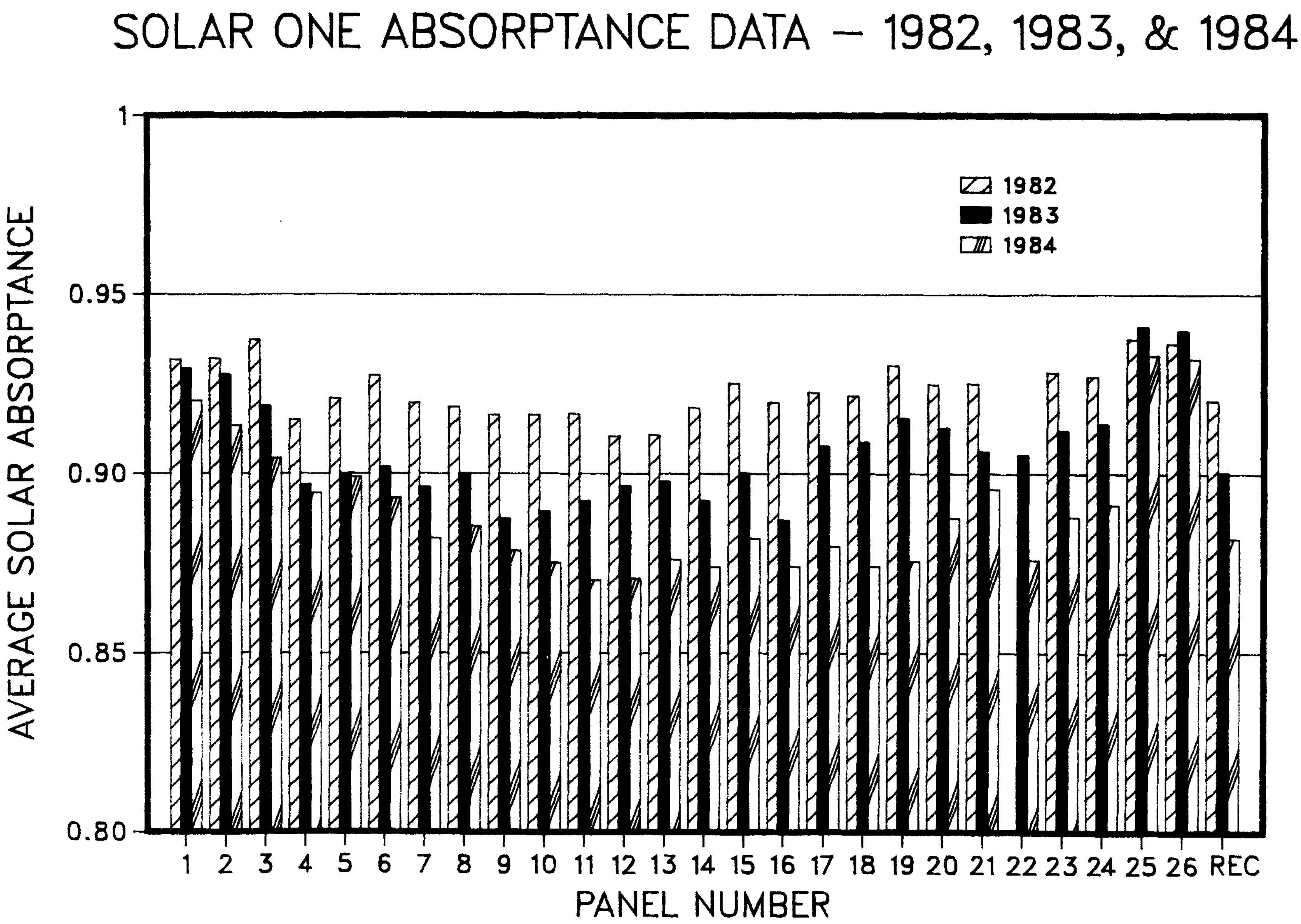


Figure 12. A comparison of the average panel and receiver solar absorptance between 1982, 1983, and 1984. No measurement was made on Panel 22 in 1982 and Panels 25 and 26 are the two spare panels.

1. The change in panel average solar absorptance from 1982 to 1983 was higher on the west side of the receiver (Panels 1 through 12) than on the east.

2. The change in panel average solar absorptance from 1983 to 1984 was higher on the east side of the receiver (Panels 13 through 24) than on the west.

3. The low temperature water preheat panels (Panels 1, 2, and 3) have consistently had the highest solar absorptance.

4. The high temperature water preheat panels (Panels 22, 23, and 24) have measured solar absorptance lower than some boiler panels even though they operate at outlet temperatures of more than 120$^{o}$C (250$^{o}$F) below the boiler panels.

5. The two spare panels (Panels 25 and 26) have had very little change in their solar absorptance over the measurement time period.

For receiver evaluation purposes the weighted average receiver solar absorptance versus day of the year was fit with a straight line. This fit and the three data points are shown in Figure 13. The data fit equation is:

$$\text{Solar absorptance} = 0.9398 - 0.00005774 * \text{Day No.}$$

where the Day No. (day number) is 1 for January 1, 1982, and 1096 for December 31, 1984. The comparison of the measured and calculated solar absorptance are:

| Day No. | Measured | Calculated |
|---|---|---|
| 324 (11/20/82) | 0.9205 | 0.9211 |
| 707 (12/08/83) | 0.9004 | 0.8990 |
| 987 (09/13/84) | 0.8820 | 0.8828 |

<u>1985 Results</u>

To develop a method to repaint the panels with Pyromark paint while they are installed on the receiver, one panel, Panel 12, was painted on March 13, 1985. Before painting Panel 12, it was washed using only water and light scrubbing with a nylon brush. After the water wash the panel was rinsed with 1, 1, 1 - Trichloroethane and air dried. While the panel was being painted some small samples were also painted. These small samples were attached to Panel 13 at several vertical locations. Prior to painting the panel on the receiver, laboratory samples of a test panel which had "aged" Pyromark paint were repainted to develop the panel cleaning and painting techniques. The laboratory samples were oven-cured following the recommended cure temperature-time cycle. Solar

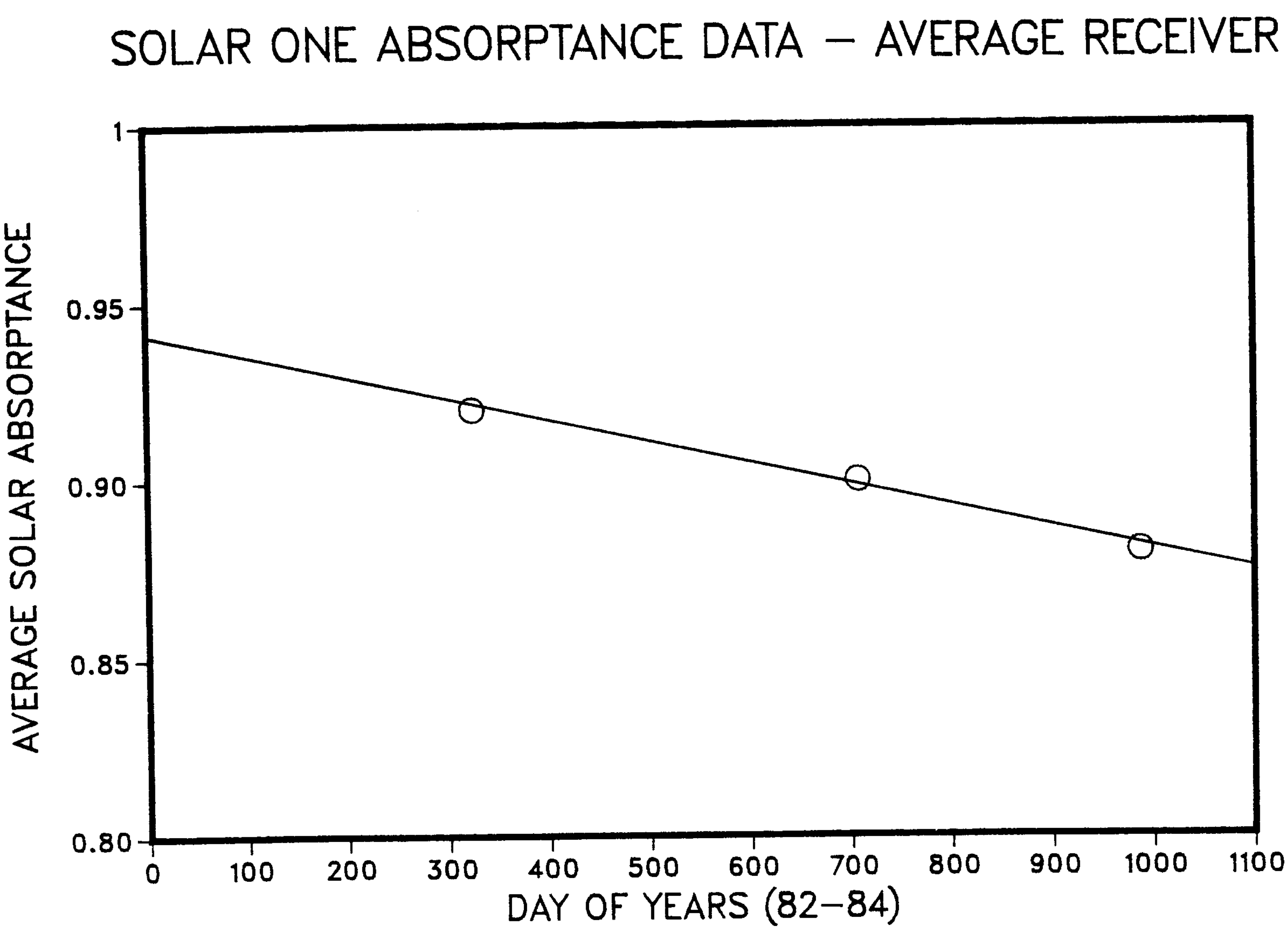


Figure 13. The weighted average receiver solar absorptance versus day of the year (1 for January 1, 1982, and 1096 for December 31, 1984) and a straight line fit of the data.

absorptance measurements on the laboratory sample before painting were about 0.92 and, after painting and curing, were about 0.97. The same cleaning and painting techniques were used on the receiver panel and small samples. This repainted panel and samples were cured using reflected solar energy from the heliostat field. Thus, the recommended final cure temperature was not achieved over most of the panel surface.

On April 12, 1985, after several weeks of receiver operation, the solar absorptance on Panels 11, 12, and 13 was measured. The solar absorptance on the two spare panels (Panels 25 and 26) was also measured. Appendix D contains the measured reflectance data, calculated absorptance data, and average data for the individual panels. Figure 14 shows the panel average solar absorptance for the three receiver panels and the two spare panels measured in 1985 compared to the data taken in 1984. Panels 11, 13, 25, and 26 had solar absorptance values near their 1984 values while the recently painted Panel 12 had an average value of 0.966. The small samples attached to Panel 13 had solar absorptance values of between 0.91 and 0.95 with an average of 0.94 for twelve samples. It was hoped that the small samples would better represent the recently painted panel since several of these samples will be removed at six month intervals and evaluated in the laboratory. These small samples may provide data on the cause of the paint degradation mechanism.

Figure 15 shows the vertical distribution of the measured solar absorptance for Panels 11, 12, and 13. On Panels 11 and 13 the solar absorptance is lowest near the bottom of the panels, fairly uniform in the middle, and highest at the top. The vertical distribution on Panel 12 is fairly uniform.

While taking the solar absorptance measurements on Panel 12 the following observation were made concerning the appearance of the panel:

1. There were many areas on the panel where strips two to six inches wide ran across the panel where the paint had a glossy appearance. The rest of the panel had a flat appearance.

2. At the flux gage B elevation on the Tube 70 side of the panels the Pyromark paint could be wiped off the panel. The residue after wiping looked like black chalk. The solar absorptance after wiping the tube was about 0.94.

3. At the flux gage A elevation on the Tube 70 side of the panel there was an area about 0.6 m by 0.6 m (2 ft by 2 ft) which had the same appearance as when the paint was wiped off at flux gage B location. The measured solar absorptance in this area was between 0.94 and 0.95.

It may have been that the panel cleaning and paint spraying techniques are not yet optimum for applying Pyromark to the panels while they are installed on the receiver tower.

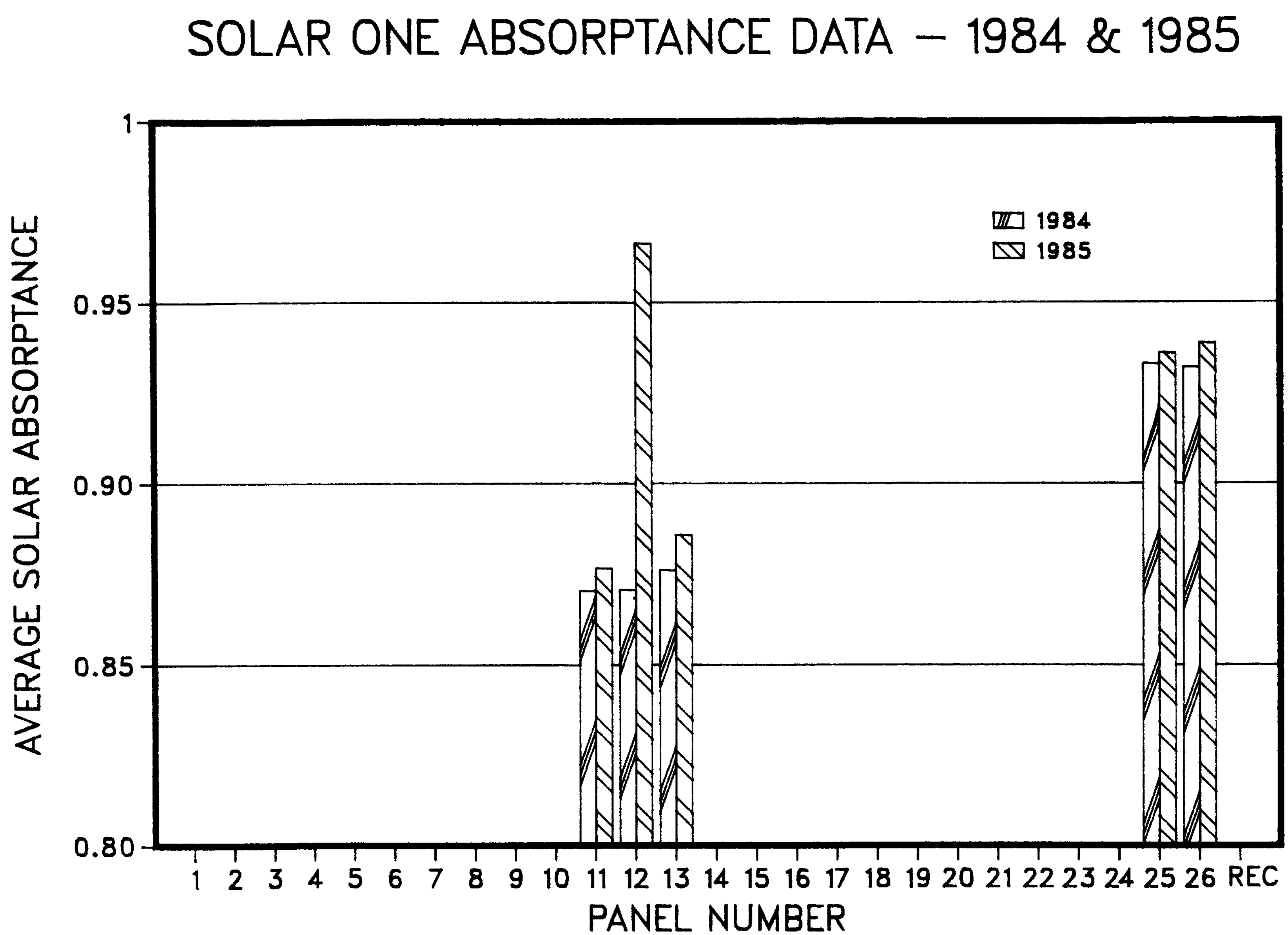


Figure 14. The panel average solar absorptance for the three receiver panels and the two spare panels measured in 1985 compared to the data taken in 1984.

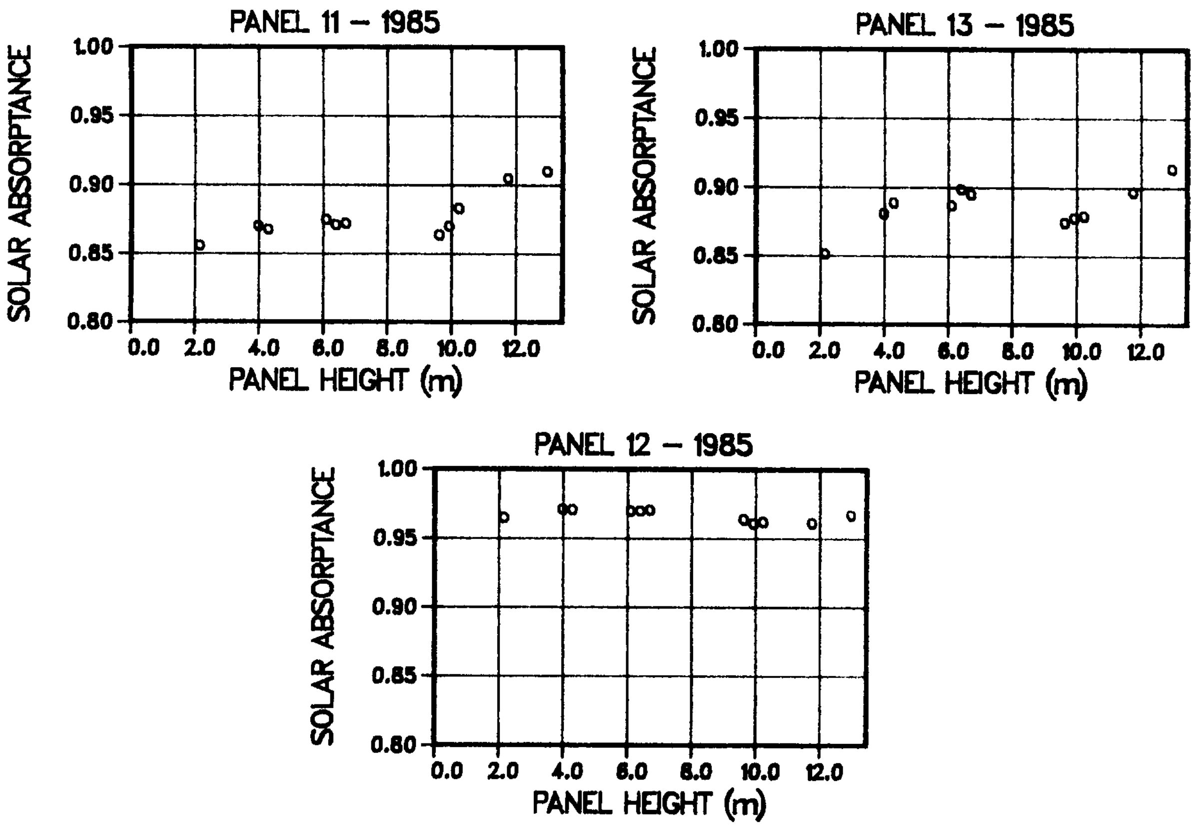


Figure 15. The vertical distribution of the measured solar absorptance for Panels 11, 12, and 13. The average at each elevation was calculated based on five measurements.

## Conclusions

Data over a two year measurement period show that the individual panel average solar absorptance and the weighted receiver average solar absorptance has steadily decreased. The receiver panels with the lowest operating temperatures, i.e. the low temperature water preheat panels, have consistently had the highest solar absorptance compared to the other receiver panels. The three high temperature water preheat panels showed average solar absorptance lower than several boiler panels which operate at higher temperature and incident solar flux levels by the second measurement period. The panel-to-panel variation in the group of low temperature water preheat panels, high temperature water preheat panels, and boiler panels, which all operate within their group with about the same temperature distribution and outlet temperatures, shows a decrease in average solar absorptance with an increase in incident solar flux. The vertical solar absorptance distribution on the boiler panels by the last measurement period shows the lowest solar absorptance near the bottom of the panel (low temperature and low incident solar flux) and in the middle of the panels (moderate temperature and highest incident solar flux). The highest solar absorptance usually occurred at the top of the boiler panels (high temperature and low incident solar flux). Over the solar absorptance measurement time period, the two spare panels showed very little change in their average solar absorptance compared to the panels on the receiver.

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