# MAINTENANCE, RELIABILITY, AVAILABILITY

Belinda Wong Swanson and Rocco Fazzolare, University of Arizona

## 1. ABSTRACT

Operation and maintenance records from January to August of 1984 were used to find the average daily and overall usage factor, solar availability, and equipment availability of a single-axis tracking and dual-axis tracking collector field subsystems. Major causes of full and partial outages were identified. The equivalent outage hours and man-hours for repair work were compared for the two fields.

## 2. INTRODUCTION

Availability of a system is the probability that a system will be ready for use at any time after the start of operation. In most applications, this parameter is calculated by taking the ratio of the available hours to the total clock hours in the period of analysis. A system is usually considered available as long as it is not undergoing repair. However, this definition cannot be applied to solar systems because there are many factors that cause nonoperation of the system, such as low insolation level and high wind velocity in addition to equipment failure. Therefore it is desirable to find instead the overall usage factor (percent of time the system was operated under normal operating conditions), and also to identify the different causes of unavailability. For unavailability due to equipment malfunctions, it is important to identify the components that require repair and the causes of failure.

This study uses the daily operation and maintenance records of a single-axis and a dual-axis tracking collector field subsystems for the first eight months of 1984 to find the usage factor of the system, the solar availability, as well as the equipment availability. The most frequent repairs, causes of failure, and impact on system shutdown are identified.

## 3. OPERATIONS ANALYSIS

The daily operations data for the collector field include: the daylight hours, hours of operation, hours with radiation above certain levels, and whether the collectors have full, partial, or no operation. In addition, they show the collector modules or loops which have been out of service, and specify if the day has been a holiday or weekend. Using these daily records over a period of time, the solar availability, equipment availability, and usage factor could be calculated.

### 3.1 Solar Availability

Solar availability is the percentage of total daylight hours (or sun hours) during which the radiation level is above the minimum operable level. According to site specifications (Ref.1), the collectors should be operated when the direct beam radiation is at least 300 $W/m^2$. Therefore, 300 $W/m^2$ is taken as the operable level in this study. Solar availability is defined by the following equation.

$$AS = \begin{matrix}\text{Solar} \\ \text{Availability}\end{matrix} = \frac{\text{hours wih radiation above 300 } W/m^2 \text{ (H300)}}{\text{total sun hours (SH)}} \tag{1}$$

### 3.2 Equipment Availability

Equipment availability is the percentage of total clock hours in a period when the equipment is available for use. It is the ratio of available hours to period hours. The available hours are obtained by subtracting the equipment downtime from the period hours, PH. Thus

$$AE = \begin{matrix}\text{Equipment} \\ \text{Availability}\end{matrix} = \frac{PH - OH \times f - OH' \times f'}{PH} = \frac{PH - EOH}{PH} \tag{2}$$

OH and f are the outage hours and fraction of the collector field out of service during working hours WH. OH' and f' are the outage hours and fraction of the collector field out of service during reserve shutdown hours RSH, where RSH = PH - WH. EOH = OH x f + OH' x f', called equivalent outage hours. This definition of equipment availability takes into consideration the times when the collector field is only partially operable.

### 3.3 Usage Factor and Daily Usage Factor

Usage factor is the ratio of hours of system operation (WH) to nonholiday hours with radiation above 300 $W/m^2$ and corrected by the equipment availability:

$$UF = \frac{WH \times AE}{\text{nonholiday hours with radiation above } 300 W/m^2} \tag{3}$$

The usage factor shows the fraction of possible operation hours when the collectors actually operated, and adjusted by AE if the collectors had not been in full operation.

Most of the calculations were done from the point of view of how often the systems operated overall in a particular period. For example, the equipment availability in January is obtained by

$$\frac{24(31) - \text{equivalent outage hours in January}}{24(31)}$$

and the usage factor for January is

$$\frac{\text{working hours in January}}{\text{nonholiday hours with radiation above } 300\ W/m^2 \text{ in January}} \times \text{January equipment availability}$$

The results would indicate, for the period as a whole, how often the system operated with respect to the possible hours of operation.

An average daily usage factor ($\overline{duf}$) is obtained in order to find out how often the system is utilized during days of normal operating conditions.* The daily usage factor for each working day in the period that has quality radiation is calculated by

$$duf = \frac{\text{working hours for the day}}{\text{hours of radiation above } 300\ W/m^2 \text{ for the day}} \times \frac{24 - \text{equivalent outage hours for the day}}{24} \quad (4)$$

Thus the average daily usage factor is

$$\overline{duf} = \frac{\sum_{i=1}^{n} duf_i}{n} \quad (5)$$

where n is the total number of working days with normal operating conditions in the period. It should be noted that there are days when the collectors are on for longer duration than there are hours of radiation above 300 $W/m^2$. Therefore duf for a given day could be greater than 1.0.

---

* Days of normal operating conditions are working days with average radiation above 300 $W/m^2$ and more than three hours of radiation above 600 $W/m^2$, and without high wind speed.

### 3.4 Results of the Operations Analysis

Daily operation data for several months of 1984 were used to calculate the solar availability, equipment availability, usage factor, and average daily usage factor for the collector field in each period. The results are tabulated in Tables 1 and 2. In Table 1, Column E is the overall solar energy availability for each period; it is the fraction of the total sun hours with radiation above 300 W/m$^2$. Column F is the actual solar energy availability; the holiday hours have been excluded in order to show the true fraction of sun hours that have enough radiation to operate the system. It can be seen that in general only about 35% of total daylight hours is available for system operation. However if the plant does not shutdown on holidays and weekends, then over 50% of the total sun hours have radiation in the operable level.

Column G is the equipment availability for the two collector fields. It shows the fraction of time the collectors are available for use, taking into consideration partial outages. For the periods analyzed, single-axis tracking collectors have much higher availability than the dual-axis tracking collectors. During the first four months of 1984, the single-axis system were available 99.8% of the time and the dual-axis system 94.8%. During the second four months, equipment availability for the single-axis and dual-axis systems were 99.6% and 97.4%, respectively.

Between May 29 and July 8, the dual-axis tracking field was taken out of service several loops at a time to replace the bolts in the swivel joint of the modules. It had been determined that loose bolts in the swivel joint assembly produced friction between the flexible hose and the metallic parts of the assembly, thus causing oil to leak from the hose (Ref.2). During this period of bolt replacement the number of possible functioning modules varied, depending on how many loops have been removed from service. When calculating the equipment availability, the fraction of the modules that are out of service is obtained by the ratio of

$$\frac{\text{number of non-working modules}}{\text{number of possible functioning modules}} .$$

For example if loops 1 and 2 were taken out of service to replace the bolts, then the denominator equals 72 = 84 - 12; the numerator is the number of non-working modules in loops 3 through 14. Consequently the results for this period do not reveal the effects on equipment availability due to bolt replacement.

Since June 19, loop 14 in the dual-axis tracking collector field was taken out of service to be used as spare replacements for the rest of the field. Therefore the number of possible functioning dual-axis tracking modules is 78 starting July 9, when bolt replacement was completed. The equipment availability of the dual-axis tracking collectors for July and August are much higher than the previous six months. This may be a result of the bolt replacement or of the corrective repairs performed earlier; operation trends in the coming months will determine which is the case.

Column H is the usage factor, defined as the ratio of the collector subsystem working hours to the possible hours of operable radiation level. It is multiplied by the equipment availability to account for times when the system is only partially available. The results from the first four months show that of the time when there was sufficient radiation to operate the system, the single-axis tracking collectors operated for 77.1% while the dual-axis collectors operated for 67.2%. Dual-axis collectors were used 74.3% of the time possible for operation as opposed to 65.8% for single-axis collectors. (Remember that these results do not account for the reduced availability of the dual-axis collectors due to the bolt replacement.)

Table 2 lists the average daily usage factor for the two collector fields for several analysis periods. Only days of good operating conditions were considered; all weekends, holidays, days off, low insolation and high wind days were excluded. The average daily usage factor is intended to indicate how much of the time and how much of the system is used on days that the collector field should operate. The results show that, in general, the dual-axis system have higher daily usage factor than that of single-axis, in spite of its lower equipment availability.

According to the maintenance personnel of the site, the reason why the dual-axis field has a higher average daily usage factor is because the insolation monitor of the dual-axis system measures direct beam radiation while the single-axis system measures beam raidation normal to the pyranometer surface. The single-axis collectors "see" 300 W/m$^2$ of beam radiation later than the dual-axis colectors and so the field circulating pump is turned on later. The operable radiation level for the single-axis tracking collectors is actually higher than 300 W/m$^2$. In the summer, the dual-axis collector field would also have longer hours of operation due to its two-axis tracking capability. During the first four months of 1984, the single-axis system has 52 normal operating days while the dual-axis system has 43 normal operating days. The average daily usage factor is 0.843 for the single-axis system and 0.909 for the dual-axis system. During the second four months, the single-axis system has 56 normal operating days compared to the dual-axis system's 55. The average daily usage factor is 0.808 for the single-axis system and 0.922 for the dual-axis system.

The pie charts in Figures 1 to 10 illustrate the results of the analysis for the first and second four months of 1984. They show how the total sun hours in each period are being utilized. The area of the circle represents the total sun hours in the period; the shaded area represents sun hours with radiation above the operable level of 300 W/m$^2$. The circle is divided into the following sections:

(1) Weekends and holidays
(2) Working hours
(3) Other - (sun hours with radiation above 300 W/m$^2$ - working hours) on days with good operating conditions.
(4) Down hours - hours of nonoperation due to equipment failure, collector washing, bad weather, as well as (sun hours with radiation above 300 W/m$^2$ - working hours) on days with bad operating conditions.

Also shown are the equipment availability and usage factor associated with the working hours for each period. The pie charts indicate at a glance how much of the radiation hours and possible operating hours that the collectors actually worked. The "OTHER" section represents the difference between hours of operable radiation level and working hours on days that have good, designed conditions. In all the periods of analysis, the single-axis system has a larger percentage for this section than the dual-axis system, showing that perhaps the single-axis system is not designed to operate at the beam radiation level of 300 W/m$^2$.

Table 3 lists the energy gain and efficiency for the two systems for the first eight months of 1984. Except for one month, the single-axis system had higher energy production than the dual-axis system, which is expected because single-axis system has higher efficiency and usually operates at full capacity.

The results of the operation analysis showed that while the dual-axis tracking design allows the collectors to have longer hours for operation, its low equipment availability and frequent partial outages limit its power production capacity. Thus single-axis tracking collectors are superior to those of dual-axis tracking.

# 4. MAINTENANCE ANALYSIS

The maintenance data that are available are:

(1) daily and monthly maintenance reports,
(2) work reports,
(3) collector washing records, and
(4) collector loop malfunction reports.

The daily maintenance reports describe briefly the type of repair performed each working day to a particular system, the job order number and the man hours required. More detailed description of the repair work may be found in the job order card listed under the job order number. The man hours spent on each subsystem are summarized in the monthly maintenance reports. The work reports are written only for failures that require major repair. The information includes date and time of failure occurrence, equipment status at time of failure, cause of failure and actions taken, repair time and man hours required. The collector washing records give the loops that are washed each time, the amount of fuel and water used, and the time required. The collector loop malfunction reports give the problems associated with the modules in each loop, the date the problem was detected, the date the module was repaired, and whether the problem has required the module or loop to be taken out of service.

The collector loop malfunction reports revealed that the major problems associated with the dual-axis tracking collectors which had caused outages of many modules were tracking and leakage at the swivel joints. Unfortunately most of these repairs were not recorded in the work reports, thus preventing detailed statistical analysis of these problems. However, the operations and maintenance data do provide insights into major problems associated with the system. The dominant causes of full and partial outages, the man-hours required to maintain the collector fields, and the equivalent outage hours are discussed in this section.

## 4.1 Full Outages

From an availability point of view, the collector field subsystem is not prone to complete failures because of the parallel loop arrangement. Full outages of the collector fields are usually not caused by failures in the collector field subsystem. Table 4 is a list of the days and reasons for nonoperation of the collector field from January through August of 1984. The equipment problems that caused full outages of the collector fields were steam generator leakage, malfunction of the MCS/DAS subsystem, and software modifications in the MCS/DAS. Only on one day was the dual-axis field shutdown because of field pump failure. The single-axis field has been down on a few occasions for washing of the mirrors.

## 4.2 Partial Outages

The single-axis field was available at full capacity most of the time except for a few days when it required routine maintenance, such as mirror inspections, repair of leaks on flexible hoses, and washing the mirrors. On the other hand, the dual-axis field operated at partial capacity most of the time. The main causes of partial outages were tracking system malfunctions, oil leakage from the swivel joint, and loose facets. Table 5 shows the maintenance man-hours requirement by the two collector fields. The dual-axis field requires about 4.5 times the man-hours needed to maintain the single-axis field. These figures do not include the bolt replacement man-hour requirement of the dual-axis field, which was performed by an outside worker.

## 4.3 Equivalent Outage Hours

Equivalent outage hours (EOH) are used to account for the periods when only part of the collector field is available for service. It is the sum of all the periods during which full or partial outages occur. For each outage period i, the outage hours OH is multiplied by the fraction f of the collector field that is down. This fraction is the ratio of downed modules to the total possible functioning modules. Thus,

$$EOH = \sum_i (OH \cdot f)_i = \sum_i \left(\text{outage hours} \times \frac{\text{number of downed modules}}{\text{number of possible functioning modules}}\right)_i$$

Table 6 compares the equivalne toutage hours of the two collector fields. These outages are for the collector modules only and do not include those due to pipings, valves, or pump failures. For the first eight months of 1984, the dual-axis system has 14.2 times the equiviaent outage hours of the single-axis system.

While the availability of the dual-axis tracking system has not been so low as to prevent system operation, it has required a lot of man-hours to maintain and has resulted in reduced capacity energy output. If the man-hour requirements are converted to labor costs and combined with the cost of lost energy production due to partial operation, the dual-axis tracking collector system may be too expensive to operate as a power plant.

# 5. CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusions

The objective of this paper was to see if the single-axis and dual-axis collector fields have been operating effectively. The measures of effective operation are equipment availability, usage factor, energy production, and maintenance requirements. From analyzing the operation and maintenance records, it was found that the single-axis tracking system has high equipment availability and requires little maintenance. However, it could not operate at 300 $W/m^2$ beam irradiance and its design limits it to peak sun hours operation. In contrast the dual-axis tracking system has lower equipment availability and requires much of the effort of the maintenance crew because of its complex design. However it is able to begin operation at 300 $W/m^2$ beam irradiance, and its dual-axis tracking capability permits it to operate in the early mornings and late afternoons. Yet the longer operation hours could not compensate for the frequent partial outages, as indicated by the consistently higher energy output of the single-axis tracking system. Therefore, the single-axis tracking system operates more effectively than the dual-axis tracking system.

## 5.2 Recommendations

The equipment availability study performed for this paper has been rather superficial due to the limited amount of detail maintenance data. Ideally statistical analysis of the failure frequency and repair time of the main components should be carried out to obtain the mean time between failures (MBTF) and mean time to repair (MTTR) of these components. The information as collected in the "work reports" (Informe de Trabajo) by the maintenance crew would be adequate for such analysis, unfortunately not all repairs are recorded in these reports. It would be unreasonable to ask the maintenance workers to spend more time on such paper work, since the DCS and CRS systems together constantly keep them very busy. Nevertheless, functioning as a demonstration plant, such data should be kept and such study should be made so that lessons could be learned on how to design and build more reliable and effective solar power systems.

Reliability and maintainability data are as important to the equipment manufacturers as to power plant operators. Power plant operators specify the reliability and maintainability requirement in order to provide good service to their customers. It is the responsibility of the plant designers and manufactures to meet these specifications. It is recommended that these parties provide financial and technical support to demonstration plants as the SSPS so that detail reliability and maintainability data could be recorded and analyzed.

## 6. ACKNOWLEDGMENTS

The authors are grateful to Cia. Sevillana for supplying all the operation and maintenance data necessary for this study.

## 7. REFERENCES

1. "Technical Requirements", SSPS/DCS Plant Data Book Nº 1, Introduction and Basic Drawings, Vol. 1.

2. Plant Operation Report and Daily Operation Summary, Plant Operation Authority (Cia. Sevillana de Electricidada, S.A.), March 1984.