Paper 3.2

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FIRST TERM WORKSHOP

Tabernas, December 6, 7, and 8, 1983

AVAILABILITY MODELS AND RELIABILITY INFORMATION FOR SOLAR SYSTEMS

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1. ABSTRACT

The availability and productivity of large distributed solar power systems depends on the proper functioning of numerous mechanical components. Moreover materials and equipment exposed to long periods of solar radiation, high temperatures and climatic variations are more prone to deterioration and require routine maintenance repair.

The anticipation of failure modes and equipment life is essential for proper system design to meet reliability criteria and availability goals. The scheduling of maintenance and equipment replacement before failure can insure dependable power output.

A review of appropriate methodology for developing availability models for designs, maintenance and operation is presented. The emphasis is on the determination and accumulation of pertinent equipment and component reliability information and data that can be applied to specific installation.

2. INTRODUCTION

The commercial use of solar systems makes it essential for such systems to provide highly efficient as well as dependable service. System shutdown due to equipment malfunction will result in extra expenditures on expensive auxiliary energy and perhaps lost revenue due to lost capacity. Therefore, reliability and availability evaluations are as important as performance evaluation in commercial solar systems. They provide estimates on annual operating and maintenance costs of the system, which are essential elements in life cycle cost analysis.

Reliability is the probability of a device performing its purpose adequately for the period of time intended under the operating conditions

encountered [1:p.1]. Maintainability is the probability that a device will be restored to operational effectiveness within a given period of time when the maintenance action is performed in accordance with prescribed procedures [1:p.113]. Availability is the probability that a system will be available for use at any time after the start of operation due to the combined effects of surviving and restored components. Thus availability evaluation includes reliability as well as maintainability analysis.

To evaluate a system's availability it is necessary to know the failure and repair data of the critical components in the system. Since solar systems in medium and high temperature applications are relatively new technologies, failure and repair data for components in these systems such as insolation monitor, tracking device and motor drive, concentrating collectors, etc. may not be well-documented. Even components that are found in ordinary processes will require new data because of different operating environment and stress levels. Such is the case of a feedpump which supplies heat transfer fluid to a field of concentrating collectors. The temperature, pressure as well as fluid type are drastically different from a feedwater pump in a conventional power plant. This paper presents the system availability evaluation methodology and the information that should be gathered to perform such evaluations. It is hoped that such data will be gathered in all solar demonstration plants so that lessons could be learned in engineering design and system operations to provide long-lasting, dependable systems.

3. SYSTEM AVAILABILITY EVALUATION METHODOLOGY

System availability evaluation covers four types of availability: instantaneous, steady state, operating and equivalent availability.

Instantaneous availability is the probability that a system is available for use at any time after the start of operation [2.p.287]. Steady state availability is the probability that a system is available for use at a given point in time long after the system has been in operation. These two availabilities may be predicted if the system components' failure and restoration rates are known. Operating availability is the ratio of actual system available hours to the total number of hours in the time period under consideration. Equivalent availability takes into account the forced and scheduled partial outages and is the probability the system is available at full capacity. These latter availabilities are calculated from the daily operation records of the system.

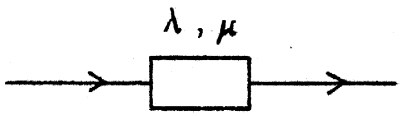
In this section the method to obtain the instantaneous availability is presented first, followed by the equations required to find the steady state, operating and equivalent availability.

The method that is used here to predict the instantaneous availability of a system is based on the assumption that the failure and restoration rates of all the system components included in the analysis are available from one data source or another. The general procedure is as follows. First divide the overall system into subsystems. Second determine which major components in each subsystem should be analyzed. Third define each subsystem's availability states. Fourth obtain reliability and maintainability data of the components. Fifth prepare the availability state transition matrix and the corresponding set of simultaneous, first order, differential equations. Finally solve the equations and analyze the results.

Available states are the possible states of the system in its ability to produce service due to the combinations of surviving components and restored components. For simplicity, the following assumptions are made: 1) Only one repair is performed at a time; 2) two or more units cannot fail in the same time interval; 3) the time interval is small; 4) the units have constant failure and repair rates. The steps to prepare the availability state transition matrix and the corresponding equations for a single unit with repair; a series system; and a parallel system are presented next.

3.1 Single unit with repair

The schematic below illustrates the availability diagram of this system, where λ and μ are the unit's failure and restoration rates, respectively. This is followed by its state transition matrix.



The states are defined as follows:

state 1 - the unit is operable and is available for use.

state 0 - the unit has failed and is unavailable.

STATE TRANSITION MATRIX FOR A SINGLE UNIT SYSTEM WITH REPAIR:

STATES AT t	STATES AT t + t: 1	0
1	$1-\lambda$	λ
0	μ	$1-\mu$

The state transition matrix shows the probability of the system remaining in the same state during time interval Δt or moving to another state. $\lambda\Delta t$ is the probability of the unit failing in Δt, $\mu\Delta t$ is the probability of the unit getting repaired during time interval Δt. Mathematically these states are represented by

$$P_1(t+\Delta t) = (1-\lambda\Delta t)\,P_1(t) + \mu\Delta t\,P_0(t)$$

$$P_0(t+\Delta t) = \lambda\Delta t\,P_1(t) + (1-\mu\Delta t)\,P_0(t) \quad ,$$

where $P_1(t)$ and $P_0(t)$ are the probability of existing in state 1 or state 0 respectively at time t. $P_1(t + \Delta t)$ and $P_0(t + \Delta t)$ are the probable states at time $t + \Delta t$. Rearranging these equations, the following differential equations result:

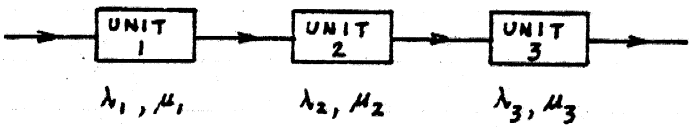
$$\frac{P_1(t+\Delta t) - P_1(t)}{\Delta t} = -\lambda P_1(t) + \mu P_0(t) = P_1'(t) \qquad (1)$$

$$\frac{P_0(t+\Delta t) - P_0(t)}{\Delta t} = \lambda P_1(t) - \mu P_0(t) = P_0'(t) \qquad (2)$$

Equations (1) and (2) are the first order differential equations for a single-unit system with repair. $P_1(t)$ and $P_0(t)$ are solved by numerical methods. The instantaneous availability of a single unit with repair is $A(t) = P_1(t)$. Its unavailability is $U(t) = 1-A(t) = 1-P_1(t) = P_0(t)$

3.2 Units in series

In series - arranged system, the system fails when at least one unit fails. The availability block diagram of a three-unit system in series is illustrated below.



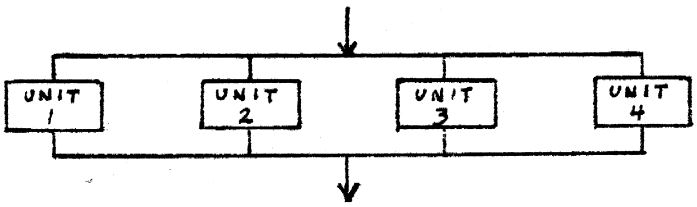
The instantaneous availability of the system is

$$A(t) = A_1(t) \cdot A_2(t) \cdot A_3(t) = \prod_{i=1}^{3} A_i(t)$$

where $A_i(t)$'s are calculated separately as three-single unit with repair systems.

3.3 Units in parallel

In a parallel system, the system continues to function until all units have failed. For a system of N identical units in parallel, there are (N+1) states of existence. For a system of N non-identical units there are 2^N possible availability states. The following are the schematic representation and transition matrix for a four-equal-unit parallel system.



$\lambda_1 = \lambda_2 = \lambda_3 = \lambda_4 = \lambda$

$\mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu$

	STATES AT $t + \Delta t$				
STATES AT t	4	3	2	1	0
4	$1-4\lambda$	4λ	0	0	0
3	μ	$1-(3\lambda+\mu)$	3λ	0	0
2	0	2μ	$1-(2\lambda+2\mu)$	2λ	0
1	0	0	3μ	$1-(\lambda+3\mu)$	λ
0	0	0	0	4μ	$1-4\mu$

The definitions of these states are:

state 4 - all four units are operable and operating

state 3 - one unit is undergoing maintenance; three units are in service

state 2 - two units are undergoing maintenance; two are in operation

state 1 - three units are undergoing maintenance, only 1 unit is operating

state 0 - all units are undergoing maintenance. System is unavailable.

The differential equations for these states are:

$$P_4'(t) = -4\lambda P_4(t) + \mu P_3(t)$$

$$P_3'(t) = 4\lambda P_4(t) - (3\lambda + \mu) P_3(t) + 2\mu P_2(t)$$

$$P_2'(t) = 3\lambda P_3(t) - (2\lambda + 2\mu) P_2(t) + 3\mu P_1(t)$$

$$P_1'(t) = 2\lambda P_2(t) - (\lambda + 3\mu) P_1(t) + 4\mu P_0(t)$$

$$P_0'(t) = \lambda P_1(t) - 4\mu P_0(t)$$

The instantaneous availability of a four-equal-unit system in parallel is

$$A(t) = P_4(t) + P_3(t) + P_2(t) + P_1(t) = 1 - P_0(t)$$

where $P_0(t)$ is the instantaneous unavailability of the system. Similar procedure may be set up for standby system with some minor adjustment; it will not be covered here. Table 1 lists the availability of some redundant systems based on exponential failure and repair distribution. Substituting

the values of failure and restoration rate into these equations will give the instantaneous availability of these systems.

The steady state availability is calculated from the instantaneous availability:

$$A_s = \lim_{t \to \infty} A(t)$$

Operating availability is defined as

$$A_o = \frac{AH}{PH} \times 100$$

where AH represents available hours and PH represents period hours.

Equivalent availability is defined as

$$A_E = \frac{SH - (EFOH - ESOH)}{PH} \times 100$$

where SH = service hours

EFOH = equivalent forced outage hours

ESOH = equivalent scheduled outage hours

In order to calculate these four availabilities, failure, repair and outage hours data are necessary. These data are referred to as reliability-availability data in this report.

Table 1 Availability of Some Redundant Systems Based on Exponential Failure and Repair Distributions [reference 6]

No. of Equipments	Conditions: Type Redundancy	Conditions: Repair	Instantaneous Availability Model	Definitions of Constants for Instantaneous Availability Model	Steady-State Availability: Model	Steady-State Availability: Av. for $\lambda = 0.01$, $\mu = 0.2$
1	—	—	$A(t) = \frac{\mu}{\mu+\lambda} + \frac{\lambda}{\mu+\lambda} e^{-(\mu+\lambda)t}$	—	$\frac{\mu}{\mu+\lambda}$	0.95
2	Standby	Single	$A(t) = \frac{\mu^2+\mu\lambda}{\mu^2+\mu\lambda+\lambda^2} - \frac{\lambda^2(s_2e^{s_1t} - s_1e^{s_2t})}{s_1s_2(s_1-s_2)}$	$s_1 = -(\lambda+\mu) - \sqrt{\mu\lambda}$ $s_2 = -(\lambda+\mu) + \sqrt{\mu\lambda}$	$\frac{\mu^2+\mu\lambda}{\mu^2+\mu\lambda+\lambda^2}$	0.998
		Multiple	$A(t) = \frac{2\mu^2+2\mu\lambda}{2\mu^2+2\mu\lambda+\lambda^2} - \frac{\lambda^2(s_2e^{s_1t} - s_1e^{s_2t})}{s_1s_2(s_1-s_2)}$	$s_1 = -\frac{1}{2}[(2\lambda+3\mu) + \sqrt{\mu^2+4\mu\lambda}]$ $s_2 = -\frac{1}{2}[(2\lambda+3\mu) - \sqrt{\mu^2+4\mu\lambda}]$	$\frac{2\mu^2+2\mu\lambda}{2\mu^2+2\mu\lambda+\lambda^2}$	0.999
	Parallel	Single	$A(t) = \frac{\mu^2+2\mu\lambda}{\mu^2+2\mu\lambda+2\lambda^2} - \frac{2\lambda^2(s_2e^{s_1t} - s_1e^{s_2t})}{s_1s_2(s_1-s_2)}$	$s_1 = -\frac{1}{2}[(3\lambda+2\mu) + \sqrt{\lambda^2+4\mu\lambda}]$ $s_2 = -\frac{1}{2}[(3\lambda+2\mu) - \sqrt{\lambda^2+4\mu\lambda}]$	$\frac{\mu^2+2\mu\lambda}{\mu^2+2\mu\lambda+2\lambda^2}$	0.996
		Multiple	$A(t) = \frac{\mu^2+2\mu\lambda}{\mu^2+2\mu\lambda+\lambda^2} - \frac{2\lambda^2(s_2e^{s_1t} - s_1e^{s_2t})}{s_1s_2(s_1-s_2)}$	$s_1 = 2(\mu+\lambda)$ $s_2 = -(\mu+\lambda)$	$\frac{\mu^2+2\mu\lambda}{\mu^2+2\mu\lambda+\lambda^2}$	0.998
3	Standby	Single	$A(t) = \frac{\mu^3+\mu^2\lambda+\mu\lambda^2}{\mu^3+\mu^2\lambda+\mu\lambda^2+\lambda^3} + \frac{\lambda^3[s_2s_2(s_2-s_3)e^{s_1t} - s_1s_3(s_1-s_3)e^{s_2t} + s_1s_2(s_1-s_2)e^{s_3t}]}{s_1s_2s_3(s_1-s_2)(s_1-s_3)(s_2-s_3)}$	s_1, s_2, and s_3 correspond to the three roots of $s^3 + s^2(3\lambda+3\mu) + s(3\lambda^2+4\mu\lambda+3\mu^2) + (\lambda^3+\mu\lambda^2+\lambda\mu^2+\mu^3)$	$\frac{\mu^3+\mu^2\lambda+\lambda^2\mu}{\mu^3+\mu^2\lambda+\lambda^2\mu+\lambda^3}$	0.9999
		Multiple	$A(t) = \frac{6\mu^3+6\mu^2\lambda+3\mu\lambda^2}{6\mu^3+6\mu^2\lambda+3\mu\lambda^2+\lambda^3} + \frac{\lambda^3[s_2s_3(s_2-s_3)e^{s_1t} - s_1s_3(s_1-s_3)e^{s_2t} + s_1s_2(s_1-s_2)e^{s_3t}]}{s_1s_2s_3(s_1-s_3)(s_1-s_3)(s_2-s_3)}$	s_1, s_2, and s_3 correspond to the three roots of $s^3 + s^2(3\lambda+6\mu) + s(3\lambda^2+9\mu\lambda+11\mu^2) + (\lambda^3+3\mu\lambda^2+6\mu^2\lambda+6\mu^3)$	$\frac{6\mu^3+6\mu^2\lambda+3\mu\lambda^2}{6\mu^3+6\mu^2\lambda+3\mu\lambda^2+\lambda^3}$	0.99998
	Parallel	Single	$A(t) = \frac{\mu^3+3\mu^2\lambda+6\mu\lambda^2}{\mu^3+3\mu^2\lambda+6\mu\lambda^2+6\lambda^3} + \frac{6\lambda^3[s_2s_3(s_2-s_3)e^{s_1t} - s_1s_3(s_1-s_3)e^{s_2t} + s_1s_2(s_1-s_2)e^{s_3t}]}{s_1s_2s_3(s_1-s_2)(s_1-s_3)(s_2-s_3)}$	s_1, s_2, and s_3 correspond to the three roots of $s^3 + s^2(6\lambda+3\mu) + s(11\lambda^2+9\mu\lambda+3\mu^2) + (6\lambda^3+6\mu\lambda^2+3\mu^2\lambda+\mu^3)$	$\frac{\mu^3+3\mu^2\lambda+6\mu\lambda^2}{\mu^3+3\mu^2\lambda+6\mu\lambda^2+6\lambda^3}$	0.9993
		Multiple	$A(t) = \frac{\mu^3+3\mu^2\lambda+3\mu\lambda^2}{(\mu+\lambda)^3} + \frac{6\lambda^3[s_2s_3(s_2-s_3)e^{s_1t} - s_1s_3(s_1-s_3)e^{s_2t} + s_1s_2(s_1-s_2)e^{s_3t}]}{s_1s_2s_3(s_1-s_2)(s_1-s_3)(s_2-s_3)}$	s_1, s_2, and s_3 correspond to the three roots of $s^3 + s^2(6\lambda+6\mu) + s[11(\mu+\lambda)^2] + 6(\mu+\lambda)^3$	$\frac{\mu^3+3\mu^2\lambda+3\mu\lambda^2}{\mu^3+3\mu^2\lambda+3\mu\lambda^2+\lambda^3}$	0.9999

NOTES:
1. $A(t)$ is the probability of a system being available at time t. $A(t)$ is a function of μ and λ the repair and failure rates. For all functions, the probability of a system being available at time zero is unity. The units of μ and λ must be the same as for t.
2. Instantaneous availability. The probability that the system will be available at any instant in time.
3. Mission availability. Expected availability for a given mission period. This value can be derived from the general model by computing the average value of $A(t)$ for the mission period. Mathematically, this is

$$A_m = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} A(t)\, dt$$

Usually t_1 is considered as zero.
4. Steady-state availability. The portion of up time expected for continuous operation. Mathematically, this is expressed

$$A_{ss} = \lim_{t \to \infty} A(t)$$

5. See also notes 1 through 4 of Table 3.1.
6. This table was prepared by W. O'Leary, RCA.

4. RELIABILITY AVAILABILITY INFORMATION REQUIREMENT AND FUNCTIONS

To properly collect the reliability-availability data, three categories of reports should be maintained: Equipment failure report, system availability report and annual system availability summary report. The contents and functions of each report category are discussed next.

4.1 Equipment failure report

The main function of the equipment failure report is to provide information for determining the equipment's failure rate and repair rate, which results in obtaining the equipment's reliability and maintainability. If the failure and repair rates of all the major components in the system could be obtained, then the steady state and instantaneous availability may be predicted. In addition to equipment failure reports, there should be reports on preventive maintenance actions that were performed on a piece of equipment. This provides an estimate on the operating and maintenance costs of the overall system as well as how the parts inventory should be kept. The failure report also identifies particular inadequacies in the equipment design so that improvements could be made in future equipment. As mentioned previously the equipment failure reports provide information to determine the reliability of an equipment. By identifying equipment of lowest reliability the design engineer can decide whether a more reliable replacement is technologically and economically feasible. If not, parallel or standby redundancy may be needed. Redundancy improves system reliability but also increases the initial cost of the system. The design engineer could also decide to stay with the unreliable equipment if he determines that the equipment requires low maintenance, ie., short time to repair,

easily accessible components, interchangeable part or low overall maintenance cost. Table 2 lists the information that should be included in the equipment failure report. Such reports should be maintained on all the major equipment in the system. The information includes both failure and repair data. From the failure data, effects of the equipment's failure on the system could be documented for different failure causes. Over a period of time, the time-to-failure of equipment may be estimated. From the repair data, proper actions to correct a particular failure could be documented. The time to restore equipment due to a specified failure may be estimated. The cost to maintain the equipment may be determined. Similar repair data should be kept when equipment undergoes preventive maintenance.

For a particular piece of equipment, the failure reports collected over a period of time provide the necessary information to determine the following:

1. the time to failure
2. the failure rate
3. the reliability
4. the time to repair
5. the restoration rate
6. the maintainability
7. the recurring failure cause that may imply poor equipment design or inappropriate operating conditions

4.2 System availability report

During the year a log book should be maintained to record information as listed in Table 2 everytime a full or partial system outage occurs. This

data provides the data to be recorded in the Annual System Availability Summary Report. More importantly these data reveal the critical components in the system that cause full or partial outages most often and those that cause the highest capacity loss. These components would require redundancy or be replaced by higher reliability components. These data should reinforce the conclusions that are drawn from the Equipment Failure Reports. Recording the reduced capacity due to failed equipment allows the determination of the system's effeciveness at a particular availability state. This information is used in system availability prediction.

4.3 Annual system availability summary report

The annual system availability evaluation is the main purpose of the reliability-availability evaluation. The ultimate goal is to determine the annual operating and maintenance costs, the extra expenditures and lost income due to partial and full outages. Table 3 lists the information to be included in the Annual System Availability Summary Report. This information allows the determination of operating availability and equivalent availability according to the Edison Electric Institute's definition. The calculated availabilities of the solar power plants may therefore be compared to those of fossil and nuclear power plants on an equal basis. Operating availability is the probability that a plant is capable of producing power at any given time, while equivalent availability is the probability that the plant is capable of producing power at full capacity. These definitions may be applied to applications other than power plants. They provide an estimate of the percent of time the system is available for service. For commercial systems, it's converse provides an estimate of lost

revenue and extra expenditures. The data also provides a basis for adjusting the planned outage schedule so as to maximize the number of system components that receive preventive maintenance at one time, thus reducing the number of forced and planned outages.

5. SUMMARY AND RECOMMENDATIONS

In order for solar energy systems to receive wide commercial applications, their dependability and effectiveness must be proven to be comparable to those of conventional systems. Reliability and availability evaluation should be included in any solar system study so that system malfunctions may be identified, investigated and avoided in future systems. Proper data should be maintained in all solar demonstration plants on major components that comprise the system. These data serve to identify recurring problems associated with a system; establishes components' failure and repair data; enable system reliability and availability prediction; and provide estimates on operation and maintenance costs.

It is recommended that such data be gathered on all solar demonstration sites as well as operating commercial solar systems, since more data will improve accuracy in the results. Industries that have well-established reliability programs such as the nuclear, automobile, airplane and military defense, all have well-documented and updated reliability-availability data. The solar industry should follow these industries and establish a reliability data network. This will strengthen the industry's credibility and public acceptability. However, such data system requires a strong foundation. It is the responsibility of the operators of solar demonstration plants to take the initiative to acquire good reliability data.

At present not much emphasis has been placed on determining the interactions of the solar insolation availability with system availability and load demand. This problem should be properly addressed so as to provide a more realistic estimation of the actual solar energy production and auxiliary energy requirement of the system.

Appendix B is a brief discussion on the relationships between solar availability, equipment availability and the collected solar heat. It is part of a study currently undertaken by the authors.

TABLE 2 Information to be included in the Equipment Failure Report

1. Component type
2. Date and time of failure
3. Status at time of failure - operating, standby, in test, maintenance or out of service.
4. Failure event description - environmental or stress factors
5. Cause of failure
6. Type of failure - castastrophic, break-in, wear-out
7. Effect of failure - loss of system operation, damage to other equipment, reduction in system capacity
8. Corrective action
9. Repair hours
10. Hours in waiting - administrative, logistics, equipment cool down etc.
11. Total man-hours
12. Part replacement

TABLE 3 Information to be included in the System Availability Report

1. Year
2. Outage number, starting with 1 for the first occurrence of each year
3. Type of outage - forced, planned, reserve shutdown, forced partial, scheduled partial
4. Cause of outage
5. Hours waiting before repair work could begin
6. Man-hours worked on cause of outage
7. Man-hours worked on other equipment
8. Outage duration in total number of hours
9. If partial outage, system capacity before and following the partial outage.

TABLE 4 Information to be included in the Annual System Availability Summary Report

1. Year
2. Period hours
3. Service hours
4. Available hours
5. Forced outage hours
6. Forced partial outage hours
7. Maintenance outage hours
8. Hours waiting
9. Number of forced outages
10. Number of forced partial outages
11. Planned outage hours
12. Planned partial outage hours
13. Number of maintenance outages
14. Number of planned outages
15. Number of planned partial outages

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7. APPENDIX A

Edison Electric Institute Electric Power Plant Availabilities

Operating availabilities $A_O\% = AH/PH \times 100$

AH = available hours = the time in hours during which a unit or major equipment is available

PH = period hours = the clock hours in the period under consideration. Generally one year.

AH = SH + RSH

SH = service hours = the total number of hours the unit was actually operated with breakers closed to the station bus.

RSH = reserve shutdown hours = reserve shutdown duration in hours (off time or idle time)

Equivalent availability $A_E\% = (SH-(EFOH+ESHO))/PH \times 100$

EFOH = equivalent forced outage hours = FOH x capacity reduction/maximum dependable capacity

ESOH = equivalent scheduled outage hours = SOH x capacity reduction/maximum dependable capacity

Relative mechanical availability $A_{RM}\% = (PH-AOT)/PH \times 100$

$A_{RM}\%$ = a form of operating availability adjusted to show relative effort

AOT = adjusted outage time = HW + MH/10

HW = hours waiting, that portion of time for any outage during which no work could be performed. This includes time for cooling down the equipment and the shipment of parts.

MH = manhours worked (measure of effort relatively independent of work schedules and crew sizes)

MH/SWF = man hours worked (MH) divided by a standard work force (SWF), a derived-time-worked based on effort

SWF has been arbitrarily taken to be 10 men as the standard work force in a power plant

Maximum dependable capacity - The dependable plant capacity in winter or summer, whichever capacity is smaller.

8. APPENDIX B*

Solar Heat Production by Concentrating Collector Systems - Effects of Solar and Equipment Availability

The hourly solar energy produced from a concentrating collector is given by the following equation.

$$\dot{Q}u = A_a \eta_o (1-\Gamma_e)(1-\Gamma_s) I_n \cos\theta - A_r U_L (T_r - T_a) - L_s$$

where $\dot{Q}u$ - hourly solar energy collected

A_a - unshaded area of the concentrator aperture

A_r - area of the receiver

η_o - optical efficiency

Γ_e - fraction of incident radiation that is lost as end losses

Γ_s - fraction of incident radiation on the concentrator that is lost to shading

I_n - direct normal irradiance to the concentrator aperture

θ - incidence angle

U_L - overall loss coefficient for the receiver

T_r - receiver temperature

T_a - ambient temperature

L_s - system heat losses due to pipings, joints and start-up requirements

*This appendix is taken from work in progress by the authors; it is of a preliminary nature.

The optical efficiency η_o is affected by the time of day and year as well as the age of the collector which deteriorates with age due to long term environmental exposure:

$$\eta_o(T,\theta) = \rho(T,\theta) \cdot \gamma(\theta) \cdot \tau(\theta) \cdot \alpha(T,\theta)$$

T - age of the reflective mirror

θ - incidence angle

ρ - specular reflectance of the reflector

γ - intercept factor

τ - transmittance of the cover system

α - absorptance for incidence solar radiation on the receiver

The threshold radiation I_{th} is defined as the radiation level above which useful energy could be collected. This may be obtained by setting $\dot{Q}u$ equal to zero. Thus the beam threshold radiation is:

$$I_{th} = \frac{A_r U_L (T_r - T_a) + L_s}{A_a \eta_o (1-\Gamma_e)(1-\Gamma_s)}$$

Assuming U_L and L_s to be constant, the threshold radiation is proportional to the incidence angle: When the incidence angle is zero (the sun is directly overhead the collector) the threshold radiation is at the minimum; near sunrise and sunset the threshold radiation approaches infinity. This may be illustrated more clearly by Figure B.1. The amount of energy above the threshold is the amount of energy that is collected by the collector. Therefore $\dot{Q}u$ is represented by:

$$\dot{Q}u = A_a \eta_o(\theta) [1-\Gamma_e(\theta)] [1-\Gamma_s(\theta)] [I_n \cos\theta - I_{th}(\theta)]$$

Let $\xi(\theta)$ be the reception efficiency as defined by:

$$\xi(\theta) = \eta_o(\theta)\left[1 - \Gamma_e(\theta)\right]\left[1 - \Gamma_s(\theta)\right]$$

The beam radiation incident on the concentrator aperture is I_b, where

$$I_b = I_n \cos\theta$$

For each hour i during the collection period, the collected energy is

$$Qu_i = A_a \xi_i (I_{b_i} - I_{th_i})$$

Let N_c be the number of hours in a day that the beam radiation exceeds the threshold level. The total daily useful energy is given by

$$Qud = A_a \sum_{i=1}^{N_c} \xi_i (I_{b_i} - I_{th_i})$$

If the average reception efficiency is determined as

$$\bar{\xi} = \frac{\sum_{i=1}^{N_c} (I_{b_i} - I_{th_i})\xi_i}{\sum_{i=1}^{N_c} (I_{b_i} - I_{th_i})}$$

then

$$Qud = A_a \bar{\xi} \sum_{i=1}^{N_c} (I_{b_i} - I_{th_i})$$

The solar availability for a day can be defined as

$$A_{sd} = \frac{\sum_{i=1}^{N_c} (I_{b_i} - I_{th_i})}{\sum_{j=1}^{N_s} I_{b_j}} = \frac{\sum_{i=1}^{N_c} (I_{b_i} - I_{th_i})}{H_b}$$

where N_s is the total hours of sunshine in a day and H_b is the daily beam radiation on the concentrator aperture. Since the numerator in the above equation would be zero for days of low insolation, the solar availability as defined necessitates clear sky condition for most of the day.

In terms of solar availability, the daily useful energy collected is

$$Q_{ud} = A_a \bar{\xi} H_b A_{sd}$$

The monthly solar energy collected can be estimated by

$$\tilde{Q}_{um} = A_a \bar{\xi} H_b A_{sd} N_{cm}$$

where N_{cm} is the number of clear days in a month. The annual amount of solar energy collected is estimated by

$$\tilde{Q}_u' = A_a \sum_{k=1}^{12} [\bar{\xi}_k H_{b_k} A_{sd_k} N_{cm_k}]$$

where k is the month of the year. This is the amount of solar heat produced by the collector if all the components of the solar system function properly whenever the beam radiation is above the threshold level. Over a year, however, there are times when the system will be shutdown due to equipment malfunction or maintenance. For example, concentrating collectors require periodic washing of the reflecting surface. A more realistic estimation of the annual solar energy collected should include the solar equipment availability for a one-year period. Therefore the annual solar heat collected should be estimated by the following equation,

$$\tilde{Q}_u = A_a A_{eq} \sum_{k=1}^{12} [\bar{\xi}_k H_{b_k} A_{sd_k} N_{cm_k}]$$

where A_{eq} is the operating availability of the solar system. The estimate of the monthly useful solar heat is:

$$\widetilde{Q}_{um} = A_a \, A_{eq}(t) \, \bar{\xi} \, H_b \, A_{sd} \, N_{cm}$$

where A_{eq} (t) is the solar system's instantaneous availability; t is the time of year in hours, with t = 0 hours at the beginning of each year.

The instantaneous collector efficiency at any time of the day t' is defined by

$$\eta(t') = \frac{\dot{Q}_u(t')}{A_a I_b(t')}$$

Over a day the collector efficiency is just the ratio of the daily useful heat gain to the daily beam radiation on the concentrator aperture:

$$\eta_d = \frac{Q_{ud}}{A_a H_b} = \frac{A_a \bar{\xi} \sum_{i=1}^{N_c} (I_{b_i} - I_{th_i})}{A_a \sum_{j=1}^{N_s} I_{b_j}}$$

$$\eta_d = \bar{\xi} \, A_{sd}$$

Thus the daily collector efficiency is the product of the daily average reception efficiency and solar availability.

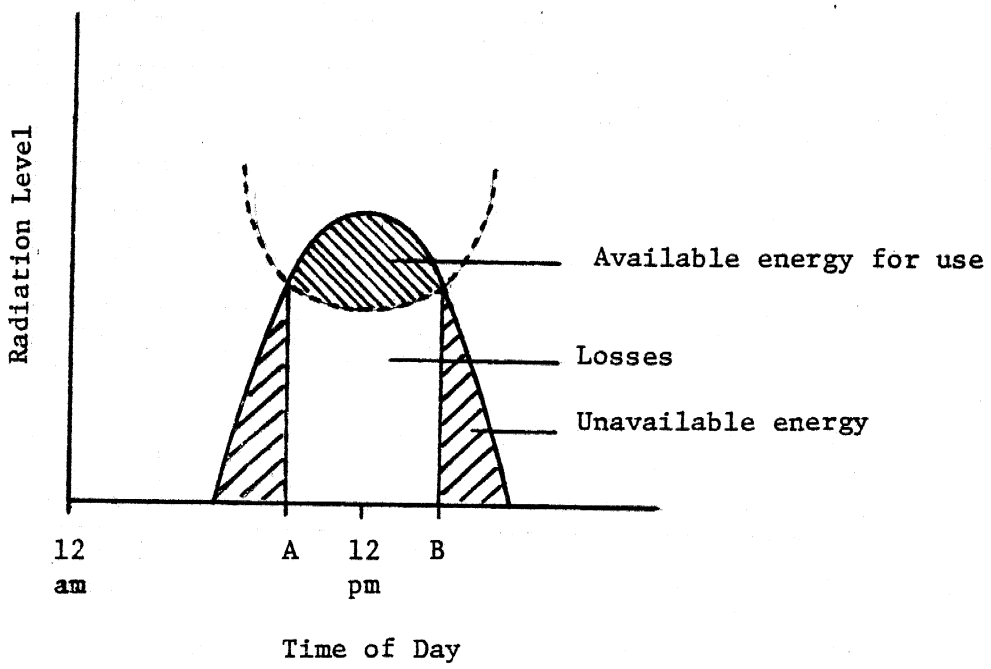

Figure B.1 Useful energy vs time of day (——)
and threshold level required (----)
A - system start-up time
B - system shutdown time