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# Performance evaluation and decision support system of water circulation system of a steam thermal power plant

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**ABSTRACT**

The present paper discusses the development of a Markov model for performance evaluation of water circulation system of a thermal power plant using probabilistic approach. A water circulation system ensures a proper supply of water for smooth working of a thermal power plant. For regular and economical generation of steam, it is necessary to maintain each sub- system of this system to ensure an optimum level of availability. In present paper, the water circulation system consists of five subsystems with three possible states i.e. working, reduced and failed state. Failure and repair rates of subsystems are taken to be constant. After drawing transition diagram, differential equations have been generated. After that, steady state probabilities are determined. The system of equations is solved for steady state availability of the system using Laplace transformation technique. Besides, some decision matrices are also developed, which provide various performance levels for different combinations of failure and repair rates of all subsystems. Based upon various performance values obtained in decision matrices and plots of failure rates/ repair rates of various subsystems, performance of each subsystem is analysed and then maintenance decisions are made for all subsystems. The developed model helps in comparative evaluation of alternative maintenance strategies.



## Introduction

In the present era of rapid technology evolution, modern technology and integrated automation of manufacturing has developed a tendency to design and manufacture equipments of greater capital cost, sophistication, complexity and capacity. The very survival of such systems is dependent upon high productivity and high payback ratios. All production systems are expected to be operational and available for the maximum time possible so as to maximize production volumes and profits. But, failure is an unavoidable phenomenon. All systems eventually fail.

It therefore becomes imperative that any system downtime resulting from these failures be kept to an absolute minimum. In most of the complex systems encountered in practice, it has been observed that they consist of components and subsystems connected in series, parallel, or standby, or a combination of these. For regular and economical generation of steam, it is necessary to maintain each subsystem of the water circulation system. The failure of each item of equipment or subsystem depends upon the operating conditions and maintenance policies used. From economic and operational points of view, it is desirable to ensure an optimum level of system availability. The goal of maximum steam generation may be achieved under the given operational conditions, making the water circulation system failure-free, by examining the behaviour of the system and making a top priority maintenance decision for the most critical subsystems.

The need and application of reliability technology in the process & production industries was discussed by many researchers. Khan and Gupta [1] have introduced the concept of a pending – failure state in order to consider usual operating and wear out periods of engineering systems and proposed 3 – state system model. Their important findings were: for a given repair rate the steady state availability of a system can be increased by decreasing the preventive maintenance intervals, and preventive maintenance is more effective for a system having a smaller deterioration factor. Gupta and Tyagi [2] calculate the availability and M.T.T.F of a standby redundant complex system incorporating the concept of human failure in two states, viz. good and failed. They assumed that single service facility is available for the service of unit failure.

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Supplementary variable technique & Laplace transformation method was used to obtain various state probabilities. To make the system more applicable to practical life problems, M.T.T.F for the system has also been computed and various graphs were plotted to highlight the utility of the model. Many researchers developed and presented various methods for determining optimal maintenance schedules. Mokaddis et al. [3] calculated reliability and availability of a two unit system with a standby unit, having a single service facility for the performance of preventive maintenance and repair. Chung [4] presented mathematical models to evaluate state probabilities and steady state availabilities for multiple – state devices and repairable parallel system with standby involving human error and common cause failure respectively. Dhillon and Rayapati [5] emphasized that chemical plants have grown larger and run at higher temperatures and pressures, thus risks associated with these plants have increased manifolds. Therefore, the chemical industry needs urgent application of reliability engineering principles. He discussed the model for the moving and firing mission reliabilities of a combat tank and the usefulness of Kim [6] described mathematical model to carry out analysis for mission reliability of a combat tank, analysis part for the tank planner or designer. Zhao [7] developed a generalized availability model for repairable components and series systems including perfect and imperfect repair. The general distribution was assumed for a repaired component. Schabe [8] presented a method for obtaining optimum replacement time of a complex system which is subjected to maintenance. Laguerre series expansions were used to compute the availability numerically. Zhang [9] studied the stochastic behavior of an [N+1]-unit standby system under preemptive priority repair rule and obtained the expressions for transient and steady states of the system using supplementary variables and Laplace transforms. Kumar et al. Nakamura.M [10] described a maintenance scheduling for Pump systems in thermal power stations in order to reduce the maintenance cost during the whole period of operation, while keeping the current reliability level of the pump system. The dimensional reduction method was used to solve the problem in which a few available data were used together with other factors relating to the failure of pumps. According to Ebling [11] factors that affect RAM of a repairable system include machinery (type, number of machines, age, arrangement of machines relative to each other, arrangement of components in the machine, inherent defects in components), operating conditions (level of skill and number of operating personnel, working habits, inter-personnel relationships, bsenteeism, safety measures, environmental conditions, severity of tasks assigned, shock loading-accidental or otherwise), maintenance conditions (competence and strength of maintenance personnel, attendance, working habits, safety measures, inter-personnel relationships, defects introduced by previous maintenance actions, effectiveness of maintenance planning and control), and infrastructural facilities (spare-parts, consumables, common and special tools). Sharma [12] reported an interesting model for optimization of redundancy in a thermal power plant using Genetic Algorithm technique. He also reported that high reliability figures are required for most critical components such as boiler, turbine and condenser unit. Sharma et al. [13], analysis the Reliability and availability of ash handling unit of a steam thermal power plant.

**System Description**

**The water circulation system consists of five sub-systems:**

1. Condensate Extraction Pump (A): Consist of two units working in parallel. The system works with one unit in reduced capacity.
2. Low Pressure Heaters (B): Consist of three units. Two units working in series and one is stand by.
3. De-aerator (C): Consist of single unit. System fails if it fails.
4. Boiler Feed Pump (D): Consist of three units. Two units working in parallel and one is stand by. This system never fails.
5. High Pressure Heaters (E): Consist of two units. The system works with one unit in reduced capacity.

**Assumptions and Notations**

1. Failure and repair rates for each subsystem are constant and statistically independent.
2. Not more than one failure occurs at a time.
3. A repaired unit is as good as new, performance wise.
4. The standby units are of the same nature and capacity as the active units.

**The notations associated with the transition diagram (Figure 2) are as follows:**

1. A, B, C, D, E: Subsystems in good operating state
2. $\bar{A}$, $\bar{B}$, $\bar{D}$, $\bar{E}$: Indicates that A,B,D,E is working in reduced capacity.
3. a,b,c,d,e: Indicates the failed state of A,B,C,D,E.
4. $\lambda_i$: Mean constant failure rates from states A,B,C,D,E,$\bar{A}$,$\bar{B}$,$\bar{D}$,$\bar{E}$ to the states $\bar{A}$,$\bar{B}$,c,$\bar{D}$,$\bar{E}$,a,b,d,e respectively.
5. $\mu_i$: Mean constant repair rates from states $\bar{A}$,$\bar{B}$,c,$\bar{D}$,$\bar{E}$,a,b,d,e to the States A,B,C,D,E,$\bar{A}$,$\bar{B}$,$\bar{D}$,$\bar{E}$ respectively.
6. $P_i$ (t): Probability that at time‘t’ the system is in ith state.
7. ': Derivatives w.r.t. ‘*t*’

**Mathematical Analysis of the System**

Probability consideration gives following differential equations associated with the Transition Diagram (Figure 1A).

$$P_0^{'}(t) + (\lambda_1 + \lambda_2 + \lambda_3)P_0(t) = \mu_1 P_1(t) + \mu_2 P_2(t) + \mu_3 P_{18}(t) \quad (1)$$

$$P_1^{'}(t)+(\lambda_2+\lambda_3+\lambda_4+\mu_1)P_1(t)= \lambda_1P_0(t)+\mu_2P_3(t)+\mu_3P_{19}(t)+\mu_1P_{20}(t) \quad (2)$$

$$P_2^{'}(t)+(\lambda_1+\lambda_2+\lambda_3+\mu_2)P_2(t)= \lambda_2P_0(t)+\mu_1P_3(t)+\mu_2P_{16}(t)+\mu_3P_{17}(t) \quad (3)$$

$$P_3^{'}(t)+(\lambda_4+\lambda_5+\mu_1+\mu_2)P_3(t)= \lambda_2P_1(t)+\lambda_1P_2(t)+\mu_4P_4(t)+\mu_5P_5(t) \quad (4)$$

$$P_4^{'}(t)+(\lambda_1+\lambda_2+\lambda_3+\lambda_4+\lambda_5+\mu_4)P_4(t)= \lambda_4P_3(t)+\mu_5P_6(t)+\mu_1P_{15}(t)+\mu_2P_{14}(t)+\mu_3P_{13}(t)+\mu_4P_{12}(t) \quad (5)$$

$$P_5^{'}(t)+(\lambda_1+\lambda_2+\lambda_3+\lambda_4+\lambda_5+\mu_5)P_5(t)= \lambda_5P_3(t)+\mu_4P_6(t)+\mu_5P_{21}(t)+\mu_3P_{22}(t)+\mu_1P_{23}(t)+\mu_2P_{24}(t) \quad (6)$$

$$P_6^{'}(t)+(\lambda_1+\lambda_2+\lambda_3+\lambda_4+\lambda_5+\mu_4+\mu_5)P_6(t)=\lambda_5P_4(t) +\lambda_4P_5(t)+\mu_1P_7(t)+\mu_2P_8(t)+\mu_3P_9(t)+\mu_4P_{10}(t)+\mu_5P_{11}(t) \quad (7)$$

$$P_7^{'}(t)+\mu_1P_7(t)=\lambda_1P_6(t) \quad (8)$$

$$P_8^{'}(t)+\mu_2P_8(t)=\lambda_2P_6(t) \quad (9)$$

$$P_9^{'}(t)+\mu_3P_9(t)=\lambda_3P_6(t) \quad (10)$$

$$P_{10}^{'}(t)+\mu_4P_{10}(t)=\lambda_4P_6(t) \quad (11)$$

$$P_{11}^{'}(t)+\mu_5P_{11}(t)=\lambda_5P_6(t) \quad (12)$$

$$P_{12}^{'}(t)+\mu_4P_{12}(t)=\lambda_4P_4(t) \quad (13)$$

$$P_{13}^{'}(t)+\mu_3P_{13}(t)=\lambda_3P_4(t) \quad (14)$$

$$P_{14}^{'}(t)+\mu_2P_{14}(t)=\lambda_2P_4(t) \quad (15)$$

$$P_{15}^{'}(t)+\mu_1P_{15}(t)=\lambda_1P_4(t) \quad (16)$$

$$P_{16}^{'}(t)+\mu_2P_{16}(t)=\lambda_2P_2(t) \quad (17)$$

$$P_{17}^{'}(t)+\mu_3P_{17}(t)=\lambda_3P_2(t) \quad (18)$$

$$P_{18}^{'}(t)+\mu_3P_{18}(t)=\lambda_3P_0(t) \quad (19)$$

$$P_{19}^{'}(t)+\mu_3P_{19}(t)=\lambda_3P_1(t) \quad (20)$$

$$P_{20}^{'}(t)+\mu_1P_{20}(t)=\lambda_1P_1(t) \quad (21)$$

$$P_{21}^{'}(t)+\mu_5P_{21}(t)=\lambda_5P_5(t) \quad (22)$$

$$P_{22}^{'}(t)+\mu_3P_{22}(t)=\lambda_3P_5(t) \quad (23)$$

$$P_{23}^{'}(t)+\mu_1P_{23}(t)=\lambda_1P_5(t) \quad (24)$$

$$P_{24}^{'}(t)+\mu_2P_{24}(t)=\lambda_2P_5(t) \quad (25)$$

Initial conditions at time $t$ = 0 are $P_i(t)=1$ for $i$ = 0, otherwise $P_i(t)=0$

**Steady State Availability**

The steady state availability of the system can be analyzed by setting t→ ∞ and d/dt→ 0.The limiting probabilities from equations (1) – (25) are:

$$(\lambda_1+\lambda_2+\lambda_3)P_0=\mu_1P_1+\mu_2P_2+\mu_3P_{18} \quad (26)$$

$$(\lambda_2+\lambda_3+\lambda_4+\mu_1)P_1=\lambda_1P_0+\mu_2P_3+\mu_3P_{19}(t)+\mu_1P_{20} \quad (27)$$

$$(\lambda_1+\lambda_2+\lambda_3+\mu_2)P_2=\lambda_2P_0+\mu_1P_3+\mu_2P_{16}+\mu_3P_{17} \quad (28)$$

$$(\lambda_4+\lambda_5+\mu_1+\mu_2)P_3=\lambda_2P_1(t)+\lambda_1P_2+\mu_4P_4+\mu_5P_5 \quad (29)$$

$$(\lambda_1+\lambda_2+\lambda_3+\lambda_4+\lambda_5+\mu_4)P_4= \lambda_4P_3+\mu_5P_6+\mu_1P_{15}+\mu_2P_{14}+\mu_3P_{13}+\mu_4P_{12} \quad (30)$$

$$(\lambda_1+\lambda_2+\lambda_3+\lambda_4+\lambda_5+\mu_5)P_5= \lambda_5P_3+\mu_4P_6+\mu_5P_{21}+\mu_3P_{22}+\mu_1P_{23}+\mu_2P_{24} \quad (31)$$

$$(\lambda_1+\lambda_2+\lambda_3+\lambda_4+\lambda_5+\mu_4+\mu_5)P_6= \lambda_5P_4+\lambda_4P_5+\mu_1P_7+\mu_2P_8+\mu_3P_9+\mu_4P_{10}+\mu_5P_{11} \quad (32)$$

$$P_7^{'}+\mu_1P_7=\lambda_1P_6 \quad (33)$$

$$P_8^{'}+\mu_2P_8=\lambda_2P_6 \quad (34)$$

$$P_9^{'}+\mu_3P_9=\lambda_3P_6 \quad (35)$$

$$P_{10}^{'}+\mu_4P_{10}=\lambda_4P_6 \quad (36)$$

$$P_{11}^{'}+\mu_5P_{11}=\lambda_5P_6 \quad (37)$$

$$P_{12}^{'}+\mu_4P_{12}=\lambda_4P_4 \quad (38)$$

$$P_{13}^{'}+\mu_3P_{13}=\lambda_3P_4 \quad (39)$$

$$P_{14}^{'}+\mu_2P_{14}=\lambda_2P_4 \quad (40)$$

$$P_{15}^{'}+\mu_1P_{15}=\lambda_1P_4 \quad (41)$$

$$P_{16}^{'}+\mu_2P_{16}=\lambda_2P_2 \quad (42)$$

$$P_{17}^{'}+\mu_3P_{17}=\lambda_3P_2 \quad (43)$$

$$P_{18}^{'}+\mu_3P_{18}=\lambda_3P_0 \quad (44)$$

$$P_{19}^{'}+\mu_3P_{19}=\lambda_3P_1 \quad (45)$$

$$P_{20}^{'}+\mu_1P_{20}=\lambda_1P_1 \quad (46)$$

$$P_{21}^{'}+\mu_5P_{21}=\lambda_5P_5 \quad (47)$$

$$P_{22}^{'}+\mu_3P_{22}=\lambda_3P_5 \quad (48)$$

$$P_{23}^{'}+\mu_1P_{23}=\lambda_1P_5 \quad (49)$$

$$P_{24}^{'}+\mu_2P_{24}=\lambda_2P_5 \quad (50)$$

Solving the above equations, we get:
Let us assume,

$P_1=L_1P_0$, $P_2=L_2P_0$, $P_3=L_3P_0$, $P_4=L_4P_0$,
$P_5=L_5P_0$, $P_6=L_6P_0$, $P_7=k_1P_6$, $P_8=k_2P_6$,
$P_9=k_3P_6$, $P_{10}=k_4P_6$, $P_{11}=k_5P_6$, $P_{12}=k_4P_4$,
$P_{13}=k_3P_4$, $P_{14}=k_2P_4$, $P_{15}=k_1P_4$, $P_{16}=k_2P_2$,
$P_{17}=k_3P_2$, $P_{18}=k_3P_0$, $P_{19}=k_3P_1$, $P_{20}=k_1P_1$,
$P_{21}=k_5P_5$, $P_{22}=k_3P_5$, $P_{23}=k_1P_5$, $P_{24}=k_2P_5$

Where, $K_1 = \frac{\lambda_1}{\mu_1}$, $K_2 = \frac{\lambda_2}{\mu_2}$, $K_3 = \frac{\lambda_3}{\mu_3}$, $K_4 = \frac{\lambda_4}{\mu_4}$, $K_5 = \frac{\lambda_5}{\mu_5}$

The values of $L_1$, $L_2$, $L_3$, $L_4$, $L_5$, $L_6$ can be calculated by matrix method using equation (27) to (32).

Now using normalizing conditions i.e. sum of all the probabilities is equal to one, we get: $\sum_{i=0}^{24} P_i = 1$

$$P_0 = \begin{bmatrix} 1 + L_1 + L_2 + L_3 + L_4 + L_5 + L_6 + K_1L_6 + K_2L_6 + \\ K_3L_6 + K_4L_6 + K_5L_6 + K_4L_4 + K_3L_4 + K_2L_4 + \\ K_1L_4 + K_2L_2 + K_3L_2 + K_3 + K_3L_1 + K_1L_1 + \\ K_5L_5 + K_3L_5 + K_1L_5 + K_2L_5 \end{bmatrix}^{-1}$$

$$[A_V] = P_0 + P_1 + P_2 + P_3 + P_4 + P_5 + P_6 = [1 + L_1 + L_2 + L_3 + L_4 + L_5 + L_6]P_0$$

**Performance Analysis**

The failure and repair rates of various subsystems of water circulation system are taken from the maintenance history sheet of thermal power plant. The decision support system deals with the quantitative analysis of all the factors viz. courses of action and states of nature, which influence the maintenance decisions associated with the water circulation system. The decision matrices are developed to determine the various availability levels for different combinations of failures and repair rates. Table 1, 2, 3, 4, 5 represent the decision matrices for various subsystems of water circulation system. Accordingly, maintenance decisions can be made for various subsystems keeping in view the repair criticality and we may select the best possible combinations of failure and repair rates.

**Results and Discussion**

Tables 1 to 5 & figures 1 to 5 show the effect of failure and repair rates of Condensate extraction pump, Low pressure heater, Dearator, Boiler feed pump & High pressure heater on the steady state availability of the Water circulation system. Table 1 & figure 1 reveals the effect of failure and repair rates of Condensate extraction pump on the availability of the system. It is observed that for some known values of failure / repair rates of Low pressure heater, Dearator, Boiler feed pump & High pressure heater ($\lambda_2$=0.005, $\lambda_3$=0.0025, $\lambda_4$=0.02, $\lambda_5$=0.0015, $\mu_2$=0.1, $\mu_3$=0.125, $\mu_4$=0.1, $\mu_5$=0.05), as the failure rates of Condensate extraction pump increases from 0.01 to 0.05 the availability decreases by about 9.17%. Similarly as repair rates of Condensate extraction pump increases from 0.125 to 0.425, the availability increases by about 0.50%.

Table 2 & figure 2 reveals the effect of failure and repair rates of Low pressure heater availability of the System. It is observed that for some known values of failure / repair rates of Condensate extraction pump, Dearator, Boiler feed pump & High pressure heater ($\lambda_1$=0.01, $\lambda_3$= 0.0025, $\lambda_4$=0.02, $\lambda_5$=0.0015, $\mu_1$=0.125, $\mu_3$=0.125, $\mu_4$=0.1, $\mu_5$=0.05), as the failure rates of Low pressure heater increases from 0.005 to 0.0102, the availability decreases by about 0.62%. Similarly as repair rates of Low pressure heater increases from 0.1 to 0.4, the availability increases by about 0.48%.

Table 3 & figure 3 reveals the effect of failure and repair rates of Dearator on the availability of the System. It is observed that for some known values of failure / repair rates of Condensate extraction pump, Low pressure heater, Boiler feed pump & High pressure heater ($\lambda_1$=0.01, $\lambda_2$=0.005, $\lambda_4$=0.02, $\lambda_5$=0.0015, $\mu_1$=0.125, $\mu_2$=0.1, $\mu_4$=0.1, $\mu_5$=0.05), as the failure rates of Dearator increases from 0.0025 to 0.0041, the availability decreases by about 1.22%. Similarly as repair rates of Dearator increases from 0.125 to 0.250, the availability increases by about 0.97%.

Table 4 & figure 4 reveals the effect of failure and repair rates of Boiler feed pump on the availability of the System. It is observed that for some known values of failure / repair rates of Condensate extraction pump, Low pressure heater, Dearator & High pressure heater ($\lambda_1$=0.01, $\lambda_2$=0.005, $\lambda_3$=0.0025, $\lambda_5$=0.0015, $\mu_1$=0.125, $\mu_2$=0.1, $\mu_3$=0.125, $\mu_5$=0.05), as the failure rates of Boiler feed pump increases from 0.02 to 0.10, the availability decreases by about 0.37%. Similarly as repair rates of Boiler feed pump increases from 0.1 to 0.5, the availability increases by about 0.02%.

Table 5 & figure 5 reveals the effect of failure and repair rates of High pressure heater on the availability of the System. It is observed that for some known values of failure / repair rates of Condensate extraction pump, Low pressure heater, Dearator & Boiler feed pump ($\lambda_1$=0.01, $\lambda_2$= 0.005, $\lambda_3$=0.0025, $\lambda_4$=0.02, $\mu_1$=0.125, $\mu_2$=0.1, $\mu_3$=0.125, $\mu_4$=0.1), as the failure rates of High pressure heater increases from 0.0015 to 0.0075, the availability decreases by about 0.01%. Similarly as repair rates of High pressure heater increases from 0.05 to 0.25, the availability increases by about 0.001%.

**Conclusions**

The Decision Support System for Water circulation system has been developed with the help of mathematical modeling using probabilistic approach. The decision matrices are also developed. These matrices facilitate the maintenance decisions to be made at critical points where repair priority should be given to some particular subsystem of Water circulation system. Decision matrix as given in table 1 clearly indicates that the Condensate extraction pump is most critical subsystem as far as maintenance aspect is concerned. So, Condensate extraction pump should be given top priority as the effect of its failure rates on the unit availability is much higher than that of other sub-systems. Therefore, on the basis of repair rates, the maintenance priority should be given as per following order:

1. Condensate extraction pump
2. De-aerator
3. Low pressure heater
4. Boiler feed pump
5. High pressure heater

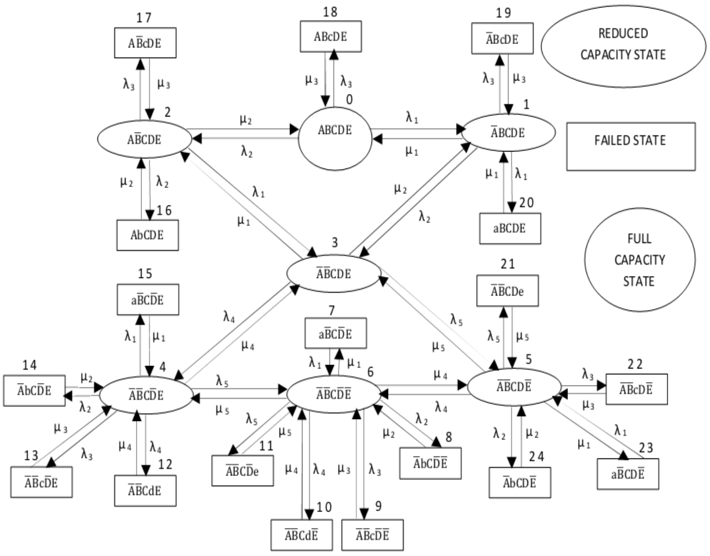


**Figure 1A : Transition diagram of water circulation system**

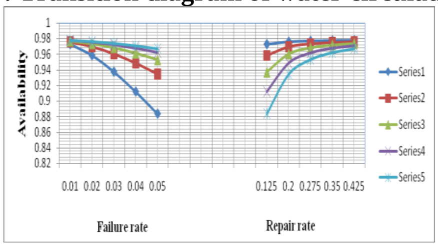


**Figure 1: Effect of Failure and Repair Rates of Condensate extraction pump on Availability**

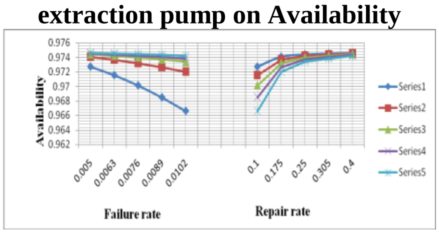


**Figure 2: Effect of Failure and Repair Rates of Low pressure heater on Availability**

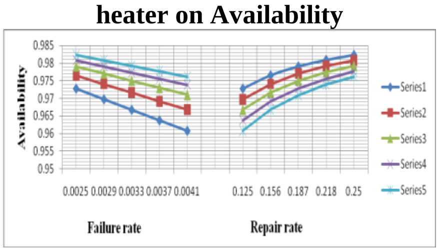


**Figure 3: Effect of Failure and Repair Rates of Dearator on Availability**

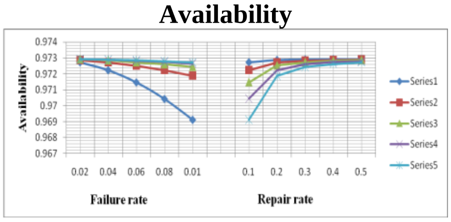


**Figure 4: Effect of Failure and Repair Rates of Boiler feed pump on Availability**

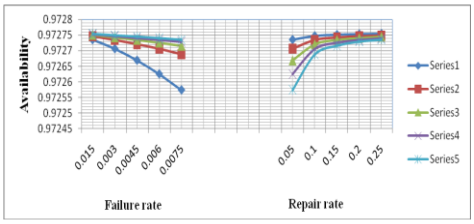


**Figure 5: Effect of Failure and Repair Rates of High pressure heater on Availability**

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**Table 1: Effect of Failure and Repair Rates of Condensate extraction pump on Availability**

| $\mu_1$ \ $\lambda_1$ | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | Constant values |
|---|---|---|---|---|---|---|
| 0.125 | 0.972735 | 0.958307 | 0.937300 | 0.911791 | 0.883444 | $\lambda_2$=0.005, $\mu_2$=0.1, $\lambda_3$=0.0025, $\mu_3$=0.125, $\lambda_4$=0.02, $\mu_4$=0.1, $\lambda_5$=0.0015, $\mu_5$=0.05 |
| 0.2 | 0.975955 | 0.969874 | 0.960518 | 0.948486 | 0.934319 | |
| 0.275 | 0.976960 | 0.973638 | 0.968398 | 0.961488 | 0.953135 | |
| 0.350 | 0.977398 | 0.975311 | 0.971974 | 0.967508 | 0.962032 | |
| 0.425 | 0.977627 | 0.976197 | 0.973889 | 0.970772 | 0.966914 | |

**Table 2: Effect of Failure and Repair Rates of Low pressure heater on Availability**

| $\mu_2$ \ $\lambda_2$ | 0.005 | 0.0063 | 0.0076 | 0.0089 | 0.0102 | Constant values |
|---|---|---|---|---|---|---|
| 0.1 | 0.972735 | 0.971563 | 0.970145 | 0.968490 | 0.966610 | $\lambda_1$=0.01, $\mu_1$=0.125, $\lambda_3$=0.0025, $\mu_3$=0.125, $\lambda_4$=0.02, $\mu_4$=0.1, $\lambda_5$=0.0015, $\mu_5$=0.05 |
| 0.175 | 0.974097 | 0.973708 | 0.973230 | 0.972666 | 0.972018 | |
| 0.250 | 0.974433 | 0.974244 | 0.974009 | 0.973731 | 0.973409 | |
| 0.305 | 0.974538 | 0.974412 | 0.974255 | 0.974068 | 0.973852 | |
| 0.4 | 0.9774625 | 0.974554 | 0.974464 | 0.974357 | 0.974231 | |

**Table 3: Effect of Failure and Repair Rates of Dearator on Availability**

| $\mu_3$ \ $\lambda_3$ | 0.0025 | 0.0029 | 0.0033 | 0.0037 | 0.0041 | Constant values |
|---|---|---|---|---|---|---|
| 0.125 | 0.972735 | 0.969727 | 0.966738 | 0.963767 | 0.960814 | $\lambda_1$=0.01, $\mu_1$=0.125, $\lambda_2$=0.005, $\mu_2$=0.1, $\lambda_4$=0.02, $\mu_4$=0.1, $\lambda_5$=0.0015, $\mu_5$=0.05 |
| 0.156 | 0.976497 | 0.974067 | 0.971649 | 0.969242 | 0.966846 | |
| 0.187 | 0.979028 | 0.976989 | 0.974959 | 0.972937 | 0.970923 | |
| 0.218 | 0.980847 | 0.979091 | 0.977342 | 0.975598 | 0.973861 | |
| 0.250 | 0.982256 | 0.980720 | 0.979189 | 0.977663 | 0.976141 | |

**Table 4: Effect of Failure and Repair Rates of Boiler feed pump on Availability**

| $\mu_4$ \ $\lambda_4$ | 0.02 | 0.04 | 0.06 | 0.08 | 0.10 | Constant values |
|---|---|---|---|---|---|---|
| 0.1 | 0.972735 | 0.972239 | 0.971471 | 0.970432 | 0.969124 | $\lambda_1$=0.01, $\mu_1$=0.125, $\lambda_2$=0.005, $\mu_2$=0.1, $\lambda_3$=0.0025, $\mu_3$=0.125, $\lambda_5$=0.0015, $\mu_5$=0.05 |
| 0.2 | 0.972881 | 0.972735 | 0.972521 | 0.972239 | 0.971889 | |
| 0.3 | 0.972914 | 0.972840 | 0.972725 | 0.972600 | 0.972434 | |
| 0.4 | 0.972927 | 0.972881 | 0.972816 | 0.972735 | 0.972637 | |
| 0.5 | 0.972935 | 0.972901 | 0.972857 | 0.972802 | 0.972735 | |

**Table 5: Effect of Failure and Repair Rates of High pressure heater on Availability**

| $\mu_5$ \ $\lambda_5$ | 0.0015 | 0.0030 | 0.0045 | 0.0060 | 0.0075 | Constant values |
|---|---|---|---|---|---|---|
| 0.05 | 0.972735 | 0.972706 | 0.972669 | 0.972625 | 0.972574 | $\lambda_1$=0.01, $\mu_1$=0.125, $\lambda_2$=0.005, $\mu_2$=0.1, $\lambda_3$=0.0025, $\mu_3$=0.125, $\lambda_4$=0.02, $\mu_4$=0.1, |
| 0.10 | 0.972747 | 0.972735 | 0.972721 | 0.972706 | 0.972688 | |
| 0.15 | 0.972751 | 0.972743 | 0.972735 | 0.972726 | 0.972716 | |
| 0.20 | 0.972753 | 0.972747 | 0.972741 | 0.972735 | 0.972729 | |
| 0.25 | 0.972754 | 0.972749 | 0.972745 | 0.972740 | 0.972735 | |