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Original Article

Pump availability prediction using response surface method in nuclear plant

Parasuraman Suganya [a,*], Ganapathiraman Swaminathan [a], Bhargavan Anoop [b]

[a] Department of Civil Engineering, National Institute of Technology, Tiruchirapalli, Tamilnadu, India
[b] Indira Gandhi Centre for Atomic Research, Kalpakkam, 603102, India

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ABSTRACT

The safety-related raw water system's strong operational condition supports the radiation defense and biological shield of nuclear plant containment structures. Gaps and failures in maintaining proper working condition of main equipment like pump were among the most common causes of unavailability of safety related raw water systems. We integrated the advanced data analytics tools to evaluate the maintenance records of water systems and gave special consideration to deficiencies related to pump. We utilized maintenance data over a three-and-a-half-year period to produce metrics like MTBF, MTTF, MTTR, and failure rate. The visual analytic platform using tableau identified the efficacy of maintenance & deficiency in the safety raw water systems. When the number of water quality violation was compared to the other O&M deficiencies, it was discovered that water quality violations account for roughly 15% of the system's deficiencies. The pumps were substantial contributors to the deficit. Pump availability was predicted and optimized with real time data using response surface method. The prediction model was significant with r-squared value of 0.98. This prediction model can be used to predict forth coming pump failures in nuclear plant.

1. Introduction

Plant management should ascertain the complex and diverse systems of the nuclear power plant to realize its expected performance during all states of operation. The failure of a sub-system within the primary system may lead to disastrous consequences resulting in the stoppage of the primary system [1]. The loss of an element or a sub-system in a whole system can lead to a serious safety situation that may impact the plant's operation and assets. A reliability modeling of power plants can be utilized to identify component importance to establish maintenance schedules [2]. Routine monitoring enables the industry to take preventive measures at an early stage which increases the system availability [3]. Operating personnel should thoroughly analyze the deep knowledge of the failure rate and up-to-date maintenance state of the equipment to optimize the availability of major components and elucidate the reliability of safety-related systems [4–6]. Out of all the plant water systems, the filtered raw water system is considered essential due to its safety categorization. This system is required for the proper removal of decay heat and to maintain the reactor vault within the permissible temperature. This research is conducted with the safety and emergency cooling water system/safety raw water system. The safety-related raw water system is required to carry out the safety functions of the plant during all states of the reactor [7]. It is a mandatory safety system, and subsequently, its reliability & availability is considered high to make it operable at all states of the reactor operation. Preventive equipment maintenance was scheduled based on the experience and values of failure & repair rate [8]. Researchers conducted extensive research on the theoretical models rather than the realistic environment. Most persons completed numerous studies on the reliability, availability, and maintenance aspects of the equipment & system [9–11]. The availability of the safety related raw water system with a particular bias towards reactor operation and maintainability analysis using advanced visual analytics remains untouched [12,13]. This study used systematic water sampling and maintenance data from all of a nuclear power plant's water systems to evaluate the maintainability of safety raw water system. The system performance is evaluated using a reliability block diagram and FTA analysis, and the results are outlined in this study. Subsequent to this analysis, pump availability was optimized using MTTR and MTBF. After evaluating the safety raw water system reliability, the effect of unavailability of the raw water system on

* Corresponding author.
E-mail addresses: suganyaparasuraman@gmail.com, suganya_bhavini@igcar.gov.in (P. Suganya).

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the nuclear plant operation is elucidated.

The main objective of this work is.

- To understand the possible causes of equipment failure and its effect on the system unavailability.
- To quantify the system availability, reliability, and failure rate of the safety raw water system
- To quantify the reliability and performance of the safety raw water system using RBD and fault tree analysis method

The maintenance data of the water system from January 2017 to May 2021 is categorized into different failures. The data is further processed, and water chemistry-related maintenances were sorted out and reliability analysis was conducted using reliability block diagram and fault tree analysis.

2. Materials and methodology

In every nuclear plant, the structure, system and components are classified based on the importance of safety function. Accordingly, safety related raw water system is classified as safety class: 3. Safety function of safety related raw water system are to transfer heat from systems to the ultimate heat sink, to ensure necessary services as a support function for the safety systems. Fig. 1 represents the step by step method involved in this research. This maintainability analysis was conducted for all the plant water system. Reliability analysis was conducted for the safety raw water system. All the maintenance data pertaining to the period 2017 to 2021 was collected and stored in the excel format. Initial data analysis and curation was carried out in Tableau Prep and interpretation of the data was carried out in Tableau student version 2021. Reliability and availability of the safety raw water system was carried out using reliability block diagram & fault tree analysis of RAM commander demo version. Once the critical equipment is identified, the major maintenance data like MTBF, MTTR was utilized to optimize and predict the response variable Pump availability using RSM in Design Expert.

2.1. Preliminary maintenance data analysis of all plant water systems

We analyzed the maintenance state of all water systems to recognize

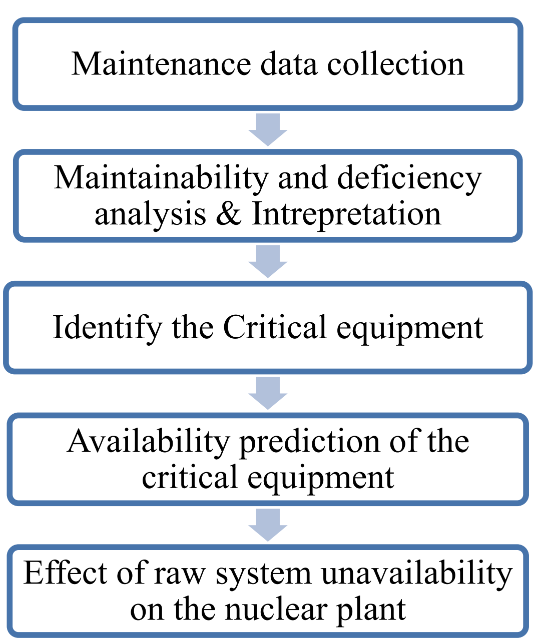

Fig. 1. Research flow.

the type of deficiency and upkeeping measures identified in all the equipment. Later, the safety-related raw water system was studied separately to fix the preventive maintenance schedule for the equipment.

We carried out data analytics for all water systems (ASW, ERW, ESW, FWS, NSW, Raw & Domestic water system, SRRW, SRSW) using Tableau student version 2021. Appendix 1 represents the 75th percentile of maintenance activity in days (X-axis) categorized under each system and equipment type. Let us examine the system's significant components viz, heat exchangers, pump, CT fan. For all systems except FWS, maintenance activity of significant components is kept below 50 days. This maintenance is not significant since the equipment could be operated with DR persisting. Accessories of the equipment like level detectors, pressure detectors, NRVs, pump accessories, etc., contributed to many DR. Many types of equipment were kept under maintenance for a sizable number of days in the ASW system. Maintenance activity undertaken in the pipe of the NSW system is found to be the highest. A low number of maintenance activities is reported in the raw and domestic water system.

2.2. Maintenance data analysis of safety raw water system

A thorough examination of the safety raw water system was carried out. The components involved in the safety raw water system and its associated makeup system are the CT basin, SRRW pump, valve, pipe, CT flow control valve, CT fans. The O&M data corresponding to the safety raw water system consists of maintenance, failure, and rectification date. Water quality failures generally lead to corrosion which is the cause of pinhole leaks and subsequent punctures in the pipeline. We can quickly identify the water quality failure by tracking the system process parameters like pressure, flow, and temperature. Any choke due to corrosion products, turbidity, and any other foreign material increases the pressure in system. A very high differential pressure at two ends of a heat exchanger indicates a choke in the heat exchanger. This condition blocks the flow and hinders the heat transferability of a heat exchanger, and raises the temperature. When corrosion is unnoticed and left unattended, it gradually develops into pinhole leaks causing a major breakdown. The leaks in the system and components will cause low pressure and more discharge establishing the fact that the water quality violation and the process parameters are linked. Early detection and prevention of water quality violations enhance the system's reliability.

By analyzing the O&M data for 3.5 years, it is found that water quality violations cause nearly 15% of the unavailability of the system. Various inputs for the reliability calculations like MTBF, MTTR, MTTF, failure rate are taken from this data. The estimation of these parameters needs to be judiciously assessed. Preliminary data classification and sorting of the maintenance data plays a significant role in producing reliable results [5,8]. For example, the mean time between failure and the mean time to recovery will vary according to the type of deficiency identified. Sometimes deficiencies like low oil levels in equipment may not require complete shutdown. Hence, those deficiencies could be exempted while calculating the MTBF.

Similarly, a choke in the gauges does not interfere with the system's reliability. Therefore, initial data screening and classification are carried out to calculate the reliability of the total deficiency in the system and the water quality, as indicated in Appendix 2. After calculating MTBF, MTTR, failure rate separately for each fault, these values are summated for the particular component, viz. Pump, valve, pipe, CT basin, and heat exchanger, and fed as input for the reliability analysis (RBD and FTA).

3. Results and discussion

3.1. Reliability analysis using RBD

Reliability is the probability that a system performs its intended function during the specified time duration. RBD is constructed by integrating all the system components and calculating the failure rate of each part to estimate the availability of the total system. The reliability calculation is carried out through RAM Commander demo version software. Fig. 2 describes the RBD of the SRRW system, whose process flows from the CT basin and ends at CT fans. SRRW pump takes cooled water from the CT basin and circulates through the heat exchangers via the inlet valve. The warm water from the heat exchanger enters the CT fan through a flow control CT valve. The individual equipment maintenance details like MTTF, MTBF, MTTR are calculated for understanding preliminary maintenance metrics of each component. Next, the reliability of the system components is calculated using the exponential method with failure rate for non-repairable component.

$$\lambda = \frac{1}{MTBF} \; for \; repairable \; components$$

$$\lambda = \frac{1}{MTTF} \; for \; non-repairable \; components$$

$$MTBF = \frac{Total \; run \; time - Breakdown \; time}{No \; of \; breakdown}$$

$$Availability = \frac{MTBF}{MTBF + MTTR}$$

$$MTTR = \frac{Total \; Breakdown \; time}{No \; of \; breakdown}$$

$$R(t) = e^{-\lambda t}$$

Meantime between critical failures (MTBCF) is defined as the time between the critical failures. MTBCF is utilized to schedule the preventive maintenance of the equipment in the system [14]. MTBCF is found by changing the maximum time till the function R(t) nearly reaches zero such that MTBCF stops changing.

$$MTBCF = \int_0^{\max \; time} R(t)dt$$

The reliability curve ultimately approaches zero as time goes to infinity. Fig. 3 shows the reliability curve of the SRRW system with complete maintenance. The curve includes the early failure rate and regular life failure rates. Nearly 40% of the failures occur within 1000 h of operation. Fig. 4 shows the reliability curve for maintenance related to water quality alone. Within 6000 h of operation, 42% of the failures are encountered.

MTBCF is calculated by integrating the reliability for the maximum operational time. It equals the area under the reliability curve between the x and y-axis. MTBCF for Figs. 3 and 4 is 427.59 and 2175.06 h, respectively.

The system reliability is presented in Table 1. The reliability of all individual components is above 0.9 (except the SRRW pump), and the total system is 0.75 since all parts are connected in series. Additional train of the same components is provided to broaden the system availability. Sufficient redundancy (200%) is ensured in the site to increase the reliability of the safety raw water system as a whole.

3.2. Fault tree analysis

A fault tree is a graphical illustration of a logical structure comprising undesired events ("failures") and their causes. The logical structure is created by using gates, and it represents undesired events by using important events. Reliability parameters are assigned to the primary events [15,16]. System failures are generally characterized as top events. Mathematical techniques can determine the probability of the top-level event [16]. There are two types of analysis, namely-qualitative analysis using Minimal Cut Sets (MCS) building and quantitative analysis by calculating the probabilities of system failures.

A Cut Set is a collection of basic events that, if all its events occur, the fault tree's top event is guaranteed to happen. A Minimal Cut Set is such a Cut Set that, if any essential event is removed from the set, the remaining events collectively are no longer a cut set. If the minimal cut sets are independent, the probability of the top event is calculated as follows,

$$Q(t) = 1 - \prod_{i=1}^{n} (1 - Q_i(t)$$

Where $Q(t)$ = *probability of top event*.

$Q_i(t)$ = *failure probability of minimal cut set*

The top event of fault tree analysis is the SRRW system's unavailability to provide the plant service for decay heat removal. This event is grouped under category four event [17]. The fault tree of one train of the SRRW system is represented in Fig. 5. SRRW system consists of raw water pumps which circulate the cooled water from the CT basin to the raw water heat exchangers. SRRW system is subdivided into two trees SRRW system and the CT system. Raw water pumps, valves, heat exchangers, pipes are branched in the SRRW system. CT basin, CT fans, CT flow control valve are the significant components of the CT system.

Minimal cut sets are represented in Table 2. SRRW pump failure contributes to 40% of the total minimal cut sets for generating the top event. The failure probability of the SRRW system is 0.225. Safety raw water system pump failure is considered critical. If the pump is not available for 48 h, reactor shutdown is enabled. Hence, this warrants proper prediction of pump availability studies.

3.3. Prediction of SRRW pump availability

The prediction of the pump availability is performed using response surface methodology (RSM). This design is conducted in Design Expert Version 10 using Central Composite design. This software can link variables in a higher degree model that cannot be done manually [3]. Pump availability being response variable is predicted using MTBF and MTTR [18]. Table 3 shows the level of the independent parameter and the factors. The experiment was repeated 13 times with 5 centre points per block. The predicted model is represented by the quadratic equation below.

Pump Availability, $Y = -16.85 + 4.85\,A - 5.89\,B + 0.07\,A\,B - 0.05\,A^2 + 0.0299B^2$

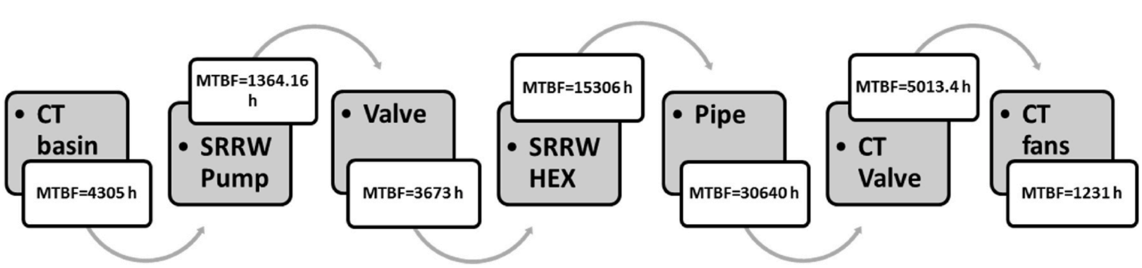

Fig. 2. Reliability Block diagram.

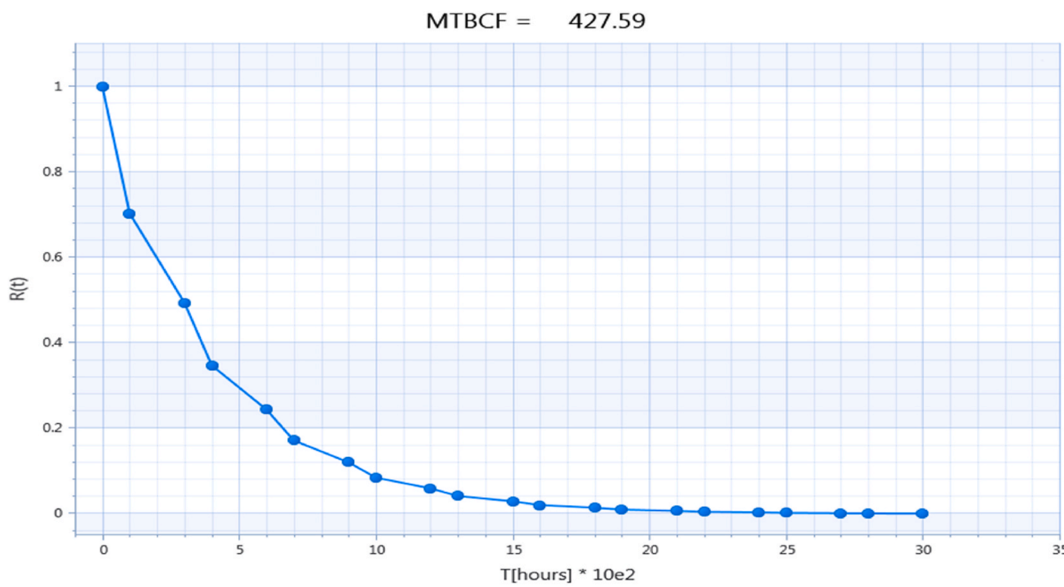

Fig. 3. Reliability versus time graph for all deficiencies, including water quality.

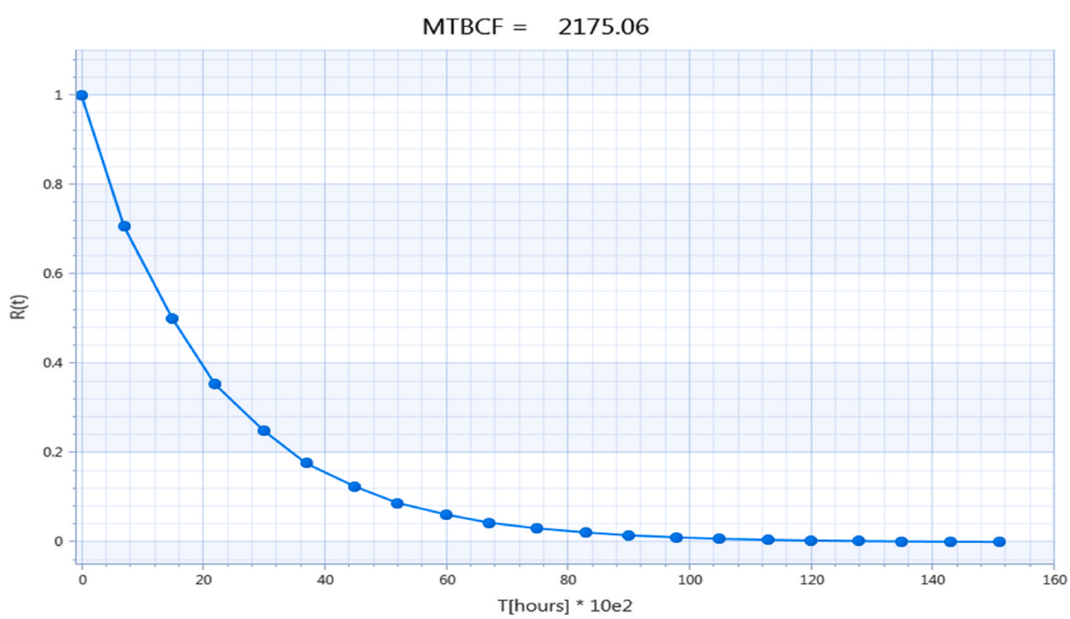

Fig. 4. Reliability curve for water quality.

Table 1
Reliability Block diagram input/output results for complete maintenance data.

	Input			Output
Component	MTBF (h)	MTTR (h)	Failure rate (λ) h^{-1}	Reliability/ Availability
CT basin	4305	74	0.000228	0.98
SRRW Pump	1364.16	168.8	0.000652	0.88
Valve	3673	159	0.000260	0.95
SRRW HEX	15,306	24	0.000065	0.99
Pipe	30,640	19.2	0.000032	0.99
CT valve	5013.4	96.6	0.000260	0.98
CT fan	1231	101	0.000750	0.92
Total system				0.75

Where A is the MTBF, B is the MTTR.

The results of the ANOVA are depicted in Table 4. The evaluation criteria for the model are given by the R^2 value and *P*-value of the model. The goodness of fit of the predicted model is determined by the R^2 value of at least 0.8. The coefficient of correlation for the model is 0.98. The *P*-value of the model is < 0.0001. This states that a model is significant and has a good fit.

The residuals are distributed evenly along the straight line (Fig. 6). Fig. 7 depicts the model's actual and predicted plots. The actual and predicted models differ only slightly. As a result, the model could be used to predict the response variable. The contour plots and response surface graphs for the response variable pump availability are shown in Figs. 8 and 9.

3.3.1. Model validation

Statistical significance of the study was conducted to validate the model. After model formulation, those results were applied for validating

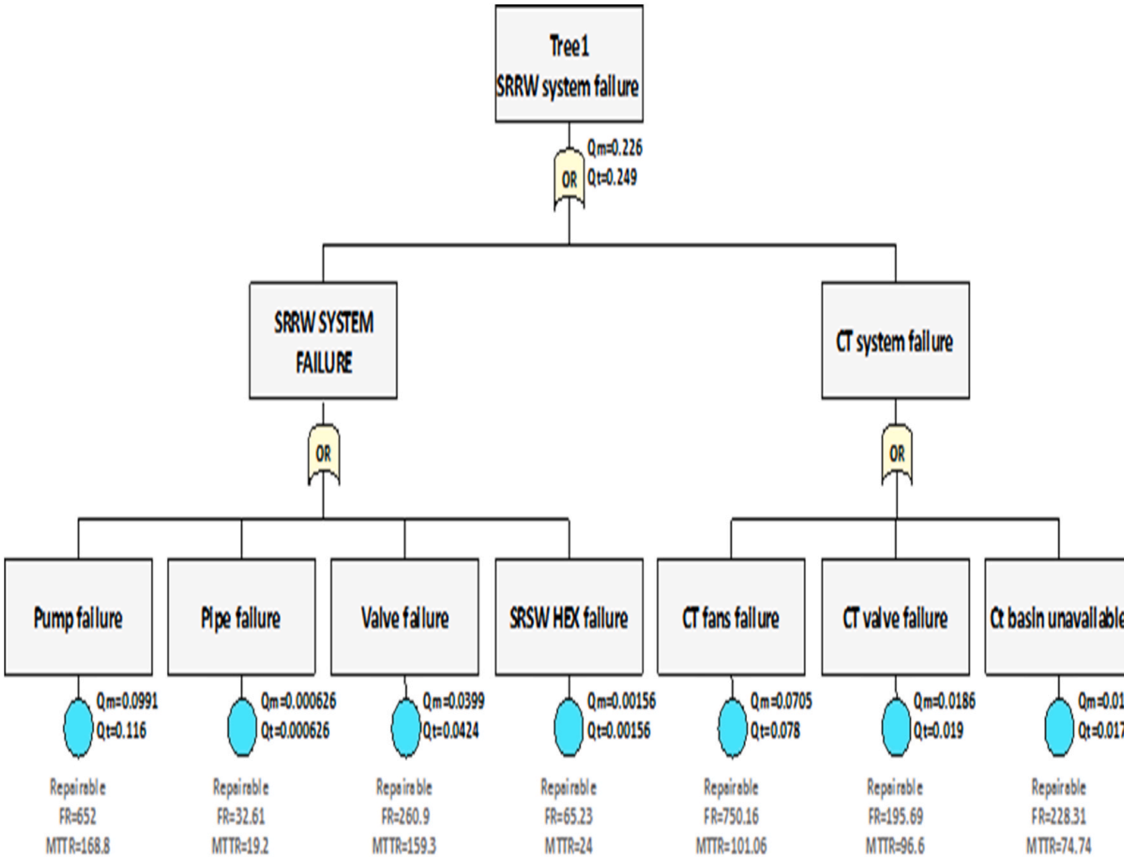

Fig. 5. FTA for the failure of SRRW system.

Table 2
Minimal cut sets for the SRRW system failure.

Event	Q (mean)	Percentage
SRRW pump failure	0.0991	40.13
CT fans failure	0.0705	28.52
Valve failure	0.0399	16.15
CT valve failure	0.0186	7.51
CT basin unavailable	0.0168	6.79
SRSW Hex failure	0.00156	0.63
Pipe failure	0.000626	0.25
Total event – SRRW system failure	0.225	

Table 3
Central composite design.

Name	Parameters	Low	High
MTBF	A	45	55
MTTR	B	3	13

Table 4
Analysis of variance table.

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	589.11	5	117.82	100.18	<0.0001	significant
A-MTBF	*43.32*	*1*	*43.32*	*36.83*	*0.0005*	
B-MTTR	*514.47*	*1*	*514.47*	*437.41*	*< 0.0001*	
AB	*14.55*	*1*	*14.55*	*12.37*	*0.0098*	
A^2	*10.88*	*1*	*10.88*	*9.25*	*0.0188*	
B^2	*3.91*	*1*	*3.91*	*3.32*	*0.1112*	
Residual	8.23	7	1.18			
Lack of Fit	*8.23*	*3*	*2.74*	*3.473E + 005*	*< 0.0001*	*significant*
Pure Error	*3.161E-005*	*4*	*7.902E-006*			
Cor Total	597.35	12				

$R^2 = 0.98$; CV (%) = 1.26.

the model. The variation found in the results of the predicted model was found to be within 2% of the experimental results. Statistical test using *t*-test was conducted to confirm this variation. Statistical evidence is generated through hypothesis testing to conclude if the statement is accurate. It is a statistical interference which uses the sample data to arrive at a meaningful conclusion about the population distribution.

Null and alternative hypothesis is formulated to test the variation of model within 2% to the field results. Nearly 11 samples were tested for validating the model. Percentage model deviation from the experimental value is computed for each value. This data represents the sample. Sample mean and standard deviation is found to be 1.135 and 0.19. One tailed *t*-test with $\alpha = 0.001$ was conducted to test the hypothesis. Null hypothesis (H_0) can be rejected with $t < t_\alpha$

$$H_0 : \mu > 2$$

$$H_1 : \mu \leq 2$$

$$t = \frac{(\overline{x} - \mu)}{\frac{s}{\sqrt{n}}} = -242.02$$

Since $t = -242.02$ which lies within the critical region, null hypothesis can be rejected with 99% confidence. Hence, Percentage deviation of model with respect to the experiment is found to be less than 2%.

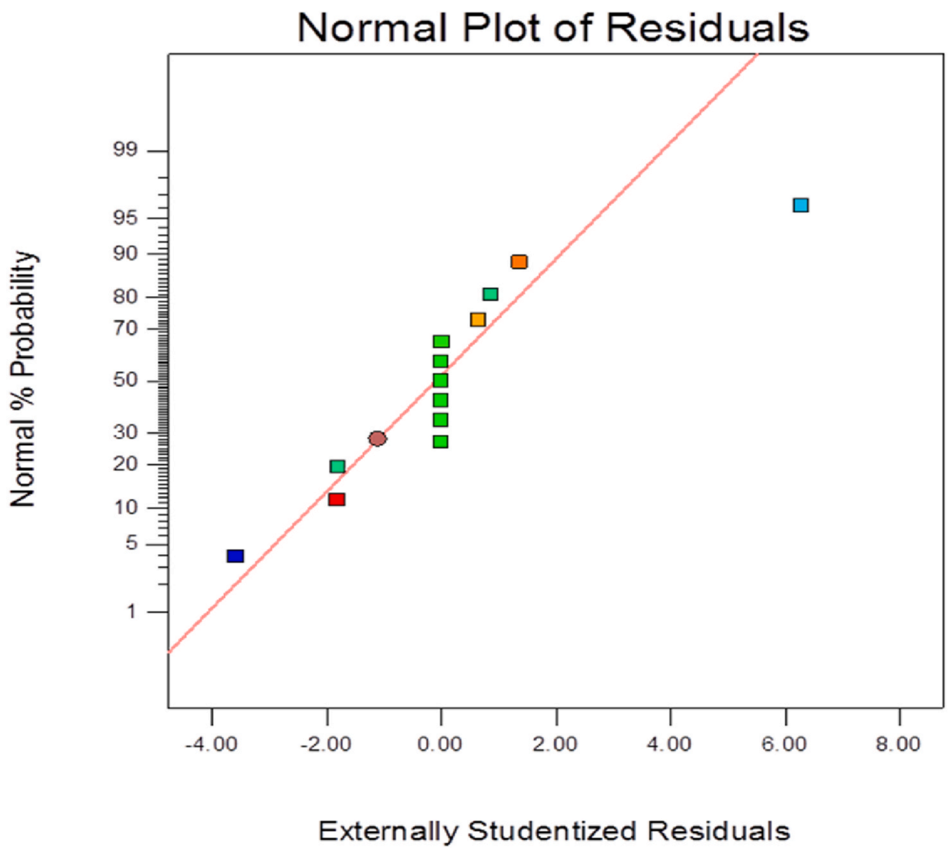

Fig. 6. Normal plot of residuals – Pump availability.

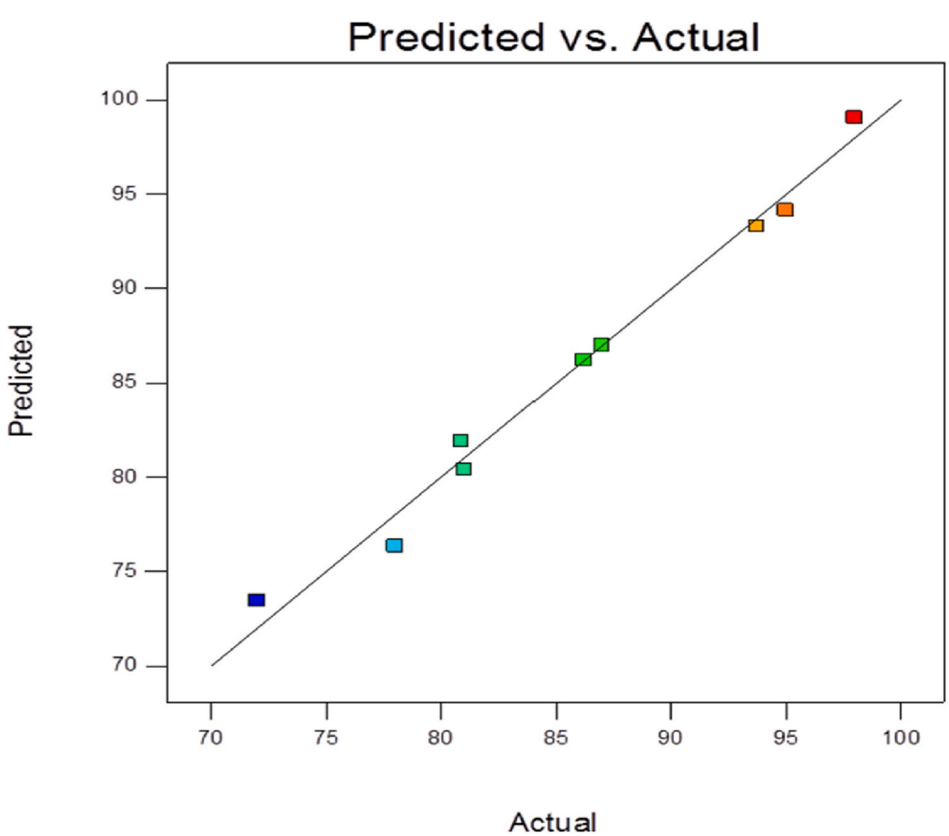

Fig. 7. Predicted Vs Actual graph.

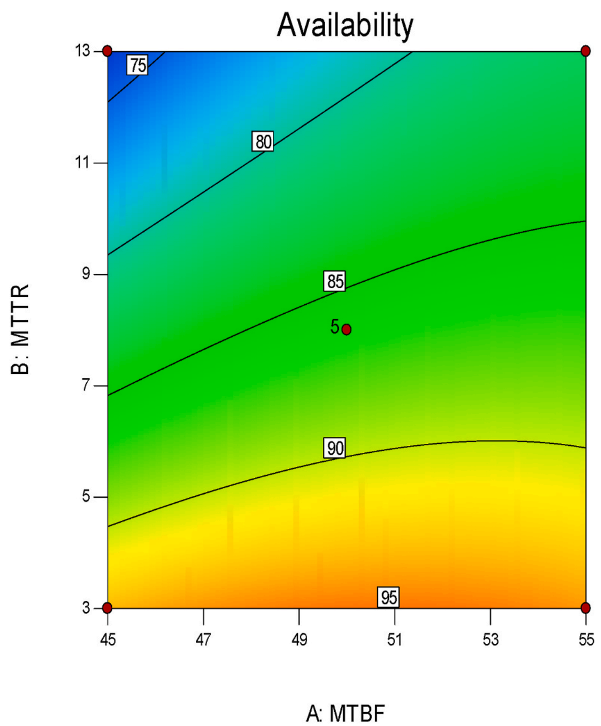

Fig. 8. Contour graph for pump availability.

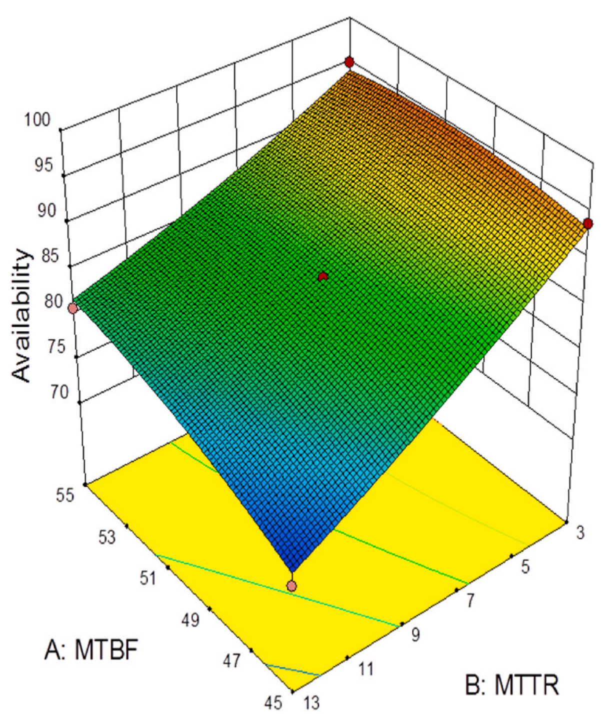

Fig. 9. Response surface graph.

4. Discussion on minimization of pump maintenance

The predicted model was analyzed to maximize the pump availability by minimizing the pump maintenance and maximizing the time taken by the pump to fail. It was observed that the pump availability increases to 94% during the minimization study in design expert. Mean time to recover has to be reduced to a minimum of 3 days for three year period. We studied SRRW system relevance to reactor power production based on the following context. When the SRRW system is unavailable, the reactor should shut down [19,20]. A controlled shutdown occurs when the SRRW system is unavailable for 24 h. It results in a reactor setback of power to 53%. It occurs when major equipment like the pump, CT fans, heat exchangers, CT basin is unavailable. Increase in the pump availability to 7% increases the reactor power production and in turn benefits the plant economically. RAM study is an integral part of reactor operation, and the PM schedules are routine activities, and the values would change according to the nature of the system operating condition. Hence, RAM analysis should be continued parallel to the reactor operation to minimize the unavailability, which saves energy.

5. Conclusion

Visual and data analytics using tableau assessed the level of deficiency records of each type in the water system. The most often repairable equipment was identified using this data. Failure rate and reliability of the safety raw water system with a studied focus on the importance to water quality failures is accomplished. It is found that 40% of the failures occur within 1000 h of operation for complete deficiency as against 6000 h of operation for lapses in water quality. The water quality failures correspond to only 15% of the total failures. The reliability of all individual components is above 0.9 (except the SRRW pump), and that of the total system is 0.75. The reliability value obtained from RBD and FTA is nearly matching. Sufficient redundancy is recommended in the field to increase the reliability and availability of the raw water system to support the decay heat removal process.

The risk level of all the equipment of the safety raw water system is evaluated using fault tree analysis. The raw water pump and CT fan are the most critical equipment in the system. Reliability and availability-based maintenance schedules were very helpful to forecast failure rates and undertake suitable up keeping measures. Prediction of equipment availability can prevent unwarranted and unprecedented failures of safety raw water systems, and the SRRW system can continuously render support to the nuclear & decay heat removal system. Prediction of pump availability model was significant with r^2 value of 0.98. By optimizing the pump maintenance schedules, pump availability can be increased to 7%.

Disclosure of potential conflict of interest

The authors did not receive support from any organization for the submitted work.

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Abbreviations

ASW	Auxiliary seawater system
AB	Auxiliary boiler
ANOVA	Analysis of variance
BSC	Biological shield cooling
CCW	Condenser cooling water
CT	Cooling tower

CW	Chilled water
DM	Demineralised water
DR	Deficiency report
ERW	Emergency raw water system
ESW	Emergency service water system
FWS	Fire water system
HEX	Heat Exchanger
MTBF	Mean time between failures
MTTF	Mean time to failure
MTBCF	Mean time between critical failures
MTTR	-Mean time to recovery
NSW	Normal service water system
NRV	Non return valve
O&M	Operation & Maintenance
PM	Preventive maintenance
RBD	Reliability block diagram
RAM	Reliability, Availability, Maintainability
RSM	Response surface methodology
SRSW	Safety service water system
SRRW	Safety raw water system

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2023.09.002.

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