The Maintenance Task Allocation Analysis in Steam Power Plant: Case Study on Closed Cooling Water System

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Abstract. The closed cooling system is one of the systems that functioned to ensure the cooling water supply can be continuously distributed and ensure that the production process does not cause the equipment or products to overheat, which can result in failure to the equipment and affect the production process due to downtime repair. Reliability Centered Maintenance (RCM) is one of the methods that can be used to analyze the cause of failure, impact, and determination of appropriate and effective maintenance tasks. The purpose of this research is to identify potential failures, determine the maintenance task and determine the optimal maintenance schedule in the closed cooling system of a steam power plant by using the Reliability Centered Maintenance method. The results of analysis on the closed cooling pump, heat exchanger, expansion tank, minimum flow valve, and level control valve obtained a total of 155 failure modes, of which 73% of total failure modes were identified as an evident failure and 27% identified as a hidden failure. While the results of the maintenance task recommendation obtained a total of 155 maintenance tasks which consists of 5 maintenance task categories. They are 88 (57%) of total failure modes recommended to scheduled on condition task, 38 (24%) scheduled restoration task, 20 (13%) scheduled discard task, 3 (2%) schedule finding failure, and 6 (4%) of total failure modes recommended to no scheduled maintenance.

Keywords: Closed cooling system, failure mode, maintenance task, RCM

1. Introduction

The process of producing electricity at a steam power plant is supported by several important components. Where these components are fully operational during the production process [1]. Production processes that take place continuously can cause temperature and pressure to rise in components [2]. Therefore, we need a cooling system for each production support component. This needs to be done to avoid damage that can occur due to excess heat generated from the production process. In this case, the cooling process can be done using water which is called the cooling water system [2-3]. If the cooling system in the generator cannot operate it will cause, such as; (1) A sudden thermal increase in equipment will cause damage to the equipment, which can have certain financial consequences in terms of equipment fixing or replacement [1-2], (2) equipment damage can cause
harm to both individuals and the environment [4], (3) the impact of the absence of cooling water, a plant can cause a blackout or unscheduled shutdown [3], [5].

Blackouts or shutdowns are common in a steam power plant, so a lot of research has been done to find out the cause [1], [6-7]. The blackout or shutdown at power plants can be divided into 2, namely planned shutdown and forced shutdown.

Therefore, based on these facts, considering the importance of a cooling water system in the steam power plant is needed to increase the reliability and availability of the main and supporting equipment from an operational and maintenance perspective. Due to the closed cooling water system consisting of equipment such as pumps, heat exchangers, and valves that have different failure modes, it is necessary to analyze the failure mode and effects on each equipment. Reliability Centered Maintenance (RCM) is a method that can be used to identify potential failures that can occur and to determine appropriate maintenance and maintenance intervals based on the criticality of components [8-9].

The application of RCM is expected to produce optimal maintenance planning and maintenance intervals to prevent damage to equipment (assets) which can have a major impact on the operational system of the equipment and impact on the costs incurred to deal with the damage, reduce breakdown rates and system production downtime [10]. RCM is known to be a well-known method and is often used to maintain operational efficiency in important industrial sectors such as the power plant industry [11][12], railway industry [13], oil and gas industry [14-15], and marine industry [16-18]. The application of RCM to a steam power plant according to Arefy (2010) can reduce labor costs for maintenance by 25.2% and savings of about 80% of the total downtime cost [19].

Furthermore, the purpose of this research is to identify potential failures that can occur in the closed cooling water system components using the Failure Mode and Effect Analysis (FMEA) method according to RCM II by John Mobray [20], determining appropriate maintenance tasks and the optimal maintenance schedule for the closed cooling water system components based on the decision diagram in RCM II.

2. Methods

2.1. Data Collection
In the data collection process, there are two processes, namely by conducting interviews with parties who directly handle or work in the maintenance section and retrieving information data from manual books, log sheets, and other documents related to maintenance and operation of equipment. The data needed in this research are:

- Manual book of each equipment
- Downtime data
- Piping and Instrument Diagram (P&ID)
- Process Flow Diagram (PFD)
- Data maintenance performed
- System description (primary and secondary functions of the system/equipment)
- Work Order (WO)

2.2. Defining the System Boundaries
From the data obtained, the next step is to determine the limits of the system be analyzed. In a power plant, there are several systems to support the production process, one of which is the closed cooling water system, where this system is functionally used as a coolant and to remove heat or transfer heat contained in other supporting equipment.

The closed cooling water system consists of several important components such as tanks, pumps, heat exchangers, and valves where these components are integrated so that when a failure occurs in one component it will affect other components and the closed cooling system in general. The
determination of system boundaries in this research is based on the system description, the PFD system, and also the asset register.

2.3. Describing the System and Functional Block Diagram (FBD)
In the next stage, identify and describe the system, where it is necessary to know the function and working system of the closed cooling water system. The work system and several identified asset functions will be illustrated in the Functional Block Diagram (FBD). Where FBD is used to describe the relationship between one function and another function in the system. In addition to showing the functions of an asset and its parts, FBD also describes the relationship and workflow between the functions that make up a system and the limitations that the system has. The determination of the FBD in this research is based on the system description and the PFD system.

2.4. Determining the System Function and Functional Failure
In this case, it covers the functions and work systems of the system in general. Function in this case can be interpreted as the ability of the equipment/component to be able to carry out its performance standards as desired by the operator. In writing the functions that need to be considered are:

- In general, each function statement should define only 1 function, although it can combine more than one performance standard. As a rule, each function only contains one verb (except for protective devices).
- Each function writing contains only verbs, nouns and must indicate the standard of performance.
- The performance standards described must be quantified and precise and must show what an asset can do in the current operating context (what it can do).
- All protective devices must be recorded, and their functions properly described (ex: to do X if Y occurs).
- The function of all measuring instruments and indicators should be recorded with the desired accuracy.

Meanwhile, functional failure is the inability of an asset to fulfill its function according to the desired performance standard. In this case what needs to be considered in writing the sequence of malfunctions includes:

- Total and partial failure,
- Upper and lower limits,
- Gauge and indicator,
- Operating context.

2.5. Failure Mode and Effect Analysis (FMEA)
Furthermore, FMEA analysis is carried out to determine the potential failure that may occur and its impact. In this case, the failure modes that can be noted and used include previous failures, failures that occurred during routine maintenance of assets, and other failures that have never happened before but have the potential to occur. Failure mode must be explained in detail to make it easier to determine a maintenance strategy. Determination of failure mode can be derived from:

- Manufacture vendor,
- Common failures that have occurred for the same asset,
- Asset damage history,
- And can be sourced from interviews with operators of assets.

While for the failure effect, it describes what happened / the impact that would have occurred if the damage occurred. The FMEA identification process can improve performance, safety and anticipate failure. The results of the FMEA analysis will be written in the information worksheet as per the RCM II worksheet and will be used to determine the appropriate maintenance task.
2.6. Logic Tree Analysis (LTA) and Define Maintenance Task
After analyzing the FMEA and filling in the RCM II information worksheet, the next step is to determine the appropriate maintenance actions and fill in the RCM II decision worksheet. Where in this case the process of selecting maintenance, actions are based on the guidelines listed in the RCM II book.

In general, maintenance actions can be categorized into 2, namely preventive task actions and default actions. Selection of maintenance actions based on the failure mode of each equipment in the RCM Information worksheet. However, previously classifying failure modes into several categories so that you can determine the type of task and the priority level of its handling using Logic Tree Analysis (LTA), then followed by determining the appropriate maintenance task by following the RCM II decision diagram.

2.7. Maintenance Schedule and Workpackage
The last stage is to determine the maintenance schedule for each failure mode according to the proposed tasks and provide recommendations for maintenance actions that can be taken to minimize the failure that can occur to systems and components of the closed cooling water system.

![Figure 1. Process flow diagram (PFD) of closed cooling system](image)

3. Result and Discussion

3.1. Asset Register and System Boundaries
Based on the data, obtained the asset register of the closed cooling system. Figure 1 shows the process flow diagram (PFD) of the closed cooling system. The main equipment that was analyzed are follows:

- **Closed Cooling Pump (7CC-P-100A / B)**, for pumping cooling water in a closed cooling system with a capacity of 11000 GPM (2500 m³/hour).
- Heat Exchanger (7CC-HX-100A), to provide heat transfer at the desired rate of 63,333,770 kJ/hour.
- Expansion Tank (7CC-TK-100), to accommodate the increased volume of cooling water with a capacity of 3.8 m³ (1000 gal).
- CC Water Pump Minimum Flow Valve (7CC-PV-804), to control and automatically shut down the cooling water supply when the expansion tank is fully filled at a capacity of 3.8 m³ (1000 gal).
- CC Water Expansion Tank Level Valve (7CC-LV-800), to control the minimum flow at the pump at 19.5 m³/minute (5146 GPM). The following is the PFD on the close cooling system for which the RCM analysis will be carried out.

3.2. The System and Functional Block Diagram (FBD)
In this stage, it is used to determine the system description from the data obtained and also to determine the Functional Block Diagram (FBD) related to the equipment being analyzed in the close cooling system. A closed cooling system, in this case, functions as a cooling system and to remove heat or transfer heat contained in components and equipment such as Boiler Feed Pump Turbine (BFPT) Oil Cooler, Main turbine cooler, Generator hydrogen cooler, and other equipment in a power plant with water media that has been chemically processed. The purpose of the Closed Cooling Water System (CC) is to circulate filtered and processed cooling water in a closed system. In principle, there are 2 close cooling pumps with a capacity of 100%, where one is used for operation, while one pump is standby and will continue to circulate in a close loop.

The water discharged from the pump passes through one of the two parallel heat exchanger shells and tubes. The water flow from the close cooling will flow through the shell side and the heat absorbed water will flow through the tube side. In operation, one heat exchanger will operate, while the other is on standby. From the heat exchanger, cooling water is circulated parallel to the heat exchangers of other equipment. The flow through the heat exchanger is controlled by the temperature valve. After passing through the close loop, the water is returned to the pump suction.

The closed cooling water pump will be regulated and protected by a minimum flow control valve. Where the valve will regulate the incoming flow according to the pump capacity. At start-up conditions, the closed cooling water system is filled from the CM system and is regulated using a valve. Then the close cooling expansion tank will operate. After the tank is filled, the water control level valve will regulate and maintain the expansion tank at the desired level. The close cooling pump is then started from the Distributed Control System (DCS). System flow balancing is performed to regulate the desired flow to equipment that is not equipped with a modulated flow valve. Meanwhile, in operational conditions, one of the closed cooling pumps will be used. The pump is controlled automatically from the DCS control room. Figure 2 shows the functional block diagram of the closed cooling system.

3.3. Function, Functional Failure, Failure Mode and Effect Analysis (FMEA)
In this case, an analysis is carried out concerning the function of each equipment which will be analyzed in the close cooling system. After knowing the function of equipment, then determine the failure that can occur. Where the results of determining the function and failure of function can be used as a reference to determine the causes of failure that may occur (failure mode) and the impact of the failure (failure effect).

Failure modes are identified through previous failures, failures that occur in routine maintenance of assets, and other failures that have never happened before but have the potential to occur. Failure mode must be explained in detail to make it easier to determine the maintenance strategy. In this research, the identification of failure modes comes from the manufacturing vendor, common failures that have occurred in the same asset, history of asset damage, and the results of interviews with operators of assets.

Based on the overall equipment in the closed cooling system which is analyzed, it is known that there are 155 failure modes. The results of the failure mode analysis in the closed cooling system show that 113 failures or 73% of the total failure modes are evident and 42 failures or 27% of the total
failure mode are hidden failures. The percentage of hidden and evident failure mode can be seen in figure 3. Then FMEA analysis will be written in the RCM II Information Worksheet. Table 1 shows the RCM worksheet for FMEA analysis.

3.4. Logic Tree Analysis (LTA)
After analyzing the failures that can occur using FMEA, then the analysis is carried out using Logic Tree Analysis (LTA) to classify each failure mode and failure effect of each equipment. Where in this case it will be classified in terms of whether the failure mode is hidden/evident, safety problem, environmental problem, operational problem, or non-operational problem. The LTA was determined according to RCM II by John Moubray as the guideline. The results of the analysis will then be written in the RCM II Decision Worksheet according to the RCM II template, see Table 2.

Based on the analysis using LTA, it can be seen that most of the failure modes are evident failures, which can be detected by staff members of workers, and have different levels of importance, where human and environmental safety are the main ones. As for hidden failures, the causes of these failures are not immediately visible and cannot be detected by workers' staff members. This is usually seen in safety or protection devices. Hidden failures are much more complex to deal with, making RCM analysis more difficult and assets usually include safety and protection devices to minimize the consequences of different failures.

**FUNCTIONAL BLOCK DIAGRAM OF CLOSED COOLING SYSTEM**

![Functional block diagram of closed cooling system](image)

**Figure 2.** Functional block diagram of closed cooling system

![Hidden vs Evident](image)

**Figure 3.** Hidden and Evident Failure
Table 1. FMEA worksheet

| FUNCTION | FUNCTIONAL FAILURE | FAILURE MODE | FAILURE EFFECT |
|----------|--------------------|--------------|----------------|
| To pump cooling water in a closed system with capacity 11000 GPM (2500 m3/hr) | (Loss of Function) | Causes no cooling water to be distributed, which is indicated by the minimum flow level pump sign that lights up in the control room. As a result, there is no suction pressure that comes out due to the absence of a given power input, so the pump will not be able to absorb the fluid. | 1) no safety and environmental effects are caused. 2) Operation, can stop the cooling water distribution but no financial penalty is given. 3) Increase maintenance costs but no other additional operational costs. 4) Production, the damage resulted in production downtime to fix it. 5) It took 4 hours to repair the damage. |

Table 2. Logic tree analysis (LTA) worksheet

| WORKSHEET | SYSTEM | Facilitator | Date | Sheet N° | FORM 6 |
|-----------|--------|-------------|------|----------|--------|
| © 1996 ALADO N LTD | Close Cooling System | | | 1 | |
| | SUB-SYSTEM | Auditor | Date of | | |
| | Close Cooling A | | | | |

| INFORMATION | Consequence Evaluation | Default Action | Proposed Action Task | Initial Interval | Can be done by |
|-------------|------------------------|----------------|----------------------|-----------------|----------------|
| F FF FM H S E O N1 N2 N3 H4 H5 S4 | | | | | |
| 1 A 1 Y N N Y Y | Check condition of motor pump (Circuit breaker, fuse and starter) | Daily | Mechanic |
| 1 A 2 Y N N Y Y | Check impeller for locked and fix it Backwash or use chemical treatment to clean | Monthly | Mechanic |
| 1 A 3 Y N N Y N Y | Check and inspect condition of corrosion and repair if necessary | Annually | Mechanic |
| 1 B 1 Y N N Y Y | Check and inspect condition of pump for priming and fix it Check for proper pump submergence | | | |
| 1 B 2 Y N N Y Y | Check the pressure in (suction and discharge) and vent well to atmosphere to eliminate vacuum at pump | | | |
| | Check the suction line for clogged Backwash or use chemical treatment to clean Check and measure the pressure then fix it | Weekly | Mechanic |

3.5. Maintenance Task Selection
The determination of maintenance is categorized into preventive and default action. Determination of appropriate maintenance is carried out in accordance with the decision diagram on RCM II as a guideline. Determination of maintenance carried out based on technical feasibility and worth doing. Where maintenance is chosen it must be technically feasible and effective to do. Based on the determination of maintenance tasks, 155 maintenance tasks were obtained. The percentage of analysis results in determining maintenance can be seen in figure 4.
The determination of the interval for each maintenance task is listed in the initial interval column in table 2. The maintenance interval considerations are as follows: (1) On condition task, the interval can use the P-F interval item; (2) Schedule restoration and discard tasks, intervals can be used from useful lifetime items; (3) As for the failure finding task, the interval can be determined by the formula and considers the consequence of multiple failures, the desired availability and the mean time between occurrences of hidden failures. In this research, the determination of the initial interval refers to the manual book and historical data maintenance that has been carried out.

Then, the results of the analysis will be summarized in a work package. Where the work package contains maintenance intervals, executors of maintenance, and proposed action tasks that can be carried out according to the maintenance task that has been determined for equipment analysis. Figure 5 shows an example of the work package of the closed cooling system pump.

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| Maintenance Task Schedule |
|---------------------------|
| Equipment Name            | Close Cooling Pump |
| Tag. Number               | 7CC-P-100A         |

Following these recommended steps should help operators reduce problems with close cooling pump. Here is a brief check list:

| Interval | Done By |
|----------|---------|
| Daily    | Mechanic|

| PROPOSED TASK | Reference |
|---------------|-----------|
| ☑ Check condition of motor pump (Circuit breaker, fuse and starter) | 1 A 1 |
| ☑ Check and inspect condition of pump for priming and fix it | 1 B 1 |
| ☑ Check for proper pump submergence | 1 B 1 |
| ☑ Check the pressure and vent well to atmosphere to eliminate vacum at pump suction | 1 B 1 |
| ☑ Check for switched power leads and make it sure that the rotation is right | 1 B 4 |
| ☑ Check and measure the pressure of pump | 1 B 6 |
| ☑ Check power supply voltage and frequency | 1 C 6 |
| ☑ Check and inspect for pump cavitation and fix it | 1 E 6 |
| ☑ Check the inlet/outlet connection of pump then fix it | 1 J 4 |
| ☑ Check the condition then lubricate the bearings | 1 I 1 |
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Figure 4. Task selection of closed cooling system

Figure 5. Work package of closed cooling system
4. Conclusion

In this research, the Reliability Centered Maintenance (RCM) method as per RCM II by John Moubray is used to determine maintenance task selection on the closed cooling system. Based on the results of system analysis using the FMEA method on the analyzed equipment, namely a close cooling pump, heat exchanger, expansion tank, minimum flow valve, and level control valve, 73% of all failure modes are classified as evident failure, while 27% are indicated as a hidden failure. Meanwhile, the results of the determination of maintenance selection, there are 155 maintenance activities which consist of 5 categories, namely scheduled on condition task (57%), scheduled restoration task (24%), scheduled discard task (13%), scheduled finding failure (4%) and no scheduled maintenance (4%).

Finally, a further recommendation from this research is to add other methods such as criticality assessment that may be applied in conducting further, more comprehensive analysis to perform RCM analysis.

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