# Failure Mode and Effect Analysis (FMEA) for Enhancing Reliability of Water Tube Boiler in Thermal Power Plant

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## Abstract

*Failure mode and effect analysis is one of the QS-9000 quality system requirement supplements, with a wide applicability in all industrial fields. FMEA is the inductive failure analysis instruments which can be defined as a methodical group of activities intended to recognize and evaluate the potential failure modes of a product/ process and its effects with an aim to identify actions which could eliminate or reduce the chance of the potential failure before the problem occur.*

*The purpose of this paper is to evaluate the FMEA research and application in the Thermal Power Plant Industry. The research will highlight the application of FMEA method to water tubes (WT) in boilers with an aim to find-out all the major and primary causes of boiler failure and reduce the breakdown for continuous power generation in the plant.*

*Failure Mode and Effect Analysis technique is applied on most critical or serious parts (components) of the plant which having highest Risk Priority Number (RPN). Comparison is made between the quantitative results of FMEA and reliability field data from real tube systems. These results are discussed to establish relationships which are useful for future water tube designs.*

## 1. INTRODUCTION

The demand for electricity is increasing day by day with rapidly change in world's economy in every country similar to India. Although, the government has put its efforts to meet out this demand by building new Power Plants but still gaps between demand and supply is very large. In India, more than 75% of electricity is based on coal, so it draws a lot of attention to improve efficiency of Thermal Power Plant as there is a large scope of saving energy in Thermal Power Plant. For continuous generation of electricity in Thermal Power Plant, engineers keep attention on how to minimize plant breakdown by reducing failure modes. In the boiler, there are the many small components. If one of them fails, whole process of boiler stops working. It is big problem for Power Plant Engineers. There are a number of failure modes due to breakdown in the Power Plant.

FMEA discipline was developed in the United States Military. Military Procedure MIL-P-1629, titled Procedures for Performing a Failure Mode, Effects and Criticality Analysis, dated November 9, 1949. FMEA is a Formal Design Methodology in the 1960s by the aerospace industry, with obvious reliability and safety requirements. In the late 1970s, the Ford Motor Company introduced FMEA to the automotive industry for safety and regulatory considerations. They also used it to improve production and design. FMEA has been adopted in many places, such as: Aerospace, Military, Automobile, Electricity, Mechanical, and Semi-conductor industries. Most current FMEA methods use the risk priority number (RPN) value to evaluate the risk of failure.

The ability to improve continually is desirable. In recent years, the reliabilities of Power Plants have become increasingly important issues in the most developed and developing countries. Reliability, Availability, Maintainability and Supportability (RAMS), as well as risk analysis, have become big issues in the power industries. Major causes of customer dissatisfaction often results from the unexpected failures, which have led to an unanticipated costs in the Thermal Power-Station. However, with proper integration of RAMS and risk analysis in each maintenance process in the Thermal Power-Station, the frequency of failures can be reduced and their consequences can be diminished.

Failures are prioritized according to how serious their consequences may be occur and how easily they can be detected. FMEA is used during the design stage with an aim to avoid future failures. Later, it is used for process control, before and during on-going operation of the process. Ideally, FMEA begins during the earliest conceptual stages of design and continues throughout the life of a product or service. The outcome of FMEA development is actions to prevent or reduce the severity or likelihood of failures, starting with the highest-priority. FMEA determines the risk priorities of failure modes through the risk priority number (RPN), which is the product of the occurrence (O), severity (S) and detection (D) of a failure. (RPN = O * S * D)

## 2. BASIC CONCEPTS OF FMEA

The main purpose for performing FMEA is to prevent the possibility that a new design, process or system fails to achieve, totally or in part the proposed requirements, under certain conditions such as defined purpose and imposed limits. Through FMEA, the client requirements are evaluated and products and processes are developed in a manner that minimizes the risks of the occurrence of potential failure modes, with an emphasis on insuring the safety and health of the personnel and the security of the systems. Another purpose of the FMEA is to develop, evaluate and enhance the design development and testing methodologies to achieve the elimination of failures and thus obtain world-class competitive products. The main advantages of using FMEA methods are: Reduction of Costs, with a critical impact on warranty returns; Reduction of the Time needed from the project phase to the market launch and Improvement of the Quality and Reliability of the products, while increasing the safety of their operation. The ultimate goal for attaining these benefits is the increase of customer satisfaction, which assures the growth of the organization's competitively and the improvement of the image on the market.

## 3. FMEA PROCESS STEPS

The description of the FMEA process steps are:

1. Establishment of FMEA team.
2. Describing the product/process/system which wants to be analyzed.
3. Creating a Block Diagram of the product or process which shows major components or process as blocks connected together by lines indicate how the components or steps are co-related.


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4. List of potential failure modes, causing of failures in the system.
5. Assign Severity, Occurrence and Detection rankings to each failure mode.
6. Calculate RPN (Risk Priority Number) by using mathematical formula (RPN= Severity X Occurrence X Detection.)
7. Develop an Action Plan and define who will do what by when.
8. Take actions those are identified by the FMEA team.
9. Calculate the resulting RPN after implementation of actions.
10. Compare RPN before and after implementation of actions and Re-evaluating each of the potential failures once improvements have been made. Determine the impact of the improvements using FMEA.

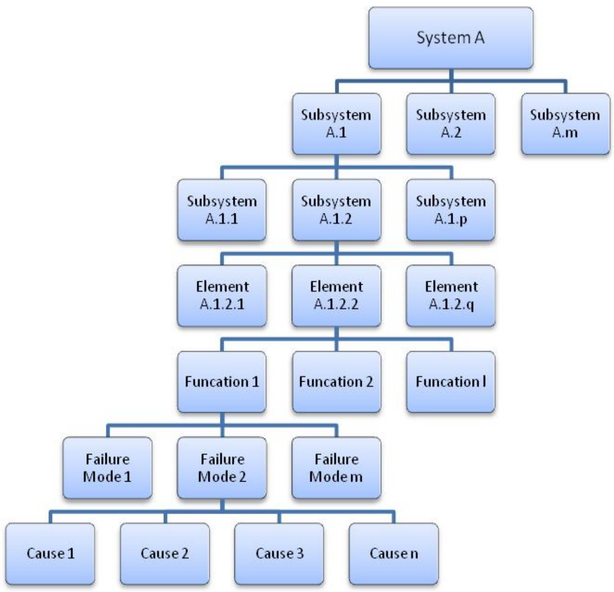


**Fig.1:** FMEA Process Steps

## 4. FMEA IN THERMAL POWER PLANT

Suratgarh Super Thermal Power Plant (SSTPS) is First Super Thermal Power Station of Rajasthan. The total planned installed capacity is 1500 MW. There are some major components in the plant failure in the following years. Table1. Shows that boiler is the most critical and serious component in a power plant because it can fail many times during years as compared to the other components. So, the team is focused on the boiler to find out all basic failure modes of it.

For finding out all the Basic Failure Modes and causes of failure of boiler, use "Cause and Effect Diagram" or "Fishbone Diagram". After finding all Basic Failure Modes of boiler, calculate Risk Priority Number of each failure mode and find out the component in boiler more serious and having the highest RPN.

Calculate RPN by using mathematical formula (RPN= Severity X Occurrence X Detection). On the basis of above analysis for RPN, it is seen that boiler tube failure has the highest Risk Priority Number (315) amongst all other failure modes.

So, the first priority is given to the boiler tube for reduction in the failures of a boiler. Boiler tube plays the most important role for shuting down of a power plant.

**Table-1:** Major Component's failure in SSTPS

| Year | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|
| **Boiler** | 34 | 62 | 68 | 70 |
| **Feed water pump** | 15 | 12 | 16 | 15 |
| **Circulating water pump** | 12 | 15 | 16 | 20 |
| **Electrical system** | 10 | 12 | 13 | 15 |
| **Emissions control system** | 14 | 20 | 38 | 40 |
| **C & I System** | 15 | 0 | 12 | 10 |
| **Turbine** | 25 | 32 | 44 | 45 |
| **Others** | 48 | 25 | 22 | 20 |



 

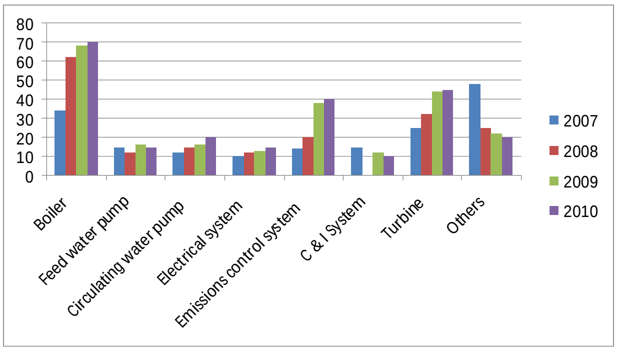


**Fig.2:** Major Component's Failure in SSTPS

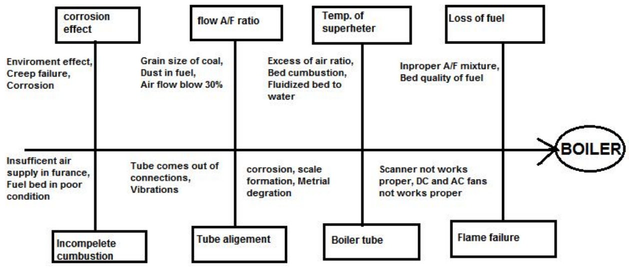


**Fig.3:** "Cause and Effect Diagram" for boiler to find out cause of Failures and their effects

**Table-2:** RPN number before implementation of FMEA

| Potential failure mode | Potential effect of failure | Potential causes of failure | Severity (S) | Occurrence (O) | Detection (D) | RPN |
|---|---|---|---|---|---|---|
| **Flow air fuel ratio** | 1. The unit had shut down due to bad proportion of air fuel mixture<br>2.bed combustion | 1. Air flow below 30 %<br>2.grain size of coal<br>3.dust in fuel increases | 5 | 3 | 5 | **75** |
| **Corrosion effect** | 1. Boiler tube material becomes weak.<br>2. Cooling of tube wall reduce so temperature increases<br>3.boiler pressure increases<br>4. Welded joint goes weak. | 1. creep failure<br>2. corrosion is associated with austenitic super heater materials<br>3. It is usually with the coal firing also with the oil firing. | 5 | 6 | 8 | **240** |
| **Temperature of super heater and re heater** | 1. Plant efficiency reduce<br>2. failure of super heater and re-heater tubes<br>3. failure of turbine blades | 1.changing the plant load<br>2. excess of air fuel mixture<br>3. bed combustion | 7 | 6 | 5 | **210** |
| **Loss of fuel (coal)** | 1. Steam not produces in proper manner.<br>2. Abnormal combustion of fuel | 1. proper air fuel mixture in furnace<br>2. quality of fuel<br>3. less air flow | 5 | 4 | 4 | **80** |
| **Flame failure** | 1.combustion does not take place<br>2. steam not produced properly | 1.scanner not works proper<br>2.DC and AC fan not works proper<br>3.reheater not works proper<br>4. moisture in coal | 6 | 3 | 3 | **54** |
| **Boiler tube** | 1.water leakage<br>2.cooling process stops<br>3.unit had shut down<br>4.water level not maintained<br>5. Inside and outside damage the tubes | 1.corrosion<br>2.scale formation<br>3. High pressure and temperature<br>4. extremely combustion<br>6.highly impurities in feed water<br>7. Creep failure<br>8. Rupture<br>9. Poor water circulation | 9 | 7 | 5 | **315** |
| **Tube alignment and setting** | 1. vibration arrestors get deformed<br>2. boiler tube had damaged | 1. tubes come out of connectors<br>2. vibration increases and tube failed | 7 | 5 | 5 | **175** |
| **Incomplete combustion** | 1. proper steam does not supply<br>2. air fuel losses<br>3. boiler tube wall damaged | 1.insufficient air supply in furnace<br>2. fuel bed in poor condition<br>3. cooling of furnace at low ratings | 6 | 5 | 5 | **150** |
| **Water level of drum** | 1.safety valve does not work steam comes at outside of boiler due to leakage<br>2. steam pressure excess<br>3. boiler may be damaged | 1. failure of boiler feed pump<br>2. water tubes corrosion<br>3. failure of feed valve<br>4. failure of water level indicator | 6 | 7 | 4 | **168** |

## 5. RECOMMENDED ACTIONS

There are some actions suggested by the FMEA team to reduce the failures of Water Tube:

- If a major failure occurs, unit shuts down for 3 to 4 days that affects power generation.
- At the time of working, alignment of the tube, excess steam temperature and pressure is to be checked in routine.
- The boiler here is a Water Tube Natural circulation type.
- Controlling the flow velocity in the raised tube is to be sufficient. Due to some abnormality, excess steam builds up in the raised tube causing over heating and exerting excessive stress in the tube.
- During the operation if the corrosion affects in tube in a small area, take necessary action by the Boiler Maintenance Department.
- If there is any doubt in the leakage of Water Tube, the setting of the tubes need to be examined.
- If temperature of the tubes rises excessively, inform quickly to the Control Room.
- Use innovative preventive techniques to reduce the failures.
- Extensive inspection of pressure load to be measured where the pressure rises.
- Shielding tube at critical zone to reduce the erosion and corrosion.
- Improve maintenance of Flue Gas part.
- Expert analysis of the tube failure.

## 6. RELIABILITY ANALYSIS

In the plant due to major failure of Water Tube, plant unit (5$^{th}$) had been shut down many times. Here reliability analysis and MTTF (Mean Time To Failure) is done, to know the failure of tube maintenance duration and working duration of boiler between two failures. Table 3 shows last three years data of Water Tube failure from 14-12-2008 to 20-01-2011.

**Table-3:** Failure Time of Water Tube in Boiler

| S. No. | Date of failure | Time of breakdown | Time of hand over after repair | Time of repair | Time duration of Maintenance (Hrs.) | Working time duration (Hrs.) |
|---|---|---|---|---|---|---|
| 1 | 14-12-08 | 10 A.M. | 17-12-08 | 6 A.M | 69 | 2,462 |
| 2 | 28-03-09 | 4 P.M. | 01-04-09 | 5 A.M | 99 | 2,501 |
| 3 | 10-07-09 | 12 P.M. | 14-08-09 | 2 P.M | 78 | 3,678 |
| 4 | 13-11-09 | 9 A.M. | 15-11-09 | 7 A.M | 44 | 2,283 |
| 5 | 10-03-10 | 2 P.M. | 13-03-10 | 11 A.M | 73 | 2,063 |
| 6 | 05-05-10 | 8 A.M. | 06-05-10 | 12 P.M | 37 | 1,345 |
| 7 | 21-08-10 | 11 A.M. | 24-08-10 | 9 P.M | 43 | 2,595 |
| 8 | 17-11-10 | 10 A.M. | 19-11-10 | 6 P.M | 42 | 2,110 |
| 9 | 20-01-11 | 4 P.M | 23-01-11 | 7 A.M | 63 | 1,538 |

Reliability for each working duration by using Rank Adjustment Method (RAM) and MTTF as shown in Table 4. For example Reliability **R (t)** for 21101hrs. i=4, n=9

$$R(t) = 1 - \frac{i-0.3}{n+0.4} = 0.6063$$

Apply the Weibull least square method

$\sum X = 69.263$, $\sum Y = -4.667$, $\sum XY = -30.210$,

$\overline{X}^2 = 59.225$, $\overline{X} = \frac{\sum X}{9} = 7.6958$,

$\overline{Y} = \frac{\sum Y}{9} = -0.5185$, $\sum X^2 = 533.72$

So slop factor in weibull distribution or Shape parameter m=b= $\beta$

For straight line y = bx +a,

**Table-4:** Analysis for Mean Time To Failure (MTTF)

| S. No. | Working hours in ascending order (t) | R (t) $=1-\frac{i-0.3}{n+0.4}$ | X=ln (t) | Y= $In\left[In\left(\frac{1}{R(t)}\right)\right]$ | X*Y | $X^2$ |
|---|---|---|---|---|---|---|
| 1 | 1345 | 0.9255 | 7.204 | -2.558 | -18.43 | 51.89 |
| 2 | 1538 | 0.8191 | 7.338 | -1.611 | -11.82 | 53.85 |
| 3 | 2063 | 0.7127 | 7.631 | -1.082 | -8.256 | 58.23 |
| 4 | 2110 | 0.6063 | 7.654 | -0.6923 | -5.298 | 58.58 |
| 5 | 2283 | 0.5 | 7.733 | -0.3665 | -2.834 | 59.8 |
| 6 | 2462 | 0.3936 | 7.808 | -0.0699 | -0.546 | 60.96 |
| 7 | 2501 | 0.2872 | 7.824 | 0.2212 | 1.7306 | 61.21 |
| 8 | 2595 | 0.1808 | 7.861 | 0.5367 | 4.219 | 61.8 |
| 9 | 3678 | 0.0744 | 8.21 | 0.9548 | 7.813 | 67.41 |

**Table-5:** Hypothesis Test by using Mann's test

| S. No. | $t_i$ | $lnt_i$ | $M_i$ | $lnt_{i+1}$ - $lnt_i$ | ($lnt_{i+1}$ - $lnt_i$)/$M_i$ |
|---|---|---|---|---|---|
| 1 | 1345 | 7.204 | 1.113 | 0.134 | 0.12 |
| 2 | 1538 | 7.338 | 0.525 | 0.294 | 0.56 |
| 3 | 2063 | 7.632 | 0.551 | 0.022 | 0.04 |
| 4 | 2110 | 7.654 | 0.267 | 0.079 | 0.295 |
| 5 | 2283 | 7.733 | 0.216 | 0.075 | 0.347 |
| 6 | 2462 | 7.808 | 0.183 | 0.016 | 0.087 |
| 7 | 2501 | 7.824 | 0.16 | 0.037 | 0.231 |
| 8 | 2595 | 7.861 | 0.142 | 0.349 | 2.458 |
| 9 | 3678 | 8.21 | | | |

Above eqn. compared with the

$$a = \overline{Y} - b\overline{X}$$

$$b = \frac{\sum_{i=1}^{n} Xi, Yi - \overline{X}\sum_{i=1}^{n} Yi}{\sum_{i=1}^{n} Xi^2 - n.\overline{X}^2}$$

$$b = \frac{-33.21-(7.6958\times -4.667)}{533.72-(9\times 59.225)} = \frac{2.769}{0.695} = 3.3894$$

And, $a = \overline{Y} - b.\overline{X}$ - 0.5185 (3.3840*7.6958) = 26.632 Find out scale parameter *(θ)* for find MTTF (Mean Time to Failure), so

Scale parameter $\theta = e^{-\frac{a}{\beta}}$

$\theta$ = 2584.889 hrs. = 2,585 hrs.

$$\text{MTTF} = \theta\Gamma\left(1+\frac{1}{\beta}\right), \{\Gamma - Gammafuncation\}$$

$$= 2{,}585, \times\Gamma\left(1+\frac{1}{3.3894}\right) = 2{,}585\ \Gamma\times(1.2950),$$

Here Γ(1.2950) =0.92877 (From the gamma function table)

= 2,585 = 2,326.50hrs. = 96.9375days

=97 days

From the Weibull least square method, MTTF is 97 days. But, here we consider the Mann's test for verifying the Weibull distribution in satisfying the failure of the Water Tube. Now, we apply the Mann's test.



 

In the last three years of failure data 36 failures occursed out of 36 failure in which 9 times of the major failure had in the water tube. Due to these failures, unit had to be shut down. For these failures MTTF is 97 days.

**Mann's Test Shows -**

n = 36;

r = 9; and the confidence level for the failures is 95 %, so

$\alpha = 0.05$

$$K_1 = K_2 \frac{r}{2} = \frac{9}{2} = 4.5 \approx 4$$

$$M = \frac{K_1 \sum_{i=k_1+1}^{r-1} [(\ln t_{i+1} - \ln t_i) / M_i]}{K_2 \sum_{i=1}^{k_1} [(\ln t_{i+1} - \ln t_i) / M_i]}$$

Where $M_i = Z_{i+1} - Z_i$, and

$$Z_i = \ln\left[-\ln(1 - \frac{i-0.5}{n+0.25})\right]$$

$$\text{So } Z_1 = \text{In}\left[-In\left(1 - \frac{1-0.5}{36+0.25}\right)\right] = -4.276$$

$$Z_2 = \text{In}\left[-In\left(1 - \frac{2-0.5}{36+.25}\right)\right] = -3.163$$

So on ……………………………

$$Z_9 = \text{In}\left[-In\left(1 - \frac{9-0.5}{36+0.25}\right)\right] = -1.319$$

And $M_1 = Z_2 - Z_1 = -3.163 -- (-4.276) = 1.113$

So on …………………………………..

M8 = 0.142

From the above calculation, we can find the following values for M:

Numerator = 12.492 and Denominator = 4.0.6,

$M = \frac{12.492}{4.06} = 3.070$ using the above eqn. with degree of freedom for both the numerator and denominator. Since $M < F_{crit\ 0.05,9,9,}$ so $H_0$ is accepted. Where ($F_{crit\ 0.05,9,9,}$ = 3.18, from the F distribution table).

## 8. RESULT

Table.6 Shows the Comparison of RPN before and after implementation of FMEA.

**Table-6:** Comparison of RPN

| | Occurrence | Severity | Detection | RPN |
|---|---|---|---|---|
| **Old RPN** | 7 | 9 | 5 | 315 |
| **New RPN** | 6 | 9 | 5 | 270 |

From the above table, after implementing FMEA on Water Tube, calculated RPN is to be reduced and recommended action is to be taken resulting in the reduction of the occurrence of the failure modes and severity in the Water Tube.

In reliability analysis of the Water Tube, major failure of the Water Tube was taken in the last three years. After calculating MTTF by the Weibull's Least Square Method its counts 2,324.00 hours or 97 days.

After applying the Mann's test on failure data, that tests the applicability of failure data in Weibull's Least Square Method. The results showed that the hypothesis is accepted.

It has been seen that there are many critical failure modes in the boiler, but, only the Water Tube failures are considered because Water Tube is a most critical and serious part of a boiler. These failures affected the boiler performance and power generation. It is concluded the Risk Priority Number (RPN) of the boiler tube is reduced by some recommendations.



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