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FAILURE MODE EFFECTIVE ANALYSIS IN A BOILER USING COMBINATION OF EVENT TREE AND FAULT TREE ANALYSIS

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Failure mode effective analysis in a boiler using combination of event tree and fault tree analysis

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ABSTRACT

Boilers are valued highly in many industrial industries and are expensive assets. In addition to their initial expense, they demand a large maintenance budget in order to guarantee output in respectable and safe working conditions. In order to avoid extreme repercussions, including the loss of lives, these assets must be carefully operated under experienced, well-trained supervision and subject to rigorous maintenance schedules and safety activities. However, this investigation is carried out with the help of the FMEA method taking into account with the previous literature' studies of boiler accidents in Asia so far. This is the Phase I, detailed information about boilers, and Asian boiler accidents, and this research paper is going to explain its nature. Subsequently, based on the data obtained in Phase I, an FMEA model will be developed in Phase II to highlight key boiler safety points. This research helps boiler manufacturers, boiler-related entrepreneurs, and boiler users to ensure maximum safety and identify any new things related to boiler safety.

Keyword- Boiler manufacturers, Accidents, FMEA method, Boiler safety.

1. INTRODUCTION

. Most industrial sectors in developing nations employ boilers as a standard and essential component. The boiler's primary function is to produce, store, and supply steam as needed. However, the malfunction of the industrial boiler may produce catastrophic mishaps that ultimately result in enormous losses to the resources and workers. China ($1.52B), South Korea ($365M), Germany ($308M), Finland ($236M), and India ($227M) were the leading exporters of steam boilers in 2020. Indonesia ($361M), Turkey ($275M), Pakistan ($255M), the United States ($251M), and Brazil ($208M) were the biggest importers of steam boilers in 2020 [1-5]. Industrial boilers are used to generate mechanical power and electricity as well as steam or heated water for space and process heating. In the food processing industry, steam boilers are employed for a variety of tasks including the processing of meat, poultry, beverages, food packaging, and vegetables. As a result, these boilers are made to be compact and user-friendly [6].

Boiler/pressure vessel explosions, fatalities, injuries, fires, property damage, and other commercial and financial losses are among the hazards that have increased as a result of the use of pressure vessels and boilers in tandem with industrial revolutions and socioeconomic affluence [7].

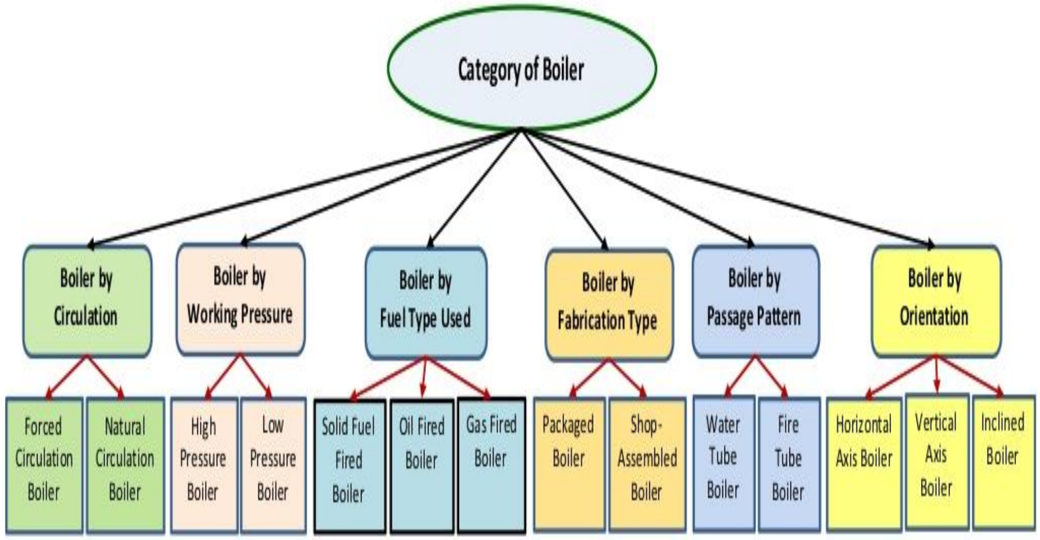

Fig.1 Different types of boilers (open access-internet)

Boiler/pressure vessel explosions are currently regarded as the biggest threat to industrial safety and public health. Statistics show that pressure vessel or boiler explosions, regardless of their size or scope, have a devastating impact on people, property, company operations, and the environment [8].

Boiler/pressure explosions have a significant negative influence on emerging (developing) nations since they not only destroy people's lives and property but also often the only source of income for those from low socioeconomic status. Often, disasters destroy a generation's hope for a better future [9].

Boilers and pressure vessels made of steel or alloy steel are typically used in factories and mills, such as those that produce fertilisers, thermal power plants, chemicals, pharmaceuticals, sugar, textiles, paper, sugar, cotton, rice, jute, garments, feed mills, and others. Boilers and pressure vessels are also used in hospitals, other public and commercial settings, residences and offices (for cooking, central heating, water heating, etc.). Boilers are typically pressure vessels with steam pressure between 0.07 and 2 MPa, and steam generators are those with pressures exceeding 2 MPa.

A boiler is defined as "An arrangement of vessels and interconnecting parts, where steam or other vapour is generated, or water or other liquid is heated at a pressure above that of the atmosphere by the application of fire or the products of combustion or process, or by electrical or solar means" according to the Australian Standard AS2593:2004 (Reconfirmed in 2016).

The boiler setting and related equipment are also included, as are valves, gauges, fittings, and controls that are directly related to the boiler and, when necessary to meet the criteria of AS2593:2004 (Reconfirmed in 2016), the boiler itself. It excludes systems that are completely submerged in water or other liquids or pressurised systems where the liquid is heated below its typical atmospheric boiling point.

Based on the fabrication or manufacturing process, the type of fuel used, the operating pressure, the orientation, the flow circulation, and the passage pattern, boilers are categorised. A broad classification of boilers and pressure vessels is shown in Figure 1.

This article's major goal is to draw attention to the horrifying human deaths and injuries brought on by boiler/pressure vessel explosions in South Asia (mostly in India, Bangladesh, and Pakistan), as well as potential reasons and corrective measures for preventing and/or minimising such accidents.

1.1 Explosion of a Boiler and its Effects

When water is vaporised, its volume multiplies by over a thousand, and the pressure of this vaporised water can cause the boiler's or pressure vessel's metal casing and poorly welded or rusted seams to fall apart. Even without the loss of the property, the sudden explosion of the pressurised steam causes fatal injuries, deaths, and the destruction of property, including the entire building and its people. The R. B. Grover shoe factory in Brockton (Boston), Massachusetts, USA saw a historic boiler explosion in 1905 that was so powerful that it not only killed 58 people and injured more than 150 others, but also completely levelled the four-story timber building. The entire factory area was evacuated after the boiler explosion [10-14].

Prior to this tragedy, there were sadly no standards or laws governing the production, use, and operation of boilers, as well as their maintenance and repair. Under the direction of the American Society of Mechanical Engineers, the Grover shoe factory boiler catastrophe served as the impetus for the development of the US national boiler/pressure vessel code (ASME). The code addressed safe boiler and pressure vessel design, construction, operation, maintenance, and repair [15-18].

Modern standards for boiler/pressure vessel design, construction, use, maintenance, and repair required roughly five years to develop. Today, the majority of national and international boiler and pressure vessel standards are based on the ASME boiler and pressure vessel code, which was tragically started after the boiler explosion at the Groover shoe factory [19-21].

Boiler explosions have drastically decreased (in some cases to zero) in developed countries in North America (USA & Canada, Mexico), Europe, North Asia, Southeast Asia, Australia, New Zealand, South Africa, and Israel due to compliance with standards and laws. However, the majority of emerging nations, particularly in South Asia, led by India, Bangladesh, and Pakistan, have seen a rapid increase in boiler fatalities rather than a decline.

For instance, on November 1, 2017, a boiler explosion at the National Thermal Power Corporation (NTPC) 550 MW power plant at Unchahar in Uttar Pradesh, India, killed 46 (forty six) persons, including two engineers and the boiler operators, and gravely injured 102 (one hundred and two) others.

On May 26, 2016, a boiler explosion at a pharmaceutical company in Dombivli, India, close to Mumbai, left 12 (12) persons dead and over 140 (140) others injured. Even though the NTPC is a state-owned power plant and normally tends to abide by the rules and regulations, this accident still took place there. To take preventive measures, it is essential to identify the accident's primary cause. Over 2000 people suffered losses as a result of the boiler explosion in Dombivli, which destroyed two buildings totally, three structures partially, and the windowpanes of every building within a 1.5 km radius.

On July 3, 2017, a boiler explosion at the "Multifabs" garment factory in Bangladesh resulted in the deaths of 13 (thirteen) persons and the grave injuries of an additional 50 (fifty) people. About 60 kilometres from the heart of Dhaka, in the Gazipur region, was where the Multifabs factory could be found [9]. The plant, which was constructed of reinforced concrete, was completely destroyed by the boiler blast. Poor workers, including the boiler operator, were all killed in the explosion.

More recently, on February 29, 2020, a boiler explosion at a paper factory in Kasur, Pakistan, close to Lahore, claimed 5 (five) lives and badly injured 9 (nine) others. Poor labourers are all victims.

2. Literature Review

Researchers put a lot of work into finding tube leaks, such as by building a mass balance equation based on a model (Xi Sun 2002), but they neglected to measure blowdown mass discharge or any other source of leakage, such as a damaged valve, malfunctioning accessories, or a water level indicator [22].

Although the algorithm can identify the leak, it cannot determine the precise location of the leak, which may be brought on by valves, gaskets, or other factors.

Similar to this, a study for early-warning for leakage in recovery boilers (Bjorn Widarsson 2007) used mass-balances on both the steam and combustion side of the boiler using Bayesian networks, and they were successful in getting an early-warning system. This approach took the blow-down mass into account [23].

Researchers also looked at non destructive tests, measuring the wall thickness and creep impacted by hot spots using ultrasonic technology and EMAT (Electro Magnetic Acoustic Transducer) (Anatoli Vakhguelt 2017).

From a different angle, studies on chemical failure assessments were conducted with the goal of assisting researchers in making informed decisions about the composition of coating materials and preventing hot spots of corrosion.

According to Santosh Kumar (2018), post-welding heat treatment is crucial for increasing ductility and preventing unstable microstructure in the HAZ, both of which contribute to cracking failure (Wei Wang 2014). Additionally, the Post Welding Heat Treatment method increases service loading because of geometrical effects that were not taken into account during design calculations (Andreas Fabricius 2016) [24].

Researchers have researched the stress corrosion cracking failure of SS316 L tubes. It was discovered through visual inspection, optical metallography, and chemical investigation that the pitting on the tube's exterior surface—caused by the presence of chloride ions in the condensate—was the source of the break (M. Ananda Rao 2018) [25].

The Microstructural evolution and oxidation of t92 boiler tubes has also been studied, and it was discovered that these tubes have three layers: an outer layer of nanoscale iron oxide (Fe2O3), an inner layer of micro scale crystals of Fe3O4, and a mixture of chromium oxide and chromite (Cr2O3andFeCr2O4) adjacent to the matrix (Kejian Lia, 2017) [26].

It was discovered that the combination of sophisticated hot and cold processes may be the cause of tube wall weakening and steam leaking in low carbon steel tubes.

With the use of an acoustic sensor, a "detection algorithm" was developed to provide the concept of adjusting burner ignition timing in response to demand changes (Thomas Neeld 2016). Failures brought on by fractures do not just affect tubes; one example is a fluidization nozzle composed of austenitic stainless steel 304 [27].

The ash obstruction was the primary factor in the failure, which occurred after more than 100,000 hours of operation at temperatures between 790 and 820 °. As a result of temperature changes, the scale on the nozzle wall cracked (Liu 2016) [28].

The life cycle time has been the subject of research. The economizers in biomass fuel boilers typically have a shorter lifespan than those in fossil fuel boilers (Liu 2013). Burner life-cycle decline was modelled using CFD and ANSYS FLUENT (Mahdi Pourramezan 2015) [29] .

Residual life is computed using measurements of the steam side oxide scale thickness obtained using non-destructive ultrasonic methods (K.S.N. Vikrant 2013). Failure probability can be calculated using the first order reliability approach (FORM) (Xueqian Fu 2017). The performance of such designs or efficiencies were also compared or detected using boiler modelling (Jan Taler 2015), Marco Tognoli 2017, and Ortiz 2011) [30-31].

Because it is expensive to conduct trials on a real boiler, building a model and validating it is a useful alternative. Additionally, optimization of the boiler start-up while accounting for thermal stresses has used modelling (Jan Taler 2015) [32].

In order to recalculate the flue gas in fuel pre-heating, fuzzy logic control algorithm was also explored to improve boiler efficiency, and they were able to boost boiler efficiency by 5.15% (Ratchaphon Suntivarakorn 2016). Since a boiler is a necessary piece of equipment, its life cycle and environmental impact had to be considered as well (Vignali 2016). (B. Monteleone 2015) [33].

3. Risk Analysis

Risk analysis is a key component of ensuring boiler safety and preventing accidents. Here are some key steps in risk analysis for boiler accidents:

1. Hazard identification: Identify potential hazards associated with boiler operation, such as overpressure, low water level, equipment malfunction, inadequate maintenance, and human error.

2. Risk assessment: Evaluate the likelihood and consequences of each identified hazard, based on past experience, industry standards, and best practices. This includes assessing the probability of the hazard occurring and the severity of its impact.

3. Risk management: Develop and implement strategies to manage and control the identified risks. This may include implementing safety procedures, training employees on proper boiler operation and maintenance, installing safety equipment such as pressure safety valves and low water level alarms, and developing emergency response plans.

4. Monitoring and review: Continuously monitor and review the effectiveness of the risk management strategies, and revise them as necessary to address new risks or changes in the operating environment.

Effective risk analysis can help identify potential hazards, reduce the likelihood of accidents, and minimize the impact of accidents that do occur. By conducting regular risk assessments and implementing appropriate risk management strategies, boiler operators can ensure safe and efficient operation of their equipment, while protecting their employees and the surrounding environment

There are several different types of risk analysis techniques that can be used in the context of boiler accidents. Here are a few examples:

1. HAZOP (Hazard and Operability) analysis: HAZOP is a systematic and structured approach for identifying and analyzing potential hazards associated with a process. It involves a team of experts reviewing the process step-by-step, and identifying potential deviations from normal operation that could lead to hazards.

2. FMEA (Failure Mode and Effects Analysis): FMEA is a method for identifying potential failures and their impacts on a system or process. It involves analyzing each component of the system and identifying potential failure modes, the effects of those failures, and the likelihood of their occurrence.

3. Fault Tree Analysis (FTA): FTA is a method for analyzing the causes of a specific event or failure. It involves constructing a logical diagram that shows the possible causes of the event, and identifying the probability of each cause contributing to the event.

4. Event Tree Analysis (ETA): ETA is a method for analyzing the consequences of a specific event or failure. It involves constructing a logical diagram that shows the possible outcomes of the event, and identifying the probability of each outcome occurring.

5. Bow-Tie analysis: Bow-Tie analysis is a method for analyzing and visualizing the potential causes and consequences of a specific hazard. It involves creating a diagram that shows the potential causes on one side of the diagram, and the potential consequences on the other side, with the hazard in the middle.

Each of these risk analysis techniques has its own strengths and weaknesses, and the appropriate technique depends on the specific context and requirements of the analysis. By using a combination of these techniques, boiler operators can gain a comprehensive understanding of the potential risks associated with their equipment and develop appropriate risk management strategies

4. RESULT AND DISCUSSION

Comparing fault tree analysis, event tree analysis, and FMEA in the context of boiler accidents:

Fault Tree Analysis (FTA): FTA is a deductive approach that starts with a specific undesired event and works backwards to identify the potential causes or contributing factors. FTA is useful in identifying the specific combination of failures or events that can lead to a specific consequence, such as a boiler explosion. FTA is good for identifying critical paths or weak points in a system that can lead to a particular failure.

Event Tree Analysis (ETA): ETA is an inductive approach that starts with a specific initiating event and analyzes the possible consequences that could result. ETA is useful in identifying the possible outcomes of an event and the probabilities associated with each outcome. ETA is good for identifying the potential cascading effects of an event and the probability of each consequence occurring.

Failure Mode and Effects Analysis (FMEA): FMEA is a proactive approach that focuses on identifying potential failures before they occur and evaluating the effects of those failures. FMEA is useful in identifying the potential modes of failure in a system and their likelihood and consequences. FMEA is good for identifying potential failure modes and developing corrective actions to mitigate them.

In terms of their application in boiler accidents, FTA, ETA, and FMEA can all be useful tools in understanding the causes and consequences of boiler accidents and developing strategies to prevent or mitigate them. FTA and ETA are typically used to analyze specific events, such as boiler explosions, while FMEA is used to identify potential failures and their effects on the overall system.

FTA and ETA are similar in that they both analyze events and their causes and consequences. However, FTA is a more focused approach that identifies specific paths or combinations of events that lead to a particular consequence, while ETA analyzes the possible outcomes of an event and their probabilities.

FMEA is a more proactive approach that focuses on identifying potential failure modes and their effects on the system. FMEA is particularly useful in identifying potential risks and developing corrective actions to mitigate them before they occur.

In conclusion, all three methods, FTA, ETA, and FMEA, have their own strengths and weaknesses and can be used in conjunction with each other to provide a comprehensive analysis of boiler safety. The specific method used will depend on the specific needs and objectives of the analysis.

A general overview of the steps involved in each analysis method to help understand their differences:

Fault Tree Analysis (FTA) numerical comparison:

- Define the undesired event (e.g. boiler explosion)
- Identify the possible causes and contributing factors (e.g. overheating, pressure build-up, malfunctioning safety devices)
- Construct a fault tree diagram, with the undesired event as the top event and the identified causes and contributing factors as branches
- Assign probabilities and/or failure rates to each event and calculate the overall probability of the undesired event occurring
- Identify the critical paths or weak points in the system that could lead to the undesired event
- Develop corrective actions to mitigate or prevent the identified causes and contributing factors

Event Tree Analysis (ETA) numerical comparison:

- Define the initiating event (e.g. loss of water supply to the boiler)
- Identify the possible consequences and their probabilities (e.g. low water level, high pressure, boiler explosion)
- Construct an event tree diagram, with the initiating event as the starting point and the possible consequences as branches

- Assign probabilities to each branch and calculate the overall probability of each consequence occurring
- Identify the critical paths or cascading effects that could lead to the undesired consequence
- Develop corrective actions to mitigate or prevent the identified consequences and their underlying causes

Failure Mode and Effects Analysis (FMEA) numerical comparison:

- Identify the system or component to be analyzed (e.g. boiler)
- Identify the potential failure modes (e.g. overheating, corrosion, component malfunction)
- Identify the potential effects of each failure mode (e.g. reduced efficiency, safety hazards, boiler shutdown)
- Assign severity, occurrence, and detection ratings to each failure mode and calculate the Risk Priority Number (RPN)
- Identify the failure modes with the highest RPNs and prioritize them for corrective action
- Develop and implement corrective actions to mitigate or prevent the identified failure modes

Each analysis method provides a different perspective on the causes and consequences of boiler accidents and can be used in conjunction with each other for a more comprehensive analysis. The specific method used will depend on the specific needs and objectives of the analysis.

Fault tree analysis in boiler accidents involves identifying all the possible events or failures that could lead to a major accident. The main things to consider for fault tree analysis in boiler accidents include:

- Identifying the top event or the major accident that is being analyzed
- Identifying the immediate causes of the top event
- Identifying the basic events that can cause the immediate causes to occur
- Determining the probability of each basic event occurring
- Determining the probability of each intermediate event occurring
- Determining the probability of the top event occurring
- Analyzing the results and identifying potential solutions or mitigation strategies

It is important to note that the accuracy of the analysis depends on the quality of data used in determining the probabilities of each event. Additionally, it is essential to consider the interdependencies between events in the fault tree analysis

5. CONCLUSION

In conclusion, fault tree analysis, event tree analysis, and FMEA analysis are three commonly used methods for analyzing and prioritizing potential risks in boiler accidents. These methods can be used to identify potential causes, consequences, and failure modes and assess their probability and severity. The risk priority number (RPN) can then be calculated to prioritize potential risks and determine which mitigation strategies should be implemented first.

Each analysis method has its strengths and weaknesses, and the choice of method(s) used depends on the specific situation and data set available. Combining multiple methods can provide a more comprehensive risk assessment and help to ensure that all potential risks are identified and addressed. It is important to note that the results and discussions would depend on the specific data set and analysis performed, and that these methods should be used in conjunction with other safety measures to minimize the risk of boiler accidents

- Some potential future directions for boiler accidents risk priority number analysis using fault tree analysis, event tree analysis, and FMEA analysis include:
- Incorporating machine learning and artificial intelligence techniques to improve the accuracy of risk assessments and identify potential risks that may not be immediately apparent.
- Developing more comprehensive and standardized databases of boiler accident data, including both near-misses and actual incidents, to improve the accuracy and reliability of risk assessments.

Evaluating the effectiveness of different mitigation strategies and refining these strategies over time based on new data and insights

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