Analyzing Human Factors in Fitness for Service Assessments – A Boiler Case Study

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Abstract

A boiler is one of the critical systems in various industries even in the food industry. The cost of boiler maintenance including repair and replacement are very high. Therefore, options such as fitness for service are used as cost effective measures to demonstrate the performance characteristic of a component that might be operating with a flaw. This option is prone to a number of avoidable human errors like other maintenance functions. This paper aims to identify and examine the human factors acting as barriers for successful performance of fitness for service assessments in a boiler. It further recommends the possible solutions for the reduction and avoidance of reoccurrence of human errors. A single exemplary case study of a boiler in an anonymous company was selected. The study adopted a documentation review and observation as data collection tools to examine the source of human errors. Human errors such as wrong and insufficient measurements, poor work planning, and improper data collection and recording were identified as key barriers for successful performance of fitness for service assessments of a boiler system. The study further revealed that human factors such as lack of experience and training, poor communication and organizational practices are key causal factors.

Keywords:
Boiler, fitness for service, flaw, human factor, human error.

1. Introduction

During the maintenance phase of a boiler system, there are times where decisions such a repair or replacement are to be made. However, such decisions are very costly in nature since they also require lengthy shutdowns of the plant during the process. Now, a process like fitness for service is one of the methods that are used to analyze the condition of a boiler with flaws such as corrosion and cracks to determine the extent to which the boiler can operate without undergoing repair or replacement to eliminate the flaw. As much as it is a cost effective method as opposed to

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immediately resorting to repair and replacement, it requires accuracy and high level of experience and understanding. Fitness for service assessment is mainly a human function like all other maintenance activities, hence it is prone to human error stemming from various factors. This paper is aimed at identifying the human errors and their causal factors acting as barriers for the successful performance of the boiler fitness for service assessments.
The API 579/ASME FFS-1:2016 defines fitness for service (FFS) assessments as "quantitative engineering evaluations that are performed to demonstrate the structural integrity of an in-service component that may contain a flaw or damage, or that may be operating under a specific condition that might cause a failure". The accurate and sufficient data need to be collected and properly recorded to support the analysis. Inaccurate and insufficient data pose a serious risk if they are considered during the analysis since the boiler or a pressure vessel is a high risk component. The human errors that can be committed during data collection can be inherited in the analysis and lie dormant within a system as latent failures until the opportunity comes for an incident or accident to occur. Now, to improve the accuracy of data collection and recording, human errors need to be carefully analyzed with an intention to unearth the possible causes.

Human errors are viewed as failures of human to perform certain tasks, to wrongly perform tasks (e.g. skipping steps and forgetting the procedure), and to not perform necessary tasks. Figure 1 shows the common types of human errors and their classifications.

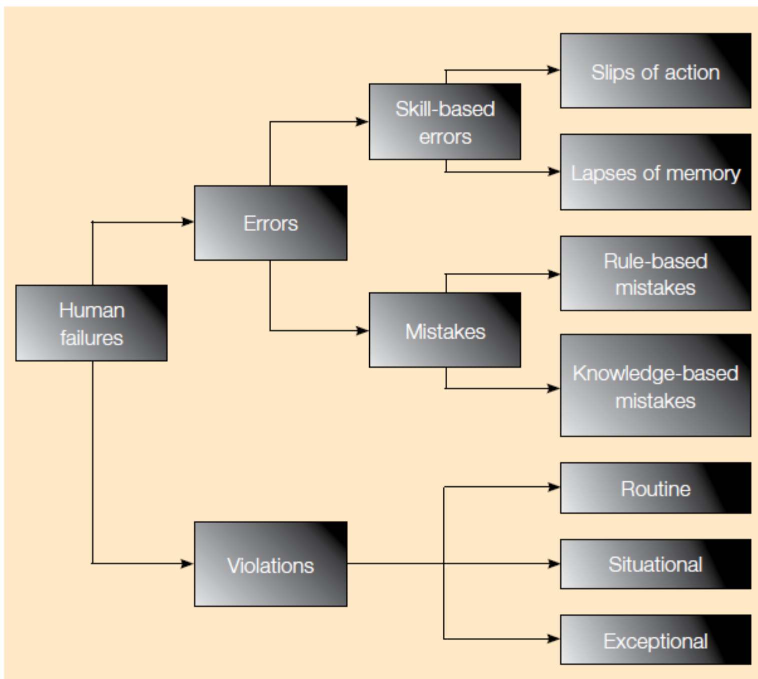

Figure 1. Types of human error, adapted from (Health and Safety Executive, 2007)

The human errors presented on the figure emerge from various human factors, such as lack of training, poor working planning, lack of or insufficient procedures, organizational practices and inaccessibility of components. (Lardner & Maitland, 2009) states that by undertaking a careful and detailed analysis of the incident, and the surrounding circumstances, it was possible to identify several factors which shaped this person's performance on that day, and explain how and why the error occurred. The proposed solution to the issue of human error in fitness for service assessments includes preventive measures aimed at reduction or elimination of these factors that shape the performance. If these factors are not properly assessed and preventive measures are not implemented, there is a high risk of incidents and accidents that can cost the organization lives of personnel, damage of equipment and impact on the economic status.

This paper examines the human error causal factors in fitness for service assessments through a boiler case study and then proposes possible solutions. The structure of this paper consists of the introduction, follows with the research methodology, literature review, results and discussions and ends with a conclusion that incorporates recommendations and proposed future work.

2. Methodology

This study uses a single exemplary case study of a boiler in an anonymous company. The paper adopted a documentation review, observation and discussions as data collection tools to examine the possible source of human errors and solutions for better managing human error in future fitness for service assessment activities.
The case company requested the contractor to perform the fitness for service assessments on one of the boilers. The inspections were done to detect the defects on the boiler and the measurements for the analysis were taken during the inspections. The file with the historical documents of the boiler were supplied for the fitness for service assessments. The boiler considered in this case study is a package coal-fired boiler with the parameters indicated in Table 1 below.

Table 1. Details of the Coal-Fired Package Boiler

User	Anonymous (Pty) Ltd
Manufacturer	Manufacturer A (Pty) Ltd
Design Code	BS 2790 - 1969
Year of Manufacture	1981
Manufacturers Serial Number	AG-1981-20
Design Pressure	1795 kPa
Operating Temperature	+/- 183.5 °C
Material	Carbon Steel

The photo presented in Figure 2 is for the case boiler taken from the anonymous food company used for the analysis of human factors in fitness for service.

Figure 2. The photo of a package coal-fired boiler taken from anonymous company

The visual inspection, non-destructive thickness measurements and metallurgical reports generated were reviewed to identify the possible human errors that could prevent the successful fitness for assessments on the boiler. The file containing historic documents of the boiler was also examined to uncover the human errors or barriers for successful completion of the fitness of service assessment. The fitness for service report which indicates the limitations and alternatives for the unsuccessful implementation of fitness for service assessments was analyzed. The observations and discussions were made to further understand the local context which is the case company to identify the sources of error.
This boiler case study was selected because the fitness for service assessment was not successfully completed, and human factors were suspected as culprits. The paper illustrates the human errors and their possible causal factors acting as barriers for successful implementation of fitness for service assessments in a boiler. The literature review

was analyzed with an intention to unearth human errors, human factors and key principles to serve as basis for discussions and recommendations.

3. Literature Review

In this section, scholarly writings pertaining fitness for service, human error, human factors, impact of human error and solutions to human error will be analyzed.

3.1. Fitness for service

Fitness for Service (FFS) assessment procedures are a basis for systematizing ways of examining the properties of in-service equipment or components to aid the decision making process concerning the acceptance of either repair, replacement or continued operation (Larrosa et al, 2017). There are international standards such BS 7910 and API 579-1/ASME FFS-1 that have been developed as guides to procedures for examining the acceptable tolerance of flaws in equipment such as pressure equipment of which the boiler forms part of. Tonti (2014) states that the deterioration of the equipment or part and the fraction of its existence should be examined considering the all the test results and all other tests required. It is further stated that the assessor of the life or condition of equipment or component is required to collect all sets of data Tonti (2014), before commencing the exercise. One can see from these statements that the historical data of equipment is very important when it comes to fitness for service assessments and other risked based inspection methods. This is the reason why Price (2014) states that the practical challenge of risk based methods is that they are data-hungry. Al-Dojayli et al (2018) indicates that significant repairs and/or replacements of aged equipment may push up the high capital costs and production revenue losses. Now, the method like fitness for service which is a cost effective method to ensuring that organizations do repairs or replacements after carefully assessing the alternatives of the acceptance criteria for operating the equipment with flaws without posing safety risks.

3.2. Huma Error

The maintenance activity is inevitably dependent on human and is impacted by various factors of interaction such as organizational, job design, individual cognitive factors, and environment promoting the inherent reliability issues in the system (Gandhi et al, 2013). Human error is defined by NOPSEMA (2015) as the lack of success in achieving the desired outcome of the arranged action. Alkhaldi et al (2017) presents the following three classifications of human error: a) a mistake – viewed as an error where there has been forgetfulness of a procedure or the individual has never been adequately trained to carry out the procedure, b) violation – is suggested as an error type when there has been an intent to ignore or violate the rule, and c) slip error – it is also classified as a procedural error, which can be simple viewed as missing of steps while performing a task and wrongly performing an activity or doing something wrong during the process of fulfilling the specific order. On the other hand Reason (1990) classifies human errors as follows: a) slips – these are categorized as actions that were not conducted as planned or meant, b) lapses – these are simple viewed as actions missed and c) mistakes – classified as errors where a plan was insufficient to accomplish the desired outcome. The exclusion of violation bye Reason (1990) may be due to the fact that in violation there is an intent while other errors are due to shortfall. Alkhaldi et al (2017) presents various types of human errors such as action errors, checking/inspction errors, retrieving information, insufficient communication of information, selection errors, and planning errors. Kontogiannis and Embrey (1992) agree with Alkhaldi et al (2017) but further bring forward human errors related diagnosis, decision making and transmission. All these errors affect maintenance of equipment including a boiler system in a number of ways. Now, the fitness for service assessment is a tool used in maintenance to decide on the flaw tolerance, it is then also affected by the same errors.

3.3. Human Factors

There are a number of error causal factors that are responsible for the occurrence of human errors that can impact the successful implementation of fitness for service activities. Due to lack of literature specifically linking the fitness for service and human factors, the human factors affecting maintenance were reviewed even though they were not all purely related with boilers. They were aimed at giving the basic knowledge on the origin of errors to prepare for mitigating strategies and then the case study to be used to verify the existence of some of these factors in boiler operation. Incompetence issues, supervision challenges and poor workload planning were categorized by Peach, et al (2016) as the key causal factors for the occurrence of human errors. On the other hand Gould and Lovell (2009) brought forward a perspective that procedures can be both an origin and a defense of human error, hence it becomes critical to establish what might go wrong. The procedures need to be carefully assessed for relevancy and easy to follow to ensure the errors that can stem from them are reduced and even eliminated. One can also break down the points of the procedure to form checklists for further simplifying the procedure. Dhillon (2014) presents inadequately documented procedures, the complexity of the maintenance tasks, insufficiency of training and experience as the major causes of human errors. Virovac et al (2017) agree with Dhillon (2014) on activity complexity, documentation, but further indicate the knowledge of individuals, coordination of activities, pressure, and disturbances during work as the key factors giving rise to human error.

The commitment of top management, improper training, inadequate or absence of reporting and recording system, and level of education are presented by Alkhaldi (2017) as the key factors that encourage the existence of human errors. In the study of analyzing risks of pressure vessels conducted by Wyckaert et al (2017), lack of knowledge concerning pressure vessel risks, inadequacy or failure of information, and ignorance to pressure vessel procedures are presented as the causes of pressure failures. The boiler is part of the pressure vessel family called pressure equipment, hence they suffer similar failures emanating from various causal factors. On the other hand Alonso and Broadribb (2018) indicate factors such as team and organizational cultures, engineering factors, situational factors, psychological matters, procedural issues, organizational perspectives, and a tendency to remain in the background as key to the occurrence of human errors. Hobbs (2008), discovered that human errors emerge from environmental factors, inadequate communication and coordination, time pressure, maintenance procedures and documentation, lack of integration in teamwork, change of shifts and handover, organizational and team norms, fatigue, sources of stress, lack of system knowledge, equipment design and fabrication deficiencies, insufficient design for maintainability, and absent minded. It can be seen that there is an agreement between the many factors extracted from various authors which are presented in this section. Nolan (2000) categorizes the missing information as a contributory factor to the complexity of tasks, hence become a source of human errors.

3.4. Impact of Human Factors

The occurrence of human errors in any system or process has a number effects on the system, people, organization and even society. The evaluation of the effects of these factors is therefore very crucial for the human's successful performance as confirmed by Gandhi et al (2013) in relation with maintenance. Virovac et al (2017) presents delays, accidents and damage to equipment as the impact that human errors can cause if they are not properly addressed. On the other hand Alkhaldi et al (2017) indicates that human error is an act that causes a disastrous/emergency situation, fatality, property and environmental damage, and limits to economic activities of any workplace. It is further stated that the rise of cost due to human factors has a great impact on the workforce, workplace, economy and society. Dunn (2004) agrees with the issue of high costs by stating that human errors have a great impact on the maintenance costs, but further states the high impact on maintenance quality, safety and equipment reliability. It is further stated that there has been an occurrence of significant accidents emanating from poorly functioning teams. These effects of human error need to be carefully analyzed and understood by any organization that is willing to eliminate or reduce human errors in their processes and activities. Majority of effects of human errors presented in this section are also believed to be the effects that can be witnessed with fitness for service assessments if human errors are not properly addressed.

3.5. Solutions to Human Factors

Taking initiatives to solve the issue of human error needs a better understanding of human errors, human factors, impact and possible solutions. It also requires a clear knowledge concerning the initiation, propagation and occurrence of incidents or accidents so as to prepare proper preventive measures. The Swiss Cheese Model is one of the models used to analyze the source of human errors by following a system approach. In this model errors are viewed as barrier defeating agents creating holes in each barrier until a point where they all match enough to create a mishap. This model relies on the holistic approach to human error in contrast to person approach which can be viewed as the "blame it on individuals" approach. The person approach is adopted by default by many organization that have not tried to address human factors in their operations. The system approach looks at the holistic factors and systems surrounding individuals performing the tasks. Figure 3 below presents the Swiss-Cheese Model of error analysis.

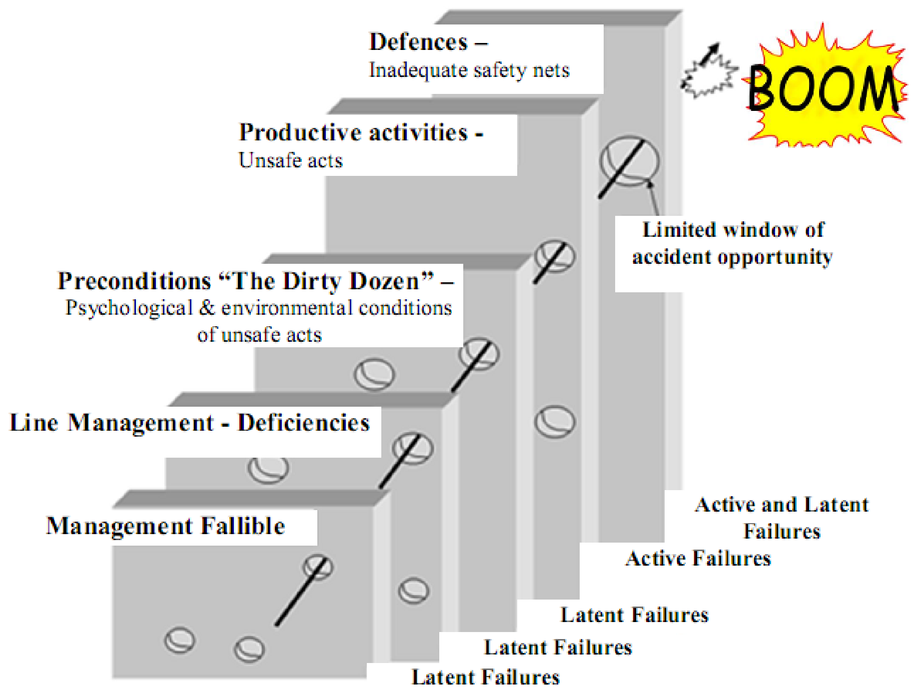

Figure 3. Swiss-Cheese Model adapted from Reason (1990) amended by (Nkosi 2014).

It can be seen from Figure 3 representing the Swiss-Cheese Model that there are various layers that are penetrated by human error first before an incident or accident occur. These layers need to be reinforced as an initiative of solving the problem of human errors.

Lardner and Maitland (2009) indicate that even though it is impossible to completely get rid of human error, however it is possible, through adopting proper maintenance management and an increasing knowledge on issues that affect error, to embark on a journey that moves towards this goal and to restrain the likelihood of error. The idea of cooperation is demonstrated through preconditions such as a) the know-how associated with capability, b) know-how-to-cooperate interconnected with synchronizing the activities and c) the need-to-cooperate to related with justification of synchronization of activities (Millot and Vanderhaegen, 2008). Knowing-how concerning the competences, knowing-how to collaborate in relation with coordinated activities and the need to collaborate in the justification of activities of collaboration are presented as three requirements of the concept of collaboration by Millot and Vanderhaegen (2008). This is in line with the Swiss-Cheese model in a sense that it looks at the activities and collaborated work joining the various facets of the organization. Now, Lardner and Maitland (2009) states that the quantitative human reliability evaluation discovered that by amending conditions and work systems would minimize the error probability. It is further stated that these amendments were implemented and resulted in the reduction of a number of errors up to 66%. (Timmons, et al., 2014) indicates that in a try to implement human factors training which was acceptable and relevant for improving performance through reduction of human error, was faced with challenges such as casual organizational cultures, and management commitment. The initiatives for eliminating or reducing human errors require changes in the organizational culture and a buy in from the management so as to successfully serve the desired goal.

4. Results and Discussion

In order to identify and analyze the human errors that are barriers to the successful performance of the fitness for service assessments, a boiler from the anonymous food company in South Africa as stated under the methodology was used. The company had difficulties to successfully complete the fitness for service assessments in one of its boilers. Table 2 below presents the human errors that were discovered through the case study and the possible causal factors that were located through observation, expert knowledge and discussions. The impact of the human errors were also identified and presented in Table 2.

Table 2. Human Errors, Causal Factors and Impact

Human Errors	**Causal Factors**	**Impact**
• Insufficient historical data • Insufficient measurements • Improper keeping of original records • Incomplete work	• Lack of knowledge • Level of education and training • Organizational practices • Poor work planning • Poor communication	• Unsuccessful Fitness for service assessments • Delays on the project completion • Additional unbudgeted cost • Continuing running the boiler without knowing the extent of risk

The results in Table 2 are presented to unearth and discuss how each error occurred and how it affected the process. In the following paragraphs these errors are analyzed and discussed.

Insufficient Historical Data

It was discovered through the inspection reports and data book supplied that there was no historical data of previous inspections, especially thickness measurements. The causal factor established as the source of this error is the organizational practice concerning data recording and safe keeping. (Alkhaldi, Pathirage &Kulatunga, 2017) confirms this factor by indicating lack of reporting and recording system as key human errors affecting the success of maintenance. The other issue is the previous inspection culture in which the thicknesses would not be measured, but only pressure testing and visual inspection could be done during inspections. Lack of understanding, training, education and experience concerning fitness for service assessments were also identified as the contributing factors to this error. These error causal factors agree with what is proposed by (Reason, 1990) and (Alkhaldi, Pathirage &Kulatunga, 2017). It is known to people who understand fitness for service that this process is data hungry, hence correct and sufficient data must be recorded and kept safely. This error contributed to the unsuccessful implementation of the fitness for service assessments, especially the prediction of the remaining life of a boiler or boiler components operating with a flaw. The previous records of thickness measurements are critical to the evaluation of corrosion/thinning rates aimed at establishing the remaining life of a boiler component. The organizational culture or practices are reported by (Alonso and Broadribb, 2018) and (Timmons, et al., 2014) as the sources of human error and hindrances to the success of tasks.

Insufficient Measurements

After realizing that the fitness for service could not be properly done, now the other option was to do thickness calculations as per original design code to determine if the provided thicknesses could handle the operating or design parameters. The error that prevented this action to be properly administered is that during the inspection when the inspector was taking thickness measurements, the tubesheet and nozzle dimensions were not taken. This is related with human error classified as lapse which is related with action missed as put forward by (Alkhaldi, Pathirage &Kulatunga, 2017). This error is related with poor planning, insufficient training and lack of understanding concerning the critical measurements required to determine the structural integrity of the boiler components.

Figure 4 illustrates the boiler shell thicknesses based on the original design code. The thinning of the boiler shell was determined through the results presented in Figure 4 since the metallurgical examination could not reveal any corrosion. This is the method that could have been used to also determine the thicknesses for nozzles and tubesheet to determine their safety or if not safe to seek alternative methods to determine the acceptance criteria.

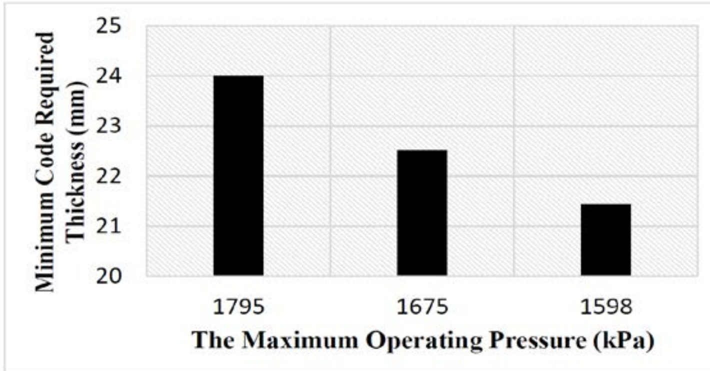

Figure 4. The thickness vs pressure results for the shell of the boiler.

The minimum measured boiler shell thickness was 22.55 mm. At a pressure of 1795 kPa the thickness of 24.01 mm was obtained which is above the minimum measured. Hence, at this pressure the boiler is deemed noncompliant with the original design code. At 1675 kPa the boiler passes with very negligible allowance. However, at 1598 kPa it passes with an allowance of 1.1 mm making it the safest pressure when re-rating is considered. But the re-rating could also not be considered due to insufficient measurements for other boiler parts. Therefore it is very important to take all relevant measurements for proper decisions in fitness for service to be made.

Improper Keeping of Original Records

Now, after noticing that there would be an issue with the calculations of the nozzles and the tubesheet, the engineer resorted to using the original drawings so that the original dimensions could be used to generate the minimum thicknesses. These minimum thicknesses were going to be set as limits of acceptable boiler parameters. This exercise was defeated by the lack of original calculations and insufficient old drawings. Now, this error of document keeping inhibited the use of the alternative methods of determining the safety thicknesses of boiler components. This complexity error serving as a barrier to successful completion of fitness for service is confirmed by (Nolan, 2000).

Incomplete Work

The error classified as incomplete work was discovered when the mechanical and metallurgical engineers went for inspections but discovered that the boiler was still wet. The inspection and testing could not be performed on that day. This error was related with poor work planning and poor communication. The issue of poor work planning as a contributory factor to human error is agreed upon by (Virovac, Domitrovic & Bazij, 2017) while insufficient communication is expressed by (Hobbs, 2008). The impact of this error was the delay of the project and cost implications for rebooking the engineers to complete their activities on another day. Holding meetings prior the fitness for service assessments could have prevented this kind of error and other errors stated in this section.

Solutions to Human Error

Table 3 presents the recommended solutions to human error that can be immediately adopted by the company to improve the fitness for service assessments to avoid future occurrence of similar errors.

Table 3. Recommended Solutions to the Issue of Human Errors

• Training on fitness of service
• Awareness and training in human factors in maintenance
• Commitment of management
• Checklists
• Procedures
• Electronic data recording
• Prepare sketches or drawings for measurements prior site measurement process

The recommended solutions presented above can be helpful in mitigating human errors however there are factors that can prevent the successful implementation of these solutions. Timmons, et al., (2014) indicates that management commitment, casual organizational cultures, and organization's local context are enablers of the perpetual occurrence of human error as they prevent successful implementation of training solutions.

5. Conclusion

The results obtained in this paper are very important to the maintenance personnel focusing on fitness for service of boilers and pressure vessel specifically those having interest in dealing with human error. The study analyzed the human errors and human factors that are regarded as barriers to the success of fitness for service assessments. It was indeed discovered that if enough attention is not paid to human error, the fitness for service assessments will not achieve the desired goal. The missing measurements, poor records of data and lack of original documentation to support decision making were leading human errors hindering the successful implementation of fitness for service. Fitness for service is one of the processes that are data hungry, hence without appropriate data it is impossible to make proper and accurate decisions concerning the life of a boiler systems operating with flaws. The lack of knowledge, low level of education and insufficient training, organizational practices, poor work planning and poor communication were regarded as error causal factors having an impact on the fitness for service assessments. The immediate solutions to the issue of human error in fitness for service assessments of boilers were presented. These included the development of checklists, training, management commitment, electronic data recording and preparation of sketches prior thickness measurements. It is then recommended that as the first step to adoption of fitness for service assessments, training must be conducted with an aim of reducing human error, hence improve the performance. The adoption of human factors principles in fitness for service assessments process can help the companies to properly manage human errors and even eliminate them.
The following are considered to be eligible for future research focus:

- Analyzing human error in fitness for service assessments to examine the state of the industry practices.
- The development of proper reporting systems that incorporate human factors principles.
- A framework for better managing human error in fitness for service of boiler systems.

6. Acknowledgements

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