

## **Design of Standard Engineering Model to Improve Occupational Health and Safety for Boiler in Sudan**

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### **Abstract**

This study has been carried out to design an engineering standard model to improve occupational health and safety steam boilers in industrial sector in Sudan, due to the lack of a standard model that determines the degree of control. In this work the boiler system was classified to four basic nodes, the failure of each of them can lead to catastrophic event. These nodes were named as insufficient fuel pressure, insufficient combustion, insufficient water level and over pressure. The seven step method, which were provided by Environmental Protection Agency (EPA), was used to identify the requirement Safety Integrity Level (SIL) for each node control system, the boiler control system was classified to four levels (SIL1, SIL2, SIL3, SIL4). Fault tree analysis, which is a quantitative risk assessment technique, was used to study the reliability of boiler systems and identify safety integrity level (SIL) for an existing control system. Redundancy and voting approaches were used to improve the existing boiler control system so as to achieve the desired safety integrity level and comply with the specific standards. A boiler control system information at localized company producing ethanol were used to assess the model accuracy, the result showed that the existing SILs were (0.0004, SIL3) (0.001, SIL2) (0.005, SIL2) (0.000007, SIL4) for each node respectively, that did not meet the designated standard

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which are (SIL3, SIL2, SIL1, SIL3 ) for the four nodes respectively. After the improvement by applying redundancy control for the four mentioned nodes, the new SILs were found to be (0.000006, SIL4) (0.0011, SIL3) (0.0004, SIL3) (0.0000007, SIL4) for the four nodes respectively, which agreed with the desired standards. Due to a lack of boiler standard in Sudan this standard is recommended to be adopted by authorized body so as to prevent and reduce accidents, preserve life and economy of the Sudan.

**Key words:** Boiler, SIL, Risk, Fault tree, Model, Safety, Improve.

### 1. Introduction

The danger of life of human beings is increasing with advancement of scientific development in different fields. The importance of industrial safety was realized because every millions of industrial accidents occur which result in either death or injuries. Boiler systems are designed for safety and efficiency. The boiler operator is the key to safe boiler operations. Having knowledge about boiler systems and maintenance can ensure years of safe, reliable service. Studies have shown that without proper operation and maintenance, boiler conditions and safety deteriorate causing potential hazards due to negligence and misunderstanding. Routine maintenance is well within the ability of most boiler operators. Boiler tune up and repairs, however, are best left to trained professionals. Understanding when to turn to qualified professionals for assistance is one of the operator's responsibilities and can save time and money. The Fault tree analysis is quantitative technique used to evaluate the risk and provide the strategies required to improve the system [Daniel,2002].

**Faik Lateef Saleh** [Faik, 2012] Studied boiler reliability in petroleum refinery by using fault tree analysis. The study deals with studying and analyzing the affecting factors on the performance of an old steam boiler operated manually, such as operational parameters deviation and human errors that include operational, maintenance, and test staff, and the influence of those factors in the sustainability of the steam

production and their impact on other boiler components. Engineering safety analysis method (front and back analysis) had been used to study those factors and to find points of failure, and to clarify the relationship between the types of failure and possible events, which facilitate reliability analysis technique. A PC program in visual basic language was designed as a tool to perform periodical evaluation of boiler reliability and its operational systems, draw boiler reliability as a function of time, and the variation of boiler failure rate with time. It is found that the maximum failure rate of the boiler under consideration is (0.000742 failure/year) and it occurs when the operation time reaches about seven months. After that the boiler failure rate will be constant.

**Karthika. S** [Karthika.2013] This project focused on a preventing the accident in boiler by using Hazard and Operability (HAZOP) study and also through work permit system during maintenance operation and periodic inspection, in that hazards will be identified and minimized. Study is carried out by visiting various work process in dairy industry and work permit checklist for each and every individual work is prepared by analyzing the type of work, nature of work, PPE's needed, precaution measure for that work and hazardous present in work through HAZOP study.

According to above mentioned studies there is a lack of guide lines and standards for boiler system design and operation in the Sudan, only NFPA85 and ASME standards, and recommendations that could be applied and all the studies focusing in to determine the level of hazard and risk systems, so you can make recommendations and create a new work instruction because there is no related previous work, this encourages the author to design an engineering standard model to improve boiler safety and reliability.

The total number of boilers in the Khartoum state is (483) distributed in the localities (Bahry, Khartoum, Omdorman, karry, Ombadda,), the total number of the accidents (17) since 2000 till 1 now it accounted for approximate (180) victims include death cases and injuries. For boilers and other combustion systems there is a lack of guidelines and

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standards for design and operation for boilers and other combustion In the Sudan. On the Sudan, only NFPA85 and ASME standards, guidelines and recommendations that could be applied. This encourages the author to design of engineering standard model to improve boiler safety and reliability [supreme council for human development and labor,2019].

## Material and Method

### 2.1 Research methodology

The research methodology framework as shown in the Figure below is used to elaborate step by step details of processes of this research project, which is described in the subsequent sections. The Figure illustrates the designed model procedure using seven steps & FTA techniques to assess the risk of a fire tube boiler as flow, described the process, determined the target SIL for each node, determined the existing SIL for each node and compared it with target SIL if it is acceptable, then the study is complete and the process is operated, otherwise the control system must be improved and the procedure is repeated, this process consequences is applicable for new design or old boiler that need to be evaluated.

Item Quantitative Risk Assessment System (IQRAS) is an approach software program to reliability, safety, and risk analysis Software tools can help to identify the risks and find the major contributors, effective ways to reduce the risks and improve understanding control, this program was used to achieve the goal of this study [Fareham,2017].

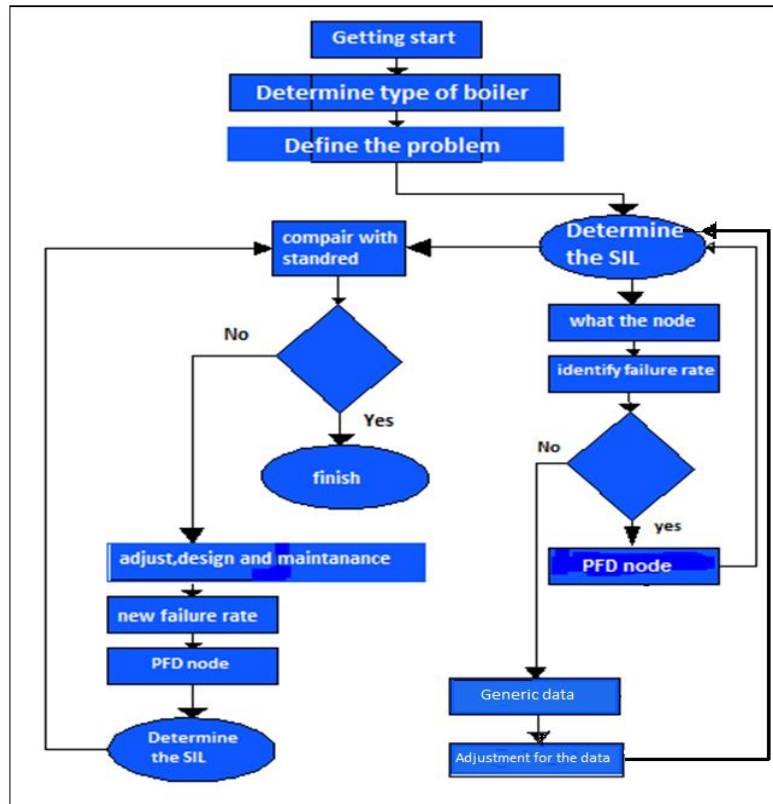


figure (1) Hazards identification and risk assessment procedure

### 1.1 Seven Steps Method

These “worst case scenario” techniques can be simplified in a seven-step method to yield the required Safety Integrity Levels.

### 3.0 Mathematical modeling

**Step 1:** Vapor Cloud Explosion Effect Zone can be calculated as follows

1. Determination of the maximum flammable mass that could be present in combustion chamber
2. Determination of the heat of combustion for the flammable material
3. Calculation of the equivalent weight of Tri Nitro Toluene (TNT) by the following equation:

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$$m_{TNT} = \left[ m_{flammable} \cdot \frac{\Delta H_c}{1155} \cdot Y_f \right]$$

Where:

$m_{TNT}$ : The equivalent weight of TNT, lbs.

$m_{flammable}$ : the flammable mass, lbs

$\Delta H_c$ : The heat of combustion, kcal/kg.

1155: the heat of combustion of TNT

$Y_f$ : The explosive yield factor, which EPA has defined as 10%.

4. Calculation of the radius of the circular impact zone by the following equation:

$$d \text{ (ft)} = m_{TNT}^{1/3} e^{3.5 - 0.7 \ln(OP) + 0.4 \ln OP^2}$$

Where:

d: The distance to a given overpressure, ft.

$O_p$ : The peak overpressure, psi,

5. Calculation of the Vapor Cloud Explosion Effect Zone by the following equation

$$VCE_{effect\ zone} = \pi d^2$$

Where:

$VCE_{effect\ zone}$ : the Vapor Cloud Explosion Effect Zone,  $ft^2$ .

d: the distance to a given overpressure, ft.

**Step 2:** Physical Explosion Effect Zone can be calculated as follows:

1. Determination of the vessel rupture pressure, psia

2. Convert pressure in vessel to equivalent weight of TNT by the following equation:

$$m_{TNT} = \left[ 9.25 \cdot 10^{-5} \cdot P \cdot V \cdot \ln \frac{P}{14.7} \right]$$

Where:

$m_{TNT}$ : The equivalent weight of TNT, lbs.

P: The bursting pressure of the vessel, psia.

V: the volume of the vessel,  $ft^3$ .

3. Calculate the radius of the circular impact zone by the following equation:

$$d \text{ (ft)} = m_{TNT}^{1/3} e^{3.5 - 0.7 \ln(OP) + 0.4 \ln OP^2}$$

Where:

d: the distance to a given overpressure, ft.

$O_p$ : The peak overpressure, psi,

4. Calculation of the Vapor Cloud Explosion Effect Zone by the following equation

$$VCE_{\text{effect zone}} = \pi d^2$$

Where:

$VCE_{\text{effect zone}}$ : the Vapor Cloud Explosion Effect Zone,  $ft^2$ .

d: The distance to a given overpressure, ft.

**step 3:** Pool Fire Effect Zone (for liquid fuels only) can be calculated as follows:

1. Determination of the area of the flammable pool. If the area is confined, use the confinement area. If not calculate the area for a 1-cm deep pool by the following equation

$$A_{\text{POOL}} = \pi d^2$$

Where:

$A_{\text{POOL}}$  : Flammable pool area,  $ft^2$ .

d: the distance to a given overpressure, ft.

2. Calculate the Pool Fire Factor as follows for liquids with boiling points above ambient

Temperature:

$$PFF = H_c \cdot \frac{0.001}{5000 \cdot \pi \cdot (H_v + C_p \cdot (T_b - 298))}$$

Where:

$H_c$  : The heat of combustion,  $\frac{J}{kg^{-1}}$

$H_v$  : The heat of vaporization,  $J/Kg \cdot^{-1}$

$C_p$  : Liquid heat capacity,  $J/Kg^{-1} - oK^{-1}$

$T_b$  : The Boiling Temperature, oK

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3. Calculation of the radius of the circular impact zone by the following equation:

$$d(\text{ft}) = 70.71 \cdot \frac{1}{R \times 1000} \cdot \text{PPF} \cdot A^{-0.5}$$

Where:

d: The distance to endpoint, ft.

R: the radiation intensity endpoint, kW/m<sup>2</sup>, which shall be 12.5 kW/m<sup>2</sup> for calculation of fatalities.

PPF: The Pool Fire Factor.

A: The area of the pool, ft<sup>2</sup>.

4. Calculation of the Pool Fire Effect Zone by the following equation:

$$PF_{effect} = d^2$$

Where:

$PF_{effect}$  : The pool Fire Effect Zone, ft<sup>2</sup>.

d: The distance to a radiation endpoint, ft.

**Step 4:** Personnel Density can be calculated as follows:

1. Utilize the largest of the areas calculated in steps 1- 3 above.

Overlay the effect zone on a General Arrangement Drawing.

2. Calculate the number of Personnel / ft<sup>2</sup> in the effect zone.

3. Calculate the Probable Loss of Life by the following equation

$$PLL = MEZ_{Area} \cdot V \cdot P$$

Where:

MEZ<sub>Area</sub> : Maximum Effect Zone Area, ft<sup>2</sup>.

V: The Vulnerability Factor, where 0.6 is typically used if the effect zone is indoors and 0.3 is typically used if the effect zone is outdoors.

P: The personnel density, people/ft<sup>2</sup>.

PLL: Probable Loss of Life (i.e. number of fatalities in the effect zone).

**Step 5:** The compensation of probabilities of failure rates for each node.

**Step 6:** Determine the Probability of Failure on Demand as follows:

1. Determine the Frequency Target by the following equation:

$$= \frac{F_{individual\ risk}}{pll}$$

Where:

$F_{target}$  : the risk target,  $\frac{\text{failure}}{\text{year}}$

$F_{individual\ risk}$  : individual risk target, failure/year.

$$PFD = \frac{F_{target}}{FA}$$

Where:

PFD: Probability of Failure of Demand.

$FA$  : *failure rates of each node*

**Step 7:** Determine the required Safety Integrity Level as follows:

$$RRF = \frac{1}{PFD}$$

Where:

RRF: Risk Reduction Factor.

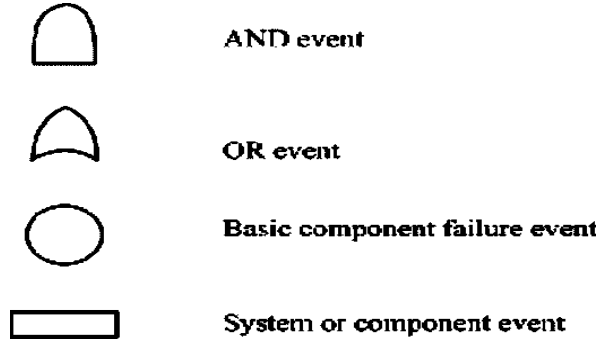
PFD: Probability of Failure of Demand.

SIL: Safety integrity level.

FTA is a logic model that graphically portrays the combinations of failures that can lead to a specific main failure or incident of interest (Top event). This method used Boolean Logic (And & Or logic gates). Assigning statistical values to each end point on a branch allows the calculation of risk. This technique is for identifying and analyzing failure. The factors identified in the tree can be events that are associated with component Fault trees provide a convenient symbolic representation of the combination of events resulting in the occurrence of the top event. Events and gates in fault tree analysis are represented by symbols. Fault trees analyses are generally performed graphically using a logical structure of AND, OR gates. Sometimes certain elements, or basic events, may need to occur together in order for that top event to occur. In this case, these events would be arranged under an AND gate, meaning that all of the basic events would need to occur to trigger the top event. If the basic events alone would trigger the top event, then they would be grouped under an OR gate. The entire system as well as human interactions would be analyzed when

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performing a fault tree analysis as one of the system reliability assessment methods; because it is providing a graphical aid and visibility to those working in the system management far from the system design changes. Also, fault tree analysis allows the analyst to concentrate on one particular system failure at a time. [American society of chemical engineering,2015]



**figure (2) Basic FTA symbols**

### 4. Results and Discussions

**Table (1) Definitions of SILs for Probability of failure**

The Table 4.2 below shows the designed safety integral level of

<b>FR</b>	<b>SIL</b>	<b>SFF</b>	<b>Risk Reduction Factor</b>
$10^{-5}to < 10^{-4}$	SIL 4	> 99 %	100000 to 10000
$10^{-4}to < 10^{-3}$	SIL 3	90 % ... 99 %	10000 to 1000
$10^{-3}to < 10^{-2}$	SIL 2	60 % ... 90 %	1000 to 100
$\geq 10^{-2}to < 10^{-1}$	SIL 1	< 60 %	100 to 10

Table 2 shows the designed safety integral level of control nodes of the boiler which was calculated by the seven-step method.

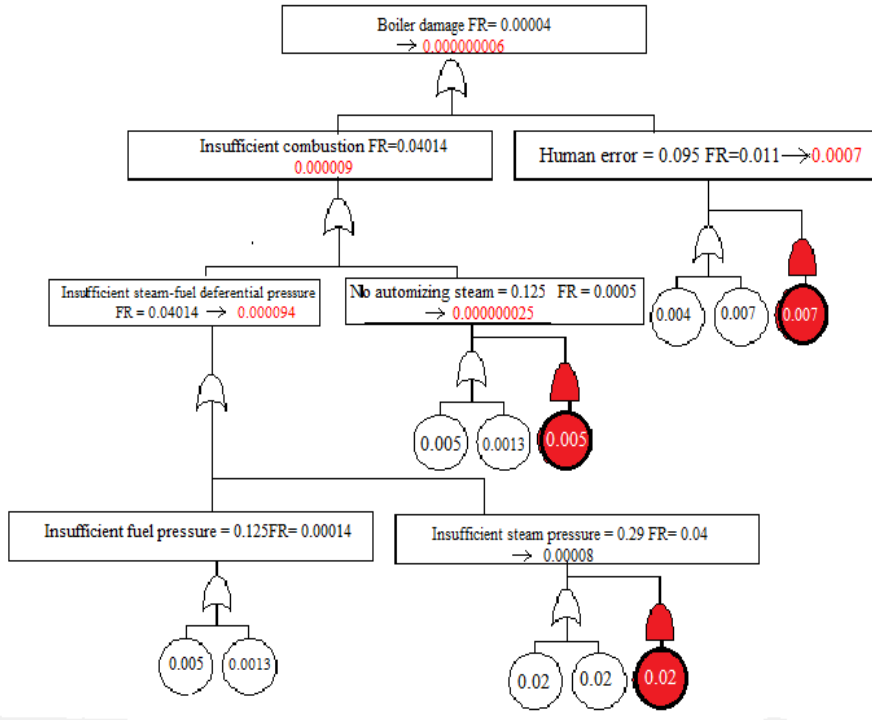
**Table (2) the Designed target safety integral level of each node**

<b>Component nodes</b>	<b>RRF</b>	<b>SFF</b>	<b>PFR</b>	<b>SIL</b>
Insufficient fuel	1375	> 99 %	0.00004	SIL 4
Insufficient combustion	183	90 % ... 99 %	0.0003	SIL 3
Insufficient water level	11	60 % ... 90 %	0.005	SIL 2
Over pressure	7857	> 99 %	0.000007	SIL 4

#### **4.2 Discussions**

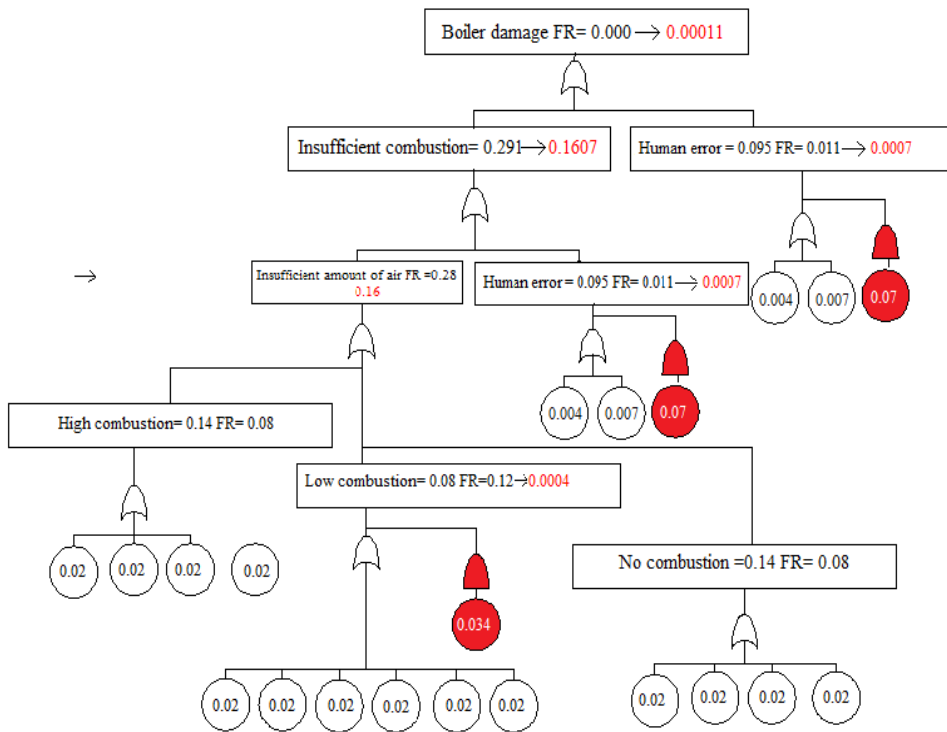
Figures (4),(5),(6),(7) and (8) show the probability of failure rates (PFR) using fault tree analysis for different nodes to determine for each the failure rate of the top event before and after redundancy and voting approaches, for all nodes the FR was reduced so as the catastrophic event failure rates leads to zero, the red color indicated the improvement. Figure (4) shows the first node of the boiler parties which is called insufficient fuel pressure, the probability of FR for the top event was reduced from 0.00004 to 0.000000006 thus the SIL was improved.

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**Figure (4) PFR for node (1)**

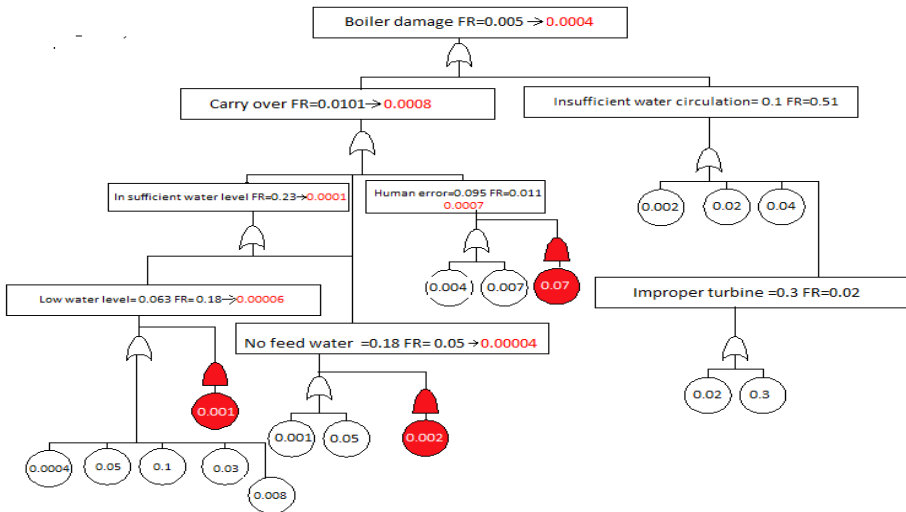
Figure (5) shows the second node of the boiler parties which is denoted insufficient combustion, the probability of FR for the top event was reduced from 0.0003 to 0.00011 thus the SIL was improved.



**Figure (5) PFR for node (2)**

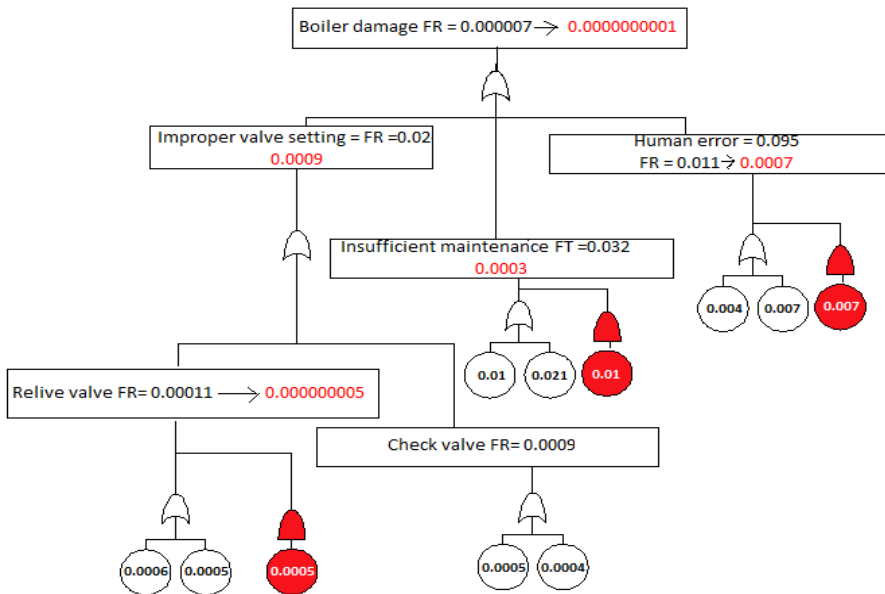
Figure (6) shows the third node of the boiler parties which is named insufficient water level, the probability of FR for the top event was reduced from 0.005 to 0.0004 thus the SIL was improved.

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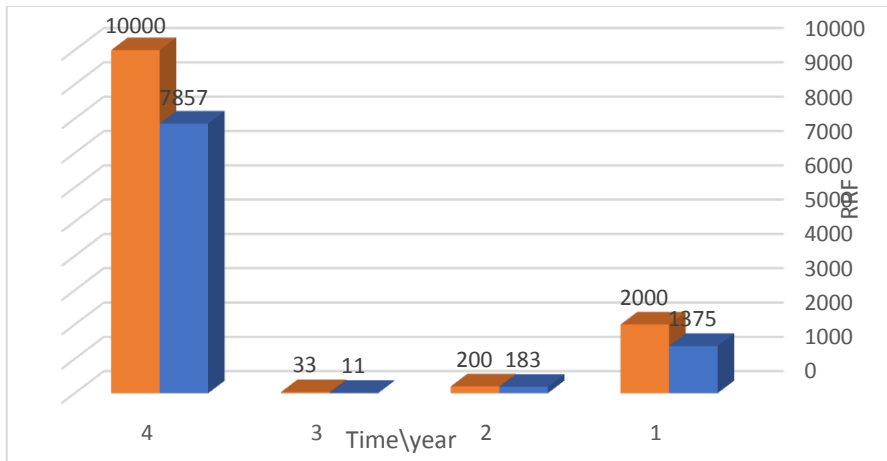
**Figure (6) PFR for node (3)**

Figure (7) shows the fourth node of the boiler parties which is named over pressure, the probability of FR for the top event was reduced from 0.000007 to 0.000000001 thus the SIL was improved.



**Figure (7) PRR for node (4)**

Figure (8) below shows the difference between the values of the RRFs of boiler control system before and after the improvement which explained that the SILs met the target required, using Excel software program.



**Figure (8) Variation of boiler RRF with time**

Redundancy and election approaches were used to improve the existing boiler control system so as to achieve the desired safety integrity level and comply with the specific standard, SILS shown on the table below.

Component nodes	RRF	SFF	FR	SIL
Insufficient fuel	-	> 99 %	0.00000001	-
Insufficient combustion	28	> 99 %	0.00011	SIL 4
Insufficient water level	104	> 99 %	0.0004	SIL 4
Over pressure	-	> 99 %	0.0000000001	-

**Table (4) New safety integral level of nodes**

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### 5. Conclusions and Recommendations

1. This study uses the Fault Tree Analysis as one of the system reliability assessment methods, because it provides a graphical aid and visibility to those working in the system management far from the system design changes. Fault tree analysis allows also the analyst to concentrate on one particular system failure at a time.
2. The boiler system classified to four basic nodes, the failure of any of them can lead to catastrophic event, and these nodes were named as follows: insufficient fuel pressure, insufficient combustion, insufficient water level and over pressure.
3. Seven steps method, which are suggested by environmental protection agency (EPA), was used to identify the required safety integrity level (SIL) for each node control system, the boiler control system was classified to four levels (SIL1, SIL2, SIL3, SIL4). Redundancy and voting approaches were used to improve the existing boiler control system so as to achieve the desired safety integrity level and comply with the specific standard.
4. The result show that the existing SILs were (0.0004, SIL3) (0.001, SIL2) (0.005, SIL2) (0.000007, SIL4) for each node, which do not meet the designated standard (SIL3, SIL2, SIL1, and SIL3) for the four nodes.
5. After the improvement by applying redundancy control for insufficient fuel pressure and insufficient combustion nodes and voting control for insufficient water level and over pressure nodes the new SILs were found to be (0.000006, SIL4) (0.0011, SIL3) (0.0004, SIL3) (0.0000007, SIL4) for the four nodes and these met the desired standards.

#### 5.1 Recommendations

1. Due to a lack of boiler standard in Sudan this standard is recommended to be adopted, by the authorized body, so as to prevent and reduce the accidents, preserve people life's and protect the economy of the Sudan.
2. It is recommended to calculate the estimated cost of improvement.
3. An occupational safety and health officer must be knowledgeable enough about the design improvement and the safety integrity level to providing with equipment before purchasing of them.

## Reference

- [1] **Daniel A. Crowl**, “understanding explosion” American Institute of Chemical Engineers Avenue New York, New York10016-5991, pp (1-5) (62),2002.
- [2] **supreme council for human development and labor**, occupational health and safety administration, boiler department, Khartoum state,2019.
- [3] **American society of chemical engineering**, “Boiler and pressure vessel code (PBVC) section IV rules of construction of heating boilers”, ASME PBVC, section IV, New York NY. (p. 27-34) April 2015.
- [4] **Faik Lateef Saleh**, “studying boiler reliability in petroleum refinery by using fault tree analysis” Vol. 25, No. 3 January 2012.
- [5] **Karthika**. “Accident prevention by using HAZOP study and work permit system in boiler”, International Journal of Advanced Engineering Research and Studies, INDIA. June, 2013.
- [6] **Fareham, Hampshire** “Software (USA)” Email: [sales@itemsoft.com](mailto:sales@itemsoft.com), 2017.