Identify the Prevention Barrier in the Steam Boiler Incident Causation Process

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Abstract—**Promising accident modelling is becoming challenging with the growing complexity of the risky process activity. The objectives of this research are to identify the safety prevention barriers in the boiler incident causation process and to assess the plausible hazards and root causes of the boiler accident in the processing industry. The data of the boiler incident are collected through the Past Accident Analysis (PAA) to determine the accident contributors and sub accident contributors. The Fault Tree Analysis (FTA) is used to calculate the failure probability of the proposed prevention barriers based on dependency of the accident contributors and sub accident contributors. The Event Tree Analysis (ETA) is applicable to predict the consequence from the causes of the accident contributors and also to calculate the successful of the proposed prevention barriers. As conclusion, the combination of the FTA and ETA are providing an overall illustration of boiler incident process. In this study, the prevention barriers in the steam boiler incident are determined.**

Keywords—steam boiler incident, explosion, prevention barrier, Fault Tree Analysis (FTA), Event Tree Analysis (ETA)

I. INTRODUCTION

Nowadays, boiler accidents have shown an increasing trend despite numerous improvement have been taken to the boiler system. This issue could have been prevented if the root causes of the boiler accidents can be identified and the consequence of the root causes can be avoided with specific prevention barrier. According to (Freudenburg, 2010), the accident investigation is conducted in order to identify the main accident contributions to avoid their constraints. To determine how and why an accident occurred can be identified, (Manatakis, 2009) state by using an appropriate accident analysis technique. Hence, accident analysis is useful to find the root causes of an accident and also their relationship to the unsafe condition.

Boiler accident is an occurrence that should not be taken for granted especially when the incidents involving injuries and death. There are less research paper discussing on the boiler accident patterns and inventory of boiler past accident analysis. There are very limited scopes of conducting such experiments in the domain of accident prevention on boiler accident.

In this research, the external factors are not considered. The accident contributors that cause boiler incidents logically are set to different safety prevention barriers along the roadway to supervision the consequences of process accidents. FTA and ETA are selected to determine the dependence of accident contributors and sub accident contributors in every prevention barrier. There are four proposed prevention barriers in the steam boiler incident process: The design error prevention barrier, the management error prevention barrier, the human error prevention barrier and the equipment error prevention barrier. However, the prevention barrier will be validated and proposed to a particular incident based on the case study. All these procedures will be done carefully to achieve the main objectives of the research

II. METHODOLOGY

A. Data collection on boiler accident

To benchmark the result of this study, the selection of datasets is very important. So the actual problem in the industrial has been chosen and the collected info is randomly to avoid any bias towards data collection. However, only incident reports with details on accident causes and reliable information were included in this study while fewer details were eliminated.

The boiler accident in this study was collected from few sources (ARIA) (United State Department of Labor) (Minnesota Department of Labor and Industry) (Failure Knowledge Database) (Labour Department) (State of Tennessee Department of Labor and Workforce Development, Division of Boiler and Elevator Inspection, 2007) starting from year 1977 till 2017 which contains 50 incidents and been summarized indicating year, location, type of accident, type of industry, accident contributor factor, sub-accident contributor factor, fatalities, injuries or hospitalized and source of the incident data.

For any set of random samples to be representative of the population being sampled, the sample size should be 40 or above (Abdolhamidzadeh, Abbasi, Rachtchian, & Abbasi, 2010). The 50 incidents in this study already greater than the sample size threshold, hence it can be deemed representative. The sources of data can be referred as in references section.

These data will be analyzed into specific tables and the result from the analysis will be used to develop the boiler incident model. The tables were categorized according to incident cases and casualties by type of incident, type of industry by accident cases and casualties, incident type by industry, contributory factors by industry and contributory factors by type of incident.

B. Construct a fault tree to represent the dependency of accident contributors and sub-contributor factors and calculate the failure probability of each prevention barriers.

Sometimes the prevention barriers can fail due to the complexity interaction of many causes. The dependence of accident contributions and sub accident contributors in every prevention barrier is presented by the fault tree. The failure probability of each prevention barrier in the steam boiler incident is calculated using the fault tree.

To construct the fault tree, the accident contributors and sub accident contributors was identify from the Past Accident Analysis (PAA) in order to recognize the pattern. A startup event that is a potential accident occurs only if an event allows something to happen or has occurred.

C. Develop the event tree to identify the suitable prevention barrier

According to (Nyvlt & Rausand, 2012), event tree analysis is a preliminary procedure that is generally used in the industrial accident processes to present prevention barriers and the development of start-up events for many possible consequences.

The proposed prevention barriers in this event tree are presented by two different branches, one representing success and another representing the certain barrier. The end state consequences will be identified at the end of the event tree model.

D. Develop a model that combining the fault tree and event tree analysis

Accident prediction based on the available data about the events is the most important aspect in order to construct a new model. FTA and ETA analysis are combined to develop the predictive model.

E. Model verification

Verification is a series of action taken to decide whether the model is a significant and precise likeness of the actual system. The incident model will be validated by using a case of Salem Harbor Generating Station boiler incident. The data that obtained from the Past Accident Analysis (PAA) will compared with the data from the case study.

F. Recommending the suitable prevention barrier

The case study of Salem Harbor Generating Station is about fire steam boiler explosion. Accidental factors contributing systematically are organized within four preventive barriers along the path of the accident to avoid the consequences of accidents. However, in this research, the prevention barrier will be validated based on characteristics of the case study.

III. RESULTS AND DISCUSSION

A. Incident classification

A total of 50 incidents cases were collected worldwide from year 1977 until 2017 using the Past Accident Analysis (PAA). In this research, 58 of accident contribution are identified through the study of Past Accident Analysis (PAA). Of these, 9 contribution were human error (15.52%), 9 contribution were equipment error (15.52%), 13 contribution error were design error (22.41%) and 27 contribution were management error (46.55%). Figure 4.1 shows management error was the highest accident contributor in the boiler incident followed by design error.

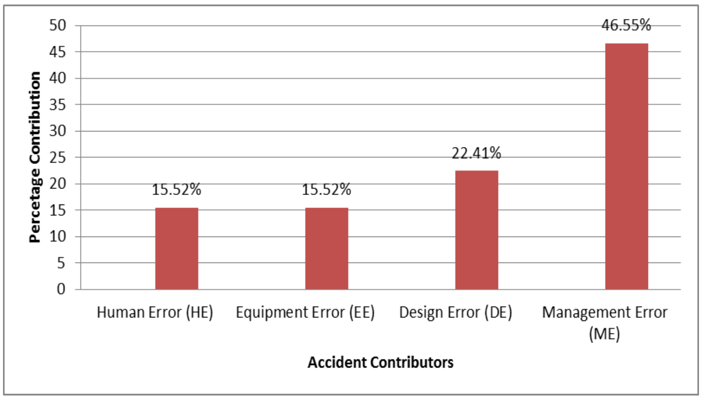


Figure 4.1: The percentage of accident contributors in boiler incident

For further analysis, this study also identifies the sub-accident contributor for the boiler incident in order to know the dependency of accident contributor and sub-accident contributor. From the Past Accident Analysis (PAA), the sub-accident contributor is identified. Figure 4.2 shows the main sub-accident contribution in the boiler incident is management error with 90.57% of contribution which is quiet high compared with other sub-accidents. The causes of management error are improper working scheduling, inadequate training and also lack of sources which results in management failure. The failure of management error can influence the human error because both parameters are dependence to each other. For an example, without a proper management procedure, the human are tendency to do some error.

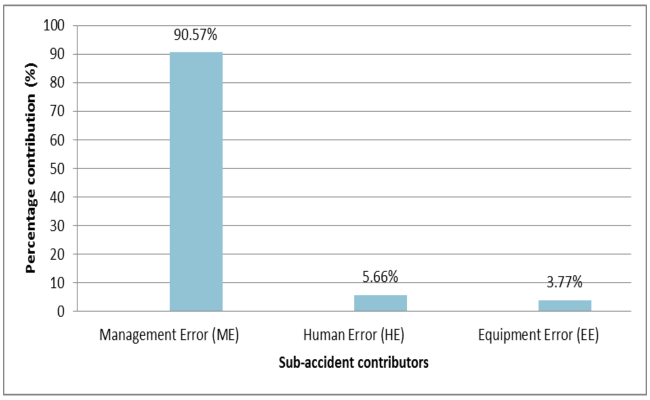


Figure 4.2: The percentage of sub-accident contributors

Meanwhile, Figure 4.3 shows the type of incident. It shows that explosion was the most often cases occur for boiler accidents which is 27 cases followed by rupture incident with 12 cases meanwhile other types of incident shows less number of cases in the boiler incident.

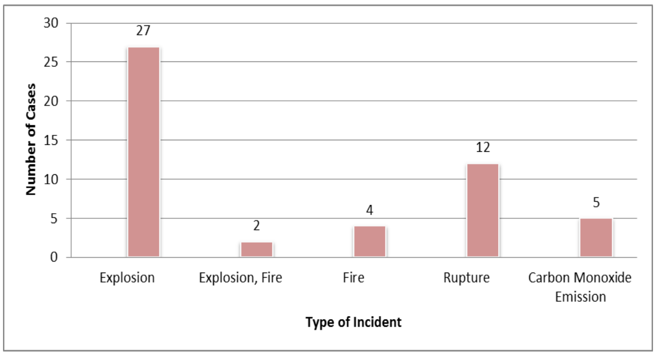


Figure 4.3: The number of cases based on different type of incident

Even the explosion stand alone as an accident event, it contributes more incident cases with 25 number of death and 114 injuries or hospitalized. Table 4.1 shows the summary of the 50 incidents indicating fatalities, injuries or hospitalized.

Table 4.1: Type of incident by severity

Type of Incident	Death	Injuries/ Hospitalized
Explosion	25	114
Explosion, fire	0	9
Fire	0	1
Rupture	7	9
Carbon monoxide release	0	6

Figure 4.4 shows the severity of the incidents. From the obtained data, it can be seen that majority of the victims are most likely to get injured during those incidents. Out of 50 cases collected, 81.27% of the victims were severely injured while the remaining 18.71% were found to be dead. This means that boiler failure incidents have severe impacts on the safety and health field.

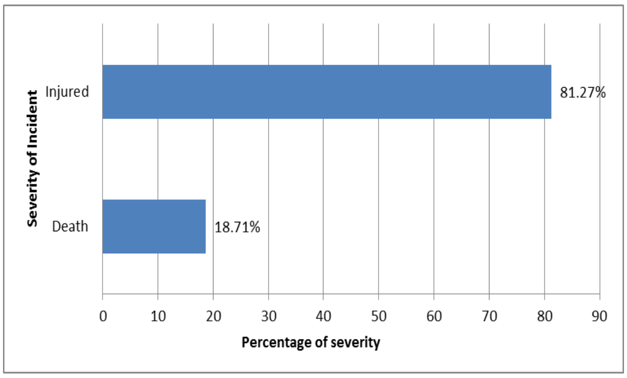


Figure 4.4: The severity of incident

Figure 4.5 shows the result of a Past Accident Analysis (PAA) in which the contributor and sub contributor are independence or interdependence to each other. Among the 50 cases, only 10 cases show the contributor and sub-contributor are interdependency to each other meanwhile another 40 cases are dependency. From the figure it is clear that majority the parameters are dependency to each other with sixty per cent difference between the two.

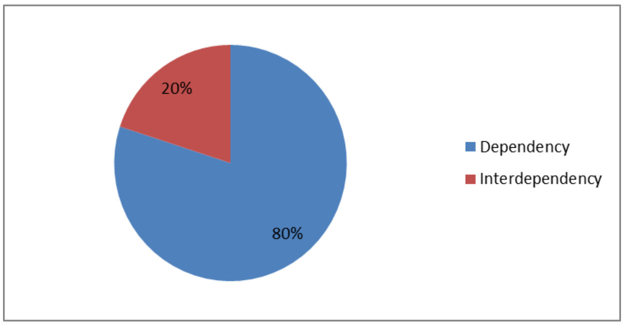


Figure 4.5: Dependency and interdependency between Contributory and Sub-contributory Factor

B. Fault Tree (FT) model calculation

For the calculation, Figure 4.6 shows computations of the failure rate, reliability and probability for the Management Error Prevention Barrier (MEPB), Design Error Prevention Barrier (DEPB), Human Error Prevention Barrier(HEPB) and Equipment Error Prevention Barrier(EEPB) based on different logic gate in the fault tree calculation.

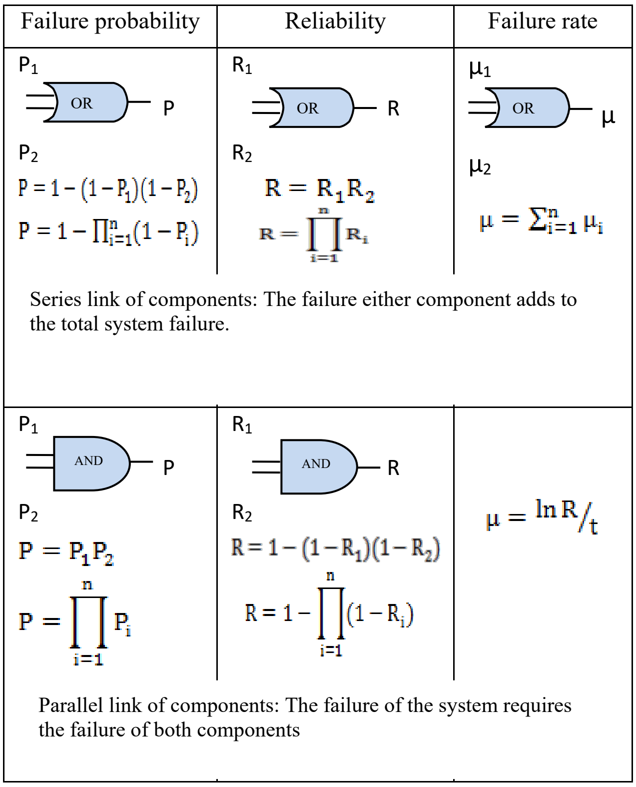


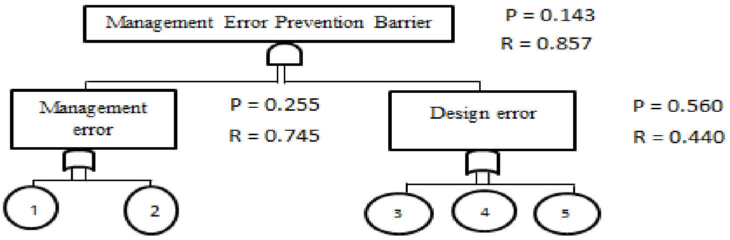
Figure 4.6 Computations for various types of component linkages

Table 4.2 shows the highest failure probability is management error prevention barrier with 0.143 followed by design error prevention barrier, human error prevention barrier and equipment error prevention barrier with 0.124, 0.042 and 0.008 respectively. The sequence of the prevention barrier in the event tree is based on failure probablility. The failure rate, reliability and probability for each prevention barries are calculated and display in the Figure 4.7 (a) (b) (c) (d). It illustrated the relationship the accident contributor and sub-accident that lead to the boiler incident in the Fault Tree diagram.

From the figures, the top event is the accident contributor connected with the sub accident contributor by 'and' gate. Each of the accident contributors are dependence to its sub accident. Its means the error of accident contributors occurred if there is an error in sub accident contributors.

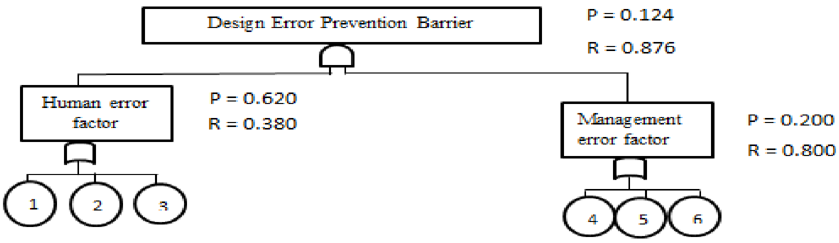
Table 4.2: Failure probability of prevention barriers from fault tree calculations

Prevention barrier	Failure rate μ (Faults/yr.)	Reliability $R = e^{-\mu t}$	Failure probability $P = 1 - R$
MEPB	0.15	0.857	0.143
DEPB	0.13	0.876	0.124
HEPB	0.04	0.958	0.042
EEPB	0.01	0.992	0.008



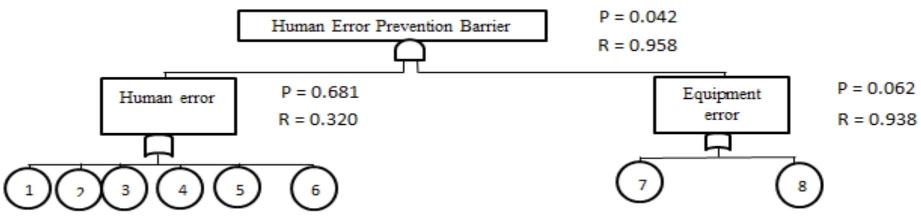
Event	Event description	Assigned probability
1	Improper boiler washing practices	0.005
2	Lack of inspection	0.25
3	Poor refractory design	0.22
4	Incorrect level control	0.12
5	Fuel supply valve inoperative	0.22

Figure 4.7 (a) Fault Tree (FT) for management error and its sub accident error within the prevention barrier



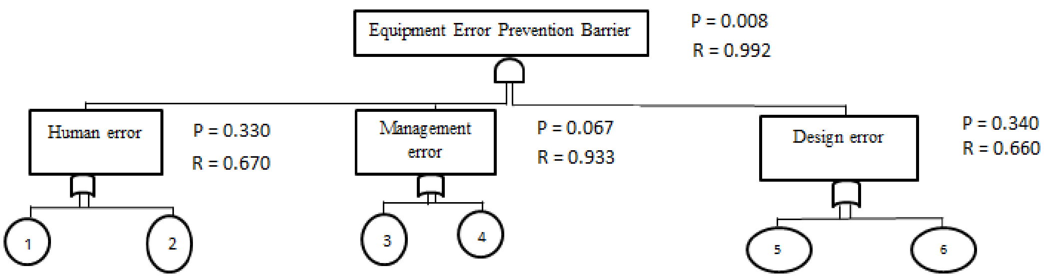
Event	Event description	Assigned probability
1	Feed water operator fail to recover	0.39
2	Feed water operator fail to detect	0.22
3	Improper maintenance	0.06
4	Inexperience	0.01
5	Improper feed water supply	0.03
6	Improper blow down	0.11

Figure 4.7 (b) Fault Tree (FT) for design error and its sub accident error within the prevention barrier



Event	Event description	Assigned probability
1	Firing system operator fail to detect	0.25
2	Improper manual control valve setting	0.36
3	Improper trainer worker	0.01
4	Power failure	0.01
5	Improper labelling	0.0005
6	Operating condition not specified	0.05
7	Blow down valve fail to close	0.031
8	Break down of blow down pipe	0.031

Figure 4.7 (c) Fault Tree (FT) for human error and its sub accident error within the prevention barrier



Event	Event description	Assigned probability
1	Inexperience	0.01
2	Improper manual control valve setting	0.32
3	Improper boiler washing practices	0.005
4	Improper manual control valve setting	0.062
5	Poor refractory design	0.22
6	Steam valve fails to open	0.12

Figure 4.7 (d) Fault Tree (FT) for equipment error and its sub accident error within the prevention barrier

C. Logic sequence of prevention barrier using Event Tree (ET)

To calculate the success of each prevention barriers and predict the consequences in the boiler incident, event tree analysis is used. Figure 4.8 shows the event tree diagram of boiler incident with the proposed prevention barriers. The failure rates for the prevention barrier are written below the column headings. The qualitative descriptions of consequences related to the failure of each prevention barrier in the accident chain are safe, near miss, mishap and accident.

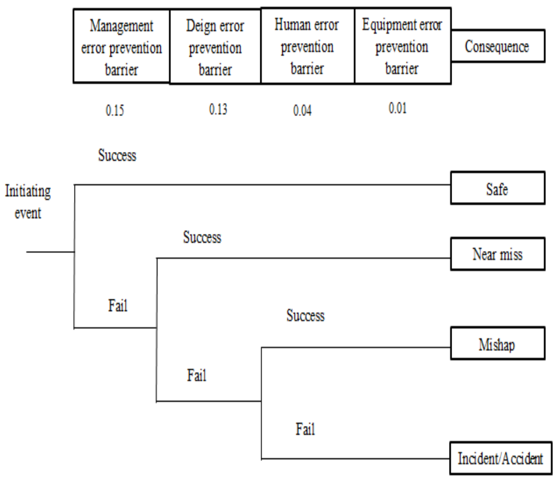


Figure 4.8: Event Tree diagram for boiler incident

D. Model development

Figure 4.9 shows the combination of the Fault Tree and Event Tree diagram to develop a model. Fault tree (FT) on the left hand side to feature all feasible accident contributors and sub accident contributors leading to an initiating event and event tree (ET) on the right hand side represents all possible accident consequences resulted from the initiating event within the failure of the prevention barrier. The combination of both diagrams is the best graphical approaches to model an accident scenario or process, starting with the causes and ending to the consequences of the accident scenario. Through the developed model, it show a clear representation of the relationship among accident contributors and sub accident contributors leading to an initiating event and how the failure of prevention barriers build up the initiating event to accident consequences.

For this model assume that management error occurs once a year. The failure rates for the prevention barriers are obtained from the previous fault tree calculation. This event tree analysis shows that an incident/accident will occur on average 0.00078 time per year. The case study will be used to validate the model developed in this research.

E. Model validation

Case study: Salem, Massachusetts

In this part, the Salem Harbor Generating Station boiler incident in the U.S is studied using the developed model. Table 4.3 shows the failure rate, reliability and failure probabilities of each component. The components are the accident contribution to the Salem Harbor boiler incident.

Table 4.3: The incident data

Component	Failure rate μ (Faults/yr.)	Reliability $R = e^{-\mu t}$	Failure probability $P = 1 - R$
Lack of inspection and poor maintenance	0.37	0.69	0.31
Poor refractory design	0.25	0.78	0.22
Inexperience operator	0.01	0.99	0.01
Tube overpressure	0.13	0.88	0.12

Equation 1 is used to calculate the overall reliability of the incident components. The components are connected with OR gate.

$$R = \prod_{i=1}^{4} R_i \qquad \text{(Equation 1)}$$

R= (0.69) (0.78) (0.99) (0.88) = 0.47

The failure probability is computed from:

P = 1 - R = 1 - 0.47 = 0.53/yr. (Equation 2)

The overall failure rate is computed using Equation $R = e^{-\mu t}$:

$$0.47 = e^{-\mu}$$

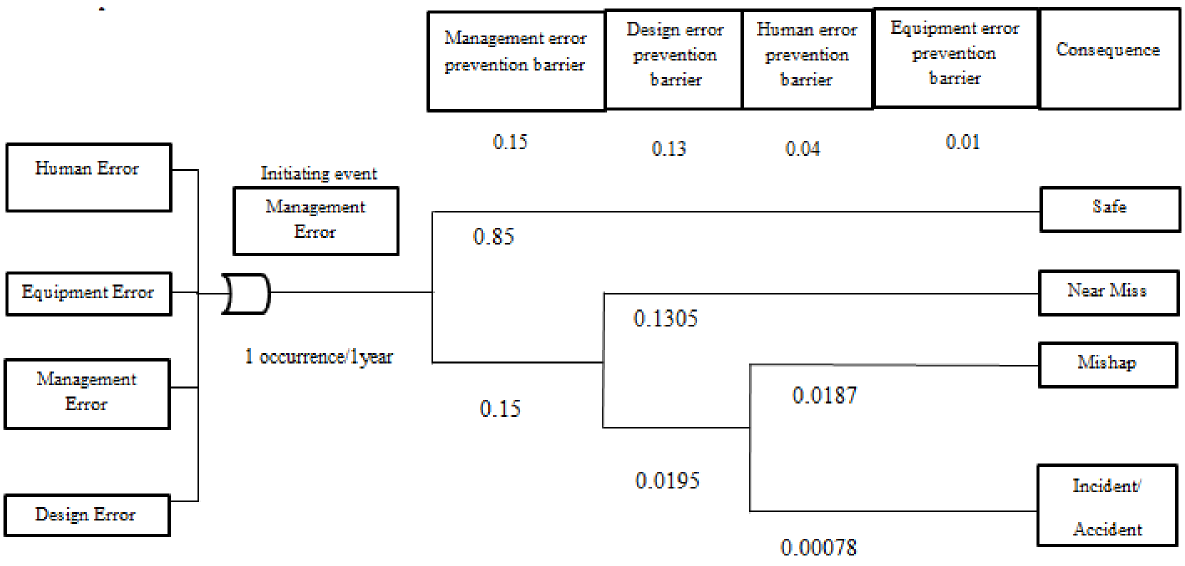
$$\mu = -\ln(0.47) = 0.76 \text{ Failures / yr.}$$

The Mean Time Between Failure (MTBF) is computed using:

$$\text{MTBF} = \frac{1}{\mu} = \frac{1}{0.76} = 1.32 \text{ yr.} \sim 1 \text{ year}$$

This system is expected to fail once every 1 yr.

Figure 4.10 shows the overall accident process in Salem Harbor Generating Station plants. The event tree can be used quantitatively if data are available on the failure rates of the prevention barrier and the occurrence rate of the initiation event. For Salem Harbor, assume that a poor boiler inspection and maintenance practices event occurs once a year. The failure rates for the prevention barrier are written below the column headings. The occurrence frequency for the initiating event is written below the line originating from the initiating event. This event tree analysis shows that an explosive rupture will occur on average 0.00078 time per year. This is considered low for this installation of the prevention barriers and same with the value calculated from the model development calculation.

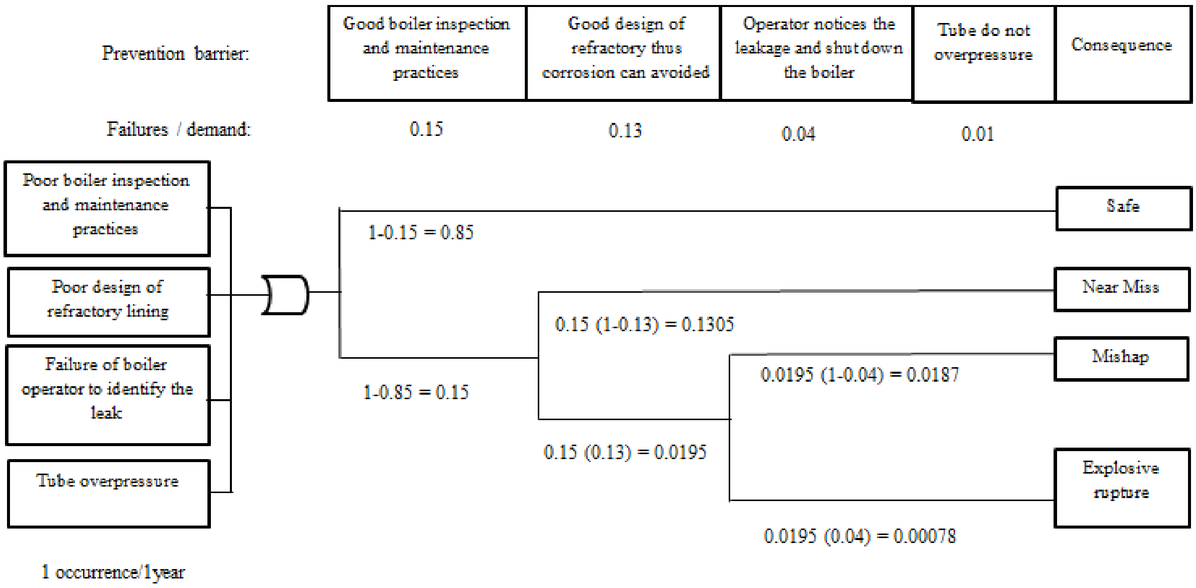


Near miss = 0.1305 occurrences/ yr.

Mishap = 0.0187 occurrences/ yr.

Incident/Accident = 0.00078 occurrences/ yr.

Figure 4.9: The combination of Fault Tree-Event Tree model



Near miss = 0.1305 occurrences /yr.

Explosive rupture = 0.00078 occurrences /yr. The value obtained is same with the previous calculation. The model is valid

Figure 4.10: The overall accident process of Salem Harbor Generating Station boiler incident

F. The suitable prevention barriers in the boiler incident

Based on the case study, the proposed prevention barriers in the steam boiler accident causation process are management error prevention barrier, design error prevention barrier, human error prevention barrier and equipment error prevention barrier. The effectiveness of the developed model which is show the causes-consequence relationship based on process accident was validated through the application of the model to the Massachusetts power plant accident. The case is valid with the developed model. The application of the model to the case study is to predict accident occurrence and help to take early actions to prevent process accidents.

IV. CONCLUSION

This study proposed a procedure process accident model which focused on dependency of accident contributors and sub accident contributors factors that lead to the failure of a specific prevention barrier in the boiler incident. Based on the study of Past Accident Analysis (PAA), management error showed a highest percentage contribution which is 46.55%, followed by design error, human error and equipment error with 22.41%, 15.52% and 15.52% respectively. Hence, four preventions barriers are characterized to forestall process accident before they expanded into catastrophic events.

The Fault Tree (FT) is able to calculate a failure probability of prevention safety barriers based on the dependency of accident contributors and sub accident contributors. The failure probabilities of MEPB, DEPB, and HEPB are 0.143, 0.124, 0.042, and 0.008 respectively.

The predicted consequence of the accidents in the construction of the Event Tree (ET) is based on the failure rate of the prevention barriers which are 0.15, 0.13, 0.04 and 0.01. The model helped to take early actions to avoid process accident and improved the safety management plan. The Fault Tree (FT) and Event Tree (ET) alone are limited to give an overall view on the boiler incident.

The proposed prevention barrier was successful calculated which is 0.85. The result obtained was compared with the previous study from Salem Harbor Generation Station and its shows a good agreement. Thus, the effectiveness of the proposed model was mostly approved through the application of the model to the previous study.

The significant study of this research is to developed Fault Tree (FT) and Event Tree (ET) model of the case study and also to developed combination of Fault Tree (FT) and Event Tree (ET) to give clearly illustration on boiler accident causation process. In future study, the data of the boiler incidents need to increase to 100 cases or more thus the result can be more accurate. To increase the reliability data, the study should include a boiler expertise judgement.

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