STUDYING BOILER RELIABILITY IN A PETROLEUM REFINERY BY USING FAULT TREE ANALYSIS [+]

دراسة معولية مرجل حراري في مصفى نفطي بأستعمال تحليل شجرة الأخطاء

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Abstract:

The paper deals with studying and analyzing of 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) and it occurs when the operation time reaches about seven months. After that the boiler failure rate will be constant.

Key words: Reliability, Probability, Fault tree, Failure Rate, Boiler.

المستخلص:

يهتم هذا البحث بدراسة وتحليل العوامل المؤثرة على أداء مرجل بخاري قديم يشغل يدوياً في مصفى نفطي مثل انحراف المتغيرات التشغيلية والأخطاء البشرية والتي تشمل أخطاء ملاكات التشغيل والصيانة والفحص، وبيان مدى تأثير تلك العوامل في ديمومة انتاج البخار وتأثيرها على اجزاء المرجل الأخرى.

تم استخدام أسلوب تحليل السلامة الهندسي(التحليل الأمامي والتحليل الخلفي) لدراسة تلك العوامل وايجاد مكامن الفشل، وتوضيح العلاقة بين انواع الفشل والأحداث الممكنة والتي تسهل تقنية تحليل المعولية.

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تم اعداد برنامج على الحاسوب بلغة فيجيوال بيسك، حيث يقوم هذا البرنامج بحساب مقدار المعولية للمرجل البخاري وأنظمته التشغيلية لمختلف الأزمنة وكذلك رسم منحني الدالة لمعولية المرجل، ورسم منحني التغير الحاصل بمعــدل الفشل للمرجل البخاري.

تبين أن أقصى قيمة لمعدل الفشل للمرجل قيد الدراسة هي (٠,٠٠٠٧٤٢) وتكون عندما تصل مدة التشغيل إلى سبعة أشهر. بعد تلك الفترة يكون معدل فشل للمرجل ثابتاً.

Introduction:

Boilers are important equipments in chemical and refinery industries. They are normally operated for an extended period of time that leading to boiler components damage because of aging, corrosion, and abnormal operation condition [1], [2]. The present work concerned with studying and analyzing of the old water tube boiler double identical drums which was built in 1968 at "*Midland Refineries Company*". Its output with is (70) ton/hour of super heated steam, the operation and control of the boiler is manual. There are multitude of failures that are caused by boiler operator's errors, boiler inspector, boiler maintainer and faults of boiler auxiliary equipments which lead to operation parameters deviations and boiler shut down.

Boiler is divided into three main components, furnace tubes, super heater tubes, and bank tubes. The stability of boiler operation is affected by the stability of its operational system (combustion system, air combustion system, feed water system, blow down system, and soot blowing system). In this work maintenance and inspection activities are considered as an additional boiler system due to its great effect on boiler reliability. There is some studies related to this study as illustrated below:

A. Raouf & A. Maged [3] showed a model to quantify reliability of human performance in man-machine system, a markovian model for estimating the number of cycles that are worker performs without committing an error. Method of collecting data, subsequent analysis, and various types of errors made by workers has been described.

R.Billinton [4] illustrated a relatively direct and sequential method of performing reliability calculations in transmission and distribution systems. The equations provided in the paper are utilized through a minimal cut-sets approach to failure modes and effect analysis, and can be used in a wide range of systems. The utilized procedures in formulating the equations for reliability quantification are similar as those that have been followed in the thesis.

Ali A. A. [5] presented a study focused on the use of a new proposed method, it is an attempt to clarify the concepts of Fault Tree and using Minimal Cut Sets (MCSs) in conjunction with Markov Modeling of binary systems. That method merges between static analysis (Fault Tree) and dynamic analysis (Markov Process).

Reliability:

Reliability is a broad term that focuses on the ability of a product to perform its intended function. Mathematically speaking, assuming that an item is performing its intended function at time equals zero, reliability can be defined as the probability that an item will continue to perform its intended function without failure for a specified period of time under stated conditions. The products could be electronic or mechanical hardware products, software products, a manufacturing process, or even services [6].

The primary problem addressed in reliability field is the selection and specification of the most appropriate reliability models. This requires the collection and analysis of failure and repair data. The derivation of the models is an application of probability theory, whereas the collection and analysis of failure and repair rates are primarily an application of descriptive and inferential statistics [7], [8].

Table (1): Symbols and its descriptions

Symbol	Description
E	Probability
FDF	Forced draft fan
FTA	Fault tree analysis
PC	Personal computer
R	Reliability
RBD	Reliability block diagram
MCS_s	Minimal cut sets
MTBF	Mean time between failure
MTTF	Mean time to failure
No	Number of failure reoccurrence in specified time
T	Period of specified time
T	Desired period of time
λ	Failure rate

System Reliability Modeling:

1- Series System: A series system (in the reliability sense) is composed of *n* elements, the failure of any of which will cause system failure, and the system reliability is [6], [9]:

$$R_{sys} = R_1 \times R_2 \times \ldots\ldots \times R_n = \prod_{i=1}^{n} R_i = \prod_{i=1}^{n} e^{-\lambda_i t} = e^{-t\sum_{i=1}^{n} \lambda_i} \quad \ldots\ldots\ldots\ldots (1)$$

$$\therefore \lambda_{sys} = \sum_{i=1}^{n} \lambda_i \quad \ldots\ldots\ldots\ldots (2)$$

$$MTBF_{sys} = \frac{1}{\sum_{i=1}^{n} \lambda_i} \quad \ldots\ldots\ldots\ldots (3)$$

2- Parallel system: A parallel system (in the reliability sense) is composed of *n* elements that perform identical functions, the success of any of which will lead to system success. In other words, all the components must fail in order to have a system failure, the system reliability is [6], [9]:

$$R_{sys} = 1-(1-R_1)(1-R_2)......(1-R_n) = 1-\prod_{i=1}^{n}(1-e^{-\lambda_i t}) \quad .... (4)$$

Although the system components have a constant failure, but the system failure rate is variable value [10], [5].

$$\lambda_{sys} = \text{var } iable = \frac{-dR_{sys}(t)}{R_{sys}(t)dt} \quad .... (5)$$

Failure Rate: is the total number of failures within an item population, divided by the total time expended by that population, during a particular measurement interval under stated conditions [11].

Failure rate data can be obtained in several ways. The most common means are:

1- Historical data about the device or system under consideration.
2- Government and commercial failure rate data.
3- Testing.

Mean-Time-Between-Failures (MTBF): A common use of the failure rate is to determine the mean-time-between-failure (MTBF), which may be thought of as the "average" time between failures. (This assumes that the system is "renewed", i.e. fixed, after each failure, and then returned to service immediately after failure) [7, 12]. MTBF is the expected time between two successive failures of a system. Therefore, MTBF is a key reliability metric for systems that can be repaired or restored

While MTBF is one of the most widely used metrics in reliability engineering, it is also one that causes a great deal of confusion. By going through the theoretical definitions and alternative uses for MTBF, the reasons for this confusion become apparent [13, 14].

Fault Tree:

A fault tree analysis (FTA) is a deductive, top-down method of analyzing system design and performance. It involves specifying a top event to analyze (such as a fire), followed by identifying all of the associated elements in the system that could cause that top event to occur. 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 tree analyses are generally performed graphically using a logical structure of AND 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 performing a fault tree analysis [15], [16].

If the fault tree is not solved for the minimal cut sets, then the probability of the top event can be calculated by hand, provided that the size and complexity of the tree are not too large. This is done proceeding in an orderly fashion from the bottom to the top of the tree and computing at each gate the probability of the output from the probabilities of the input events, using the laws of probability corresponding to that gate structure (AND, OR) [17].

Qualitative Analysis: A fault tree can be described by a set of Boolean algebraic equations, one for each gate of the tree. For each gate, the input events are the independent variables and the output event is the dependent variable. Utilizing the rules for Boolean algebra it is then possible to solve these equations so that the top event is expressed in terms of sets which involve only the primary events which is called "minimal cut set". (A minimal cut set is a set of events, which cannot be reduced in number, whose occurrence causes the top event) [15].

Quantitative Analysis: Quantitative analysis of the fault tree consists of transforming its logical structure into an equivalent probability form and numerically calculating the probability of occurrence of the top event from the probabilities of occurrence of the basic events [17]. The probability of the basic event is the failure probability of the component or subsystem during the mission time of interest [15].

Table (2): Meaning of initiated events symbols

Symbol	MEANING	Symbol	MEANING
Fp1	Incorrect manual valve setting.	NW1	Feed water source fails to supply water.
Fp2	Fuel Supply line valves inoperative or not fully open.	NW2	Break down of feed water line.
Sp1	Supply line valves inoperative or not fully open.	LWC1	Tube leak
Sp2	Improper manual control valve setting.	LWC2	Improper blow down
Sp3	Low supply pressure.	LWC3	Riser or down comer tube are partially blockage due to improper turbining
Ft1	Faulty and/or fouled heater element	SB1	Leaking soot blower
Ft2	Oil temperature control setting too low.	SB2	Improper maintenance of soot blower.
Ft3	Heater electric power off.	SB3	Human errors during performing soot blowing
St1	Steam wet from source.	BD1	Human errors.
St2	Steam line not insulated.	BD2	Blow down valve fails to close.
St3	Steam traps not working.	BD3	Break down of blow down pipe.
Ns1	Supply line valves fails to open	HFS1	Stack damper fails to open.
Ns2	Supply pipe lines break down.	HFS2	Blockage of bank tube passes
La1	Insufficient boiler room air openings.	HFS3	High speed of forced draft fan (FDF).
La2	Dirty combustion air blower.	LFSI	Improper position of stack damper.
La3	Combustion air blower running too slow or slipping.	LFS2	Low speed of FDF.
La4	Incorrect fuel/air ratios adjustment.	LFS3	Escaping flue gases due to destroyed insulation and metal case.
La5	Blower inlet partial blockage.	M1	Improper turbining
La6	Outlet damper blockage.	M2	Bad joint welding
Ha1	Insufficient burner air damper opening.	M3	Improper fabrication of joint
Ha2	Combustion air blower running too fast	M4	Improper cleaning of outside tubes.
Ha3	Insufficient Outlet damper opening.	M5	Improper maintaining and replacement of all external valves and gaskets.
Ha4	Incorrect fuel/air ratios setting.	M6	Improper replacement of refractory.
Na1	Burner air damper blockage.	I1	Improper checking of turbining.
Na2	fails of blower turbine	I2	Improper checking of welding of joint.
Na3	Fails of blower.	I3	Improper checking of fabrication of joint.
Na4	Steam valve of blower turbine fails to open.	I4	Improper checking of cleaning of outside tubes
HW1	Loose control	I5	Improper checking of improper maintaining and replacement of all external valves and gaskets.
HW2	Error reading in gauge glass	INSP1	Improper hammer test.
HW3	Electrical power failure	INSP2	Improper visual test.
LW1	Feed water source improper supply water	Hw	Feed Water operator fails to detect.
LW2	Loose control	Hw1	Feed Water operator fails to recover.
LW3	Error reading in gauge glass	Hf	FDF operator fails to detect.
LW4	Improper blow down	Hf1	FDF operator fails to recover.

LW5	Tube leakage	Hb	Firing system operator fails to detect.
LW6	Incorrect level control	Hb1	Firing system operator fails to recover.

Fault Tree Construction:

Actual construction of fault trees is an art as well as a science and comes only through experience. The top events of the fault trees represent boiler components damages, each initiated events in the fault trees are representing operational systems failures which they are indicated by symbols [see table (2)]. In order to find and visualize causal relation by fault tree, it is required to build blocks to classify and connect a large number of events; there are two types of building blocks: gate symbols and event symbols [17]. Gate symbols connect events according to their causal relation; a gate may have one or more input events but only one output event.

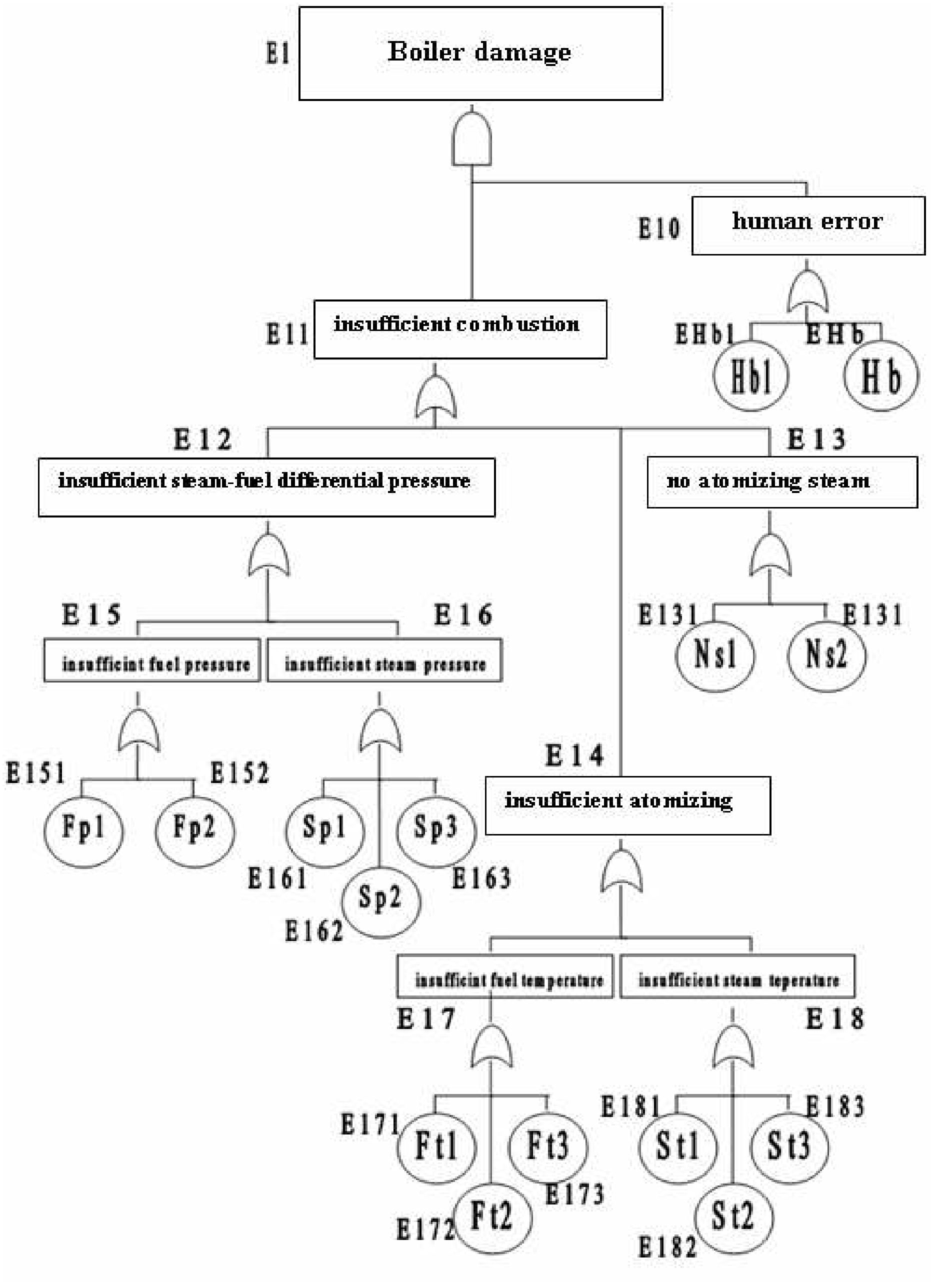


Figure (1): Fault tree for node (1)

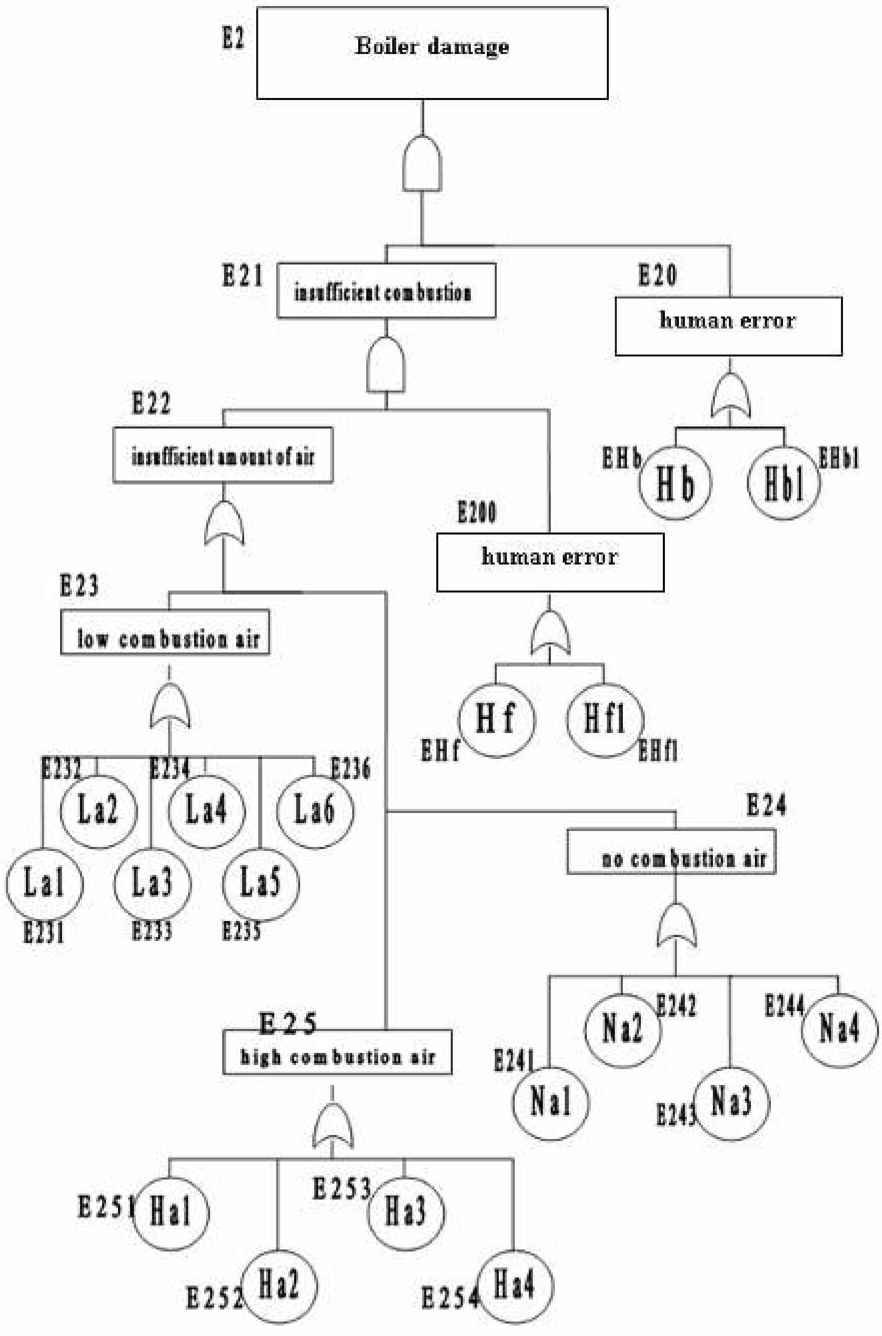


Figure (2): Fault tree for node (2)

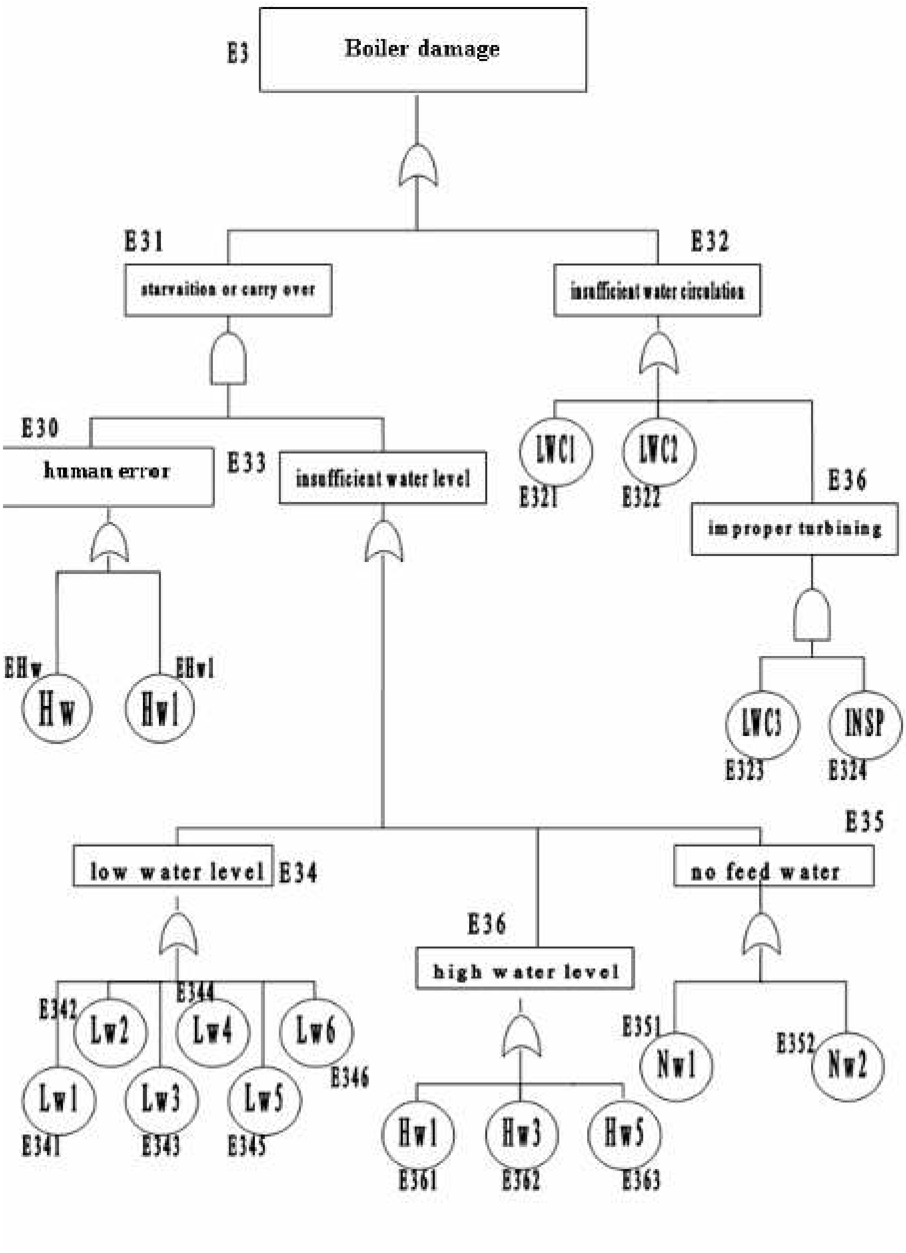


Figure (3): Fault tree for node (3)

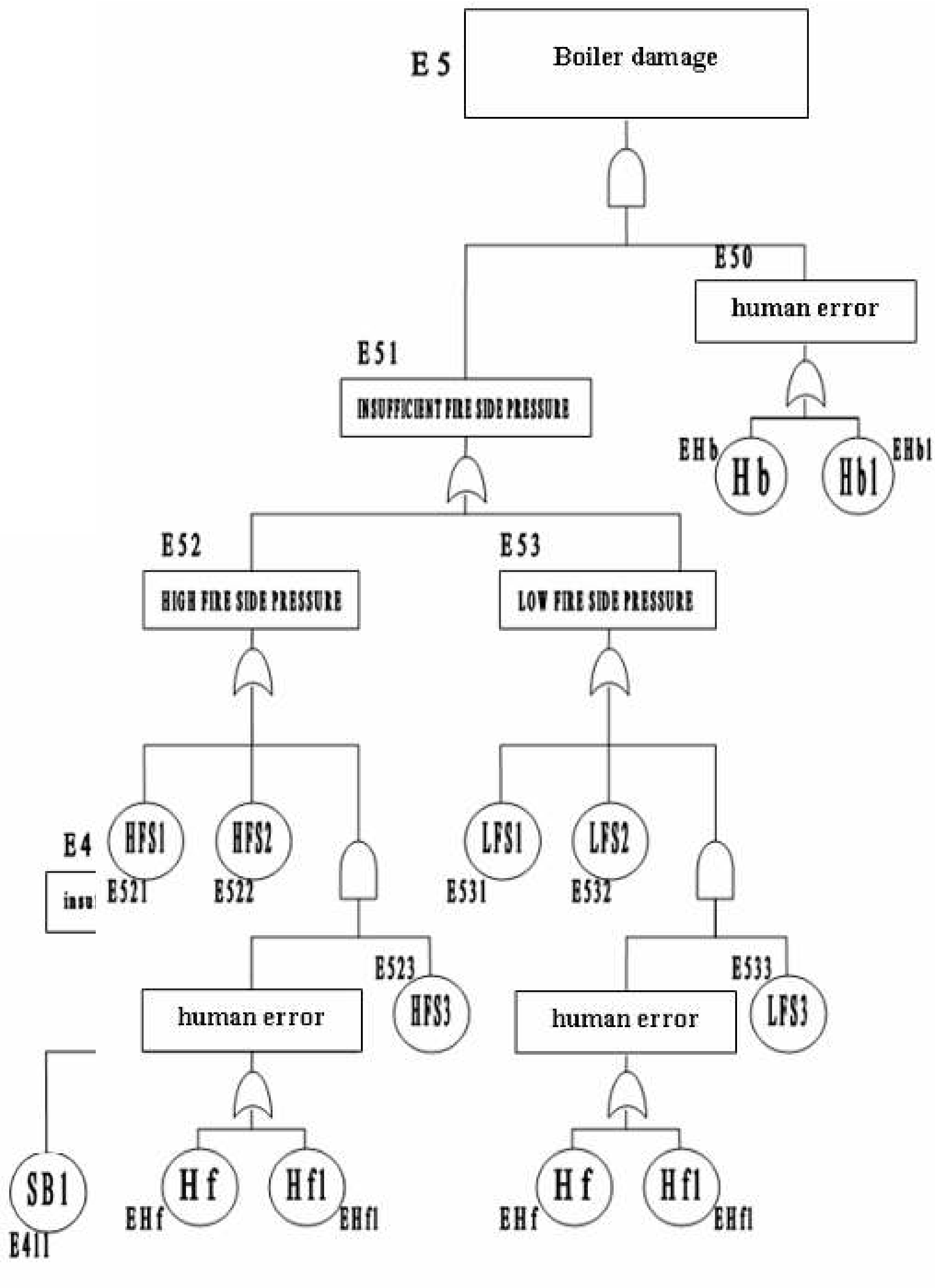


Figure (5): Fault tree for node (6)

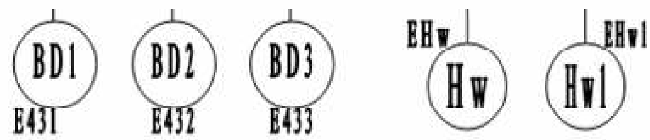


Figure (4): Fault tree for node (4) and node (5)

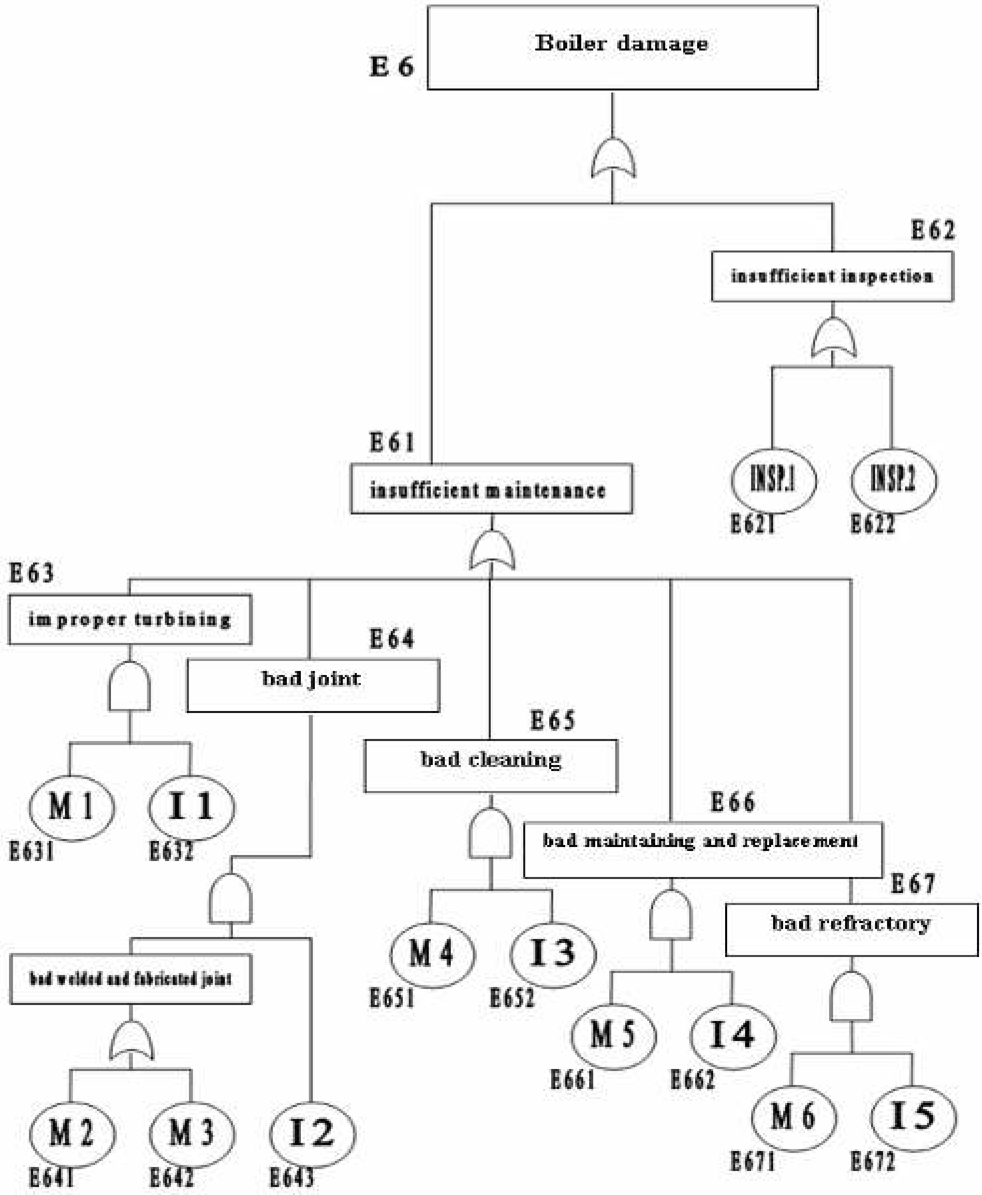


Figure (6): Fault tree for node (7) and node (8)

To reduce the fault trees shown in figures (1 to 6) to a logically equivalent form in terms of specific combinations of basic events (primary faults) sufficient to cause the undesired top event to occur. Each combination will be a "minimal cut set" of failure modes for the tree. (A minimal cut set is a set of events, which cannot be reduced in number, whose occurrence causes the top event). Minimal cut sets are exhibited in item as following:

Etotal= (probability of boiler failure)

= probability of failure of each nodes in parallel = E1+E2+E3+E4+E5+E6

E1=E11.EHb

E11=E12+E13+E14

E14=E17+E18

E18=E181+E182+E183

E17=E171+E172+E173

E13=E131+E132

E12=E15+E16

E16=E161+E162+E163

E15=E151+E152+E153

Then:-

E14=E171+E172+E173+E181+E182+E183

E12=E151+E152+E153+E161+E162+E163

E11= E151+E152+E153+E161+E162+E163+ E131+E132+E171+E172+E173+E181+E182+E183

E1 = (E151+E152 +E161+E162+E163+ E131+E132+ E171+E172 + E173 +E181+ E182+E183). (EHb1+EHb2)

E1 = (E151 EHb1+ E151 EHb2 +E152 EHb1+ E152EHb2 +E161 EHb1+ E161EHb2+E162 EHb1+ E162EHb2+E163 EHb1+ E163EHb2+ E131 EHb1+ E131EHb2+E132 EHb1+ E132EHb2+ E171 EHb1+ E171EHb2+E172 EHb1+ E172EHb2+ E173 EHb1+ E173EHb2 +E181 EHb1+ E181EHb2+ E182 EHb1+ E182EHb2+E183 EHb1+ E183EHb2) ………………………………………….. (6)

E2 =E21.EHb

E21=E22.Hf

E22=E23+E24+E25

E25=E251+E252+E253+E254

E24=E241+E242+E243+E244+E245

E23=E231+E232+E233+E234+E235+E236

Then :-

E22=E231+E232+E233+E234+E235+E236+E241+E242+E243+E244+E245+E251+E252+E253+E254

E21=(E231+E232+E233+E234+E235+E236+ E241+E242+E243+E244 +E245+ E251+E252+E253+E254).Hf

E2 =(E231+E232+E233+E234+E235+E236+ E241+E242+E243+E244 + E251+E252+E253+E254).(EHf+EHf1).(EHb+EHb1)

E2 = (E231 EHf+ E231EHf1+E232 EHf+ E232EHf1+E233 EHf+ E233EHf1+E234 EHf+ E234EHf1 +E235 EHf+ E235EHf1+E236 EHf+ E236EHf1+ E241 EHf+ E241EHf1+E242 EHf+ E242EHf1+E243 EHf+ E243EHf1+E244 EHf+ E244EHf1 + E251 EHf+ E251EHf1+E252 EHf+ E252EHf1+E253 EHf+ E253EHf1+E254 EHf+ E254EHf1).(EHb+EHb1)

E2 = (E231 EHf EHb+ E231 EHf EHb1+ E231EHf1 EHb+ E231EHf1EHb1 1+E232 EHf EHb+ E232 EHf EHb1+ E232EHf1 EHb+ E232 EHf1EHb1 +E233 EHf EHb+ E233 EHf EHb1 + E233EHf1 EHb+ E233 EHf1EHb1 +E234 EHf EHb+ E234EHf EHb1 +

E234EHf1 EHb+ E234 EHf1EHb1 +E235 EHf EHb+ E235 EHf EHb1 + E235EHf1 EHb+ E235 EHf1EHb1 +E236 EHf EHb+ E236EHf EHb1 + E236EHf1 EHb+ E236 EHf1EHb1 + E241 EHf EHb+ E241EHf EHb1 + E241EHf1 EHb+ E241 EHf1EHb1 +E242 EHf EHb+ E242 EHf EHb1 + E242EHf1 EHb+ E242 EHf1EHb1 +E243 EHf EHb+ E243 EHf EHb1 + E243EHf1 EHb+ E243 EHf1EHb1 +E244 EHf EHb+ E244 EHf EHb1 + E244EHf1 EHb+ E244 EHf1EHb1 + E251 EHf EHb+ E251 EHf EHb1 + E251EHf1 EHb+ E251 EHf1EHb1 +E252 EHf EHb+ E252EHf EHb1 + E252EHf1 EHb+ E252 EHf1EHb1 +E253 EHf EHb+ E253 EHf EHb1 + E253EHf1 EHb+ E253 EHf1EHb1 +E254 EHf EHb+ E254 EHf EHb1 + E254EHf1 EHb+ E254EHf1EHb1)
……………... (7)

E3=E31+E32

E32=E321+E322+E36

E36= E323.E324

E31=E33. EHw

E33=E34+E35+E36

E36=E361+E362+E363

E35=E351+E352

E34=E341+E342+E343+E344+E345+E436

E33=E341+E342+E343+E344+E345+E436+E351+E352+E361+E362+ E363

E31=(E341+E342+E343+E344+E345+E436+ E351+E352+E353+E354+E35+ E361+E362+E363).EHw

E3 =[(E341+E342+E343+E344+E345+E436+ E351+E352+E353+E354
+E35+E361+E362+E363).(EHw+Ew1)]+E321+E322+E323.E324

E3 =E341EHw+E341EHw1+E342EHw+E342EHw1+ E343EHw+E343EHw1+E344EHw+E344EHw1+E345EHw+E345EHw1+E436EHw+E436 EHw1+E351EHw+E351EHw1+E352EHw+E352EHw1+E353EHw+E353EHw1+E354EH w+E354EHw1+E335EHw+E335EHw1+E361EHw+E361EHw1+E362EHw+E362EHw1+E 363EHw+E363EHw1+E321+E322+E323.E324
……………………………... (8)

E4 =E41+E42

E42=E43.E40

E43=E431+E432+E433

E41=E411+E412+E413

E42= (E431+E432+E433).(EHw+ EHw)

E4 = E411+E412+E413+ (E431+E432+E433). (EHw+ EHw)

E4 = E411+E412+E413+E431 EHw + E431 EHw1+E432 EHw + E432 EHw1+E433 EHw +E433 EHw ………………………..………………………………………… (9)

E5 =E51.E50

E51=E52+E53

E53=E531+E532+E533.(EHf+EHf1)

E52=E521+E522+E523.(EHf+EHf1)

E51= E521+E522+E523. (EHf+EHf1)+ E531+E532+E533(EHf+EHf1)

E5 = (E521+E522+E523. (EHf+EHf1)+ E531+E532+E533. (EHf+EHf1)) . (EHb+EHb1)

E5 = E521 EHb+ E521EHb1+E522 EHb+ E522EHb1+E523.EHf EHb+ E523.EHf EHb1+ E523.EHf1 EHb+ E523.EHf1 EHb1+ E531 EHb+ E531 EHb1 +E532 EHb+ E532EHb1 +E533.EHf EHb+ E533.EHf EHb1 + E533.EHf1 EHb+ E533.EHf1 EHb1…………….... (10)

E6 =E61+E62

E62=E621+E622

E61=E63+E64+E65+E66+E67

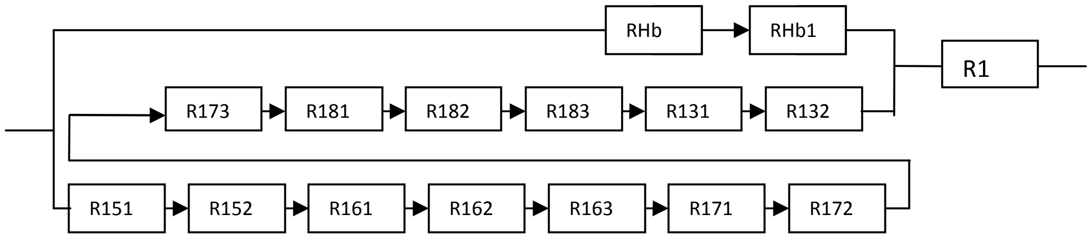
E6 =E63+E64+E65+E66+E67+ E621+E622 …………………………………………….. (11)

E total = E1+E2+E3+E4+E5+E6

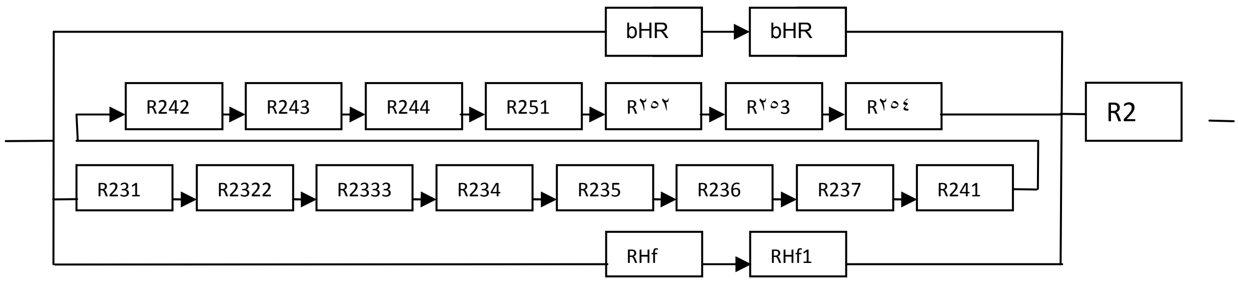
E total = E151 EHb1+ E151 EHb2 +E152 EHb1+ E152EHb2 +E161 EHb1+E161EHb2+E162EHb1+E162EHb2+E163EHb1+E163EHb2+E131EHb1+E131EHb2+E132EHb1+E132EHb2+E171EHb1+E171EHb2+E172EHb1+E172EHb2+E173EHb1+E173EHb2+E181EHb1+E181EHb2+E182EHb1+E182EHb2+E183EHb1+E183EHb2+E231EHfEHb+E231EHfEHb1+E231EHf1EHb+E231EHf1EHb1 E232EHfEHb+E232EHfEHb1+E232EHf1EHb+E232 EHf1EHb1+E233EHfEHb+E233EHfEHb1+E233EHf1EHb+E233EHf1EHb1+E234EHfEHb+E234EHfEHb1+E234EHf1EHb+E234EHf1EHb1+E235EHfEHb+E235EHfEHb1+E235EHf1EHb+E235EHf1EHb1 +E236EHfEHb+E236EHfEHb1+E236EHf1EHb+E236EHf1EHb1+E241EHfEHb+E241EHfEHb1+E241EHf1EHb+E241EHf1EHb1+E242EHfEHb+E242EHfEHb1+E242EHf1EHb+E242EHf1EHb1+E243EHfEHb+E243EHfEHb1+E243EHf1EHb+E243EHf1EHb1+E244EHfEHb+E244EHfEHb1+E244EHf1EHb+E244EHf1EHb1+E251EHfEHb+E251EHfEHb1+E251EHf1EHb+E251EHf1EHb1+E252EHfEHb+E252EHfEHb1+E252EHf1EHb+E252EHf1EHb1+E253EHfEHb+E253EHfEHb1+ E253EHf1 EHb+ E253EHf1EHb1+E254EHfEHb+E254EHfEHb1+E254EHf1EHb +E254EHf1EHb1+E341EHw+E341EHw1+E342EHw+E342EHw1+E343EHw+E343EHw1+E344EHw+E344EHw1+E345EHw+E345EHw1+E436EHw+E436EHw1+E351EHw+E351EHw1+E352EHw+E352EHw1+E353EHw+E353EHw1+E354EHw+E354EHw1+E335EHw+E335EHw1+E361EHw+E361EHw1+E362EHw+E362EHw1+E363EHw+E363EHw1+E321+E322+E323.E324+E411+E412+E413+E431EHw+E431EHw1+E432EHw+E432EHw1+E433EHw+E433EHw+E521EHb+E521EHb1+E522EHb+E522EHb1+E523.EHfEHb+E523.EHf EHb1+E523.EHf1EHb+E523.EHf1EHb1+E531EHb+E531 EHb1+E532EHb+E532EHb1+E533.EHfEHb+E533.EHfEHb1+E533.EHf1EHb+E533.EHf1EHb1+E63+E64+E65+E66+E67+ E621+E622 …….…………………………………………….. (12)

System Reliability Modeling:

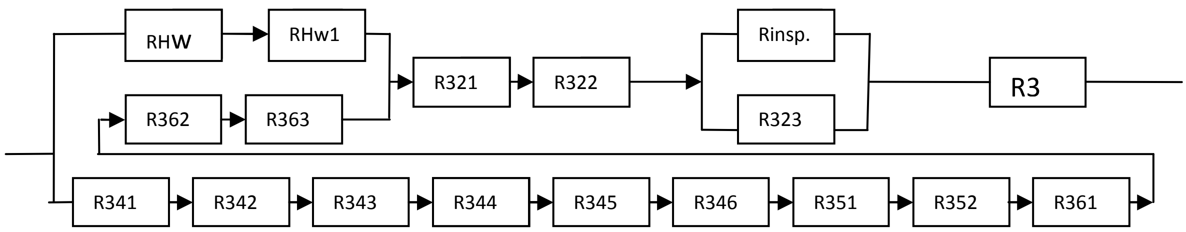
It is clear from the fault trees that all the boiler systems are simple systems and they consist of series and parallel arrangements. Since reliability block diagram is used to model simple system and usually when thinking of a reliability block diagram (RBD), the application that most often comes into mind is the analysis of a system based on the component reliabilities, but the same methodology can be used for a single component system and its associated failure modes [18]. So the models of these operation systems can be analyzed by use of block diagram method. Figures (7 to 13) respectively show the block diagrams for boiler and each system.



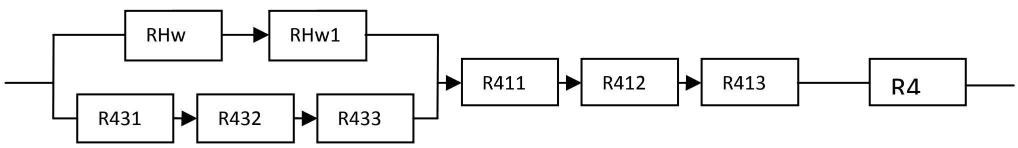
Figure(7): Reliability block diagram for node (1)



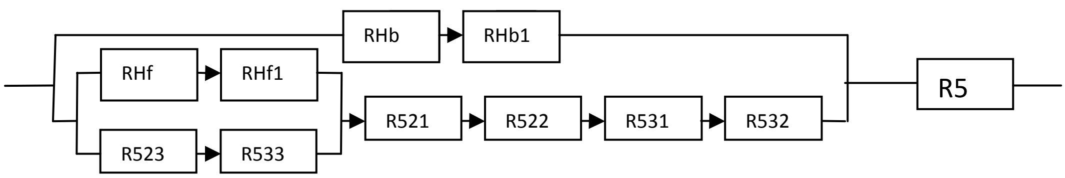
Figure(8): Reliability block diagram for node (2)



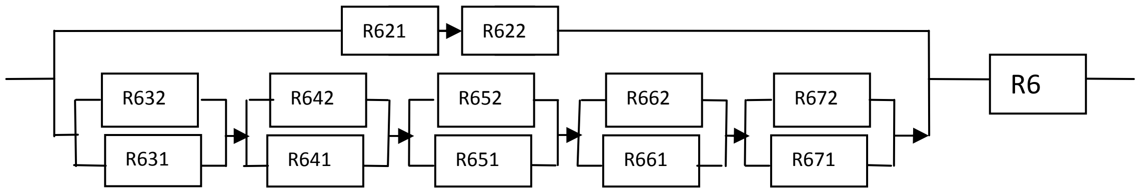
Figure(9): Reliability block diagram for node (3)



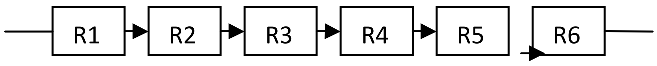
Figure(10): Reliability block diagram for node (4) and (5)



Figure(11): Reliability block diagram for node (6)



Figure(12): Reliability block diagram for node (7) and node (8)



Figure(13): Reliability block diagram for boiler

Calculation of Failure Rate, MTBF, and Reliability of Components:

The reliability, MTBF, and failure rate of system components can be determined by measuring recurrence rate of each initiated events. Table (3) shows the number of recurrence of all initiated events (frequency of events) and the failure rates corresponding to them. The frequency of events collected from field data are the base of calculation of components failure rates, mean time between failure, and reliability according to the equations below:

$$\lambda = \frac{No}{T} \quad \ldots\ldots (13)$$

Where:

λ = Failure rate.

No= number of failure reoccurrence in specified time.

T= period of specified time.

$$\text{MTTF} = \frac{1}{\lambda} \quad \ldots\ldots (14)$$

Reliability for constant failure rate is:

$$R = e^{(-\lambda t)} \quad \ldots\ldots (15)$$

Where: t = desired period of time

Evaluation of System and Boiler Reliability:-

To evaluate system and boiler reliability, the reliability model equations have to be determined by referring to reliability block diagrams in figures (7, 8, 9, 10, 11, 12, and 13), as illustrated below:

$R_1=1-(1-R_{HB}.R_{HB1}).(1-R_{131}.R_{132}.R_{151}.R_{152}.R_{161}.R_{162}.R_{163}.R_{171}.R_{172}.R_{173}.R_{181}.R_{182}.R_{183})$ ……….. (16)

$R_2=1-(1-R_{HB}.R_{HB1}).(1-R_{231}.R_{232}.R_{233}.R_{234}.R_{235}.R_{236}.R_{237}.R_{241}.R_{242}.R_{243}.R_{244}.R_{251}.R_{252}.R_{253}.R_{254}).(1-R_{HF}.R_{HF1})$ ………………………………………………………………………………… (17)

$R_3=[1-(1-R_{HW}.R_{HW1}).(1-R_{341}.R_{342}.R_{343}.R_{344}.R_{345}.R_{346}.R_{351}.R_{352}.R_{361}.R_{362}.R_{363})].R_{321}.R_{322}.[1-(1-R_{INSP}).(1-R_{323})]$ ………………………………………………………………………… (18)

$R_4=[1-(1-R_{HW}.R_{HW1}).(1-R_{431}.R_{432}.R_{433})].R_{411}.R_{412}.R_{413}$ ………………………………………… (19)

$R_5=1-[1-((1-(1-R_{HF}.R_{HF1}).(1-R_{523}.R_{533})).R_{521}.R_{522}.R_{531}.R_{532})].[1-(1-R_{HB}.R_{HB1})]$ ……………… (20)

$R_6= R_{63}.R_{64}.R_{65}.R_{66}.R_{67}.R_{162}.R_{621}.R_{622}$ ……………………………………………………… (21)

$R_{SYSTEM} = R_1. R_2 .R_3.R_4 .R_5 .R_6$ …………………………………………………………………….. (22)

Where: $R = e^{-\lambda t}$

Applying equations (10 to 16) into (17) and simplifying by use of Boolean algebra rules (Idempotent and Absorption Law), the boiler reliability equation will be:

$R_{SYSTEM}=[1-(1-R_{131}.R_{132}.R_{151}.R_{152}.R_{161}.R_{162}.R_{163}.R_{171}.R_{172}.R_{173}. R_{181}.R_{182}.R_{183} .(1- (1-R_{231}.R_{232}.R_{233}.R_{234}.R_{235}.R_{236}.R_{237}.R_{241}.R_{242}.R_{243}.R_{244}.R_{251}.R_{252} .R_{253}.R_{254}) . (1-R_{HF}.R_{HF1})) . R_{521}.R_{522}. R_{532}) . (1-R_{HB}.R_{HB1})] . [1-(1-R_{341}.R_{342}.R_{343}.R_{344}.R_{345}.R_{346}.R_{351}.R_{352}.R_{361}.R_{362}.R_{363} R_{431}.R_{432}.R_{433}).(1-R_{HW}.R_{HW1})] . R_{411}.R_{412}.R_{413} . R_{63}.R_{64}.R_{65}.R_{66}.R_{67}.R_{162}.R_{621}.R_{622}$ ……………………………….. (23)

Reliability equations are formulated into a program with visual basic language to be used as a tool to perform the cyclic procedure of calculations after entering the entire required data base. The constructed program is designed to calculate boiler and its systems reliability at any desired time, by clicking the command "reliability and unreliability at any desired time" an input box appears asking for the period of time at which reliability has to be calculated. After entering the period of time and clicking O.K button the input box will disappear and the reliability and probability of failure values as well as the selected time will appear in the text boxes in the main window of the program.

The calculation of boiler systems reliability can be done by clicking the button of "*reliability bar chart of boiler systems*", input box will appear asking for entering the period of time, then by clicking O.K button the reliability of all boiler systems will appear as a bar chart.

Reliability Function:

Reliability engineers, usually, draw equipment reliability function by using of approximation method which assumes the equipment with constant failure rate as its components although there is a redundant arrangement.

The program draw reliability curve by using of approximation and exact methods (constant and variable boiler failure rate). It can be performed by clicking the button of "***boiler reliability function curve***"; new window will appear which contains two command buttons, first button to draw the actual reliability function curve, second bottom to draw three approximation reliability function curves. Figure (14) shows the output of the program after clicking the two buttons, which consists of four curves of boiler reliability function at different taken times:

1-curve (1) is plotted at constant boiler failure rate which was calculated at t=720hour.

2-curve (2) is plotted at constant boiler failure rate which was calculated at t=1800hour.

3-curve (3) is plotted at constant boiler failure rate which was calculated at t= 4880 hour.
4-curve (4) is plotted at variable boiler failure rates according to the variation of period of time.
It can be recognized that curve 4 (variable failure rate) converges to curve 1 at low period of time less than 720 hours, and they lie at t=720 hours, greater than 720 hours curve 4 diverges to curve 1 and starts to converge curve 2 and meets it at t=1800 hours, at a higher period than t=1440 hours curve 4 diverges to curve 2 and converges to curve 3 until they intersect at t=2880 hour.

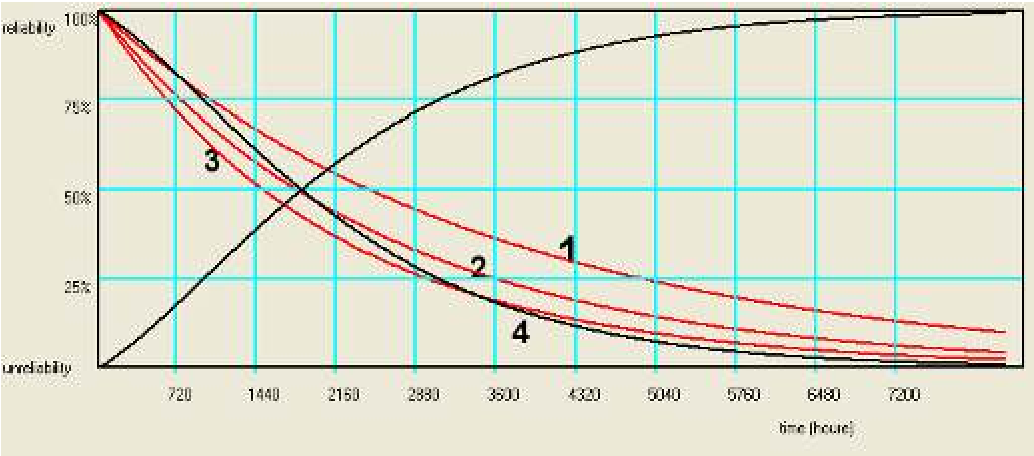


Figure (14): Variation of boiler reliability function with time

System Failure Rate:

It is important to recognize from system reliability block diagrams that all boiler systems are as an active parallel or redundant system, they are not of the form $e^{(-cons\tan t \times t)}$ although constant failure rate components have been used but the system itself has a variable failure rate. Therefore to obtain the failure rate of the systems, the expression below has to be employed, [10], [19].

$$Failure\ rate = -\frac{dR(t)}{R(t)d(t)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (24)$$

All reliability engineers evaluate the failure rate of redundant systems by using of approximation method. The fundamental basis for the approximation method is that the reliability function for equipments be approximated by an exponential time-between-failure distribution with constant failure rate, with reasonable error [19].

$$R_A(t) = \exp(-\lambda_A \times t) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (25)$$

Where: $R_A(t)$ is the approximated system reliability. (λ_A) Is an approximated constant value and represents failure rate of the system. (λ_A) Is calculated by determining of the real system reliability by use system reliability model at a selected time (R_C), usually 24 hour, and then compensate real reliability value in the equation below:

$$\lambda_A = -\frac{\ln(R_c)}{t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (26)$$

The equation (11) applies to evaluate boiler failure rate by derive equation (9), and formulated the final equation into the program to draw the variation of boiler failure rate, the program is activated by return to the main window and click the bottom of "boiler failure rate", failure rate curve will appear click the single command bottom as shown in figure (15).

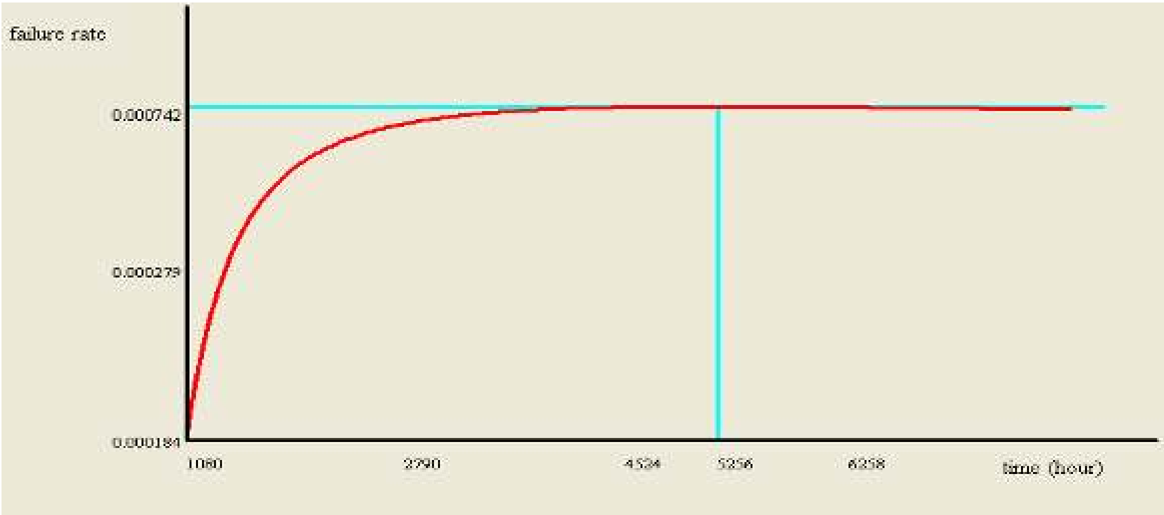


Figure (15): Boiler failure rate curve

table (3): Recurrence and failure rate of events

Item	Symbol	Number of recurrence (1/year)	Mean time to failure (year)	Failure Rate (1/hour)	Item	Symbol	Number of recurrence (1/year	Mean time to failure (year)	Failure Rate (1/hour)
1	E151	0.0625	16	7.1347-06	42	E411	0.0625	16	7.1347-06
2	E152	0.25	4	2.85388-05	43	E412	0.0625	16	7.1347-06
3	E161	0.25	4	2.85388-05	44	E413	0.25	4	2.85388-05
4	E162	0.3125	3.2	3.56735-05	45	E431	0.25	4	2.85388-05
5	E163	0.125	8	1.42694-05	46	E432	0.3125	3.2	3.56735-06
6	E171	0.3125	3.2	3.56735-05	47	E433	0.3125	3.2	3.56735-06
7	E172	0.3125	3.2	3.56735-05	48	E521	0.3125	3.2	3.56735-06
8	E173	0.25	4	2.85388-05	49	E522	0.3125	3.2	3.56735-06
9	E181	0.125	8	1.42694-04	50	E523	0.25	4	2.85388-05
10	E182	0.3125	3.2	3.56735-05	51	E531	0.3125	3.2	3.56735-06
11	E183	0.3125	3.2	3.56735-05	52	E532	0.3125	3.2	3.56735-06
12	E131	0.0625	16	7.1347-06	53	E533	0.25	4	2.85388-05
13	E132	0.0625	16	7.1347-06	54	E63	0.125	8	1.42694-05
14	E231	0.125	8	1.42694-05	55	E64	0.25	4	2.85388-05
15	E232	0.25	4	2.85388-05	56	E65	0.3125	3.2	3.56735-06
16	E233	0.25	4	2.85388-05	57	E66	0.125	8	1.42694-05
17	E234	0.5	2	5.70776-05	58	E67	0.25	4	2.85388-05
18	E235	0.3125	3.2	3.56735-05	59	E621	0.25	4	2.85388-05
19	E236	0.3125	3.2	3.56735-05	60	E622	0.25	4	2.85388-05
20	E251	0.25	4	2.85388-05	61	EHw	0.5	2	5.70776-05
21	E252	0.125	8	1.42694-05	62	EHw1	0.25	4	2.85388-05
22	E253	0.0625	16	7.1347-06	63	EHb	0.25	4	2.85388-05
23	E254	0.5	2	5.70776-05	64	EHb1	0.5	2	5.70776-05

24	E241	0.25	4	2.85388-05	65	EHf	2	0.5	2.2831-04
25	E242	0.3125	3.2	3.56735-05	66	EHf1	0.25	4	2.85388-05
26	E243	0.3125	3.2	3.56735-05	67	e1	0.1	10	1.14155-05
27	E244	0.125	8	1.42694-05	68	e2	0.333	3	3.80517-05
28	E361	2	0.5	2.2831-04	69	e3	0.25	4	2.90697-04
29	E362	0.25	4	2.85388-05	70	e4	0.0833	12	9.51293-06
30	E363	0.125	8	1.42694-05	71	r1	0.1	10	1.14155-05
31	E341	0.3125	3.2	3.56735-06	72	r2	0.1	10	1.14155-05
32	E342	2	0.5	2.2831-04	73	r3	0.1	10	1.14155-05
33	E343	0.5	2	5.70776-05	74	r4	0.1	10	1.14155-05
34	E344	0.125	8	1.42694-05	75	r5	0.1	10	1.14155-05
35	E345	0.125	8	1.42694-05	76	r6	0.1	10	1.14155-05
36	E346	0.125	8	1.42694-05	77	r7	0.333	3	3.80517-05
37	E351	0.3125	3.2	3.56735-06	78	r8	0.25	4	2.90697-04
38	E352	0.3125	3.2	3.56735-06	79	r9	0.0833	12	9.51293-06
39	E321	0.125	8	1.42694-05	80	r10	0.0833	12	9.51293-06
40	E322	0.125	8	1.42694-05	81	r11	0.0833	12	9.51293-06
41	E323	0.0625	16	7.1347-06	82	r12	0.0833	12	9.51293-06

Results:

Since there are parallel (redundant) arrangements in the boiler systems reliability models, the failure rates of the boiler systems have then variable values, although they have constant components failure rates, so that, reliability of the boiler is not conforming to the exponential function, and during the drawing of the variation of boiler reliability, exact method has to be employed rather than approximation method. By referring to figure (14), it is clear that boiler reliability function (curve 4) can not be represented by exponential function. The other three curves (1, 2, 3) are exponential functions, because their failure rates are assumed to be constant at time (720, 1800, 4880 hour) respectively.

Each system is considered as a reliable system if the probability of failure of its components does not exceed (0.01) [7], and since the reliability is a function of failure rate and time. Therefore, all systems may be reliable whatever their failure rates may be, which depend on the system mission time. Referring to figure (14), it is clear that the boiler under study is a reliable system through the range of operation time (0-48) hour. Thus, to draw the reliability variation curve during this operation time range, approximation and exact approaches can be employed without any problem; there is no sensible difference between the two procedures, which is clear from figure (14), where all the four curves coincide.

Referring to figure (15) that shows the variation of the boiler failure rate with time (hazard function). It can be recognized that boiler failure rate will increase with time until a specified value is reached at which the boiler reaches its maximum failure rate. Maximum failure rate of the boiler under consideration is (0.000742) and it occurs when the operation time reaches (5256 hours$\cong$ seven months). After this period of operation (seven months) the boiler failure rate will be constant as can be seen from figure (14). It is clear that (curve 4) conform to the exponential function after the period of operation exceeds (7 months) as the other three curves (1, 2, and 3).

Conclusions:

This study shows 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.

Also, studying boiler reliability help engineers in a petroleum refinery to depend on the variation of equipment failure rate as an indication to the optimum period of time between maintenance for achieving maximum availability without need to availability simulation.

References:

1- Xi Sun, Tongwen Chen, & Horacio J. Marquez, "*Boiler Leak Detection Using a System Identification Technique*", American chemical society, 2002

2- Stephen Michael Elonka, "*standard boiler operators' questions and answers*", McGraw-HILL publishing company LTD. New Delhi, 1991

3- A. Raouf & A. Maged "*A model to quantify reliability of human performance in man-machine system*", pergamon press, New York, 1978.

4- R. Billinton, "*Reliability Evaluation in Distribution and Transmission Systems*", PROC. IEEE, Vol. 122, No. 5, May 1975.

5- B. Ali A. A., "A *new method for reliability evaluation of electrical power system",* university of Baghdad, collage of engineering, 2003.

6- E. E. LEWIS, "*introduction to reliability engineering*", second edition, John Wiley & Sons, Inc. New York, 1996.

7- Relex software "*Reliability overview*" http://relexsoftware.com, of relex engineering software corporation, 2006

8- Patrick D.T. OCNNER "*practical reliability engineering*", fourth edition, JOHN WILEY & SONS, LTD, 2002

9- PAUL KALES "*reliability for technology engineering and management*" university of Massachusetts, 2008.

10- NASA, "*Active Redundancy*" NASA Preferred Reliability Practices No.PD-ED-1216, http://www.hq.nasa.gov/office/codeq/relpract/n1216 .PDF, NASA Headquarters, Washington.

11- Knowles, D.I., *"Acceptable Failure Rate"*, Communications in Reliability Maintainability and Supportability, International RMS Committee, USA Vol. 2, No. 1, P. 23, 1995.

12- Relex software, *"Theoretical Definitions and Alternative Uses for MTBF*" http://relexsoftware.com of relex engineering software corporation 2005.

13- Mitchell J. Mondro, "*Approximation MTBF when a system has periodic maintenance*", IEEE, 2002.

14- Reliability hotwire "*the reliability function*", http://www.weibull.com, the Magazine of reliability professional, issue 7, September, 2001.

15- "*Fault tree analysis*", MIL-HDBK-338, Section 8, 2004.

16- A.D.S Carter, "*mechanical reliability*", Macmillan education Ltd. second edition, 1988.

17- Fussell, J., "*Fault tree analysis-concept and technology*", UCID, 16238, 31, may, 1993.

18- Reliability hotwire "*Using Reliability Block Diagrams to Analyze Dependent and Independent Failure Modes*", http://www.weibull.com, the Magazine of reliability professional, issue 27, may 2003.

19- Reliability Toolkit "*Commercial Practices Edition*", Rome Laboratory and Reliability Analysis Center, p. 159, 2001.