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Improvement Reliability of Old Boiler Using Programmable Logic Controls (PLC)

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ABSTRACT.

This research aims to increase the reliability of steam generation plant through modifies boiler operation performance by introducing modern control system to avoid the operation parameters deviation and overcome the error of operators.

Two control loops systems were designed to control the operation and to avoid operational deviations of boiler feed water, combustion, and air combustion systems.

PC program in visual basic language is designed as a tool of simulation technique to perform periodical evaluation of boiler reliability and its operational systems, also draw boiler reliability as a function of time.

The results showed that the boiler reliability is increased by (23.57%) at mission time (4320) hour by introducing each of feed water, combustion, and combustion air control loops system to operate boiler systems rather than manual operation.

Key words: Reliability, Boiler, Programmable Logic Control, Improvement, System.

1. INTRODUCTION.

The use of fired and unfired pressure vessels is rapidly expanding in industry, commercial building, and apartment houses, and in every economic activity around the world. Control devices, automatic equipment, computers, and other items are being applied to fire pressure vessels. But boilers and other pressure vessels those automated are perfectly reliable because of they operate as a robot, on the contrary, these safety devices make the inherent danger even greater when complete dependences is placed on them [1& 2].

Boiler was divided to 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) [2&3].

Control systems were designed to control the operation of the main boiler systems, overcome the operational parameters deviations and increasing of the boiler reliability. The methodology to perfection boiler reliability is summarized as mentioned below:

- Showing the abilities of overcoming operator errors by use of control system rather than manual operation, in addition to design control loops, which are required to improve boiler systems performance.
- Recalculate boiler reliability in the case of connecting control loops to control the operation of the boiler, instead of manual operation.

All the evaluated values of reliability depending on the collected field data. Necessary data base are collected from the operation, maintenance, and inspection department documents of "*MidLand Refineries Company*" for the last ten years. There are some studies related to this study as illustrated below:

Dr. A. Raouf [4] shows 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.
Samir basu&raidiszemdegs [5] explain the methods of reliability analysis of control system for nuclear power plants. High reliability is one of the main objective of the design and operation of control systems in nuclear power plants, researchers present a paper which illustrates the methods of reliability analysis for these systems using various reliability techniques and engineering judgment. The step by step analysis includes system study, field data, failure mode and effect analysis, fault tree, human factors, reliability targets, and design review. To illustrate this method, the liquid zone control system for CANDU nuclear reactor control is used.
Xi Sun, Tongwen Chen, and Horacio J. Marquez [6] describe the process design and control of boiler leak detection by using a system identification technique, the model-based method is the conventional method of fault detection and diagnosis which uses static or dynamic models of the process. This method can provide an efficient solution for most fault detection problems, but in some cases it cannot give correct detection results since the valid process mathematical model required in this technique is difficult to obtain in some industrial processes.
Klass B. Klaassen [7] shows that when applying redundancy, the system designer face the dilemma of weighing the better life prospects of passive redundant hardware against the lower system complexity in the case of active redundant hardware. This dilemma is analyzed by comparing the MTTF and the reliability obtained with active, stand-by, and passive redundancy, the analysis makes use of markov diagrams and generalized reliability model that embraces all three types of redundancy and covers all types of failure which can occur in practice.
Soroor K. H. [8] designs an integrated programmable system for failure diagnosis and RAM evaluation as a tool for improving the operating efficiency inSouth Baghdad Power Generating Plant, and for controlling the whole system's operation.
Ali A. A. [9] presents a study which it is constrained on Reliability evaluation using 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. So, it is a first method, which merges between statically analysis (Fault Tree) and dynamic analysis (Markov Process).

This work is concerned with the improvement reliability of the old water tube boiler double identical drums which was build in 1968 in "***Midland Refineries Company***". Its output capacity is (70) ton/hour of super heated steam, the operation and control of the boiler is manual. There are a multitude of failures that are caused by boiler operator's errors, which lead to operation parameters deviations and boiler shut down.

2. BOILER CONTROL SYSTEM.

A modern control system design is introduced which is called (PLC), (a Programmable Logic Control system). It is one of the most recent control system which has a long storage capacity, small size , wide range ,accuracy and easy to connect with personal computer (PC). [10]
The primary purpose of any boiler control system is to manipulate the firing and water rates so that the supply of steam remains in balance with the demand for steam over the full load range. In addition, it is necessary to maintain an adequate supply of feed water and to correct mixture of air and fuel / atomizing steam for safe and economical combustion. [3&12]

3. CONTROL LOOPS FUNCTIONS.

All control loops are designed for safe operation (shutdon the systems down in the event of operating problems) and maintain. The boiler control systems to be introduced must perform the following functions:

- Provide feed water to the boiler to maintain the desired drum water level.
- Provide draft to the furnace, flue and stack.
- Provide blow down of the drums.
- Maintain steam output pressure.
- Provide and control sufficient amount of combustion air to the furnace.
- Provide and control sufficient amount of fuel to the burners.
- Provide and control sufficient amount of atomizing steam to the burners.
- Shutdown boiler burners in emergency cases.

To achieve these functions properly feed water and combustion control system are introduced.

4. FEED WATER CONTROL SYSTEM.

The flow of feed water entering the boiler must equal the flow of steam and blow down water leaving the boiler. Also the feed water control system must maintain feed water; steam flow rates and steam drum level at the same time, which is known as the three-element control system [11]. The steam flow transmitter that is compensated for pressure, temperature and the feed water flow transmitter (when the design steam pressure exceeds 500 psig, pressure compensation of the drum level signal is recommended, gives signals to the steam and water flow computing relay. The two signals balance each other in the computing relay. Any change in the flow rates will be transmitted to steam flow, water flow and drum level computing relay. The level transmitter, compensated for pressure and temperature, at the steam drum also sends a signal to this relay. At this point, the signal from the level transmitter is balanced with the signal from the steam flow/water flow relay. Any difference between the two signals is transmitted through the manual/automatic selector switch to the feed water control valve. This signal positions the valve to provide the rate of feed water flow equal to the steam flow rate, while maintaining the steam drum level at the same time.

Blow down control normally uses the conductivity of the boiler water to establish the blow down flow rate.

5. SINGLE / THREE - ELEMENT DRUM LEVEL CONTROL.

During startup or low load operation, the flow measurements used in the three-element control strategy may fall well below the range ability limits of these flow meters. In that situation, three-element drum level control becomes erratic, and it is better to control the drum level with a single loop (one-element) control strategy. As shown in **Fig.(1)**, drum level control switches automatically from three-element to one-element when steam flow falls below an adjustable low limit.

6. COMBUSTION CONTROL SYSTEM.

On the fireside of the boiler the primary control functions must be kept in proper balance to maintain and provide the correct steam ratio with correct fuel/air rate to the furnace to control steam pressure in the steam header.

The airflow must be kept in proportion to the steam flow, this is because, there is a direct relationship between the energy input (fuel and air) and the energy output (steam), by keeping the steam flow/air flow ratio at the proper value, maximum combustion efficiency can be maintained [10& 11].

7. FULL - METERED, CROSS - LIMITED CONTROL.

The full-metered, cross-limited control scheme is sometimes referred to as the standard control arrangement. For metered, cross-limiting control, the fuel and combustion air flows are used to improve control of the air to-fuel-ratio. The benefits of this control scheme are: compensates for fuel and combustion air flow variations and provides active safety constraints to prevent hazardous conditions.

In a metered control system, three measurements are used to balance the fuel/air mixture. These are the steam header pressure, the fuel flow, and the air flow. As shown in **Fig. (2)**, the combustion controls consist of fuel flow and air flow control loops that are driven by the firing rate demand signal. The characterizer on the air flow measurement scales the air flow signal relative to the fuel flow signal to provide the optimum air/fuel ratio.

The characterizer points are determined empirically by testing the boiler at various loads and adjusting the fuel relative to the air at each test load as needed to achieve optimum combustion. This allows the air and fuel flow set points to be driven by the same firing rate demand signal. The cross-limiting (or lead-lag) circuit assures an air-rich mixture since the air flow set point will always lead the fuel on an increasing load and lag when the load is decreasing.

8. O2 TRIM CONTROL.

Automatic air/fuel ratio adjustment is generally based on the percentage of excess oxygen (O2) in the flue gas. If air and fuel are mixed in chemically correct (stoichiometric) proportions, the theoretical products of combustion are carbon dioxide and water vapor. Under ideal conditions, all of the oxygen supplied with the air would be consumed by the combustion process. Due to incomplete mixing, however, it is always necessary to provide more air than the theoretically correct mixture. This results in a small percentage of excess O2 in the flue gas. A flue gas oxygen analyzer supplies feedback on the combustion process and is the basis for trimming the air/fuel ratio to maintain optimum combustion.

Fig. (3) shows the method of trimming the air/fuel ratio based on O2 control. The optimum percentage of O2 in the flue gas depends on the type of fuel and varies with load. Therefore, the O2 set point is characterized as a function of steam flow, which provides an index of the boiler load. **Fig. (4)** shows a plot of excess O2 as a function of steam flow for a particular application. The controller output is clamped by high and low limits to prevent driving the air/fuel ratio beyond unsafe or inefficient limits.

9. CONTROL SYSTEM REQUIREMENTS.

The boiler control system needs some control Loops as mentioned below:

1. Water drum level transmitter.
2. Steam production flow transmitter.
3- Feed water flow transmitter.
4. Combustion air flow transmitter.
5. Flame detector signal transmitter.
6. Steam production pressure transmitter.
7. Fuel oil flow transmitter.
8. Atomizing steam flow transmitter.
9. Drum pressure transmitter.
10- Feed water pressure transmitter.
11- Atomizing steam control valve.
12- Fuel oil control valve.
13- Pneumatic actuator air damper.

14- Fuel oil cutoff valve.
15- Power supply.
16- PLC.
17- Four electric-pneumatic converter.

According to these requirements, it can be estimated that there are nine transmitter signals getting into PLC system and there are another five output signals controlling the operation of the control valves, so that it need an analog input/output card with nine signals, discrete output card are used for sending signals to indicating lamps and cutoff valve, author scheme the control loops as indicated in **Fig. (5)** and **Fig. (6)**.

10. SYSTEM RELIABILITY MODELING.

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 [12, 13&14]. So the models of these operation systems can be analyzed by use of block diagram method. **Figs.(7 to 13)** respectively show the block diagrams for boiler and each system.

11. EVALUATION OFSYSTEM AND BOILER RELIABILITY.

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

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

$$R_2=1-(1-R_{HB}.R_{HB1}).(1-R_{231}.R_{232}.R_{233}.R_{234}.R_{235}.R_{236}.R_{237}.R_{241}.R_{242}.R_{243}.R_{244}.R_{251}.R_{252}.R_{253}.R_{254}).(1-R_{HF}.R_{HF1}) \quad (2)$$

$$R_3=[1-(1-R_{HW}.R_{HW1}).(1-R_{341}.R_{342}.R_{343}.R_{344}.R_{345}.R_{346}.R_{351}.R_{352}.R_{361}.R_{362}.R_{363})].R_{321}.R_{322}.[1-(1-R_{INSP}).(1-R_{323})] \quad (3)$$

$$R_4=[1-(1-R_{HW}.R_{HW1}).(1-R_{431}.R_{432}.R_{433})].R_{411}.R_{412}.R_{413} \quad (4)$$

$$R_5=1-[1-((1-(1-R_{HF}.R_{HF1}).(1-R_{523}.R_{533})).R_{521}.R_{522}.R_{531}.R_{532})].[1-(1-R_{HB}.R_{HB1})] \quad (5)$$

$$R_6= R_{63}.R_{64}.R_{65}.R_{66}.R_{67}.R_{162}.R_{621}.R_{622} \quad (6)$$

$$R_{SYSTEM}= R_1.R_2.R_3.R_4.R_5.R_6 \quad (7)$$

Where: $R = e^{-\lambda t}$ (8)

Applying equations (1 to 6) into (7) and simplifying by use of Boolean algebra rules (Idempotent and Absorption Law), the boiler reliability equation will be:

$$R_{SYSTEM}=[1-(1-R_{131}.R_{132}.R_{151}.R_{152}.R_{161}.R_{162}.R_{163}.R_{171}.R_{172}.R_{173}.R_{181}.R_{182}.R_{183}.(1-(1-R_{231}.R_{232}.R_{233}.R_{234}.R_{235}.R_{236}.R_{237}.R_{241}.R_{242}.R_{243}.R_{244}.R_{251}.R_{252}.R_{253}.R_{254}).(1-R_{HF}.R_{HF1})).$$

$R_{521}.R_{522}.\ R_{532}\ ).\ (1-R_{HB}.R_{HB1})]\ .\ [1-(1-R_{341}.R_{342}.R_{343}.R_{344}.R_{345}.R_{346}.R_{351}.R_{352}.R_{361}.R_{362}.R_{363}$
$R_{431}.R_{432}.R_{433}).(1-R_{HW}.R_{HW1})]\ .\ R_{411}.R_{412}.R_{413}\ .\ R_{63}.R_{64}.R_{65}.R_{66}.R_{67}.R_{162}.R_{621}.R_{622}$ (9)

Reliability equations was formulated into a program with visual basic language which constructed 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*" as shown in **Fig. (14- A)**, input box will appear asking for entering the period of time as shown in **Fig. (14- B)**, then by clicking O.K button the reliability of all boiler systems will appear as a bar chart as shown in **Fig. (14- C)**.

12. 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 $e^{(-constant \times t)}$ 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, [15&16].

$$Failure\ rate = -\frac{dR(t)}{R(t)d(t)} \quad (10)$$

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 [16].

$$R_A(t) = \exp(-\lambda_A \times t) \quad (11)$$

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:

$$\lambda_A = -\frac{\ln(R_c)}{t} \quad (12)$$

Formulated the final equation (12) 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 **Fig. (15)**.

13. CONTROL SYSTEM FAILURE ANALYSIS.

13.1. Single/Three Elements Control Failure Analysis.

To analyze (single /three) elements control system it is divided into three control loops

- level control loop
- steam flow control loop
- feed water control loop

This control system is designed in some way that the failure of level control loop will lead to the failed down of control system. Failure of the other two control loops will not cause failure down of the system but the PLC will alarm the operators to repair the root of the failure. The control system works continuously depending on single element control loop, so that; the system reliability will depend on level control loop. To estimate system reliability, level control system has to be analyzed to its components, and failure rate of all components have to be found too. In this work all control loops components failure rates are found by similarity method, in some way, all control loops consist of the same main components (signals transmitter, processor, and control device). Furthermore, the same function control loops exists and connect to control operation of other equipments. Data of these loop components are collected by field data method, as mentioned in table (2), due to the similarity in the function and operation conditions. These data are applied to evaluate failure rates of control loops under consideration.
From **Fig. (16)**, it can be recognized that power supply (e2) and PLC processor (e3) have an active stand by component (e21 and e31 respectively). (e21) will works immediately when e2 fails (works with the same failure rate), and e31 will works immediately when e3 fails (works with the same failure rate). Therefore failure rates of the two standby subsystems are determined and considered as an important step for preparing input data for the constructed program (the program deals with components failure rates to evaluate reliability and other parameters), by assuming the conditions for the two subsystem :

1- Constant failure rate.
2- Repairable subsystem with Constant repair rate.
3- Active standby system.

It can be recognized that these condition are conforming to the assumption of Markov method (transition states) [17], therefore, author employ this method to evaluate the failure rates of the two subsystems.
The transition states of the two standby subsystem are illustrated in the **Fig. (18)**, considering that state (0) represents the state of the subsystem at which the two components work properly and state (1) represents the state at which main component is failed and standby component works properly, state (2) represents the state at which the two components are failed and (μ, λ) are repair rate and failure rate respectively which represent transition rates from state to another. Therefore to perform Markov method [17], the probability equation for each stage have to be determined in form of partial deferential equation, in which p_0 represents the probability of being in stage (0), p_1 represents probability of being in stage (1) and p_2 represents the probability of being in stage (2). [18, 19]

$$\delta p_0/\delta t = -\lambda p_0 + \mu p_1 \tag{13}$$

$$\delta p_1/\delta t = \lambda p_0 - (\lambda + \mu) p_1 \tag{14}$$

$$\delta p_2/\delta t = \lambda p_1 \tag{15}$$

It can be represented by matrix form as shown below:

$$\begin{vmatrix} P_0 \\ P_1 \\ P_2 \end{vmatrix} = \begin{vmatrix} -\lambda & \mu & 0 \\ \lambda & -(\lambda+\mu) & 0 \\ 0 & \lambda & 0 \end{vmatrix} \begin{vmatrix} p_0 \\ p_1 \\ p_2 \end{vmatrix}$$

Since: $R_s = p_0 + p_1$ and $MTBF = \int_0^\infty P_0 + P_1 MTBF \rightarrow \int_0^\infty P_0 + \int_0^\infty P_1 = T_0 + T_1$ [18, 19]

$$\int_0^\infty \begin{vmatrix} P_0 \\ P_1 \\ P_2 \end{vmatrix} = \begin{vmatrix} -\lambda & \mu & 0 \\ \lambda & -(\lambda+\mu) & 0 \\ 0 & \lambda & 0 \end{vmatrix} \int_0^\infty \begin{vmatrix} p_0 \\ p_1 \\ p_2 \end{vmatrix}$$

$$\begin{vmatrix} P_0(\infty) - P_0(0) \\ P_1(\infty) - P_1(0) \\ P_2(\infty) - P_2(0) \end{vmatrix} = \begin{vmatrix} -\lambda & \mu & 0 \\ \lambda & -(\lambda+\mu) & 0 \\ 0 & \lambda & 0 \end{vmatrix} \begin{vmatrix} T_0 \\ T_1 \\ T_2 \end{vmatrix}$$

By applying steady-state condition at: $t=0$, $P_0=1$, $P_1=P_2=0$ and when $t=\infty$, $P_2=1$, $P_1=P_0=0$

$$\begin{vmatrix} 0 - 1 \\ 0 - 0 \\ 1 - 0 \end{vmatrix} = \begin{vmatrix} -\lambda & \mu & 0 \\ \lambda & -(\lambda+\mu) & 0 \\ 0 & \lambda & 0 \end{vmatrix} \begin{vmatrix} T_0 \\ T_1 \\ T_2 \end{vmatrix}$$

Then: $T_1 = 1/\lambda$; $T_2 = (\lambda + \mu)/\lambda^2$ and $MTBF = (2\lambda + \mu)/\lambda^2$ [18, 19]

$$\lambda_{standby} = \frac{1}{MTBF} = \frac{\lambda^2}{(2\lambda + \mu)} \text{ [18, 19, 20]} \tag{16}$$

Finely the level control loop is considered as a single component with failure rate as calculated below:

$$\lambda_{cl\ system} = \lambda_1 + \frac{\lambda_2^{\ 2}}{2\lambda_2 + \mu_2} + \frac{\lambda_3^{\ 2}}{2\lambda_3 + \mu_3} + \lambda_4 \tag{17}$$

From **Table (2)** with $\mu_2 = 1$ hour and $\mu_3 = 24$ hour:

$$\lambda_{cl\ system} = (1.14155\times10^{-5}) + \frac{(3.8051\times10^{-5})^2}{2\times(3.8051\times10^{-5})+1} + \frac{(2.9069\times10^{-4})^2}{2\times(2.9069\times10^{-4})+24} + (9.51293\times10^{-6})$$

$$\therefore \lambda_{clsystem} = 2.09334\times10^{-5}$$

13.2. Full Metered- Cross Limited Control Failure Analyses.

As shown in **Fig. (5)**, this control system consist of six parameter signal transmitters, two control valves and control damper in addition to power supply and PLC with its standby components. In fact, the failure of any component may impede main function of control system which cause loses of control that may harm the boiler and lead to boiler down time. **Fig. (19)** shows reliability block diagram of the control system.

According to the RBD in **Fig. (19)**, the control system failure rate is:

$$\lambda_{c2\ system}=\lambda_5+\lambda_6+\lambda_7+\lambda_8+\lambda_9+\lambda_{10}+\frac{\lambda_{11}^2}{2\lambda_{11}+\mu_{11}}+\frac{\lambda_{12}^2}{2\lambda_{12}+\mu_{12}}+\lambda_{13}+\lambda_{14}+\lambda_{15}+\lambda_{16} \quad (18)$$

From **Table (2)** with μ_{11}= 1 hour and μ_{12}= 24 hour:

$$\lambda_{c2\ system}=6\times(1.14155\times10^{-5})+(\frac{(3.8051\times10^{-5})^2}{2\times(3.8051\times10^{-5})+1}+\frac{(2.9069\times10^{-4})^2}{2\times(2.9069\times10^{-4})+24}+4\times(9.51293\times10^{-6})$$

$$\therefore \lambda_{c2system}=1.06575\times10^{-4}$$

It can be recognized from **Fig. (20)**, that full metered cross limited system has two main functions, control combustion system and control air combustion system, so that, by use of single – three elements system and full metered-cross limited system, three most important boiler systems could be controlled to avoid manual operation errors and overcome operation parameter deviations.

According to **Fig. (20)**, which represents reliability, block diagram of the boiler after applying control loops (full-metered cross limited and level control systems), boiler reliability model will be:

$$R_s=((R_1.R_2)+R_{C2}).(R_3+R_{C1}).R_4.R_5.R_6 \quad (19)$$

Where

$$R_{c1}=e^{-\left(\lambda_1+\frac{\lambda_2^2}{2\lambda_2+\mu_2}+\frac{\lambda_3^2}{2\lambda_3+\mu_3}+\lambda_4\right)\times t}=e^{-(0.0000209334\quad\times t)} \quad (20)$$

$$R_{c2}=e^{-(\lambda_5+\lambda_6+\lambda_7+\lambda_8+\lambda_9+\lambda_{10}+\frac{\lambda_{11}^2}{2\lambda_{11}+\mu_{11}}+\frac{\lambda_{12}^2}{2\lambda_{12}+\mu_{12}}+\lambda_{13}+\lambda_{14}+\lambda_{15}+\lambda_{16})\times t}=e^{-(0.000106575\times t)} \quad (21)$$

Referring to equation (9) the final reliability model of boiler with control system will be:

$$R_{SYSTEM}=[1-(1-R_{131}.R_{132}.R_{151}.R_{152}.R_{161}.R_{162}.R_{163}.R_{171}.R_{172}.R_{173}.R_{181}.R_{182}.R_{183}.(1-(1-R_{231}.R_{232}.R_{233}.R_{234}.R_{235}.R_{236}.R_{237}.R_{241}.R_{242}.R_{243}.R_{244}.R_{251}.R_{252}.R_{253}.R_{254}).(1-R_{HF}.R_{HF1})).R_{521}.R_{522}.R_{532}).(1-R_{HB}.R_{HB1}).(1-R_{c2})].[1-(1-R_{341}.R_{342}.R_{343}.R_{344}.R_{345}.R_{346}.R_{351}.R_{352}.R_{361}.R_{362}.R_{363}R_{431}.R_{432}.R_{433}).(1-R_{HW}.R_{HW1}).(1-R_{c1})].R_{411}.R_{412}.R_{413}.R_{63}.R_{64}.R_{65}.R_{66}.R_{67}.R_{162}.R_{621}.R_{622} \quad (22)$$

Equation (22) is reformulated in the same program and failure rate of control system components are calculated from the collected number of recurrence (frequency) of failure events which are mentioned in **Table (2)** by field data method.

To find the new values of boiler and its systems reliability (after connecting control loops systems), click "*reliability of boiler and its systems*" bottom, input box will appear asking for period of time, entering the desired period of time and clicking O.K bottom will display a new window that contains systems reliability as a bar charts and boiler reliability in a text box as exhibited in **Fig.(21- A, B, and C)**. To draw variation of boiler reliability with time after introducing control system, just click *"reliability curve after improvement"* bottom at the main window of program as shown in fig. (22- A), new window with three commands will appear. The first command use to draw reliability function without control system; and the second command use to draw reliability with feed water and combustion control system which its failure rates are ($2.09334x10^{-5}$), ($1.06575x10^{-4}$) respectively. The third command use to draw two other reliability functions with two failure rates of feed water control system ($1x10^{-5}$), ($5x10^{-6}$), also with two failure rates of combustion system ($5x10^{-5}$), ($2.5x10^{-5}$) as shown in **Fig. (22- B)**.

14. RESULTS.

By introducing control loop system to modify the operation of feed water system, combustion system, and air combustion system; the reliability of the boiler is increased by (22.89%) at mission time equal to 4320 hour. Where boiler reliability without control loop system at mission time 4320 hour is (0.1141), but its reliability will be (0.3020) at the same mission time after introducing control systems. As shown in **Fig. (14- C) and Fig. (21- C)**.

Fig. (22- B) shows the effect of estimated value of control loops system failure rate on the increasing amount of the boiler reliability, curves (2), (3) and (4) are boiler reliability functions after introducing control system with variable estimated control loops failure rate; this will be options to the decision makers while choosing the proper control system.

15. CONCLUSIONS.

In the past, human performance was obviously very important, but as the machines and equipments began to take over more complexity, the role of the peoples in industry became somewhat obscured, in the refineries industry all the operational systems have to be automated by use of modern control systems to keep the process and equipments safe.

To increase performance efficiency and maintain steam availability of the boiler under consideration, control system must be introduced to control the operation of feed water system, combustion system, and air combustion system. The diagram illustrated in **Fig. (22- C)**; will help boiler manager to evaluate the increasing amount in boiler reliability related to the failure rate of the control system.

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Table (1): Symbols and its descriptions.

Symbol	Description
MTBF	Mean time between failure
P	Probability
PC	Personal computer
PLC	Programmable Logic Controls
R	Reliability
RBD	Reliability block diagram
T	Desired period of time
μ	Period of specified time
λ	Failure rate

Table (2): Recurrence and Failure Rate of Events.

Item	Symbol	Number of Recurrence (1/year)	Mean Time to Failure (year)	Failure Rate (1/hour)1
1	λ_1	0.1	10	1.14155-05
2	λ_2	0.333	3	3.80517-05
3	λ_3	0.25	4	2.90697-04
4	λ_4	0.0833	12	9.51293-06
5	λ_5	0.1	10	1.14155-05
6	λ_6	0.1	10	1.14155-05
7	λ_7	0.1	10	1.14155-05
8	λ_8	0.1	10	1.14155-05
9	λ_9	0.1	10	1.14155-05
10	λ_{10}	0.1	10	1.14155-05
11	λ_{11}	0.333	3	3.80517-05
12	λ_{12}	0.25	4	2.90697-04
13	λ_{13}	0.0833	12	9.51293-06
14	λ_{14}	0.0833	12	9.51293-06
15	λ_{15}	0.0833	12	9.51293-06
16	λ_{16}	0.0833	12	9.51293-06

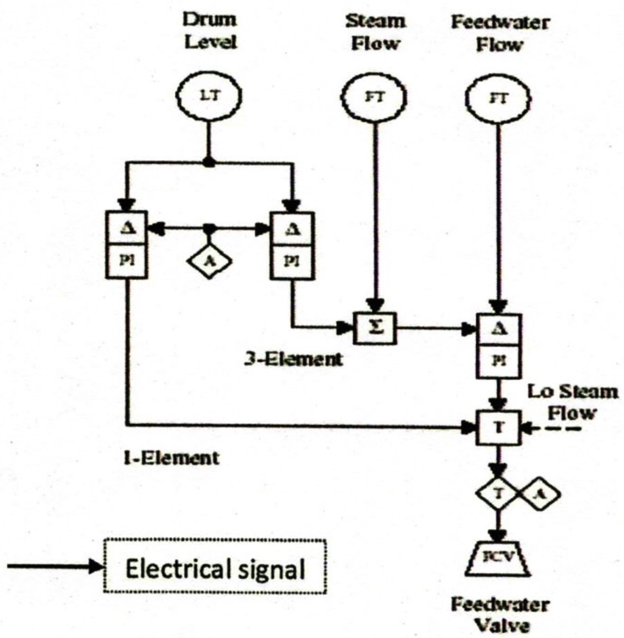


Figure (1): Single-three elements drum level control [3, 11].

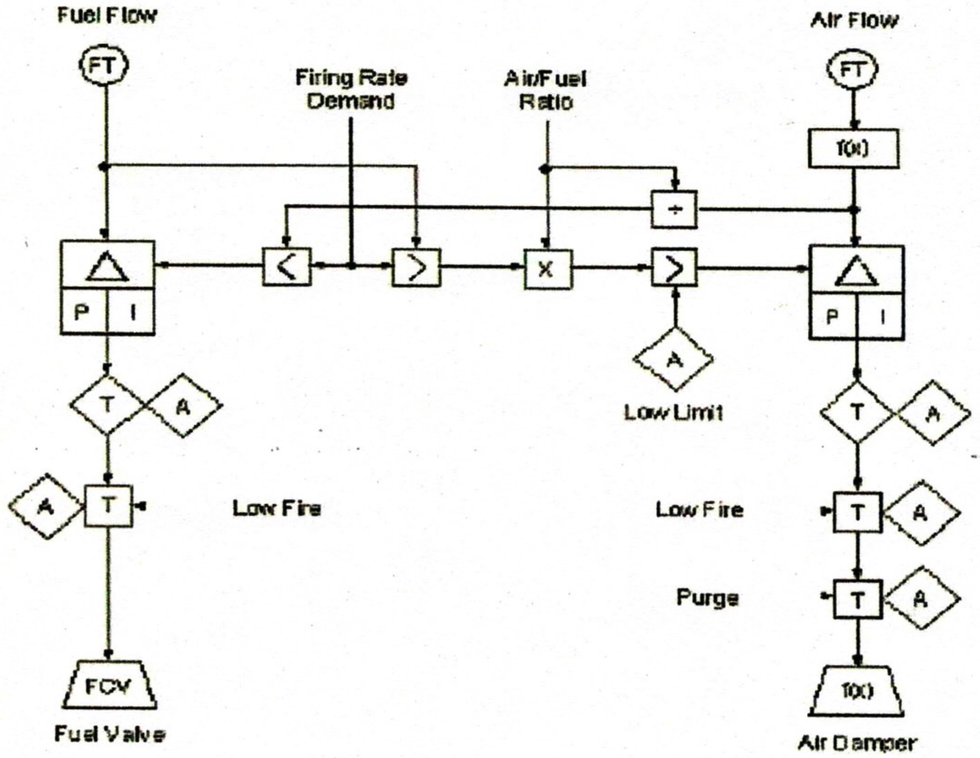


Figure (2): Flow chart of Full-Metered, Cross-Limited Combustion Control [3, 12].

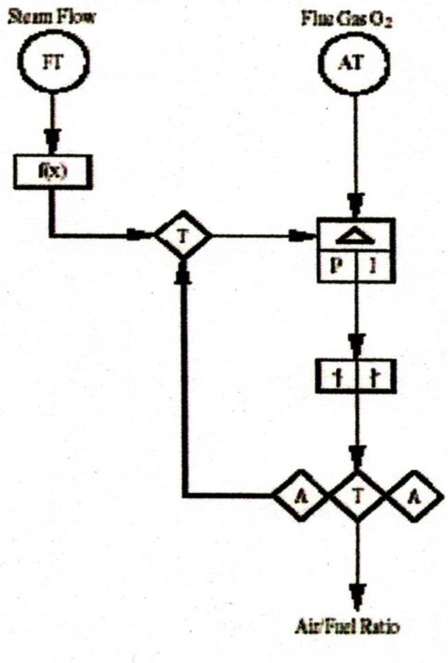


Figure (3): O2 Trim Control [3, 11].

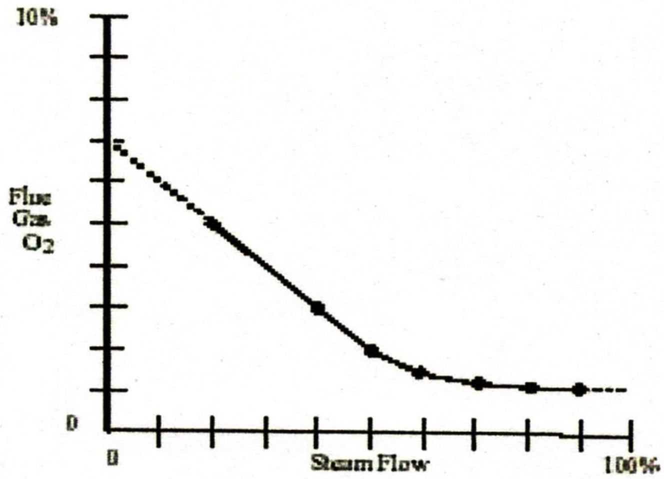


Figure (4): O2 Characterizer [3, 11].

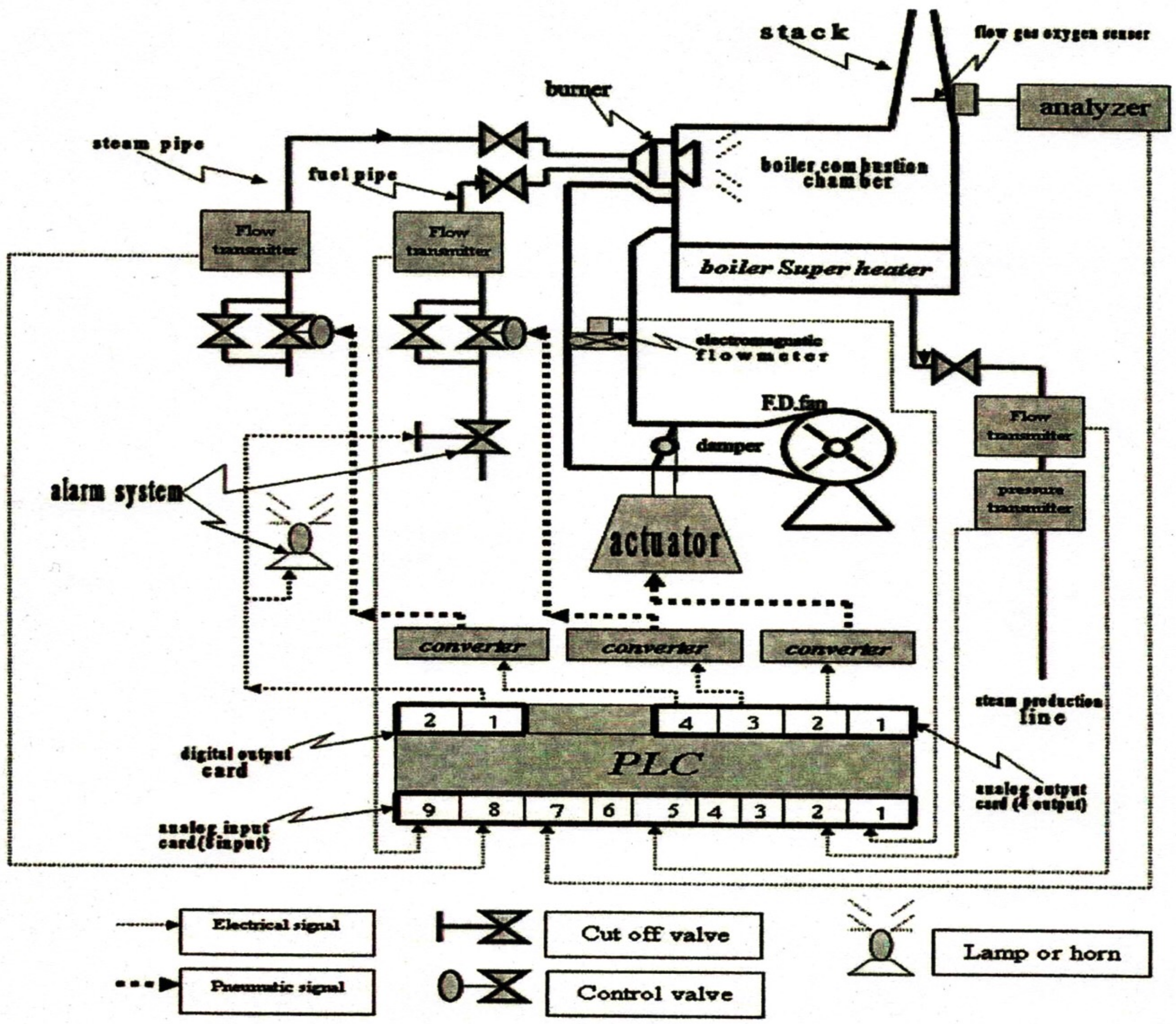


Figure (5): Combustion and air combustion systems with full metered control loops.

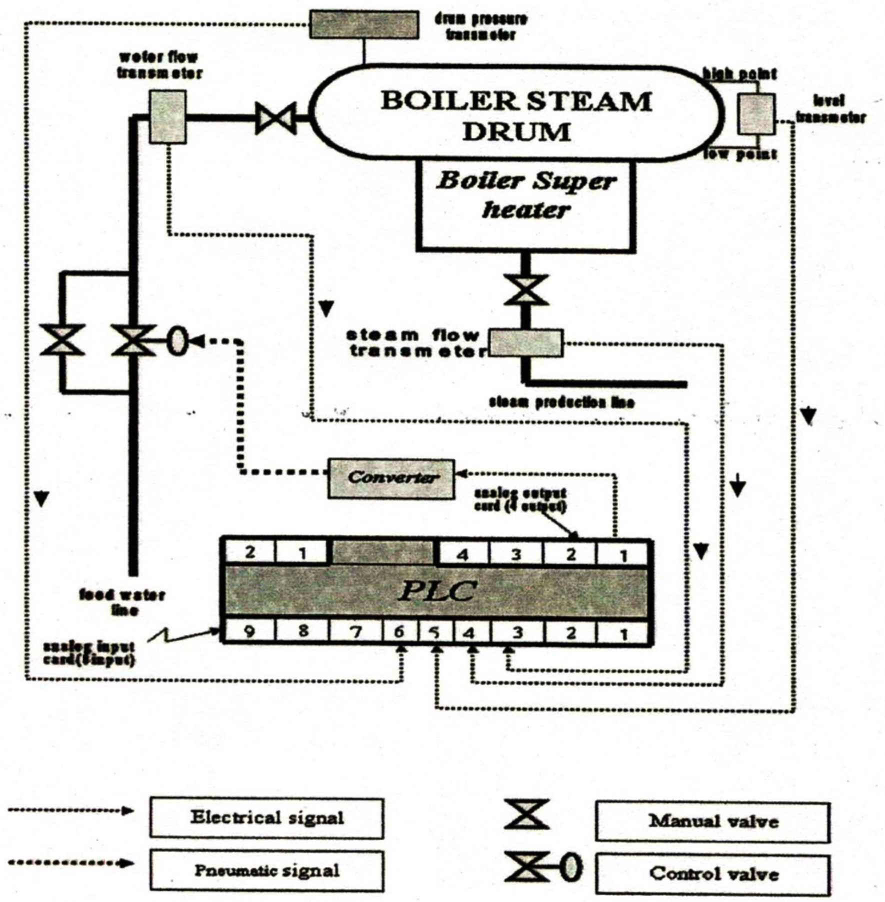


Figure (6): Boiler feed water system with control loops (single / three elements).

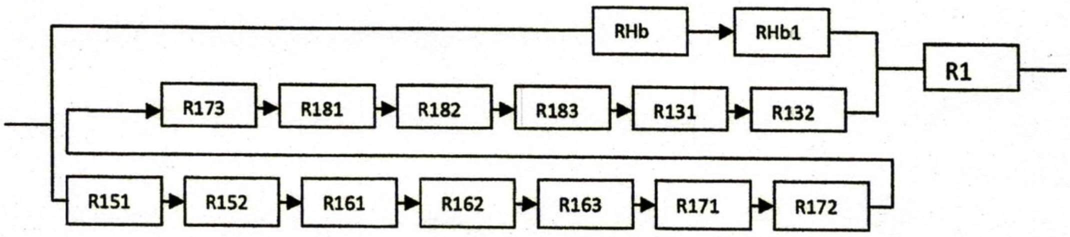


Figure (7): Reliability block diagram for firing system.

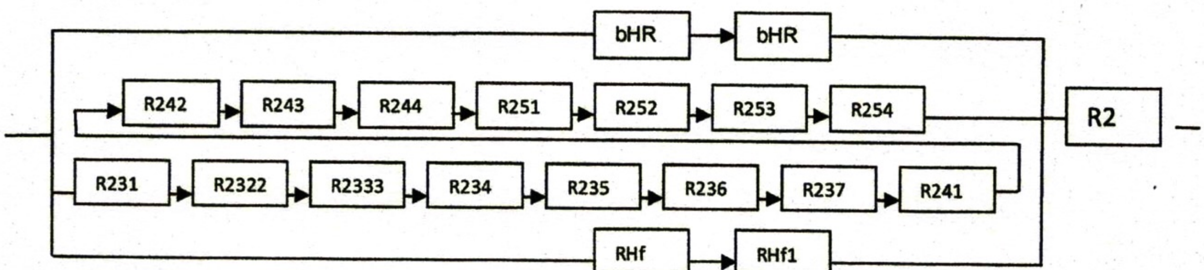


Figure (8): Reliability block diagram for water system.

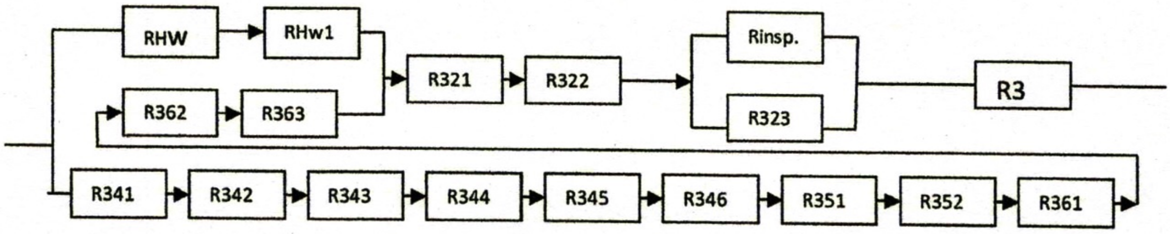


Figure (9): Reliability block diagram for air combustion system.

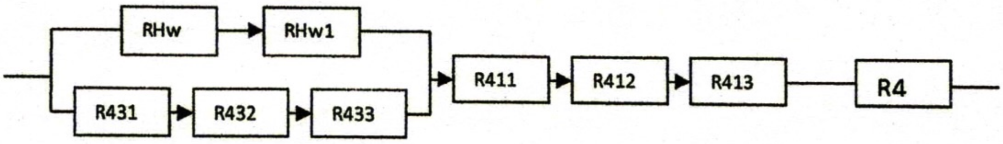


Figure (10): Reliability block diagram for soot blowing and blow down systems.

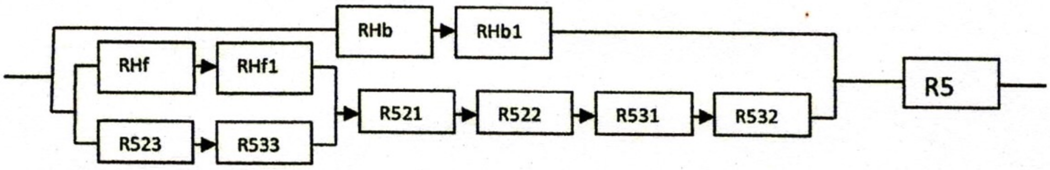


Figure (11): Reliability block diagram for boiler fire side.

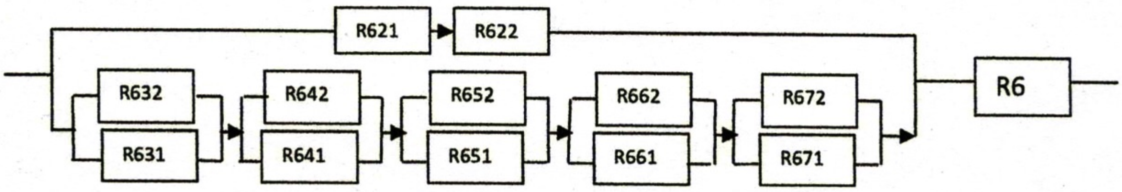


Figure (12): Reliability block diagram for boiler maintenance and boiler inspection.

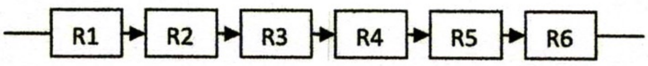
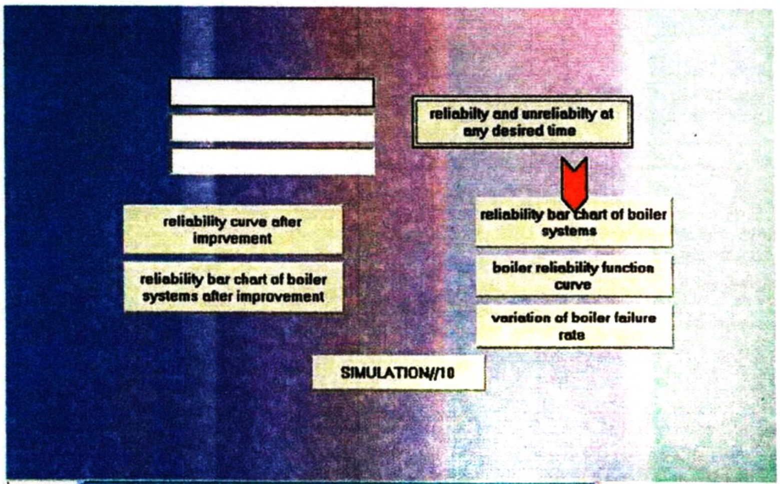
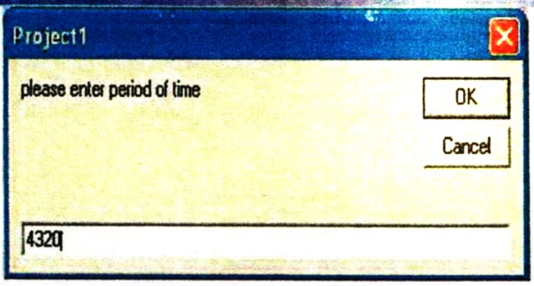


Figure (13): Reliability block diagram for boiler.





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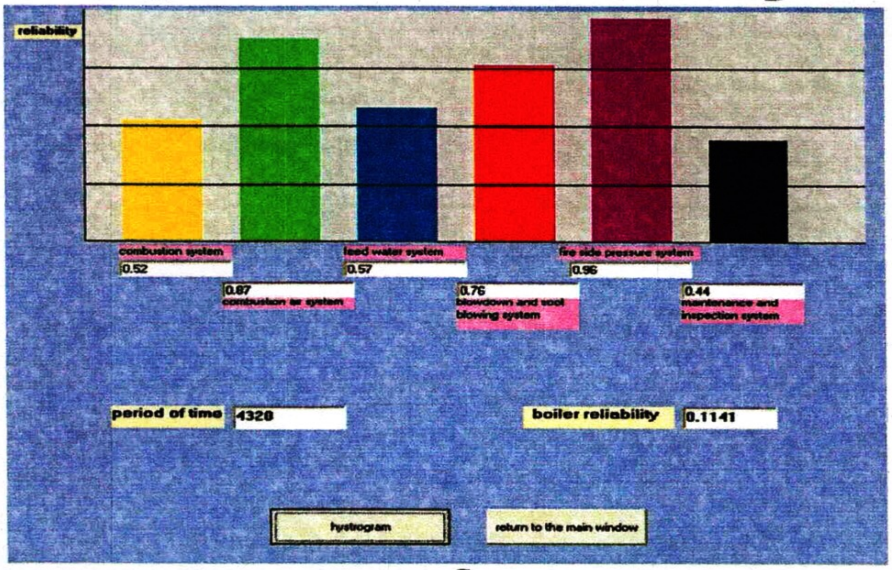

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Figure (14): (A) main window, (B) input box, (C) boiler and its systems reliability.

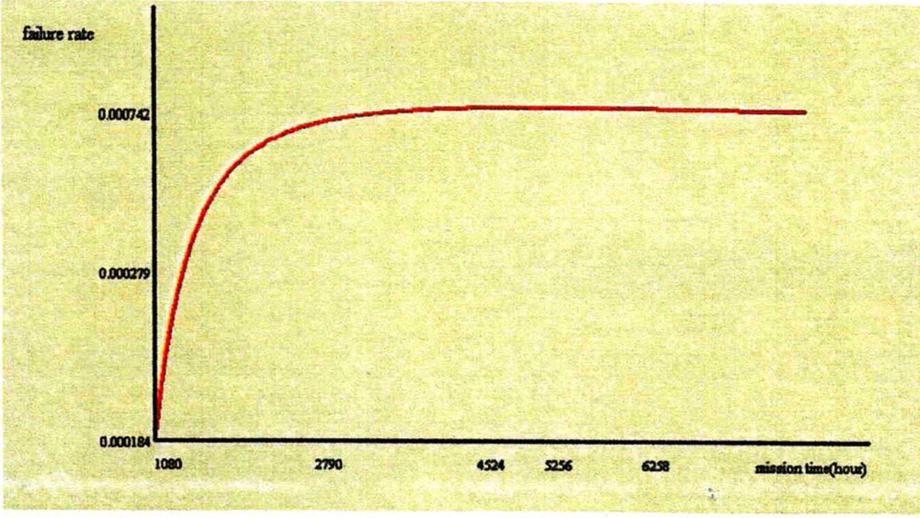


Figure (15): Boiler failure rate curve.

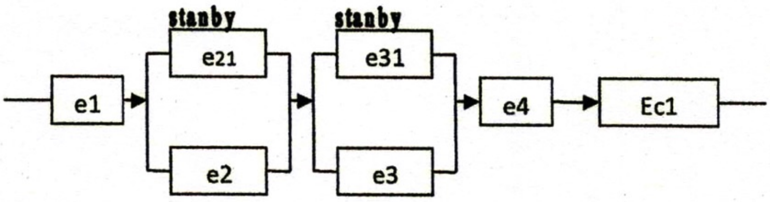


Figure (16): Reliability block diagram for level control loop.

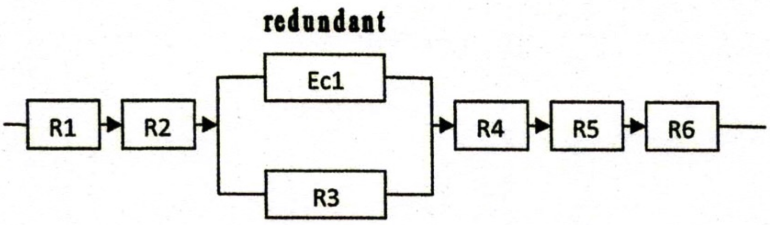


Figure (17): Reliability block diagram for boiler with level control.

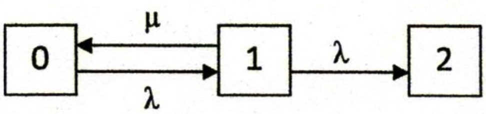


Figure (18): Transition state of system with two identical standby components.

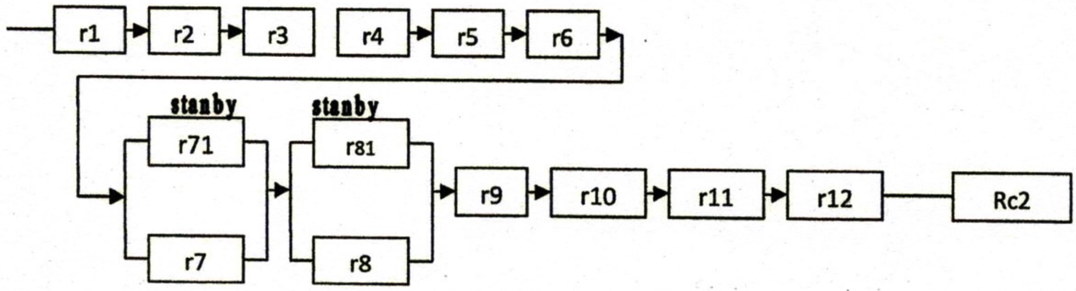


Figure (19): Reliability block diagram for full metered cross limited control system.

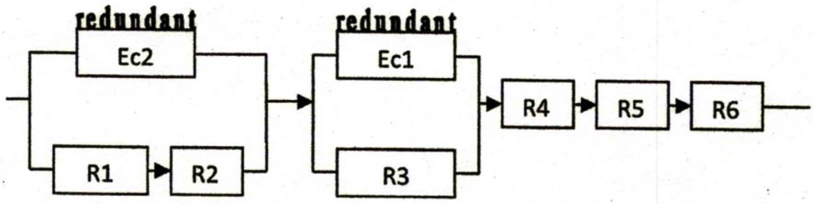


Figure (20): Reliability block diagram for boiler with level control and full metered cross limited control system.

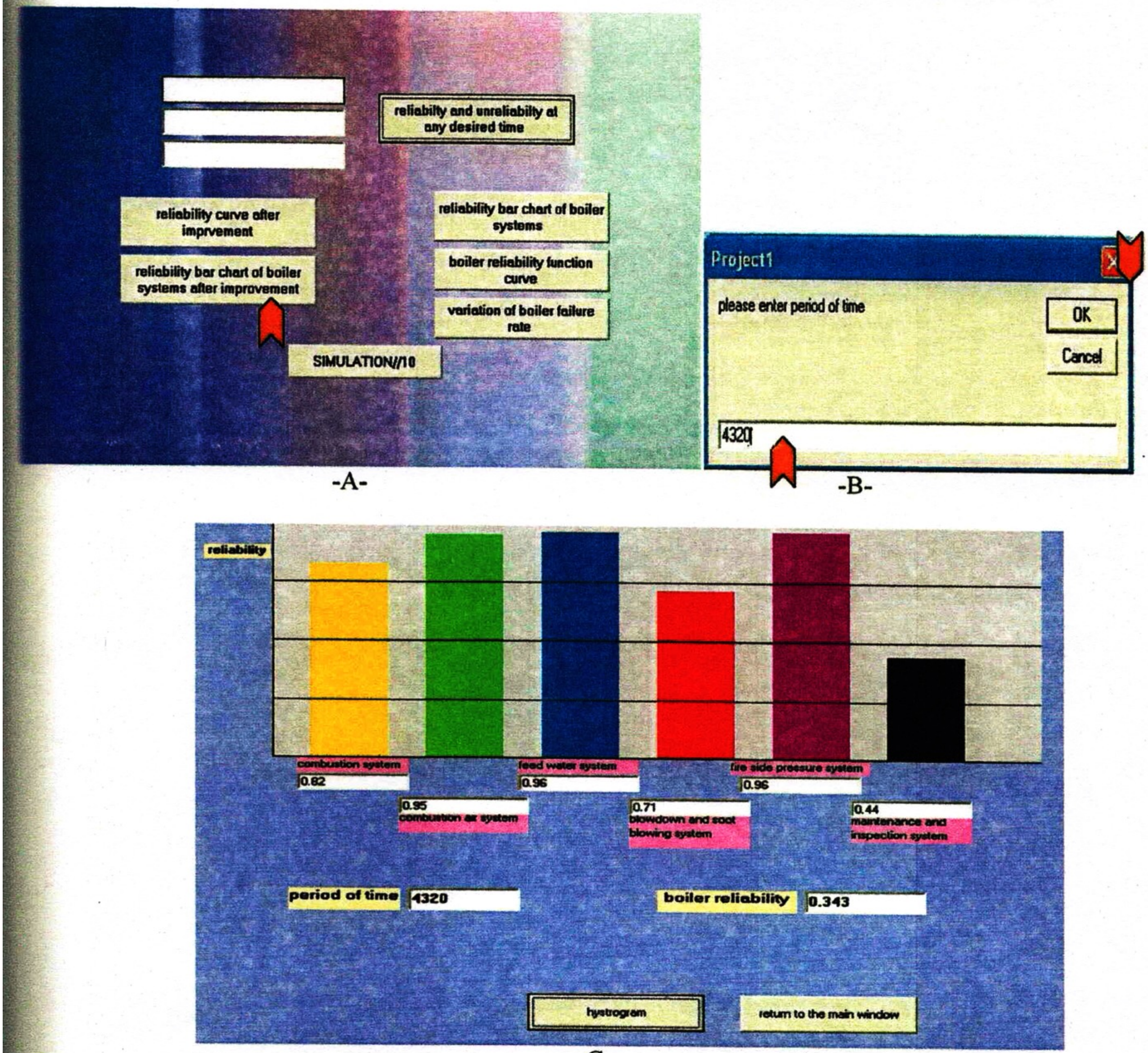
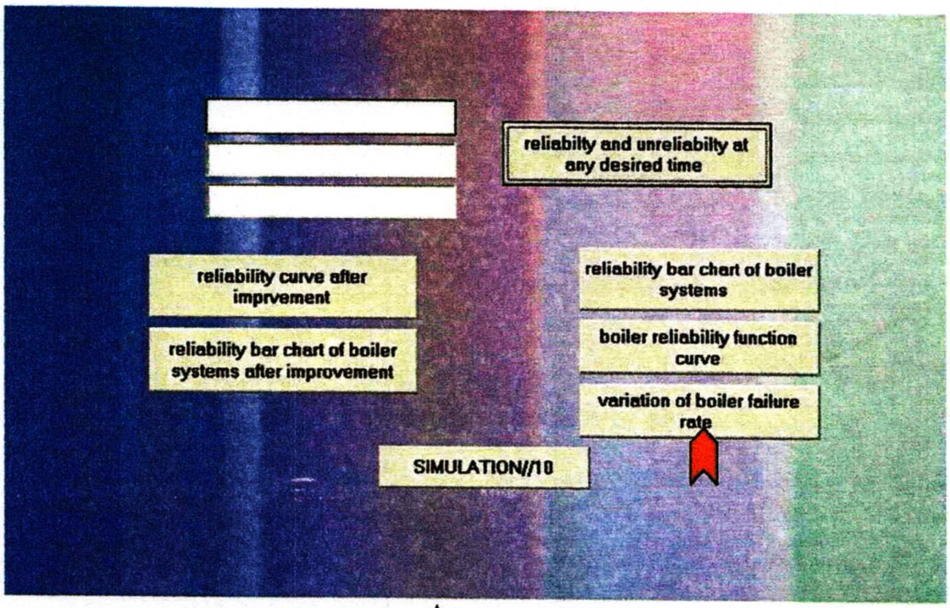


Figure (21): (A) main window, (B) input box, (C) boiler and its systems reliability.



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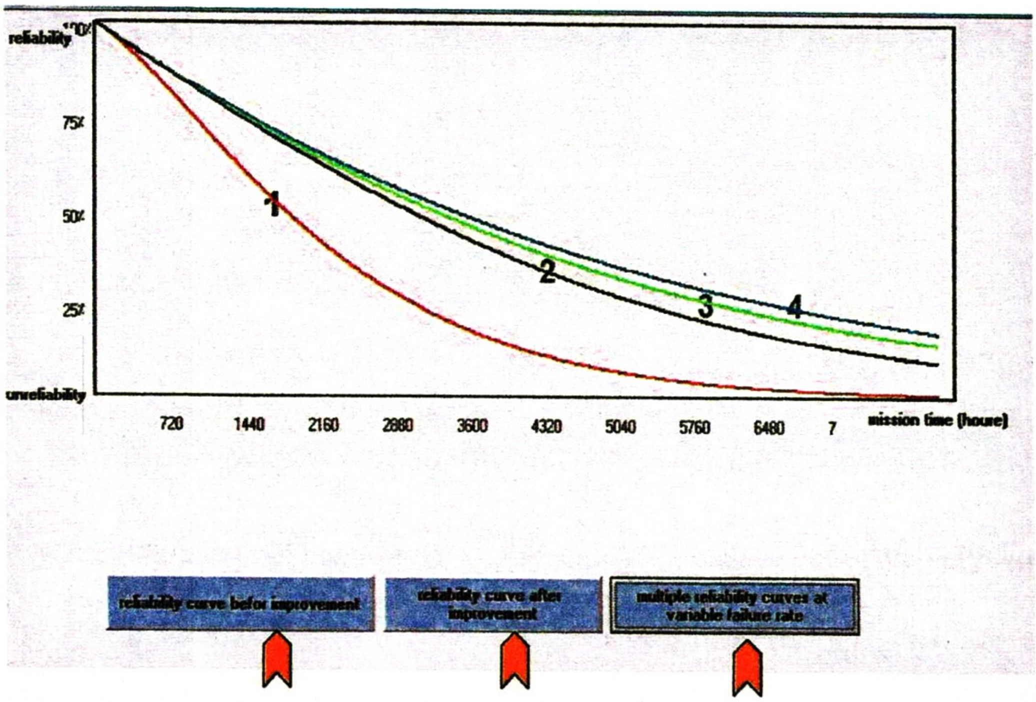

-B-

Figure (22): (A) main window, (B) four reliability functions.