# Availability based maintenance scheduling in Domestic Hot water of HVAC system

Omid Pourhosseini

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Under supervision of
Dr. Fuzhan Nasiri

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By: Omid Pourhosseini

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| **Dr. F. Haghighat** | Chair |
| **Dr. M. Nikbakht** | Examiner |
| **Dr. A. Mohamadi** | Examiner |
| **Dr. F. Nasiri** | Supervisor |

Approved by:

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Dean of Faculty

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# Abstract

Reliability centered maintenance is an analytical tool for preventive maintenance planning. The availability based maintenance method is a branch of reliability centered maintenance, which considers mean time to failure (MTTF) and mean time to repair (MTTR). MTTF of a system is identified from the reliability distribution of its components, and MTTR defines maintenance period of components. In this sense, a reliability function is determined from historic failure data of components during their operation period (in form of a bathtub curve). MTTF is calculated based on this reliability function. This thesis is based on availability based maintenance on the domestic hot water (DHW) of HVAC system, which incorporates the time needed for maintenance of components in availability analysis. The Keeping system availability (KSA) method provides maintenance scheduling by considering the outcomes of the maintenance on the DHW system, while maintaining the availability of the current system. This method has been developed in the maintenance scheduling of power plants as the continual availability of the power generation systems is a critical issue. We have adopted this approach for DHW system of HVAC, which is a critical component in provision of hot water during long cold seasons in Canada. The availability based maintenance approach with KSA decision process has been developed to optimize the maintenance schedule of components in order to prevent over-maintenance. For this purpose, we rely on MTTF and MTTR. MTTF is quantified by the reliability function in a component, and its value should be modified based on pre-defined scenarios, which indicate average maintenance interval (AMI) types. Then, the existing components with a different maintenance times are sorted according to the maintenance effect on keeping the availability of the system, while reducing the maintenance cost. The sorting list is divided into two groups: top loop (components with low maintenance effect), and bottom loop (components with high maintenance effect). After running the KSA decision process, the outcomes consist of different "STEP NO" with different combinations of maintenance scenarios in the existing components in the DHW system. The main criterion in selection of the "STEP NO" is to have the modified availability (system with maintenance plan) equal to or greater than the current system availability

(system without maintenance plan). In the next step, we examine changing the arrangement of the heat transfer sub-system from parallel to standby in order to reduce maintenance cost, while keeping the availability of the system at the same level. In addition, a replacement analysis is performed on the heat exchanger to identify the replacement time in its repairable subcomponents. Finally, a life cycle cost (LCC) analysis is performed to compare the maintenance cost and replacement cost between these two options.

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# Nomenclatures

| | | | |
|---|---|---|---|
| DHW | Domestic Hot Water | a | Availability |
| RCM | Reliability centered Maintenance | $\Delta a$ | Maintenance effect |
| RRCM | Reliability& Risk centered Maintenance | α | Weibull scale parameter |
| MTTR | Mean Time to Failure | β | Weibull shape parameter |
| MTTF | Mean Time to Repair | λ | Exponential failure rate |
| λ(t) | Hazard function | k | Rayleigh parameter |
| f(t) | Failure density function | t | time |
| R(t) | Reliability function | $f_T^*(t)$ | Modified failure density function |
| $R_{pi}$ | Pipe reliability function | $R_T^*(t)$ | Modified reliability function |
| $R_B$ | Boiler reliability function | AMI | Average maintenance interval |
| $R_{Bu}$ | Burner reliability function | $T_M$ | Maintenance interval time |
| $R_{Fa}$ | Fan reliability function | $N_f$ | Number of failure |
| $R_{Sv}$ | Safety valve reliability function | $N_s$ | Number of survive |
| $R_{Tu}$ | Tube reliability function | $N_0$ | Total number |
| $R_{Cv}$ | Check valve reliability function | $C_1$ | Repair cost |
| $R_{Gv}$ | Gate valve reliability function | $C_2$ | Replacement cost |
| $R_p$ | Pump reliability function | $T^*$ | Optimum replacement time |
| $R_{He}$ | Heat Exchanger reliability function | F | Future value |
| $R_{Tb}$ | Tube Bundle reliability function | P | Present value |
| $R_{Bp}$ | Baffle Plates reliability function | i | Interest rate |
| $R_G$ | Gasket reliability function | HEC | Heat Exchanger cost (purchase) |
| $R_{HT}$ | Heat Transfer component reliability function | X | Unit man-hour cost |
| $R_{DHW}$ | Domestic Hot Water reliability function | TB | Tube Bundle cost (spare part) |
| $R_{HP}$ | Heat production reliability function | BP | Baffle Plates cost (spare part) |
| $R_{DU}$ | Distribution (Utility medium) reliability function | G | Gasket cost (spare part) |

| | | | |
|---|---|---|---|
| $R_{DP}$ | Distribution (Process medium) reliability function | erf(x) | Error function |
| $R_{HT}$ | Heat transfer reliability function | | |

# Introduction

The concept of maintenance, be it preventive or corrective, plays a very important role in sectors such as manufacturing, construction, production to mention but a few. It plays a key role in enhancing the efficiency of any system as well as decreasing the possibility of the occurrence of accidents. Maintenance can either be predictive, preventive or corrective; however, a periodic preventive maintenance provides the possibility of cost efficiency gains by improving the reliability of a system, avoiding failure and preventing defects.

The conventional approach to maintenance relies on the accuracy of failure data as well as the experience of the operations team. However, in reality, obtaining a reliable failure database is a demanding task that is not easily accomplished. Improvements in technology also lead to corresponding changes in failure pattern, thereby increasing the difficulty in obtaining a reliable failure database. This reduces the advantages gained from the long term experience of operators as their experience is usually not compatible with the advanced systems. In order to reduce the chances of failure, maintenance teams typically choose over-maintenance, which leads to a considerable increase in the maintenance cost. Adopting the preventive maintenance approach also has its own disadvantages, which include, having difficulty to access sufficient failure data, Involving many physical parameters, getting involved with complex models, and having difficulty in determining model parameters by using actual data.

The main objective of reliability centered maintenance (RCM) is to reduce maintenance cost, while increasing reliability and safety at the same time. Several researchers have proposed methodological improvements in RCM. Stremel [1] suggested a probabilistic maintenance scheduling method for organizing system planning using hourly load distribution and the system generating outage distribution. Yamayee, Mukherjee [2] [3] considered minimizing production cost as a criterion for maintenance scheduling by presenting a multi-component objective function, which includes the reliability and production cost. Marvn [4] proposed a sequence to RCM approach and discussed. Selvik and Aven [5] proposed reliability and risk centered methodology (RRCM), which is an extension of RCM. R. Jamshidi [6] proposed a mixed integer nonlinear model to optimize the quality cost, maintenance cost, earliness-tardiness cost, and interruption cost simultaneously for identical parallel components. C. Li, Y. Zhang [7] proposed a reliability based maintenance under imperfect predictive maintenance, which keeps the system reliability at the same level. J. A. Caldeira Duarte [8] suggested an algorithm to determine the frequency of preventive maintenance for components with linear hazard function and constant repair rate. Although there are many methods in reliability based maintenance in the literature, they are difficult in application especially for complicated systems.

This research relies on the availability based maintenance. In this method, the time during maintenance in components is involved in availability analysis, which has an advantage in comparison with the reliability based maintenance approaches. The maintenance scheduling of a domestic hot water subsystem (DHW) in the HVAC system is targeted by optimizing availability time. The availability-based maintenance approach has been developed to optimize the maintenance schedule of components in order to prevent over-maintenance, and it relies on mean time to failure (MTTF) and mean time to repair (MTTR). MTTF is calculated based on the reliability analysis of each component, and the quantitative value of MTTF should be modified based on pre-defined maintenance interval times, which are called average maintenance interval (AMI) types. It is important to note that the measure of availability in the components and system are relevant to the AMI. Then, the components with different AMI types are sorted in ascending order based on the maintenance effect, which is derived from component availability. Increasing the amount of maintenance in components with high maintenance effect improves system availability, while decreasing the amount of maintenance in components with low maintenance effect reduces over-maintenance in the system. In this rearrangement process of average maintenance interval, increase in system reliability must be greater than or equal to a reduction in system availability. The optimized maintenance interval is obtained by application of a decision process, which is detailed in section 2. Before starting this research, I had lots of meetings with facility manager, and he explained me about the problem whenever the heat exchanger in the DHW system is out of service especially in the winter. The main focus of this work, however, is on the heat exchanger as part of the heat transfer sub-system, which is a critical component in domestic hot water system in terms of cost. The failure of a heat exchanger in a cold season leads to considerable energy cost as the system is switched to an electrical heater. Therefore, seasonal availability plays a major role in planning.

The main subcomponents of a heat exchanger, which usually require replacement due to the propensity for failure, are the tub bundle and baffle plates. It therefore becomes imperative to organize a replacement plan for these subcomponents. The replacement plan should identify the replacement interval in order to optimize the usage of spare parts as well as ensure the steady availability of the component.

The aim is to provide preventive maintenance scheduling for the DHW system of HVAC in a commercial building. It is located in Canada, which has a long cold season, so seasonality has a major role in preventive maintenance in the DHW system. In fact, lack of hot water during winter could have major consequences for occupants. Therefore, the availability of the existing sub-systems (heat production sub-system, distribution sub-system, heat transfer sub-system) and their components in the DHW system plays a key role during the operation period. In addition, it is possible to improve the reliability of the system by changing the system structure (parallel to standby).

As a result of the climate in Canada, it is necessary for HVAC systems to operate without interruption during long cold seasons, the motivation for selecting availability based maintenance is to have steady state in operation period without interruption especially in the winter. So, the availability of components in the mentioned system has a major role in maintenance planning. In fact, availability based maintenance is common in a number of industries such as power plants that the continual availability of power generation system is a critical issue.

We will go through the following steps to plan availability based maintenance in DHW of HVAC system.

1. Determining reliability function in components based on failure data along with system reliability analysis
2. Identifying the degree of sensitivity in reliability parameters in the components Performing

3. Performing availability based maintenance along with applying KSA decision process for maintenance scheduling
4. Switching from parallel to standby system to improve system reliability and decline maintenance cost
5. Performing optimum replacement analysis on the heat exchanger in order to determine the replacement interval in its repairable subcomponents
6. Doing life cycle cost (LCC) analysis to compare maintenance cost between the parallel structure and the proposed standby structure in the heat transfer sub-system

This research is divided into five sections:

**Section one** provides background information on the research. The aim, objectives and significance of the study are provided. It covers the literature review of reliability centered maintenance (RCM), the concept of reliability and some important aspects of reliability applicable to this research. An explanation about the function of DHW system and its related components is also given.

**Section two** covers maintenance scheduling methodology based on availability analysis by Keeping System Available (KSA) as well as related decision process. The application of optimum replacement interval method is used to quantify the time interval in replacement components. The mathematical procedure for solving equations is also explained.

**Section three** presents a case study along with methodology, sequence in reliability analysis, sensitivity analysis, availability analysis, KSA approach, and optimum replacement method. In addition, an alternative for restructuring heat transfer sub-system from parallel to standby is proposed, and related analysis, availability impact, and cost impact are also explained. Finally, this proposed sub-system is compared with the current parallel heat transfer sub-system.

In **Section four**, the research results are presented together with the applied research methods and the assumptions made in the entire process of the analysis.

**Section five**, discusses the research outcome, which includes finding, limitation as well as future work (mathematical modeling). Also a proposed numerical model to calculate MTTF based on the Weibull reliability parameters (the scale and shape parameters) is presented in the “Future Work”.

# 1. Literature Review

## 1.1 Reliability theory and background

In the reliability approach, there are some key terms, which are fundamental, in the system analysis based on the uncertainty approach. Therefore, it is vital to explain these terms before discussing the analysis [9].

**Component** is a piece of equipment or unit, which is part of a system or sub-system. Components are independent in the system in terms of functioning, and its failure does not influence the failure of other components.

**System** is a collection of components in different structural organizations such as series, parallel, standby, complex, and it is expected to perform predetermined functions.

**Failure** is defined as any disorder in the functioning of a system, which causes unsatisfactory performance in the system operation.

**Failure rate** is an immediate conditional probability per unit time, which indicates the failure probability of the component in the next time interval given that it has survived up to that time.

**Hazard function** is taking the limit of the failure rate as the length of the interval approaches zero (Eq-1) [9].

$$\lambda(t) = \lim_{\Delta t \to 0} \left(\frac{survived\ unit\ at\ t\ and\ failure\ during\ (T, T + t)}{survived\ unit\ during\ (0, T)} \times \frac{1}{\Delta t}\right)$$

$$\lambda(t) = \lim_{\Delta t \to 0} \frac{Q_c(t)}{\Delta t} \tag{1}$$

Where $Q_c(t)$ is conditional probability.

**Reliability** is defined as the probability of the component or system that will perform its intended function in a specific time interval under stated conditions.

**Availability** is the ability of a component, which is required to perform expected function in specific time, and it is concerned with the duration of up-time in operations.

Reliability function is a continuous probabilistic approach, which represents the chance of survival in components. The mathematical form is given by (Eq-2) [9]:

$$R(t) = P(T \geq t) \tag{2}$$

Where R(t) is reliability of the component, $P(T \geq t)$ is the probability that a component will fail after its service time, T is time to failure, and $t$ is continuous random variable [9].

Hazard function $(\lambda(t))$ identifies the potential of a component in terms of failure as a function of its age or operation time. It represents the fluctuations of reliability versus time as a result of different factors such as environment, maintenance, loading, and operating condition. The general form of hazard function is given by (Eq-3) [9]:

$$\lambda(t) = \frac{f(t)}{R(t)} \tag{3}$$

Where $f(t)$ is failure density function and R(t) is reliability function.

The hazard function can be increased, decreased or stayed constant, which illustrates the failure pattern of most mechanical and electrical components. This is known as bathtub curve, which is shown in Figure 1. The first zone illustrates a high initial failure rate, which has a descending trend versus time until it reaches a constant value. This area is called infant mortality region (burn-in), and it is associated with workmanship or quality control. The second zone represents the useful life phase, which has a constant hazard rate. In this area, components fail as a result of random events. Finally, the third zone indicates the wear-out phase where aging and deterioration are the main causes of failure in components.

Generally, the useful life region in electromechanical devices is much longer than the other two regions in the bathtub curve. In electronic components, the failure characteristics is dominated by useful life region, while in mechanical units, the failure pattern is controlled by wear-out region. Two examples of bathtub curves in the mechanical and electrical components are given in both Figure 2a, Figure 2b.

Mean Time to Failure (MTTF) is defined as the expected value of the continuous random variable, which evaluates the quality of a component in terms of functionality during operation [9]. The general form of MTTF is defined in Eq-4 [9].

$$MTTF = \int_0^{\infty} t \times f(t)dt = \int_0^{\infty} R(t)dt \tag{4}$$

In engineering reliability, there are different distribution functions, which are compatible with the pattern of failure in an equipment. The distribution functions, which are used commonly, are exponential, Weibull, and Rayleigh. A brief explanation concerning their characteristics and mathematical aspects will be given in this part.

The exponential distribution is a type of distribution, which is used more often in reliability analysis. It gives the simple, constant hazard rate model, and it is defined by one model parameter. Deterioration effect is not considered in exponential distribution, but it is a good measure during the useful life of components. All relevant equations are illustrated as follows (Eq-5, 6) [9]:

$$f(t) = \lambda \times \exp[-\int_0^{t} \lambda\, d\xi] = \lambda \times \exp(-\lambda t) \tag{5}$$

$$R(t) = \exp[-\int_0^{t} \lambda\, d\xi] = \exp(-\lambda t) \tag{6}$$

The mean time to failure (MTTF) is the average length of the life in all components, which are selected as population of a sample. In exponential distribution, $MTTF$ is given by (Eq-7) [9]:

$$MTTF = \frac{1}{\lambda} \tag{7}$$

The Rayleigh distribution is defined in terms of a single parameter (K), and it is beneficial in the modeling of both the burn-in and wear-out regions. All relevant equations are illustrated as follows (Eq-8,9,10) [9]:

$$\lambda(t) = Kt \tag{8}$$

$$f(t) = Kt\, \exp[-\frac{Kt^2}{2}] \tag{9}$$

$$R(t) = \exp[-\frac{Kt^2}{2}] \quad (10)$$

The Weibull distribution has a wide range of application in reliability analysis as a result of its flexibility in representing hazard function. All three zones in the bathtub curve (burn-in, useful life, and wear-out region) can be presented by Weibull distribution. It is defined by scale parameter (α) and shape parameter (β). Hazard function, failure density function, and reliability function in Weibull distribution are denoted as follows (Eq-11, 12, 13) [9]:

$$\lambda(t) = \frac{\beta t^{\beta-1}}{\alpha^{\beta}} \quad (11)$$

$$f(t) = \frac{\beta t^{\beta-1}}{\alpha^{\beta}} \exp[-\left(\frac{t}{\alpha}\right)^{\beta}] \quad (12)$$

$$R(t) = \exp[-\left(\frac{t}{\alpha}\right)^{\beta}] \quad (13)$$

Weibull distribution is appropriate for a system or complex component with several parts. For $0 < \beta < 1$, the Weibull distribution represents burn-in or early failure. In a unit shape parameter, the Weibull distribution is similar to an exponential distribution, and it represents useful life. For shape parameter greater than one, the Weibull distribution explains wear-out characteristics in components. If β=1, the form of Weibull distribution is changed to the exponential distribution with a constant hazard rate of $1/\alpha$. If β=2, the Weibull distribution is transformed to the Rayleigh distribution with $k = 2/\alpha^2$.

## 1.2 Engineering reliability analysis

Generally, a system includes a collection of components, which have their own individual roles, in the system function, and system reliability analysis starts form its components. In reliability analysis, it is important to identify the reliability function in all individual components, and define their relationship in a system. Finally, a failure distribution, which is compatible with the reliability trend of the system, should be assigned.

In terms of system analysis, complex systems are disintegrated into sub-systems, components, and sub-components in order to perform reliability analysis. In addition, network modeling techniques are used to connect components in series, parallel, series-parallel, star & delta or any combination and to calculate the reliability of the system. Usual structures are determined based on parallel or series methods. For complicated structures, in order to calculate a system reliability, it is necessary to consider other advanced methods such as event-space, decomposition, minimal cut-set, minimal path-set, connection matrix technique, and so on. In brief, a number of common system structures are illustrated in this study. A basic reliability prediction relies on a simplified block diagram, which is applicable in reliability analysis of the entire system. In series structure, the whole system fails if any individual component in the system fails. Thus, the system operation relies on the successful working of all components in the system [9]. In this configuration, the reliability of the system has a negative correlation with the number of components. This system can be schematically represented by the block diagram, which is shown in Figure 3.

The system reliability in this case with $N$ independent components in time $t$ is quantified by Eq-14[9].

$$R_s(t) = R_A(t) \times R_B(t) \times R_C(t) \times \ldots\ldots R_N(t) \tag{14}$$

The failure rate in series structure is quantified by the summation of failure rate in the system (Eq-15) [9].

$$\lambda_s(t) = \sum_{i=1}^{N} \lambda_i(t) \tag{15}$$

In a system with parallel structure, the system fails whenever all of the components stop functioning; so, the performance of the system is dependent on the functioning of at least one component [9]. The block diagram in parallel system is illustrated in Figure 4.

The system reliability calculation in parallel structure is given by Eq-16, 17) [9].

$$R_s(t) = 1 - [1 - R_A(t)] \times [1 - R_B(t)] \times [1 - R_C(t)] \quad (16)$$

Or

$$R_s(t) = 1 - \prod_{i=1}^{N} [1 - R_i(t)] \quad (17)$$

The failure rate in parallel structure is measured by Eq-18, 19) [9].

$$\lambda_s(t) = -\frac{d}{dt}[Ln\, R_s(t)] \quad (18)$$

$$\lambda_s(t) = -\frac{d}{dt}\left[Ln\,\{1 - \prod_{i=1}^{N} [1 - R_i(t)]\}\right] \quad (19)$$

Another configuration which is used widely is standby structure. A two-component standby redundant system consists of a main component and a standby unit, which is ready to be in operation whenever the main component is failed. At that time, the standby component is put to service immediately by using a manual or automatic switch device (changeover switch).

Standby structure with one standby component is classified into two major groups [9]: perfect switching, which is assumed that switch never fails, and Imperfect switching that considers the possibility of switch failing. There are also more cases in which the number of standby components are more than one, and they are classified into six types as follow:

**Case1** (Perfect switching) includes two identical components-one main unit and one standby unit.

**Case2** (Perfect switching) consists of three identical components-one main unit as well as two standby unit.

**Case3** (Perfect switching) contains one main unit and “n” standby unit.

**Case4** (Imperfect switching) includes one main unit plus an identical standby unit.

**Case5** (Perfect switching) contains two non-identical units-one main unit and one standby unit.

**Case6** is the same as Case5 except the failure in standby unit is also taken into account.

In this research, the P&ID indicates that the two components in the heat transferring sub-system are identical. In addition, for the sake of easiness in calculation, it is assumed that the failure in the changeover switch, and failure in standby components are not considered, so the Case1 is proposed in the heat transfer sub-system as an alternative instead of parallel structure. The relevant calculation is given in details in the section 3 (Case study).

The concept of perfect switching in standby structure (one main unit and one standby unit) illustrates that the standby component is brought into service by changeover switch whenever the main component fails [9]. Success of the system is dependent on zero failure or one failure in the system (Eq-20) [9].

$$P_0(t) = P(zero\ failure)$$
$$P_1(t) = P(one\ failure)$$
$$R_s(t) = P_0(t) + P_1(t) \tag{20}$$

The general form in the standby structure (perfect switching) is defined based on the fact that both the main component and standby component are not identical in terms of characteristics and reliability. The period of operation is between 0 and t. The reliability of the system is calculated based on the summation of two events (zero failure reliability and one failure reliability), which are illustrated as follows [9]:

- The main unit does not fail in the time interval $(0, t)$, which denotes zero failure $(P(zero\ failure))$
- The main unit does not fail until time $\tau < t$, and the standby unit does not fail in the time interval$(\tau, t)$ , which implies one failure $(P(one\ failure))$ .

In this expression, $\tau$ is the time when the main component stop functioning. The general form of reliability function in a standby system is illustrated based on the following analysis in (Eq-21, 22, 23) [9].

$$P(zero\ failure) = R_m(t) \tag{21}$$

$$P(one\ failure) = \int_0^t f_m(\tau)d\tau * R_s(t-\tau) \tag{22}$$

$$R_{sub-system} = P(zero\ failure) + P(one\ failure) \tag{23}$$

$R_m(t)$, $f_m(\tau)$, and $R_s(t-\tau)$ are reliability function of main component, failure density function of main component at the time of failure $(\tau)$ , and reliability function of standby component after failure of main component $(\tau)$ until time $t$ when the standby unit is failed $(t-\tau)$, respectively. In this study, it is assumed that the standby unit does not fail at time $\tau$ (changeover time), so the effect of this failure in the standby unit is ignored. This system is schematically represented by the block diagram which is shown in Figure 5.

Generally, complex system is a combination of series and parallel structures. The principle in the analysis of complex system is to break it down into basic series and parallel sub-systems. Then, the reliability of these sub-systems is calculated separately. The probability of entire system is determined based on how these sub-systems are connected. This system is represented by block diagram, which is shown in Figure 6.

## 1.3 Reliability centered maintenance

Reliability centered maintenance (RCM) is a technique to organize preventive maintenance (PM), which relies on the reliability of the equipment as a function of design and build quality, but it cannot improve the reliability of the system [4]. RCM is an analytical method for planning a preventive maintenance in systems and reliability is a quantitative tool utilized in order to identify preventive maintenance task and its interval.

Preventive maintenance is performed at constant time interval even if the system is still functioning, so it is expected to improve the life span of the existing components in the system, reduce system failure and increase the Mean Time to Failure (MTTF) of the system [9]. RCM is applied to stabilize both the cost and benefits, which are important in preventive maintenance. The outcomes of PM are usually a reduction in the expected loss related to personal injuries, environment damage, production loss and material damage.

Generally, Preventive Maintenance cannot prevent all failures within a system, so the consequence and the probability of each failure should be identified. RCM method is analyzed based on twelve stages as follows [4]:

1. Study preparation
2. System selection and definition
3. Functional failure analysis (FFA)
4. Critical item selection
5. Data collection and analysis
6. FMECA (Failure mode ,effect and critically analysis)
7. maintenance type selection
8. Determination of maintenance interval
9. Preventive maintenance comparison analysis
10. Treatment of non-critical items
11. Implementation
12. In-service data collection and updating

The sequence in RCM is presented in the following diagram in Figure 7.

## 1.4 Availability analysis

Conceptually, Availability is the ability of a component, which is required, to perform expected function in specific time interval. “Availability deals with the duration of up-time in operation, and it is a measure to assess how often a system or component is alive and well” [10]. It is illustrated as the rate of up-time to the accumulation of up-time as well as downtime, which indicates the probability of a component or system while it is up-time.

Effectiveness in a production system is dependent upon the number of indices such as the magnitude, frequency, and duration of failure in the system as well as cost. Availability analysis is an approach, which leads operators toward improving the productivity of a system. The answer for the optimization of system productivity is based on the outcomes of availability analysis.

Generally, the system is affected during operation period by existing disorders in the functioning of component. Therefore, the maintenance approach has an important role in keeping system functioning optimally. A number of factors (availability, reliability, and cost of shut-down period) should be taken into account before selecting a method for improving the productivity of a system, because of uncertainty in operation during the useful life of a system. The MTTR in a component is an index, which evaluates maintainability of the component, and the MTTF is an index of its reliability. The main requirement in minimizing cost in scheduling a maintenance plan is to balance maintainability and reliability. Availability analysis therefore provides an approach, which minimizes operation cost, and satisfies reliability requirement. In availability analysis, it is assumed that components are repairable.

The definition of availability is dependent on what types of downtime are taken into account in the analysis. Generally, availability is classified into different categories in terms of definition. This classification is presented as follows [10]:

- Point (instantaneous) availability
- Mean availability
- Steady state availability
- Operational availability
- Inherent availability

**Point (instantaneous) availability** is the probability that a system or component is in operational state at a certain time "t". This approach is applicable in military operations in order to measure the availability during certain mission performance.

**The mean availability** is the portion of time during the time interval that a system or component is available in operation. It describes the point availability functioning over the specific time period.

**The steady state availability** illustrates long-term availability. In this case, the system availability could be unstable as a result of training, optimizing repair performance, burn-in state in the system, and so on.

**The operational availability** calculation relies on all experienced sources of downtime. It is based on actual events, which happened in the system. The equation for operational availability is given by Eq-21 [10].

$$A_0 = \frac{Uptime}{Uptime + Downtime} \tag{24}$$

While the up-time is the total time period that a system or component is in functioning during the operating cycle period, the operational cycle is the overall time period of operation as well as downtime,

**Inherent availability** is the steady state availability when considering only corrective maintenance downtime of the system. Some factors such as preventive maintenance downtime, logistic delay, supply delay, and administrative delay are not taken into account in this category, so the considered availability value is the corrective downtime, which is an intrinsic property of the system. In fact, the corrective downtime illustrates the efficiency of maintenance performance, which include the degree of experience in the maintenance team to handle maintenance issues. Estimation of inherent availability relies on mean time to failure (MTTF) and mean time to repair (MTTR).  In this study, inherent availability is used to compute the availability of the components and system in different time intervals.

## 1.5 DHW system in HVAC

### 1.5.1 Service water heating

Service water heating is one of the most important facilities in different types of buildings. In some climate conditions, water heating system consumes a large amount of energy in buildings, so a proper design in water heating system can reduce operation cost. A water heating system includes different parts: heat energy sources, heat transfer equipment, distribution system, and water-heating equipment [11].

Energy can be obtained from a wide range of sources (fuel combustion, electrical conversion, solar energy, geothermal, air, or other environmental energy). It also can be recovered from wasted heat from different sources (flue gases, ventilation and air-condition system) [11].

Concerning heat transfer equipment, it could be direct, indirect or combination of both systems. Concerning direct equipment, heat is extracted from combustion of fuel or indirect conversion of electrical energy into heat. In contrast, in indirect equipment, heating energy is extracted from distance heat sources such as boiler, solar energy collection, air, geothermal or other environmental sources, and it is transferred to water which, is placed in other equipment [11].

Distribution system is in charge of circulating utility medium, and process medium through entire system. Distribution systems transfer produced hot water to terminal hot-water usage device. The consumed water should be refilled from the main water system in a building [11].

Water-heating equipment can be found in different types such as gas-fired system, electrical, indirect water heating, and Instantaneous Indirect Water Heater (tank-less coil). The explanation about indirect water heating is given in this research [11]. Generally, the heating medium in indirect water heating is steam, hot water, or other fluid that has been heated in separate boiler. The heat water obtains heat through an external or internal exchanger. If heating medium is steam, there is a high rates of condensation especially in the case of sudden demand, which causes an inflow of cold water. Indirect water heating is divided into two types as follows [11]:

**Storage water heaters** are required for conditions with variable hot-water demand, and a large volume of hot-water is stored for period of peak load. Generally, an individual tank or a number of tanks for required storage are connected by manifolds.

**External storage water heater** has a separate tank, which is connected to hot-water system. Water in the boiler is circulated through the heater shell, and service water is flowed from storage tank through the tube, and back to the tank. Circulating pump are installed in both the boiler water piping loop and the loop between heat exchanger and storage tank. In this system, steam can be used as a heat transfer substance. (Figure 8)

Waste heat recovery can decrease cost of energy, which results in reducing energy consumption in both building heating and service water heating. Waste heat can be extracted from equipment or process by application of heat exchanger in the hot gaseous or liquid steam. The recovered heat is generally used to preheat the entering water in the service water heater [11].

If one heater does not have enough capacity, two or more water heaters should be used in parallel structure. In this case, parallel heaters should have the same technical characteristics such as input and storage capacity, so the received flow from each heater should be similar. One easy approach to keep balance among parallel heaters is to apply reverse/return piping (Figure 9) [11].

**Boiler for indirect water heating**: Indirect heaters include immersion coil in boiler as well as exchanger with space-heating medium.

### 1.5.2 Equipment

Generally, boilers, centrifugal pumps, and heat exchangers play key role in the function of DHW system. More explanation about the mentioned equipment is given as follows:

**Boilers** are pressure vessels, which are designed, to burn fossil fuels and transfer the released heat to fluid. It is made of cast-iron, carbon, or stainless-steel pressure vessel. A boiler includes burner, fire chamber, tube, fan, flue gas passage, fuel train, and safety and operation controls.

Heat, which is added to medium (steam, hot water) by boiler, is distributed through a building. Heat transfer could be performed from electrical resistance elements to the fluid or by direct action of electrodes on the fluid. Generally, fluid is water in the form of liquid or steam. Steam usually transfers heating energy long distance. Then, steam is converted to low-temperature hot water in a heat exchanger near the point of use. Although steam is an acceptable medium for heat transfer, low-temperature hot water is the most common medium to provide heat [12].

Boilers are classified based on working pressure and temperature, fuel, and material of construction. Concerning pressure, boilers are categorized in different types as low-pressure boiler, High-pressure boiler, steam boiler, and water boiler [12]. Boilers are designed to burn coal, wood, various types of oil fuel, various types of gas fuel, or operate by electricity energy. In terms of construction materials, boilers mostly are made of cast iron or steel. Some small boilers are made of copper covered steel. Condensing boilers are made of stainless steel or aluminum to prevent corrosion in acidic condensate process.

**Centrifugal pumps** provide the primary force to distribute and recirculate the hot water in different places in the system, so pumps provide specific flow water through the system. The hydraulic are divided into different parts as below [12]:

- Condensation water circuits to cooling water
- Water-source heat pumps
- Boiler feeds
- Condensate returns

In centrifugal pumps, an electro-motor or other power sources rotates the impeller at the motor's rate speed. Impeller rotation adds energy to the fluid whenever it is directed to the center of impeller. Then, the fluid is acted by centrifugal and rotational force, which have effect on fluid velocity.

Most centrifugal pumps are single-stage pumps with a single or double-inlet impeller. Double-inlet impeller is applicable in high flow system. In a large system, pump arrangement is classified into three categories: multiple pumps in parallel, multiple pumps in series, and standby pump [12]. In terms of multiple parallel pumps, each pump operates at the same pressure, and provides its effect on the flow of system. In this case, pumps are in the same size. The piping system in parallel pumps should allow each pumps to work individually (Figure 10). A check valve is required to be installed at discharged side of the pump in order to prevent backward flow while pump shutdown. The hand valve (gate valve) allows a pump to be serviced while the other part of system is operating. In addition, a pump is protected from foreign particles by using strainers.

Concerning multiple series pumps, any pump operate at the same flow rate and has its share in total pressure of the system. In order to have successive pressure, all series pumps must work (Figure 11). A bypass hand valve (gate valve) permits servicing one pump while the other pumps are in operation. A strainer removes particles from entering the pump.

Standby pump has the same capacity and pressure is installed in parallel to the main pump, and it is suggested to operate during an emergency situation, when the main pump is broken, to assure that the operation function is performed continuously. The pump arrangement in standby is the same as parallel system.

**Heat exchangers** provide operational and energy recovery opportunities for central heating parts. In addition, air-to-water and water-to-water heat exchangers provide conditions for economizing and heating recovery in a central heating plants. Heat exchangers transfer heat from one fluid to another without any direct contact between fluids. “Heat transfer involves bringing two mediums (utility and process medium) close to each other, so that one medium heats or cools the other one” [12]. Heat transfer performs in exchanger, whenever physical condition of a fluid is changed. These changes could be from liquid to vapor (evaporation) or from vapor to liquid (condensation). Heat transfer also could be performed without phase change such as heat transfer from water to water. Heat exchangers are employed, when heating energy is transferred by different mediums with different pressure and temperature. In fact, specific temperature can be transferred from one medium (utility medium) to another medium (process medium) in heat exchangers.

Heat exchangers are used in most steam systems. Steam-to water heat exchanger are used to heat domesticate hot water systems. These heat exchangers could be plate type or shell-and-tube type. In shell-and-tube exchanger, the steam passes through the shell and the water is heated as it circulates through the tubes [12].

Heat exchangers, which are usually used in HVAC system, are counter flow shell-and-tube, and plate units. **Shell-and-tube heat exchangers** contain the shell for passing utility medium, and the tubes inside the shell for passing process fluid. Heat exchanger can be used as a heater or a cooler. It is applicable in a wide range of industries such as HVAC system, power plants, refineries, petrochemical industries, and so on [14]. Generally, potable water is used as utility medium and process medium in the Domestic Hot water system. Figure 12 shows a shell-and-tube heat exchanger. The fluid with temperature $T_1$ enters from inlet into the shell which, is outside the tube and inside the shell. Then, the fluid goes out from outlet at temperature $T_2$ . The other fluid flows inside the tube with temperature $t_1$ and goes out at the other end with temperature$t_2$. Inside the shell, there is a tube bundle, and it is constructed from metal tubes, which mechanically rolled or welded at one end (U-bend heat exchanger) or both ends (single pass heat exchanger) into the tube sheets [14]. In single pass heat exchanger, the fluid has one entry and one exit for the both process and utility medium, which is shown in Figure 13.

Concerning U-bend heat exchanger, the medium is flowed back and forth to get better heat condition. This type is shorter than single pass heat exchanger, which is shown in Figure 14.

The shell is usually a piece of pipe, which has inlet and outlet connections. These connections are located along the longitudinal centerline of shell.

The tube bundle is assembled with the tube supports (baffle plates), which are held together with the rod and spacers.

**Plate heat exchangers** are made of double metal thin plates, which are corrugated. Each pair of plate produces two separate paths for the both mediums (utility and process medium), and heat transfer occurs between these two metal plates. The plates have an opening at each corner. After assembling, which is along with sealing plates, each hole acts as a manifold to distribute medium in the separate flow paths. The following figure indicates a plate heat exchanger (Figure 15) [12].

Figure 16 reflects the sub-components, which are part of the shell-and-tube heat exchanger. The shell-and –tube heat exchanger is made of four major sub-components: shell, baffle plates, tube, and tube sheet.

**Shells** are usually made of steel pipe. In some cases, it could be brass or stainless steel. The inlet and outlet nozzles are made with standard flange opening in different orientations. Nozzles are installed to prevent excessive fluid velocity and violent impact on the tubes, which are placed in opposite side of the shell inlet connection [13]. **Baffle plates** are a number of plates, which are installed inside the shell. They are usually made of steel, brass, and stainless steel .It has two major functions: supporting tubes to ensure an effective flow, and providing uniform flow around tubes to improve the productivity of the heat exchanger in heat transferring process [14]. The number and spacing of the baffles plates are dominated by the velocity inside the heat exchanger. **Concerning tube bundle**, the process medium flows through the tubs. It is made of high potential materials in heat transferring to improve the efficiency of the heat exchanger. In addition, these materials should have high degree of corrosion resistance in order to prevent leakage of the process medium inside the utility medium (internal leakage) [14]. They are usually made of copper, special grade of brass, and stainless steel. Some factors such as tube diameter, gage (wall thickness of the tube) and type of material are significant in heat transfer coefficient and performance [13]. The function of **tube sheet** is to support tubes. It is available in the same material as baffle plates. Tube-sheets are drilled for a specific tube layout, which is called pitch pattern. The holes are serrated (saw-tooth edge) to improve the connection between tubes and tube-sheet [13].

A block diagram provides an overview of maintenance items in the heat exchanger, which is beneficial, to identify the failure modes. Maintainable items in heat exchangers are classified in three main categories: external, internal, and Control &Monitoring [24].

**External items** ae divided into supports, body/shell, valves, piping, and instruments.

**Internal items** are divided into body/shell, instruments, baffle plates, seals (gaskets), and tubes.

**Control &monitoring** items are categorized into actuating devices, cabling & junction boxes, control units, instruments, monitoring, internal power supply, and valves.

The combination of maintainable items in heat exchanger are indicated in Figure 17.

### 1.5.3 Failure modes and effect analysis in the heat exchanger (FEMA)

FEMA is an analytical approach, which determines the potential of failure in the design or process by examining the lower level of failures. FEMA deals with analyzing failure modes, determining effect of each failure, and identifying critical failures.

The failure modes, which are associated with heat exchangers, are highlighted below [24]:

- External leakage-utility medium
- Insufficient heat transfer
- Internal leakage- process medium
- Plugged/chocked
- Structure deficiency

Generally, the major recorded failures in heat exchangers occurs in the main sub-components: tube bundle, baffle plates, and gasket. The failure mode in the baffle plates is defined as structural deficiency which, is a broad range. It includes corrosion and buckling of the baffle plates as a result of imposing external force such as vibration, erosion, or corrosion. Any defect in the baffle plates, which have supportive role for the tubes, can cause crack in the tubes. Therefore, the outcome of this failure mode is internal leakage of process medium [24]. Another observed problem is tube denting. This problem results in galvanic corrosion of the plain carbon steel (tube supports plates) in the area between the plates and alloy tubes. The growth of iron oxide formation in this area imposes the pressure to the tubs, and dents them inward. Consequently, they could not slip axially in the plates, which creates differential expansion. This problem could be solved by better support plate design, and better materials quality [13]. The observed defects in the tube bundle are corrosion, pitting, or buckling of the tubes. Internal leakage results in the deficiency of the tube bundle [24].

Another cause of internal leakage is stress-corrosion cracking (SCC) of the tubes with small-radius U-bends, which are placed in the center row in the tube bundles. This type of failure is vanished by recognizing this failure mode and plugging defected tubes. The other observed failure is corrosion as a result of phosphate sludge deposition on the top of the tube sheet. This problem can be corrected by application of high-pressure water jet to remove sludge deposits [13]. In terms of Gasket, the cap is connected to the body/shell of heat exchanger by means of the flange connection. The gasket is used in order to prevent external leakage from the mentioned connection. The recent study on gaskets indicates that the major cause of failure are insufficient load as well as using wrong gasket. The outcomes of defect on gaskets are crushing, cavitation (the formation of an empty space within a solid object or body), or erosion [17]. The failure mode in the body/shell is external leakage of the utility medium, which results in existing crack through the wall. There are some factors such as corrosion/pitting, erosion, or external forces (vibration), which play key role in existence and improvement of cracks in the body/shell [24].

## 1.5.4 OREDA (Offshore& Onshore Reliability Data)

OREDA is a project organization, which sponsored by oil and gas companies with world-wide operations. The main purpose of using OREDA is to collect and exchange reliability data among the participant companies, and act as the forum for co-ordination and management of reliability data collection within oil and gas industries. The main objective of OREDA project is to contribute to an improved safety and cost effectiveness in design and operation of oil and gas E&P (Exploration and production) facilities; trough collection and analysis of maintenance and operation data, establishment of a high quality reliability database, and exchange of reliability, maintenance and safety technology among the participant companies. Participants at OREDA are major oil companies such as Eni/Agip, British Petrolium, Chevron, ExxonMobil, Norsk Hydro, Conocophilips, Statoil/Hydro, Shell, Texaco, Total. The preparation of handbook has been carried out by SINTEF and is marketed by DNV (Det Norske Veritas). The applied failure data in this research are obtained from the version of failure handbook form 1988, and presented in case study section [23], [24]

# 2. Methodology

## 2.1 Availability-based method

Availability based maintenance method provides maintenance scheduling by considering the outcomes of the maintenance on a system, while keeping availability of the current system (before maintenance). "The maintenance effect $(\Delta a)$ refers to the system availability increase due to the increase in components availabilities between the neighboring average maintenance interval types" [19].

Hazard function$(\lambda(t))$ is calculated by regression analysis on the result of failure historic data (bathtub curve). Consequently, the failure density function, the reliability function as well as the mean time to failure can be defined based on Eq-25, 26, 27 [18].

$$f(t) = \lambda(t)\ exp\left[-\int_0^t \lambda(\xi)\, d\xi\right] \tag{25}$$

$$R(t) = exp\left[-\int_0^t \lambda(\xi)\, d\xi\right] \tag{26}$$

$$MTTF = \int_0^\infty t \times f(t)dt = \int_0^\infty R(t)dt \tag{27}$$

The availability of a component can be quantified by the mean time to failure (MTTF), and the mean time to repair (MTTR) as follow (Eq-28) [18]:

$$a_{i,j,k} = \frac{MTTF}{\mathrm{MTTF} + \mathrm{MTTR}} \tag{28}$$

In this equation $i, j$ and $k$ reflect the number of systems, number of components and maintenance intervals. It should be noted that Weibull distribution is highly adoptable and is applied in reliability engineering [9]. The value of mean time to failure in Weibull distribution is calculated by scale parameter $(\alpha)$ and shape parameter $(\beta)$ in Eq-29 [18].

$$\Gamma(x) = \int_0^\infty t^{x-1} e^{-t} dt$$

$$MTTF = \alpha \times \Gamma \frac{1+\beta}{\beta} \tag{29}$$

The value of MTTF illustrates the mean time to failure of the $j^{th}$ element with the $k^{th}$ average maintenance interval , and this value is modified based on average maintenance interval types.

## 2.1.1 Effect of maintenance on failure density function and reliability function

Generally, the aim for preventive maintenance is to increase the lifetime of the component, postpone its failures, decrease amount of failures and increase the mean time to failure (MTTF) of the system. Preventive maintenance is suitable in components, which have an increasing hazard rate (failure rate). If the component is repairable, the failure density function and reliability function must be modified based on the maintenance interval time ($T_M$). Therefore, mean time to failure (MTTF), which is the outcome of reliability and failure density functions is updated. In this approach, $f_{T\ (t)}$ is denoted as the failure density function, $T_M$ is the fixed time interval between maintenances and R(t) is the reliability function (Eq-30) [9].

$$f_1(t) = \begin{cases} f_T(t) & 0 < t < T_M \\ 0 & otehwise \end{cases} \tag{30}$$

Then, the modified failure density function in the component, after performing maintenance, could be illustrated in Eq-31 [9].

$$f_T^*(t) = \sum_{k=0}^{\infty} f_1\,(t - kT_M) R^k(T_M) \tag{31}$$

The value of $T_M$ indicates the predefined maintenance interval time. In this case, all of the existing components in the system follow Weibull distribution, so the general form of reliability and failure density functions, which are dependent on the scale parameter (α), and the shape parameter (β)**,** are illustrated as follow:

$$\boldsymbol{R(t) = exp\left[-(\frac{t}{\alpha})^{\beta}\right]}$$

$$f(t) = \frac{\beta t^{\beta-1}}{\alpha^{\beta}} \boldsymbol{exp}\left[-(\frac{\boldsymbol{t}}{\boldsymbol{\alpha}})^{\boldsymbol{\beta}}\right]$$

The failure density function in time $t - kT_M$ and the reliability function in time $T_M$ are derived as follows:

$$f(t - kT_M) = \frac{\beta(t - kT_M)^{\beta-1}}{\alpha^{\beta}} \boldsymbol{exp}\left[-(\frac{t - kT_M}{\boldsymbol{\alpha}})^{\boldsymbol{\beta}}\right]$$

$$\boldsymbol{R}(T_M) = \boldsymbol{exp}\left[-(\frac{T_M}{\boldsymbol{\alpha}})^{\boldsymbol{\beta}}\right]$$

Finally, the general form of the failure density function with Weibull distribution, which is modified by the maintenance interval time, is presented in the following form (Eq-32).

$$f_T^*(t) = \sum_{k=0}^{\infty} \frac{\beta(t - kT_M)^{\beta-1}}{\alpha^{\beta}} exp\left[-(\frac{t - kT_M}{\alpha})^{\beta}\right] R^k(T_M) \qquad (32)$$

$f_T^*(t)$ as a modified failure density function is dominated by maintenance interval time $T_M$, and number of maintenance during operation period (K).

A typical $f_T^*(t)$ graph is indicated in Figure 20. The time scale is divided into equal time intervals, which is denoted by $T_M$. The function $f_T^*(t)$ in each maintenance interval time between two consecutive maintenances is reduced in size in comparison with the previous time interval by the scaling factor($R^k(T_M)$) . Figure 18 is extracted from the result of the pipe in maintenance interval time ($T_M$) equal to 1.25 years. With reference to Figure 19, the modified failure density function reveals an exponential tendency. In some cases this trend follows Weibull distribution with two adjustment parameters (scale as well as shape parameters). In general, the Periodic preventive maintenance changes the failure density function from its original shape to the exponential or Weibull form by the scale parameter($R^k(T_M)$) [9].

In the modified failure density function, k=0 is used only between $t = 0$ and $t = T_M$ , k=1 is used only between $t = T_M$ and $t = 2T_M$ and so on.

The general form of the modified reliability function, which has been modified by $T_M$, is illustrated in Eq-33.

$$R_T^*(t) = \int_t^\infty f_T^*(\xi)d\xi = \int_t^\infty \sum_{k=0}^{\infty} f_1\,(\xi - kT_M)R^k(T_M)\,d\xi \tag{33}$$

The modified reliability function, which follows Weibull distribution in general form, is presented by Eq-34.

$$R_T^*(t) = \int_t^\infty \sum_{k=0}^{\infty} \frac{\beta(\xi - kT_M)^{\beta-1}}{\alpha^\beta} exp\left[-(\frac{\xi - kT_M}{\alpha})^\beta\right] R^k(T_M)d\xi \tag{34}$$

The final result after solving the above equation is illustrated by Eq-35.

$$R_T^*(t) = \sum_{k=0}^{\infty} exp\left[-(\frac{t - kT_M}{\alpha})^\beta\right] R^k(T_M) \tag{35}$$

A typical graph for $R_T^*(t)$ is indicated in Figure 19.This modified reliability function is reduced in size by the scaling factor in each maintenance interval time ($T_M$) in comparison with the previous time interval. This indicates the effect of preventive maintenance on deterioration of the component within the operation period. Figure 19 is obtained from the result of the pipe in the average maintenance interval ($T_M$) equal to 1.25 years.

It is required to compare the modified failure density function (preventive maintenance) with the current failure density function (run to failure). Figure 20 indicates the failure density function associated with run to failure, and the modified failure density function with a maintenance interval time 1.25 years through the operation period of the pipe.

Generally, the failure density function is a measure of the overall speed at which a failure is occurring. Concerning the original failure density function, increasing the failure density function denotes a reduction in the component reliability, while deduction in its ability to tolerate failure. The component will continue to degrade until the end of its useful life. Periodic maintenance improves continuous time random variable, which prolongs the component's useful life. In addition, $R^k(T_M)$ is the scaling factor, which indicates degrading of the component during the operation period, after doing any periodic preventive maintenance.

The modified reliability function (with preventive maintenance) is also compared with the current reliability function (run to failure) in Figure 21. In general, the reliability function is an important indicator in order to quantify deterioration in the component during the operation period. It can be observed that the reliability of the component with preventive maintenance is higher than the case without maintenance as preventive maintenance slows down the deterioration process.

Figure 21 illustrates the effect of preventive maintenance on the component. In performing preventive maintenance, deterioration in component is expected to occur at a slower rate than the case without maintenance (run to failure), so the chance of failure occurrence is reduced, while the useful life of the component is extended.

Figure 22 describes the maintenance behavior on the pipe in two different maintenance interval times ($T_M$) 1.25 and 2.5 years. Increasing the time between two consecutive maintenance reduces the continuous time random variable. Therefore, reliability with longer maintenance interval time ($T_M$=2.5 years) declines as it increases the rate of deterioration.

Figure 23 compares the trend of modified reliability function for two different maintenance interval times $T_M$=1.25 and 2.5 year. Generally, extending maintenance interval time increases the component deterioration rate. Therefore, the reliability trend slope would be steeper. In addition, reducing number of maintenance converges the reliability trend to the case of run to failure.

### 2.1.2 Maintenance scheduling with keeping system availability (KSA)

System availability is dependent on component availability, and it is calculated in the same way as system reliability, which depends on the arrangement of components in the system. System reliability analysis relies on the configuration of components in a system. The system reliability could be compatible with series, parallel, N tuple modular redundancy or complex structure. The principle in proposing availability-based maintenance scheduling is to provide a maintenance plan, which has high availability in a system, high level of safety and low maintenance cost. The objective of this research is to reduce the number of maintenance tasks. The limitation in this technique is that the availability in modified system should not be less than current system [19].

Reliability reflects degree of assurance in a system in order for it to be operated in specified environment in a certain period of time. For repairable systems, the reliability of a system is quantitatively illustrated by its availability in specific period of time. In this study, availability can be determined in different average maintenance interval types (AMI) based on the actual data; maintenance effect is an important criterion for organizing a maintenance schedule of repairable system.

Before starting the KSA decision process, all of the existing components with different AMI are required to be sorted. In the ordering process, component availabilities in each average maintenance interval types are ordered based on maintenance effect, which is the availability difference between two neighboring average maintenance intervals. It is denoted by $\Delta a_{i,j,k}$ in Eq-36 [18] as follows:

$$\Delta a_{i,j,k} = a_{i,j,k} - a_{i,j,k+1} \tag{36}$$

In this equation, $i$, $j$ and $k$ reflect the number of systems, number of components and maintenance intervals. Each component has $N_Z$ possible types of average maintenance interval types, so there are $N_{Z-1}$ availability differences for any single component. The purpose of the ordering process is to reduce maintenance cost without reducing the availability of the system [19]. In this approach, components with large maintenance effect (components with major effect in the system availability) are selected to be maintained more frequently. Components with small maintenance effect (components with minor effect in the system availability) are also selected, and the number of maintenance tasks for these components is decreased to avoid or prevent over-maintenance in order to reduce maintenance cost [19].

In the sorting process, all components with different average maintenance interval types are sorted in ascending order (Figure 24).

KSA approach relies on keeping the system available after maintenance scheduling through a decision process. In order to decrease maintenance time, it is required to reduce average maintenance interval (AMI) types in some components, while increasing average maintenance interval (AMI) types in other components based on the ordering list. The whole process is divided into two sub-loops known as "bottom-loop" and "top-loop" [18]. Components with high maintenance effect are placed in the "bottom-loop", while components with low maintenance effect are placed in the "top-loop". In any round of calculation in the decision process for both the "top-loop" and "bottom-loop", it is required to assign a "STEP No", which represents the component, and its assigned maintenance interval in the sorting list. The decision process is explained as follows [18]:

Firstly, the availability ($A_i$) for the current system is determined. Then, the decision process starts from the "bottom-loop". The component is selected from the bottom of the ordered list, and its average maintenance interval type is reduced by one level ($Z_k \to Z_{k-1}$). So, the number of maintenance tasks is increased, as the maintenance interval of the component is shortened. This results in increasing both the component availability and system availability. The aim is to create larger room in order to reduce maintenance tasks for components at the "top-loop". After calculation of modified availability ($A_i^*$ ), it is compared with current system availability ($A_i$) for validation.

If the modified system availability is less than the current system availability, the "bottom-loop" is adjusted again until it attains at least the current system availability. If there is improvement in the system availability, the decision process will move to the "top-loop".

In the next sequence, the component from the "top-loop" of the ordered list is selected, and its average maintenance interval type is raised by one level($Z_k \to Z_{k+1}$) . So the number of maintenance tasks is decreased, and maintenance interval time in the component is lengthened. This results in decreasing both the component availability and system reliability. After calculation of modified system availability ($A_i^*$ ), the resulting value should be compared with the current system availability ($A_i$). If the modified system availability is greater than the current system availability, the "top-loop" will continue to run. Otherwise, the decision process will be transferred to the "bottom-loop". This process will continue until the "STEP No" for “bottom loop” and “top-loop” become the same. During the decision process, the variation of system availability ($e_i$), which is the difference between modified and current system availability, is quantified.

The decision process flowchart, which indicates the calculation process, is presented in Figure 25 [18].

## 2.2 Optimum replacement intervals with useful life

This approach relies on replacement, which occurs at a specific time interval (T) along with minimal repair (preventive maintenance) between two consecutive replacements [20]. The time horizon interval (useful life) is a continuous random variable, and the total expected cost is the optimization criterion.

A number of assumptions in this model, which are taken into account, are as follows [21]:

- In minimal repair, repair time is negligible
- System is under replacement at time interval T
- Time horizon (Useful life) follows exponential distribution.

Replacement interval is identified in different periods as T, 2T, 3T… . The expected maintenance cost in each time interval is defined in Eq-37 [21].

$$C_1H(T) + C_2 \tag{37}$$

In this equation, $C_1$ is the repair cost, $C_2$ is the replacement cost, and $H(T)$ is cumulative hazard function.

It is assumed that time horizon (useful life) covers the first k cycles, and ends during the (k+1)$^{th}$ cycle. So, the total maintenance cost from the first cycle up to the beginning of the (k+1)$^{th}$ cycle is given by Eq-38 [21].

$$k[C_1H(T) + C_2] \tag{38}$$

Moreover, the maintenance cost during the (k+1)$^{th}$ cycle (the last cycle) is calculated as follows (Eq-39) [21]:

$$C_1H(t - kT) \tag{39}$$

The expected total cost based on the time horizon (useful life) in its general form is defined as (Eq-40) [21]:

$$ETC(T) = \sum_{k=0}^{\infty} \int_{kT}^{(k+1)T} \{k[C_1 H(T) + C_2] + C_1 H(t - KT)\} f(t) dt \tag{40}$$

Based on the assumption that the time horizon (useful life) follows exponential distribution, the failure density function is defined as $f(t) = \lambda e^{-\lambda t}$. By substituting the failure density function into Eq-37, the resulting equation $(ETC(T))$ is given by Eq-41 [21].

$$ETC(T) = \sum_{k=0}^{\infty} k[C_1 H(T) + C_2] \int_{kT}^{(k+1)T} \lambda e^{-\lambda t} dt + \sum_{k=0}^{\infty} \int_{kT}^{(k+1)T} C_1\, H(t - kT)\, \lambda e^{-\lambda t} dt \tag{41}$$

The expected total cost for a general distribution is difficult to calculate; so, it is required to assign distribution function such as Weibull distribution, which is valid for a wide range of mechanical equipment. Therefore, $H(T)$, as a cumulative hazard function, can be identified in Eq-42.

$$\begin{gathered} H(T) = \int_0^T \frac{\beta t^{\beta-1}}{\alpha^\beta} = \frac{T^\beta}{\alpha^\beta} \\ \eta = \frac{1}{\alpha^\beta} \\ H(t) = \eta t^\beta \end{gathered} \tag{42}$$

$\alpha$ and $\beta$ are parametric values in Weibull distribution, which are estimated based on performing regression analysis on extracted failure data trend in components.

The expected total cost is then calculated by substituting the Weibull distribution into Eq-41. The outcome is shown in Eq-43. After substitution, the result of total expected cost is determined based on the following formula (Eq-43) [21].

$$\begin{gathered} ETC(T) = \left(C_1 \eta T^\beta + C_2\right) \sum_{k=0}^{\infty} k \int_{kT}^{(k+1)T} \lambda e^{-\lambda t} d\, t + C_1 \eta \sum_{k=0}^{\infty} \int_{kT}^{(k+1)T} (t - kT)^\beta\, \lambda e^{-\lambda t} d \\ ETC(T) = \left(C_1 \eta T^\beta + C_2\right)(1 - e^{-\lambda T}) \sum_{k=0}^{\infty} k\, e^{-k\lambda T} + C_1 \eta \sum_{k=0}^{\infty} \int_{kT}^{(k+1)T} (t - kT)^\beta\, \lambda e^{-\lambda t} dt \end{gathered} \tag{43}$$

Some simplifications for the above equation are detailed in Eq-44, 45

$$\sum_{k=0}^{\infty} k\, e^{-k\lambda T} = \frac{e^{-\lambda T}}{(1 - e^{-\lambda T})^2} \tag{44}$$

$$\sum_{k=0}^{\infty} e^{-\lambda kT} = \frac{1}{1-e^{-\lambda T}} \tag{45}$$

For Eq-40, the time reference is changed from zero to $KT$, so T is changed to $t + KT$ . The outcome of the calculation is illustrated as follows:

$$\sum_{k=0}^{\infty} \int_{kT}^{(k+1)T} (t-kT)^{\beta}\, \lambda e^{-\lambda t} dt = \sum_{k=0}^{\infty} \int_{0}^{T} t^{\beta} \lambda e^{-\lambda(t+kT)} dt = \sum_{k=0}^{\infty} \int_{0}^{T} t^{\beta} \lambda e^{-\lambda t} e^{-\lambda kT} dt =$$
$$= \sum_{k=0}^{\infty} e^{-\lambda kT} \int_{0}^{T} t^{\beta} \lambda e^{-\lambda t} dt$$

After substitution, the result of total expected cost $(ETC(T))$ is determined as Eq-46 [21].

$$ETC(T) = \frac{\left(C_1 \eta T^{\beta} + C_2\right) + C_1 \eta \lambda e^{\lambda T} \int_0^T t^{\beta} e^{-\lambda t} dt}{e^{\lambda T} - 1} \tag{46}$$

## 2.2.1 Optimal period of replacement with minimal repair

In this part, it is required to compute the replacement interval (T), which satisfies minimal expected total cost. The optimum value of replacement interval is a finite and unique value, which can be calculated based on Eq-47 [21].

$$\frac{dETC(T)}{dT} = 0 \tag{47}$$

After simplification, the optimum time, which is denoted by $W(T)$, is defined as follows:

$$W(T) = \frac{\beta T^{\beta-1}\left(1-e^{-\lambda T}\right)}{\lambda} - T^{\beta} e^{-\lambda T} - \lambda \int_0^T t^{\beta} e^{-\lambda t} dt = \frac{C_2}{C_1 \eta}$$

In this equation, hazard rate is denoted by λ, and parametric values in Weibull distribution are represented by α and β. Moreover, $\int_0^T t^{\beta} e^{-\lambda t} dt$ is the incomplete gamma function. The general format for the calculation of an incomplete gamma function$(\gamma(s,T) = \int_0^T t^{\beta} e^{-t} dt)$ is listed in Eq-48, 49, 50.

$$\gamma(s,T) = \Gamma(s) - \Gamma(s,T) \tag{48}$$

$$\Gamma(s) = \int_0^\infty t^\beta e^{-t} dt \tag{49}$$

$$\Gamma(s,T) = (S-1)\Gamma(s-1,T) + T^{s-1}e^{-T} \tag{50}$$

If failure rate ($\lambda$) is close to 0, which implies infinite time horizon (useful life), the total expected cost becomes infinite ($ETC(T) = \infty$). Consequently, the optimal replacement time ($T^*$ ) is determined by Eq-51 [21].

$$\lim_{\lambda \to 0} W(T) = \frac{\beta T^{\beta-1}(Te^{-\lambda T})}{1} - T^\beta e^{-\lambda T} = \frac{C_2}{C_1 \eta}$$

$$\beta T^\beta - T^\beta = \frac{C_2}{C_1 \eta}$$

$$T^* = [\frac{C_2}{C_1 \eta(\beta - 1)}]^{\frac{1}{\beta}} \tag{51}$$

As an example, for the tube bundle, the periodic replacement strategy with minimal repair is calculated at different numerical values of $C_2/C_1$ in order to compare the effect on $T^*$. The scale parameter and shape parameter are $\alpha = 32000$ and $\beta = 3$ respectively. The results are shown in Figure 26 as $T$ versus $1/\lambda$ for different rates of $C_2/C_1$(that is $\frac{C_2}{C_1} = 5$ and $\frac{C_2}{C_1} = 10$ ). $C_2/C_1$ indicates the rate of replacement cost to repair cost. The detailed calculation will be given in case study. This graph illustrates that as soon as $\lambda$ converges to zero, the replacement time can be obtained (5 years for $\frac{C_2}{C_1} = 5$ and 6 years for $\frac{C_2}{C_1} = 10$)

The results indicate that optimal interval time is a decreasing function, which converges to an infinite time horizon at high values of component mean time to failure ($1/\lambda$). In addition, increase in $C_2/C_1$ results in prolonging the optimal replacement time [21]. It should be noted that as a result of direct interaction between sub-components in some cases, deferring replacement time causes significant damage to other subcomponents. Consequently, the replacement cost will increase.

# 3. Case Study

The method and theoretical background in this research relies on reliability centered maintenance with focus on availability of the components. The motivation for selecting availability based maintenance is to have steady state in operation period without interruption especially in the winter. In fact, availability based maintenance is common in a number of industries such as power plants that the continual availability of the power plants is a critical issue. In this study, maintenance plan in Domestic Hot Water of HVAC system in the commercial environment in Canada is taken into account. As a result of climate in Canada, there is restriction for HVAC system to be in operation without interruption during the long cold season, so the availability of components in the mentioned system has a major role in maintenance planning. In addition, heat exchanger plays a key role in heat transferring from utility to process medium, so whenever the heat exchanger is out of service, the heat transfer sub-system should be replaced with electrical system to prevent the lack of hot water. As a result, considerable cost imposes to the operation.

## 3.1 HVAC as a repairable system

HVAC system is categorized as a repairable system. It means that all components are repaired, maintained, adjusted or changed during the life time of the system. Repairing or adjusting a component is important in keeping the system in function. In some studies, reliability assessment is performed in the steady state period of the bathtub curve (useful life) for the sake of simplicity. In this region, the value of failure rate is constant, so the reliability function follows exponential distribution.  After steady state period, it is expected to have increase in the failure rate in the component which is denoted as wear-out region. In this research, the combination of these areas in the bathtub curve is taken into account.

Generally, performing the “Availability Based Maintenance” method requires a number of steps, which are fundamental in maintenance scheduling, and these steps are derived from reliability principles. The related steps in this approach are presented sequentially as below, and description with details are given in the following parts. The calculation steps are as follows:

1. System reliability measurement which relies on reliability in components as well as configuration of components in sub-system and system.
2. Quantifying the availability of components based on the outcome of reliability analysis (MTTF) and Mean Time to Repair (MTTR). The following stages are performed in availability analysis.
    a. Assigning different Average Maintenance Interval (AMI) types, which identify different maintenance interval times ($T_M$) in components.
    b. Drawing $f_T^*(t)$ versus time graph based on different maintenance interval times ($T_M$) in order to estimate reliability parameters in Weibull distribution (α, β) or in exponential distribution (λ) in each AMI, which require for calculation of MTTF.
    c. Calculation of availability in each components in different $AMI$ types based on MTTF and MTTR as well as maintenance effect.
    d. Sorting components with different AMI types in ascending order based on maintenance effect.
    e. Calculation of availability in system without maintenance (current availability) as a reference
    f. Performing KSA decision process to calculate the availability of the system with maintenance plan (modified availability) in different combinations of components with different AMI. Each calculation step is called “STEP No”.
    g. Selecting “STEP No”, which indicates maintenance intervals for all existing components.

The steps in availability analysis is presented in the following diagram in Figure 27.

## 3.2 System reliability measurement and analysis

Generally, reliability is quantified as the probability that a system continues its intended function in time "t" without repair and maintenance. The reliability function relies on the number of components as well as structural arrangement in the system [22]. Maintenance planning models are based on reliability theories. The variable which is used in these models, is continuous time random variable, and it is dependent on both the technical characteristics of the systems and maintenance organization. In order to have continuous function in a system, it is required to organize preventive maintenance which relies on the system reliability.

Mean time to repair (MTTF) is the expected value of continuous time random variable, and it is beneficial to evaluate the quality and usefulness of a component. MTTR reflects the time when a system is in repair period, so it is used to measure the availability of components.

Concerning the structure of Domestic Hot Water system, it is divided into three main sub-systems as follows:

- **Heating production sub-system (HP)**, which is in charge of heating utility medium in the DHW system.
- **Distribution sub-systems in both the utility and process lines (DU, DP),** which circulate the utility and process medium in the DHW system.
- **Heat transfer sub-system (HT)**, which is in charge of transferring heat from utility medium to process medium.

The process and instrument diagram indicates components and the way in which they connect to one another (Figure 28).
Each sub-system consists of different components which participate in the operation function of the system.

The list of components in each sub-system is presented in Table 1.

The four mentioned sub-systems have a series arrangement in the “Domestic Hot Water” system, and the system arrangement is defined in the following block diagram in Figure 29. In fact, the failure in any sub-system in the DHW system results in the failure of the whole system, and therefore a lack of hot water.

The reliability analysis of the series system is based on general form in Eq-14, and it is illustrated in Eq-52 as follows:

$$R_{DHW}(t) = R_{HP} * R_{DU} * R_{DP} * R_{HT} \tag{52}$$

In this formula $\boldsymbol{R_{\mathrm{HP}}}$ , $\boldsymbol{R_{\mathrm{DU}}}$ , $\boldsymbol{R_{\mathrm{DP}}}$ and $\boldsymbol{R_{\mathrm{HT}}}$ are reliability functions of the heating production” sub-system, distribution sub-systems*, and* heat transfer sub-system.

**Heating production sub-system,** which is indicated as HP, includes a couple of boilers, the pipe and check valves that are installed in the system in parallel in order to increase the reliability of the sub-system. The role of check valve is to prevent the flow from returning back into the boiler when the fluid pressure is low. This sub-system is in charge of heating utility medium. The arrangement of heating production sub-system is illustrated in Figure 30.

The reliability in the heating production system, which has series-parallel structure, is calculated based on general form in Eq-14, 17, and it is defined in Eq-53 as follows:

$$\boldsymbol{R_{\mathrm{HP}} = 1 - (1 - R_{pi} * R_{B} * R_{Cv})^{2}} \tag{53}$$

In this formula $\boldsymbol{R_{pi}}$ , $\boldsymbol{R_{B}}$ , and $\boldsymbol{R_{CV}}$ are reliability functions of the pipe, the boiler and the Check valves.

**Distribution sub-system,** which is called circulation system, is responsible for distributing utility medium and process medium in the entire system, and it is defined into two: a sub-system that manages the utility medium (DU) and a sub-system for the process medium (DP). The utility medium is circulated between the boiler and the heat exchanger by means of three centrifugal pumps. It is made up of three lines in parallel. In addition to the centrifugal pump, each line comprises of two gate valves, which are installed before and after the pump, to align the flow through the system, and a check valve in order to prevent the flow from returning back into the pump when the fluid pressure is low. Furthermore, there is a strainer before the centrifugal pump to remove tiny particles in the fluid that could damage the pump. The arrangement of this sub-system is shown in Figure 31.

In the utility distribution sub-system, which combines series and parallel structure (Eq-14, 17), the reliability is quantified based on the following formula (Eq-54).

$$\boldsymbol{R}_{\mathbf{DU}} = \mathbf{1} - (\mathbf{1} - \boldsymbol{R}_{\boldsymbol{pi}} * \boldsymbol{R}_{\boldsymbol{p}} * \boldsymbol{R}_{\boldsymbol{Cv}} * R_{Gv}^{2})^{\mathbf{3}} \tag{54}$$

In this formula $\boldsymbol{R}_{\boldsymbol{pi}}$ , $\boldsymbol{R}_{\boldsymbol{p}}$ , $\boldsymbol{R}_{\boldsymbol{GV}}$,and $\boldsymbol{R}_{\boldsymbol{CV}}$ ,are reliability functions of the pipe, the pump, the gate valve, and the check valve*. The* process medium is circulated through the heat exchanger by another distribution system which is made of two lines in parallel. Each line has a couple of centrifugal pumps, one check valve, and one gate valve before and after the centrifugal pumps. Also, there is a strainer before the centrifugal pump to remove tiny particles in the fluid that could damage the pump. The arrangement of this sub-system is illustrated in Figure 32.

In this distribution sub-system, which combines series and parallel structure (Eq-14, 17), the reliability is quantified based on the following formula (Eq-55).

$$\boldsymbol{R}_{\mathbf{DP}} = \mathbf{1} - (\mathbf{1} - \boldsymbol{R}_{\boldsymbol{pi}} * R_{p}^{2} * \boldsymbol{R}_{\boldsymbol{Cv}} * R_{Gv}^{2})^{\mathbf{2}} \tag{55}$$

**Heat transfer sub-system,** which is denoted by HT, is made of two lines in parallel. Each line has a heat exchanger and one gate valve before and after the heat exchanger (to align fluid through the system). The parallel structure is chosen in order to improve the structure's reliability. This arrangement is presented in Figure 33.

In the heat transfer distribution sub-system, which combines series and parallel structure (Eq-14, 17), the reliability is quantified based on the following formula Eq-56.

$$\boldsymbol{R}_{\mathbf{HT}} = \mathbf{1} - (\mathbf{1} - \boldsymbol{R}_{\boldsymbol{pi}} * \boldsymbol{R}_{\boldsymbol{He}} * R_{Gv}^{2})^{\mathbf{2}} \tag{56}$$

In this formula $\boldsymbol{R}_{\boldsymbol{pi}}$ *,* $\boldsymbol{R}_{\boldsymbol{He}}$ *, and* $\boldsymbol{R}_{\boldsymbol{GV}}$ are reliability functions of pipe, heat exchanger and gate valve.

In general, the hazard function and reliability function are determined from analysis of the failure data. So, these functions and the pattern of deterioration are dependent on the nature of components in the system (mechanical, electrical, instrument) in terms of their failure [22].

In this study, the reliability functions for all components such as pipe, boiler, pump, gate valve, check valve (which are installed in the Domestic Hot Water system) have been extracted from literature. Although boilers are widely used in many industries, it was very different to find information on the reliability function of boilers in HVAC system. So, it was decided to find reliability functions of major sub-components in a boiler in order to obtain the reliability function of the whole component (boiler).Therefore, the reliability functions of the boiler sub-components are extracted directly from literature. Also, the reliability of the heat exchanger is computed based on the failure data, which were extracted from "Failure Data Handbook".

Generally, the reliability function of mechanical components mainly follows Weibull distribution (Eq-10).

$$R(t) = \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right]$$

**Concerning the boiler**, it is divided into four sub-components: burner, fan, safety valve, and tube. The reliability function in these sub-components also complies with Weibull distribution too.

*The scale parameter and shape parameter in these sub-components are presented in*

Table 2 [27] [28] [29] [30].

The operation of the boiler relies on the functioning of all sub-components such as burner, tube, fan, and safety valve, so the arrangement of these sub-components are defined in series. The block diagram of the boiler is shown in Figure 34.

The arrangement of sub-components in the boiler is in series, because, a failure in any sub-component results in the failure of the whole boiler (Eq-14). The reliability function in the boiler is calculated by Eq-57.

$$R_B = R_{Bu} * R_{Fa} * R_{Sv} * R_{Tu} \tag{57}$$

In this formula $\boldsymbol{R_{Bu}}$ *,* $\boldsymbol{R_{Fa}}$ *,* $\boldsymbol{R_{Sv}}$*and* $\boldsymbol{R_{Tu}}$ are the reliability functions of the burner, fan, safety valve and tube. After performing regression analysis on the boiler reliability trend, a Weibull distribution, with a scale parameter ($\alpha$) equal to 7600 and shape parameter ($\beta$) equal to 1.8, is the best fit for the reliability trend in the boiler ($R^2 = 0.9994$). (Eq-58)

$$R_B(t) = \exp\left[-\left(\frac{t}{7600}\right)^{1.80}\right] \tag{58}$$

The trend of reliability in boiler also is shown as follows in Figure 35. Further details are given in the Appendix A

**Concerning the heat exchanger**, the reliability function is extracted based on failure data, which is available in the “OREDA Reliability Handbook”. There are three main failure modes: structure deficiency in the baffle plates as a result of corrosion and buckling of these plates; internal leakage in the tube bundle as a result of corrosion and buckling in these tubes; and external leakage in connection between shell and cap as a result of improper gasket function.

The process of reliability function determination in components is illustrated in the following steps.

1. Finding failure modes in components
2. Choosing a sample, and determining the number of components in the sample
3. Finding the number of failures in each failure mode in different time intervals
4. determining of hazard rate in different time intervals ($h(t) = \frac{N_f}{N_s} * \frac{1}{\Delta t}$)
5. calculation of reliability function in different time interval ($R(t) = \frac{N_s}{N_0}$)
6. Drawing a hazard rate diagram for the whole operation period based on available data (bathtub curve)
7. Separation of burn-in, useful life, and wear out regions
8. Performing regression analysis to derive suitable hazard functions, which are compatible with data trends
9. Calculation of a reliability function in the component based on the accumulation of derived hazard functions in burn-in, useful life, and wear out regions
10. Drawing graphs for hazard function, and reliability function.

11. Performing regression analysis to derive suitable reliability functions, which are compatible with reliability trends

The sequence of reliability function determination is presented in the following chart in Figure 36.

In this calculation process, $N_f$ is the number of failed components, $N_0$ is the total number of components in the sample, and $N_s$ is the number of survived components. According to the failure data which, is extracted from "OREDA Handbook", the sample population is 191 heat exchangers [23]. Among these components, there were 30 failure records in terms of internal leakage as a result of corrosion and deterioration in tube bundles. There were also 32 failures concerning structural deficiency because of deformation in baffle plates, which support tube bundles. Finally, 51 recorded failures were associated with external leakage due to mal-function in the gasket, which is installed between the shell and cap to prevent leakage.

The time interval for studying these samples is 17000 hours based on the "OREDA Handbook" [23]. The historic failure data within 17000 hours are shown as follows in Table 3.

The summary of historic failure data is illustrated in the following table (Table 4) [23].

The graphs associated with hazard rate, reliability, and failure density trend in the tube bundle (internal leakage failure mode), are presented as follows in Figure 37.

The diagrams associated with hazard rate, reliability, and failure density trend in the baffle plates (structure deficiency failure mode), are presented in Figure 38.

The charts associated with hazard rate, reliability, and failure density trend in the gasket (external leakage failure mode), are presented in Figure 39.

Generally, the bathtub curve is extracted from the hazard rate graph. In this stage, the three different regions of the bathtub curve (burn-in, useful life, and wear-out) should be separated visually. The best hazard distribution function (Weibull, exponential, Rayleigh, Gama, and Beta) should be fitted to the available hazard trend in the current graph. Based on the "OREDA" assumption, the available data are based on two regions: useful life, and Wear-out.

Figure 40 and Figure 41 are associated with the useful life and wear-out regions in bathtub curve (Hazard Rate graph). The hazard functions corresponding to the graphs are also shown.

In the above graphs (Figure 40 & Figure 41), the useful life region follows exponential distribution, and the Wear-out region complies with Weibull distribution. The general form of hazard functions for these regions are illustrated in the following equations (Eq-59, 60) [9].

$$\lambda(t)_{exponential} = cte \tag{59}$$

$$\lambda(t)_{Weibull} = \frac{\beta t^{\beta-1}}{\alpha^{\beta}} \tag{60}$$

After performing regression analysis on the tube bundle failure rate trend, a Weibull distribution, with a scale parameter (α) equal to 30000 and shape parameter (β) (equal to 3.4, is the best fit for the failure rate trend in the tube bindle ($R^2$=0.9130).

Figure 42 and Figure 43are associated with the useful life and wear-out regions in bathtub curve (Hazard Rate graph). The hazard functions corresponding to the graphs are also shown.

Similarly, In the above graphs (Figure 42& Figure 43),  the useful life region follows exponential distribution, and the Wear-out region complies with Weibull distribution .The values of scale parameter (α) and shape parameter (β) are equal to 30300 and 3.24 which matched with hazard trend in the wear-out region with accuracy of $R^2$=0.9398.

Figure 44 is associated with the useful life (Hazard Rate graph). The hazard function corresponding to the graph is also shown.

In this graph ( Figure 44), there is only the useful life region which follows, which follows an exponential distribution. Generally, a gasket is not repairable. So it functions until the end of its useful life. Consequently, its hazard function has only one region, which is the useful life region. The value of failure rate ($\lambda$) is equal to $1.708 \times 10^{-5}$.

In the next step, the reliability functions of each sub-component in the heat exchange such as tube bundle, baffle plates, and gasket are extracted based on the obtained hazard functions in the useful life and wear-out regions. In general, the reliability function is calculated as an accumulating hazard functions of different regions in the bathtub curves, which is illustrated in Eq-6 as follows:

$$R(t) = \exp\left[-\int_0^t \lambda(\xi)d\xi\right]$$

For the tube bundle, the reliability calculation for the useful life and wear-out region is described below.

$$\begin{cases} \lambda(t) = 1.97 \times 10^{-6} & 0 < t \leq 6000 \\ \lambda(t) = 2.04 \times 10^{-15} t^{2.4} & 6000 < t \leq 17000 \end{cases}$$

$$\begin{cases} R(t) = \exp[(-1.97 \times 10^{-6} t)] & 0 < t \leq 6000 \\ R(t) = \exp\left[-(\int_0^{6000} 1.97 \times 10^{-6} dt + \int_{6000}^{t} 2.04 \times 10^{-15} t^{2.4}\, dt)\right] & 6000 < t \leq 17000 \end{cases}$$

The trend of reliability in the tube bundle is obtained by solving the above mathematical equations. The result of reliability trend in the tube bundle is:

$$\begin{cases} R(t) = \exp[(-1.97 \times 10^{-6} t)] & 0 < t \leq 6000 \\ R(t) = \exp[-(7.614 \times 10^{-3} + 6 \times 10^{-16} t^{3.4})] & 6000 < t \leq 17000 \end{cases}$$

A Weibull distribution, with a scale parameter ($\alpha$) equal to 32000 and shape parameter ($\beta$) equal to 3, is the best fit for the reliability trend in the tube bundle ($R^2$=0.9822) (Eq-61).

$$R(t)_{Tb} = \exp\left[-\left(\frac{t}{32000}\right)^3\right] \tag{61}$$

The graphs of hazard function and reliability function graphs in the tube bundle are presented in Figure 45 and Figure 46.

For the baffle plates, the reliability calculation for the useful life and wear-out region is described as follows:

$$\begin{cases} \lambda(t) = 2.94 \times 10^{-6} & 0 < t \leq 6000 \\ \lambda(t) = 9.79 \times 10^{-15} t^{2.24} & 6000 < t \leq 17000 \end{cases}$$

$$\begin{cases} R(t) = \exp[(-2.94 \times 10^{-6} t)] & 0 < t \leq 6000 \\ R(t) = \exp\left[-(\int_0^{6000} 2.94 \times 10^{-6} dt + \int_{6000}^{t} 9.79 \times 10^{-15} t^{2.24}\, dt)\right] & 6000 < t \leq 17000 \end{cases}$$

The trend of reliability in the baffle plates is acquired by solving the above mathematical equations. The result of reliability trend in the baffle plates is:

$$\begin{cases} R(t) = \exp[(-2.94 \times 10^{-6} t)] & 0 < t \leq 6000 \\ R(t) = \exp[-(0.01237 \times 10^{-3} + 3.02 \times 10^{-15} t^{3.24})] & 7000 < t \leq 17000 \end{cases}$$

A Weibull distribution, with a scale parameter ($\alpha$) equal to 30700 and shape parameter ($\beta$) equal to 3, is the best fit for the reliability trend in the baffle plates ($R^2$=0.9822) (Eq-62).

$$R(t)_{Bp} = \exp\left[-\left(\frac{t}{30700}\right)^3\right] \qquad (62)$$

The graphs of hazard function and reliability function graphs in the baffle plates are presented in Figure 47and Figure 48.

For the gasket, the reliability function in useful life region is shown as follows:

$$\lambda(t) = 1.708 \times 10^{-5}$$

$$R(t)_G = \exp[(-(1.708 \times 10^{-5} t)]$$

It is noticeable that Gasket is not a repairable sub-component, and it should be replaced after ending its useful life. The gasket must also be replaced during maintenance period if the flange between the shell and cap is opened. The trend of reliability in the gasket follows an exponential distribution. Hazard function and reliability function graphs in the gasket are shown in both Figure 49 and Figure 50.

The reliability function analysis in the heat exchanger relies on three major sub-components: Tube bundle, Baffle plate, and Gasket. The reliability functions of these sub-components also follow Weibull distribution except in gasket, which shows an exponential distribution. A summary of the scale parameter and shape parameter is presented in Table 5.

Technically, the operation of the heat exchanger relies on the successful working of the sub-components such as tube bundle, baffle plates except gasket. The failure in the gasket results in the leakage of the utility medium without interruption in the functioning of the heat exchanger. So, the configuration of the tube bundle and baffle plates are defined as series. Also, the gasket is in parallel with the both the tube bundle and baffle plates. The block diagram of the heat exchanger is shown in Figure 51.

As a result, the reliability function of the heat exchanger is calculated using combination of Eq-11 and Eq-14, which is presented in (Eq-63).

$$R_{He} = 1 - (1 - R_{Tb} * R_{Bp}) * (1 - R_G) \tag{63}$$

In Eq-60, $\boldsymbol{R_{Tb}}$ ,$\boldsymbol{R_{Bp}}$ *and* $\boldsymbol{R_G}$ are the reliability functions of Tube bundle, Baffle plates, and Gasket.

After performing regression analysis on the heat exchanger reliability trend, a Weibull distribution, with a scale parameter (α) equal to 50500 and shape parameter (β) equal to 2.58, is the best fit for the reliability trend in the heat exchanger ($R^2$=0.9685) (Eq-64).

$$R_{He}(t) = \exp\left[-\left(\frac{t}{50500}\right)^{2.58}\right] \tag{64}$$

The trend of reliability in the heat exchanger is also shown in Figure 52.

In summary, the scale parameter and shape parameter of components in Domestic Hot Water (DHW) are presented in Table 6 [25] [26] [31] [32]. The unit of the scale parameter is measured in hours. Further details about heat exchanger and gate valve are represented in the Appendix B and Appendix C.

**In terms of Domestic Hot water system**, the system reliability is quantified based on the reliability functions of all components that participate in the operation of the whole system. So, the reliability function of domestic hot water is obtained by multiplying the reliability functions of its four sub-system based on Eq-52 as follows:

$$R_{DHW}(t) = R_{HP} * R_{DU} * R_{DP} * R_{HT}$$

After performing a regression analysis on the system's reliability trend, a Weibull distribution, with a scale parameter (α) equal to 2660 and shape parameter (β) equal to 3.3, is the best fit for the reliability trend in the domestic hot water system ($R^2$=0.9996) (Eq-65).

$$R_{DHW}(\mathrm{t}) = \exp\left[-\left(\frac{t}{2660}\right)^{3.3}\right] \quad (65)$$

The trend of reliability in Domestic Hot Water is shown as follows in Figure 53.

It is necessary to compare the reliability of each sub-systems in order to identify which is the more critical in terms of failure. Figure 54 indicates that the distribution sub-systems ($R_{DU}$&$R_{DP}$) have a major influence in reducing the reliability of the system. This is firstly due to the existence of pumps, check valves as well as gate valves, and also the series configuration of these sub-components. Heating production sub-system and heat transfer sub-system contain components, which have no significant effect on decreasing the system reliability.

# 3.3 Sensitivity Analysis

Sensitivity analysis is an approach used to identify the degree of uncertainty in the outcome of a mathematical system by examining the sources of uncertainty in the input parameters. This technique evaluates the impact of an independent variable (input parameter) on a particular dependent variable (outcome). It is a beneficial tool that helps the user to predict the result of a system calculation by imposing particular input variable. This analysis indicates how changes in one variable affect the target variable.

In order to perform sensitivity analysis of the mathematical model, the following sequence should be taken into account. For all assigned input parameters, the minimum and maximum changes in the mentioned parameters should be identified.

1. Each parameter should fluctuate in uniform increments, between the Minimum and Maximum. While a parameter is being altered incrementally, the other input parameters are held constant, at the original value.
2. The final result for each change in a single parameter is collected in a plot of the outcome versus incremental changes for different input parameters. It assists reliability engineer with quantifying and comparing the result of changes in different input parameters visually.
3. A steep curve on a Sensitivity Plot, illustrates that the outcome of a mathematical model or system is sensitive to the mentioned parameter.
4. A relatively "flat" curve indicates that the outcome of a mathematical model or system is not sensitive to the allocated parameter.

In this study, independent variables are defined as a scale parameter (α) *as* well as a shape parameter (β) in the components such as the pipe, boiler, heat exchanger, pump, gate valve, and check valve in the Weibull distribution, and dependent variable is the reliability of Domestic Hot Water system at the point of mean time to failure in the system without maintenance (MTTF=2386.06 hours). The purpose is to evaluate the degree of system sensitivity to input parameters. Regarding the above procedure, the sensitivity analysis is performed for both input parameters individually.

**In terms of scale parameter**, the value of α in each component is altered in the range of -40% to 40% of its original value. Then, the reliability of the system for different scale parameters (α), which are in the above mentioned range, is computed. The results are illustrated in Figure 55.

In this graph, CV, GV, PI, P, HE, and B are check valve, gate valve, pipe, pump, heat exchanger, and boiler respectively. The results show that the most sensitive parameter with regard to the scale parameter is associated with the check valve; the growing scale parameter enhances the reliability. Meanwhile reducing the scale parameter drops the system reliability. Pertaining to the pump and gate valve in particular, the growing scale parameter enhances the reliability. Meanwhile reducing the scale parameter drops system reliability, however, the degree of intensity on the system reliability is less than the check valve. Regarding to the arrangement of the components in the distribution sub-system, the check valves and the pumps are in a series structure, so the circulation sub-systems are more sensitive in comparison with other sub-systems. The other components have no major effect on the system reliability. Therefore, a focus on the scale parameter on the check valve, pump, and gate valve can control the system reliability.

**Concerning the shape parameter**, the same calculations are performed on β in the same range of the input parameter fluctuation of -40% to 40% to calculate the system reliability. The outcome is presented as follows in Figure 56.

In this graph, CV, GV, PI, P, HE, and B are check valve, gate valve, pipe, pump, heat exchanger, and boiler respectively. The results indicate that the sensitivity of the shape parameter on the system is not as significant as the scale parameter. The most critical component in terms of the shape parameter is the pump. Increasing shape parameter improves the system reliability, while reducing shape parameter drops the system reliability. The next most critical component in terms of the shape parameter after the pump is the gate valve and the check valve respectively. The other components have no major effect on the system reliability.

An overview on the outcome of the sensitivity analysis on the scale parameter (α) indicates that the scale parameter controls the component functionality. The most sensitive components in terms of the scale parameter are the check valve, the pump, and the gate valve. Whenever the pressure is increased in the system, the impact load is imposed to the check valve (sealing, and hinge), which has two functional positions (on and off), so the check valve is sensitive to the manufacturing quality. It can be concluded that the higher the manufacturing quality, the better the system reliability. The impact load also exists in the pump whenever it is going to be started in order to increase the pressure of the system, but this effect is less than the check valve. Finally, the gate valve is exposed to the cyclic pressure load during its operation time, which effects on the sealing sub-component; it causes disorder in the functioning of the gate valve in the system.

However, sensitivity in the gate valve is less than both the other components. In the remaining components, such as the pipe, the boiler, and the heat exchanger, the effect of the impact force is not major, so fluctuation in the system reliability is not considerable.

In terms of the shape parameter (β), the pump, gate valve, and check valve are the most sensitive components. In fact the, shape parameter controls the rate of failure modes in components. Generally, failure modes in components are classified into five categories: primary, auxiliary, protective, information, and interface. The primary failure mode is associated with the core purpose of a component [34]. The shape parameter (β) controls the rate of primary failure modes to total failure modes. In terms of the shape parameter, a component is considered to be more sensitive when the rate of primary to total failure mode is decreased. In addition, the component should have interconnection of movable sub-components. Among the pump, gate valve, and check valve, the pump has the least rate of primary to total failure mode. Following the pump, is the gate valve and then the check valve. Concerning the boiler and heat exchanger, there is no inter-connection among the sub-components, so these components do not show any sensitivity in the β parameter. Also, the rate indicates how sub-components have more inter-connection together. Whenever failure begins in a sub-component, other connected sub-components compensate for the defective sub-component in order to postpone the immediate function interruption. In fact, as a result of domino effect, a failure in one sub-component has an effect on the functioning of the other inter-connected sub-components. Domino effect is best known as a mechanical effect. It typically refers to a linked sequence of events where the time between successive events is relatively small. This leads to a major failure along with a rapid reduction in the component reliability.

## 3.4 Availability Analysis of the system

In general, availability considers the duration of up-time in operation, and it is a criterion to evaluate how often a system or component is alive or well [10]. The main assumption in reliability and availability analysis is that components are repairable. In this study, $A$ is defined as the current system availability, which implies a system without maintenance (run to failure), and $A^*$ is defined as the modified system availability, which reflect the system with preventive maintenance (periodic maintenance).

In this stage, the availability of all components are measured by the mean time to repair (MTTR), and the mean time to failure (MTTF). MTTR is calculated based upon the constant average time to repair in components, which relies on past experiences. In this research, these values for mechanical components are extracted from the “OREDA Hand Book” except for the pipe, which is obtained from the $IEEE$ standard. The summary of the results are presented in Table 7 [23] [24] [33].

The outcome of reliability analysis indicates that the distribution function for the existing components in the Domestic Hot Water follows Weibull distribution, so the value of the MTTF in these components is dependent on the scale factor (α) and the shape factor (β) (Eq-29) as follows:

$$\Gamma(x) = \int_0^{\infty} t^{x-1} e^{-t} dt$$

$$MTTF = \alpha \times \Gamma(1 + \frac{1}{\beta})$$

The summary of the results in terms of evaluation of the MTTF is illustrated in the following table (Table 8).

Theoretically, MTTF is the time period that a component is expected to remain in operation and continue its intended function. The reliability of the component is decreased until reaching an unacceptable reliability level during its useful life as a result of a deterioration process. In reality, preventive maintenance in components can increase its reliability (in comparison to run to failure case) and return it to its original situation by decreasing the failure rate. In fact, some part of reliability loss is compensated through maintenance, and the reliability of a component can be kept at a reasonable rate.

In this part, the modified failure density function in the existing components in the Domestic Hot Water system should be calculated based on different average maintenance interval types, which represent the time between two consecutive maintenances. These AMI types are predefined scenarios on different components. Along with the decision process, the best combination of these AMI types is identified. These predefined time intervals are presented in Table 9.

The related graph in the modified failure density function with the Weibull distribution is drawn based on Eq-32 as follows:

$$f_T^*(t) = \sum_{K=0}^{\infty} \frac{\beta(t-kT_M)^{\beta-1}}{\alpha^{\beta}} \boldsymbol{exp}\left[-(\frac{t-kT_M}{\boldsymbol{\alpha}})^{\boldsymbol{\beta}}\right] \times \left[\boldsymbol{exp}\left[-(\frac{T_M}{\boldsymbol{\alpha}})^{\boldsymbol{\beta}}\right]\right]^K$$

Regarding to the above mentioned equation, the calculation of reliability parameters in the modified system is based on the following sequence:

Firstly, different maintenance intervals time ($T_M$), which define the average maintenance interval types($AMI$), are assigned. For instance, if $T_M = 2.5$ , the allocated time intervals are 0-2.5, 2.5-5, 5-7.5, and so on. Then the average time in each time interval is taken into account for calculation. The value of $f_T^*(t)$ in each mentioned $T_M$ is determined, and the results are indicated in a graph “failure density function versus time”. In the next step, an exponential or Weibull distribution with the form of $\lambda \exp(-\lambda t)$ or $\frac{\beta t^{\beta-1}}{\alpha^{\beta}} \boldsymbol{exp}\left[-(\frac{\boldsymbol{t}}{\boldsymbol{\alpha}})^{\boldsymbol{\beta}}\right]$ is fitted to the failure density function trend using regression analysis in order to estimate the reliability parameters to compute $MTTF$ in each specific maintenance interval time($T_M$). A careful look at the failure density function of component with preventive maintenance indicates that the failure density function is changed from its original distribution to exponential form by scaling factor ($R^K(T_M)$). A number of examinations in this case study indicates that the outcome of modified failure density function has a complicated trend, so these cases comply with the Weibull distribution, because the Weibull distribution consists of two parameters in order to fit assigned function to the existing trend using regression analysis.

The graph presented in Figure 57 indicates the calculation details of mean time to failure of existing components in Domestic Hot Water system has an average maintenance interval equal to 1.25 years along with parametric values associated with the Weibull or exponential distribution.

In this study, the outcome of calculations such as the shape parameter as well as the scale parameter in the Weibull distribution, along with the failure rate in the exponential distribution, the MTTF, and $R^2$ in different $T_M$ are presented for all existing components. Concerning the pipe, these maintenance interval time values ($T_M$) such as 0.5, 1, 1.25, 2.5, 5, 10, 12, and 15 years are presented as follows (Table 10). Further details including numerical values and related graphs in the different maintenance intervals time in the existing component in the DHW system, are illustrated in Appendix D.

Concerning the boiler, these maintenance interval time values ($T_M$) such as 1, 1.25, 2.5, 5, and 10 years are presented in Table 11.

In terms of the pump, these maintenance interval time values ($T_M$) such as 1, 1.25, 2.5, 5, 10, and 12 years are presented below as follows (Table 12):

In terms of the gate valve, these maintenance interval time values ($T_M$) such as 1, 1.25, 2.5, and 5 years are presented in Table 13.

Regarding the check valve, these maintenance interval time values ($T_M$) such as 0.25, 0.5, 1, 1.25, and 2.5 years are presented in Table 14.

Regarding heat exchanger, these maintenance interval time values ($T_M$) such as 1, 1.25, 2.5, 5, 10, and 12 years are presented in Table 15.

Now, based on the available information in terms of MTTF in different average maintenance interval types (AMI) as well as MTTR for each component, the inherent availability of these components in the Domestic Hot Water system are calculated based on Eq-28 as follows:

$$a_{i,j,k} = \frac{MTTF}{\mathrm{MTTF} + \mathrm{MTTR}}$$

In the next stage, the maintenance effect ($\Delta a_{i,j,k}$) is calculated based on the difference between two consecutive average maintenance intervals ($\Delta a_{i,j,k} = a_{i,j,k} - a_{i,j,k+1}$) for all existing components. The calculation outcomes, which indicate availability and maintenance effect, are presented in both Table 16 and Table 17.

In the subsequent stage, the existing components with different average maintenance interval types (AMI) are sorted in ascending order based on the maintenance effect index ($\Delta a_{i,j,k}$) to establish a sorting list. The information in this sorting list is a base in assigning the maintenance plan for components in order to keep the availability of the system without any over maintenance. The ordering list is divided into two parts as the top list and the bottom list. The top list presents components with a low maintenance effect in different average maintenance interval types (AMI), while the bottom loop consists of the components with high maintenance effect on the system.

An organized e sorting list for the existing components in the Domestic Hot Water system along with the bar chart are indicated in Table 18 as well as Figure 58.

In terms of availability analysis, the system availability is measured the same way as the reliability analysis by a general formula in series, parallel (Eq-14,17), so all current equations concerning the system reliability analysis, which were obtained in the last section, are valid in the availability analysis, and they are presented in Eq-66, 67, 68, 69,70.

$$A(t) = A_1 * A_2 * A_3 * A_4 \text{ (System availability analysis)} \tag{66}$$

$$\boldsymbol{A_1 = 1 - (1 - A_{pi} * A_B * A_{Cv})^2} \text{ (Heating production sub-system)} \tag{67}$$

$$\boldsymbol{A_2 = 1 - (1 - A_{pi} * A_p * A_{Cv}} * A_{Gv}^2 * A_{St}\boldsymbol{)^3} \text{ (Distribution sub-system)} \tag{68}$$

$$\boldsymbol{A_3 = 1 - (1 - A_{pi} * A_{He}} * A_{Gv}^2\boldsymbol{)^2} \text{ (Heat transfer sub-system)} \tag{69}$$

$$\boldsymbol{A_4 = 1 - (1 - A_{pi}} * A_p^2 * \boldsymbol{A_{Cv}} * A_{Gv}^2 * A_{St}\boldsymbol{)^3} \text{ (Circulation sub-system)} \tag{70}$$

The quantitative analysis is based on the “Inherent Availability” method in the system by considering different average maintenance interval types (AMI), which are indicated in Table 9.

The main aspect of KSA analysis is to organize maintenance plan in order to keep system availability equal or greater than current system without imposing over maintenance.

The availability of the components in DHW as well as current system (A) are illustrated in Table 19.

After quantitative analysis, the availability of the current system is measured as 0.978644. This value is quantified based on series structure of four sub-systems as a heating production sub-system, distribution sub-systems and a heat transfer sub-system. The details of analysis are presented in Table 20.

Based on existing data, it is possible to perform maintenance scheduling by the KAS approach. The explanation concerning this method is given in the literature review. It is required to present different combinations of maintenance plans, which comply with the decision process in the KSA method. These maintenance plans are extracted from the ordering list. Each component should be updated based on the sequence in order list. The outcome is presented in Table 21.

As indicated above, the KSA approach relies on comparing the current system availability and the availability of a system with a defined maintenance plan, which is called modified system availability. The modified availability is quantified by the integration of existing components with different maintenance interval time ($T_M$). The explanation concerning decision process (KSA flowchart) is given in the methodology. Whenever, the STEP No in the top and the bottom list become the same, the calculation process will be finished.

The result after running the $KSA$ flowchart are shown a below in Table 22.

In terms of “STEP No” selection, it is required to have the two following criteria.

- In each “STEP No”, the maintenance plan for all existing components should be considered.
- The system availability in each “STEP No” (modified availability) is equal to or greater than the current system availability($A = 0.978644$).

Among the outcomes of decision process, some options, which do not meet the above mentioned criteria, should be ignored. After selecting suitable options, it is suggested to calculate the average value of "e" $(e = A^* - A)$. The nearest value to the average "e" is selected as a possible choice. The aim is to avoid over-maintenance as well as being safe in terms of system availability. The results are illustrated in Figure 59. The STEP No 9T, which includes maintenance plans for all existing components in the DHW system, is the nearest point to the average. The preventive maintenance plans in the DHW system are represented in Table 23.

The modified system reliability is determined, and it is compared with the current system reliability. The final result indicates that the revised system reliability compromises with the current system reliability trend. In fact, there are difference between the current system and modified system in terms of reliability, but the differences are negligible. The outcome is shown in the following graph in Figure 60.

## 3.5 Switching from parallel to standby system

In this section, it has been decided to change the arrangement of the heat transfer sub-system in order to diminish maintenance cost, while keeping the availability of the system at the same level as the existing sub-system. In the current sub-system, the both heat exchangers, which have the same capacity, are in parallel; it is recommended to change the current structure to a standby configuration. In this new arrangement, one heat exchanger performs as a main component and the other one is kept as a standby, however, both heat exchangers are identical. The arrangement of this proposed heat transfer sub-system is shown in Figure 61. In this proposed structure, it is assumed that the reliability of both the main and standby component are the same, and the failure in the changeover switch is not taken into account (known as perfect switching). In addition, for the sake of simplicity in calculation, the series system, which contains the pipe, a couple of gate valves, and the heat exchanger, is replaced with a single component in terms of reliability. This single component is called heat transfer component. The proposed sub-system arrangement is represented by Figure 62.

The reliability function in the heat transfer component is obtained by multiplying the reliability functions of the pipe, two gate valves, and the heat exchanger as a series structure (Eq-14) which is given by Eq-71.

$$R_{HT}(t) = R_{Pi}(t) * R_{He}(t) * R_{Gv}^{2}(t) \tag{71}$$

In this equation, $R_{HT}(t)$ , $R_{Pi}(t)$, $R_{He}(t)$, and $R_{Gv}(t)$ are the reliability functions of the heat transfer component, the pipe, the heat exchanger, and the gate valve.

The outcome of calculation is given by a graph"$Reliability\ versus\ time$", which indicates the trend of reliability in the heat transfer component in the operation period. Afterwards, a suitable function, which is more representative of that data trend is chosen. In this study, the regression analysis is performed by exponential function and Rayleigh function in order to identify the best function, which has the best fit with the existing trend. The results are indicated in Figure 63.

The comparison between the two indicated functions shows that the Rayleigh function ($R^2$=0.9940) is more compatible with the existing trend rather than the exponential function ($R^2$=0.9940). Therefore, the Rayleigh reliability function in the heat transfer component is given by Eq-72.

$$R_{HT}(t) = R_m(t) = R_s(t) = exp[-\frac{4 \times 10^{-8} t^2}{2}] \tag{72}$$

The general form of the Rayleigh function is presented in Eq-73. K is the Rayleigh parameter.

$$R(t) = exp[-\frac{Kt^2}{2}] \tag{73}$$

The Rayleigh parameter in this equation is equal to $K = 4 \times 10^{-8}$

In the next step, the reliability function of the heat transfer sub-system, which includes the main component and the standby component, is estimated. The operation period is between $0$ and $t$. The reliability of the heat transfer sub-system is the summation of two events, which are illustrated as follows:

- The main unit does not fail in the time interval $(0, t)$ which denotes zero failure ($P(zero\ failure)$)
- The main unit does not fail until time $\tau < t$, and the standby unit does not fail in the time interval$(\tau, t)$ which implies one failure ($P(one\ failure)$) .

The reliability function in the proposed sub-system (standby heat transfer sub-system), which follows the general form of the standby system in a perfect switching case (Eq-18,19 ,20), is illustrated as follows (Eq-74,75 ,76 ,77):

$$R_{sub-system} = P(zero\,failure) + P(one\,failure) \tag{74}$$

$$P(zero\,failure) = R_m(t) = exp[-\frac{Kt^2}{2}] \tag{75}$$

$$f_m(t) = Kt \times exp[-\frac{Kt^2}{2}] \tag{76}$$

$$P(one\,failure) = \int_0^t f_m(\tau)d\tau * R_s(t-\tau) \tag{77}$$

Finally, the reliability function in the standby heat transfer sub-system in perfect switching case is given in Eq-78)

$$R_{sub-system} = e^{-\frac{Kt^2}{2}} + \int_0^t K\tau e^{-\frac{K\tau^2}{2}} * e^{-\frac{k(t-\tau)^2}{2}} d\tau \tag{78}$$

$$R_{sub-system} = A + B$$

The sequence of solving the above mentioned equation is described as below:

$$A = e^{-\frac{Kt^2}{2}}$$

$$B = \int_0^t K\tau e^{-\frac{K\tau^2}{2} - \frac{k(-\tau+t)^2}{2}} d\tau = \int_0^t \frac{K\tau}{e^{\frac{K((\tau-t)^2+\tau^2)}{2}}} d\tau = K\int_0^t \frac{\tau}{e^{\frac{K((\tau-t)^2+\tau^2)}{2}}} d\tau$$

The $\tau$ can be written in another form as follows:

$$\tau = \frac{\frac{1}{2}(2(\tau-t)+2\tau)}{2} + \frac{t}{2}$$

$$\int_0^t \frac{\tau}{e^{\frac{K((\tau-t)^2+\tau^2)}{2}}} d\tau = \int_0^t \frac{\frac{\frac{1}{2}(2(\tau-t)+2\tau)}{2} + \frac{t}{2}}{e^{\frac{K((\tau-t)^2+\tau^2)}{2}}} d\tau = \frac{1}{2}\int_0^t \frac{2\tau - t}{e^{\frac{K((\tau-t)^2+\tau^2)}{2}}} d\tau + \frac{t}{2}\int_0^t \frac{d\tau}{e^{\frac{K((\tau-t)^2+\tau^2)}{2}}}$$

The suggested equation is divided into two part which are calculated separately. The solution for the first part($\int_0^t \frac{2\tau-t}{e^{\frac{K((\tau-t)^2+\tau^2)}{2}}} d\tau$) is given by substitution of variables in order to simplify this integral.

$$u = -\frac{K((\tau-t)^2+\tau^2)}{2} \Longrightarrow du = -\frac{K(2(\tau-t)+2\tau)}{2} d\tau = -K(2\tau - t)d\tau$$

$$\int_0^t \frac{2\tau - t}{e^{\frac{K((\tau-t)^2+\tau^2)}{2}}} d\tau = \frac{1}{k}\int -\frac{1}{e^{-u}} du = -\frac{e^u}{k} = \left[-\frac{1}{K}\frac{1}{e^{\frac{K((\tau-t)^2+\tau^2)}{2}}}\right] \ (0 < \tau < t)$$

$$\int_0^t \frac{2\tau - t}{e^{\frac{K((\tau-t)^2+\tau^2)}{2}}} d\tau = -\frac{1}{K}\left[-\frac{1}{2e^{\frac{Kt^2}{2}}} + \frac{1}{2e^{\frac{Kt^2}{2}}}\right] = 0$$

The second part can be converted to the error function, which is illustrated as follows:

$$\int_0^t \frac{d\tau}{e^{\frac{K((\tau-t)^2+\tau^2)}{2}}} = \int_0^t e^{-\frac{K((\tau-t)^2+\tau^2)}{2}} d\tau = \int_0^t e^{-\frac{K((\tau-t)^2}{2} - \frac{K\tau^2}{2}} d\tau$$

$$= \int_0^t e^{-\frac{K}{2}(\tau^2 - 2\tau t + \frac{t^2}{2} + \frac{t^2}{2}) - \frac{K\tau^2}{2}} d\tau = \int_0^t e^{-(\frac{K}{2}\tau^2 - K\tau t + \frac{Kt^2}{4} + \frac{Kt^2}{4}) - \frac{K\tau^2}{2}} d\tau = \int_0^t e^{-(K\tau^2 - K\tau t + \frac{Kt^2}{4}) - \frac{Kt^2}{4}} d\tau$$

$$= \int_0^t e^{-(\sqrt{K}\tau - \frac{\sqrt{K}t}{2})^2 - \frac{Kt^2}{4}} d\tau = \int_0^t e^{-K(\tau - \frac{t}{2})^2 - \frac{Kt^2}{4}} d\tau = \int_0^t \frac{d\tau}{e^{K(\tau-\frac{t}{2})^2}} \times \frac{1}{e^{\frac{Kt^2}{4}}}$$

The general form of the error function is defined by Eq-79.

$$erf(x) = \int_0^x \frac{2}{\sqrt{\pi}e^{u^2}} du \tag{79}$$

For simplification, the changing variable is necessary as described below:

$$v = \sqrt{K}\frac{(2\tau - t)}{2} \Rightarrow dv = \sqrt{K} d\tau$$

$$\tau = 0 \ \Rightarrow v = -\frac{\sqrt{k}t}{2}$$

$$\tau = t \ \Rightarrow v = \frac{\sqrt{k}t}{2}$$

$$\int_0^t \frac{d\tau}{e^{K(\tau-\frac{t}{2})^2}} \times \frac{1}{e^{\frac{Kt^2}{4}}} = \frac{1}{e^{\frac{Kt^2}{4}}}\int_0^t \frac{d\tau}{e^{K(\tau-\frac{t}{2})^2}} = \frac{1}{e^{\frac{Kt^2}{4}}}\int_{-\frac{\sqrt{k}t}{2}}^{\frac{\sqrt{k}t}{2}} \frac{dv}{\sqrt{K}e^{v^2}} = \frac{\sqrt{\pi}}{2\sqrt{K}e^{\frac{Kt^2}{4}}}\int_{-\frac{\sqrt{k}t}{2}}^{\frac{\sqrt{k}t}{2}} \frac{2}{\sqrt{\pi}e^{v^2}} dv$$

$$\frac{\sqrt{\pi}}{2\sqrt{K}e^{\frac{Kt^2}{4}}} \times \left(\int_{-\frac{\sqrt{k}t}{2}}^{0} \frac{2}{\sqrt{\pi}e^{v^2}} dv + \int_0^{\frac{\sqrt{k}t}{2}} \frac{2}{\sqrt{\pi}e^{v^2}} dv\right) = \frac{\sqrt{\pi}}{2\sqrt{K}e^{\frac{Kt^2}{4}}}\left[-\operatorname{erf}\left(-\frac{\sqrt{k}t}{2}\right) + \operatorname{erf}\left(\frac{\sqrt{k}t}{2}\right)\right]$$

The answer of these integrals are summarized as follows:

$$\int_0^t \frac{2\tau - t}{e^{\frac{K((\tau-t)^2+\tau^2)}{2}}} d\tau = \left[-\frac{1}{K}\frac{1}{e^{\frac{K((\tau-t)^2+\tau^2)}{2}}}\right] \ (0 < \tau < t)$$

$$\int_0^t \frac{d\tau}{e^{\frac{K((\tau-t)^2+\tau^2)}{2}}} = \frac{\sqrt{\pi}}{2\sqrt{K}e^{\frac{Kt^2}{4}}} \times \left[-\operatorname{erf}\left(-\frac{\sqrt{k}t}{2}\right) + \operatorname{erf}\left(\frac{\sqrt{k}t}{2}\right)\right]$$

$$B = K\left[\frac{1}{2}[0] + \frac{t}{2} \times \frac{\sqrt{\pi}}{2\sqrt{K}e^{\frac{Kt^2}{4}}}\left[-\operatorname{erf}\left(-\frac{\sqrt{k}t}{2}\right) + \operatorname{erf}\left(\frac{\sqrt{k}t}{2}\right)\right]\right]$$

$$B = K\left(\frac{\sqrt{K\pi}t}{4e^{\frac{Kt^2}{4}}}\left[-\operatorname{erf}\left(-\frac{\sqrt{k}t}{2}\right) + \operatorname{erf}\left(\frac{\sqrt{k}t}{2}\right)\right]\right)$$

The reliability function of the standby heat transfer sub-system is quantified by Eq-80.

$$R_{sub-system} = e^{-\frac{Kt^2}{2}} + K\left(\frac{\sqrt{K\pi}t}{4e^{\frac{Kt^2}{4}}}\left[-\operatorname{erf}\left(-\frac{\sqrt{k}t}{2}\right) + \operatorname{erf}\left(\frac{\sqrt{k}t}{2}\right)\right]\right) \tag{80}$$

With the substitution of the K parameter (Rayleigh parameter), the trend of the reliability function in the heat transfer sub-system is indicated in Figure 64.

A Weibull distribution, with a scale parameter (α) equal to 14000 and a shape parameter (β) equal to 2.65, is the best fit for the reliability trend in the heat transfer sub-system ($R^2$=0.9941). it is defined by Eq-81.

$$R_{sub-system} = \exp\left[-\left(\frac{t}{14000}\right)^{2.65}\right] \tag{81}$$

The reliability in the proposed sub-system (standby heat transfer sub-system) is compared with the current parallel structure in the following chart (Figure 65).

The result indicates that the standby structure improves the reliability of the heat transfer sub-system significantly in comparison to the parallel structure.

In the proposed system (standby sub-system), the calculation of availability is the same as the current system (parallel sub-system) except in the suggested standby heat transfer sub-system which follows the new reliability function in Eq-75. The steps in analysis are explained as follows:

The average maintenance interval (AMI) types in the components in the proposed system is the same as the current system except in the heat exchanger, which is replaced with the heat transfer component. The assigned maintenance interval time ($T_M$) in the standby heat transfer sub-system is represented as 1, 1.25, 2.5, 5, 10, and 12 years. While there are six failure density function vs time graphs, for the purpose of explaining MTTF in the purposed heat transfer system, the following two graphs will be discussed. The two graphs have an average maintenance interval of 1 and 1.25, respectively, with parametric values associated with the Weibull distribution. These graphs are shown in Figure 66.

In this study, the outcomes of calculation for the shape parameter, the scale parameter in the Weibull distribution, the failure rate in the exponential distribution, the MTTF, and $R^2$ in different average maintenance intervals are presented for the proposed sub-system (standby heat transfer sub-system). These values in maintenance interval times ($T_M$) such as 1, 1.25, 2.5, 5, 10 and 12 years are presented in Table 24. Further details including numerical values and related graphs in the different maintenance interval times in the proposed heat transfer sub-system are represented in Appendix E.

In the next step, the availability and maintenance effect in the proposed system (standby heat transfer sub-system) are quantified by the MTTF and MTTR in the components of the DHW system, in the different AMI. The outcomes are presented in Table 25 and Table 26.

The sorting step in the proposed system (standby heat transfer sub-system) is the same as the current system (parallel heat transfer sub-system). In this proposed standby sub-system, however, all related components such as the heat exchanger, the gate valve and the pipe are replaced by heat transfer components. Therefore, the availability of the standby heat transfer sub-system is determined by the derived reliability function (Eq-78).

The sorting list for existing components in the DHW system along with its respective bar chart are indicated in Table 27 as well as Figure 67.

Based on existing data in the proposed sub-system, the KSA approach is performed in order to identify the maintenance schedule with respect to the availability of the current system.  Although the system availability in the proposed system (standby heat transfer sub-system) is computed in the same way as the current system (parallel heat transfer sub-system), the key difference between them is due to the type of structure in the heat transfer sub-system. As it was proved, the proposed heat transfer sub-system follows the Weibull distribution with the scale and shape parameters equal to $14000$ and $2.65$ respectively. The value of MTTF, with reference to the general form (Eq-29) is calculated by Eq-82. In addition, the value of MTTR is quantified by summation of the MTTR in the pipe, the gate valve, and the heat exchanger (Eq-83). Finally, the availability in the heat transfer sub-system is calculated by Eq-84.

$$MTTF_{HT\ sub-system} = \alpha \times \Gamma(1 + \frac{1}{\beta}) \tag{82}$$

$$MTTR_{HT\ sub-system} = MTTR_{PI} + 2 \times MTTR_{GV} + MTTR_{HE} \tag{83}$$

$$A'_3 = \frac{MTTF_{HT\ sub-system}}{MTTF_{HT\ sub-system} + MTTR_{HT\ sub-system}} \tag{84}$$

The availability of the current system (A) is illustrated in the following table (Table 28) [25] [26] [31] [32]. After performing an analysis, the availability of the proposed system (standby sub-system) is measured to be 0.971204. The analysis outcome on the proposed system indicates a 0.76% deduction in the availability of the whole system in comparison with the existing system (parallel sub-system), which is negligible.

$$A_{parallel\ structure\ sub-syatem} = 0.978644$$

$$A_{standby\ structure\ sub-syatem} = 0.971204$$

$$\frac{A_{standby\ structure\ sub-syatem} - A_{parallel\ structure\ sub-syatem}}{A_{parallel\ structure\ sub-syatem}} = \frac{0.971204 - 0.978644}{0.978644} = -0.76\%$$

The analysis on the proposed system (standby sub-system) is the same as the current system (parallel sub-system) except for the calculation in the heat transfer sub-system. The detail of analysis is represented in Table 29.

Concerning the decision process in KSA approach, it was illustrated in the section 2. Different combinations of the maintenance plans in the components in the DHW system with proposed heat transfer sub-system, which are denoted “STEP No”, are shown by Table 30.

After running the KSA decision process, the outcomes, which include the current system availability (without maintenance) (A) and the availability of the system with different combinations of maintenance plans (A*) for the components in the DHW system, are given by Table 31.

The valid results of the decision process are given in Figure 68.

The three options in “STEP NO” (16B, 12T, 11T) impose extra maintenance costs as a result of declining average maintenance interval from 2.5 years to 1 year in heat the transfer system compared to the “STEP NO” 14B. Therefore, it is has been decided to opt for the last option (14B), which has an availability far closer to the availability of the original system. The final maintenance plan for the proposed system (standby heat transfer sub-system) is presented in Table 32.

It can be concluded that with improving reliability in heat transfer sub-system as a result of changing from parallel to standby, there could be a potential to reduce the number of maintenances in other components. The result indicate that the number of maintenance in the components such as the pump and the check valve is decreased.

## 3.6 Replacement analysis

### 3.6.1 Mathematical method

In this study, an optimum replacement analysis is performed on repairable sub-components of the heat exchanger such as the tube bundle and the baffle plates in order to identify the right time for replacement. As previously mentioned, this method relies on the replacement at a certain time interval (T) as well as the minimal repair (preventive maintenance) between two consecutive replacements.

Based on extracted failure data from the “OREDA Handbook”, the reliability function of the tube bundle and baffle plates also follow the Weibull distribution. The scale parameter and the shape parameter for these sub-components in the heat exchanger are presented in the following table (Table 33).

Generally, the optimal replacement time relies on the Weibull parameters and the cost (the rate of replacement cost to maintenance cost.  The literature review explains the mathematical concept of the method and proves the relevant equations. The optimal replacement time (T*) in a component is calculated based on Eq-51, which is presented below.

$$T^* = [\frac{C_2}{C_1\eta(\beta - 1)}]^{\frac{1}{\beta}}$$
$$\eta = \frac{1}{\alpha^\beta}$$

In this equation, the time replacement interval and the cost rate $(\frac{C_2}{C_1})$ are unknown. It is recommended to compute the time of replacement (T*) based on reliability of both the tube bundle and baffle plates at the time of preventive maintenance in every 2.5 years ($T_M$=2.5 years) by the reliability function diagram. The outcome of modified reliability diagrams indicate the reliability of both sub-components in the heat exchanger in the maintenance interval times 2.5 year. It is beneficial in making decisions about the time of replacement.

The modified reliability diagrams in the tube bundle and the baffle plates in the maintenance interval time 2.5 years are illustrated in Figure 69 and Figure 70.

As a result of deterioration during the useful life (operation time) of these sub-components, the reliability is diminished at the point of periodic maintenance time compared to the previous maintenance time. The modified and current reliability equations which are used in the calculation are denoted as follows:

$$R_T^*(t) = \sum_{k=0}^{\infty} exp\left[-(\frac{t - kT_M}{\alpha})^\beta\right] R^k(T_M)$$
$$R(t) = exp\left[-(\frac{t}{\alpha})^\beta\right]$$

The quantitative reliability values at the maintenance interval time 2.5 years ($T_M$=2.5 years) in the tube bundle and the baffle plates are presented as follows in Table 34.

A careful look at the Table 34 indicates that the revised reliabilities at the maintenance time 5 years are 52.6% in the tube bundle and 48.3% in the baffle plates. In addition, the mentioned value at maintenance time 7.5 years are 38.2% in tube bundle and 33.6% in baffle plates.

Concerning the system with the parallel heat transfer sub-system, both identical heat exchangers are in service, so the chance of having continuous function at the point of 5 years in both sub-components in the heat exchange with a 2.5 years maintenance interval time ($T_M$=2.5 years) is around 50%, which seems reasonable. The main purpose of replacement planning is to keep replacement cost low as much as possible. In this case, the replacement in both the tube bundle and baffle plates are performed periodically in a 5 year interval.

The modified scale parameter and shape parameter in the tube bundle and the baffle plates are obtained by fitting the Weibull distribution function on a modified failure density trend for the maintenance interval time ($T_M$) 2.5 years, which are shown in Figure 71, and Figure 72 as follows:

The modified reliability parameters in the tube bundle and the baffle plates are presented in Table 35. Further details including numerical values and related graphs in the maintenance intervals time 2.5 years in the tube bundle and baffle plates , are explained in Appendix F.

The cost rate $(\frac{C_2}{C_1})$ is calculated based on Eq-51. In this equation, the modified scale and shape parameters are used.

$$T^* = \left[\frac{C_2}{C_1\eta(\beta-1)}\right]^{\frac{1}{\beta}}$$

$$5*365*24 = \left[\frac{C_2}{\frac{C_1}{83100^{1.01}}*(1.01-1)}\right]^{\frac{1}{1.01}} => \frac{C_2}{C_1} = 5.24\times10^{-3}$$

$$5*365*24 = \left[\frac{C_2}{\frac{C_1}{71700^{1.01}}*(1.01-1)}\right]^{\frac{1}{1.01}} => \frac{C_2}{C_1} = 6.08\times10^{-3}$$

The average cost rate $(\frac{C_2}{C_1})$ in the 5 year replacement interval is equal to $5.66\times10^{-3}$ $\left(\frac{5.24+6.08}{2}\times10^{-3} = 5.66\times10^{-3}\right)$.

In the proposed system (standby heat transfer sub-system), only one heat exchanger is in service as a main component. Table 34 indicates that the chance of functioning at 5 years in both the tube bundle and baffle plates seems reasonable. In addition, as a result of having one component in standby, it is possible to accept greater reduction in the reliability of the heat exchanger, because the standby heat exchanger could be in service, while the main one is subjected to the failure. Consequently, it has been decided to extend the replacement interval in the heat exchanger from 5 years to 7.5 years. The chance of having functioning is around 35% (38.2% in tube bundle and 33.6% in baffle plates). The cost rates $(\frac{C_2}{C_1})$ are quantified as follows:

$$7.5 * 365 * 24 = \left[\frac{C_2}{\frac{C_1}{83100^{1.01}} * (1.01 - 1)}\right]^{\frac{1}{1.01}} => \frac{C_2}{C_1} = 7.89 \times 10^{-3}$$

$$7.5 * 365 * 24 = \left[\frac{C_2}{\frac{C_1}{71700^{1.01}} * (1.01 - 1)}\right]^{\frac{1}{1.01}} => \frac{C_2}{C_1} = 9.16 \times 10^{-3}$$

The average cost rate $(\frac{C_2}{C_1})$ in the 7.5 year replacement interval is equal to $8.52 \times 10^{-3}$ $\left(\frac{7.89+9.16}{2} \times 10^{-3} = 8.52 \times 10^{-3}\right)$. As it was illustrated previously, the gasket is not a repairable sub-component, so this suggested equation is not valid for the gasket. In fact, after each repair or replacement in the heat exchanger, the gasket should be replaced.

The summarized information concerning the replacement cost in the tube bundle and the baffle plates are presented in Table 36.

Figure 73 and Figure 74 illustrate the modified failure density function ($T_M$=2.5 years) and current failure density function in the tube bundle and the baffle plates.

## 3.6.2 Verification of the maintenance interval in the heat exchanger

It is required to verify the maintenance interval times in the heat exchanger, which is calculated by the KSA approach, by analyzing the modified reliability function graph. The current maintenance interval time in the heat exchanger is 2.5 years. It has been decided to extend the maintenance interval time in the heat exchanger form 2.5 years to 5 years. The modified reliability function in the tube bundle and the baffle plates in the maintenance interval time 5 years is analyzed. Then, the modified reliability function is compared to the current reliability function. The result are presented as the following graphs in Figure 75 and Figure 76.

The quantitative reliability values at the maintenance interval time ($T_M$=5 years) in the tube bundle and baffle plates are presented in Table 37.

A close look indicates that the trend of modified reliability function ($T_M$=5 years) in both the tube bundle and baffle plates almost converges into the current reliability function. So, the modified reliability function diminishes rapidly, which indicates a high rate of a progressive deterioration process in the heat exchanger and its sub-components. Comparing the trend of modified reliability function in both the maintenance interval times 5 years and 2.5 years determines that 2.5 years maintenance interval time is a suitable time frame for the heat exchanger (Figure 69, Figure 70, Figure 75, and Figure 76).

### 3.6.3 Life-Cycle-Cost analysis on the parallel and standby sub-system

After performing reliability and availability analysis to validate the proposed system (standby heat transfer sub-system), it is vital to determine the maintenance cost in both the parallel and standby sub-system with consideration of the maintenance and replacement plans by application of LCC analysis (Life-Cycle-Cost). The aim is to compare the long term maintenance cost in both alternatives. In this study, the future value (FV) as a comparison criterion in the both options is computed to identify the reasonable scenario in terms of saving cost in the long term. LCC analysis is performed by a number of items such as the cost of purchasing the heat exchanger (HEC), the maintenance cost ($C_1$), the replacement cost ($C_2$), the unit man-hour cost (x), the cost of purchasing spare parts: the tube bundle (TB), the baffle plates (BP), and the gasket (G). A number of assumptions made in the LCC analysis are listed as follows:

1. The interest rate is considered to be 3% compounded annually
2. The spent human resources in preventive maintenance is 24 man-hours ($C_1$).
3. The spent man-hour in a 5 year replacement interval in the parallel heat transfer sub-system is $5.66 \times 10^{-3}$ times of the preventive maintenance (2.5 years maintenance interval time) ($C_2$).

4. The consumed man-hour in a 7.5 year periodic replacement process in the standby heat transfer sub-system is $8.52 \times 10^{-3}$ times of the preventive maintenance (2.5 year maintenance interval time) ($C_2$).
5. In the parallel heat transfer sub-system, replacement in either both of heat exchangers is performed in two consecutive maintenance periods, where one heat exchanger is in replacement and the other one is in preventive maintenance.
6. The gasket after the preventive maintenance and the replacement process should be changed.
7. In the standby heat transfer sub-system, the preventive maintenance is performed on the standby heat exchanger after the replacement on the main heat exchanger.
8. The time period in the LCC analysis is taken into account for 15 years.

*The maintenance cash flow in the parallel heat transfer sub-system in both heat exchanger are presented in the both*

Table 38 and Table 39.

In the above tables, $x$ is defined as the rate of man-Hour. The future cost in the LCC analysis is determined by Eq-85.

$$F = P(1+i)^t \tag{85}$$

In this equation, $F$ is future cost, $P$is present cost, i is interest rate per period, and $t$ is the operation time.

The future value in the parallel heat transfer sub-system is calculated as follows:

$$F_0 = 2 \times HEC(1+i)^{15}$$
$$F_1 = 2 \times 24x(1+i)^{12.5} + 2 \times G(1+i)^{12.5}$$
$$F_2 = 1.00566 \times 24x(1+i)^{10} + G(1+i)^{10} + (TB + BP + G)(1+i)^{10}$$
$$F_3 = 1.00566 \times 24x(1+i)^{7.5} + G(1+i)^{7.5} + (TB + BP + G)(1+i)^{7.5}$$
$$F_4 = 1.00566 \times 24x(1+i)^{5} + G(1+i)^{5} + (TB + BP + G)(1+i)^{5}$$
$$F_5 = 1.00566 \times 24x(1+i)^{2.5} + G(1+i)^{2.5} + (TB + BP + G)(1+i)^{2.5}$$
$$F_6 = 1.00566 \times 24x(1+i)^{0} + G(1+i)^{0} + (TB + BP + G)(1+i)^{0}$$
$$\boldsymbol{F_{parallel}} = F_0 + F_1 + F_2 + F_3 + F_4 + F_5 + F_6$$

The future value is derived as follows (Eq-86):

$$\boldsymbol{F_{parallel}} = 3.12HEC + 210.12x + 14.56G + 5.83(TB + BP) \tag{86}$$

The maintenance cash flow in the standby heat transfer sub-system in the main and standby heat exchangers are presented in the both Table 40 and Table 41.

The future value in the standby heat transfer sub-system is calculated as follows:

$$F_0 = 2 \times HEC(1 + i)^{15}$$

$$F_1 = 24x(1 + i)^{12.5} + G(1 + i)^{12.5}$$

$$F_2 = 24x(1 + i)^{10} + G(1 + i)^{10}$$

$$F_3 = 1.00852 \times 24x(1 + i)^{7.5} + G(1 + i)^{7.5} + (TB + BP + G\,)(1 + i)^{7.5}$$

$$F_4 = 24x(1 + i)^{5} + G(1 + i)^{5}$$

$$F_5 = 24x(1 + i)^{2.5} + G(1 + i)^{2.5}$$

$$F_6 = 1.00852 \times 24x(1 + i)^{0} + G(1 + i)^{0} + (TB + BP + G\,)(1 + i)^{0}$$

$$\boldsymbol{F_{parallel}} = F_0 + F_1 + F_2 + F_3 + F_4 + F_5 + F_6$$

The future value is derived as follows (Eq-87).

$$\boldsymbol{F_{standby}} = 3.12HEC + 175.06x + 8.53G + 2.25(TB + BP) \tag{87}$$

Comparison between the future value of parallel and standby heat transfer sub-system indicates that the preventive maintenance cost and the replacement cost in the standby sub-system $(175.06x)$ is less than that of the parallel sub-system$(210.12x)$. In addition, the cost of spare parts in the standby sub-system $(8.53G + 2.25(TB + BP))$ is also less than that of the parallel sub-system $(14.56G + 5.83(TB + BP))$ .Thus, the standby heat transfer sub-system alternative has the advantage of saving costs compared to the parallel heat transfer sub-system, while the availability of the both alternatives are almost the same.

# 4. Result Analysis

The method and theoretical background in this research rely on reliability centered maintenance with a focus on availability of the components. In this study, maintenance plan in Domestic Hot Water of HVAC system in a commercial building in Canada is taken into account. As a result of the climate in Canada, it is necessary for HVAC systems to operate without interruption during long cold seasons. So, the availability of components in the mentioned system has a major role in maintenance planning. This research is performed based on a number of assumptions, which are categorized in five groups: availability based maintenance, standby heat transfer sub-system, and replacement interval analysis.

Concerning availability based maintenance, the following assumptions and facts are taken into account.

- HVAC system is categorized as a repairable system. It means that all components are repaired, maintained, adjusted or changed during the life time of the system. Repairing or adjusting a component is important in keeping system in function.
- Organizing periodic preventive maintenance in a component causes compression or reduction in the failure density function value and an extension of the time, which prolongs component useful life.
- A component is being deteriorated by aging during the operation period, however, preventive maintenance slows down the deterioration rate. In fact, the preventive maintenance cannot bring back the component to the new condition.
- Availability takes into account the duration of up-time for operation, and it is a measure to assess how often a system or component is functioning properly.
- The KSA approach relies on the comparison between the current system availability and the modified system availability. So the availability of the system with different combinations of maintenance plans in the existing components is calculated, and compared with the current system availability. The modified availability is expected to be equal or greater than the current system availability.

Concerning standby heat transfer sub-system, the following assumptions and facts are considered.

- In the proposed system (standby heat transfer sub-system), it is assumed that the reliability of both the main and standby components are the same, and the failure in the changeover switch is not taken into account (perfect switching)

- In the heat transfer component, the regression analysis is performed both by the exponential function as well as the Rayleigh function in order to determine which of the two offer the best fit with the existing trend.
- The comparison between two indicated functions in the heat transfer component shows that the Rayleigh function ($R^2$=0.9940) is more representative of that data trend than exponential function ($R^2$=0.8706) so the heat transfer component follows Rayleigh distribution.
- The reliability of the heat transfer sub-system is the summation of two events: The main unit does not fail in the time interval $(0, t)$ which denotes zero failure $(P(zero\ failure))$, the main unit does not fail until time $\tau < t$, and the standby unit does not fail in the time interval$(\tau, t)$, which implies one failure $(P(one\ failure))$ .
- In the standby heat transfer sub-system, the probability of failure in the standby component at the time of changeover is not considered in reliability analysis, and it is assumed that the standby component is ready to function.
- The analysis outcome on the proposed system (standby heat transfer sub-system) indicates a 0.76% deduction in the availability of the whole system in comparison with the current system (parallel heat transfer sub-system), which is negligible.

Concerning replacement interval analysis, the following assumptions and facts are considered.

- In the replacement analysis, the time replacement interval and the rate of replacement cost to repair cost ($\frac{C_2}{C_1}$) are unknown (one equation, and two unknown). Therefore, the time of replacement (T*) is being decided by the reliability values of both the tube bundle and baffle Plates at the time of preventive maintenance in different time period. In the current system (parallel heat transfer sub-system), both identical heat exchangers are in service, so the chance of having continuous function at the 5 years point in the both heat exchangers with $T_M$=2.5 years is around 50% ,which is considered to be acceptable. Moreover, In the proposed system (standby heat transfer sub-system) , it is possible to accept greater reduction in the reliability of the heat exchanger, because the standby heat exchanger could be in service, while the main one is subjected to the failure. Consequently, it has been decided to extend the replacement interval in the heat exchanger from 5 years to 7.5 years, and the chance of having continuous function is around 35%.

- LCC analysis (Life-Cycle-Cost) is a beneficial tool to compare the long term maintenance costs in both alternatives. In this study, the future value (FV) as a comparison criterion in both options is quantified to identify the reasonable scenario in terms of saving cost in long term.

# 5. Conclusion

## 5.1 Findings

The conclusion is divided into six major areas: reliability centered maintenance, effect of preventive maintenance on component, sensitivity analysis, KSA method, comparison between parallel and standby heat transfer sub-system, and LCC analysis on these sub-systems.

In general, $RCM$ is an analytical method to plan the preventive maintenance in systems, and reliability is a quantitative tool to identify appropriate preventive maintenance task and interval. The aim of preventive maintenance is to increase the lifetime of the component (MTTF), postpone its failure, and decrease the number of failures in the system. In addition, the outcome of reliability analysis indicates that the distribution function for the existing components in the Domestic Hot Water follows the Weibull distribution. The value of mean time to failure (MTTF) in these components is dependent on the scale parameter (α) and the shape parameter (β).

In maintenance scheduling, failure density function and reliability function should be modified by the effect of preventive maintenance and deterioration during operation period (scaling factor). Performing preventive maintenance improves the ability of the component to resist failure. The potential of component in failure resistance is reduced by increasing the number of maintenance as a result of its deterioration during operation period. Moreover, in performing preventive maintenance, deterioration in component is expected to occur at a slower rate than the case without maintenance.

In terms of sensitivity analysis on the both scale and shape parameters in the existing components of DHW system, Scale parameter (α) controls the component functionality. Therefore, It can be concluded that the higher the manufacturing quality, the better the system reliability. The most sensitive components in terms of scale parameter are check valve, pump, and gate valve. In addition, Shape parameter (β) controls the rate of primary failure modes to total failure modes. In terms of the shape parameter, a component is considered to be more sensitive when the rate of primary to total failure mode is decreased. Among the pump, gate valve, and check valve, the pump has the least rate of primary to total failure mode. Following the pump is the gate valve and then the check valve.

Concerning availability based maintenance method, the principle is to provide reliable maintenance plan along with high availability of the system, high level of safety and finally reducing maintenance cost. KSA decision process provides optimal maintenance schedule on the system, while keeping the availability of the current system. So, the main outcome is to increase maintenance interval in components with low maintenance effect to prevent over-maintenance, and decrease maintenance interval in components with high maintenance effect to be more available in operation period.

Concerning the proposed standby heat transfer sub-system, the result indicates that compared to the parallel structure, standby structure improves the reliability of the heat transfer sub-system. Therefore, Switching from parallel to standby structure provides extra room to increase the average maintenance interval type, so the number of maintenance decreased. The result indicates that the number of maintenance in the components such as pump and check valve decreased.

Finally, the maintenance cost in the heat exchanger in both cases (parallel and standby heat transfer sub-system) are compared. The maintenance cost consists of preventive maintenance cost, replacement cost as well as spare part cost. The results indicate that the replacement time in the heat exchanger sub-component with parallel structure is 5 years, while the replacement time in standby scenario is 7.5 years. After performing LCC analysis, the result in both alternatives indicates that the preventive and replacement maintenance cost in standby sub-system is less than that of the parallel sub-system. Moreover, the cost of spare parts in standby sub-system is less than that of the parallel sub-system, so the proposed heat transfer sub-system has an advantage of saving maintenance cost in comparison with the current one (parallel).

## 5.2 Limitations

Performing availability based maintenance in the DHW of HVAC system relies on the steps, which were explained in this research. In some steps, it is required to consider simplification assumptions to continue calculation process. These assumptions are identified as limitations in calculation, which are explained as follow:

In deriving reliability function in the heat exchanger, the failure data are extracted form OREDA failure handbook, which is a collection of equipment failure data form major oil companies. In fact, the type of heat exchangers, which are used in Oil& Gas industries, are not compatible with these heat exchangers in HVAC systems, so the reliability function could be different. In addition, in the system reliability analysis, it is assumed that the functioning of a component in the system is independent of the other components.

Moreover, proposing standby heat transferred sub-system is based on a number of assumptions. Firstly, the both heat exchanger, the main, and standby heat exchangers, are identical. Secondly, the standby sub-system follows perfect switching case, which ignores the chance of failure in the changeover switch. Finally, the chance of failure in the standby heat exchanger is not considered, so these assumptions were made to simplify the mathematical equation. In order to take into account the both mentioned failure, the general form of reliability function in the standby heat transfer sub-system is given by Eq-88

$$P(one\ failure) = R_m(t) + \int_0^t f_m(\tau)d\tau * R_s(\tau) * R_{cs}(\tau) * R_s(t-\tau) \tag{88}$$

In this mathematical equation, $R_s(\tau)$ is the failure in the standby unit at the time $\tau < t$, and $R_{cs}(\tau)$ defines the failure in the changeover switch at the time $\tau < t$.

## 5.3 Future work

As discussed, in order to obtain the mean time to failure (MTTF) from failure density function, which was modified by average maintenance interval types ($T_M$), it is required to perform the following sequence:

1. Specifying maintenance interval time ($T_M$) for each component
2. Modifying failure density function by scale factor $(R^k(T_M))$
3. Computing quantitative values of modified failure density function based on the maintenance interval time in different time periods $(1T_M, 2T_M, 3T_M, 4T_M, \dots \dots .)$
4. Performing regression analysis to obtain a function, which is more compatible with the trend of data
5. Calculating the failure rate ($\lambda$) if the trend follows exponential distribution
6. Quantifying the scale and shape parameters (α, β) if the trend is compatible with the Weibull distribution.
7. Calculation of mean time to failure (MTTF), which is dependent on the type of distribution function. Generally, the applicable distributions are exponential or Weibull $({}^{1}/_{\lambda}, \alpha * \Gamma(1+\frac{1}{\beta}))$

The above numerical analysis sequence is complicated and time-consuming. Therefore, it is necessary to develop a mathematical model in order to obtain results easily and accurately.

A careful look at the outcome of the mean time to failure (MTTF) in different components such as pipe, boiler, gate valve, ball valve, and relief valve in different maintenance interval times indicates that the correlation between MTTF and $T_M$ follows power function ($y = ax^b$). The results in different components are indicated in Figure 77, Figure 78, Figure 79, Figure 80, and Figure 81.

As can be observed above, the general form of the power function equation, which presents the relation between the mean time to failure (MTTF) and the maintenance interval time ($T_M$) is given by:

$$MTTF = A \times (T_M)^B$$

Both **A** and **B** are model parameters, which are dependent on the functionality of the component and its failure characteristics. These values are derived from regression analysis on the abovementioned components. The outcomes for the boiler, pipe, gate valve, ball valve, and relief valve are presented in Table 42.

As it was discussed above, **A** and **B** are parametric variables, which are component dependent. The aim is to propose an adequate mathematical model, which is defined by the Weibull parameters (α, β). This model also requires the equipment parameters ($\eta, \eta'$), which are defined in this research, in order to decline the deviations between the data trend and the model. The equipment parameters imply failure characteristics and functionality in components. The general forms in both variable parameter **A** and **B** are defined as follows:

$$A = F(\frac{\alpha}{\beta}, \eta)$$
$$B = F(\frac{\alpha}{\beta}, \eta')$$

Generally, the intended functions are affected by different types of failure modes within its operation time, and these failure modes rely on the failure and functional aspect of the components, so classification of components in terms of failure mode and functionality has an important role in proposing mathematical models. After all, each group has its own model parameters, which are called equipment parameters ($\eta, \eta'$). These parameters are derived by evolution method, and they follow the trend of existing data in both

$A\ versus\ \frac{\alpha}{\beta}$ and $B\ versus\ \frac{\alpha}{\beta}$ graphs in order to fill the gap between the mathematical models and the existing values. The suggested values for these equipment parameters are dependent on the accuracy of the failure database, the reliability function, and the accessibility to a wide range of data associated with more components. In this study, components are classified in two major groups: The pipe and boiler are categorized in one group, and the gate valve, ball valve and relief valve are categorized in the other group.

In the first stage, the explanation about the sequence of proposing mathematical model on variable parameter $A$ is given as follows:

The Weibull Parameters (α,β) and the model parameters (A,B) are summarized in Table 43

Below, a graph $\log(A)\ versus\ \log({}^{\alpha}/_{\beta})$, which consists of the failure characteristics of these components, can be found. Then, regression analysis is performed on existing data in order to obtain an appropriate function, which is compatible with the data trend. The result is given in Figure 82.

The result indicates that the exponential function is a reasonable function that illustrates the data trend. This function is given by:

$$\log(A) = 0.715 \times \exp(0.4702 \times \log({}^{\alpha}/_{\beta})$$

The results of the suggested function is compared with the real data to validate the accuracy of the model. The results are presented as follows in Table 44.

The derived results identified that there are considerable deviations between the data and the model ($R^2$=0.9878), so it is required to define the modification factor, which is called the equipment parameter (in this research), in order to diminish the existing deviation between the real data and the mathematical model. This parameter is a constant number, which is individual in equipment based on its functionality and failure characteristics. The presented components are classified into two categories: in terms of functionality and failure behavior. The boiler and pipe are in one group and the rest (valves) are in the other group. The suggested equipment parameters in both groups are given by:

$$\eta_1 = \log(1 + average\ deviation\ of\ boiler\&\ pipe)$$

$$\eta_2 = \log(1 + average\ deviation\ of\ valves)$$

The suggested parameters are indicated as follows:

$$\eta_1 = \log(1 + average\ (0.2034, 0.1807)) = 0.0763$$

$$\eta_2 = \log(1 + average\ (-0.1876, -0.015, -0.0981)) = -0.0518$$

The outcomes of the new equations after performing modification by equipment parameters are compared with the real data to identify the deviation. The results are shown in Table 45.

The final results indicate considerable deduction in deviation of suggested model from the real data, and the proposed model complies with the real data ($R^2$=0.9878). The proposed equation for parameter **A** is illustrated as follows:

$$\log(A) = \eta - 0.715 \times \exp(0.4702 \times \log(^{\alpha}/_{\beta})$$

In the last step, the sequence of the proposed mathematical model on variable parameter $B$ is described as follows.

The graph $B\ versus \log(^{\alpha}/_{\beta})$, which carries the failure aspect of these components, is plotted as shown in Figure 85 and the regression analysis is performed on the existing data in order to obtain a suitable function, which is compatible with the data trend. The result is shown in Figure 83.

The current outcome reflects that the linear function satisfies the existing trend, and it is given by:

$$B = -1.1697 \times \log\left(^{\alpha}/_{\beta}\right) + 4.1298$$

The results of the proposed function is compared with the real data to validate the accuracy of the model. The results are given in below in Table 46.

The outcomes denote deviation between the real data and the mathematical model, which is positive in the boiler and pipe, while it is negative in the gate valve, ball valve, and relief valve. However, these differences are not quantitatively considered. The proposed model complies with the real data ($R^2$=0.9995), which is reasonable. As a result of high degree of accuracy in the proposed model, it is not required to modify the proposed model with the correction factor. So, the equipment parameter $(\eta')$ in variable parameter **B** is equal to 1. The form of the variable parameter equation **B** is illustrated as follows:

$$B = \eta' \times (-1.1697 \times \log\left({}^{\alpha}/_{\beta}\right) + 4.1298)$$

The summary of suggested equipment parameters $(\eta, \eta')$ for both variable parameters $(A, B)$ are given by Table 47.

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# Figures

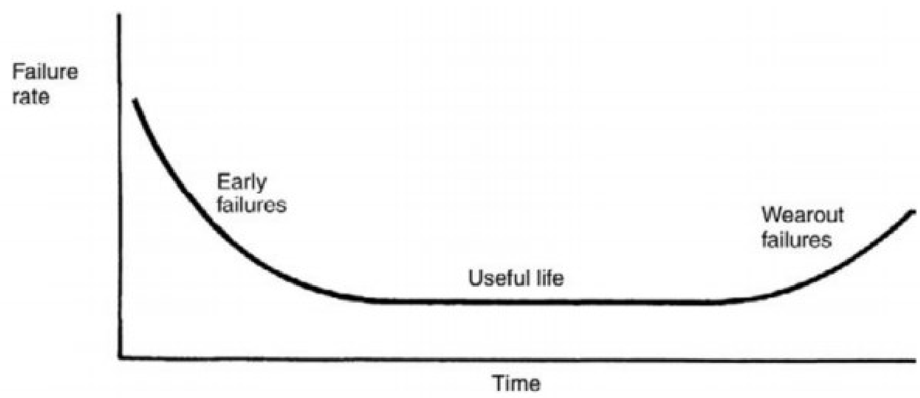


*Figure 1: General form of Bathtub curve [9]*

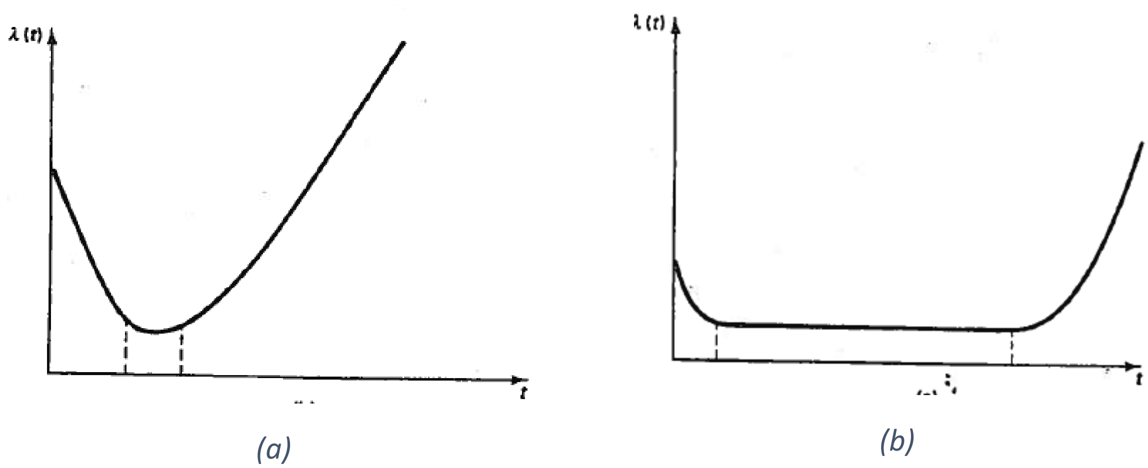


*Figure 2: Bathtub curve in mechanical components (a) and electrical components (b) [9]*

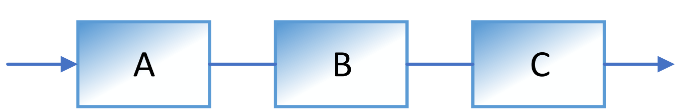


*Figure 3: Series structure*

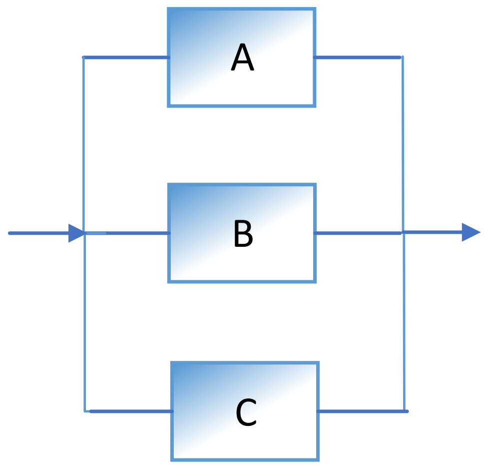


*Figure 4: Parallel structure*

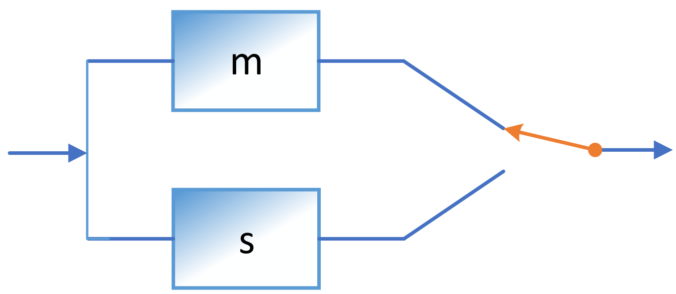


*Figure 5: Standby structure*

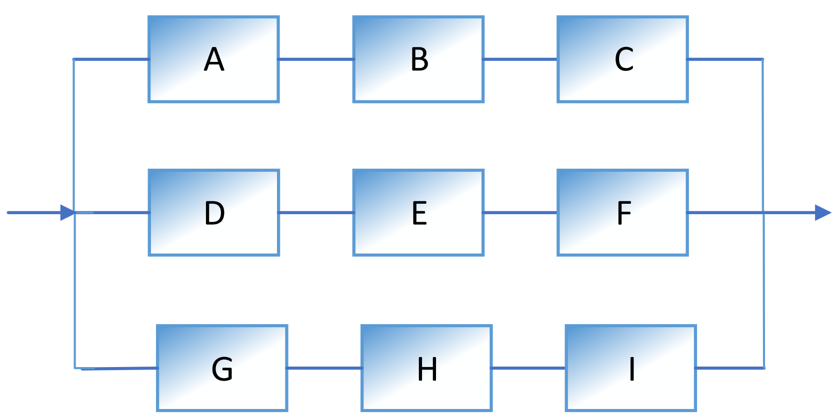


*Figure 6: Complex structure*

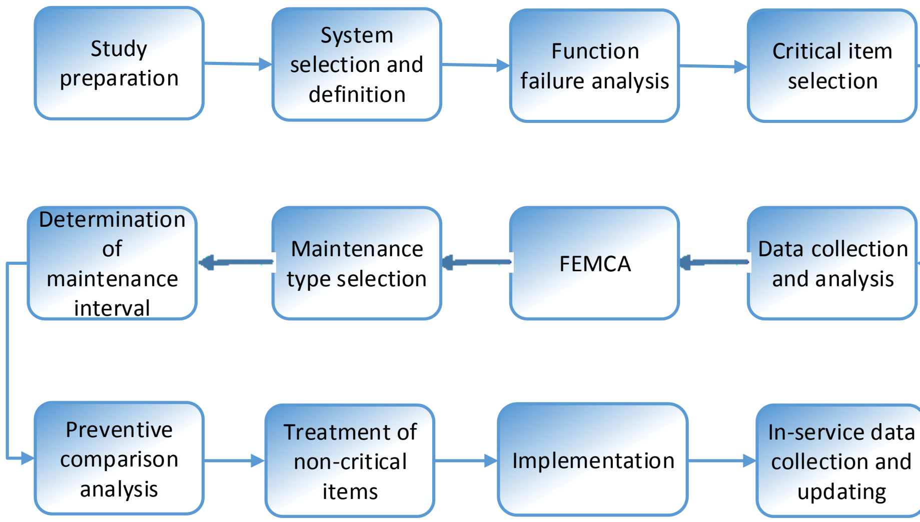


*Figure 7: RCM sequence*

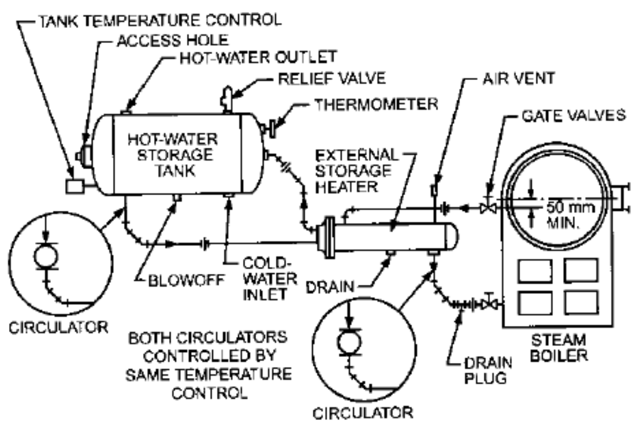


*Figure 8: Indirect, External Storage Water Heater [11]*

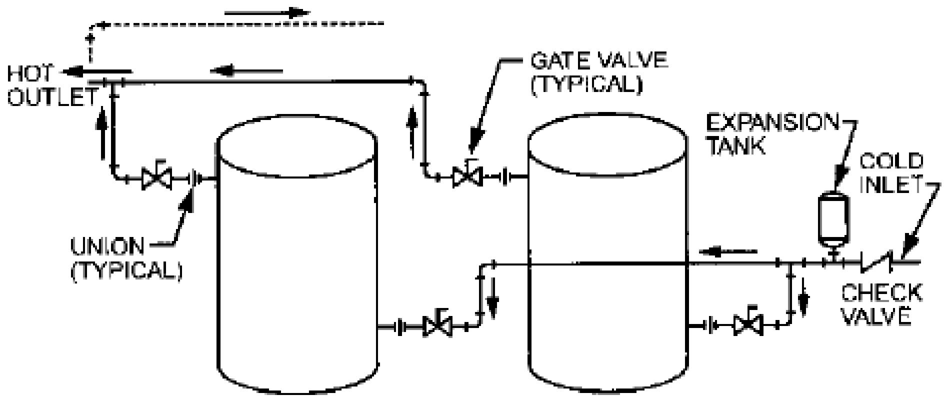


*Figure 9: Return Manifold System [11]*

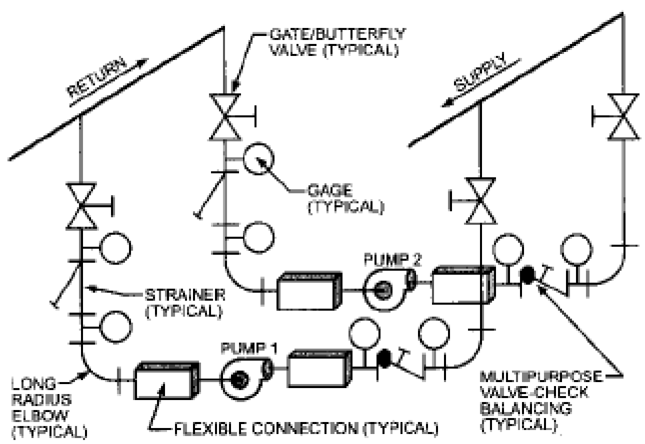


*Figure 10: Typical piping for parallel pumps*

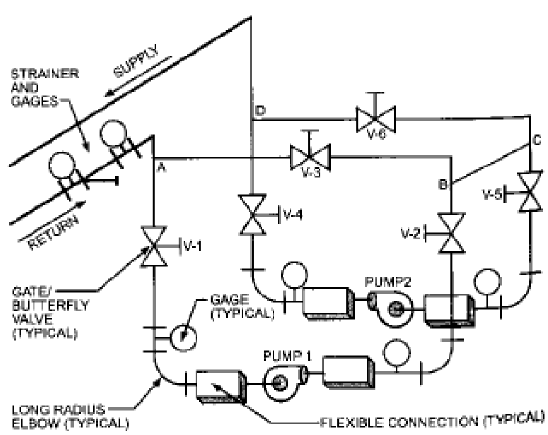


*Figure 11: Typical piping for series pumps*

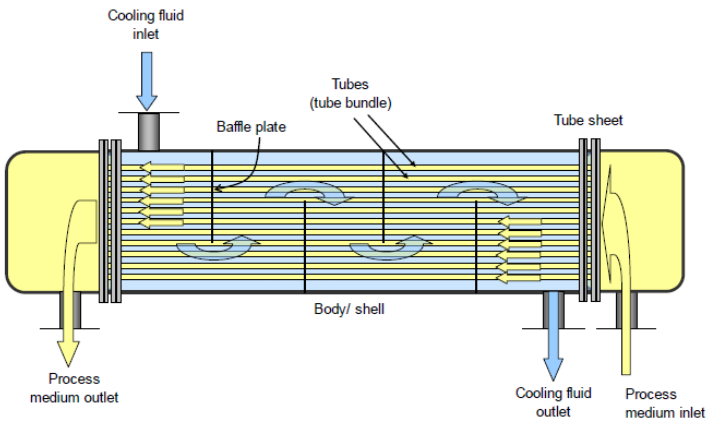


*Figure 12: Shell-and-Tube Heat Exchanger [14]*

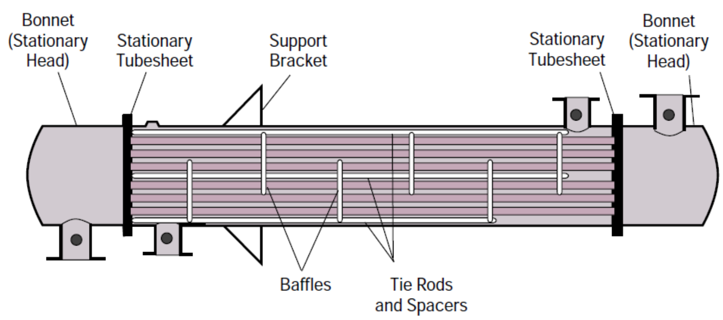


*Figure 13: Single pass Heat Exchanger [15]*

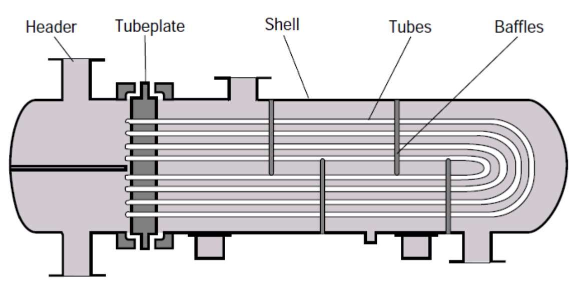


*Figure 14: U-bend Heat Exchanger [15]*

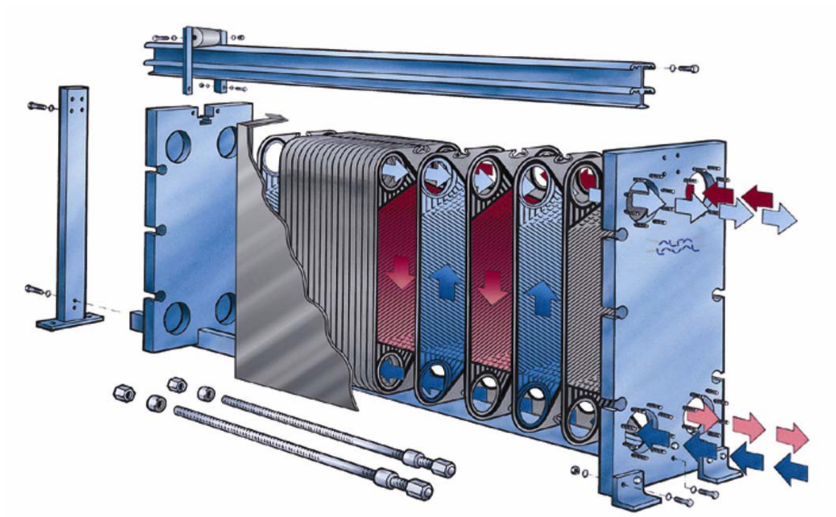

*Figure 15: Plate Heat Exchanger [16]*

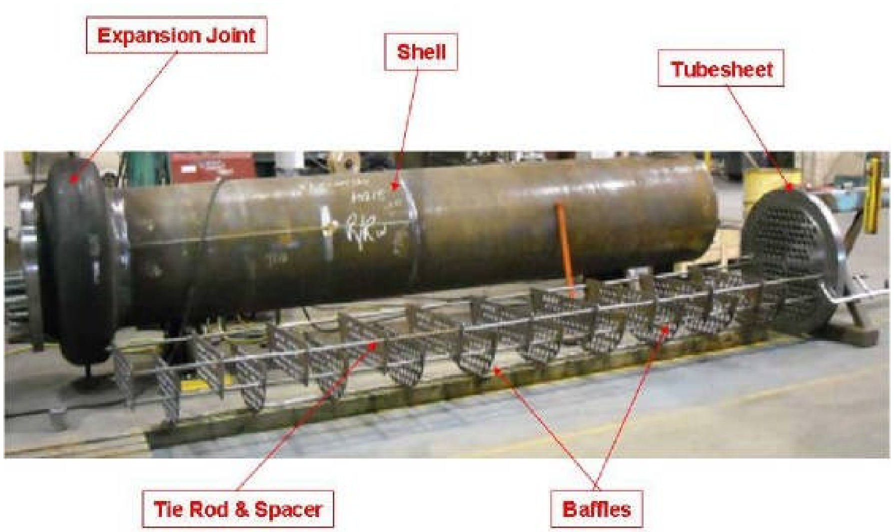


*Figure 16: Heat Exchanger sub-components [16]*

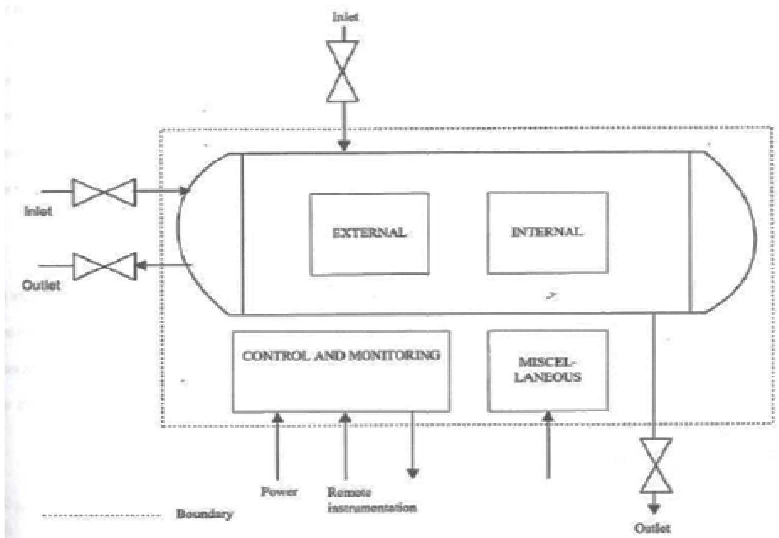


*Figure 17: Maintainable items in Heat Exchanger [24]*

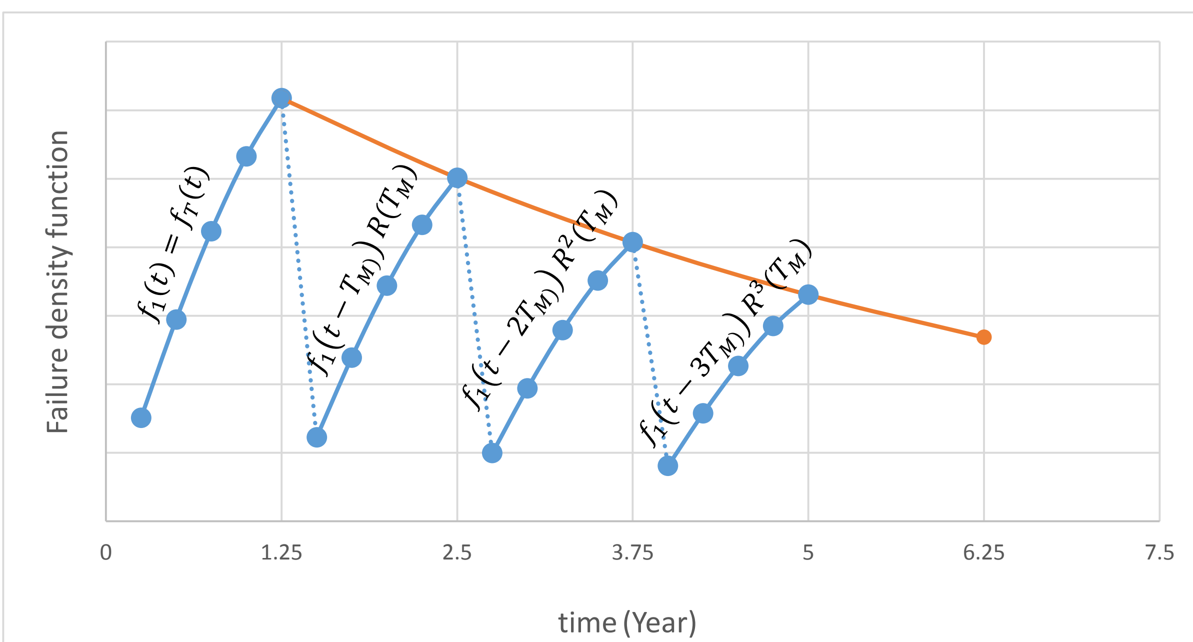


*Figure 18: Failure density function versus time, failure density function with periodic maintenance (modified failure density function)*

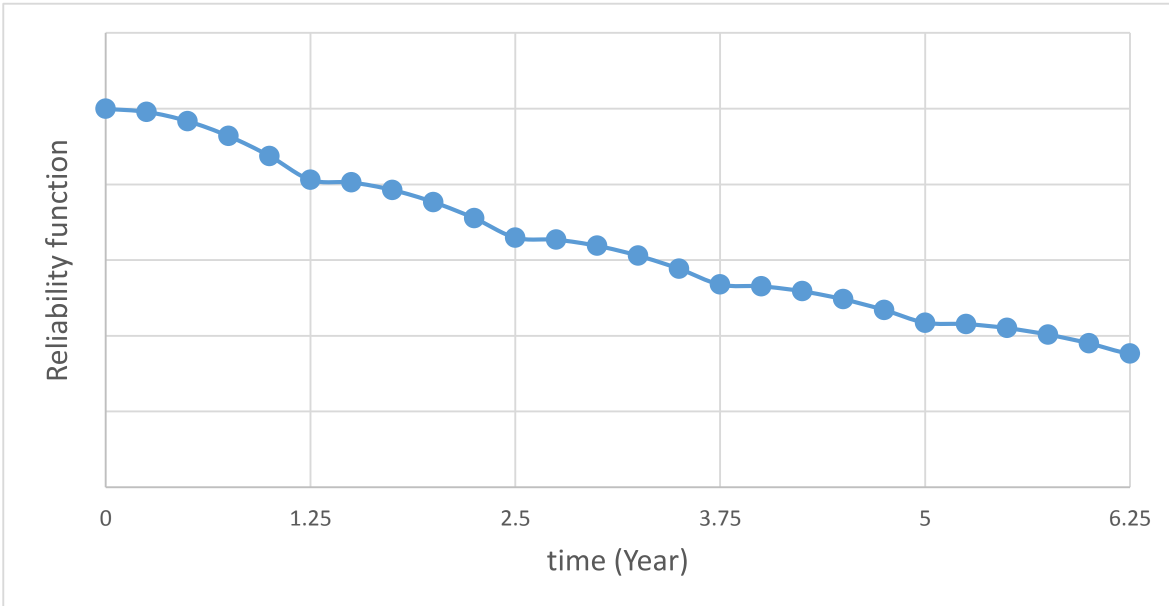


*Figure 19: Reliability function versus time, Reliability function with periodic maintenance (modified reliability function)*

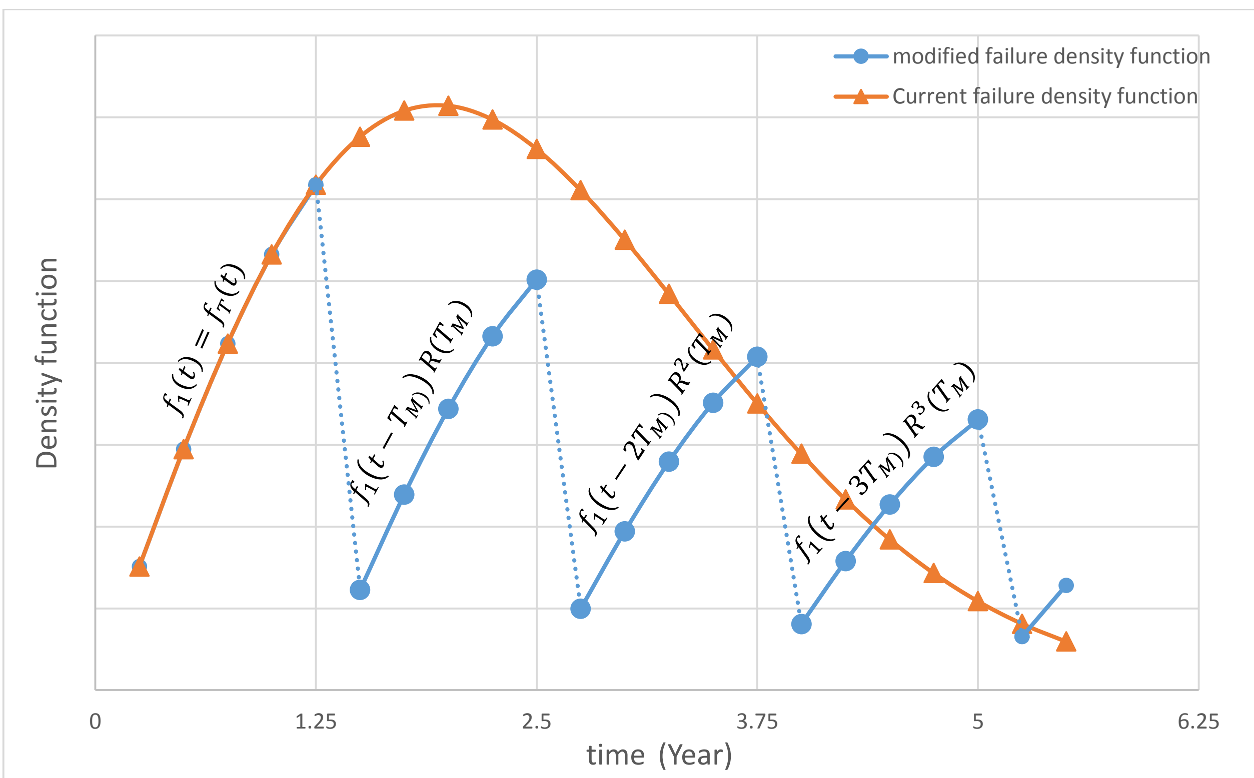


*Figure 20: Failure density function versus time, comparison between modified and current failure density function*

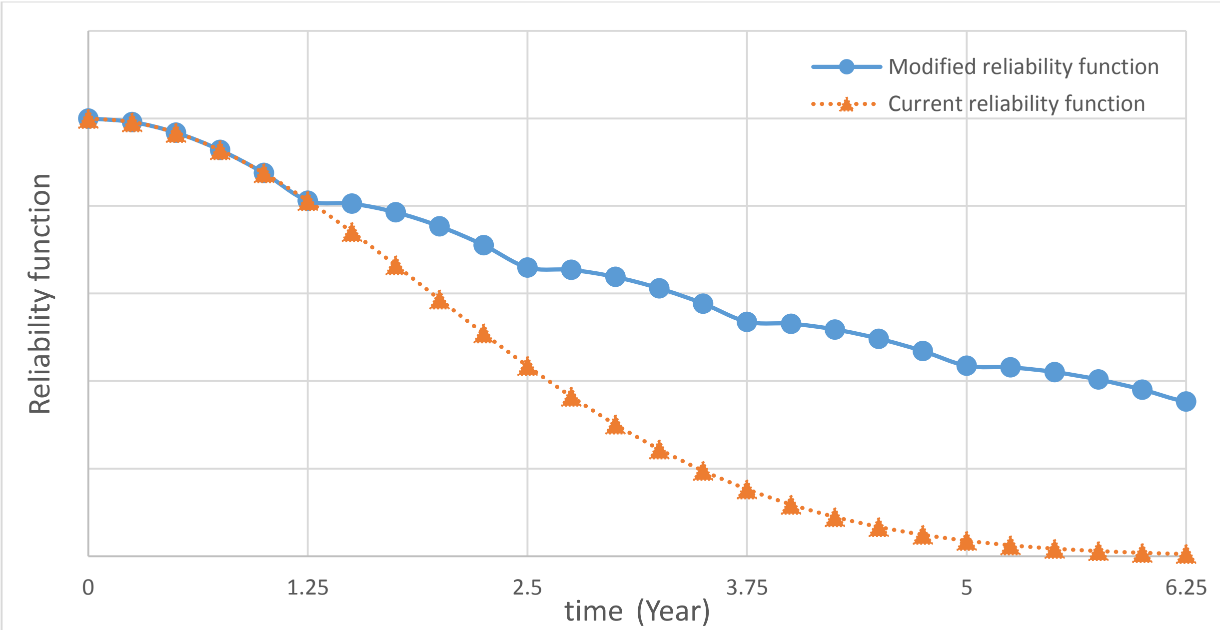


*Figure 21: Reliability function versus time, comparison between modified and current reliability function*

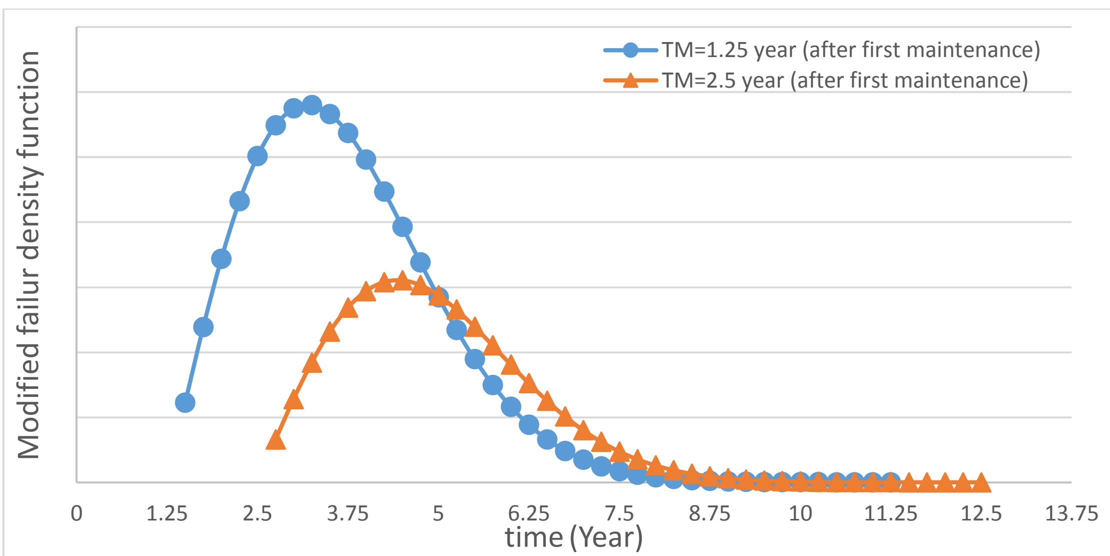


*Figure 22: Failure density function versus time, comparison between modified failure density function in* $T_M = 1.25\ years$ *and* $T_M = 2.5\ years$

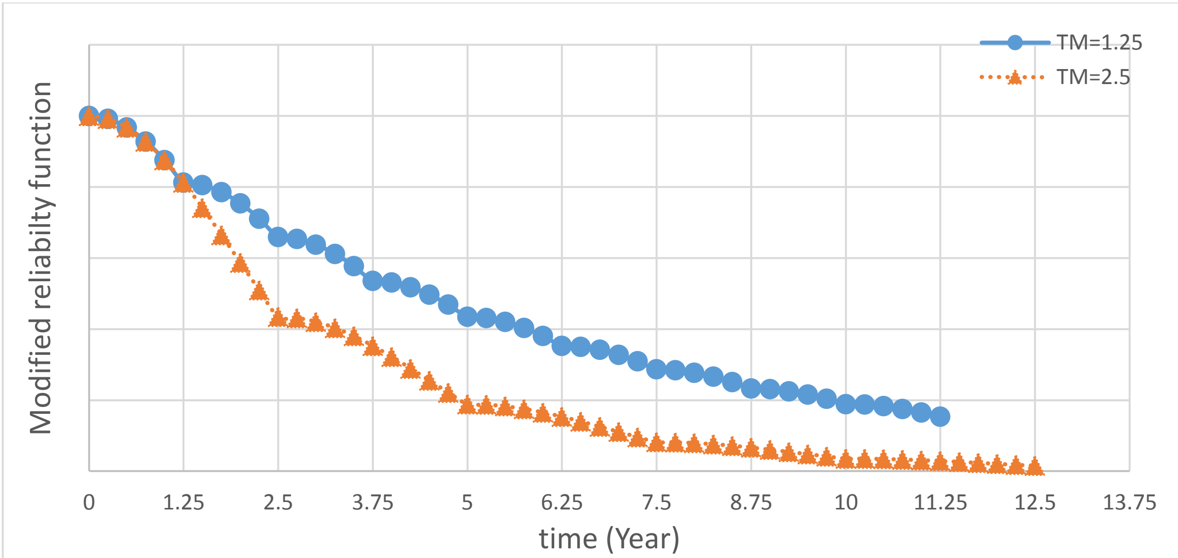


*Figure 23: Reliability function versus time, comparison between modified reliability function in* $T_M = 1.25\ years$ *and* $T_M = 2.5\ years$

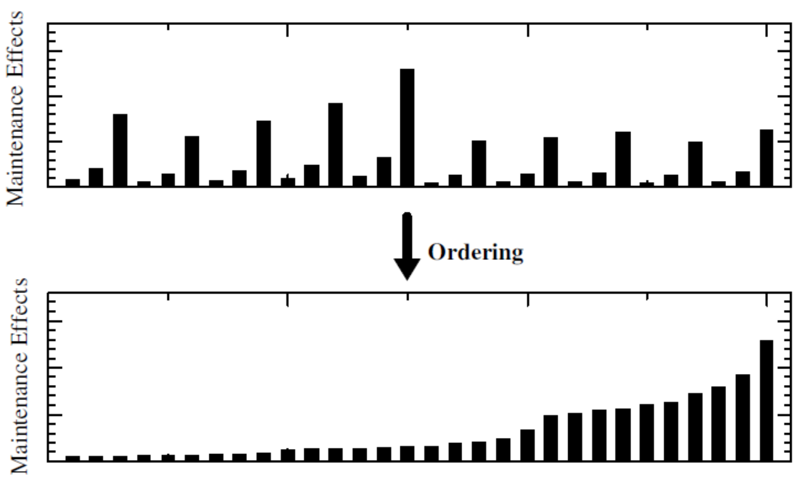


*Figure 24: Ordering the maintenance effects of existing components [19]*

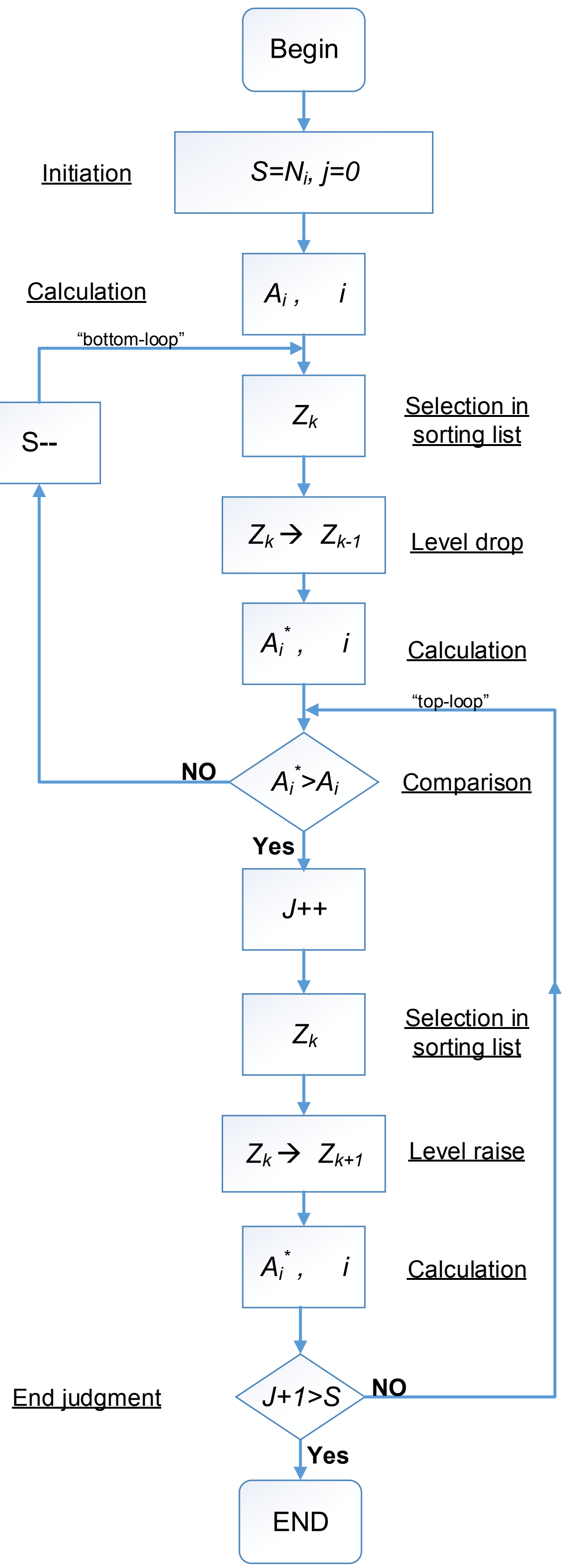


*Figure 25: Decision process in KSA method*

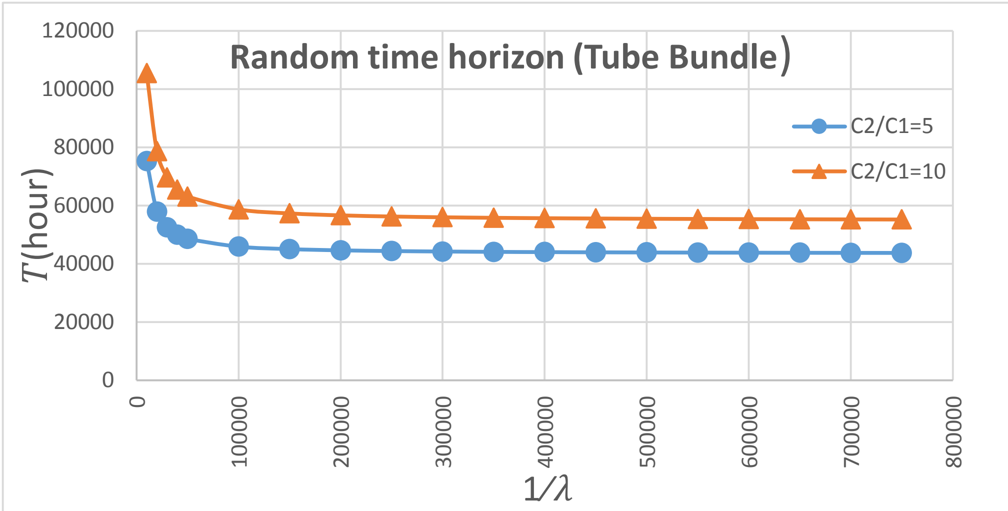


*Figure 26: Optimal replacement intervals with mean time* $(1/\lambda)$

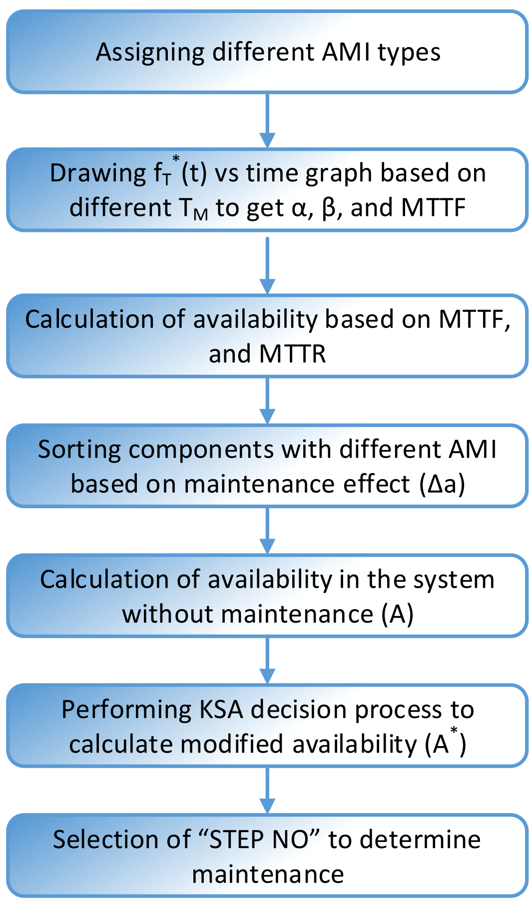


*Figure 27: The steps in availability analysis*

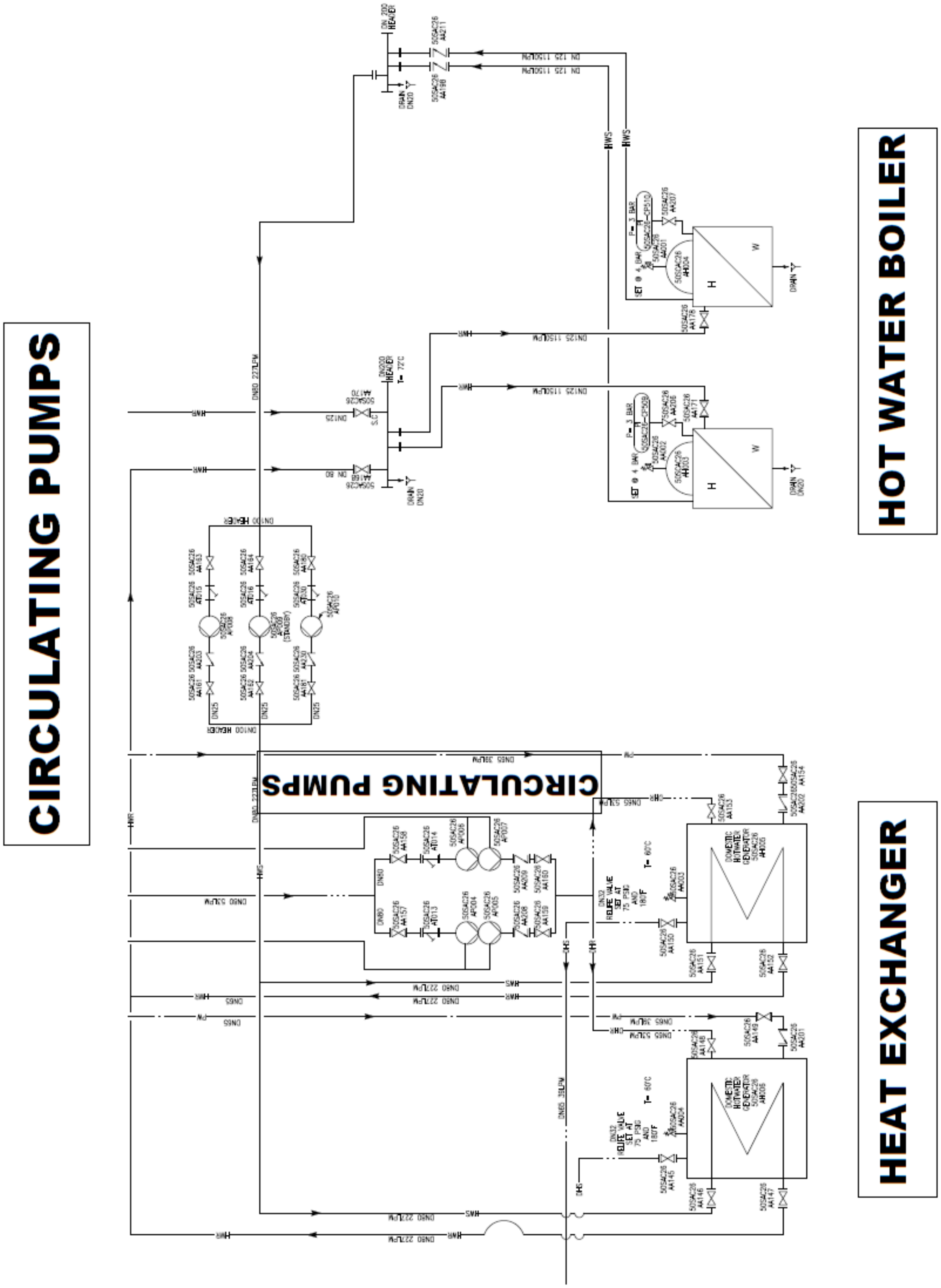


*Figure 28: Process and instrument diagram in HVAC*

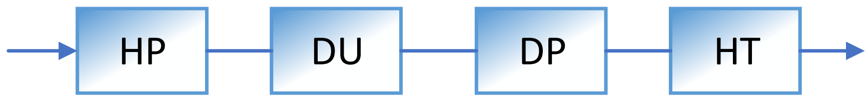


*Figure 29: Domestic Hot Water system Diagram in series structure*

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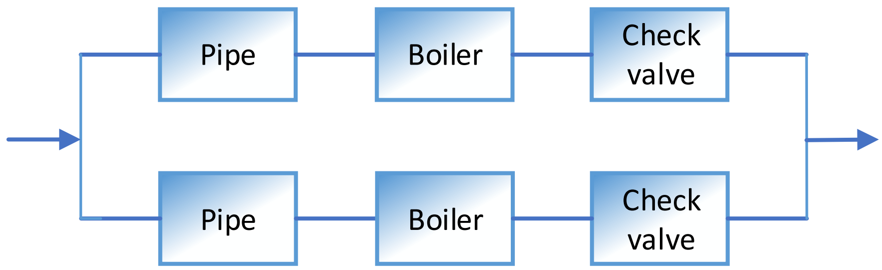



*Figure 30: Heating Production sub- system*

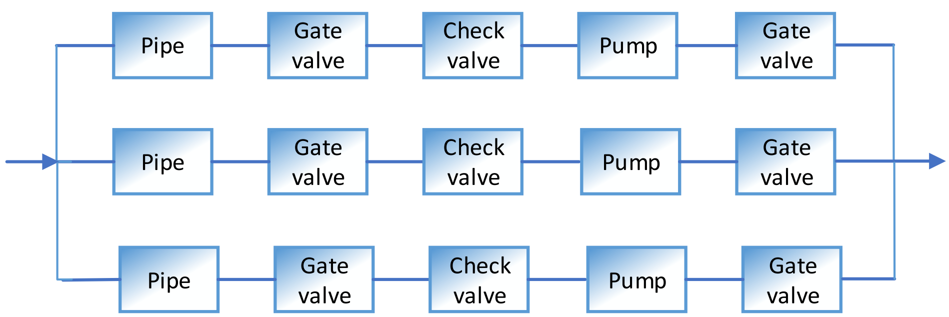



*Figure 31: Distribution sub- system (utility medium)*

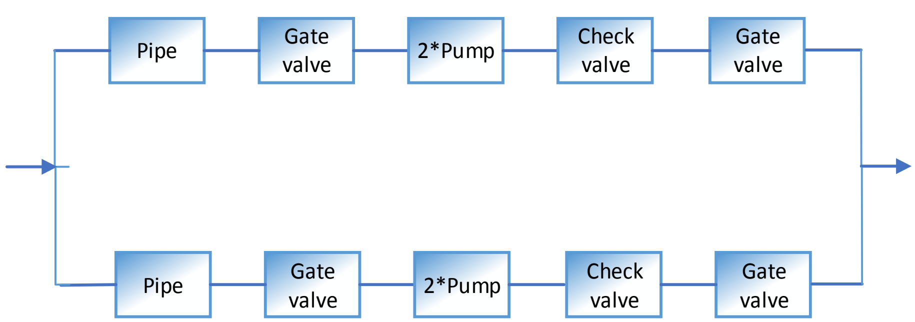



*Figure 32: Distribution sub- system (process medium)*

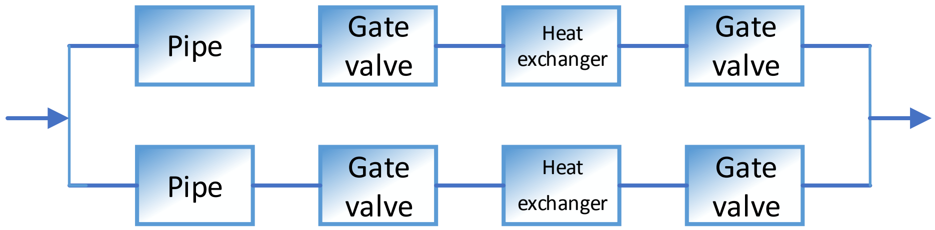



*Figure 33: Heat Transfer sub- system*

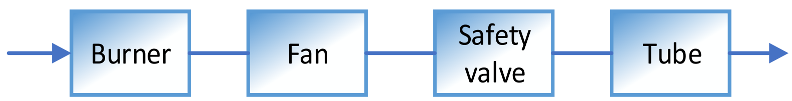



*Figure 34: Boiler system diagram*

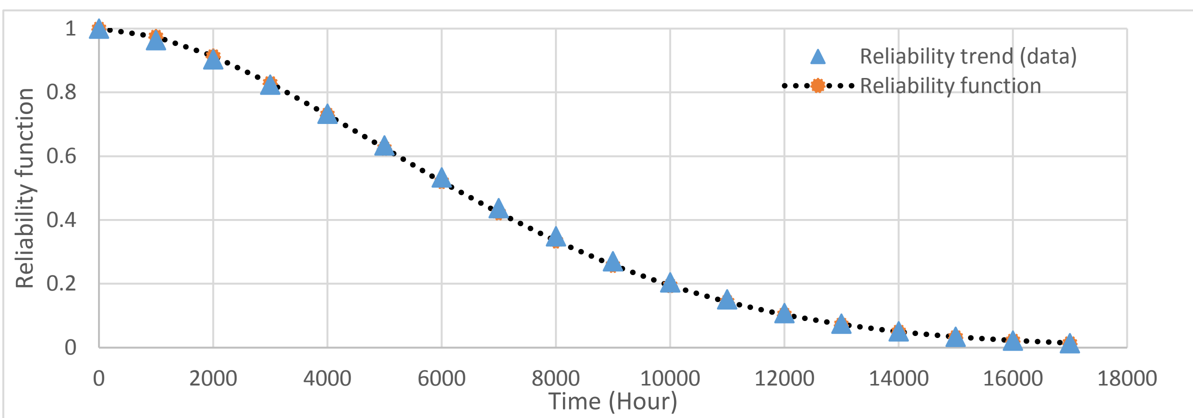



*Figure 35: Reliability function versus time, Reliability trend& proposed Reliability function in Boiler*

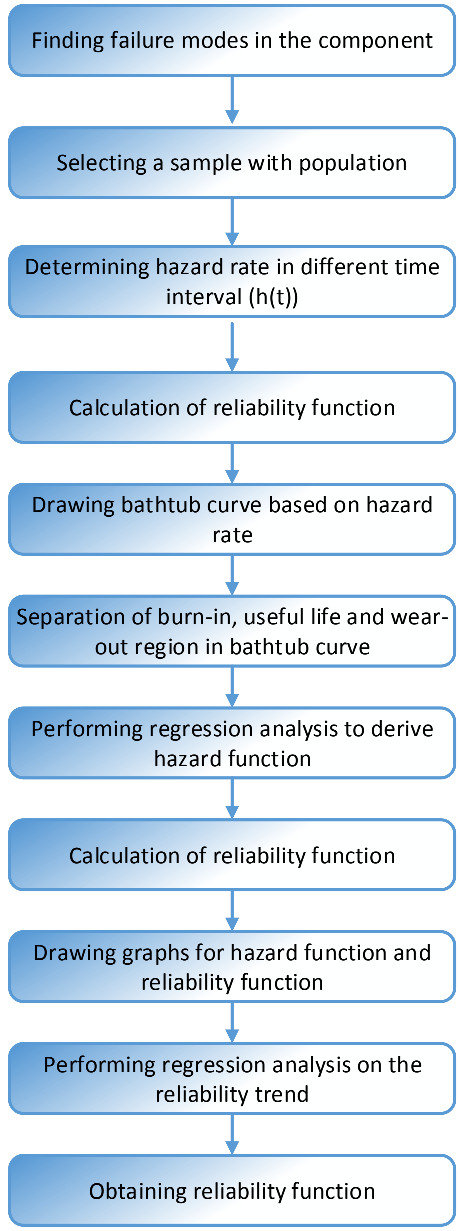



*Figure 36: Sequence in the reliability function determination*

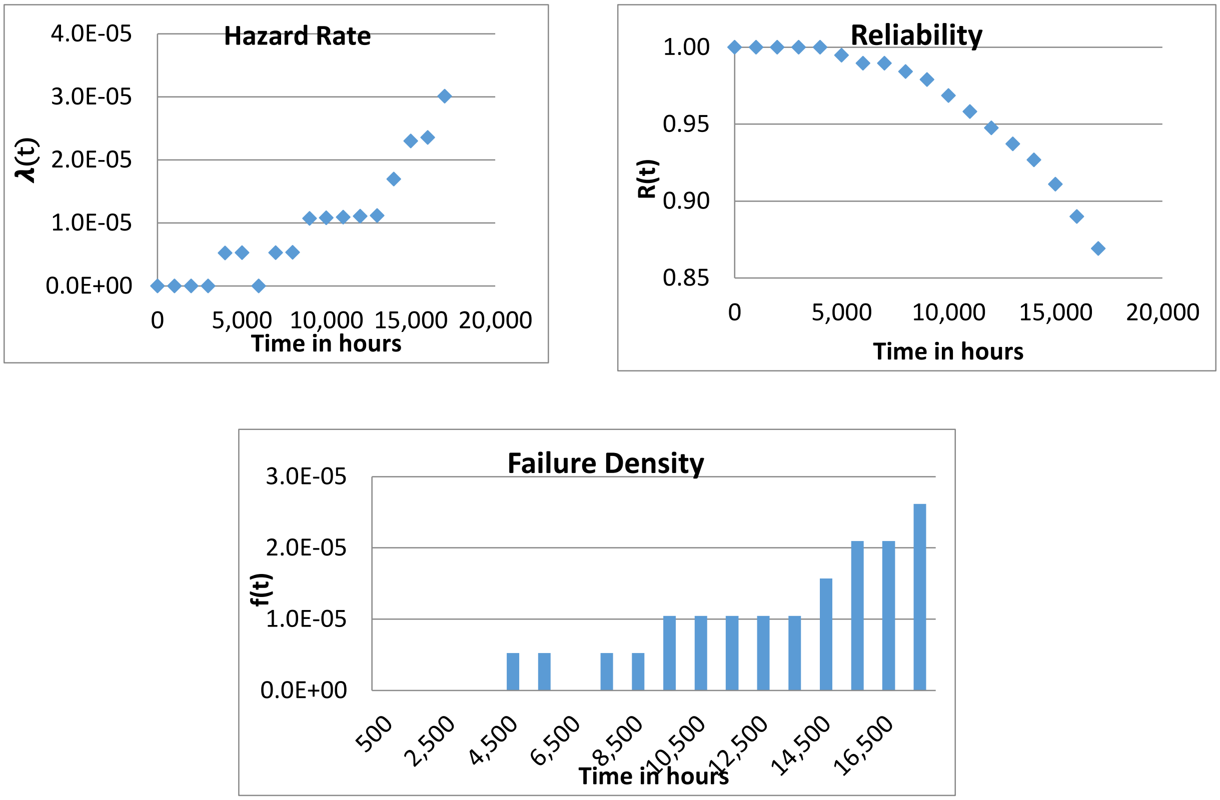



*Figure 37: Hazard rate, Reliability, and Failure density in "Tube Bundle"*

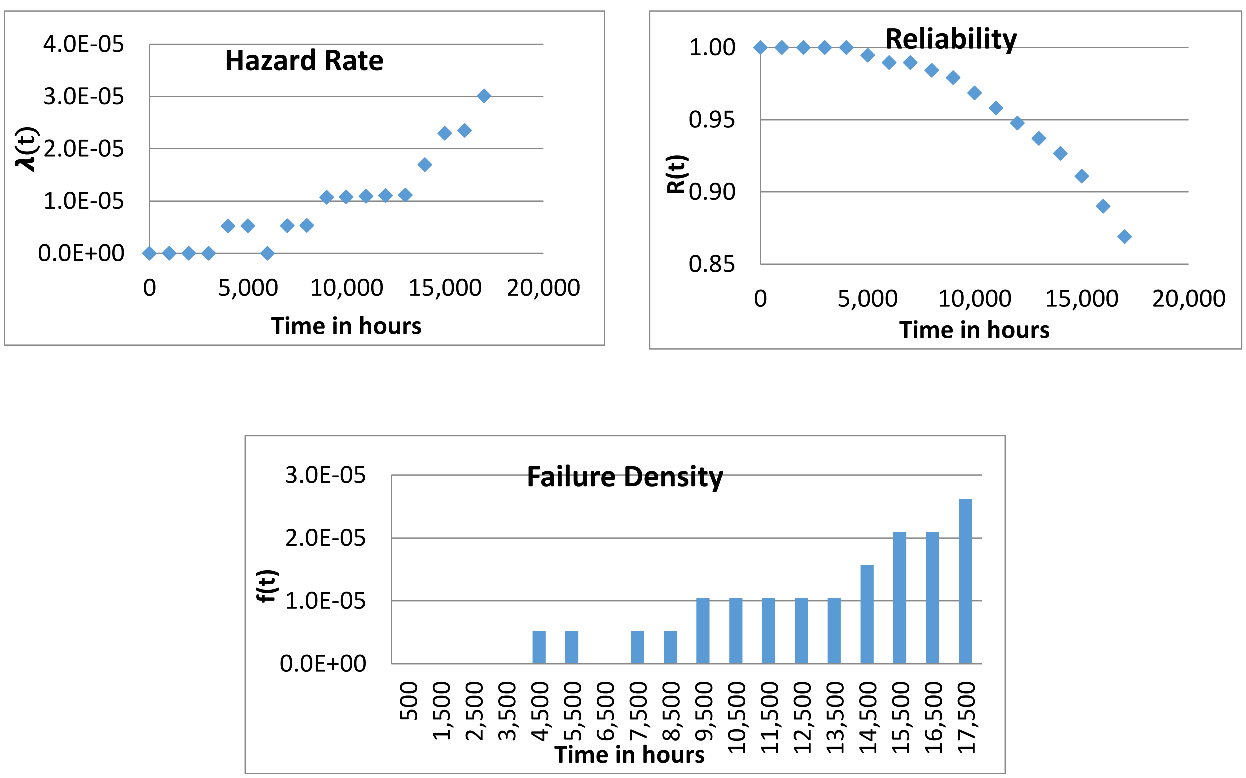



*Figure 38: Hazard rate, Reliability, and Failure density in "Baffle Plates*

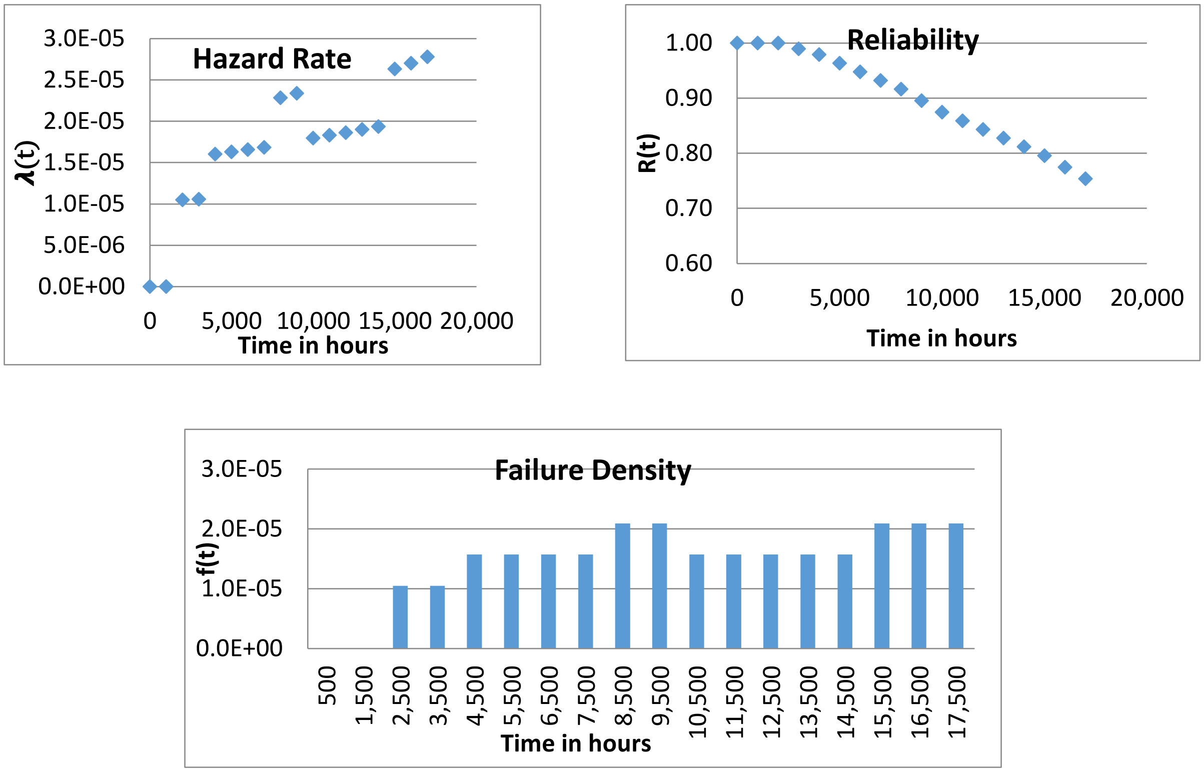



*Figure 39: Hazard rate, Reliability, and Failure density in "Gasket"*

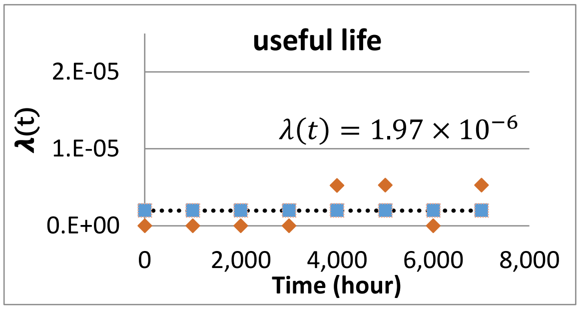



*Figure 40: Hazard rate vs time, useful life in "Tube Bundle"*

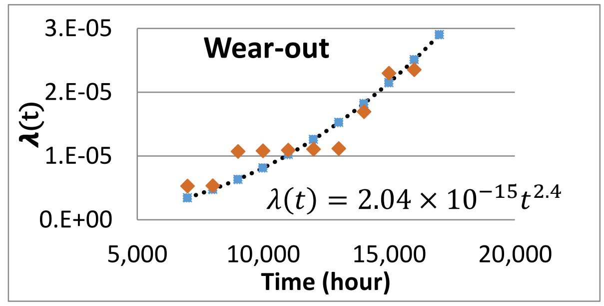



*Figure 41: Hazard rate vs time, wear out in " Tube Bundle"*

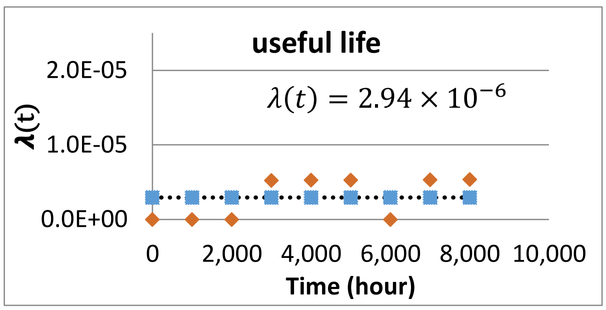



*Figure 42: Hazard rate vs time, useful life in "Baffle Plates"*

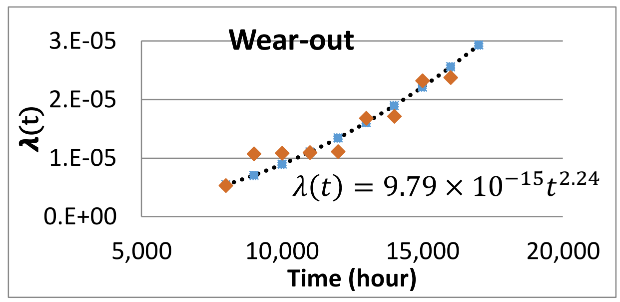



*Figure 43: Hazard rate vs time, wear out in " Baffle Plates"*

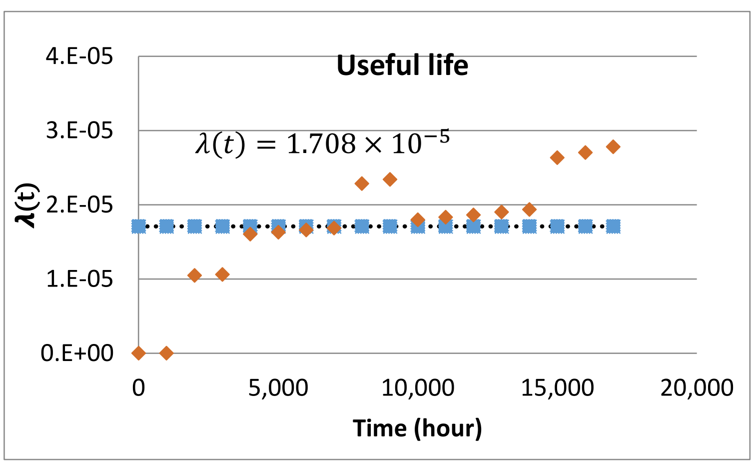



*Figure 44: Hazard rate vs time, useful life in "Gasket"*

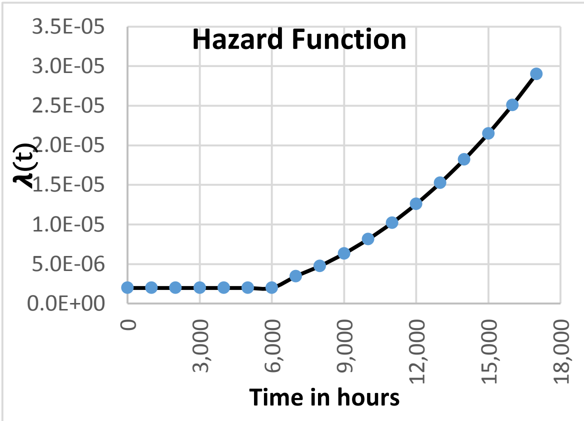



Figure 45:Bathtub curve in "Tube Bundle"

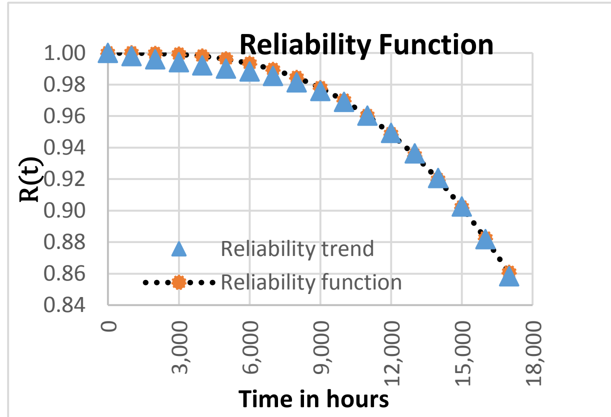



Figure 46: Reliability function in "Tube Bundle"

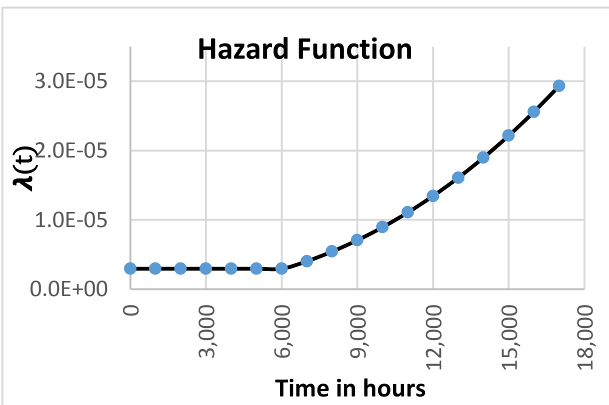



Figure 47: Bathtub curve in "Baffle Plates"

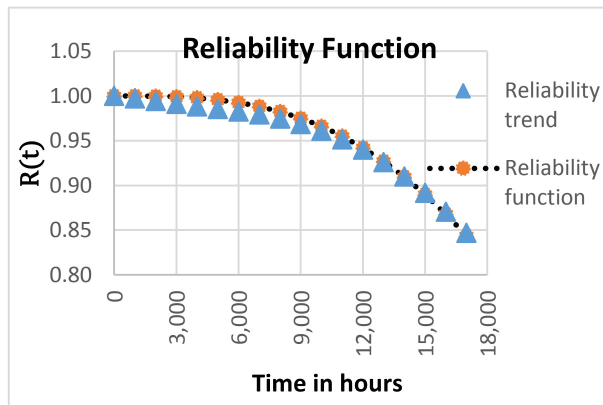



Figure 48: Reliability function in "Baffle Plates"

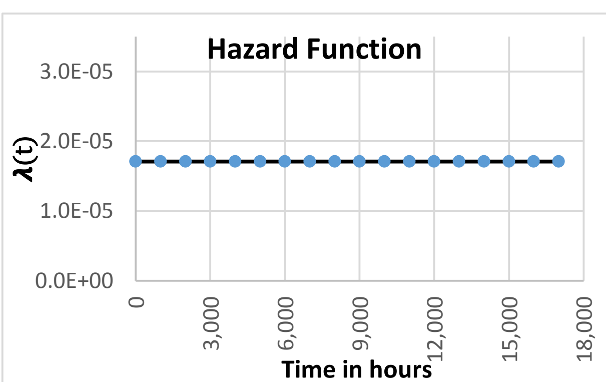



Figure 49: Bathtub curve in "Gasket"

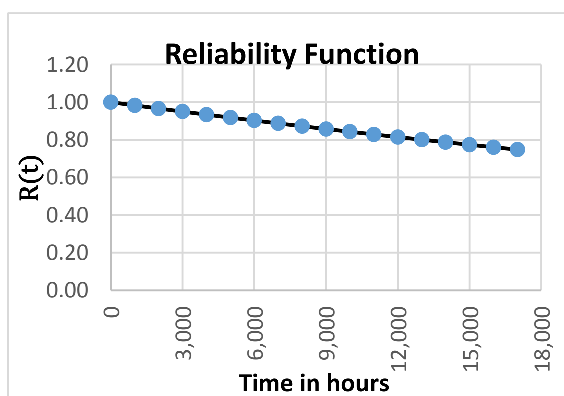



Figure 50: Reliability function in "Gasket"

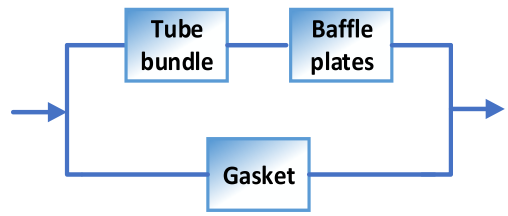



*Figure 51: “Heat Exchanger” system diagram*

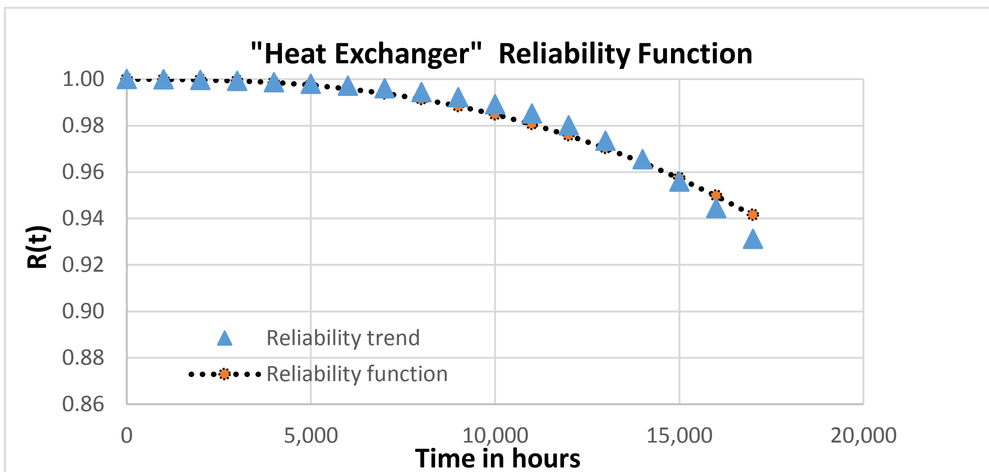



*Figure 52: Reliability function versus time, Reliability trend& proposed Reliability function in “Heat Exchanger”*

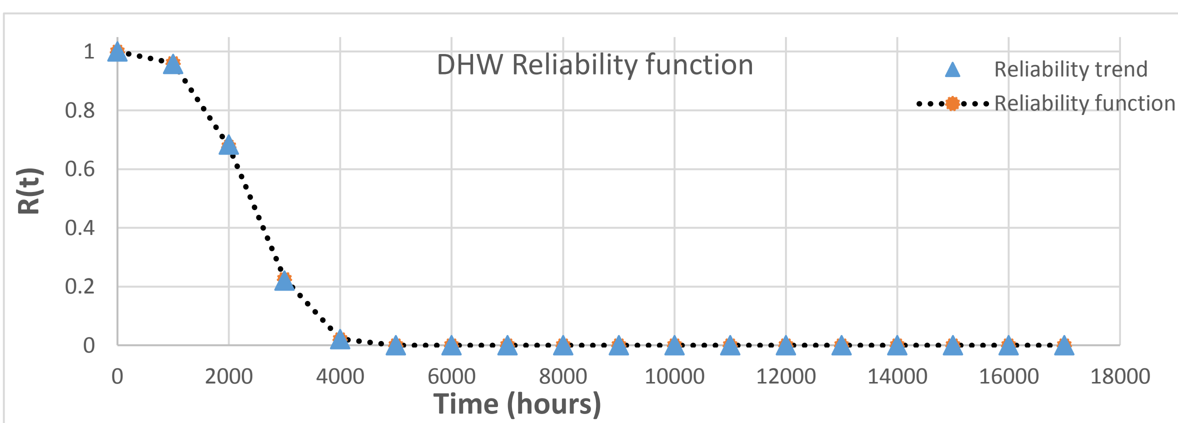



*Figure 53: Reliability function versus time, Reliability trend& proposed Reliability function in Domestic Hot Water system*

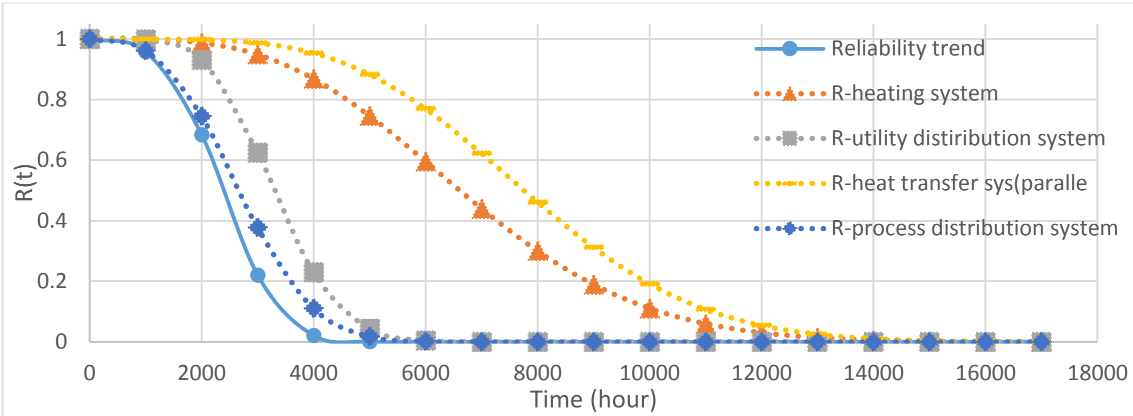



*Figure 54: DHW, heating sub-system, distribution sub-system, and heat transfer subsystem Reliability function*

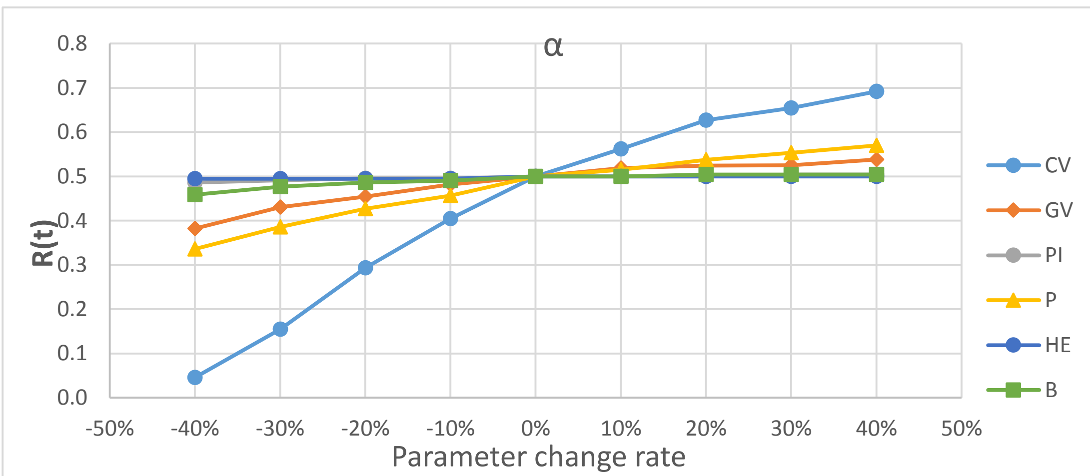



*Figure 55: Reliability function versus change rate, Sensitivity analysis on scale parameter of Weibull distribution (α)*

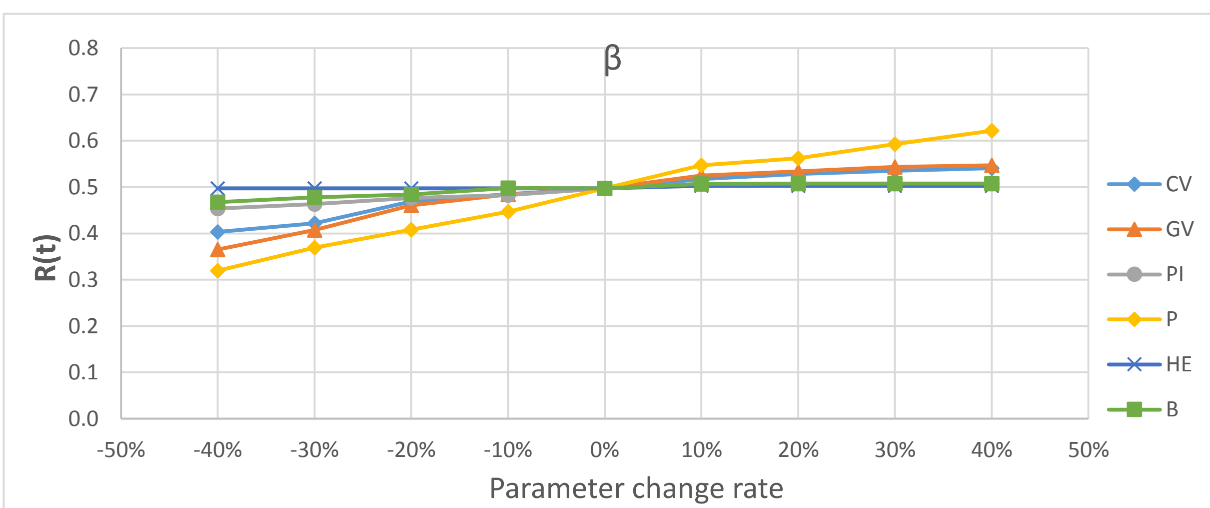



*Figure 56: Reliability function versus change rate, Sensitivity analysis on shape parameter of Weibull distribution (β)*

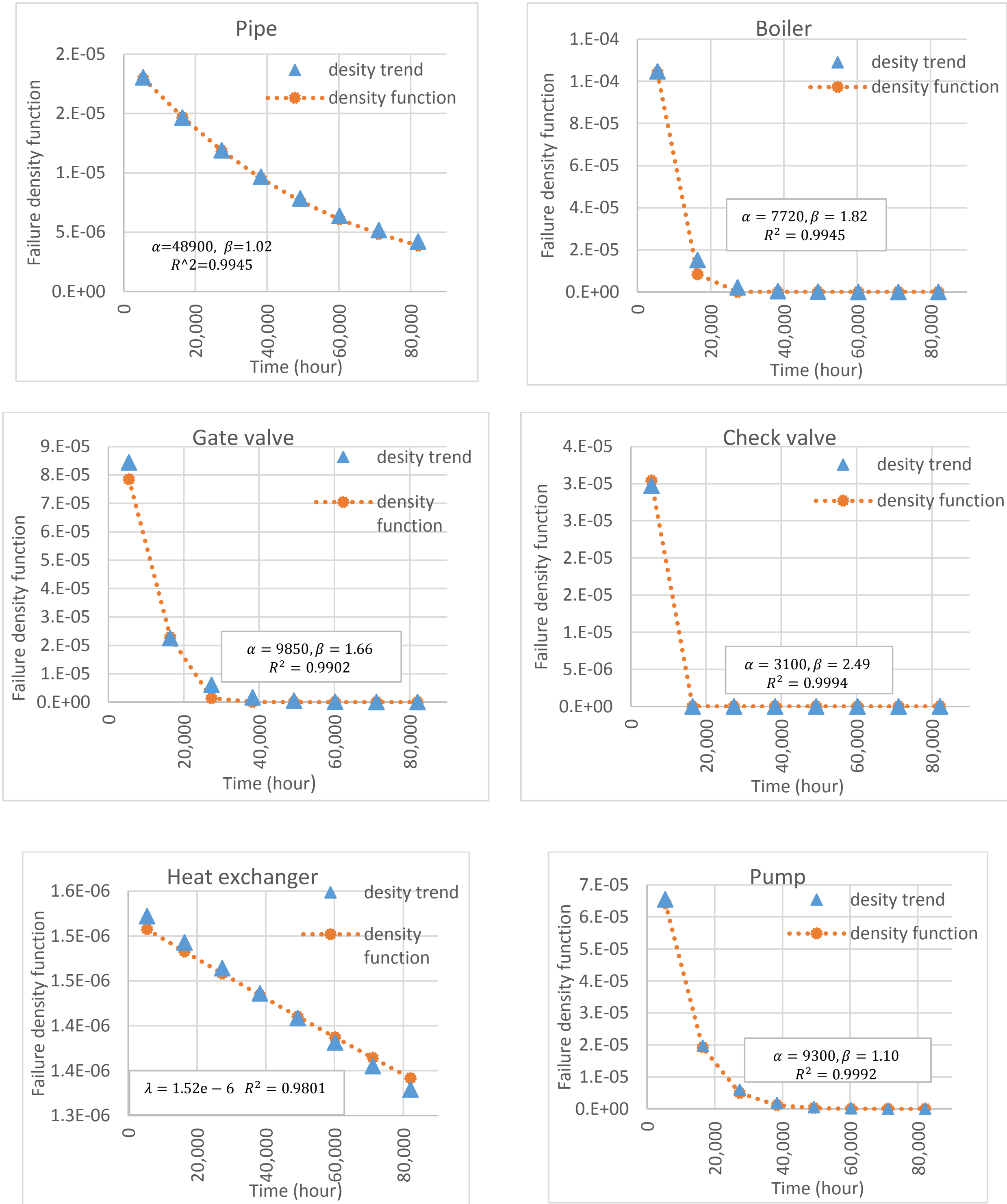



*Figure 57: Reliability parameter (Weibull or exponential) in DHW components with $T_M = 1.25$ years*

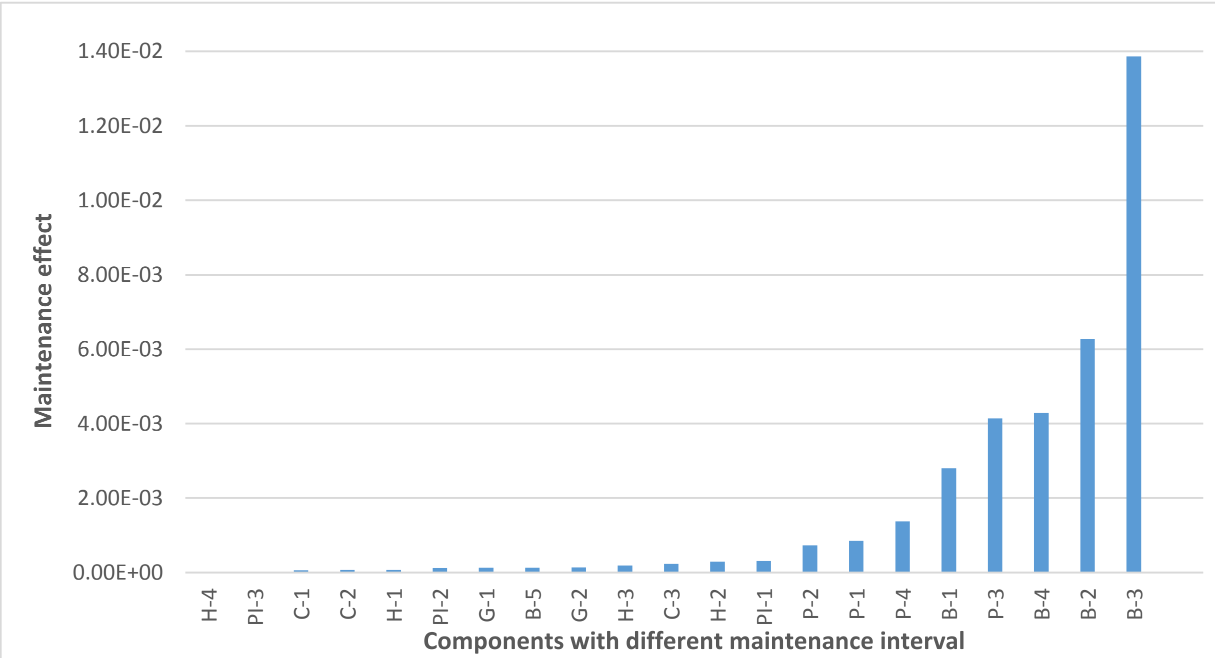



*Figure 58: Sorting List in DHW component in different AMI*

| STEP NO | e=A*-A |
|---|---|
| 20B | |
| 1T | |
| 2T | |
| 3T | |
| 4T | |
| 5T | |
| 6T | |
| 7T | |
| 17B | 0.000230 |
| 9T | 0.000176 |
| 10T | 0.000169 |
| 11T | 0.000081 |
| 12T | 0.000084 |
| 13T | 0.000132 |
| 15B | 0.000488 |
| 15T | 0.000132 |
| **mean** | **0.000186** |

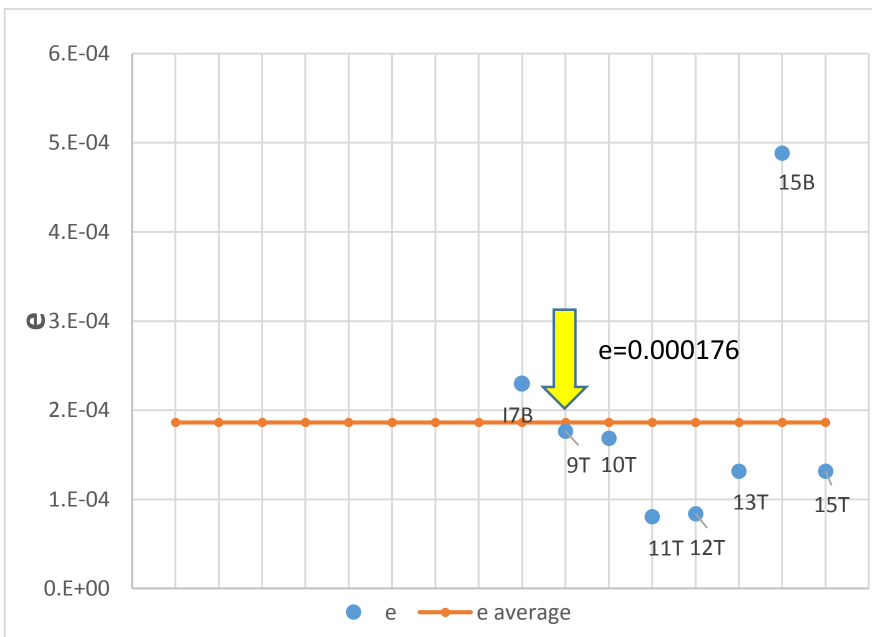



*Figure 59: selection Step No among available options*

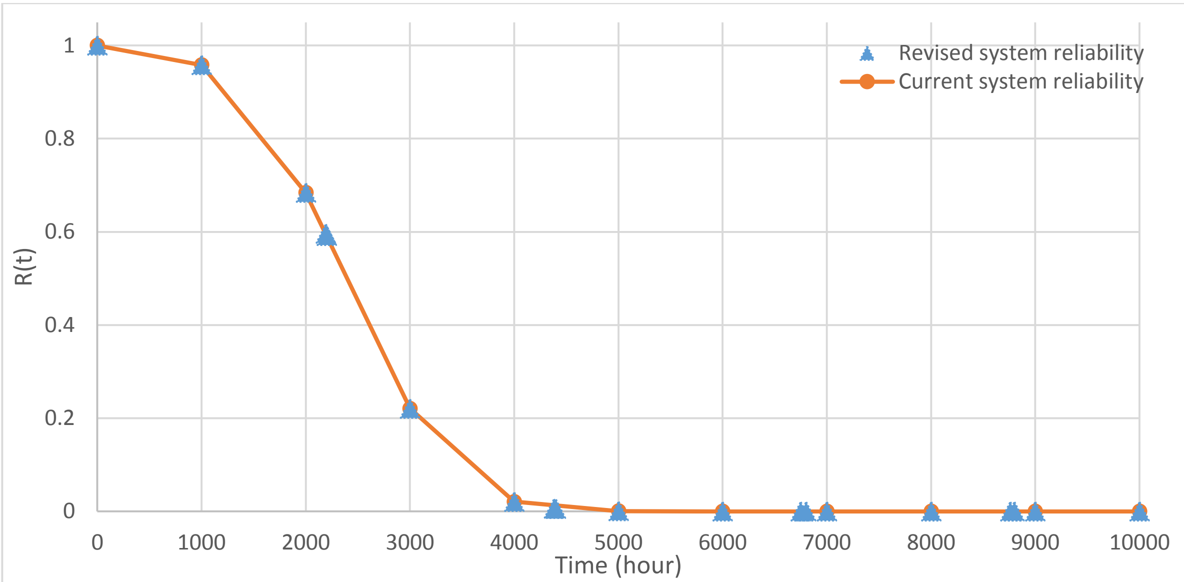



*Figure 60: Reliability versus time, comparison between current and modified system reliability*

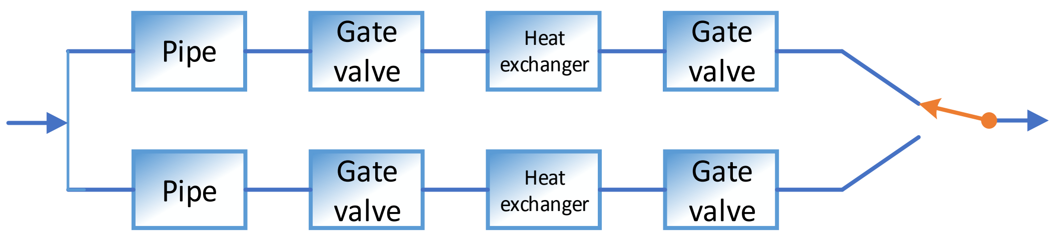



*Figure 61: proposed Heat Transfer sub- system in standby structure*

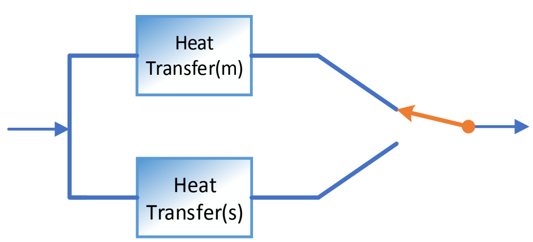
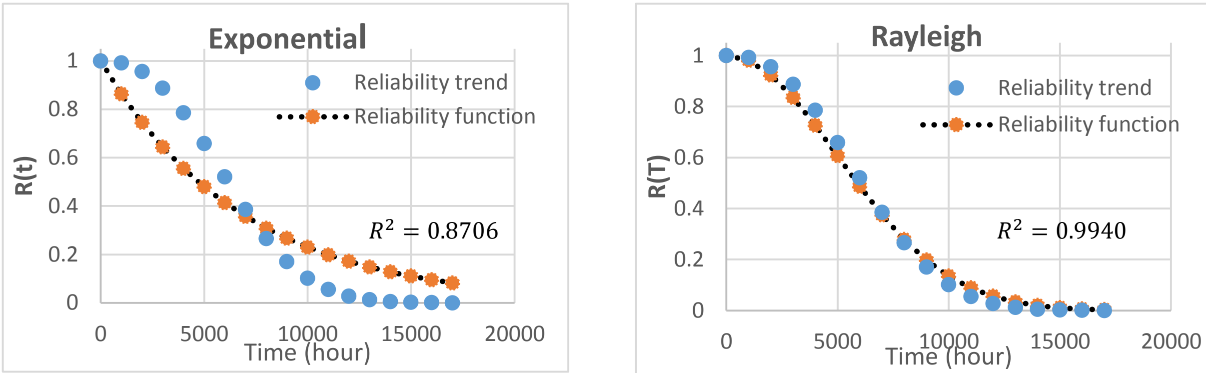



*Figure 62: Simplified standby heat transfer sub- system (heat transfer component)*




$$R(t) = exp[-1.47 \times 10^{-4}t]$$

$$R(t) = \exp[-\frac{4 \times 10^{-8}t^2}{2}]$$

*Figure 63: Reliability function vs time, two suggested functions (the exponential" and Rayleigh distribution function) in the heat transfer reliability trend*

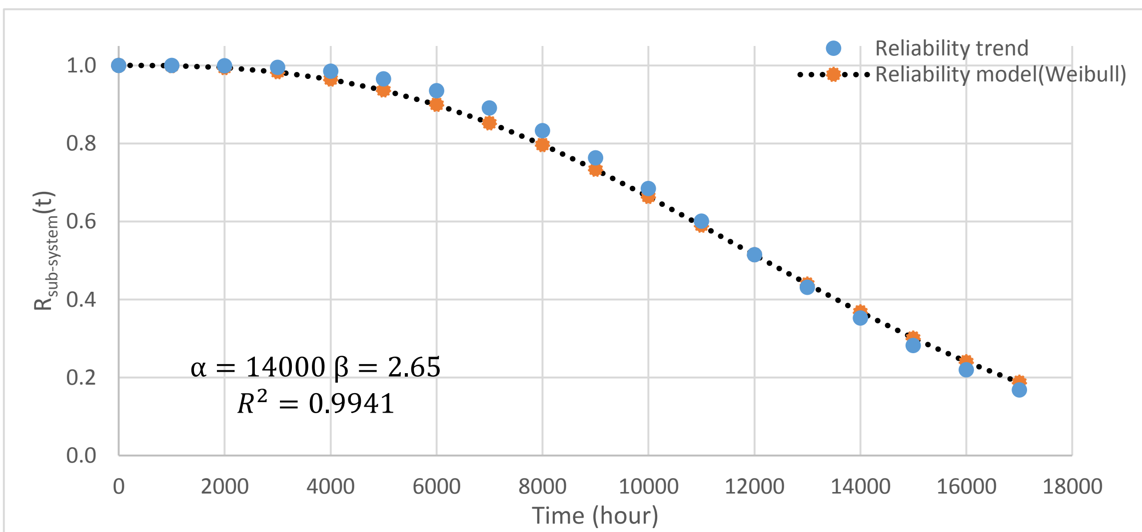



*Figure 64: Reliability function vs time, Reliability trend& suggested Reliability function in the heat transfer sub-system*

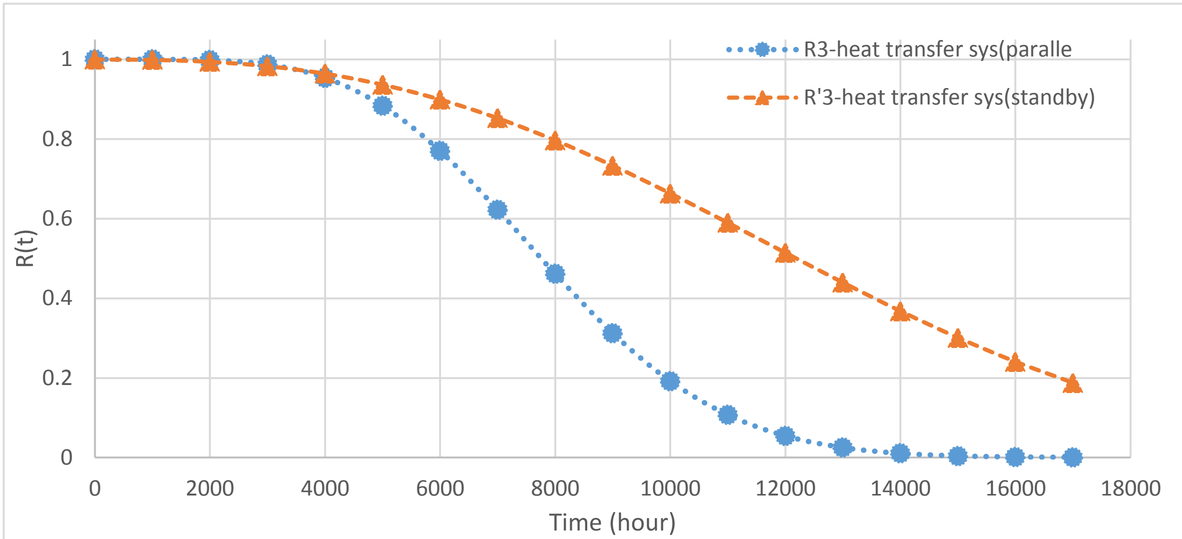
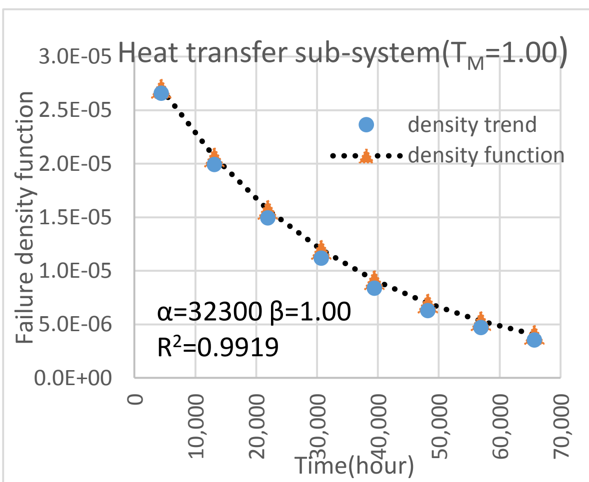



*Figure 65: Reliability function vs time, comparison between parallel and standby heat transfer sub-system*



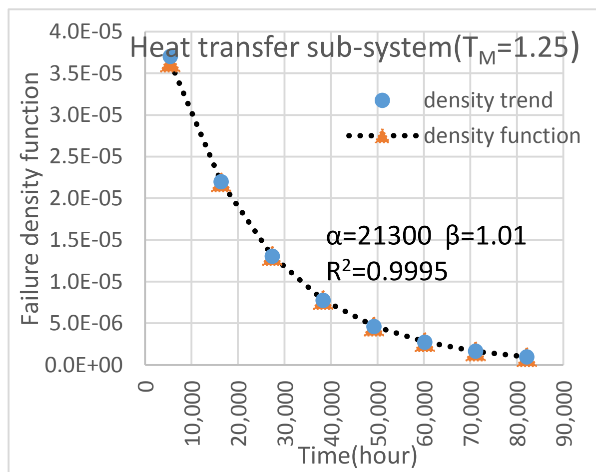




*Figure 66: failure density function vs time, Weibull reliability parameter in the standby heat transfer sub-system with* $T_M = 1\&1.25\ year$

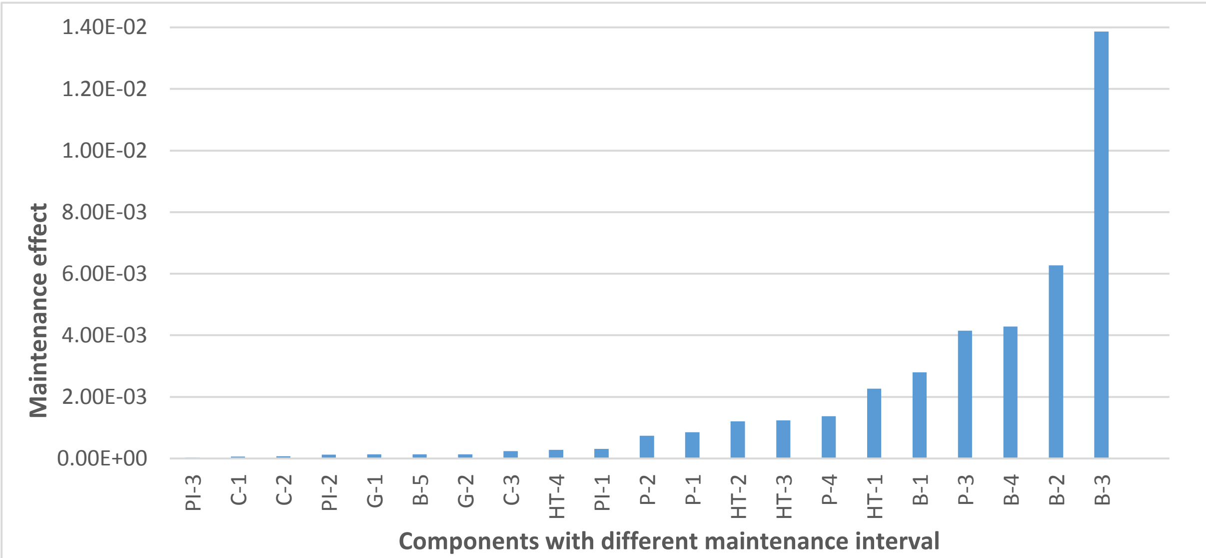



*Figure 67: Sorting List in DHW component in different AMI in the proposed system (standby heat transfer sub-system)*

| STEP NO | e=A*-A |
|---|---|
| 21B | |
| 1T | |
| 2T | |
| 3T | |
| 4T | |
| 5T | |
| 6T | |
| 7T | |
| 8T | |
| 9T | |
| 16B | 0.004732 |
| 11T | 0.004458 |
| 12T | 0.004732 |
| 14B | 0.000735 |
| **mean** | **0.003664** |

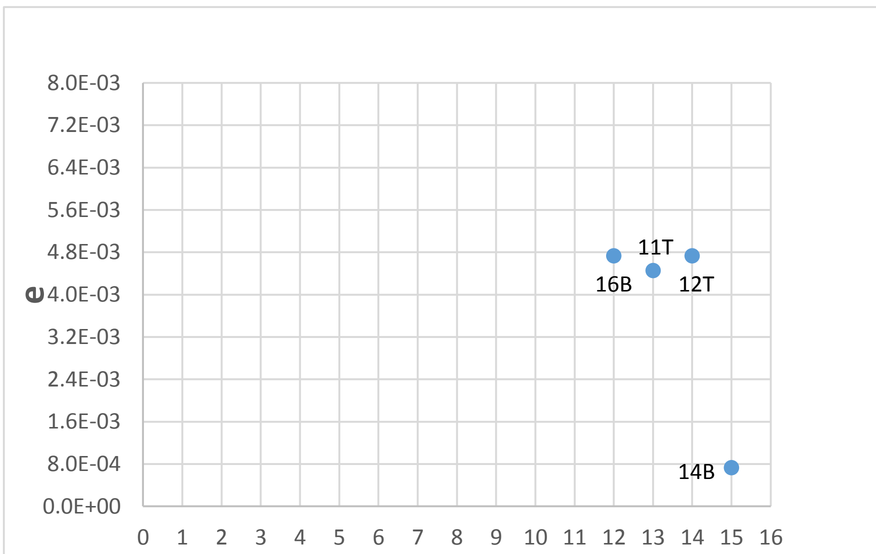



*Figure 68: selection Step No among available options in the proposed system (standby heat transfer sub-system)*

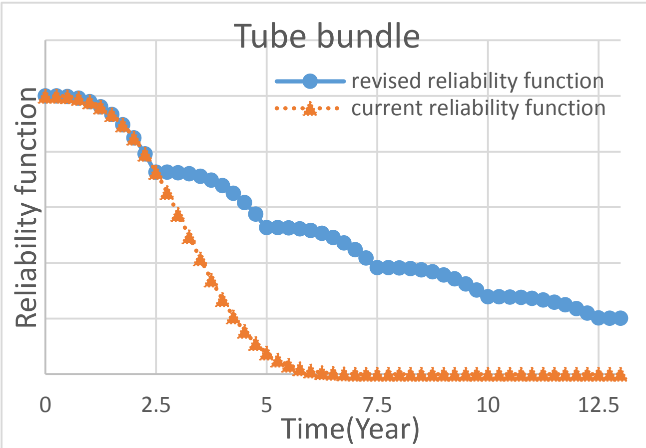



*Figure 69: Revised and current reliability function in "Tube Bundle" in $T_M = 2.5\ year$*

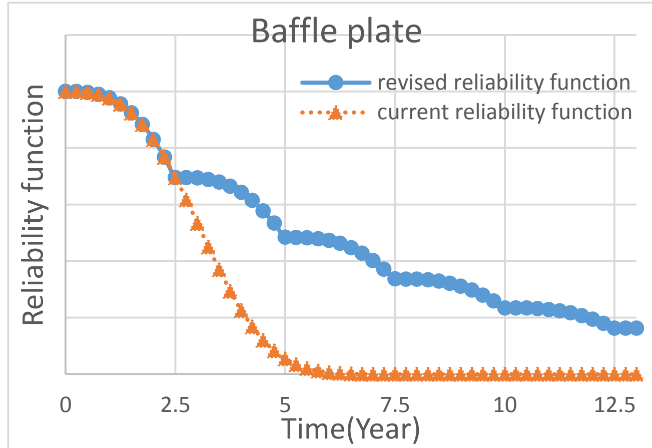



*Figure 70: Revised and current reliability function in "Baffle Plates" in $T_M = 2.5\ years$*

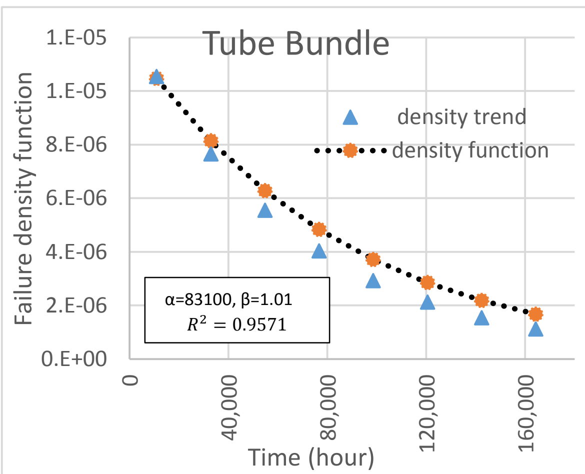



*Figure 71: Weibull parameter in "Tube Bundle" with $T_M = 2.5\ years$*

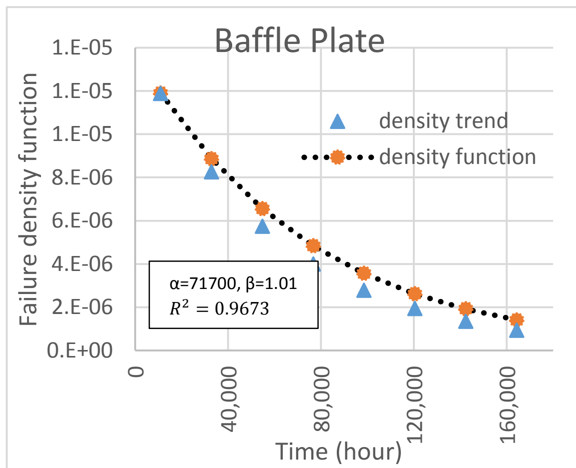



*Figure 72: Weibull parameter in "Baffle Plates" with $T_M = 2.5\ years$*

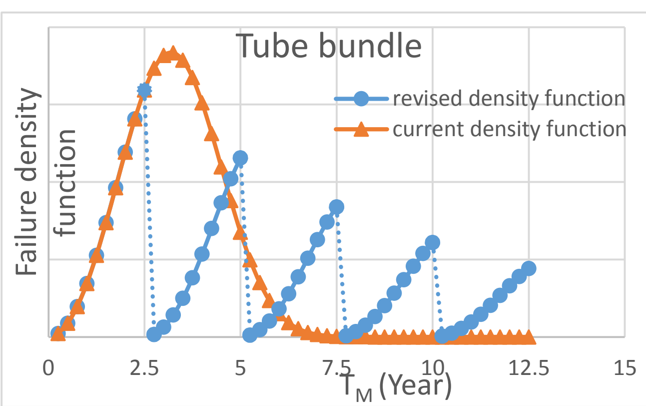



*Figure 73: Revised and current failure density function in "Tube Bundle" in $T_M = 2.5\ year$*

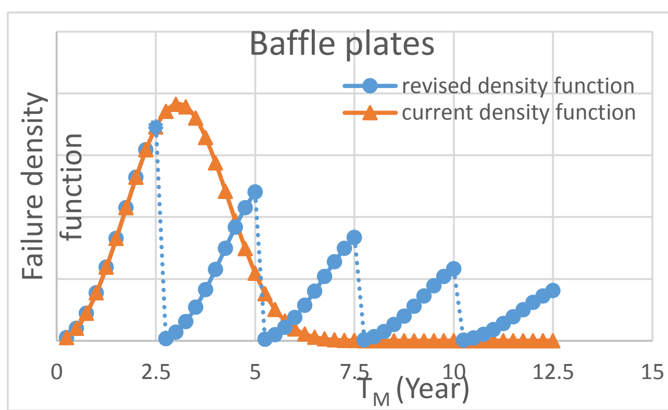



*Figure 74: Revised and current failure density function in "Baffle Plates" in $T_M = 2.5\ year$*

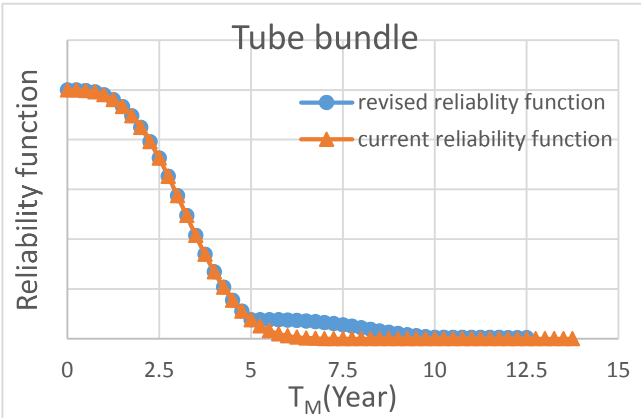



*Figure 75: Revised and current reliability function in "Tube Bundle" in $T_M = 5\ year$*

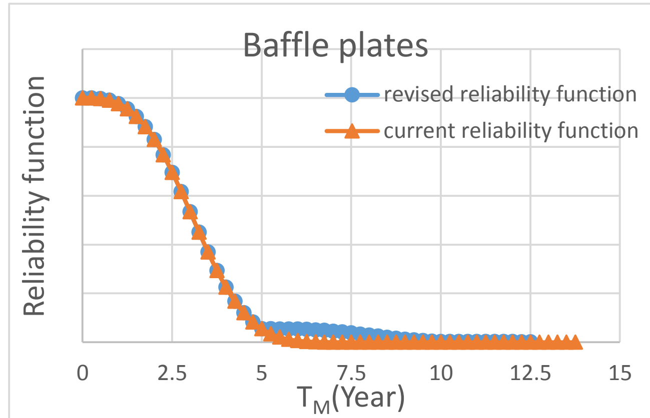



*Figure 76: Revised and current reliability function in "Baffle Plates" in $T_M = 5\ year$*

| Pipe | |
|---|---|
| **TM (Year)** | **MTTF (hour)** |
| 0.50 | 130000.00 |
| 1.00 | 62738.82 |
| 1.25 | 48502.34 |
| 2.50 | 23516.40 |
| 5.00 | 19502.94 |
| 10.00 | 18796.79 |
| 12.00 | 16484.40 |
| 15.00 | 10714.91 |

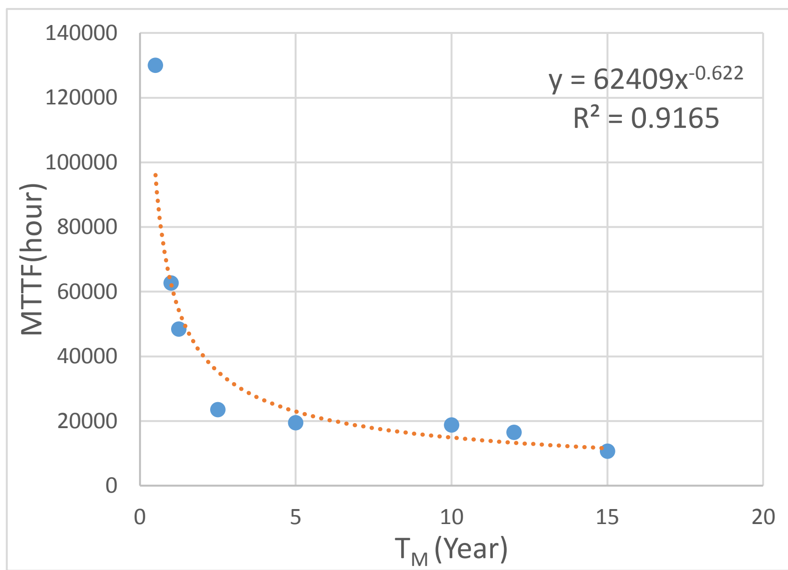



*Figure 77: MTTF vs $T_M$ in "Pipe"*

| Boiler | |
|---|---|
| **TM (Year)** | **MTTF (hour)** |
| 1.00 | 6928.06 |
| 1.25 | 6861.75 |
| 2.50 | 6664.10 |
| 5.00 | 6256.52 |
| 10.00 | 5496.00 |
| 12.00 | 5292.89 |
| 15.00 | 5286.80 |

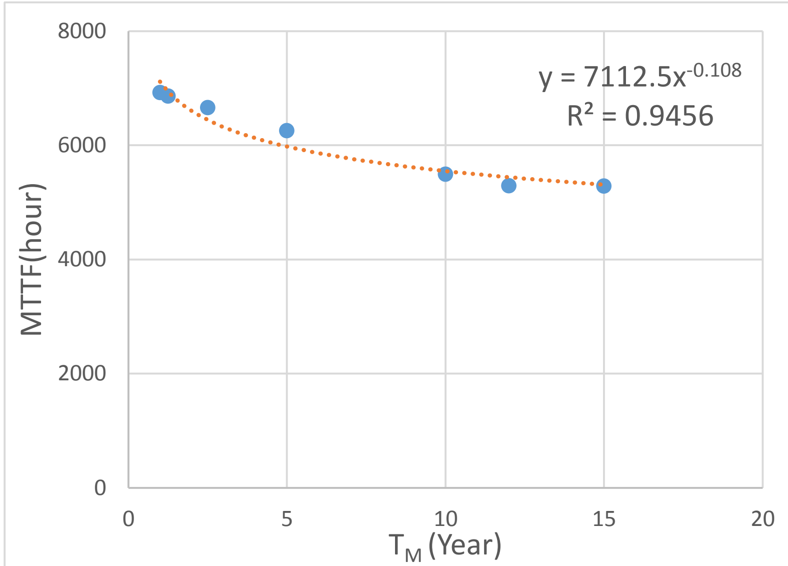



*Figure 78: MTTF vs $T_M$ in "Boiler"*

| Gate valve | |
|---|---|
| **TM (Year)** | **MTTF (hour)** |
| 1.00 | 9383.78 |
| 1.25 | 8803.82 |
| 2.50 | 8465.10 |
| 5.00 | 8141.97 |
| 10.00 | 7520.72 |

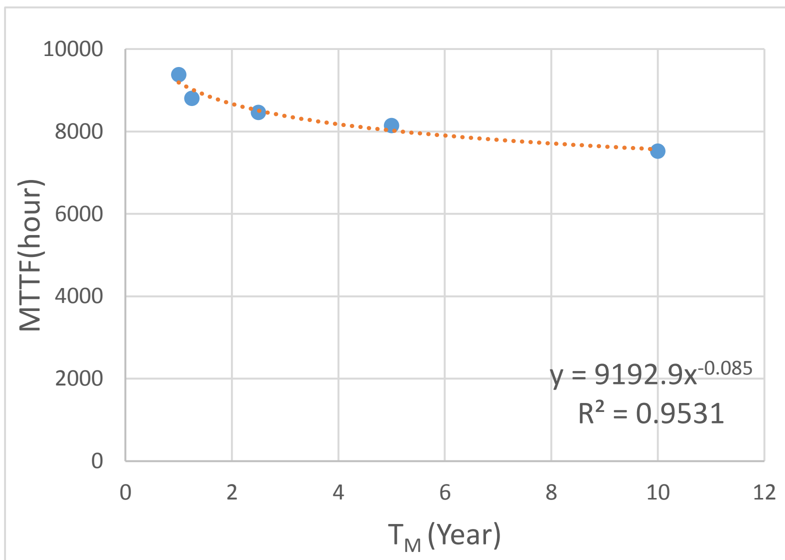



*Figure 79: MTTF vs $T_M$ in "Gate Valve"*

| Ball valve | |
|---|---|
| **TM (Year)** | **MTTF (hour)** |
| 1.00 | 11354.46 |
| 1.25 | 9425.25 |
| 2.50 | 8859.15 |
| 5.00 | 8079.42 |
| 10.00 | 7532.93 |

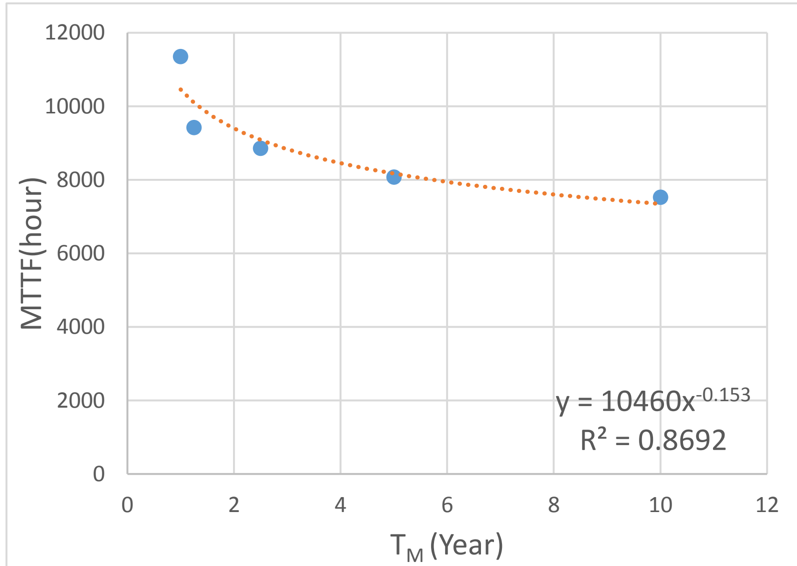



*Figure 80: MTTF vs $T_M$ in "Ball Valve"*

| Relief valve | |
|---|---|
| **TM (Year)** | **MTTF (hour)** |
| 1.00 | 3421142.66 |
| 1.25 | 2559508.57 |
| 2.50 | 1038421.60 |
| 5.00 | 413223.14 |
| 10.00 | 142857.14 |

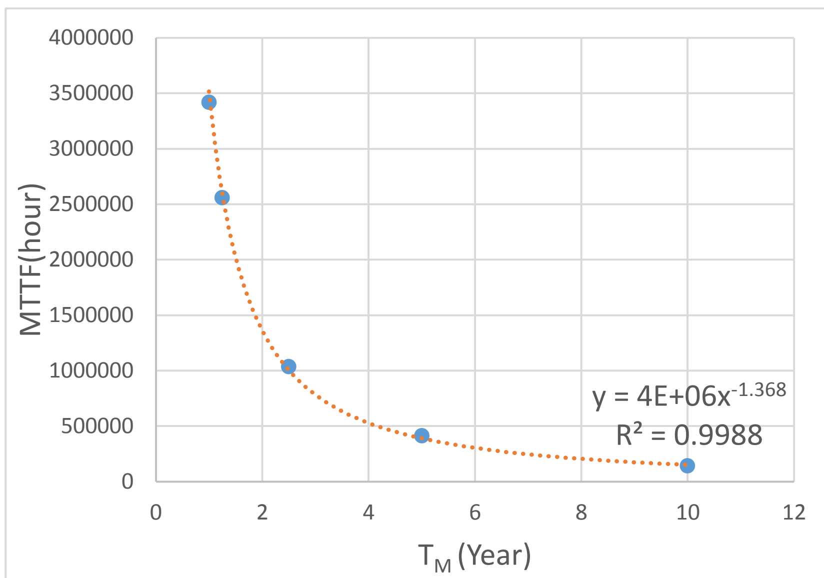



*Figure 81: MTTF vs $T_M$ in "Relief Valve"*

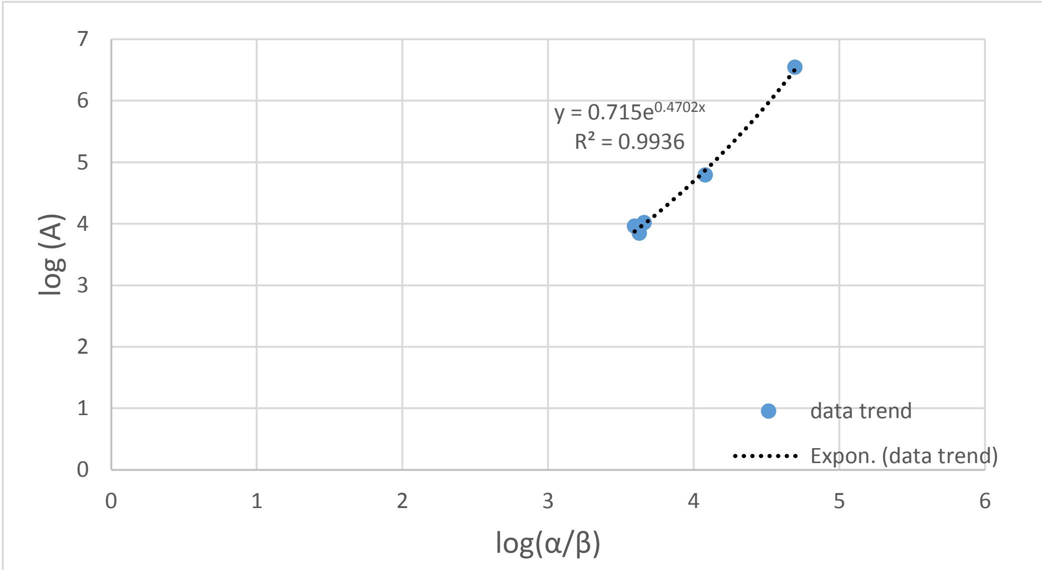



*Figure 82:* $Log(A) vs\ Log(^{\alpha}/_{\beta})$

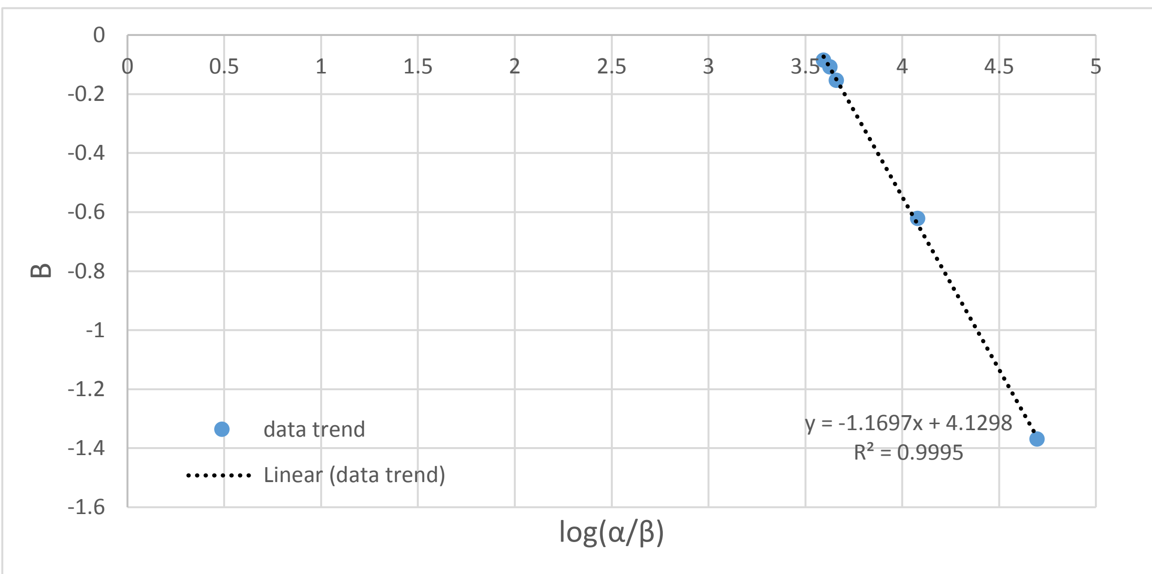



*Figure 83 :* $B\ vs\ Log(^{\alpha}/_{\beta})$

# Tables

*Table 1: Sub-systems and components in DHW system*

| Sub-system | Component | Description |
|---|---|---|
| HP | Pipe, Boiler, Check Valve | Heating production |
| DU | Pipe, Gate Valve, Check Valve, Pump | Distribution system |
| HT | Pipe, Gate Valve, Heat Exchanger | Heat transferring system |
| DP | Pipe, Gate Valve, Check Valve, Pump | Distribution system |

*Table 2: Sub- components in boiler [27] [28] [29] [30]*

| sub-component | scale parameter (α) | shape parameter (β) |
|---|---|---|
| burner | 33901.20 | 1.05 |
| fan | 73798.94 | 2.50 |
| safety valve | 209364.00 | 1.80 |
| tube | 8775.00 | 2.01 |

*Table 3: Historic failure data in different time interval in different sub-component in heat exchanger*

| time interval (hour) Δt | failures (Tube) | failures (Baffle plate) | failures (Gasket) |
|---|---|---|---|
| 0-1000 | 0 | 0 | 0 |
| 1000-2000 | 0 | 0 | 0 |
| 2000-3000 | 0 | 0 | 2 |
| 3000-4000 | 0 | 1 | 2 |
| 4000-5000 | 1 | 1 | 3 |
| 5000-6000 | 1 | 1 | 3 |
| 6000-7000 | 0 | 0 | 3 |
| 7000-8000 | 1 | 1 | 3 |
| 8000-9000 | 1 | 1 | 4 |
| 9000-10000 | 2 | 2 | 4 |
| 10000-11000 | 2 | 2 | 3 |
| 11000-12000 | 2 | 2 | 3 |
| 12000-13000 | 2 | 2 | 3 |
| 13000-14000 | 2 | 3 | 3 |
| 14000-15000 | 3 | 3 | 3 |
| 15000-16000 | 4 | 4 | 4 |
| 16000-17000 | 4 | 4 | 4 |
| 17000-more | 5 | 5 | 4 |
| **Total** | **30** | **32** | **51** |

*Table 4: Quantitative failure in heat exchanger sub-component based on different failure mode [23]*

| Failure mode | Sub-component | Failure No |
|---|---|---|
| Internal leakage | Tube bundle | 30 |
| Structural deficiency | Baffle plate | 32 |
| External leakage | Gasket | 51 |
| Sample population | | **191** |

Table 5: Weibull parameters as well as exponential parameter in Heat Exchanger sub-components

| sub-component | scale parameter (α) | shape parameter (β) |
|---|---|---|
| Tube bundle | 32000.00 | 3.00 |
| Baffle plate | 30700.00 | 3.00 |
| Gasket | $\lambda = 1.708 \times 10^{-5}$ | |

Table 6: Weibull parameters in DHW components [25] [26] [31] [32]

| component | scale parameter (α) (hour) | shape parameter (β) |
|---|---|---|
| Pipe | 24000.00 | 2.00 |
| Pump | 9311.56 | 1.13 |
| Gate valve | 9800.00 | 2.50 |
| Check valve | 3150.00 | 2.60 |
| Boiler | 7600.00 | 1.80 |
| Heat Exchanger | 50500.00 | 2.58 |

Table 7: Mean Time to Repair in DHW components [23] [24] [33]

| component | MTTR(hour) |
|---|---|
| Pipe | 14.08 |
| Pump | 378.00 |
| Gate valve | 29.00 |
| Check valve | 6.00 |
| Boiler | 813.00 |
| Heat Exchanger | 24.00 |
| Strainer | 40.00 |

Table 8: Mean Time to Failure in DHW components

| component | MTTF(hour) |
|---|---|
| Pipe | 21269.45 |
| Pump | 8908.38 |
| Gate valve | 8695.19 |
| Check valve | 2797.86 |
| Boiler | 6758.58 |
| Heat Exchanger | 44844.50 |
| Strainer | 5000.00 |

Table 9: suggested Average Maintenance Interval types in DHW components

| component | $Z_0$ | $Z_1$ | $Z_2$ | $Z_3$ | $Z_4$ | $Z_5$ | $Z_6$ |
|---|---|---|---|---|---|---|---|
| Pipe | 1.00 | 1.25 | 2.50 | 5.00 | 10.00 | - | - |
| Pump | 1.00 | 1.25 | 2.50 | 5.00 | 10.00 | 12.00 | - |
| Gate valve | 1.00 | 1.25 | 2.50 | 5.00 | 10.00 | - | - |
| Check valve | 0.25 | 0.50 | 1.00 | 1.25 | 2.50 | - | - |
| Boiler | 1.00 | 1.25 | 2.50 | 5.00 | 10.00 | 12.00 | 15.00 |
| Heat exchanger | 1.00 | 1.25 | 2.50 | 5.00 | 10.00 | - | - |

Table 10: Modified reliability parameters as well as MTTF based on $T_M$ in pipe

| $T_M$ | α | β | λ | MTTF | $R^2$ |
|---|---|---|---|---|---|
| 1.00 | 63000.00 | 1.01 | - | 62738.82 | 0.9990 |
| 1.25 | 48900.00 | 1.02 | - | 48502.34 | 0.9976 |
| 2.50 | 25000.00 | 1.20 | - | 23516.40 | 0.9838 |
| 5.00 | 22000.00 | 1.97 | - | 19502.94 | 0.9986 |
| 10.00 | 19800.00 | 1.16 | - | 18796.79 | 0.9999 |

*Table 11: Modified reliability parameters as well as MTTF based on $T_M$ in boiler*

| $T_M$(Year) | α | β | λ | MTTF | $R^2$ |
|---|---|---|---|---|---|
| 1.00 | 7800.00 | 1.85 | - | 6928.06 | 0.9928 |
| 1.25 | 7720.00 | 1.82 | - | 6861.75 | 0.9945 |
| 2.50 | 7510.00 | 1.90 | - | 6664.10 | 0.9999 |
| 5.00 | 7000.00 | 1.66 | - | 6256.52 | 0.9997 |
| 10.00 | 6130.00 | 1.60 | - | 5496.00 | 0.9992 |
| 12.00 | 5900.00 | 1.59 | - | 5292.89 | 0.9998 |
| 15.00 | 5900.00 | 1.61 | - | 5286.80 | 0.9999 |

*Table 12: Modified reliability parameters as well as MTTF based on $T_M$ in pump*

| $T_M$(Year) | α | β | λ | MTTF | $R^2$ |
|---|---|---|---|---|---|
| 1.00 | 9240.00 | 1.07 | - | 9000.52 | 0.9986 |
| 1.25 | 9300.00 | 1.10 | - | 8973.69 | 0.9992 |
| 2.50 | 9100.00 | 1.10 | - | 8780.70 | 0.9987 |
| 5.00 | - | - | 0.000116 | 8620.69 | 0.9948 |
| 10.00 | - | - | 0.000118 | 8474.58 | 0.9999 |
| 12.00 | - | - | 0.000132 | 7575.76 | 0.9999 |

*Table 13: Modified reliability parameters as well as MTTF based on $T_M$ in gate valve*

| $T_M$ | α | β | λ | MTTF | $R^2$ |
|---|---|---|---|---|---|
| 1.00 | 9860.00 | 1.15 | - | 9383.78 | 0.9881 |
| 1.25 | 9850.00 | 1.66 | - | 8803.82 | 0.9902 |
| 2.50 | 9500.00 | 2.85 | - | 8465.10 | 0.9923 |
| 5.00 | 9190.00 | 2.31 | - | 8141.97 | 0.9970 |

*Table 14: Modified reliability parameters as well as MTTF based on $T_M$ in check valve*

| $T_M$(Year) | α | β | λ | MTTF | $R^2$ |
|---|---|---|---|---|---|
| 0.25 | - | - | 0.0002001 | 4997.50 | 0.9741 |
| 0.50 | 3230.00 | 3.90 | - | 2923.49 | 0.9894 |
| 1.00 | 3180.00 | 3.10 | - | 2843.89 | 0.9990 |
| 1.25 | 3100.00 | 2.49 | - | 2750.25 | 0.9994 |
| 2.50 | 2800.00 | 2.37 | - | 2481.60 | 0.9902 |

*Table 15: Modified reliability parameters as well as MTTF based on $T_M$ in heat exchanger*

| $T_M$(Year) | α | β | λ | MTTF | $R^2$ |
|---|---|---|---|---|---|
| 1.00 | - | - | 0.00000107 | 934579.44 | 0.9799 |
| 1.25 | - | - | 0.00000152 | 657894.74 | 0.9801 |
| 2.50 | - | - | 0.00000460 | 217391.30 | 0.9895 |
| 5.00 | 61000.00 | 1.10 | - | 58859.66 | 0.9967 |
| 10.00 | 45000.00 | 2.40 | - | 39891.69 | 0.9994 |
| 12.00 | 42800.00 | 3.60 | - | 38567.32 | 0.9996 |

*Table 16: MTTF, MTTR, availability as well as maintenance effect in boiler, pump, and gate valve in different Average Maintenance Interval (AMI)*

| COMP | | TM (year) | | MTTF (Hour) | MTTR (Hour) | $a_{i,j,k}$ | $\Delta a_{i,j,k}$ |
|---|---|---|---|---|---|---|---|
| Boiler | B-0 | 1.00 | $Z_0$ | 6928.06 | 813 | 0.8949756 | 9.0736E-04 |
| | B-1 | 1.25 | $Z_1$ | 6861.75 | 813 | 0.8940683 | 2.8003E-03 |
| | B-2 | 2.5 | $Z_2$ | 6664.10 | 813 | 0.8912680 | 6.2687E-03 |
| | B-3 | 5 | $Z_3$ | 6256.52 | 813 | 0.8849993 | 1.3863E-02 |
| | B-4 | 10 | $Z_4$ | 5496.00 | 813 | 0.8711365 | 4.2867E-03 |
| | B-5 | 12 | $Z_5$ | 5292.89 | 813 | 0.8668498 | 1.3289E-04 |
| | B-6 | 15 | $Z_6$ | 5286.80 | 813 | 0.8667169 | |
| Pump | P-0 | 1.00 | $Z_0$ | 9000.52 | 378 | 0.9596951 | 1.1566E-04 |
| | P-1 | 1.25 | $Z_1$ | 8973.69 | 378 | 0.9595795 | 8.5170E-04 |
| | P-2 | 2.5 | $Z_2$ | 8780.70 | 378 | 0.9587278 | 7.3390E-04 |
| | P-3 | 5 | $Z_3$ | 8620.69 | 378 | 0.9579939 | 4.1449E-03 |
| | P-4 | 10 | $Z_4$ | 7812.50 | 378 | 0.9538490 | 1.3737E-03 |
| | P-5 | 12 | $Z_5$ | 7575.76 | 378 | 0.9524753 | |
| Gate Valve | G-0 | 1 | $Z_0$ | 9383.78 | 29 | 0.9969191 | 2.0229E-04 |
| | G-1 | 1.25 | $Z_1$ | 8803.82 | 29 | 0.9967168 | 1.3093E-04 |
| | G-2 | 2.5 | $Z_2$ | 8465.10 | 29 | 0.9965859 | 1.3501E-04 |
| | G-3 | 5 | $Z_3$ | 8141.97 | 29 | 0.9964509 | |

*Table 17: MTTF, MTTR, availability as well as maintenance effect in check valve, heat exchanger, and pipe in different Average Maintenance Interval (AMI)*

| COMP | | TM (year) | | MTTF (Hour) | MTTR (Hour) | $a_{i,j,k}$ | $\Delta a_{i,j,k}$ |
|---|---|---|---|---|---|---|---|
| Check Valve | C-0 | 0.25 | $Z_0$ | 4997.50 | 6 | 0.9988008 | 8.4898E-04 |
| | C-1 | 0.5 | $Z_1$ | 2923.49 | 6 | 0.9979519 | 5.7204E-05 |
| | C-2 | 1 | $Z_2$ | 2843.89 | 6 | 0.9978947 | 7.1526E-05 |
| | C-3 | 1.25 | $Z_3$ | 2750.25 | 6 | 0.9978231 | 2.3509E-04 |
| | C-4 | 2.5 | $Z_4$ | 2481.60 | 6 | 0.9975880 | |
| Heat Exchanger | H-0 | 1.00 | $Z_0$ | 934579.44 | 24 | 0.9999743 | 1.0799E-05 |
| | H-1 | 1.25 | $Z_1$ | 657894.74 | 24 | 0.9999635 | 7.3909E-05 |
| | H-2 | 2.5 | $Z_2$ | 217391.30 | 24 | 0.9998896 | 2.9720E-04 |
| | H-3 | 5 | $Z_3$ | 58859.66 | 24 | 0.9995924 | 1.9368E-04 |
| | H-4 | 10 | $Z_4$ | 39891.69 | 24 | 0.9993987 | 2.0634E-05 |
| | H-5 | 12 | $Z_5$ | 38567.32 | 24 | 0.9993781 | |
| pipe | PI-0 | 1.00 | $Z_0$ | 62738.82 | 14.08 | 0.9997756 | 6.5839E-05 |
| | PI-1 | 1.25 | $Z_1$ | 48502.34 | 14.08 | 0.9997098 | 3.0816E-04 |
| | PI-2 | 2.50 | $Z_2$ | 23516.40 | 14.08 | 0.9994016 | 1.2305E-04 |
| | PI-3 | 5.00 | $Z_3$ | 19502.94 | 14.08 | 0.9992786 | 2.7082E-05 |
| | PI-4 | 10.00 | $Z_4$ | 18796.79 | 14.08 | 0.9992515 | |

*Table 18: Sorting List in DHW component in different AMI*

| | STEP NO | Component | AMI type | AMI (Year) | $\Delta a_{i,j,k}$ |
|---|---|---|---|---|---|
| **Top loop** | 1 | H-4 | Z4 | 10 | 2.063E-05 |
| | 2 | PI-3 | Z3 | 5 | 2.708E-05 |
| | 3 | C-1 | Z1 | 0.5 | 5.720E-05 |
| | 4 | C-2 | Z2 | 1 | 7.153E-05 |
| | 5 | H-1 | Z1 | 1.25 | 7.391E-05 |
| | 6 | PI-2 | Z2 | 2.5 | 1.230E-04 |
| | 7 | G-1 | Z1 | 1.25 | 1.309E-04 |
| | 8 | B-5 | Z5 | 12 | 1.329E-04 |
| | 9 | G-2 | Z2 | 2.5 | 1.350E-04 |
| | 10 | H-3 | Z3 | 5 | 1.937E-04 |
| | 11 | C-3 | Z3 | 1.25 | 2.351E-04 |
| | 12 | H-2 | Z2 | 2.5 | 2.972E-04 |
| | 13 | PI-1 | Z1 | 1.25 | 3.082E-04 |
| | 14 | P-2 | Z2 | 2.5 | 7.339E-04 |
| | 15 | P-1 | Z1 | 1.25 | 8.517E-04 |
| | 16 | P-4 | Z4 | 10 | 1.374E-03 |
| | 17 | B-1 | Z1 | 1.25 | 2.800E-03 |
| | 18 | P-3 | Z3 | 5 | 4.145E-03 |
| | 19 | B-4 | Z4 | 10 | 4.287E-03 |
| | 20 | B-2 | Z2 | 2.5 | 6.269E-03 |
| **bottom loop** | 21 | B-3 | Z3 | 5 | 1.386E-02 |

*Table 19: Reliability parameters, MTTF, MTTR as well as availability in current system*

| Component | α | β | λ | MTTF (Hour) | MTTR (Hour) | Availability |
|---|---|---|---|---|---|---|
| boiler | 7600.00 | 1.80 | 0 | 6758.58 | 813 | 0.8926248 |
| check valve | 3150.00 | 2.60 | 0 | 2797.86 | 6 | 0.9978601 |
| gate valve | 9800.00 | 2.50 | 0 | 8695.19 | 29 | 0.9966759 |
| pump | 9311.56 | 1.13 | 0 | 8908.38 | 378 | 0.9592952 |
| heat exchanger | 50500.00 | 2.58 | 0 | 44844.50 | 24 | 0.9994651 |
| Pipe | 24000.00 | 2.00 | 0 | 21269.45 | 14.08 | 0.9993385 |

*Table 20: Availability analysis in DHW sub-systems*

| system availability | | | | |
|---|---|---|---|---|
| **Sub-system 1** | **Sub-system 2** | **Sub-system 3(p)** | **Sub-system 4** | **system** |
| Boiler+ Check Valve+ Pipe | Gate Valve+ Check Valve+ Pump+ Pipe | Gate Valve+ Heat Exchanger+ Pipe | Gate Valve+ Check Valve+ Pump+ Pipe | $A_i$ |
| 0.987928 | 0.999812 | 0.999939 | 0.990850 | 0.978644 |

*Table 21: Step No analysis details in KSA decision process*

| STEP NO:21(Bottom Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6664.10 | 813.00 | 0.8912680 |
| check valve | 2797.86 | 6.00 | 0.9978601 |
| gate valve | 8695.19 | 29.00 | 0.9966759 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| heat exchanger | 44844.50 | 24.00 | 0.9994651 |
| Pipe | 21269.45 | 14.08 | 0.9993385 |

| STEP NO:20(Bottom Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6861.75 | 813.00 | 0.8940683 |
| check valve | 2797.86 | 6.00 | 0.9978601 |
| gate valve | 8695.19 | 29.00 | 0.9966759 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| heat exchanger | 44844.50 | 24.00 | 0.9994651 |
| Pipe | 21269.45 | 14.08 | 0.9993385 |

| STEP NO :1(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6861.75 | 813.00 | 0.8940683 |
| check valve | 2797.86 | 6.00 | 0.9978601 |
| gate valve | 8695.19 | 29.00 | 0.9966759 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| heat exchanger | 38567.32 | 24.00 | 0.9993781 |
| Pipe | 21269.45 | 14.08 | 0.9993385 |

| STEP NO:2(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6861.75 | 813.00 | 0.8940683 |
| check valve | 2797.86 | 6.00 | 0.9978601 |
| gate valve | 8695.19 | 29.00 | 0.9966759 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| heat exchanger | 38567.32 | 24.00 | 0.9993781 |
| Pipe | 18796.79 | 14.08 | 0.9992515 |

| STEP NO:3(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6861.75 | 813.00 | 0.8940683 |
| check valve | 2843.89 | 6.00 | 0.9978947 |
| gate valve | 8695.19 | 29.00 | 0.9966759 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| heat exchanger | 38567.32 | 24.00 | 0.9993781 |
| Pipe | 18796.79 | 14.08 | 0.9992515 |

| STEP NO:4(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6861.75 | 813.00 | 0.8940683 |
| check valve | 2750.25 | 6.00 | 0.9978231 |
| gate valve | 8695.19 | 29.00 | 0.9966759 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| heat exchanger | 38567.32 | 24.00 | 0.9993781 |
| Pipe | 18796.79 | 14.08 | 0.9992515 |

| STEP NO:5(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6861.75 | 813.00 | 0.8940683 |
| check valve | 2750.25 | 6.00 | 0.9978231 |
| gate valve | 8695.19 | 29.00 | 0.9966759 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| heat exchanger | 217391.30 | 24.00 | 0.9998896 |
| Pipe | 18796.79 | 14.08 | 0.9992515 |

| STEP NO:6(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6861.75 | 813.00 | 0.8940683 |
| check valve | 2750.25 | 6.00 | 0.9978231 |
| gate valve | 8695.19 | 29.00 | 0.9966759 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| heat exchanger | 217391.30 | 24.00 | 0.9998896 |
| Pipe | 19502.94 | 14.08 | 0.9992786 |

| STEP NO:7(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6861.75 | 813.00 | 0.8940683 |
| check valve | 2750.25 | 6.00 | 0.9978231 |
| gate valve | 8465.10 | 29.00 | 0.9965859 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| heat exchanger | 217391.30 | 24.00 | 0.9998896 |
| Pipe | 19502.94 | 14.08 | 0.9992786 |

| STEP NO:8(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 5286.80 | 813.00 | 0.8667169 |
| check valve | 2750.25 | 6.00 | 0.9978231 |
| gate valve | 8465.10 | 29.00 | 0.9965859 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| heat exchanger | 217391.30 | 24.00 | 0.9998896 |
| Pipe | 19502.94 | 14.08 | 0.9992786 |

| STEP NO:19(Bottom Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6256.52 | 813.00 | 0.8849993 |
| check valve | 2750.25 | 6.00 | 0.9978231 |
| gate valve | 8465.10 | 29.00 | 0.9965859 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| heat exchanger | 217391.30 | 24.00 | 0.9998896 |
| Pipe | 19502.94 | 14.08 | 0.9992786 |

| STEP NO:18(Bottom Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6256.52 | 813.00 | 0.8849993 |
| check valve | 2750.25 | 6.00 | 0.9978231 |
| gate valve | 8465.10 | 29.00 | 0.9965859 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8780.70 | 378.00 | 0.9587278 |
| heat exchanger | 217391.30 | 24.00 | 0.9998896 |
| Pipe | 19502.94 | 14.08 | 0.9992786 |

| STEP NO:17(Bottom Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6928.06 | 813.00 | 0.8949756 |
| check valve | 2750.25 | 6.00 | 0.9978231 |
| gate valve | 8465.10 | 29.00 | 0.9965859 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8780.70 | 378.00 | 0.9587278 |
| heat exchanger | 217391.30 | 24.00 | 0.9998896 |
| Pipe | 19502.94 | 14.08 | 0.9992786 |

| STEP NO:9(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6928.06 | 813.00 | 0.8949756 |
| check valve | 2750.25 | 6.00 | 0.9978231 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8780.70 | 378.00 | 0.9587278 |
| heat exchanger | 217391.30 | 24.00 | 0.9998896 |
| Pipe | 19502.94 | 14.08 | 0.9992786 |

| STEP NO:10(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6928.06 | 813.00 | 0.8949756 |
| check valve | 2750.25 | 6.00 | 0.9978231 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8780.70 | 378.00 | 0.9587278 |
| heat exchanger | 39891.69 | 24.00 | 0.9993987 |
| Pipe | 19502.94 | 14.08 | 0.9992786 |

| STEP NO:11(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6928.06 | 813.00 | 0.8949756 |
| check valve | 2481.60 | 6.00 | 0.9975880 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8780.70 | 378.00 | 0.9587278 |
| heat exchanger | 39891.69 | 24.00 | 0.9993987 |
| Pipe | 19502.94 | 14.08 | 0.9992786 |

| STEP NO:12(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6928.06 | 813.00 | 0.8949756 |
| check valve | 2481.60 | 6.00 | 0.9975880 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8780.70 | 378.00 | 0.9587278 |
| heat exchanger | 58859.66 | 24.00 | 0.9995924 |
| Pipe | 19502.94 | 14.08 | 0.9992786 |

| STEP NO:13(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6928.06 | 813.00 | 0.8949756 |
| check valve | 2481.60 | 6.00 | 0.9975880 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8780.70 | 378.00 | 0.9587278 |
| heat exchanger | 58859.66 | 24.00 | 0.9995924 |
| Pipe | 23516.40 | 14.08 | 0.9994016 |

| STEP NO:14(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6928.06 | 813.00 | 0.8949756 |
| check valve | 2481.60 | 6.00 | 0.9975880 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8620.69 | 378.00 | 0.9579939 |
| heat exchanger | 58859.66 | 24.00 | 0.9995924 |
| Pipe | 23516.40 | 14.08 | 0.9994016 |

| STEP NO:16(Bottom Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6928.06 | 813.00 | 0.8949756 |
| check valve | 2481.60 | 6.00 | 0.9975880 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8620.69 | 378.00 | 0.9579939 |
| heat exchanger | 58859.66 | 24.00 | 0.9995924 |
| Pipe | 23516.40 | 14.08 | 0.9994016 |

| STEP NO:15(Bottom Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6928.06 | 813.00 | 0.8949756 |
| check valve | 2481.60 | 6.00 | 0.9975880 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 9000.52 | 378.00 | 0.9596951 |
| heat exchanger | 58859.66 | 24.00 | 0.9995924 |
| Pipe | 23516.40 | 14.08 | 0.9994016 |

| STEP NO:15(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6928.06 | 813.00 | 0.8949756 |
| check valve | 2481.60 | 6.00 | 0.9975880 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8780.70 | 378.00 | 0.9587278 |
| heat exchanger | 58859.66 | 24.00 | 0.9995924 |
| Pipe | 23516.40 | 14.08 | 0.9994016 |

*Table 22: Result of KSA decision process*

| STEP No | Bottom Top | Types of Interval | | A* | A | e=A*-A |
|---|---|---|---|---|---|---|
| | | current | changed | | | |
| 21B | B | B-3 | B-2 | 0.9783479 | 0.9786443 | 0.000296 |
| 20B | B | B-2 | B-1 | 0.9789556 | 0.9786443 | 0.000311 |
| 1T | T | H-4 | H-5 | 0.9789542 | 0.9786443 | 0.000310 |
| 2T | T | PI-3 | PI-4 | 0.9789205 | 0.9786443 | 0.000276 |
| 3T | T | C-1 | C-2 | 0.9789334 | 0.9786443 | 0.000289 |
| 4T | T | C-2 | C-3 | 0.9789068 | 0.9786443 | 0.000262 |
| 5T | T | H-1 | H-2 | 0.9789145 | 0.9786443 | 0.000270 |
| 6T | T | PI-2 | PI-3 | 0.9789249 | 0.9786443 | 0.000281 |
| 7T | T | G-1 | G-2 | 0.9788897 | 0.9786443 | 0.000245 |
| 8T | T | B-5 | B-6 | 0.9722896 | 0.9786443 | 0.006355 |
| 19B | B | B-4 | B-3 | 0.9768646 | 0.9786443 | 0.001780 |
| 18B | B | P-3 | P-2 | 0.9766558 | 0.9786443 | 0.001988 |
| 17B | B | B-1 | B-0 | 0.9788741 | 0.9786443 | 0.000230 |
| 9T | T | G-2 | G-3 | 0.9788205 | 0.9786443 | 0.000176 |
| 10T | T | H-3 | H-4 | 0.9788128 | 0.9786443 | 0.000169 |
| 11T | T | C-3 | C-4 | 0.9787248 | 0.9786443 | 0.000081 |
| 12T | T | H-2 | H-3 | 0.9787279 | 0.9786443 | 0.000084 |
| 13T | T | PI-1 | PI-2 | 0.9787758 | 0.9786443 | 0.000132 |
| 14T | T | P-2 | P-3 | 0.9785009 | 0.9786443 | 0.000143 |
| 16B | B | P-4 | P-3 | 0.9785009 | 0.9786443 | 0.000143 |
| 15B | B | P-1 | P-0 | 0.9791325 | 0.9786443 | 0.000488 |
| 15T | T | P-1 | P-1 | 0.9787758 | 0.9786443 | 0.000132 |

*Table 23: suggested maintenance schedule for DHW*

| Comp NO:9(Top Loop)-parallel | | | |
|---|---|---|---|
| **equipment** | **MTTF (Year)** | **MTTR (Year)** | **$T_M$ (Year)** |
| boiler | 6928.06 | 813.00 | 1.00 |
| check valve | 2750.25 | 6.00 | 1.25 |
| gate valve | 8141.97 | 29.00 | 5.00 |
| pump | 8780.70 | 378.00 | 2.50 |
| heat exchanger | 217391.30 | 24.00 | 2.50 |
| Pipe | 19502.94 | 14.08 | 5.00 |

*Table 24: Modified reliability parameters as well as MTTF based on $T_M$ in the heat transfer sub-system in proposed standby heat transferring sub-system*

| $T_M$ | α | β | λ | MTTF | $R^2$ |
|---|---|---|---|---|---|
| 1.00 | 32300.00 | 1.00 | - | 32300.00 | 0.9919 |
| 1.25 | 21300.00 | 1.01 | - | 21211.70 | 0.9995 |
| 2.50 | 15570.00 | 3.91 | - | 14094.51 | 0.9935 |
| 5.00 | 13500.00 | 2.27 | - | 11958.24 | 0.9987 |
| 10.00 | 11670.00 | 2.28 | - | 10337.66 | 0.9997 |
| 12.00 | 11320.00 | 2.28 | - | 10027.62 | 0.9998 |

*Table 25: MTTF, MTTR, availability as well as maintenance effect in the boiler, pump, and gate valve in different Average Maintenance Interval (AMI) in the proposed system (standby heat transfer sub-system)*

| COMP | | TM (year) | | MTTF (Hour) | MTTR (Hour) | $a_{i,j,k}$ | $\Delta a_{i,j,k}$ |
|---|---|---|---|---|---|---|---|
| Boiler | B-0 | 1.00 | $Z_0$ | 6928.06 | 813 | 0.8949756 | 9.0736E-04 |
| | B-1 | 1.25 | $Z_1$ | 6861.75 | 813 | 0.8940683 | 2.8003E-03 |
| | B-2 | 2.5 | $Z_2$ | 6664.10 | 813 | 0.8912680 | 6.2687E-03 |
| | B-3 | 5 | $Z_3$ | 6256.52 | 813 | 0.8849993 | 1.3863E-02 |
| | B-4 | 10 | $Z_4$ | 5496.00 | 813 | 0.8711365 | 4.2867E-03 |
| | B-5 | 12 | $Z_5$ | 5292.89 | 813 | 0.8668498 | 1.3289E-04 |
| | B-6 | 15 | $Z_6$ | 5286.80 | 813 | 0.8667169 | |
| Pump | P-0 | 1.00 | $Z_0$ | 9000.52 | 378 | 0.9596951 | 1.1566E-04 |
| | P-1 | 1.25 | $Z_1$ | 8973.69 | 378 | 0.9595795 | 8.5170E-04 |
| | P-2 | 2.5 | $Z_2$ | 8780.70 | 378 | 0.9587278 | 7.3390E-04 |
| | P-3 | 5 | $Z_3$ | 8620.69 | 378 | 0.9579939 | 4.1449E-03 |
| | P-4 | 10 | $Z_4$ | 7812.50 | 378 | 0.9538490 | 1.3737E-03 |
| | P-5 | 12 | $Z_5$ | 7575.76 | 378 | 0.9524753 | |
| Gate Valve | G-0 | 1 | $Z_0$ | 9383.78 | 29 | 0.9969191 | 2.0229E-04 |
| | G-1 | 1.25 | $Z_1$ | 8803.82 | 29 | 0.9967168 | 1.3093E-04 |
| | G-2 | 2.5 | $Z_2$ | 8465.10 | 29 | 0.9965859 | 1.3501E-04 |
| | G-3 | 5 | $Z_3$ | 8141.97 | 29 | 0.9964509 | |

*Table 26: MTTF, MTTR, availability as well as maintenance effect in the check valve, heat transfer sub-system, and "Pipe" in different Average Maintenance Interval (AMI) in the proposed system (standby heat transfer sub-system)*

| COMP | | TM (year) | | MTTF (Hour) | MTTR (Hour) | $a_{i,j,k}$ | $\Delta a_{i,j,k}$ |
|---|---|---|---|---|---|---|---|
| Check Valve | C-0 | 0.25 | $Z_0$ | 4997.50 | 6 | 0.9988008 | 8.4898E-04 |
| | C-1 | 0.5 | $Z_1$ | 2923.49 | 6 | 0.9979519 | 5.7204E-05 |
| | C-2 | 1 | $Z_2$ | 2843.89 | 6 | 0.9978947 | 7.1526E-05 |
| | C-3 | 1.25 | $Z_3$ | 2750.25 | 6 | 0.9978231 | 2.3509E-04 |
| | C-4 | 2.5 | $Z_4$ | 2481.60 | 6 | 0.9975880 | |
| Heat Transfer sub-system | HT-0 | 1.00 | $Z_0$ | 32300.00 | 96.08 | 0.9970342 | 1.5434E-03 |
| | HT-1 | 1.25 | $Z_1$ | 21211.70 | 96.08 | 0.9954908 | 2.2615E-03 |
| | HT-2 | 2.5 | $Z_2$ | 14094.51 | 96.08 | 0.9932293 | 1.1999E-03 |
| | HT-3 | 5 | $Z_3$ | 11958.24 | 96.08 | 0.9920294 | 1.2380E-03 |
| | HT-4 | 10 | $Z_4$ | 10337.66 | 96.08 | 0.9907914 | 2.8202E-04 |
| | HT-5 | 12 | $Z_5$ | 10027.62 | 96.08 | 0.9905094 | |
| pipe | PI-0 | 1.00 | $Z_0$ | 62738.82 | 14.08 | 0.9997756 | 6.5839E-05 |
| | PI-1 | 1.25 | $Z_1$ | 48502.34 | 14.08 | 0.9997098 | 3.0816E-04 |
| | PI-2 | 2.50 | $Z_2$ | 23516.40 | 14.08 | 0.9994016 | 1.2305E-04 |
| | PI-3 | 5.00 | $Z_3$ | 19502.94 | 14.08 | 0.9992786 | 2.7082E-05 |
| | PI-4 | 10.00 | $Z_4$ | 18796.79 | 14.08 | 0.9992515 | |

*Table 27: Sorting List in DHW component in different AMI in the proposed system (standby heat transfer sub-system)*

| | STEP NO | Component | AMI type | AMI (Year) | $\Delta a_{i,j,k}$ |
|---|---|---|---|---|---|
| **Top loop** | 1 | PI-3 | Z3 | 5 | 2.708E-05 |
| | 2 | C-1 | Z1 | 0.5 | 5.720E-05 |
| | 3 | C-2 | Z2 | 1 | 7.153E-05 |
| | 4 | PI-2 | Z2 | 2.5 | 1.230E-04 |
| | 5 | G-1 | Z1 | 1.25 | 1.309E-04 |
| | 6 | B-5 | Z5 | 12 | 1.329E-04 |
| | 7 | G-2 | Z2 | 2.5 | 1.350E-04 |
| | 8 | C-3 | Z3 | 1.25 | 2.351E-04 |
| | 9 | HT-4 | Z4 | 10 | 2.820E-04 |
| | 10 | PI-1 | Z1 | 1.25 | 3.082E-04 |
| | 11 | P-2 | Z2 | 2.5 | 7.339E-04 |
| | 12 | P-1 | Z1 | 1.25 | 8.517E-04 |
| | 13 | HT-2 | Z2 | 2.5 | 1.200E-03 |
| | 14 | HT-3 | Z3 | 5 | 1.238E-03 |
| | 15 | P-4 | Z4 | 10 | 1.374E-03 |
| | 16 | HT-1 | Z1 | 1.25 | 2.262E-03 |
| | 17 | B-1 | Z1 | 1.25 | 2.800E-03 |
| | 18 | P-3 | Z3 | 5 | 4.145E-03 |
| | 19 | B-4 | Z4 | 10 | 4.287E-03 |
| | 20 | B-2 | Z2 | 2.5 | 6.269E-03 |
| **bottom loop** | 21 | B-3 | Z3 | 5 | 1.386E-02 |

*Table 28: Reliability parameters, MTTF, MTTR as well as availability in current system in the proposed system (standby heat transfer sub-system) [25] [26] [31] [32]*

| Component | α | β | λ | MTTF (Hour) | MTTR (Hour) | Availability |
|---|---|---|---|---|---|---|
| boiler | 7600.00 | 1.80 | 0 | 6758.58 | 813 | 0.8926248 |
| check valve | 3150.00 | 2.60 | 0 | 2797.86 | 6 | 0.9978601 |
| gate valve | 9800.00 | 2.50 | 0 | 8695.19 | 29 | 0.9966759 |
| pump | 9311.56 | 1.13 | 0 | 8908.38 | 378 | 0.9592952 |
| heat transfer sub-system | 14000.00 | 2.65 | 0 | 12442.26 | 96.08 | 0.9923371 |
| Pipe | 24000.00 | 2.00 | 0 | 21269.45 | 14.08 | 0.9993385 |

*Table 29: Availability analysis in DHW sub-systems in the proposed system (standby heat transfer sub-system)*

| system availability | | | | |
|---|---|---|---|---|
| **Sub-system 1** | **Sub-system 2** | **Sub-system 3(S)** | **Sub-system 4** | **system** |
| Boiler+ Check Valve+ Pipe | Gate Valve+ Check Valve+ Pump+ Strainer+ Pipe | Gate Valve+ Heat Exchanger+ Pipe | Gate Valve+ Check Valve+ Pump+ Strainer+ Pipe | $\mathbf{A_i}$ |
| 0.987928 | 0.999812 | 0.992337 | 0.990850 | 0.971204 |

*Table 30: Step No analysis details in KSA decision process in the proposed system (standby heat transfer sub-system)*

| STEP NO:21(Bottom Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6664.10 | 813.00 | 0.8912680 |
| check valve | 2797.86 | 6.00 | 0.9978601 |
| gate valve | 8695.19 | 29.00 | 0.9966759 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| Heat transfer sys | 12442.26 | 24.00 | 0.9980748 |
| Pipe | 21269.45 | 14.08 | 0.9993385 |

| STEP NO:1(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6664.10 | 813.00 | 0.8912680 |
| check valve | 2797.86 | 6.00 | 0.9978601 |
| gate valve | 8695.19 | 29.00 | 0.9966759 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| Heat transfer sys | 12442.26 | 24.00 | 0.9980748 |
| Pipe | 18796.79 | 14.08 | 0.9992515 |

| STEP NO :2(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6664.10 | 813.00 | 0.8912680 |
| check valve | 2843.89 | 6.00 | 0.9978947 |
| gate valve | 8695.19 | 29.00 | 0.9966759 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| Heat transfer sys | 12442.26 | 24.00 | 0.9980748 |
| Pipe | 18796.79 | 14.08 | 0.9992515 |

| STEP NO:3(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6664.10 | 813.00 | 0.8912680 |
| check valve | 2750.25 | 6.00 | 0.9978231 |
| gate valve | 8695.19 | 29.00 | 0.9966759 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| Heat transfer sys | 12442.26 | 24.00 | 0.9980748 |
| Pipe | 18796.79 | 14.08 | 0.9992515 |

| STEP NO:4(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6664.10 | 813.00 | 0.8912680 |
| check valve | 2750.25 | 6.00 | 0.9978231 |
| gate valve | 8695.19 | 29.00 | 0.9966759 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| Heat transfer sys | 12442.26 | 24.00 | 0.9980748 |
| Pipe | 19502.94 | 14.08 | 0.9992786 |

| STEP NO:5(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6664.10 | 813.00 | 0.8912680 |
| check valve | 2750.25 | 6.00 | 0.9978231 |
| gate valve | 8465.10 | 29.00 | 0.9965859 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| Heat transfer sys | 12442.26 | 24.00 | 0.9980748 |
| Pipe | 19502.94 | 14.08 | 0.9992786 |

| STEP NO:6(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 5286.80 | 813.00 | 0.8667169 |
| check valve | 2750.25 | 6.00 | 0.9978231 |
| gate valve | 8465.10 | 29.00 | 0.9965859 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| Heat transfer sys | 12442.26 | 24.00 | 0.9980748 |
| Pipe | 19502.94 | 14.08 | 0.9992786 |

| STEP NO:7(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 5286.80 | 813.00 | 0.8667169 |
| check valve | 2750.25 | 6.00 | 0.9978231 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| Heat transfer sys | 12442.26 | 24.00 | 0.9980748 |
| Pipe | 19502.94 | 14.08 | 0.9992786 |

| STEP NO:8(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 5286.80 | 813.00 | 0.8667169 |
| check valve | 2481.60 | 6.00 | 0.9975880 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| Heat transfer sys | 12442.26 | 24.00 | 0.9980748 |
| Pipe | 19502.94 | 14.08 | 0.9992786 |

| STEP NO:9(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 5286.80 | 813.00 | 0.8667169 |
| check valve | 2481.60 | 6.00 | 0.9975880 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| Heat transfer sys | 10027.62 | 24.00 | 0.9976123 |
| Pipe | 19502.94 | 14.08 | 0.9992786 |

| STEP NO:10(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 5286.80 | 813.00 | 0.8667169 |
| check valve | 2481.60 | 6.00 | 0.9975880 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| Heat transfer sys | 10027.62 | 24.00 | 0.9976123 |
| Pipe | 23516.40 | 14.08 | 0.9994016 |

| STEP NO:20(Bottom Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6861.75 | 813.00 | 0.8940683 |
| check valve | 2481.60 | 6.00 | 0.9975880 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| Heat transfer sys | 10027.62 | 24.00 | 0.9976123 |
| Pipe | 23516.40 | 14.08 | 0.9994016 |

| STEP NO:19(Bottom Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6256.52 | 813.00 | 0.8849993 |
| check valve | 2481.60 | 6.00 | 0.9975880 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8908.38 | 378.00 | 0.9592952 |
| Heat transfer sys | 10027.62 | 24.00 | 0.9976123 |
| Pipe | 23516.40 | 14.08 | 0.9994016 |

| STEP NO:18(Bottom Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6256.52 | 813.00 | 0.8849993 |
| check valve | 2481.60 | 6.00 | 0.9975880 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8780.70 | 378.00 | 0.9587278 |
| Heat transfer sys | 10027.62 | 24.00 | 0.9976123 |
| Pipe | 23516.40 | 14.08 | 0.9994016 |

| STEP NO:17(Bottom Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6928.06 | 813.00 | 0.8949756 |
| check valve | 2481.60 | 6.00 | 0.9975880 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8780.70 | 378.00 | 0.9587278 |
| Heat transfer sys | 10027.62 | 24.00 | 0.9976123 |
| Pipe | 23516.40 | 14.08 | 0.9994016 |

| STEP NO:16(Bottom Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6928.06 | 813.00 | 0.8949756 |
| check valve | 2481.60 | 6.00 | 0.9975880 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8780.70 | 378.00 | 0.9587278 |
| Heat transfer sys | 32300.00 | 24.00 | 0.9992575 |
| Pipe | 23516.40 | 14.08 | 0.9994016 |

| STEP NO:11(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6928.06 | 813.00 | 0.8949756 |
| check valve | 2481.60 | 6.00 | 0.9975880 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8780.70 | 378.00 | 0.9587278 |
| Heat transfer sys | 58859.66 | 24.00 | 0.9995924 |
| Pipe | 19502.94 | 14.08 | 0.9992786 |

| STEP NO:12(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6928.06 | 813.00 | 0.8949756 |
| check valve | 2481.60 | 6.00 | 0.9975880 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8780.70 | 378.00 | 0.9587278 |
| Heat transfer sys | 32300.00 | 24.00 | 0.9992575 |
| Pipe | 23516.40 | 14.08 | 0.9994016 |

| STEP NO:13(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6928.06 | 813.00 | 0.8949756 |
| check valve | 2481.60 | 6.00 | 0.9975880 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8780.70 | 378.00 | 0.9587278 |
| Heat transfer sys | 11958.24 | 24.00 | 0.9979970 |
| Pipe | 23516.40 | 14.08 | 0.9994016 |

| STEP NO:15(Bottom Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6928.06 | 813.00 | 0.8949756 |
| check valve | 2481.60 | 6.00 | 0.9975880 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8620.69 | 378.00 | 0.9579939 |
| Heat transfer sys | 11958.24 | 24.00 | 0.9979970 |
| Pipe | 23516.40 | 14.08 | 0.9994016 |

| STEP NO:14(Bottom Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6928.06 | 813.00 | 0.8949756 |
| check valve | 2481.60 | 6.00 | 0.9975880 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8620.69 | 378.00 | 0.9579939 |
| Heat transfer sys | 14094.51 | 24.00 | 0.9983001 |
| Pipe | 23516.40 | 14.08 | 0.9994016 |

| STEP NO:14(Top Loop) | | | |
|---|---|---|---|
| **equipment** | **MTTF** | **MTTR** | **Availability** |
| boiler | 6928.06 | 813.00 | 0.8949756 |
| check valve | 2481.60 | 6.00 | 0.9975880 |
| gate valve | 8141.97 | 29.00 | 0.9964509 |
| strainer | 5000.00 | 40 | 0.9920635 |
| pump | 8620.69 | 378.00 | 0.9579939 |
| Heat transfer sys | 10337.66 | 24.00 | 0.9976838 |
| Pipe | 23516.40 | 14.08 | 0.9994016 |

*Table 31: Result of KSA decision process in the proposed system (standby heat transfer sub-system)*

| STEP No | Bottom Top | Types of Interval | | A* | A | e=A*-A |
|---|---|---|---|---|---|---|
| | | current | changed | | | |
| 21B | B | B-3 | B-2 | 0.9781906 | 0.9712045 | 0.006986 |
| 1T | T | PI-3 | PI-4 | 0.9781554 | 0.9712045 | 0.006951 |
| 2T | T | C-1 | C-2 | 0.9781684 | 0.9712045 | 0.006964 |
| 3T | T | C-2 | C-3 | 0.9781414 | 0.9712045 | 0.006937 |
| 4T | T | PI-2 | PI-3 | 0.9781524 | 0.9712045 | 0.006948 |
| 5T | T | G-1 | G-2 | 0.9781146 | 0.9712045 | 0.006910 |
| 6T | T | B-5 | B-6 | 0.9721236 | 0.9712045 | 0.000919 |
| 7T | T | G-2 | G-3 | 0.9720670 | 0.9712045 | 0.000863 |
| 8T | T | C-3 | C-4 | 0.9719698 | 0.9712045 | 0.000765 |
| 9T | T | HT-4 | HT-5 | 0.9719123 | 0.9712045 | 0.000708 |
| 10T | T | PI-1 | PI-2 | 0.9630241 | 0.9712045 | 0.008180 |
| 20B | B | B-2 | B-1 | 0.9695660 | 0.9712045 | 0.001638 |
| 19B | B | B-4 | B-3 | 0.9675586 | 0.9712045 | 0.003646 |
| 18B | B | P-3 | P-2 | 0.9673511 | 0.9712045 | 0.003853 |
| 17B | B | B-1 | B-0 | 0.9695500 | 0.9712045 | 0.001654 |
| 16B | B | HT-1 | HT-0 | 0.9759368 | 0.9712045 | 0.004732 |
| 11T | T | P-2 | P-3 | 0.9756627 | 0.9712045 | 0.004458 |
| 12T | T | P-1 | P-2 | 0.9759368 | 0.9712045 | 0.004732 |
| 13T | T | HT-2 | HT-3 | 0.9710379 | 0.9712045 | 0.000167 |
| 15B | B | P-4 | P-3 | 0.9707651 | 0.9712045 | 0.000439 |
| 14B | B | HT-3 | HT-2 | 0.9719393 | 0.9712045 | 0.000735 |
| 14T | T | HT-3 | HT-4 | 0.9695537 | 0.9712045 | 0.001651 |

*Table 32: suggested maintenance schedule for DHW in the proposed system (standby heat transfer sub-system)*

| STEP NO:14(Bottom Loop)-standby | | | |
|---|---|---|---|
| **equipment** | **MTTF (Year)** | **MTTR (Year)** | **$T_M$ (Year)** |
| boiler | 6928.06 | 813.00 | 1.00 |
| check valve | 2481.60 | 6.00 | 2.5 |
| gate valve | 8141.97 | 29.00 | 5.00 |
| pump | 8620.69 | 378.00 | 5 |
| Heat transfer sys | 14094.51 | 24.00 | 2.50 |
| Pipe | 23516.40 | 14.08 | 2.5 |

*Table 33: Reliability parameters in repairable "Heat Exchanger" sub-components*

| **sub-component** | **α(hour)** | **β** |
|---|---|---|
| tube bundle | 32000 | 3.00 |
| baffle plates | 30700 | 3.00 |

*Table 34: Quantitative value of modified as well as current reliability in "Heat Exchanger" sub-components in $T_M = 2.5$ years in different preventive maintenance period*

| **K** | **t (Years) Maintenance** | Tube bundle | | Baffle plates | |
|---|---|---|---|---|---|
| | | $R^*_T(t)$ | **R(t)** | $R^*_T(t)$ | **R(t)** |
| 0 | 2.5 | 0.725 | 0.725 | 0.695 | 0.695 |
| 1 | 5 | 0.526 | 0.076 | 0.483 | 0.054 |
| 2 | 7.5 | 0.382 | 0.0001 | 0.336 | 5.54E-05 |
| 3 | 10 | 0.277 | 1.23E-09 | 0.234 | 8.13E-11 |
| 4 | 12.5 | 0.201 | 3.97E-18 | 0.162 | 1.97E-20 |

*Table 35: Modified reliability parameters in "Tube Bundle" and "Baffle Plates"*

| $T_{M(Year)}$ | α | α | β | $R^2$ |
|---|---|---|---|---|
| 2.50 | Tube Bundle | 83100.00 | 1.01 | 0.9571 |
| 2.50 | Baffle Plates | 71700.00 | 1.01 | 0.9673 |

*Table 36: Average value of $\frac{C_2}{C_1}$ in both the tube bundle and baffle plates in $T^* = 5\&\ 7.5\ years$*

| sub-component | $C_2/C_1$ | |
|---|---|---|
| | 5 years | 7.5 years |
| Tube bundle& Baffle plate | 5.66E-03 | 8.52E-03 |

*Table 37: Quantitative value of modified as well as current reliability in the tube bundle and baffle plates in $T_M = 5$ year in both the 5 and 10 years preventive maintenance period*

| K | $T_M$ (Years) | Tube bundle | | Baffle plates | |
|---|---|---|---|---|---|
| | | $R^*_T(t)$ | R(t) | $R^*_T(t)$ | R(t) |
| 0 | 5 | 0.076 | 0.076 | 0.054 | 0.054 |
| 1 | 10 | 0.005 | 1.23E-09 | 0.003 | 8.13E-11 |

*Table 38: Maintenance cash-flow for system with parallel heat transfer sub-system (heat exchanger NO.1)*

| Time interval (year) | Heat Exchanger 1 (Parallel) | | | |
|---|---|---|---|---|
| | maintenance cost(M-H) | maintenance cost(spare) | replacement cost(M-H) | replacement cost(spare) |
| 0 | $1 \times HEC$ | | | |
| 2.5 | $24x$ | $G$ | | |
| 5 | | | $5.66 \times 10^{-3} \times 24x$ | $TB + BP + G$ |
| 7.5 | $24x$ | $G$ | | |
| 10 | | | $5.66 \times 10^{-3} \times 24x$ | $TB + BP + G$ |
| 12.5 | $24x$ | $G$ | | |
| 15 | | | $5.66 \times 10^{-3} \times 24x$ | $TB + BP + G$ |

*Table 39: Maintenance cash-flow for system with parallel heat transfer sub-system (heat exchanger NO.2)*

| Time interval (year) | Heat Exchanger 2 (Parallel) | | | |
|---|---|---|---|---|
| | maintenance cost(M-H) | maintenance cost(spare) | replacement cost(M-H) | replacement cost(spare) |
| 0 | $1 \times HEC$ | | | |
| 2.5 | $24x$ | $G$ | | |
| 5 | $24x$ | $G$ | | |
| 7.5 | | | $5.66 \times 10^{-3} \times 24x$ | $TB + BP + G$ |
| 10 | $24x$ | $G$ | | |
| 12.5 | | | $5.66 \times 10^{-3} \times 24x$ | $TB + BP + G$ |
| 15 | $24x$ | $G$ | | |

Table 40: Maintenance cash-flow in the proposed system (standby heat transfer sub-system) (Main heat exchanger)

| Time interval (year) | Heat Exchanger 1(main) | | | |
|---|---|---|---|---|
| | maintenance cost(M-H) | maintenance cost(spare) | replacement cost(M-H) | replacement cost(spare) |
| 0 | $1 \times HEC_{main}$ | | | |
| 2.5 | $24x$ | $G$ | | |
| 5 | $24x$ | $G$ | | |
| 7.5 | | | $8.52 \times 10^{-3} \times 24x$ | $TB + BP + G$ |
| 10 | $24x$ | $G$ | | |
| 12.5 | $24x$ | $G$ | | |
| 15 | | | $8.52 \times 10^{-3} \times 24x$ | $TB + BP + G$ |

Table 41: Maintenance cash-flow in the proposed system (standby heat transfer sub-system) (standby heat exchanger)

| Time interval (year) | Heat Exchanger 2(standby) | | | |
|---|---|---|---|---|
| | maintenance cost(M-H) | maintenance cost(spare) | replacement cost(M-H) | replacement cost(spare) |
| 0 | $1 \times HEC_{standby}$ | | | |
| 2.5 | | | | |
| 5 | | | | |
| 7.5 | $24x$ | $G$ | | |
| 10 | | | | |
| 12.5 | | | | |
| 15 | $24x$ | $G$ | | |

.

*Table 42: A and B parameters in different components*

| Component | A | B | $R^2$ |
|---|---|---|---|
| Boiler | 7112.5 | -0.108 | 0.9165 |
| Pipe | 62409 | -0.622 | 0.9456 |
| Gate Valve | 9192.9 | -0.085 | 0.9531 |
| Ball Valve | 10460 | -0.153 | 0.8692 |
| Relief Valve | 3515636 | -1.37 | 0.9988 |

*Table 43: Weibull parameters as well as model parameters in different components*

| Component | α | β | A | B | Log(α/β) | Log(A) |
|---|---|---|---|---|---|---|
| Boiler | 7600 | 1.8 | 7112.5 | -0.108 | 3.625541 | 3.852022 |
| Pipe | 24000 | 2 | 62409 | -0.622 | 4.079181 | 4.795247 |
| Gate Valve | 9800 | 2.5 | 9192.9 | -0.085 | 3.593286 | 3.963453 |
| Ball Valve | 10512 | 2.3 | 10460 | -0.153 | 3.659958 | 4.019532 |
| Relief Valve | 113880 | 2.3 | 3515636 | -1.37 | 4.69472 | 6.546004 |

*Table 44: Comparison between trend and model in parameter A*

| Component | A | A (model) | Deviation |
|---|---|---|---|
| Boiler | 7112.500 | 8559.070 | 20.34% |
| Pipe | 62409.000 | 73687.204 | 18.07% |
| Gate Valve | 9192.900 | 7468.548 | -18.76% |
| Ball Valve | 10460.000 | 9921.588 | -5.15% |
| Relief Valve | 3515636.430 | 3170916.124 | -9.81% |

*Table 45: Comparison between trend and modified model in parameter A*

| Component | A | A (Final model) | Deviation |
|---|---|---|---|
| Boiler | 7112.500 | 7180.131 | 0.95% |
| Pipe | 62409.000 | 61815.569 | -0.95% |
| Gate Valve | 9192.900 | 8414.005 | -8.47% |
| Ball Valve | 10460.000 | 11177.580 | 6.86% |
| Relief Valve | 3515636.430 | 3572328.287 | 1.61% |

*Table 46: Comparison between trend and modified model in parameter B*

| Component | B | B(model) | Deviation |
|---|---|---|---|
| Boiler | -0.108 | -0.111 | 2.77% |
| Pipe | -0.622 | -0.642 | 3.15% |
| Gate Valve | -0.085 | -0.073 | -13.80% |
| Ball Valve | -0.153 | -0.151 | -1.14% |
| Relief Valve | -1.370 | -1.362 | -0.61% |

*Table 47: Quantitative value of equipment parameter*

| Classification | Component | η | η' |
|---|---|---|---|
| Group 1 | Boiler, Pipe | 0.076 | 1 |
| Group 2 | Gate, Ball and Relief Valve | -0.052 | 1 |

# Appendix A

*Table 48: summary of reliability calculation in the boiler*

| time (hour) | Burner $R_{Bu}(t)$ | Fan $R_{Fa}(t)$ | Safety valve $R_{SV}(t)$ | Tube $R_{Tu}(t)$ | Boiler $R_{B}(t)$ |
|---|---|---|---|---|---|
| 0 | 1 | 1 | 1 | 1 | 1 |
| 1000 | 0.976406216 | 0.999978627 | 0.99993357 | 0.987372519 | 0.963992017 |
| 2000 | 0.951437744 | 0.999879101 | 0.999768698 | 0.950102789 | 0.903645302 |
| 3000 | 0.926343267 | 0.999666876 | 0.999520167 | 0.890800853 | 0.824516662 |
| 4000 | 0.901414552 | 0.999316283 | 0.999194789 | 0.813699221 | 0.732388624 |
| 5000 | 0.87679136 | 0.998805901 | 0.998797013 | 0.724081276 | 0.633347285 |
| 6000 | 0.85255379 | 0.998117029 | 0.998330118 | 0.6276612 | 0.533215433 |
| 7000 | 0.828751645 | 0.997232942 | 0.997796698 | 0.529976853 | 0.43703879 |
| 8000 | 0.805417023 | 0.996138467 | 0.997198895 | 0.435877559 | 0.348727996 |
| 9000 | 0.782570713 | 0.994819715 | 0.996538533 | 0.349166681 | 0.27089118 |
| 10000 | 0.76022582 | 0.993263911 | 0.995817206 | 0.272425806 | 0.20484961 |
| 11000 | 0.738389997 | 0.991459266 | 0.995036327 | 0.207013545 | 0.150798972 |
| 12000 | 0.717066899 | 0.989394902 | 0.994197175 | 0.153205164 | 0.108062565 |
| 13000 | 0.696257174 | 0.98706078 | 0.993300912 | 0.110423666 | 0.075380077 |
| 14000 | 0.675959175 | 0.984447667 | 0.992348615 | 0.07750966 | 0.051183879 |
| 15000 | 0.65616947 | 0.981547098 | 0.991341282 | 0.052984139 | 0.033829551 |
| 16000 | 0.63688323 | 0.978351354 | 0.990279848 | 0.035271535 | 0.021763912 |
| 17000 | 0.618094529 | 0.974853451 | 0.989165197 | 0.022865666 | 0.013628464 |

# Appendix B

*Table 49: The summary of reliability calculation based on failure data in the tube bundle*

| time interval (hour) Δt | time (hour) | mean value time interval (hour) | number of failures $N_f$ | failure density function $f(t)=(N_f/N_0)*1/\Delta t$ | hazard rate $\lambda(t)=(N_f/N_s)*1/\Delta t$ | Reliability $R(t)=N_s/N_0$ |
|---|---|---|---|---|---|---|
| 0-1000 | 0 | 500 | 0 | 0.000E+00 | 0.000E+00 | 1.0000 |
| 1000-2000 | 1,000 | 1,500 | 0 | 0.000E+00 | 0.000E+00 | 1.0000 |
| 2000-3000 | 2,000 | 2,500 | 0 | 0.000E+00 | 0.000E+00 | 1.0000 |
| 3000-4000 | 3,000 | 3,500 | 0 | 0.000E+00 | 0.000E+00 | 1.0000 |
| 4000-5000 | 4,000 | 4,500 | 1 | 5.236E-06 | 5.236E-06 | 1.0000 |
| 5000-6000 | 5,000 | 5,500 | 1 | 5.236E-06 | 5.263E-06 | 0.9948 |
| 6000-7000 | 6,000 | 6,500 | 0 | 0.000E+00 | 0.000E+00 | 0.9895 |
| 7000-8000 | 7,000 | 7,500 | 1 | 5.236E-06 | 5.291E-06 | 0.9895 |
| 8000-9000 | 8,000 | 8,500 | 1 | 5.236E-06 | 5.319E-06 | 0.9843 |
| 9000-10000 | 9,000 | 9,500 | 2 | 1.047E-05 | 1.070E-05 | 0.9791 |
| 10000-11000 | 10,000 | 10,500 | 2 | 1.047E-05 | 1.081E-05 | 0.9686 |
| 11000-12000 | 11,000 | 11,500 | 2 | 1.047E-05 | 1.093E-05 | 0.9581 |
| 12000-13000 | 12,000 | 12,500 | 2 | 1.047E-05 | 1.105E-05 | 0.9476 |
| 13000-14000 | 13,000 | 13,500 | 2 | 1.047E-05 | 1.117E-05 | 0.9372 |
| 14000-15000 | 14,000 | 14,500 | 3 | 1.571E-05 | 1.695E-05 | 0.9267 |
| 15000-16000 | 15,000 | 15,500 | 4 | 2.094E-05 | 2.299E-05 | 0.9110 |
| 16000-17000 | 16,000 | 16,500 | 4 | 2.094E-05 | 2.353E-05 | 0.8901 |
| 17000-more | 17,000 | 17,500 | 5 | 2.618E-05 | 3.012E-05 | 0.8691 |

| | |
|---|---|
| time interval( Δt) | 1,000 |
| **number of failures** | **30** |
| **number of samples** | **191** |

*Table 50: The summary of reliability calculation based on failure data in the baffle plates*

| time interval (hour) Δt | time (hour) | mean value time interval (hour) | number of failures $N_f$ | failure density function $f(t)=(N_f/N_0)*1/\Delta t$ | hazard rate $\lambda(t)=(N_f/N_s)*1/\Delta t$ | Reliability $R(t)=N_s/N_0$ |
|---|---|---|---|---|---|---|
| 0-1000 | 0 | 500 | 0 | 0.000E+00 | 0.000E+00 | 1.0000 |
| 1000-2000 | 1,000 | 1,500 | 0 | 0.000E+00 | 0.000E+00 | 1.0000 |
| 2000-3000 | 2,000 | 2,500 | 0 | 0.000E+00 | 0.000E+00 | 1.0000 |
| 3000-4000 | 3,000 | 3,500 | 1 | 5.236E-06 | 5.236E-06 | 1.0000 |
| 4000-5000 | 4,000 | 4,500 | 1 | 5.236E-06 | 5.263E-06 | 0.9948 |
| 5000-6000 | 5,000 | 5,500 | 1 | 5.236E-06 | 5.291E-06 | 0.9895 |
| 6000-7000 | 6,000 | 6,500 | 0 | 0.000E+00 | 0.000E+00 | 0.9843 |
| 7000-8000 | 7,000 | 7,500 | 1 | 5.236E-06 | 5.319E-06 | 0.9843 |
| 8000-9000 | 8,000 | 8,500 | 1 | 5.236E-06 | 5.348E-06 | 0.9791 |
| 9000-10000 | 9,000 | 9,500 | 2 | 1.047E-05 | 1.075E-05 | 0.9738 |
| 10000-11000 | 10,000 | 10,500 | 2 | 1.047E-05 | 1.087E-05 | 0.9634 |
| 11000-12000 | 11,000 | 11,500 | 2 | 1.047E-05 | 1.099E-05 | 0.9529 |
| 12000-13000 | 12,000 | 12,500 | 2 | 1.047E-05 | 1.111E-05 | 0.9424 |
| 13000-14000 | 13,000 | 13,500 | 3 | 1.571E-05 | 1.685E-05 | 0.9319 |
| 14000-15000 | 14,000 | 14,500 | 3 | 1.571E-05 | 1.714E-05 | 0.9162 |
| 15000-16000 | 15,000 | 15,500 | 4 | 2.094E-05 | 2.326E-05 | 0.9005 |
| 16000-17000 | 16,000 | 16,500 | 4 | 2.094E-05 | 2.381E-05 | 0.8796 |
| 17000-more | 17,000 | 17,500 | 5 | 2.618E-05 | 3.049E-05 | 0.8586 |

| | |
|---|---|
| time interval(Δt) | 1,000 |
| number of failures | 32 |
| number of samples | 191 |

Table 51: The summary of reliability calculation based on failure data in the gasket

| time interval (hour) Δt | time (hour) | mean value time interval (hour) | number of failures $N_f$ | failure density function $f(t)=(N_f/N_0)*1/\Delta t$ | hazard rate $\lambda(t)=(N_f/N_s)*1/\Delta t$ | Reliability $R(t)=N_s/N_0$ |
|---|---|---|---|---|---|---|
| 0-1000 | 0 | 500 | 0 | 0.000E+00 | 0.000E+00 | 1.0000 |
| 1000-2000 | 1,000 | 1,500 | 0 | 0.000E+00 | 0.000E+00 | 1.0000 |
| 2000-3000 | 2,000 | 2,500 | 2 | 1.047E-05 | 1.047E-05 | 1.0000 |
| 3000-4000 | 3,000 | 3,500 | 2 | 1.047E-05 | 1.058E-05 | 0.9895 |
| 4000-5000 | 4,000 | 4,500 | 3 | 1.571E-05 | 1.604E-05 | 0.9791 |
| 5000-6000 | 5,000 | 5,500 | 3 | 1.571E-05 | 1.630E-05 | 0.9634 |
| 6000-7000 | 6,000 | 6,500 | 3 | 1.571E-05 | 1.657E-05 | 0.9476 |
| 7000-8000 | 7,000 | 7,500 | 3 | 1.571E-05 | 1.685E-05 | 0.9319 |
| 8000-9000 | 8,000 | 8,500 | 4 | 2.094E-05 | 2.286E-05 | 0.9162 |
| 9000-10000 | 9,000 | 9,500 | 4 | 2.094E-05 | 2.339E-05 | 0.8953 |
| 10000-11000 | 10,000 | 10,500 | 3 | 1.571E-05 | 1.796E-05 | 0.8743 |
| 11000-12000 | 11,000 | 11,500 | 3 | 1.571E-05 | 1.829E-05 | 0.8586 |
| 12000-13000 | 12,000 | 12,500 | 3 | 1.571E-05 | 1.863E-05 | 0.8429 |
| 13000-14000 | 13,000 | 13,500 | 3 | 1.571E-05 | 1.899E-05 | 0.8272 |
| 14000-15000 | 14,000 | 14,500 | 3 | 1.571E-05 | 1.935E-05 | 0.8115 |
| 15000-16000 | 15,000 | 15,500 | 4 | 2.094E-05 | 2.632E-05 | 0.7958 |
| 16000-17000 | 16,000 | 16,500 | 4 | 2.094E-05 | 2.703E-05 | 0.7749 |
| 17000-more | 17,000 | 17,500 | 4 | 2.094E-05 | 2.778E-05 | 0.7539 |

| | |
|---|---|
| time interval(Δt) | 1,000 |
| number of failures | 51 |
| number of samples | 191 |

*Table 52: summary of reliability calculation in the heat exchanger*

| time (hour) | tube bundle $R_{Tb}(t)$ | buffle plates $R_{Bp}(t)$ | gasket $R_G(t)$ | Heat Exchanger $R_{He}(t)$ |
|---|---|---|---|---|
| 0 | 1.0000 | 1.0000 | 1.0000 | 1.0000 |
| 1,000 | 0.9980 | 0.9971 | 0.9831 | 0.9999 |
| 2,000 | 0.9961 | 0.9941 | 0.9664 | 0.9997 |
| 3,000 | 0.9941 | 0.9912 | 0.9501 | 0.9993 |
| 4,000 | 0.9922 | 0.9883 | 0.9340 | 0.9987 |
| 5,000 | 0.9902 | 0.9854 | 0.9181 | 0.9980 |
| 6,000 | 0.9882 | 0.9825 | 0.9026 | 0.9972 |
| 7,000 | 0.9854 | 0.9792 | 0.8873 | 0.9960 |
| 8,000 | 0.9814 | 0.9746 | 0.8723 | 0.9944 |
| 9,000 | 0.9760 | 0.9686 | 0.8575 | 0.9922 |
| 10,000 | 0.9690 | 0.9609 | 0.8430 | 0.9892 |
| 11,000 | 0.9602 | 0.9513 | 0.8287 | 0.9852 |
| 12,000 | 0.9493 | 0.9398 | 0.8147 | 0.9800 |
| 13,000 | 0.9362 | 0.9261 | 0.8009 | 0.9735 |
| 14,000 | 0.9207 | 0.9100 | 0.7873 | 0.9655 |
| 15,000 | 0.9026 | 0.8915 | 0.7740 | 0.9559 |
| 16,000 | 0.8819 | 0.8705 | 0.7609 | 0.9445 |
| 17,000 | 0.8584 | 0.8470 | 0.7480 | 0.9312 |

# Appendix C

*Table 53: summary of reliability calculation in the gate valve*

| time (hour) | Stem gasket $R_{SG}(t)$ | sealing ring $R_{SR}(t)$ | Gate valve $R_{GV}(t)$ |
|---|---|---|---|
| 0 | 1 | 1 | 1 |
| 1,000 | 0.999887049 | 0.999999995 | 0.999887044 |
| 2,000 | 0.998194321 | 0.999999827 | 0.998194147 |
| 3,000 | 0.990892214 | 0.999998683 | 0.990890909 |
| 4,000 | 0.971497109 | 0.999994451 | 0.971491718 |
| 5,000 | 0.931836312 | 0.999983065 | 0.931820531 |
| 6,000 | 0.863818810 | 0.999957861 | 0.86378241 |
| 7,000 | 0.762456590 | 0.999908923 | 0.762387148 |
| 8,000 | 0.629599246 | 0.999822438 | 0.629487453 |
| 9,000 | 0.476584265 | 0.999680051 | 0.476431783 |
| 10,000 | 0.323172263 | 0.999458224 | 0.322997176 |
| 11,000 | 0.191320909 | 0.999127609 | 0.191154003 |
| 12,000 | 0.096108657 | 0.998652431 | 0.095979144 |
| 13,000 | 0.039709523 | 0.997989902 | 0.039629703 |
| 14,000 | 0.013044936 | 0.997089652 | 0.013006971 |
| 15,000 | 0.003284808 | 0.995893230 | 0.003271318 |

# Appendix D

## Pipe

| | | | |
|---|---|---|---|
| α | 63000.00 | | |
| β | 1.01 | | |
| λ | | $T_M$=1.00 | |
| **K** | **time interval** | **$f^*(t)$ (data trend)** | **$f^*(t)$ (function)** |
| 0 | 0-1 | 1.4710E-05 | 1.4588E-05 |
| 1 | 1-2 | 1.2875E-05 | 1.2853E-05 |
| 2 | 2-3 | 1.1269E-05 | 1.1246E-05 |
| 3 | 3-4 | 9.8637E-06 | 9.8178E-06 |
| 4 | 4-5 | 8.6334E-06 | 8.5600E-06 |
| 5 | 5-6 | 7.5565E-06 | 7.4572E-06 |
| 6 | 6-7 | 6.6140E-06 | 6.4926E-06 |
| 7 | 7-8 | 5.7890E-06 | 5.6502E-06 |
| | | **$R^2$=0.9990** | |

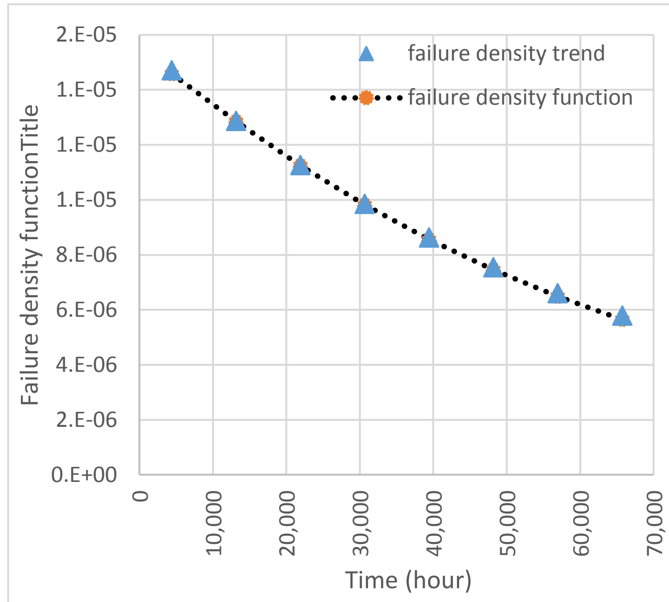



*Figure 84: The modified density function parameters in the pipe with $T_M = 1$ years*

| | | | |
|---|---|---|---|
| α | 48900.00 | | |
| β | 1.02 | | |
| λ | | $T_M$=1.25 | |
| **K** | **time interval** | **$f^*(t)$ (data trend)** | **$f^*(t)$ (function)** |
| 0 | 0-1.25 | 1.8046E-05 | 1.7936E-05 |
| 1 | 1.25-2.5 | 1.4655E-05 | 1.4692E-05 |
| 2 | 2.5-3.75 | 1.1901E-05 | 1.1856E-05 |
| 3 | 3.75-5 | 9.6644E-06 | 9.5160E-06 |
| 4 | 5-6.25 | 7.8482E-06 | 7.6149E-06 |
| 5 | 6.25-7.5 | 6.3734E-06 | 6.0812E-06 |
| 6 | 7.5-8.75 | 5.1756E-06 | 4.8491E-06 |
| 7 | 8.75-10 | 4.2030E-06 | 3.8620E-06 |
| | | **$R^2$=0.9976** | |

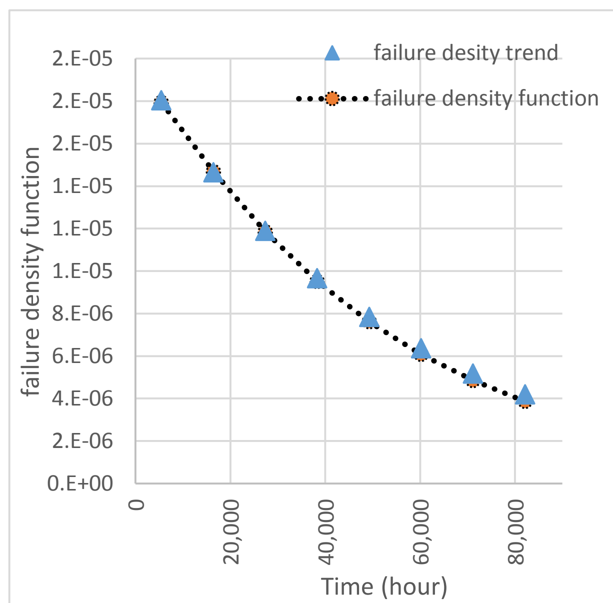



*Figure 85: The modified density function parameters in the pipe with $T_M = 1.25$ years*

| | | | |
|---|---|---|---|
| α | 25000.00 | | |
| β | 1.2 | | |
| λ | | $T_M$=2.5 | |
| **K** | **time interval** | **$f^*(t)$ (data trend)** | **$f^*(t)$ (function)** |
| 0 | 0-2.5 | 3.0876E-05 | 2.8072E-05 |
| 1 | 2.5-5 | 1.3428E-05 | 1.2655E-05 |
| 2 | 5-7.5 | 5.8396E-06 | 4.3330E-06 |
| 3 | 7.5-10 | 2.5396E-06 | 1.2959E-06 |
| 4 | 10-12.5 | 1.1044E-06 | 3.5318E-07 |
| 5 | 12.5-15 | 4.8032E-07 | 8.9569E-08 |
| 6 | 15-17.5 | 2.0889E-07 | 2.1408E-08 |
| 7 | 17.5-20 | 9.0843E-08 | 4.8637E-09 |
| | | **$R^2$=0.9838** | |

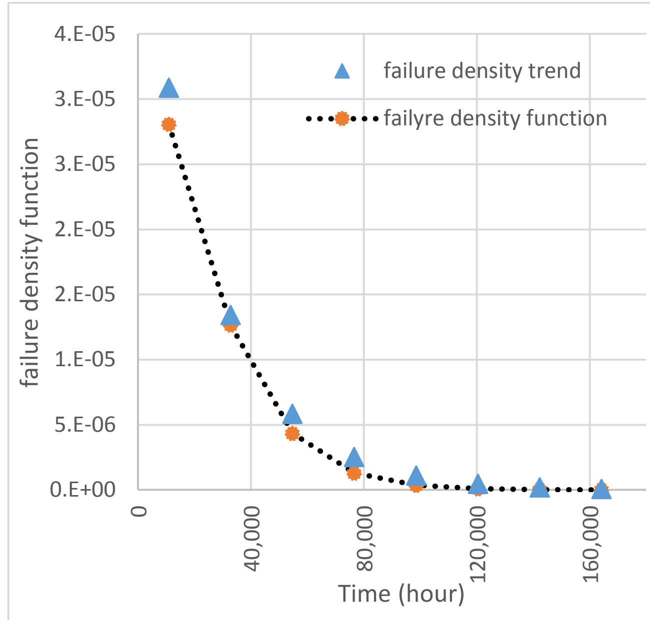



*Figure 86: The modified density function parameters in the pipe with $T_M = 2.5$ years*

| | | | |
|---|---|---|---|
| α | 22000.00 | | |
| β | 1.97 | | |
| λ | | $T_M$=5 | |
| **K** | **time interval** | **$f^*(t)$ (data trend)** | **$f^*(t)$ (function)** |
| 0 | 0-5 | 3.3070E-05 | 3.3091E-05 |
| 1 | 5-10 | 1.1829E-06 | 4.6216E-08 |
| 2 | 10-15 | 4.2315E-08 | 2.3712E-14 |
| 3 | 15-20 | 1.5136E-09 | 7.5080E-24 |
| 4 | 20-25 | 5.4143E-11 | 1.7226E-36 |
| 5 | 25-30 | 1.9367E-12 | 3.1265E-52 |
| | | **$R^2$=0.9986** | |

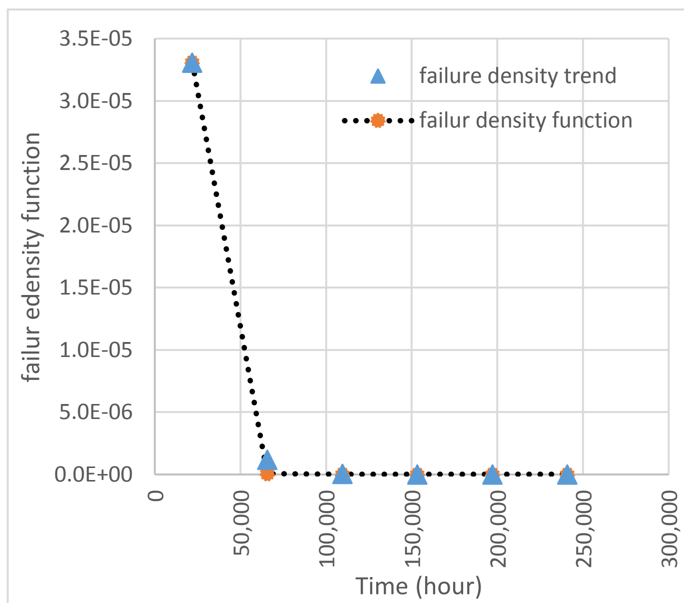



*Figure 87: The modified density function parameters in the pipe with $T_M = 5$ years*

| α | 19800.00 | | |
|---|---|---|---|
| β | 1.16 | | |
| λ | | $T_M$=10 | |
| **K** | **time interval** | **$f^*(t)$ (data trend)** | **$f^*(t)$ (function)** |
| 0 | 0-10 | 5.4401E-06 | 5.3966E-06 |
| 1 | 10-20 | 8.9068E-12 | 9.9512E-09 |
| 2 | 20-30 | 1.4583E-17 | 7.5622E-12 |
| 3 | 30-40 | 2.3875E-23 | 3.4133E-15 |
| | | **$R^2$=0.9999** | |

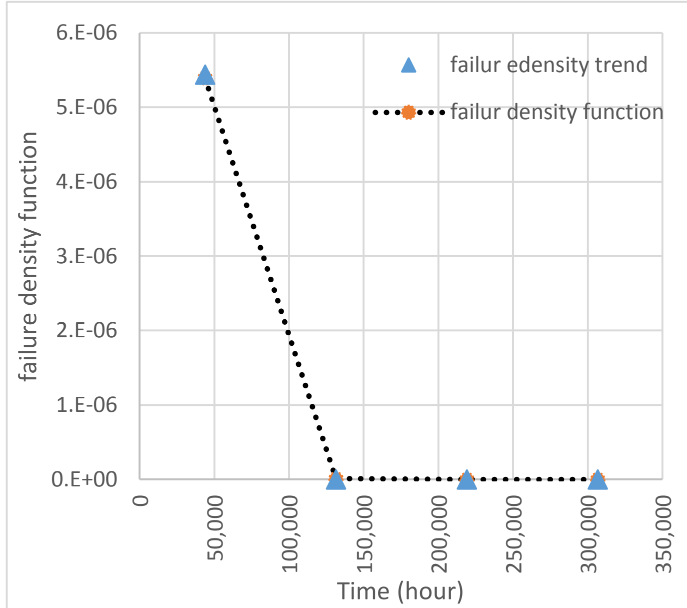



*Figure 88: The modified density function parameters in the pipe with $T_M = 10$ years*

# Pump

| | | | |
|---|---|---|---|
| α | 9240.00 | | |
| β | 1.07 | | |
| λ | | $T_M=1.00$ | |
| K | time interval | $f^*(t)$ (data trend) | $f^*(t)$ (function) |
| 0 | 0-1 | 7.1824E-05 | 7.0086E-05 |
| 1 | 1-2 | 2.8244E-05 | 2.7631E-05 |
| 2 | 2-3 | 1.1107E-05 | 9.9201E-06 |
| 3 | 3-4 | 4.3677E-06 | 3.4111E-06 |
| 4 | 4-5 | 1.7176E-06 | 1.1402E-06 |
| 5 | 5-6 | 6.7542E-07 | 3.7314E-07 |
| 6 | 6-7 | 2.6560E-07 | 1.2007E-07 |
| 7 | 7-8 | 1.0445E-07 | 3.8093E-08 |
| | | $R^2=0.9986$ | |

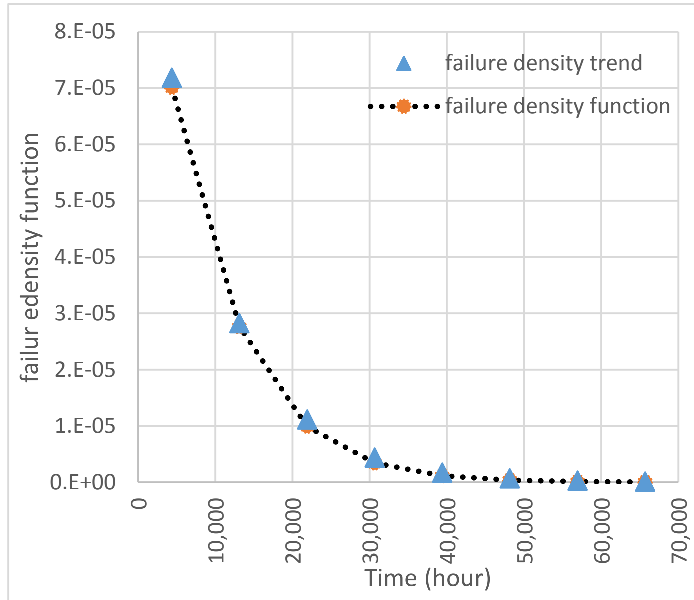



*Figure 89: The modified density function parameters in the pump with $T_M = 1$ year*

| | | | |
|---|---|---|---|
| α | 9300.00 | | |
| β | 1.10 | | |
| λ | | $T_M=1.25$ | |
| K | time interval | $f^*(t)$ (data trend) | $f^*(t)$ (function) |
| 0 | 0-1.25 | 6.5426E-05 | 6.4183E-05 |
| 1 | 1.25-2.5 | 1.9686E-05 | 1.9306E-05 |
| 2 | 2.5-3.75 | 5.9235E-06 | 4.9624E-06 |
| 3 | 3.75-5 | 1.7823E-06 | 1.1815E-06 |
| 4 | 5-6.25 | 5.3629E-07 | 2.6714E-07 |
| 5 | 6.25-7.5 | 1.6137E-07 | 5.8073E-08 |
| 6 | 7.5-8.75 | 4.8554E-08 | 1.2228E-08 |
| 7 | 8.75-10 | 1.4610E-08 | 2.5065E-09 |
| | | $R^2=0.9992$ | |

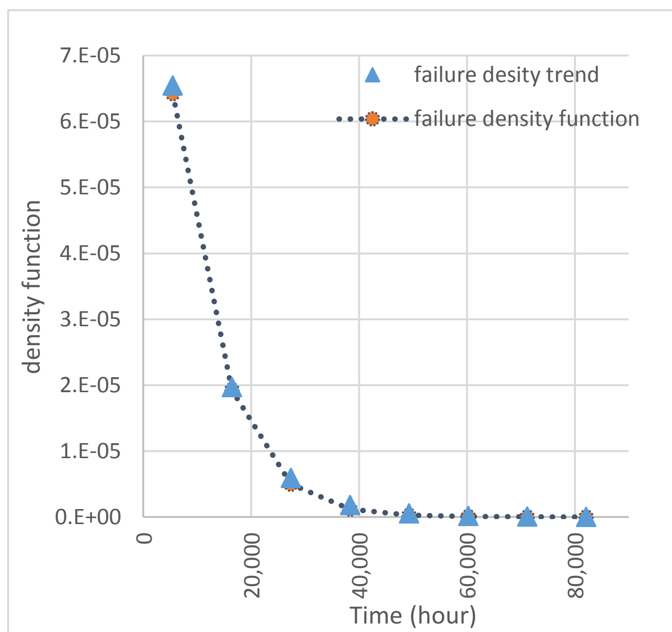



*Figure 90: The modified density function parameters in the pump with $T_M = 1.25$ years*

| α | 9100.00 | | |
|---|---|---|---|
| β | 1.10 | | |
| λ | | $T_M$=2.5 | |
| **K** | **time interval** | **$f^*(t)$ (data trend)** | **$f^*(t)$ (function)** |
| 0 | 0-2.5 | 3.7292E-05 | 3.6144E-05 |
| 1 | 2.5-5 | 2.6920E-06 | 2.2678E-06 |
| 2 | 5-7.5 | 1.9433E-07 | 1.0808E-07 |
| 3 | 7.5-10 | 1.4028E-08 | 4.4462E-09 |
| 4 | 10-12.5 | 1.0127E-09 | 1.6496E-10 |
| 5 | 12.5-15 | 7.3101E-11 | 5.6481E-12 |
| 6 | 15-17.5 | 5.2770E-12 | 1.8104E-13 |
| 7 | 17.5-20 | 3.8093E-13 | 5.4859E-15 |
| | | **$R^2$=0.9987** | |

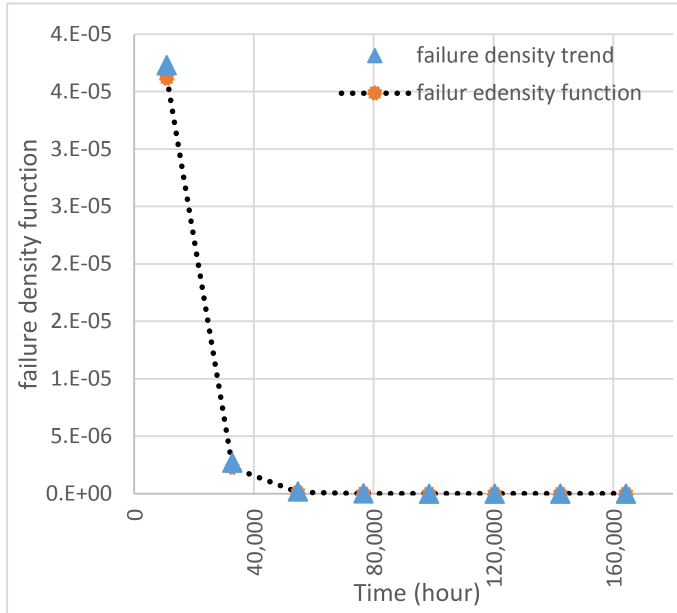



*Figure 91: The modified density function parameters in the pump with $T_M = 2.5$ years*

| α | | | |
|---|---|---|---|
| β | | | |
| λ | 1.16E-04 | $T_M$=5 | |
| **K** | **time interval** | **$f^*(t)$ (data trend)** | **$f^*(t)$ (function)** |
| 0 | 0-5 | 9.7904E-06 | 9.1448E-06 |
| 1 | 5-10 | 3.1077E-08 | 5.6835E-08 |
| 2 | 10-15 | 9.8647E-11 | 3.5322E-10 |
| 3 | 15-20 | 3.1313E-13 | 2.1953E-12 |
| 4 | 20-25 | 9.9396E-16 | 1.3643E-14 |
| 5 | 25-30 | 3.1551E-18 | 8.4793E-17 |
| | | **$R^2$=0.9948** | |

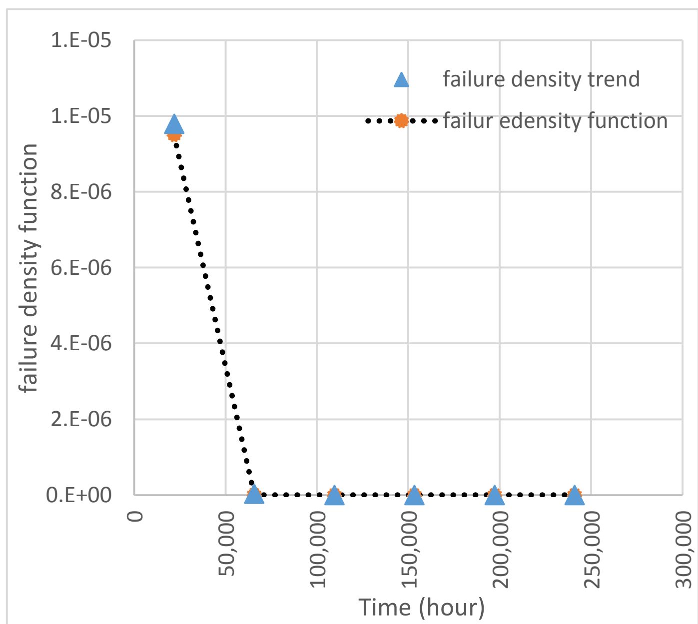



*Figure 92: The modified density function parameters in the pump with $T_M = 5$ years*

| | | | |
|---|---|---|---|
| α | | | |
| β | | | |
| λ | 1.28E-04 | $T_M$=10 | |
| K | time interval | $f^*(t)$ (data trend) | $f^*(t)$ (function) |
| 0 | 0-10 | 4.7110E-07 | 4.7031E-07 |
| 1 | 10-20 | 1.6041E-12 | 6.3493E-12 |
| 2 | 20-30 | 5.4622E-18 | 8.5717E-17 |
| 3 | 30-40 | 1.8599E-23 | 1.1572E-21 |
| | | $R^2$=0.99999 | |

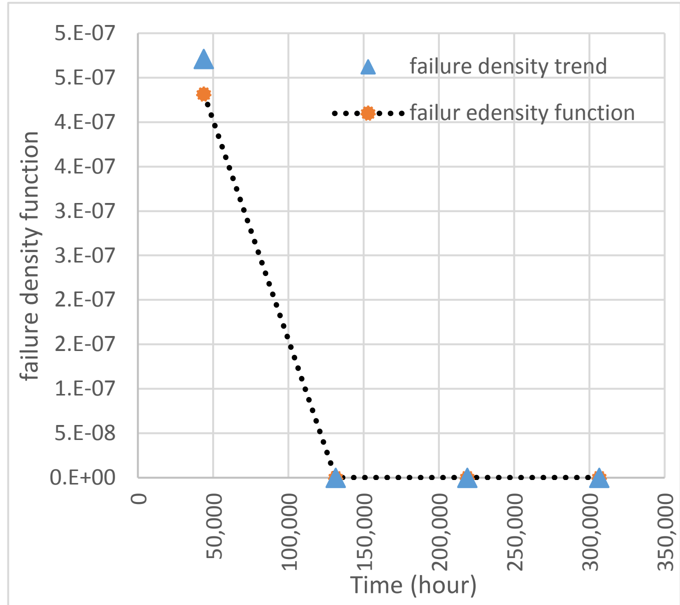



*Figure 93: The modified density function parameters in the pump with $T_M = 10$ years*

| | | | |
|---|---|---|---|
| α | | | |
| β | | | |
| λ | 1.32E-04 | $T_M$=12 | |
| K | time interval | $f^*(t)$ (data trend) | $f^*(t)$ (function) |
| 0 | 0-12 | 1.2937E-07 | 1.2808E-07 |
| 1 | 12-24 | 2.4718E-14 | 1.2058E-13 |
| 2 | 24-36 | 4.7226E-21 | 1.1352E-19 |
| 3 | 36-48 | 9.0230E-28 | 1.0687E-25 |
| | | $R^2$=0.9999 | |

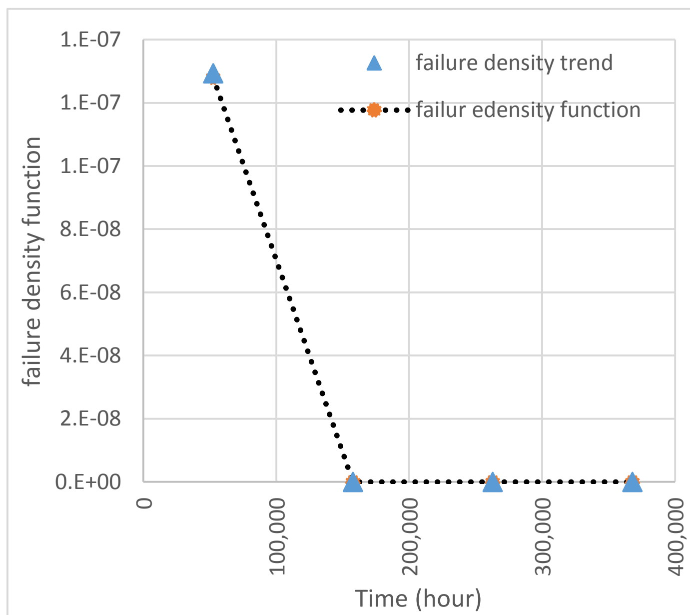



*Figure 94: The modified density function parameters in the pump with $T_M = 12$ years*

## Boiler

| α | 7800.00 | | |
|---|---|---|---|
| β | 1.85 | | |
| λ | | $T_M$=1.00 | |
| K | time interval | $f^*(t)$ (data trend) | $f^*(t)$ (function) |
| 0 | 0-1 | 1.0518E-04 | 1.0297E-04 |
| 1 | 1-2 | 2.8914E-05 | 2.6782E-05 |
| 2 | 2-3 | 7.9485E-06 | 6.6638E-07 |
| 3 | 3-4 | 2.1850E-06 | 2.6041E-09 |
| 4 | 4-5 | 6.0067E-07 | 1.8786E-12 |
| 5 | 5-6 | 1.6512E-07 | 2.7371E-16 |
| 6 | 6-7 | 4.5392E-08 | 8.5610E-21 |
| 7 | 7-8 | 1.2478E-08 | 6.0173E-26 |
| | | $R^2$=0.9928 | |

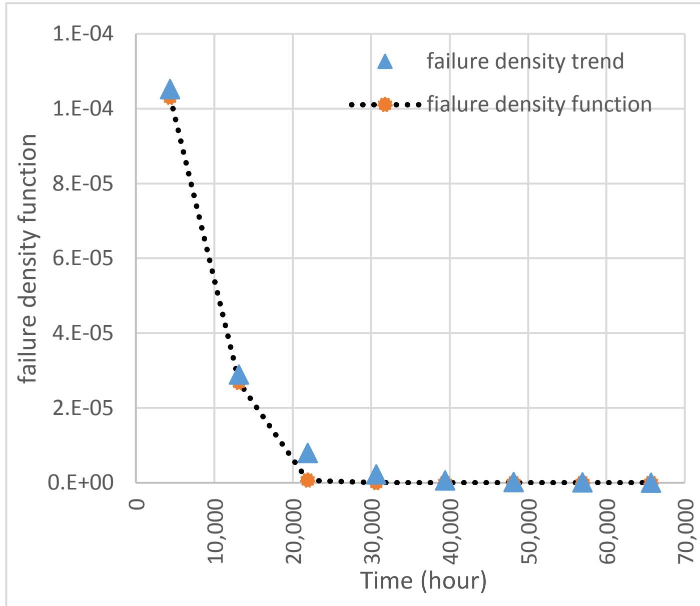



*Figure 95: The modified density function parameters in the boiler with $T_M = 1$ year*

| α | 7720.00 | | |
|---|---|---|---|
| β | 1.82 | | |
| λ | | $T_M$=1.25 | |
| K | time interval | $f^*(t)$ (data trend) | $f^*(t)$ (function) |
| 0 | 0-1.25 | 1.0468E-04 | 1.0416E-04 |
| 1 | 1.25-2.5 | 1.5199E-05 | 8.4184E-06 |
| 2 | 2.5-3.75 | 2.2068E-06 | 2.9859E-08 |
| 3 | 3.75-5 | 3.2043E-07 | 8.3466E-12 |
| 4 | 5-6.25 | 4.6525E-08 | 2.2852E-16 |
| 5 | 6.25-7.5 | 6.7553E-09 | 6.9734E-22 |
| 6 | 7.5-8.75 | 9.8086E-10 | 2.5975E-28 |
| 7 | 8.75-10 | 1.4242E-10 | 1.2664E-35 |
| | | $R^2$=0.9945 | |

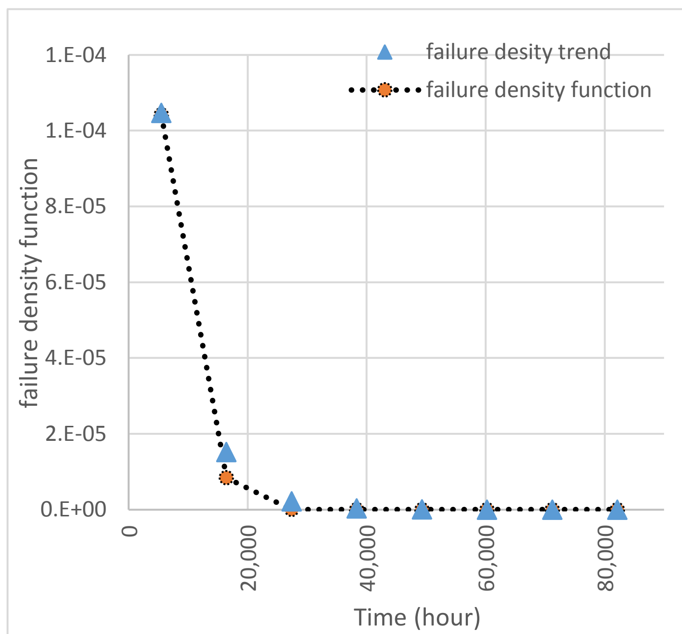



*Figure 96: The modified density function parameters in the boiler with $T_M = 1.25$ years*

| | | | |
|---|---|---|---|
| α | 7510.00 | | |
| β | 1.90 | | |
| λ | | $T_M$=2.5 | |
| **K** | **time interval** | **$f^*$(t) (data trend)** | **$f^*$(t) (function)** |
| 0 | 0-2.5 | 4.6057E-05 | 4.5857E-05 |
| 1 | 2.5-5 | 5.5599E-08 | 6.4636E-11 |
| 2 | 5-7.5 | 6.7118E-11 | 1.8039E-22 |
| 3 | 7.5-10 | 8.1024E-14 | 2.8088E-39 |
| 4 | 10-12.5 | 9.7811E-17 | 3.9590E-61 |
| 5 | 12.5-15 | 1.1807E-19 | 6.9623E-88 |
| 6 | 15-17.5 | 1.4254E-22 | 1.9428E-119 |
| 7 | 17.5-20 | 1.7207E-25 | 1.0425E-155 |
| | | **$R^2$=0.99998** | |

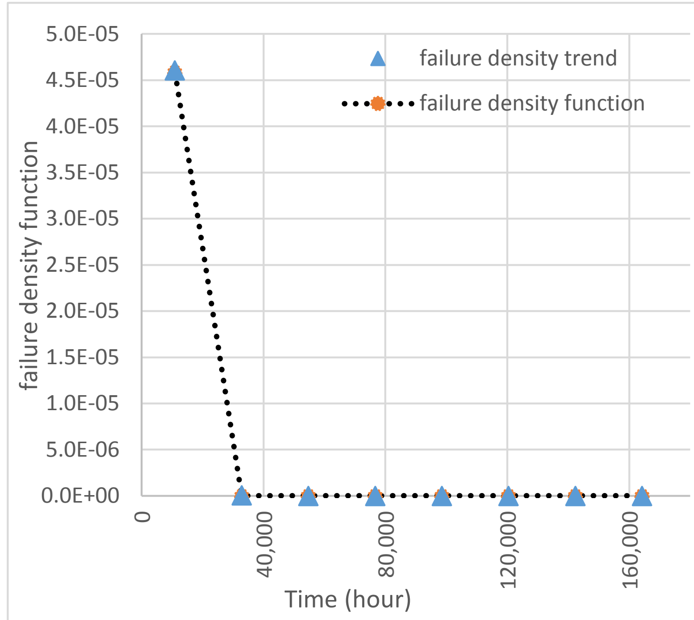



*Figure 97: The modified density function parameters in the boiler with $T_M = 2.5$ years*

| | | | |
|---|---|---|---|
| α | 7000.00 | | |
| β | 1.66 | | |
| λ | | $T_M$=5 | |
| **K** | **time interval** | **$f^*$(t) (data trend)** | **$f^*$(t) (function)** |
| 0 | 0-5 | 6.6671E-07 | 6.5693E-07 |
| 1 | 5-10 | 4.5928E-17 | 1.4082E-21 |
| 2 | 10-15 | 3.1638E-27 | 2.7721E-45 |
| 3 | 15-20 | 2.1795E-37 | 2.1239E-76 |
| 4 | 20-25 | 1.5014E-47 | 4.4008E-114 |
| 5 | 25-30 | 1.0343E-57 | 8.8185E-158 |
| | | **$R^2$=0.9997** | |

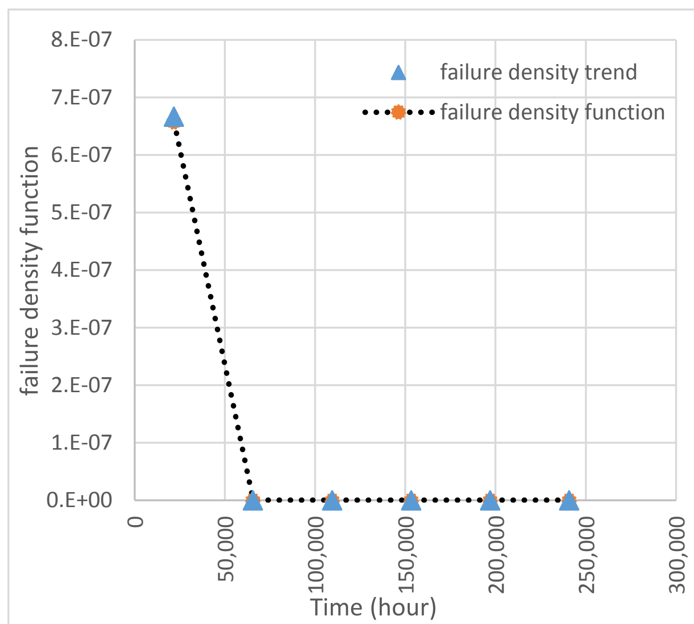



*Figure 98: The modified density function parameters in the boiler with $T_M = 5$ years*

| α | 6130.00 | | |
|---|---|---|---|
| β | 1.60 | | |
| λ | | $T_M$=10 | |
| **K** | **time interval** | **f*(t) (data trend)** | **f*(t) (function)** |
| 0 | 0-10 | 6.6241E-14 | 6.7881E-14 |
| 1 | 10-20 | 2.7257E-49 | 5.6101E-60 |
| 2 | 20-30 | 1.1215E-84 | 3.1984E-135 |
| 3 | 30-40 | 4.6149E-120 | 9.0603E-234 |
| | | **$R^2$=0.9992** | |

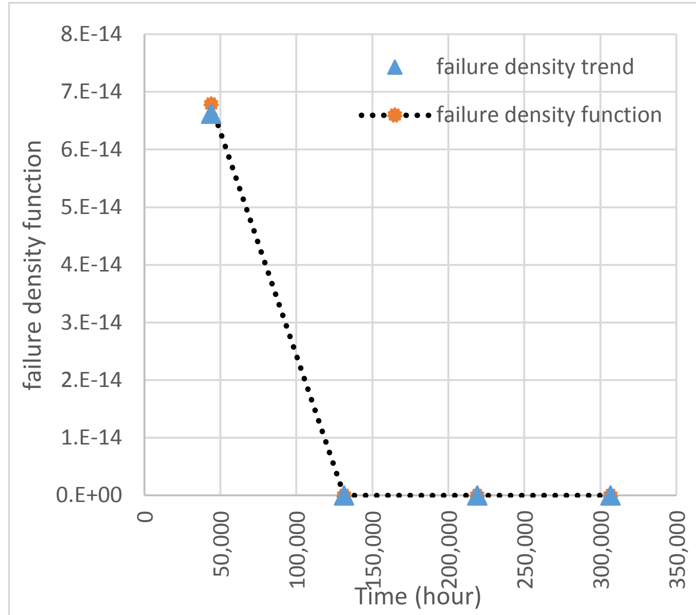



*Figure 99: The modified density function parameters in the boiler with $T_M = 10$ years*

| α | 5900.00 | | |
|---|---|---|---|
| β | 1.59 | | |
| λ | | $T_M$=12 | |
| **K** | **time interval** | **f*(t) (data trend)** | **f*(t) (function)** |
| 0 | 0-12 | 8.6542E-18 | 8.5383E-18 |
| 1 | 12-24 | 6.4042E-67 | 4.2100E-84 |
| 2 | 24-36 | 4.7392E-116 | 5.1535E-185 |
| 3 | 36-48 | 3.5071E-165 | 0.0000E+00 |
| | | **$R^2$=0.9998** | |

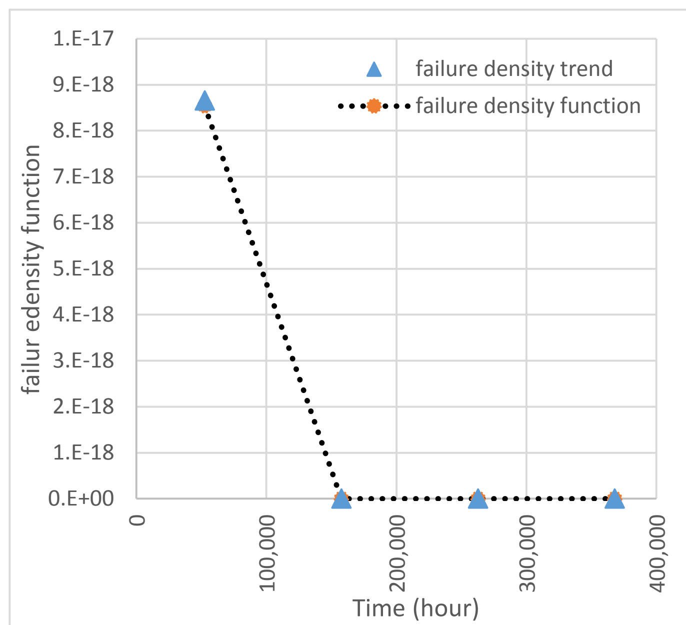



*Figure 100: The modified density function parameters in the boiler with $T_M = 12$ years*

| | | | |
|---|---|---|---|
| α | 5900.00 | | |
| β | 1.61 | | |
| λ | | $T_M$=15 | |
| **K** | **time interval** | **$f^*(t)$ (data trend)** | **$f^*(t)$ (function)** |
| 0 | 0-15 | 1.0980E-24 | 1.0890E-24 |
| 1 | 15-30 | 4.2119E-98 | 1.0236E-126 |
| 2 | 30-45 | 1.6157E-171 | 5.5119E-284 |
| 3 | 45-60 | 6.1975E-245 | 0.0000E+00 |
| | | **$R^2$=0.9999** | |

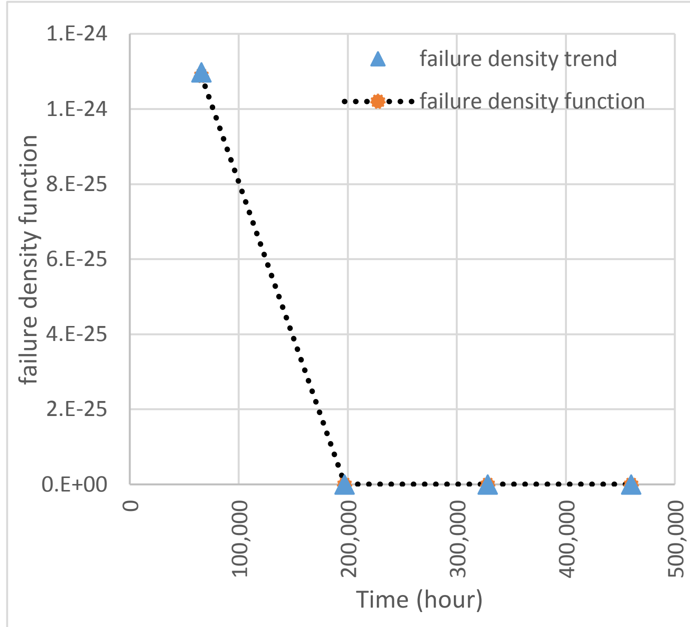



*Figure 101: The modified density function parameters in the boiler with $T_M = 15$ years*

# Check valve

| | | | |
|---|---|---|---|
| α | | | |
| β | | | |
| λ | 2.00E-04 | $T_M$=0.25 | |
| **K** | **time interval** | **$f^*(t)$ (data trend)** | **$f^*(t)$ (function)** |
| 0 | 0-0.25 | 1.4275E-04 | 1.6073E-04 |
| 1 | 0.25-0.5 | 9.6784E-05 | 1.0370E-04 |
| 2 | 0.5-0.75 | 6.5618E-05 | 6.6905E-05 |
| 3 | 0.75-1.00 | 4.4487E-05 | 4.3166E-05 |
| 4 | 1.00-1.25 | 3.0162E-05 | 2.7850E-05 |
| 5 | 1.25-1.50 | 2.0449E-05 | 1.7968E-05 |
| 6 | 1.50-1.75 | 1.3864E-05 | 1.1593E-05 |
| 7 | 1.75-2.00 | 9.3994E-06 | 7.4796E-06 |
| | | **$R^2$=0.9741** | |

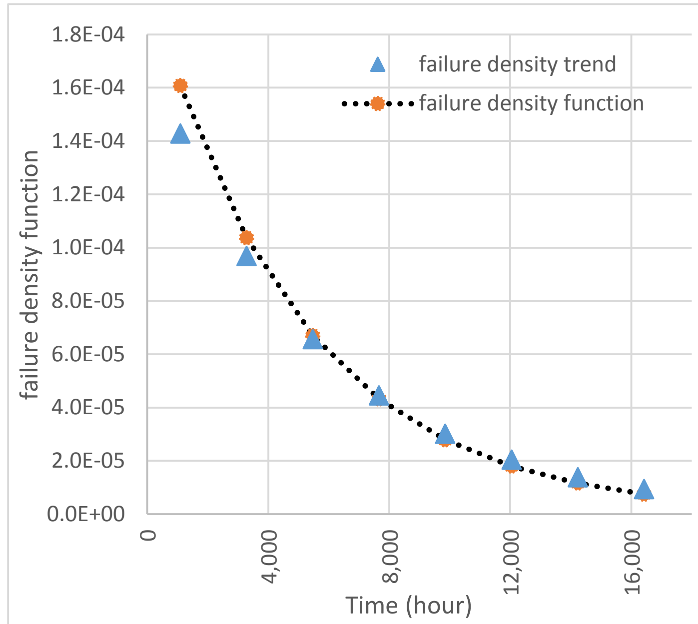



*Figure 102: The modified density function parameters in the check valve with $T_M = 0.25$ year*

| | | | |
|---|---|---|---|
| α | 3230.00 | | |
| β | 3.9 | | |
| λ | | $T_M$=0.5 | |
| **K** | **time interval** | **$f^*(t)$ (data trend)** | **$f^*(t)$ (function)** |
| 0 | 0-0.5 | 3.1282E-04 | 3.1408E-04 |
| 1 | 0.5-1 | 2.9647E-05 | 1.1257E-09 |
| 2 | 1-1.5 | 2.8097E-06 | 7.0664E-53 |
| 3 | 1.5-2 | 2.6628E-07 | 2.8674E-190 |
| 4 | 2-2.5 | 2.5237E-08 | 0.0000E+00 |
| 5 | 2.5-3 | 2.3917E-09 | 0.0000E+00 |
| 6 | 3-3.5 | 2.2667E-10 | 0.0000E+00 |
| 7 | 3.5-4 | 2.1482E-11 | 0.0000E+00 |
| | | **$R^2$=0.9894** | |

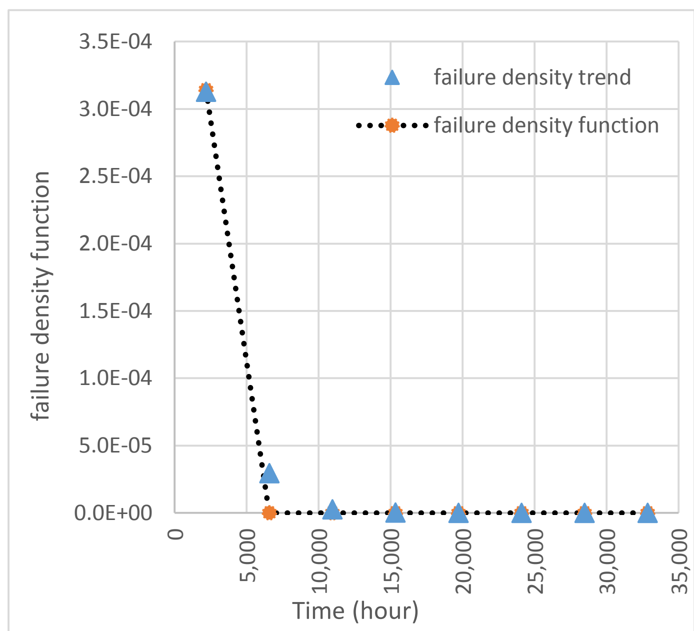



*Figure 103: The modified density function parameters in the check valve with $T_M = 0.50$ year*

| | | | |
|---|---|---|---|
| α | 3180.00 | | |
| β | 3.1 | | |
| λ | | $T_M$=1 | |
| **K** | **time interval** | **$f^*$(t) (data trend)** | **$f^*$(t) (function)** |
| 0 | 0-1 | 1.3256E-04 | 1.2859E-04 |
| 1 | 1-2 | 8.2829E-11 | 9.3805E-38 |
| 2 | 2-3 | 5.1756E-17 | 5.0790E-174 |
| 3 | 3-4 | 3.2340E-23 | 0.0000E+00 |
| 4 | 4-5 | 2.0207E-29 | 0.0000E+00 |
| 5 | 5-6 | 1.2627E-35 | 0.0000E+00 |
| 6 | 6-7 | 7.8897E-42 | 0.0000E+00 |
| 7 | 7-8 | 4.9298E-48 | 0.0000E+00 |
| | | **$R^2$=0.9990** | |

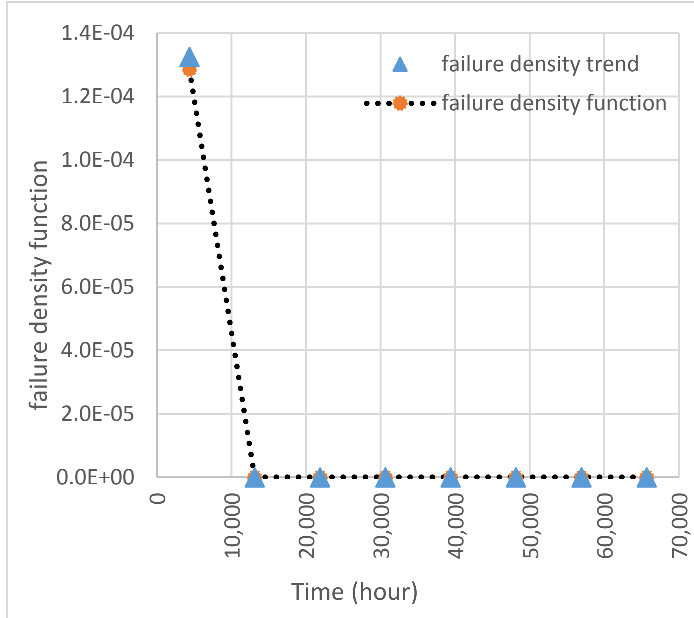



*Figure 104: The modified density function parameters in the check valve with $T_M = 1$ year*

| | | | |
|---|---|---|---|
| α | 3100.00 | | |
| β | 2.49 | | |
| λ | | $T_M$=1.25 | |
| **K** | **time interval** | **$f^*$(t) (data trend)** | **$f^*$(t) (function)** |
| 0 | 0-1.25 | 2.9702E-05 | 3.0397E-05 |
| 1 | 1.25-2.5 | 2.4540E-16 | 2.4225E-30 |
| 2 | 2.5-3.75 | 2.0276E-27 | 6.9826E-101 |
| 3 | 3.75-5 | 1.6752E-38 | 8.6353E-230 |
| 4 | 5-6.25 | 1.3841E-49 | 0.0000E+00 |
| 5 | 6.25-7.5 | 1.1436E-60 | 0.0000E+00 |
| 6 | 7.5-8.75 | 9.4484E-72 | 0.0000E+00 |
| 7 | 8.75-10 | 7.8064E-83 | 0.0000E+00 |
| | | **$R^2$=0.9994** | |

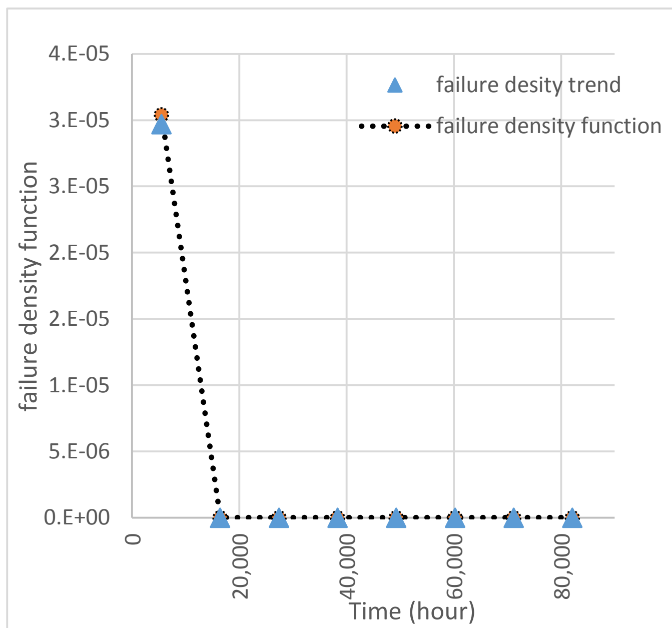



*Figure 105: The modified density function parameters in the check valve with $T_M = 1.25$ years*

| | | | |
|---|---|---|---|
| α | 2800.00 | | |
| β | 2.37 | | |
| λ | | $T_M$=2.5 | |
| **K** | **time interval** | **$f^*(t)$ (data trend)** | **$f^*(t)$ (function)** |
| 0 | 0-2.5 | 5.0064E-14 | 5.4702E-14 |
| 1 | 2.5-5 | 3.2015E-81 | 5.3417E-151 |
| 2 | 5-7.5 | 2.0473E-148 | 0.0000E+00 |
| 3 | 7.5-10 | 1.3093E-215 | 0.0000E+00 |
| 4 | 10-12.5 | 8.3726E-283 | 0.0000E+00 |
| | | **$R^2$=0.9902** | |

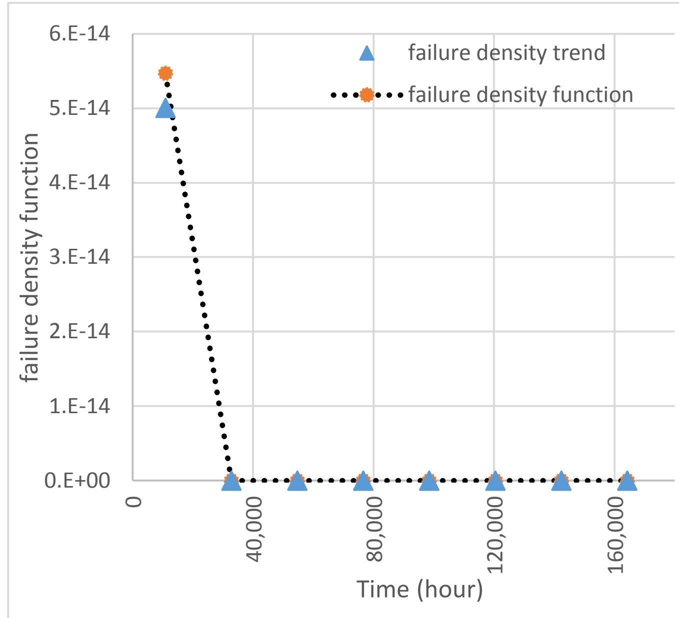



*Figure 106: The modified density function parameters in the check valve with $T_M = 2.5$ years*

# Gate valve

| | | | |
|---|---|---|---|
| α | 9860.00 | | |
| β | 1.15 | | |
| λ | | $T_M=1$ | |
| **K** | **time interval** | **$f^*(t)$ (data trend)** | **$f^*(t)$ (function)** |
| 0 | 0-1 | 6.6694E-05 | 6.9686E-05 |
| 1 | 1-2 | 3.1334E-05 | 3.0289E-05 |
| 2 | 2-3 | 1.4721E-05 | 1.0753E-05 |
| 3 | 3-4 | 6.9159E-06 | 3.4654E-06 |
| 4 | 4-5 | 3.2492E-06 | 1.0462E-06 |
| 5 | 5-6 | 1.5265E-06 | 3.0052E-07 |
| 6 | 6-7 | 7.1715E-07 | 8.2892E-08 |
| 7 | 7-8 | 3.3692E-07 | 2.2092E-08 |
| | | **$R^2$=0.9881** | |

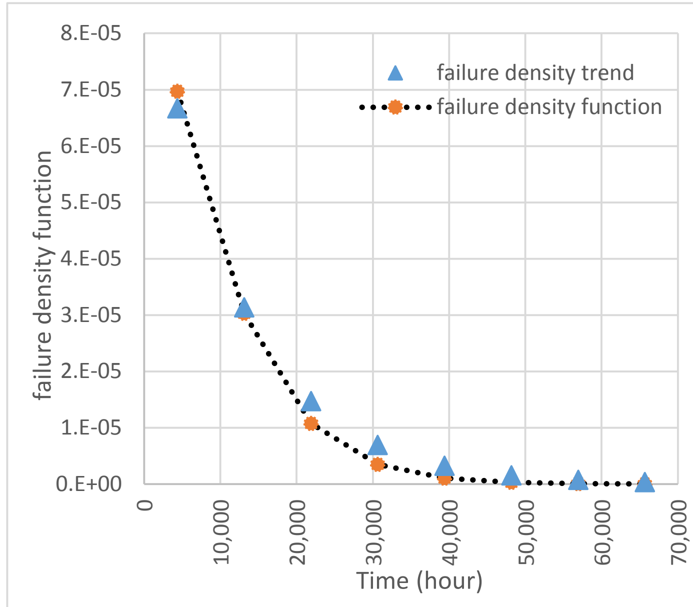



*Figure 107: The modified density function parameters in the gate valve with $T_M = 1$ year*

| | | | |
|---|---|---|---|
| α | 9850.00 | | |
| β | 1.66 | | |
| λ | | $T_M=1.25$ | |
| **K** | **time interval** | **$f^*(t)$ (data trend)** | **$f^*(t)$ (function)** |
| 0 | 0-1.25 | 8.4360E-05 | 7.8434E-05 |
| 1 | 1.25-2.5 | 2.2543E-05 | 2.2822E-05 |
| 2 | 2.5-3.75 | 6.0238E-06 | 1.4125E-06 |
| 3 | 3.75-5 | 1.6097E-06 | 2.9759E-08 |
| 4 | 5-6.25 | 4.3014E-07 | 2.5187E-10 |
| 5 | 6.25-7.5 | 1.1494E-07 | 9.4066E-13 |
| 6 | 7.5-8.75 | 3.0715E-08 | 1.6517E-15 |
| 7 | 8.75-10 | 8.2075E-09 | 1.4293E-18 |
| | | **$R^2$=0.9902** | |

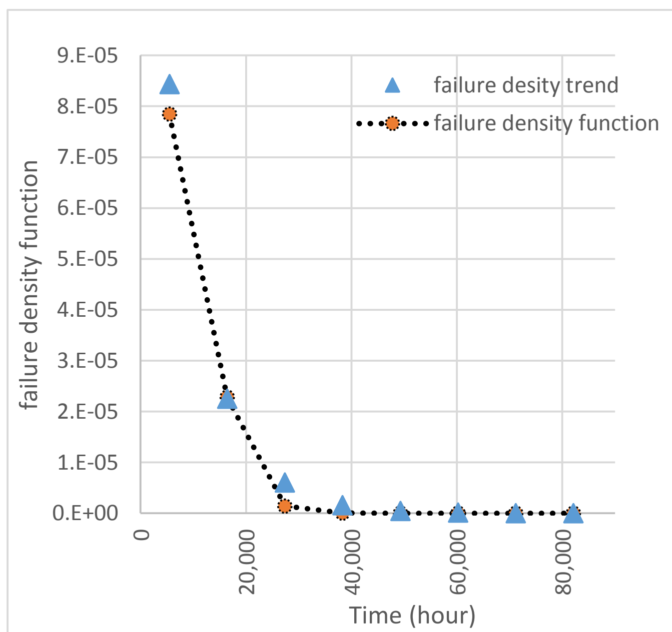



*Figure 108: The modified density function parameters in the gate valve with $T_M = 1.25$ years*

| | | | |
|---|---|---|---|
| **α** | 9500.00 | | |
| **β** | 2.85 | | |
| **λ** | | **$T_M$=2.5** | |
| **K** | **time interval** | **$f^*(t)$ (data trend)** | **$f^*(t)$ (function)** |
| 0 | 0-2.5 | 8.0513E-05 | 8.7140E-05 |
| 1 | 2.5-5 | 4.6104E-08 | 3.6869E-18 |
| 2 | 5-7.5 | 2.6401E-11 | 9.1185E-67 |
| 3 | 7.5-10 | 1.5118E-14 | 2.3955E-169 |
| 4 | 10-12.5 | 8.6571E-18 | 0.0000E+00 |
| 5 | 12.5-15 | 4.9574E-21 | 0.0000E+00 |
| 6 | 15-17.5 | 2.8388E-24 | 0.0000E+00 |
| 7 | 17.5-20 | 1.6256E-27 | 0.0000E+00 |
| | | **$R^2$=0.9923** | |

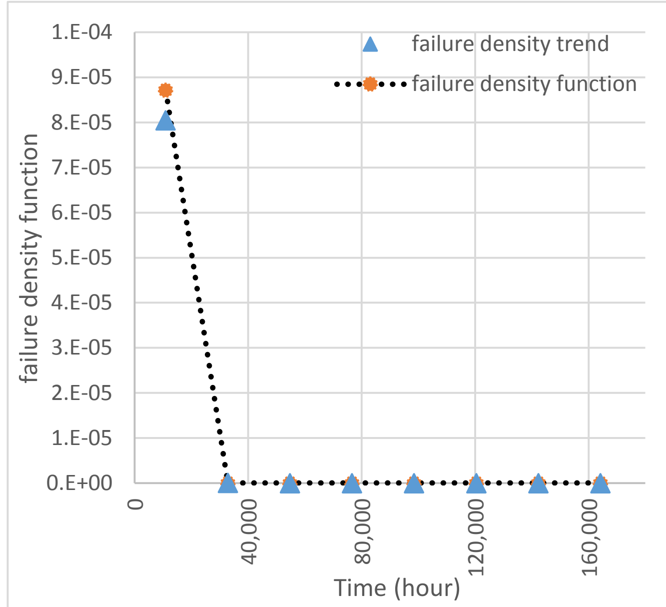



*Figure 109: The modified density function parameters in the gate valve with $T_M = 2.5$ years*

| | | | |
|---|---|---|---|
| **α** | 9190.00 | | |
| **β** | 2.31 | | |
| **λ** | | **$T_M$=5** | |
| **K** | **time interval** | **$f^*(t)$ (data trend)** | **$f^*(t)$ (function)** |
| 0 | 0-5 | 4.8800E-07 | 4.6366E-07 |
| 1 | 5-10 | 2.2295E-25 | 4.7630E-44 |
| 2 | 10-15 | 1.0186E-43 | 7.8626E-136 |
| 3 | 15-20 | 4.6535E-62 | 7.0520E-292 |
| 4 | 20-25 | 2.1260E-80 | 0.0000E+00 |
| 5 | 25-30 | 9.7129E-99 | 0.0000E+00 |
| | | **$R^2$=0.9970** | |

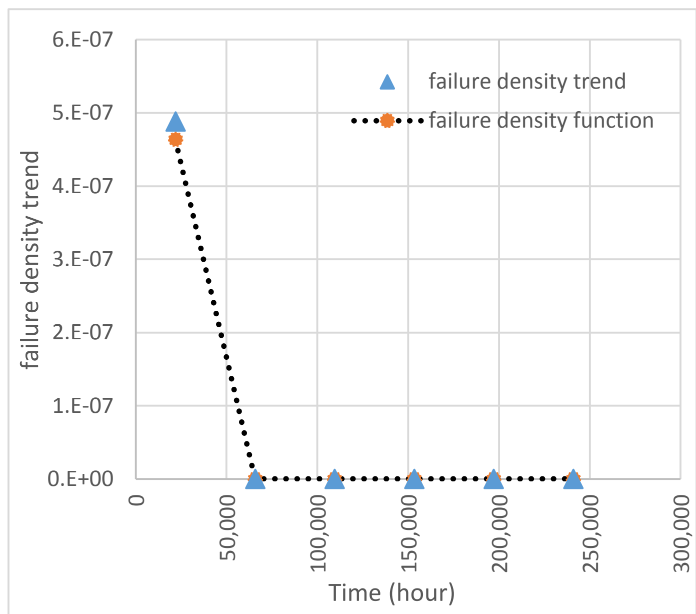



*Figure 110: The modified density function parameters in the gate valve with $T_M = 5$ years*

# Heat exchanger

| α | | | |
|---|---|---|---|
| β | | | |
| λ | 1.07E-06 | $T_M$=1 | |
| **K** | **time interval** | **$f^*(t)$ (data trend)** | **$f^*(t)$ (function)** |
| 0 | 0-1 | 1.0712E-06 | 1.0650E-06 |
| 1 | 1-2 | 1.0596E-06 | 1.0551E-06 |
| 2 | 2-3 | 1.0481E-06 | 1.0452E-06 |
| 3 | 3-4 | 1.0367E-06 | 1.0355E-06 |
| 4 | 4-5 | 1.0255E-06 | 1.0258E-06 |
| 5 | 5-6 | 1.0144E-06 | 1.0162E-06 |
| 6 | 6-7 | 1.0034E-06 | 1.0068E-06 |
| 7 | 7-8 | 9.9254E-07 | 9.9736E-07 |
| | | **$R^2$=0.9799** | |

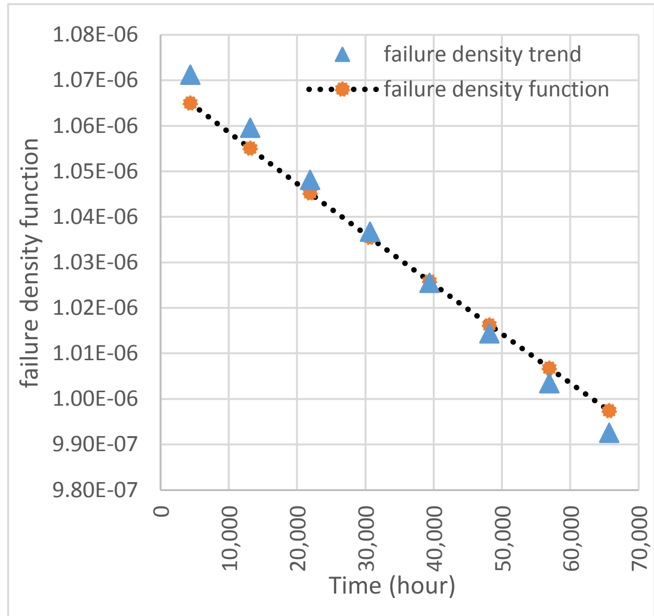



*Figure 111: The modified density function parameters in the heat exchanger with $T_M = 1$ year*

| α | | | |
|---|---|---|---|
| β | | | |
| λ | 1.52E-06 | $T_M$=1.25 | |
| **K** | **time interval** | **$f^*(t)$ (data trend)** | **$f^*(t)$ (function)** |
| 0 | 0-1.25 | 1.5218E-06 | 0.0000E+00 |
| 1 | 1.25-2.5 | 1.4926E-06 | 1.5074E-06 |
| 2 | 2.5-3.75 | 1.4640E-06 | 1.4825E-06 |
| 3 | 3.75-5 | 1.4359E-06 | 1.4581E-06 |
| 4 | 5-6.25 | 1.4084E-06 | 1.4340E-06 |
| 5 | 6.25-7.5 | 1.3813E-06 | 1.4103E-06 |
| 6 | 7.5-8.75 | 1.3548E-06 | 1.3870E-06 |
| 7 | 8.75-10 | 1.3288E-06 | 1.3641E-06 |
| | | **$R^2$=0.9801** | |

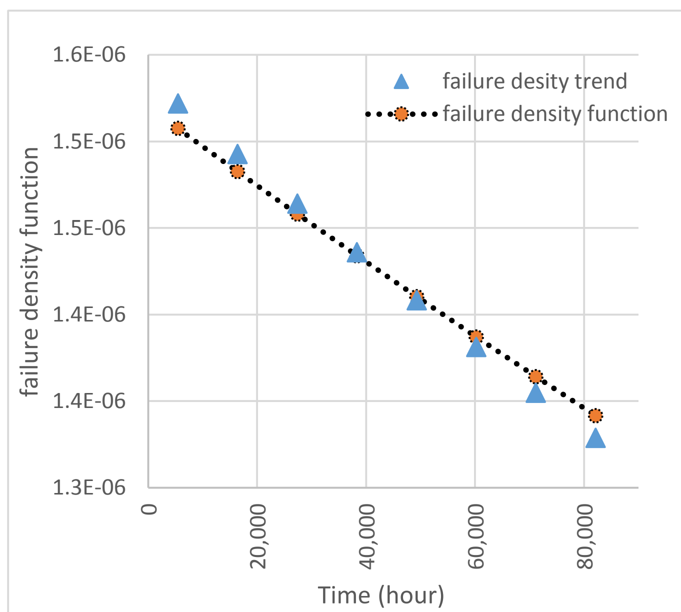



*Figure 112: The modified density function parameters in the heat exchanger with $T_M = 1.25$ years*

| α | | | |
|---|---|---|---|
| β | | | |
| λ | 4.60E-06 | $T_M$=2.5 | |
| **K** | **time interval** | **$f^*(t)$ (data trend)** | **$f^*(t)$ (function)** |
| 0 | 0-2.5 | 4.4770E-06 | 0.0000E+00 |
| 1 | 2.5-5 | 3.9873E-06 | 4.3740E-06 |
| 2 | 5-7.5 | 3.5512E-06 | 3.9549E-06 |
| 3 | 7.5-10 | 3.1627E-06 | 3.5759E-06 |
| 4 | 10-12.5 | 2.8168E-06 | 3.2332E-06 |
| 5 | 12.5-15 | 2.5087E-06 | 2.9233E-06 |
| 6 | 15-17.5 | 2.2343E-06 | 2.6432E-06 |
| 7 | 17.5-20 | 1.9899E-06 | 2.3899E-06 |
| | | **$R^2$=0.9895** | |

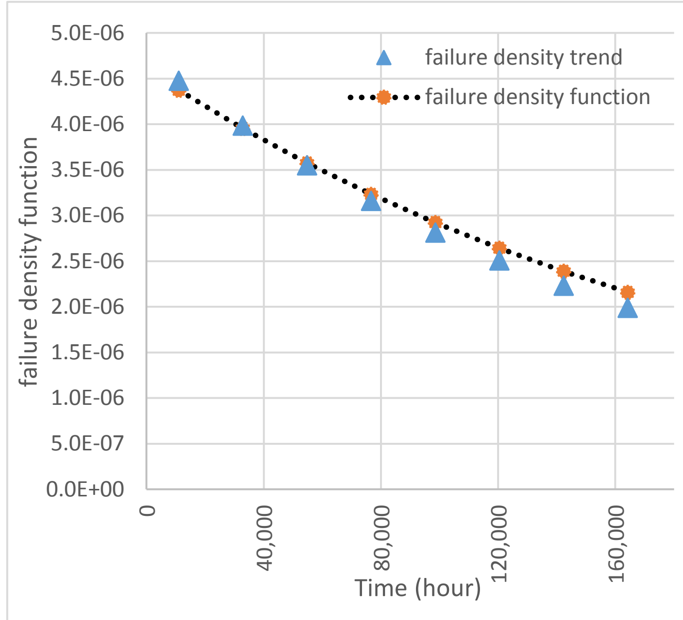



*Figure 113: The modified density function parameters in the heat exchanger with $T_M = 2.5$ years*

| α | 61000.00 | | |
|---|---|---|---|
| β | 1.1 | | |
| λ | | $T_M$=5 | |
| **K** | **time interval** | **$f^*(t)$ (data trend)** | **$f^*(t)$ (function)** |
| 0 | 0-5 | 1.2154E-05 | 1.1772E-05 |
| 1 | 5-10 | 6.0801E-06 | 6.1383E-06 |
| 2 | 10-15 | 3.0416E-06 | 2.8504E-06 |
| 3 | 15-20 | 1.5215E-06 | 1.2569E-06 |
| 4 | 20-25 | 7.6115E-07 | 5.3593E-07 |
| 5 | 25-30 | 3.8077E-07 | 2.2289E-07 |
| | | **$R^2$=0.9967** | |

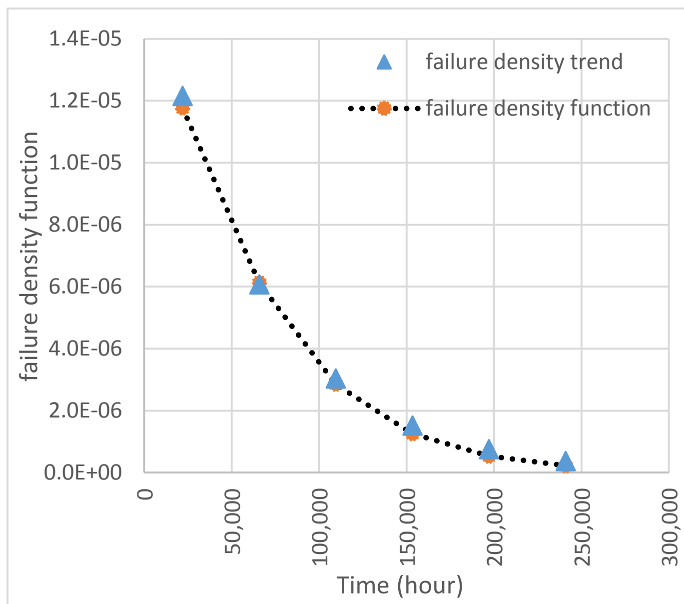



*Figure 114: The modified density function parameters in the heat exchanger with $T_M = 5$ years*

| | | | |
|---|---|---|---|
| α | 45000.00 | | |
| β | 2.4 | | |
| λ | | $T_M$=10 | |
| **K** | **time interval** | **$f^*$(t) (data trend)** | **$f^*$(t) (function)** |
| 0 | 0-10 | 2.0410E-05 | 2.0116E-05 |
| 1 | 10-20 | 3.2446E-07 | 4.9419E-10 |
| 2 | 20-30 | 5.1581E-09 | 2.0828E-23 |
| 3 | 30-40 | 8.2000E-11 | 2.8704E-47 |
| | | **$R^2$=0.9994** | |

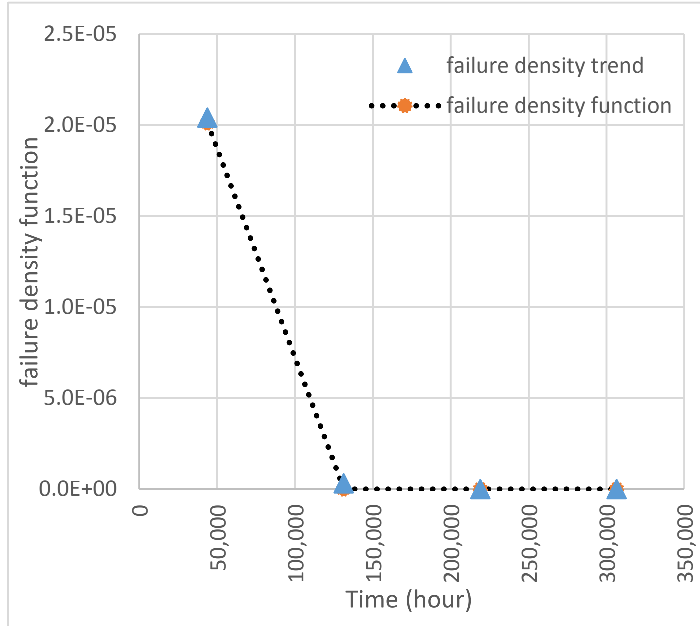



*Figure 115: The modified density function parameters in the heat exchanger with $T_M = 10$ years*

| | | | |
|---|---|---|---|
| α | 42800.00 | | |
| β | 3.6 | | |
| λ | | $T_M$=12 | |
| **K** | **time interval** | **$f^*$(t) (data trend)** | **$f^*$(t) (function)** |
| 0 | 0-12 | 1.7959E-05 | 1.7661E-05 |
| 1 | 12-24 | 2.3729E-08 | 8.1184E-51 |
| 2 | 24-36 | 3.1354E-11 | 1.8715E-301 |
| 3 | 36-48 | 4.1428E-14 | 0.0000E+00 |
| | | **$R^2$=0.9996** | |

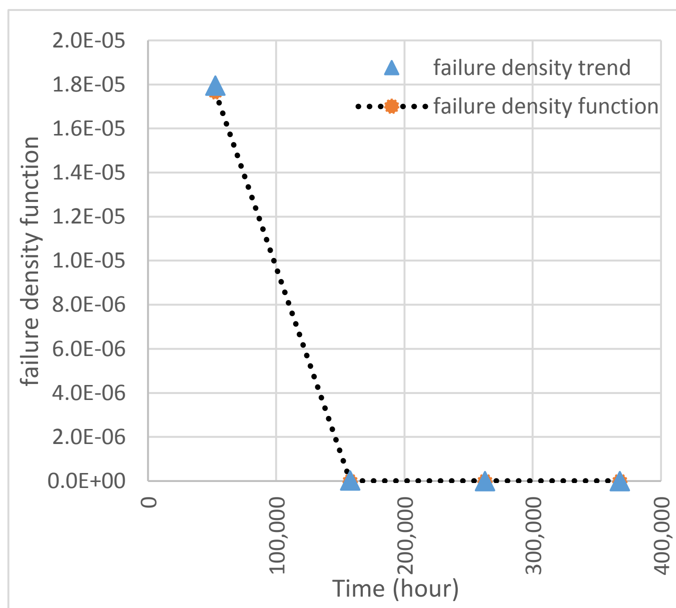



*Figure 116: The modified density function parameters in the heat exchanger with $T_M = 12$ years*

# Appendix E

## Heat transfer system (standby)

| | | | |
|---|---|---|---|
| **α** | 32300.00 | | |
| **β** | 1.00 | | |
| **λ** | | **$T_M$=1.00** | |
| **K** | **time interval** | **$f^*(t)$ (data trend)** | **$f^*(t)$ (function)** |
| 0 | 0-1 | 2.6575E-05 | 2.7034E-05 |
| 1 | 1-2 | 1.9911E-05 | 2.0612E-05 |
| 2 | 2-3 | 1.4919E-05 | 1.5716E-05 |
| 3 | 3-4 | 1.1178E-05 | 1.1983E-05 |
| 4 | 4-5 | 8.3753E-06 | 9.1363E-06 |
| 5 | 5-6 | 6.2753E-06 | 6.9660E-06 |
| 6 | 6-7 | 4.7018E-06 | 5.3113E-06 |
| 7 | 7-8 | 3.5229E-06 | 4.0497E-06 |
| | | **$R^2$=0.9919** | |

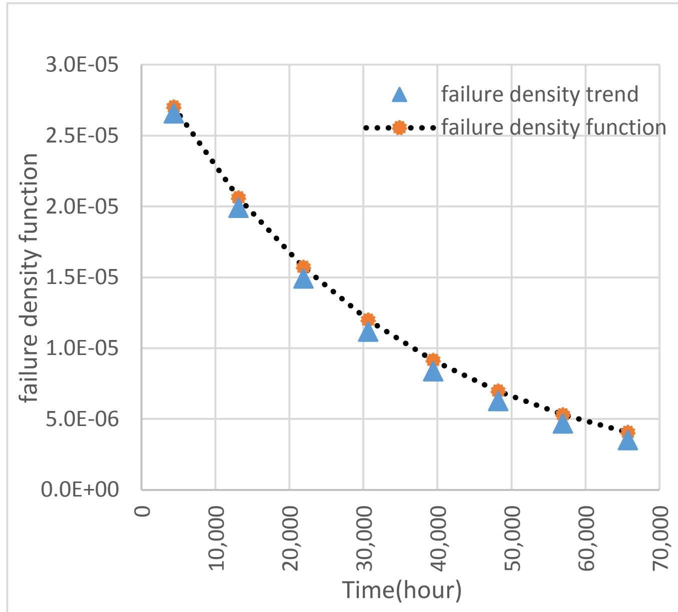



*Figure 117: The modified density function parameters in the heat transfer system (standby) with $T_M = 1$ year*

| | | | |
|---|---|---|---|
| **α** | 21300.00 | | |
| **β** | 1.01 | | |
| **λ** | | **$T_M$=1.25** | |
| **K** | **time interval** | **$f^*(t)$ (data trend)** | **$f^*(t)$ (function)** |
| 0 | 0-1.25 | 3.7005E-05 | 3.6301E-05 |
| 1 | 1.25-2.5 | 2.1968E-05 | 2.1917E-05 |
| 2 | 2.5-3.75 | 1.3042E-05 | 1.3106E-05 |
| 3 | 3.75-5 | 7.7425E-06 | 7.8067E-06 |
| 4 | 5-6.25 | 4.5964E-06 | 4.6391E-06 |
| 5 | 6.25-7.5 | 2.7287E-06 | 2.7522E-06 |
| 6 | 7.5-8.75 | 1.6199E-06 | 1.6306E-06 |
| 7 | 8.75-10 | 9.6169E-07 | 9.6510E-07 |
| | | **$R^2$=0.9995** | |

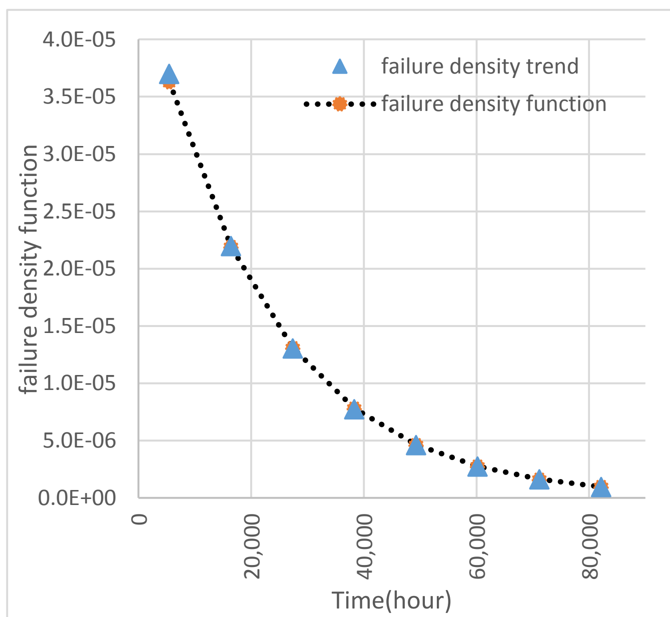



*Figure 118: The modified density function parameters in the heat transfer system (standby) with $T_M = 1.25$ years*

| α | 15570.00 | | |
|---|---|---|---|
| β | 3.91 | | |
| λ | | $T_M$=2.5 | |
| **K** | **time interval** | **$f^*(t)$ (data trend)** | **$f^*(t)$ (function)** |
| 0 | 0-2.5 | 7.4917E-05 | 7.0043E-05 |
| 1 | 2.5-5 | 2.8390E-06 | 1.9828E-11 |
| 2 | 5-7.5 | 1.0758E-07 | 4.9439E-62 |
| 3 | 7.5-10 | 4.0768E-09 | 2.6383E-223 |
| 4 | 10-12.5 | 1.5449E-10 | 0.0000E+00 |
| 5 | 12.5-15 | 5.8545E-12 | 0.0000E+00 |
| 6 | 15-17.5 | 2.2186E-13 | 0.0000E+00 |
| 7 | 17.5-20 | 8.4072E-15 | 0.0000E+00 |
| | | $R^2$=0.9935 | |

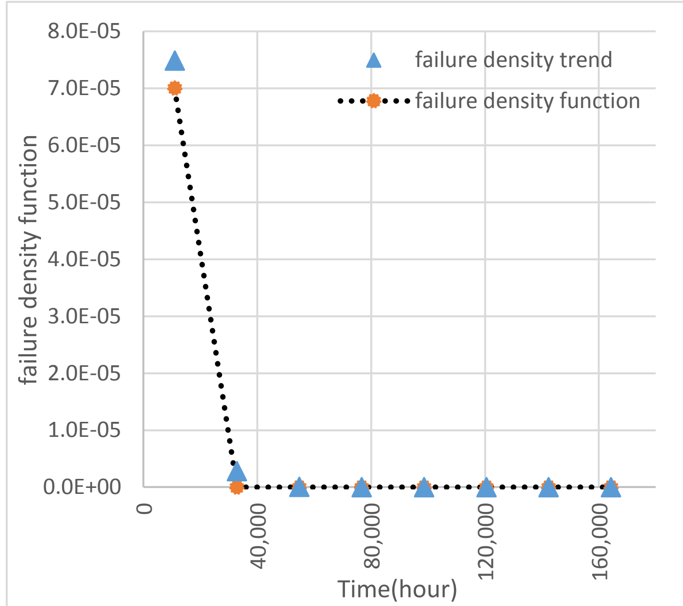



*Figure 119: The modified density function parameters in the heat transfer system (standby) with $T_M = 2.5$ years*

| α | 13500.00 | | |
|---|---|---|---|
| β | 2.27 | | |
| λ | | $T_M$=5 | |
| **K** | **time interval** | **$f^*(t)$ (data trend)** | **$f^*(t)$ (function)** |
| 0 | 0-5 | 1.5008E-05 | 1.5494E-05 |
| 1 | 5-10 | 1.7970E-14 | 2.1361E-19 |
| 2 | 10-15 | 2.1516E-23 | 1.2591E-53 |
| 3 | 15-20 | 2.5762E-32 | 4.4102E-111 |
| 4 | 20-25 | 3.0847E-41 | 6.0024E-194 |
| 5 | 25-30 | 3.6934E-50 | 5.3113E-304 |
| | | $R^2$=0.9987 | |

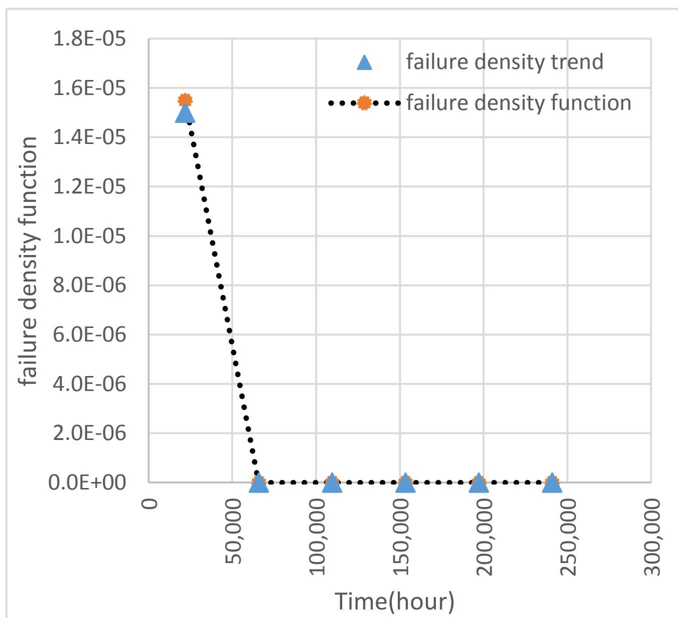



*Figure 120: The modified density function parameters in the heat transfer system (standby) with $T_M = 5$ years*

| α | 11670.00 | | |
|---|---|---|---|
| β | 2.28 | | |
| λ | | $T_M$=10 | |
| K | time interval | $f^*(t)$ (data trend) | $f^*(t)$ (function) |
| 0 | 0-10 | 1.4882E-12 | 1.4666E-12 |
| 1 | 10-20 | 1.4914E-68 | 1.5107E-111 |
| 2 | 20-30 | 1.4945E-124 | 0.0000E+00 |
| 3 | 30-40 | 1.4977E-180 | 0.0000E+00 |
| | | $R^2$=0.9997 | |

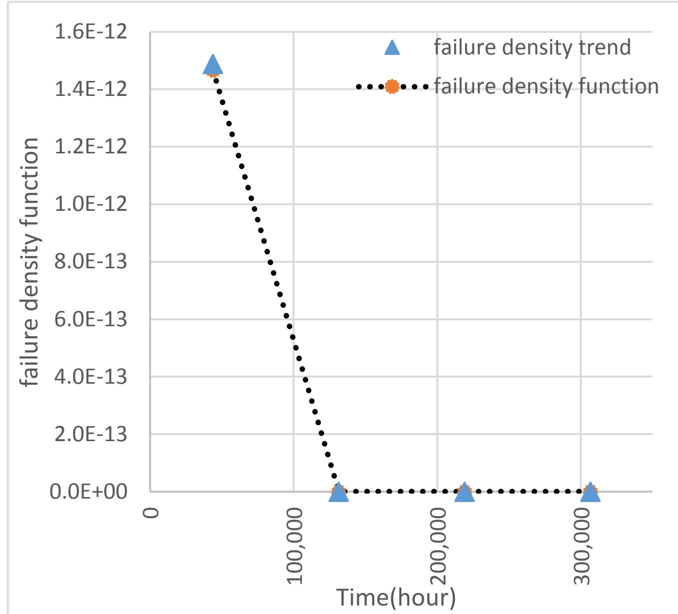



*Figure 121: The modified density function parameters in the heat transfer system (standby) with $T_M = 10$ years*

| α | 11320.00 | | |
|---|---|---|---|
| β | 2.28 | | |
| λ | | $T_M$=12 | |
| K | time interval | $f^*(t)$ (data trend) | $f^*(t)$ (function) |
| 0 | 0-12 | 5.7718E-18 | 5.8347E-18 |
| 1 | 12-24 | 9.4824E-109 | 3.9172E-179 |
| 2 | 24-36 | 1.5578E-199 | 0.0000E+00 |
| 3 | 36-48 | 2.5593E-290 | 0.0000E+00 |
| | | $R^2$=0.9998 | |

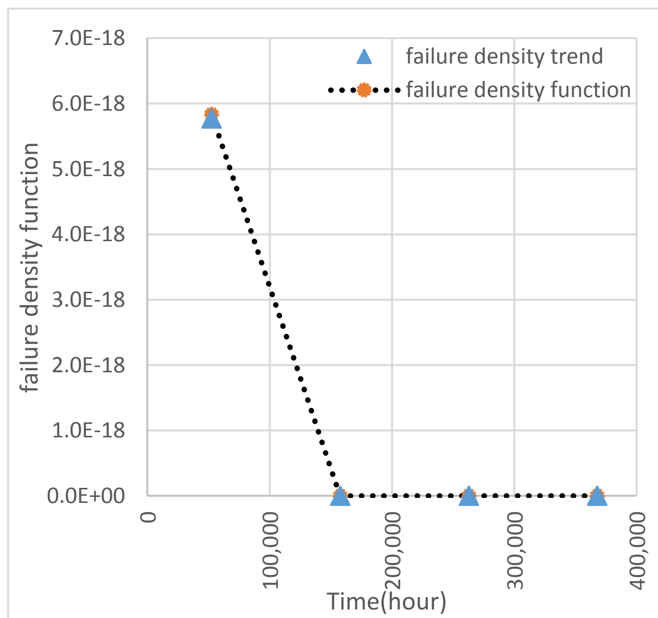



*Figure 122: The modified density function parameters in the heat transfer system (standby) with $T_M = 12$ years*

# Appendix F

## Tube bundle and baffle plates

| | | | |
|---|---|---|---|
| α | 83100.00 | | |
| β | 1.01 | | |
| λ | | $T_M$=2.5 | |
| **K** | **time interval** | **$f^*$(t) (data trend)** | **$f^*$(t) (function)** |
| 0 | 0-2.5 | 1.0546E-05 | 1.0467E-05 |
| 1 | 2.5-5 | 7.6540E-06 | 8.1395E-06 |
| 2 | 5-7.5 | 5.5550E-06 | 6.2801E-06 |
| 3 | 7.5-10 | 4.0315E-06 | 4.8318E-06 |
| 4 | 10-12.5 | 2.9259E-06 | 3.7114E-06 |
| 5 | 12.5-15 | 2.1235E-06 | 2.8477E-06 |
| 6 | 15-17.5 | 1.5412E-06 | 2.1832E-06 |
| 7 | 17.5-20 | 1.1185E-06 | 1.6727E-06 |
| | | **$R^2$=0.9571** | |

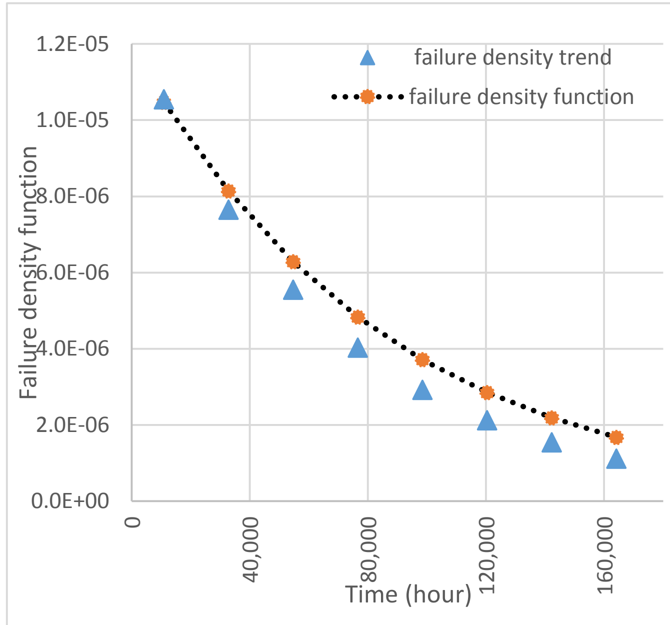



*Figure 123: The modified density function parameters in the tube bundle (heat exchanger) with $T_M = 2.5$ years*

| | | | |
|---|---|---|---|
| α | 71700.00 | | |
| β | 1.01 | | |
| λ | | $T_M$=2.5 | |
| **K** | **time interval** | **$f^*$(t) (data trend)** | **$f^*$(t) (function)** |
| 0 | 0-2.5 | 1.1880E-05 | 1.1900E-05 |
| 1 | 2.5-5 | 8.2637E-06 | 8.8712E-06 |
| 2 | 5-7.5 | 5.7481E-06 | 6.5599E-06 |
| 3 | 7.5-10 | 3.9982E-06 | 4.8362E-06 |
| 4 | 10-12.5 | 2.7811E-06 | 3.5592E-06 |
| 5 | 12.5-15 | 1.9345E-06 | 2.6163E-06 |
| 6 | 15-17.5 | 1.3456E-06 | 1.9214E-06 |
| 7 | 17.5-20 | 9.3596E-07 | 1.4101E-06 |
| | | **$R^2$=0.9673** | |

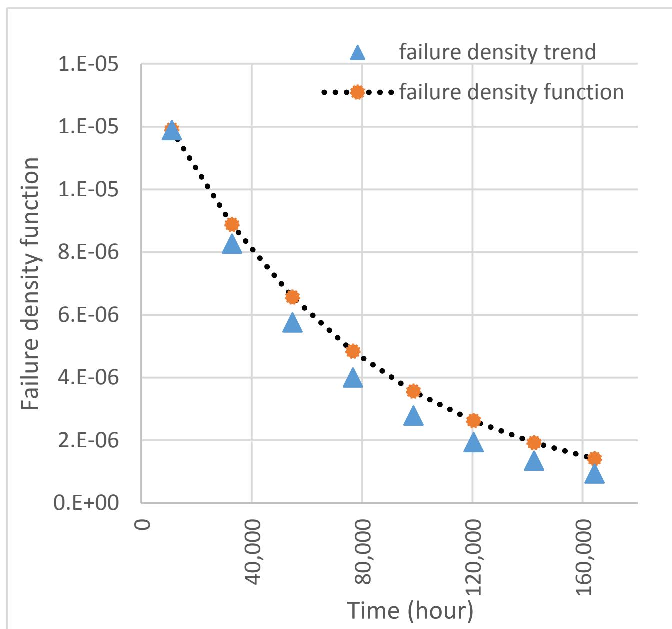



*Figure 124: The modified density function parameters in the baffle plates (heat exchanger) with $T_M = 2.5$ years*

# Appendix G

## Incomplete Gamma function Analysis (DHW)-case study (APENDIX)

The mathematical method for solving incomplete Gamma function with the assumption of $\beta = 3$ is illustrated as follows:

$$\int_{T}^{\infty} t^3 e^{-\lambda t} dt = \frac{1}{\lambda^3} \int_{T}^{\infty} (\lambda t)^3 e^{-\lambda t} dt$$

$$\lambda t = u \to dt = \frac{du}{\lambda}$$

$$\int_{T}^{\infty} t^3 e^{-\lambda t} dt = \frac{1}{\lambda^4} \int_{\lambda T}^{\infty} u^3 e^{-u} du$$

$$\int_{\lambda T}^{\infty} u^3 e^{-u} du = \Gamma(4, \lambda T) = 3\Gamma(3, \lambda T) + (\lambda T)^3 e^{-\lambda T}$$

$$\Gamma(3, \lambda T) = 2\Gamma(2, \lambda T) + (\lambda T)^2 e^{-\lambda T}$$

$$\Gamma(2, \lambda T) = \Gamma(1, \lambda T) + (\lambda T)^1 e^{-\lambda T}$$

$$\Gamma(1, \lambda T) = e^{-\lambda T}$$

$$\frac{1}{\lambda^4} \int_{\lambda T}^{\infty} u^3 e^{-u} du = \frac{1}{\lambda^4}\left((\lambda T)^3 e^{-\lambda T} + 3(\lambda T)^2 e^{-\lambda T} + 6(\lambda T)^1 e^{-\lambda T} + 6e^{-\lambda T}\right)$$

$$\int_{0}^{\infty} t^3 e^{-\lambda t} dt = \frac{1}{\lambda^4} \int_{0}^{\infty} u^3 e^{-u} du = \frac{1}{\lambda^4} \Gamma(4)$$

$$\int_{T}^{\infty} t^3 e^{-\lambda t} dt = \frac{1}{\lambda^4} (\Gamma(4) - (\lambda T)^3 e^{-\lambda T} - 3(\lambda T)^2 e^{-\lambda T} - 6(\lambda T)^1 e^{-\lambda T} - 6e^{-\lambda T})$$