INSPECTION OPTIMIZATION BASED ON RISK BASED APPROACH

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INSPECTION OPTIMIZATION BASED ON RISK BASED APPROACH

By

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ABSTRACT

The American Society of Mechanical Engineers has issued guidelines for methods using risk based information to develop optimization of inspection and maintenance. These guidelines have been applied to a thermal power plant data to develop optimization of maintenance and inspection.

The optimization of maintenance and inspection is becoming increasingly important especially in oil fired thermal power plants as the fuel cost is on the rise. High production impact components such as, waterwall tubes, superheater tubes, reheater, forced draft fan, boiler feed pump, and condenser have been considered for developing component replacement optimization. An optimized inspection program has been developed for waterwall tubes. The financial implications of both maintenance optimization through component replacement and inspection optimization have been calculated in terms of Net Present Value for presentation to the corporate office. A link between the Engineering world and corporate world is established.

This work begins at the analysis of field data of each component using Least Squares Approach to obtain Shape Factor and Characteristic Life for Weibull distribution. With the aid of Weibull distribution, probability of failure is calculated. Time ordered influence diagram is drawn for maintenance optimization. A decision

model is developed to determine the maximum Net Present Value for the Optimization of Inspection.

This work further demonstrates the application of ASME guidelines, Volume 3, (1994) 'Fossil fuel fired electric power generating station applications, Risk based inspection' to field data Weibull reliability model using Excel spreadsheets. This work has established a simple easy to use means of developing maintenance and inspection optimization.

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NOMENCLATURE

a	intercept
β	shape parameter
C_A	alternate case cost
C_B	base case cost
C_P	project cost
$\Gamma(x)$	gamma function
λ	hazard rate
NPV	Net Present Value
σ	standard deviation
σ^2	variance
r^2	regression coefficient
θ	characteristic life
z	standardized normal variate
f(t)	probability density function
F (t)	cumulative distribution function
R (t)	reliability function
$R_S(t)$	component reliability for S spares
$\lambda(t)$	hazard rate function
C	carbon
CH_4	methane

Fe	iron
Fe_3C	iron carbide
Fe_3O_4	magnetite
H_2	hydrogen
H_2O	water
Na	sodium
NaOH	sodium hydroxide
O_2	oxygen
OH	hydroxide

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Chapter 1

INTRODUCTION

1.1 BACKGROUND

The application of Risk Assessment to the field of engineering is not a new practice. Mechanical Engineers in the 19th century evaluated the reliability and safety of operating boilers. Boiler codes were developed after studying the causes and effects of boiler related accidents. Those mechanical engineers were in effect performing qualitative and quantitative risk assessment. The formal risk assessment came into existence after the nuclear power industry started to conduct risk assessments to their plants. The nuclear industry in the United States has been using probabilistic risk assessment (PRA) following the U.S. Nuclear Regulatory Commission (NRC) Reactor Safety Study (WASH-1400) (1975). This study identifies seven basic tasks in reactor safety. This has become the model for other industrial risk assessments. Figure1.1 describes the seven steps to be followed in the risk assessment of nuclear reactors. When this study was done its results were contested because of its societal implications. However the methodology used in the study has not been questioned so far. No uniform terminology for risk assessment existed prior to 1984 because of the interdisciplinary nature of the discipline. The National Academy of Sciences in the United States and the Royal Society in the United Kingdom were two organizations among others, who attempted to develop a consensus on the objectives, the process, and the terminology used in risk assessment.

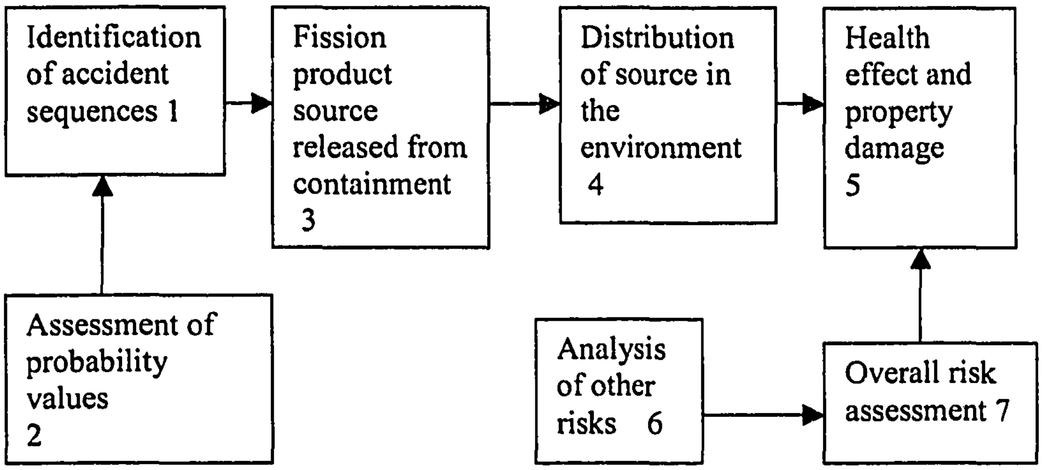


Figure 1.1: Seven Basic Tasks in Reactor Safety Study (Rasmussan, 1975)

Probabilistic structural mechanics (PSM) provide tools for assessing the risk and reliability of components and structures. PSM established the nondestructive examination criteria. PSM deals with the application of microscopic assessment of components to address the mechanistic uncertainties such as stress, load and material properties. PRA and PSM need to be applied together in evaluating the risk of a component. The inspection of boiler tubes will require PSM established methods such as, ultrasonic thickness measurement, ultrasonic flaw detection, and low frequency electromagnetic thickness measurement.

The American Society of Mechanical Engineers recognizing the need for developing risk based codes and standards, formed a Risk Analysis Task Force in 1985. This task force recommended a research program to determine how can risk based methods be used to develop inspection requirements and guidelines for the maintenance of systems and components. The Task Force members put in place a work plan in 1988. The guidelines developed by ASME in 1991 are comprised of the following documents:

1. Volume-1 General Document Risk Based Inspection Development of Guidelines
2. Volume-2 Light Water Reactor Nuclear Power Plant risk Based In-service Testing.
3. Volume-3 Fossil Fuel Fired Electric Power Generating Station Applications Risk Based Inspections
4. Risk Based Methods for Equipment Life Management An Application Handbook

Other Societies were also developing Risk Based Inspection Codes. The American Petroleum Institute in May, 1993 initiated a Risk Based Inspection Project. API issued the following documents:

a. Risk Based Inspection Base Resource Document API 581 in May, 2000
b. Risk Based Inspection API Recommended Practice 580 in May, 2001

1.2 OBJECTIVES

The main objective of this work is to develop an optimal maintenance inspection plan for an actual industrial plant using risk based approach. A thermal power plant is used as a case study to illustrate the methodology.

1.3 METHODOLOGY

The guidelines developed by the ASME and the API will be used as the main tools to develop the optimal maintenance policy. Risk is will be measured in terms of the net present value. This will make the results more easy to understand and appreciate for people in the industry.

The methodology consists of the following steps:

Step-1: Obtaining Failure Data

Step-2: Ranking Failure Data

Step-3: Evaluating the constants, 'Shape Factor' and 'Characteristic Life' for Weibull distribution

Step-4: Evaluating the failure rate and consequences

Step-5: Estimate cost/benefit analysis for replacement of defective component

Step-6: Inspection development and optimization.

1.4 SCOPE OF RESEARCH

The research reported in this thesis focuses on the use of the ASME and API guidelines to a existing thermal power plant. The failure data from eight major components will be used to develop an optimal maintenance model. A cost benefit analysis is performed to assess the effectiveness of replacement versus maintenance.

1.5 ORGANIZATION OF THE THESIS

The thesis is organized as follows:

Chapter –1 Provides a background of the research study. It also states the scope and objectives of the thesis.

Chapter-2 Reviews the technique available to develop a risk based inspection program. Discusses the process for developing a risk based inspection. This includes system definition, qualitative risk assessment, quantitative risk analysis, failure modes, effects and criticality analysis methodology and inspection program development

Chapter-3 Discusses the theory applied to Risk Based Inspection technique. The time dependent failure model is explained. The Weibull Distribution is discussed. Determination of the 'Shape Factor' and 'Characteristic life' from the data using the 'Least Squares Fit is explained.

Chapter-4 Provides the System description of the Boiler and the failure data obtained for Superheaters, Waterwalls, and Reheater, Forced Draft Fan, Boiler Feed Pump, Boiler Feed Pump Recirculation Valve, and Condenser Tubes.

Chapter-5 Qualitative Risk Assessment is done for the Boiler Components. Based on engineering judgment, failure probabilities and consequences are estimated. The Qualitative Risk Matrix is drawn based on the failure probabilities and consequences.

Chapter-6 The available data for Superheater, Waterwalls, Reheater, Forced Draft Fan, Boiler Feed Pump, Boiler Feed Pump Recirculation Valve, and Condenser Tubes are quantitatively analyzed. Failure probability is established.

Chapter-7 Financial optimization is done to have the component replaced by calculating Net Present Value. Time Ordered Influence Diagram for the Maintenance Optimization is developed.

Chapter-8 Optimum Inspection Program is developed. After considering the various damage mechanisms and inspection procedures the best strategy for inspection is developed for Waterwalls.

Chapter-9 Conclusions and recommendations are provided in this chapter.

References and appendices are also included in the thesis.

Chapter 2

REVIEW OF RISK BASED METHODOLOGIES

2.1 RISK BASED INSPECTION

Risk assessment has existed in some form or other in industry and commerce for a long time. The first paper on risk assessment was written subsequent to a study by the US Nuclear Regulatory Commission for formal application to the Nuclear Plants. It consisted of seven steps (Rasmussan, 1975). American Society of Mechanical Engineers extended the Risk assessment to Inspections based on Risk Assessment and developed general guidelines. The risk based inspection consisted of four parts according to ASME general guidelines (ASME, 1991). Subsequently, ASME issued guideline specific to Nuclear and Fossil Fuel fired Plants. ASME expanded the initial four parts guidelines to a five parts document for the Fossil Fired Plants. The addition of an extra part is due to substantial industry data, risk assessment models, inspection information and structural and economic models, currently being proposed for fossil power plants. API published recommended practice 580 for risk based inspection in 2002 (API 580, 2002). API 580 suggests eleven steps. API has included extra steps such as 'Other Risk Mitigation Activities', 'Reassessment and Updating', 'Roles, Responsibilities, Training and Qualification' and ' Documentation and Updating'. The five steps of the ASME guidelines for Fossil Fired Plants are enumerated and discussed below.

The five steps are:

1. System definition consists of boundaries, success criteria, data collection from plant and obtaining generic data.

2. Qualitative risk assessment consists of system tabulation with components, estimation of failure probabilities, consequences and drawing risk matrix.

3. Quantitative risk assessment consists of obtaining and combining data for data analysis.

4. Multiple component ranking based on optimization consists of influence diagrams, decision trees and spread sheet models.

5. Inspection program development consists of strategy tables, influence diagrams, decision trees, decision models and best strategy determination.

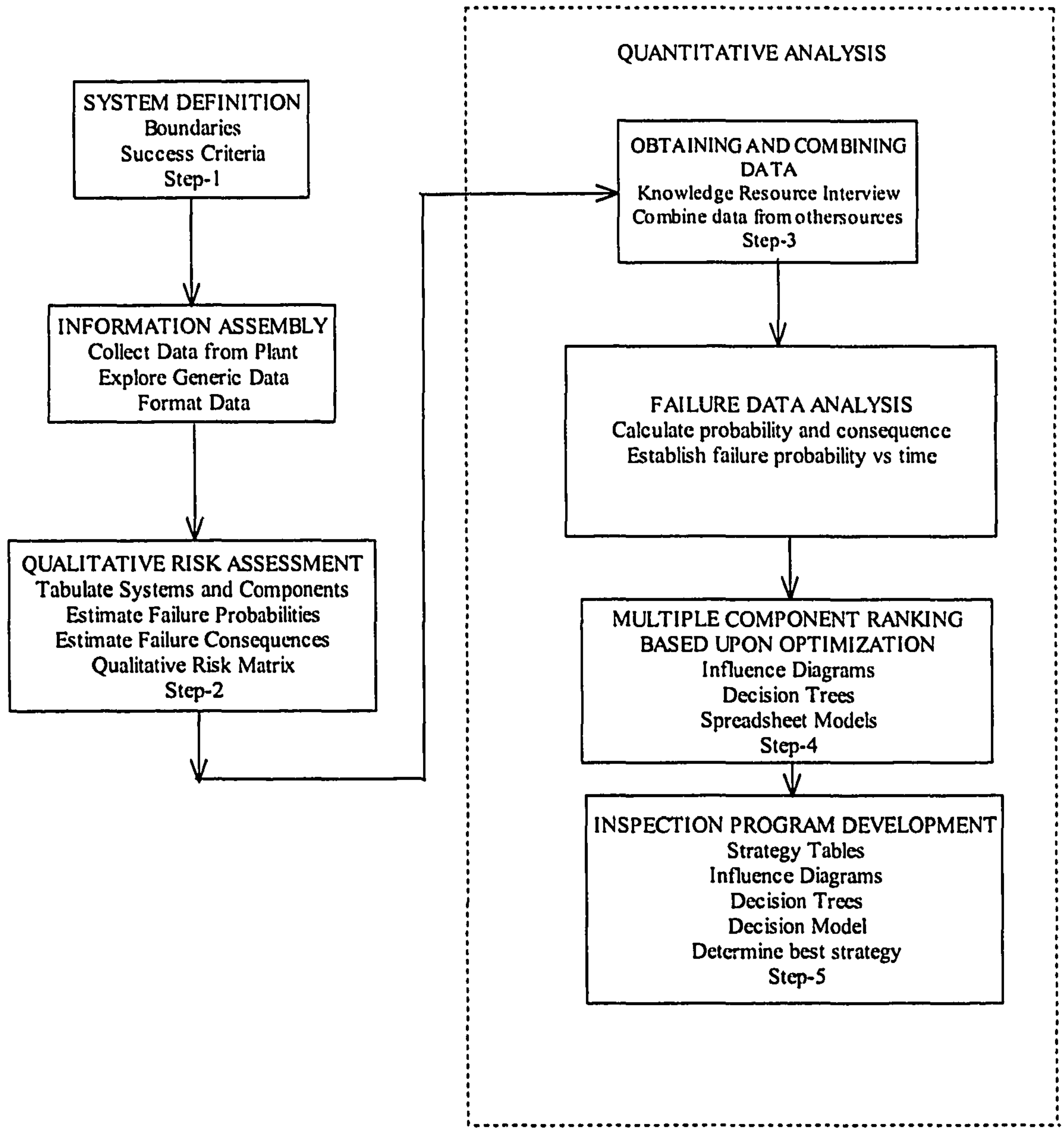


Figure 2.1: Risk Based Inspection Methodology (ASME, 2003)

2.1.1 SYSTEM DEFINITION

System definition is the first step in identifying the components to be inspected and defining the purpose of the inspection. A system is an identifiable entity that has a production function. In a risk based inspection process for a fossil plant the first step is to establish the system and its boundaries. A system is characterized by two main concepts: the boundary and the success criteria. The boundary specifies the components which constitute. The success criteria define the expected performance the system. In order to define meaningful boundaries, the operational or safety criteria used for system definitions should be defined on the same basis as the available data. System unavailability is caused by failure. Failure scenarios are tied to the mode of operation. System success is defined on the basis of the corresponding mode of operation. Fossil power plants are designed to perform specific functions. Thus it is necessary to define their physical and performance or functional boundaries. Sub-systems or components necessary for the successful operation of the plant in one operating mode may become redundant or standby units in another operating mode. For example, a feedwater pump system comprising three pumps is fully operational at full power with all the three pumps running. The same system at less than full power contains one redundant pump with two pumps running; the third is a standby unit available on demand. At full power, the performance boundary reflects the availability of all the three pumps. At partial power, the performance boundary reflects the operational availability of two out of three units and the availability upon demand for the third unit.

A system's performance is influenced by its components. All the components should be identified and their influence on the system performance. For example, a boiler can be considered as a system or as a component. If the forced outages are due to tube failures, the question arises as to which tubes whether, superheater, waterwall or reheater. When boiler is defined as a system the resources required can be reduced to a manageable level as the focus would be on the component of the boiler. Therefore a system should be defined such that it contains all the critical components.

Success criteria should be defined along the lines of forced outage rate between statutory inspections or economic outages.

A system definition requires the specifications of each component, materials of construction, operating and design parameters and history. The difficulty is that most plants do not have all the data about the components in the plant due reorganizations in the plant or new record keeping systems being brought in. Some plants have excellent data acquisition systems but others have none. If plant data are not available generic data can be used to begin the program. The program can then be modified using the actual data collected for the plant.

2.1.2 QUALITATIVE RISK ASSESSMENT

Qualitative risk assessment is a screening technique based on plant specific or generic data and assumptions that are used to evaluate accident sequences, frequencies, and consequences. The objective of this part of the process is to identify and rank the importance of the equipment necessary to achieve and maintain safe and efficient operation based on the availability of the plant systems and the impact of their failure during normal operation or on demand. The qualitative analysis is performed through the use of systematic deductive procedures such as failure modes and effect analysis, hazard and operability analysis, fault tree analysis, master logic diagrams and what if analysis. The use of those tools facilitates the identification of the systems, the important components in each system, the failure modes of these components and how they in turn affect the system. Some procedures (e.g. FMEA) are more effective in examining the components that make up the system. The major steps in qualitative procedures are selecting a deductive procedure (FMEA) (ASME, 1991), identifying the system, tabulating system components, identifying and listing failure modes of each component, identifying effects of component failures on the system, classifying likelihood of failure of each failure mode, classifying consequences for each failure mode and ranking system/subsystem/component failure mode based on likelihood and consequences. For example, failure mode of waterwall tube is tube deformation in the form of metal elongation and reduction in the wall area or cross section. This failure mode could be due to short term overheating (failure mechanism). In fact short term overheating is the immediate cause while the loss of coolant or excessive boiler gas temperature may act as contributing factors. Further analysis of the contributing causes may identify that loss of coolant or excessive boiler gas temperature are caused by any of the following factors, internal tube blockage, low water level, loss of coolant due to upstream tube failure and overfiring of burners (Lamping 85). Some of the root causes that will lead to the blockage failure mechanisms are scale deposits, repair debris, steel shot, pre boiler oxides, deposits from carryover or loose bolts, nuts and plates inside the tube. Qualitative risk assessment ranks the problems according to its importance. There may be more than one solution to the problem. In this case, either the problem or the solution needs to be ranked in importance. Even in a narrowly defined system say, superheater, some tubes are more important than others. The tubes failing due to ash erosion are more frequent than those due to creep. The failure mode needs to be identified to perform qualitative risk assessment. The failure probability for each component is estimated based on different failure modes. The failure probability will be classified as "high", "medium", and "low". For example, the failure probability of water wall tubes is high and that of condenser tubes are medium.

At this step, the importance of risk based methodology is evident. Using risk, instead of probability or only consequence cost, provides the ability to identify what is required to meet the success criteria. The quantitative analysis provides further an ability to focus on those problems which have the most adverse effect on production. A risk matrix is prepared comprising of probability and consequence severity.

2.1.3 QUANTITAIVE RISK ASSESSMENT

Quantitative risk analysis methods are used to integrate the numerous engineering disciplines to prioritize and develop programs for the inspection of components and structural elements. Some of the engineering disciplines include non-destructive examination, fracture mechanics analysis, system and component design, and operation of facilities. Risk based models are developed by expanding on the logic that is used in the qualitative risk assessment process to quantify the frequency of component/system failure and direct and indirect consequences of failures. Probabilities of component failure that are based on component material, potential degradation mechanisms and loading conditions are also factored into the model. The overall model is used to identify the most important systems and their components for inspection using quantitative measures. The quantitative methodology which can be based on safety or economic risk is then used to prioritize all the components or elements of interest. Once the components are prioritized, inspection models are applied to evaluate appropriate inspection strategies for these components or structural elements. These models are used to evaluate the reliability and quality of inspections relative to potential failure criteria, e.g; leaks or catastrophic rupture. Economic models can be used to optimize the inspection program over multiple components across fossil units. The overall quantitative risk analysis approach has three basic steps; 1.application of system assessment methods to prioritize components for inspection, 2. application of decision analysis models to evaluate the appropriate frequency, methods, and acceptance criteria for developing inspection programs, and 3. application of decision analysis models to optimize the inspection programs over multiple components based on safety and economic constraints.

While evolving a quantitative analysis, "high", "medium" or "low" probability and consequence estimates will be replaced with failure probability and consequence in dollar values. The qualitative assessment only screens and does not identify the course of action. Risks of different units can not be compared in qualitative assessment. There is no ranking of importance for resources allocation among the same ranked projects in qualitative assessment. The qualitative assessment does not provide financial or other quantitative information required to support recommendations. The quantitative risk assessment addresses these shortcomings of qualitative assessment.

The failure consequence in terms of dollars can be obtained from a company's corporate office or from the plant administration. This information will be required later but at this stage failure rate probability with time is required. There are two class of data, one is specific data and the other is generic data. Specific data are obtained from the plant and pertains to a particular component. On the other hand Generic data is compiled information usually from an industry or a public source. This thesis uses plant specific data. The data and the failure modes are used for failure modeling and also to predict remaining life. Fault tree and event tree analysis will be required in case the relationship between component failure and mission failure is not clear.

2.1.4 MUTIPLE COMPONENT RANKING BASED UPON OPTIMAZATION

In the initial quantitative assessment, the risk ranking is quite simple. As the fossil powered plants are concerned mainly about megawatt (MW) generated, the production loss is the criterion that determined the rank. A different output measure can be used if a different kind of facility is analyzed. In this step, the economic and safety factors are accounted for. A decision analysis model is developed to evaluate inspection and replacement decisions to maximize net present value while addressing the budget constraints. This model will, based, on unit need optimally balance resources among components and units and help develop a complete productive resource management strategy. A component replacement strategy is also developed.

2.1.5 INSPECTION PROGRAM DEVELOPMENT

An inspection program is developed after having determined the components and their acceptable net present value. The year of inspection is decided. Inspections along with the information on the risk provide confidence in the reliability of the component. Inspections reduce uncertainty in the risk assessment. An inspection strategy is developed to optimize risk. The method, sample size, the access and the type of inspection will be the factors that produce a strategy for examining a component. The costs involved in the inspection and access will be taken into account. The inspection program starts with either "do nothing" or "arrange inspections".

Multiple component ranking based upon optimization and inspection program development use spreadsheet models to help make decisions. Sensitivity analysis is a tool that will identify the variables that have the greatest effect on the final decision i.e. maximizing the net present value.

2.2 REVIEW OF WORK DONE ON RISK ASSESSMENT

Rasmussan, et al (1975) developed the basic seven tasks for the assessment of reactor safety. He used event trees to analyze the damage likely to be caused by a pipe breakage. He investigated the property damage, cancer fatalities, and early fatalities for 100 reactors per year of failure probability. This initial work forms the basis for this thesis and the probability distribution developed for property damage and other failures inform the researcher the necessity of a probability distribution when determining the risk. There was no mention of employing risk for calculating failure probability of equipment. Subsequent to this initial paper, risk began to play a major role in equipment maintenance along with safety.

Moghissi (1984) states that "Risk analysis is a complex and logical process and like any other branch of science and engineering must be refined by the devotion of time, effort and resources". He termed political and legal constraints as uncertainty of risk value. The importance of the cost impact, and cost/benefit analysis well described in this article are the basis for developing optimized programs for component replacement and inspection. As this an early work, the cost/benefit analysis is viewed as benefits derived from reduction in risk. There is no thought given to other expenses that will result when projects are undertaken to reduce risk. The principle of corporate finance such as net present value needs to be applied when assets are either modified or replaced to reduce risk.

Vo (1989) used data from existing probabilistic risk assessments for eight representative nuclear power plants to identify and prioritize the most relevant systems for plant safety. Inspection importance ranking was calculated for eight systems. The objective was to assess current in service inspection requirements for pressure boundary systems and components and to develop recommendations for improvements. This study used failure probabilities based on historical data. According to Vo rigorous failure analysis (eg. fracture mechanics calculations using actual plant specific information) will shift the system importance results. Systematic evaluation of the sensitivity of the results to plant specific design factors and operating procedures should be made. This study demonstrated the feasibility of using risk based methods to develop plant specific inspection plans.

Rettedal (1990) discussed the integration of structural reliability analysis and quantitative risk assessment by adopting Bayesian approach. This paper used data provided by experts. His paper concluded that following the "classical Bayesian approach" the true objective risk, is estimated whereas in the "fully Bayesian approach", risk is a way of expressing uncertainty about future observable quantities. To estimate the true objective risk, the true probability of an accident event is used. To estimate just the risk, subjective probabilities are used to express the uncertainties of the occurrence or not of an accidental event, the number of accidental events in a given period of time or lost production in a period of time. The risk result is a total measure of uncertainty. The author of this work is of the opinion that there is a possibility that there will be variable results from one approach to the other approach. Rettadel calculated the navigational failure using both the approaches. He obtained a failure probability ranging from 0.01 to 0.04 for the classical Bayesian approach whereas the failure probability was 0.013 for fully Bayesian approach. To eliminate unwanted variability in results from one analysis to the other, guidelines/standards related to methods and data are required.

Vesely (1993) used probabilistic risk assessment as a tool for maintenance prioritization applications. This paper focuses on PRA importance measures which can be useful for maintenance prioritization applications. Specific importance measures are identified which can be used to identify risk important maintenances. Risk importance maintenance is defined as maintenance that is necessary to avoid the risk sensitive to the proper functioning of the component. Two different measures are identified that can be used to determine risk important maintenances. One importance measure determines the risk importance of the maintenance based on the risk importance of the equipment being maintained. The other importance measure determines the importance of the maintenance based on the risk impact that would occur if maintenance were not carried out effectively. Two measures, minimal cutsets contribution and risk reduction importance were calculated. Using minimal cutsets or risk reduction importance, the basic events and their associated maintenance are prioritized for their risk level. A study should be made as to compare the results obtained in applying each importance measure.

Vaurio (1995) presented a procedure for optimizing the test inspection and maintenance intervals of safety related systems and components. He analysed the downtime of a stand by system and the cost of the risk involved in the unavailability of the standby system while the system is tested. There is no data analysis in this paper. Component failures, common cause failures and human errors were included and modeled by basic events. Analytical solutions had been obtained for several risk models, such as component model, component group model and multiple system model illustrating how different factors influence the optimization. The minimum risk acceptable for the loss of system needs to be studied for effective application of the models suggested in this paper.

Nicholls (1995) developed the risk assessment package for Koeberg Nuclear Power Station, South Africa. His work is comprised of computerizing the manual probabilistic risk assessment done by the contractors. There were two main driving forces for this. One was to include some of the lessons learned concerning nuclear safety since the original study had been started some ten years ago. The other was to allow for a rapid analysis of the impact of changes to the plant. He developed the overall requirement to allow for an integral approach to risk assessment. He used plant data and wrote computer codes for component database, failure modes, fault tree, event tree, probabilistic risk assessment analysis and documented results for the nuclear power plant. The language used was PASCAL. ORACLE was chosen to hold the vast database. To link these two languages, ORACLE compatible FORTRAN was chosen. The code included a module to update the data with actual plant data by means of a Bayesian Analysis. Minimal Cutsets were generated. Value of the cutest, number of elements in the cutest, number of components in the cutest, number of locations in the cutest and the degree of common mode in the cutest were all considered before dropping a cutest. The probabilistic risk assessment integrated a number of event trees to determine the risk. This computerized system is useful to resolve conventional reliability issues. In a power plant there are many systems which provide various functions contributing to the successful operation of the plant. Most of these systems are interlinked and a failure of a system can cause an outage. The computerized system has all the event trees in the data base. Therefore the computerized system is useful in determining the failure of systems when a malfunction has occurred in one of the systems. The conventional reliability issues are the reliabilities of boilers, turbines, pumps, fans and condensers and can be developed for any process industry. A study to develop a similar system for a thermal plant should be done.

Hagemeijr (1998) developed a methodology on the determination of risk by evaluating the consequences and the likelihood of equipment failure. Likelihood of equipment failure was assessed by means of extrapolation for the future planned maintenance work to identify the corrective maintenance works. The objective was to optimize the inspection and maintenance to minimize risk in Brunei Petroleum plant. A new term called "integrity parameter" has been introduced. The reasons for introducing the integrity parameter are 1) the condition (state of integrity) of equipment can be directly expressed in terms of measurable integrity parameter values. 2) the parameter values together with their acceptance limits can be used as equipment integrity performance indicators. Such indicators are essential to drive inspection activities and corrective actions at task level. Since the parameter can be either physical (i.e. wall thickness) or non physical (i.e. trip settings) the concept is generally acceptable. Having defined the integrity parameters, the acceptance ranges (i.e. performance limits to the parameter values) are established. The acceptance ranges are determined by "fitness for purpose" analysis which takes into account the prevailing operational requirements and satisfying the safety standards related pressure containment. The deviation from acceptance ranges dictates the corrective action. The likelihood of failure with respect to time is obtained by the use of historical data and the integrity parameter value. Thus the relative risk of equipment failure is evaluated and this is used to prioritize the inspection activities. This procedure applies a qualitative consequence analysis to filter subsequent analysis. The integrity parameters have subdivided into critical integrity parameters and non critical integrity parameters. The fit for purpose approach should be studied for its acceptability in other process industries

Harnly (1998) developed a risk ranked inspection recommendation procedure that was used by one of Exxon's chemical plants to prioritize maintenance works that had been identified during equipment inspection. The equipment were prioritized based on severity index which is failure potential combined with consequences .He assigned values to low, medium and high for consequences and probabilities. Thus a failure which fitted a co-ordinate in the risk matrix had a value. He also assigned values to failure potential and consequences. He defined a severity index for each failure which combined all the values obtained for a failure and produced a new number indicating how severe the failure is. A study can be made whether such values can be assigned to other process industries

Ponnambalam (2001) demonstrated the advantages of utilizing available data and knowledge of experts in assigning probabilities in estimating risk to manage regulation of stream flow. He used Bayesian rule in computing estimated risk while at the same time making choice of designs to ensure reliability. He has used real data and also simulated data in his paper. His procedure consists of specifying an acceptable failure rate an unacceptable failure rate and use a permitted number of failures to be used as a control variable. He has shown that statistical and stochastic analyses can be used to integrate risk and reliability for system function design. A study should be pursued whether this approach can be made in process industries.

Jovanovic (2001) reviewed the current practices and trends in the area of risk based inspection/ risk based life management primarily by comparing European and US work. He highlighted the background and needs of industry and showed the relationship between risk based inspection/risk based life management and other possible approaches to maintenance. There is no data analysis in this report. Risk based life management of the plant is a concept which includes external damages, explosions and similar purely random causes. Therefore, an overall concept of RBI/RBLM should be specified. Available methods, tools, codes, standards etc should be embedded into the above concept. Additional needed methods, tools, etc should be developed and included into the new concept. Necessary steps towards the development of new codes, standards and other similar documents should be studied.

Faber (2002) addressed the framework for risk based inspection planning (RBI) The RBI problem is summarized and the individual aspects of RBI are highlighted. The paper addresses the theoretical framework for risk based inspection and planning. There are no data analyses in this paper. The paper describes the uncertainties of inspection measurement attributed to deterioration and uncertain performance of inspection. There are other uncertainties such as basic variables, representing physical uncertainties, uncertainties related to new information, and finally the model uncertainties. The physical uncertainties are typically uncertainties associated with loading, environmental exposure, geometry and material properties. The statistical uncertainties arise from incomplete statistical information, e.g. due to smaller number of material tests. The model uncertainties are due to the idealized mathematical descriptions used to approximate the actual physical behavior of the components. These uncertainties should study and procedures should be developed to accommodate these uncertainties while developing an inspection model.

Krishnasamy, Faisal Khan and Haddara (2004) presented a methodology for designing maintenance programs based on risk. The methodology consisted of four parts, identification of scope, risk assessment, risk evaluation and maintenance planning. It was found that the steam generator, the high pressure feed water system and the air and flue gas systems were responsible for 62% of the overall risk of Unit-3 at Holyrood Generation Station. A schedule for preventive maintenance was developed. An acceptable risk criterion was developed. A study should be made to determine the contractual obligations of the utility when it fails to produce power due to a breakdown. This cost will add up to the down time cost.

Brickstad (2005) showed the results of a benchmark study with five different Structural Reliability Models (SRMs) conducted in the frame of the European Project NURBIM (Nuclear Risk Based Inspection Methodology for passive components). Pipes of small, medium and large diameters were evaluated for failure probability in 40 years. The fatigue and stress corrosion crack were the two damage mechanisms under consideration. Five different softwares were applied to fifteen parameters to forecast the occurrence of leaks and damages in 40 years. The paper states "The benchmark analyses are performed by first defining a baseline case and then varying each parameter one by one, keeping all other parameters fixed at their baseline values." This procedure of varying one parameter keeping the rest constant will not indicate the interaction between the parameters. Design of experiments principles should be applied to reflect the interaction between various parameters into consideration. The failure probability may have a different value when interaction between the fifteen parameters considered in this study.

Conley (2005) discussed the application of risk assessment technology in general and more specifically risk based inspection. He applied RBI to ammonia storage and analyzed the hazards presented by corrosion or other ongoing degrading mechanisms. The method of risk presentation via 'risk matrix' expounded in this article was informative while developing the thesis. The example shown for risk as events/year, times $/event was used in this thesis while linking the engineering world to the corporate world. There were no data analyses as in this thesis. In the risk matrix the consequence is the area that would be affected by fire or explosion if flammables are released from a refinery. The consequences should be the area affected by ammonia release. This area would be a larger area if there is a downwind. Therefore, the release of ammonia and the area this would cover should be studied and risk matrix redrawn.

Kirchsteiger(2006) of European Commission discussed various issues with regard to risk assessment such as including aging as a factor while evaluating risk. He concluded that investigations showed that different failure rate behaviour among different Nuclear Power Plants was mostly due to better failure reporting than truly worse performance. He mentioned the lack of international legislation which would make it mandatory to report hydrogen related incidents and accidents to a closed, partly open, or open user group. He has proposed the establishment of European Energy Risk Monitor (ERMON) which will consist of a web based information system on energy risks, method on energy risk comparison and a network of European energy stakeholders. To minimize the risks to human health and environment resulting from the use of the different energy technologies (fossil, nuclear, renewable), study should be made to compare the risks among different energy systems.

Chapter 3

FAILURE DATA MODELLING

3.1 RELIABILITY MODELS

There are several models which can describe a failure process. They are based upon the exponential, Weibull, normal, and lognormal probability functions. These are theoretical distributions and are mathematically derived. First the distribution which will suit the failure process has to be determined. A distribution that has a constant failure rate is called an exponential probability distribution. Failures due to completely random or chance events will follow this distribution. This model is present during the useful life of the system or component. Memorylessness is a characteristic of this distribution. This means that the time of failure of a component is not dependent on how long the component has been operating. There is no aging or wear out effect. The normal distribution has been used to model fatigue and wear out phenomena.(Ebeling,1997). Before applying the normal distribution to model failures, the question whether failure times are normally distributed has to be answered. In thermal power plants any of the following factors, chemical, mechanical, electrical and environmental issues can cause a failure. As normal distribution is for modeling fatigue and wear out phenomena, it is not possible to state the failures in a thermal are normally distributed. Log normal distribution can be applied when the random variable T, the time to failure, has a log normal distribution. Thus the logarithm of T has a normal distribution. The Weibull failure distribution can be used to model increasing, constant, and decreasing failure rates. The advantage of Weibull failure data analysis is the ability to provide reasonably accurate failure analysis and failure forecasts with comparatively lesser samples. Another advantage of Weibull failure data analysis is that it provides a simple and useful graphical plot, well accepted by academic and industrial practice. The main advantage of Weibul distribution is that it represents a family of distributions.

The reliability model in this thesis is based upon Weibull distribution. However other models such as exponential, lognormal and normal are also described for reference. These models are described below.

3.1.1 THE EXPONENTIAL RELIABILITY MODEL

A failure distribution that has a constant failure rate is called an exponential probability distribution. Many systems exhibit constant failure rates. When all the failure modes of a component have constant failure rates the overall failure rate of the component is also constant. Failures due to completely random or chance events will follow this distribution. The reliability model represents the useful life of a component (Ebeling, 1997).

3.1.1.1 DEVELOPMENT OF CONSTANT FAILURE RATE MODEL

Assuming the failure rate function, $\lambda(t) = \lambda$, $t \geq 0$,

The reliability function, $R(t) = \exp\left[-\int_0^{\infty} \lambda dt\right] = e^{-\lambda t}$, $t \geq 0$ (3.1)

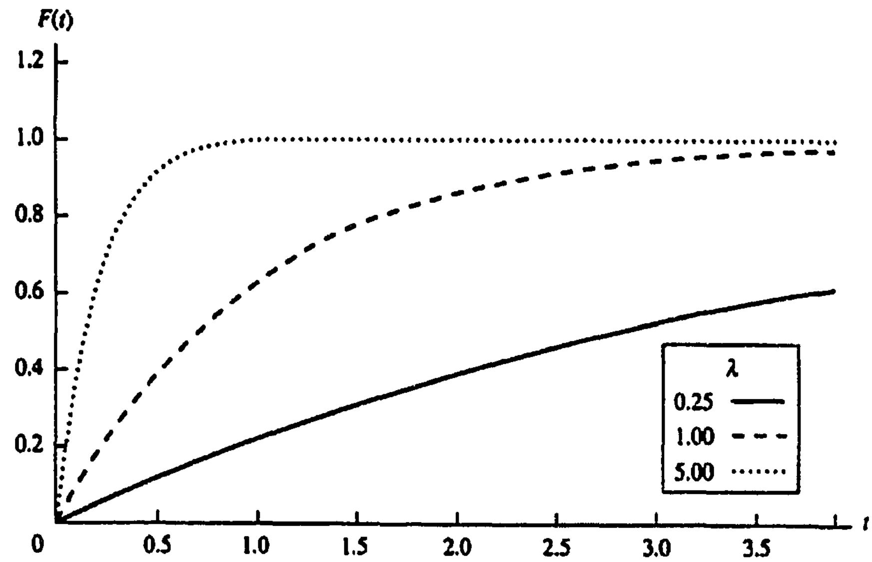
The cumulative distribution function, $F(t) = 1 - e^{-\lambda t}$ (3.2)

The probability density function, $f(t) = -\frac{dR(t)}{dt} = \lambda\, e^{-\lambda t}$ (3.3)

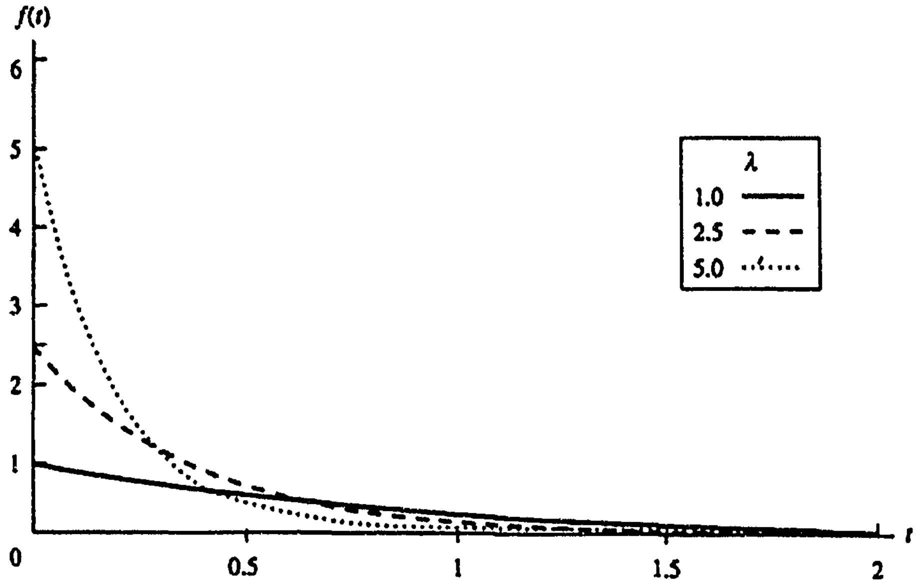
The mean time to failure $MTTF = \int_0^\infty e^{-\lambda t}\, dt = \frac{e^{-\lambda t}}{-\lambda} = \frac{1}{\lambda}$ (3.4)

The variance $\sigma^2 = \int_0^\infty \left(t - \frac{1}{\lambda}\right)^2 \lambda e^{-\lambda t} dt = \frac{1}{\lambda^2}$ (3.5)

The standard deviation is $(1/\lambda)$ =MTTF. This means that the variability of failure time increases as the reliability increases. The characteristics of exponential distribution are shown in the graphical expressions in figure 6.1, and figure 6.2 (Ebeling, 1997).



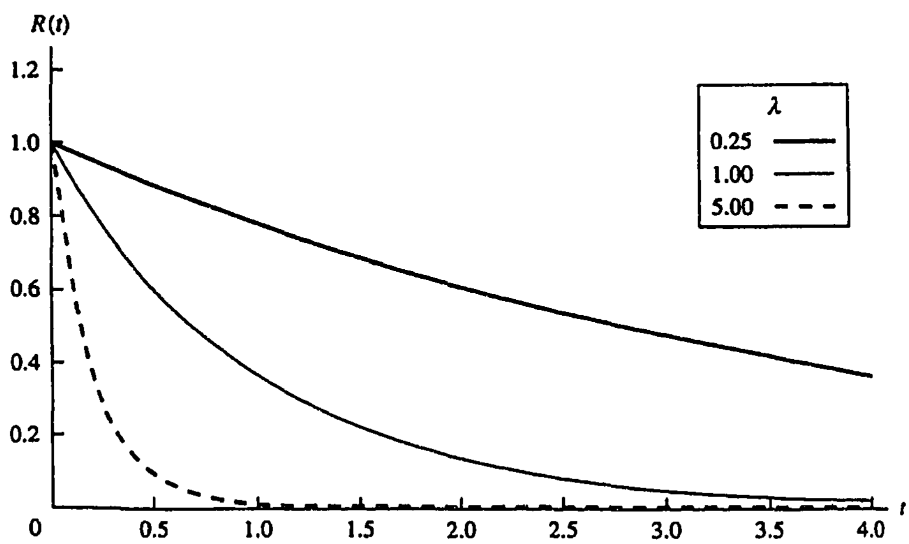
(a)



(b)

Figure 3.1: (a) The exponential cumulative distribution function.

(b) The exponential probability function (Ebeling, 1997).



3.2: The exponential reliability function (Ebeling, 1997).

In the industry, the failure time vary very much. It should be noted that the mean time to failure is the reciprocal of failure rate. Though [$1/\lambda$ (t)] is always in units of time it is the mean of the failure distribution for the constant failure rate model only.

A second observation is that R (MTTF) = $e^{-MTTF/MTTF} = e^{-1} = 0.368$

A component having a constant failure rate has a one third chance of survival up its mean time to failure. The design life of a component having an exponentially distributed failure time may be obtained by solving for the inverse of the reliability function (Ebling, 1997)

$R(t_R) = e^{-\lambda t_R} = R$

$$T_R = -\frac{1}{\lambda}\ln 0.5 = \frac{0.69315}{\lambda} = 0.69315\ \text{MTTF}$$

The median is always less than the mean as the exponential distribution is skewed to the right.

3.1.1.2 MEMORYLESSNESS

A well-known characteristic of CFR model is its lack of memory. Other distributions do not have this characteristic. The failure of the component does not depend on its age. The failure can happen regardless of its age. This property is consistent with the completely random and independent nature of the failure process. When external forces cause a failure, the component's history is not relevant (Ebeling, 1997).

This property can be demonstrated using conditional reliability

$$R\left(\frac{t}{T_0}\right) = \frac{R(t+T_0)}{R(T_0)} = \frac{e^{-\lambda(t+T_0)}}{e^{-\lambda t}}$$

$$= \frac{e^{-\lambda t}}{e^{-\lambda T_0}} \frac{e^{-\lambda T_0}}{} = e^{-\lambda t} = R(t) \qquad (3.6)$$

The burn in period T_0 has no effect on the reliability. Time to failure depends only on the observed operating time (t) (Ebeling, 1997).

3.1.1.3 FAILURE MODES WITH CFR MODEL

When a system has n independent components which are connected in series and each having a constant failure rate then

$$\lambda(t) = \sum_{i=1}^{n} \lambda_i(t) \qquad (3.9)$$

$$R(t) = \exp\left[-\int_0^t \lambda dt\right] = \exp[-\lambda t] \qquad (3.10)$$

$$\text{Where MTTF} = \frac{1}{\lambda} = \frac{1}{\sum_{i=1}^{n} \lambda_i} = \frac{1}{\sum_{i=1}^{n} \frac{1}{\text{MTTF}_i}}; \quad \text{MTTF}_i = \frac{1}{\lambda_i} \qquad (3.11)$$

In other words, the system itself will have an exponential failure time.

If the components are also all identical (i.e., $\lambda_i = \lambda_1$ for $i = 2, 3 \ldots n$) then

$$\lambda = n\lambda_i, \text{ and MTTF} = \frac{1}{n\lambda_1} \qquad (3.12)$$

3.1.1.4 NUMBER OF SPARES DETERMINATION

The Poisson distribution is often used to determine the number of spare components when the time between the failures is exponential. If S spare components are available to support a continuous operation over a time period, t, then (Ebeling, 1997)

$$R_s(t) = \sum_{n=0}^{s} P_n(t) \qquad (3.25)$$

where R_S is Component reliability for S spares)

Where $P_n(t)$ is the Poisson mass probability mass function.

$$P_n(t) = \frac{e^{-\lambda t}(\lambda t)^n}{n!} \qquad n = 0, 1, 2 \qquad (3.26)$$

3.1.2 WEIBULL DISTRIBUTION

The Weibull distribution may be used to model constant, increasing and decreasing failure rates. It is characterized by a hazard rate function of the form

$$\lambda(t) = at^b \qquad (3.30)$$

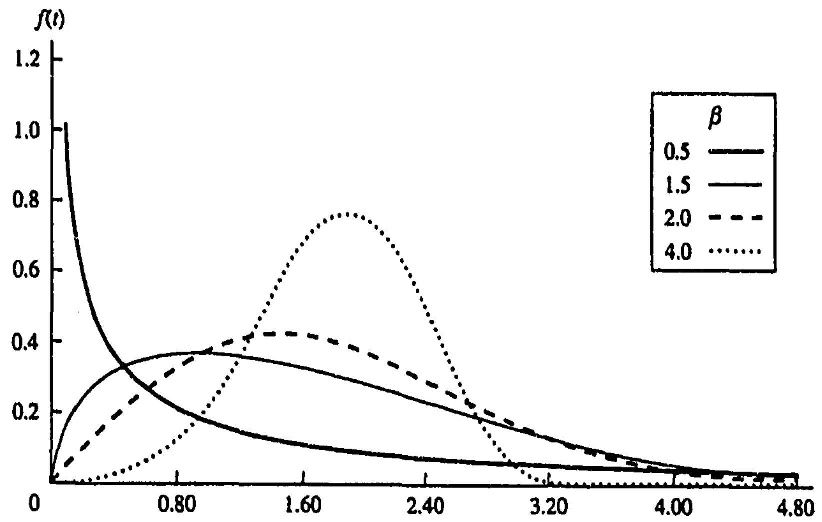
For mathematical convenience $\lambda(t)$ is expressed as below

$$\lambda(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1} \quad \theta>0,\ \beta>0,\ t \geq 0 \qquad (6.31)$$

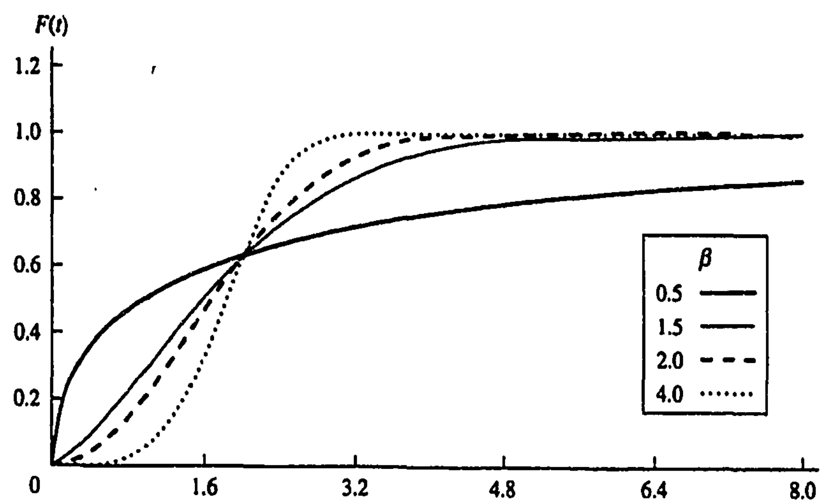
$$R(t) = e^{-\left(\frac{t}{\theta}\right)^{\beta}} \qquad (3.32)$$

$$f(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1} e^{-\left(\frac{t}{\theta}\right)^{\beta}} \qquad (3.33)$$

Beta (β) is referred as the shape factor. Its effect on the distribution can be seen in Figure 3.3 (a) for several different values. For $\beta<1$, the probability density function is similar in shape to that of the exponential and for large values of β (e.g., $\beta=3$), the PDF is somewhat symmetrical like the normal distribution. For $1<\beta<3$, the density function is skewed (Ebeling, 1997).



(a)



(b)

Figure 3.3: (a) The effect of β on Weibull probability density function
(b) The effect of β on Weibull cumulative distribution function (Ebeling, 1997).

When $\beta = 1$, λ (t) is a constant and the distribution is identical to the exponential with $\lambda = (1/\theta)$. As seen in figure 6.3 (b) and 6.4 each of the cumulative distribution function and reliability curves passes through the same point where $t = \theta$, since from Eq 3.32, exp (-1) = 0.368. Therefore, 63.2% of all Weibull failures will occur by time $t = \theta$ regardless of the value of the shape parameter (Ebeling, 1997).

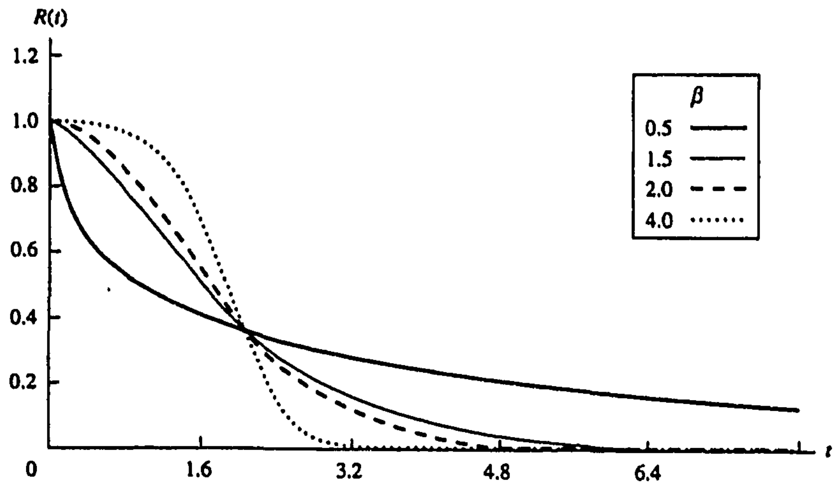


Figure 3.4: The effect of β on the Weibull reliability function (Ebeling, 1997).

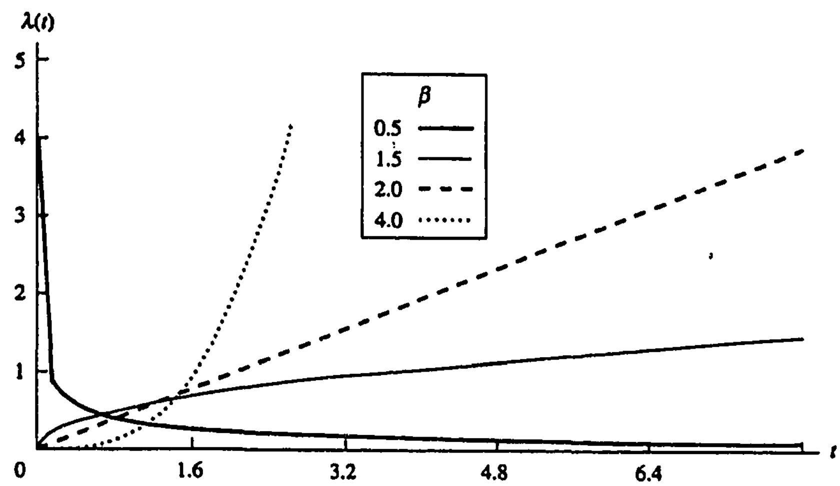


Figure 3.5: The effect of β on the Weibull hazard rate curve (Ebeling, 1997)

Figure 3.5 shows the hazard rate function can be increasing or decreasing depending the value of β (Ebeling, 1997).

Theta (θ) is a scale parameter that influences both the mean and the spread or dispersion of the distribution. The effect of θ on the spread of the probability density function is shown in figure 6.6(a), for several different values. As θ increases as shown figure the reliability increases at a given point in time In figure6.7 the slope of the hazard rate decreases as θ increases. The hazard rate curve is linear in this example since β=2. The parameter θ is also called the characteristic life and it has units identical to those of the failure time T (Ebeling, 1997).

$$MTTF = \theta\Gamma\left(1+\frac{1}{\beta}\right) \quad (3.34)$$

$$\sigma^2 = \theta^2\left\{\Gamma\left(1+\frac{2}{\beta}\right)-\left[\Gamma\left(1+\frac{1}{\beta}\right)\right]^2\right\} \quad (3.35)$$

Where, $\Gamma(x)$ is the gamma function:

$$\Gamma(x) = \int_0^\infty y^{x-1}e^{-y}\,dy \quad (3.36)$$

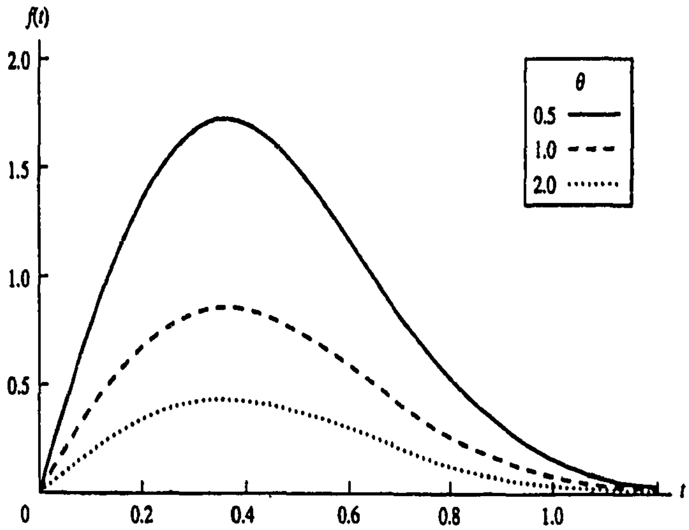
The values of Γ(x) can be found in standard Tables. With these tables, along with the fact that, for x>0,

$$\Gamma(x) = (x-1)\Gamma(x-1) \quad (3.37)$$

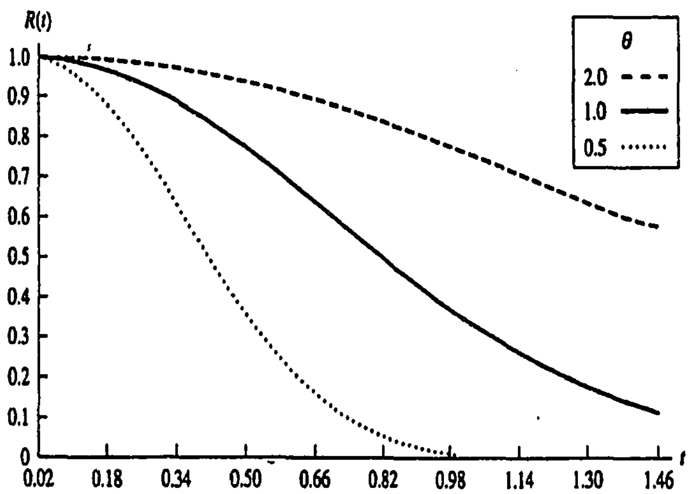
The mean and variance can be computed. Unlike the exponential distribution there is no direct relationship between the MTTF and λ (t).

The value of the shape parameter β provides insight into the behavior of the failure process. Table 3.1 summarizes the behavior. Hazard rate functions that increase at an increasing rate reflect a very aggressive wear out phenomenon. The hazard rate curve in

Fig 3.5, for β=4 is convex, and for β=1.5, it is concave. Weibull provides a good model for much of the failure data found in practice, considering the variety of shapes and properties that are obtainable



(a)



(b)

Figure 3.6: (a) The effect of θ on the Weibull probability density function
(b) The effect of θ on the Weibull reliability function (Ebeling, 1997)

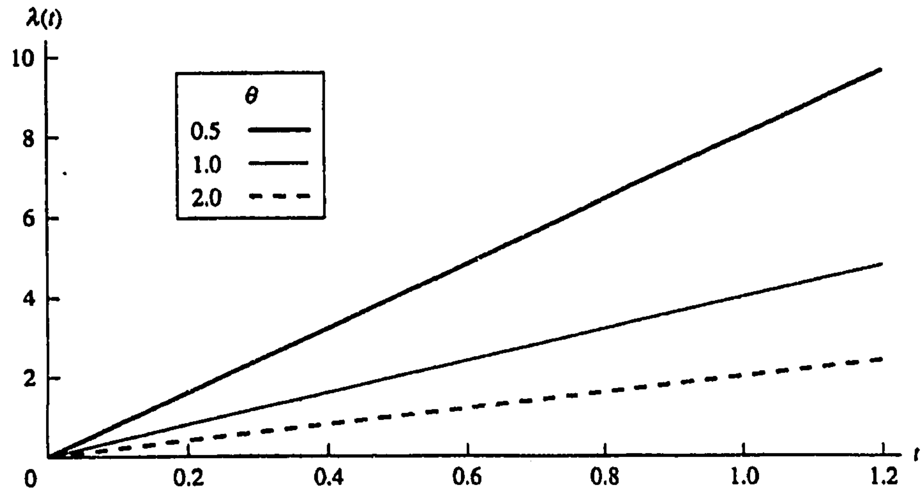


Figure 3.7: The effect of θ on the Weibull rate curve (Ebeling, 1997)

3.1.2.1 FAILURE MODES WITH WEIBULL

For a system comprised of n serially related components or having n independent failure modes, each having an independent Weibull failure distribution with shape parameter β and scale parameter θ_i, the system failure rate function can be determined from

$$\lambda(t) = \beta t^{\beta-1}\left[\sum_{i=1}^{n}\left(\frac{1}{\theta_i}\right)^{\beta}\right] \tag{3.44}$$

This reproductive property of the Weibull distribution is true only when each component has the same shape parameter. If the all failure modes are Weibull with differing shape parameters, then the system failure distribution will not be Weibull (Ebeling, 1997).

3.1.3 THE NORMAL DISTRIBUTION

The normal distribution has been used successfully to model fatigue and wear-out phenomena. It is also useful in analyzing lognormal probabilities. The density function of the normal distribution is shown in figure 3.8 (Ebeling, 1997).

$$f(t)=\frac{1}{\sqrt{2\pi\sigma}}\exp\left[-\frac{1}{2}\frac{(1-\mu)^2}{\sigma^2}\right] \qquad -\infty<t<\infty \tag{3.56}$$

The parameters μ and σ^2 are the mean and variance of the distribution respectively. The effect of σ standard deviation is seen in figure 6.9 and on the normal hazard rate

$$\text{The reliability function } R(t)=\int_t^\infty \frac{1}{\sqrt{2\pi\sigma}}\exp\left[-\frac{1}{2}\frac{(1-\mu)^2}{\sigma^2}\right]dt \tag{3.57}$$

However, there is no closed form solution to this integral and it must be evaluated numerically. If the transformation

$$z=\frac{T-\mu}{\sigma} \tag{3.58}$$

is made then z will be normally distributed with a mean of zero and a variance of one . The PDF for z is given by

$$\phi(z)=\frac{1}{\sqrt{2\pi}}e^{-z^{\frac{1}{2}}} \tag{3.59}$$

and z is referred to as the standardized normal variant. Its cumulative distribution function is

$$\Phi(z)=\int_{-\infty}^{z}\phi(z')dz' \tag{3.60}$$

Cumulative probabilities of any normally distributed random variable can be obtained from standard tables.

Therefore in general,

$$R(t)=1-\Phi\left(\frac{t-\mu}{\sigma}\right) \tag{3.61}$$

$$F(t) = \Phi\left(\frac{t-\mu}{\sigma}\right) \tag{3.62}$$

The hazard rate function is

$$\lambda(t) = \frac{f(t)}{1-\Phi[(t-\mu)/\sigma]} \tag{3.63}$$

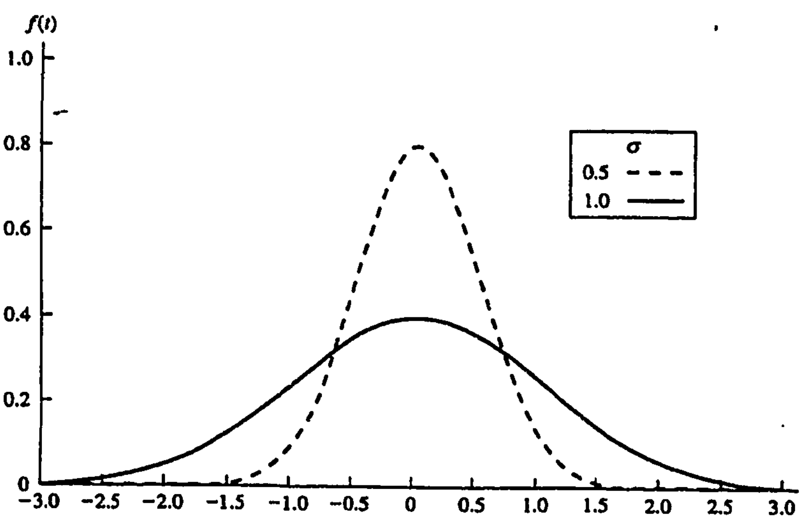
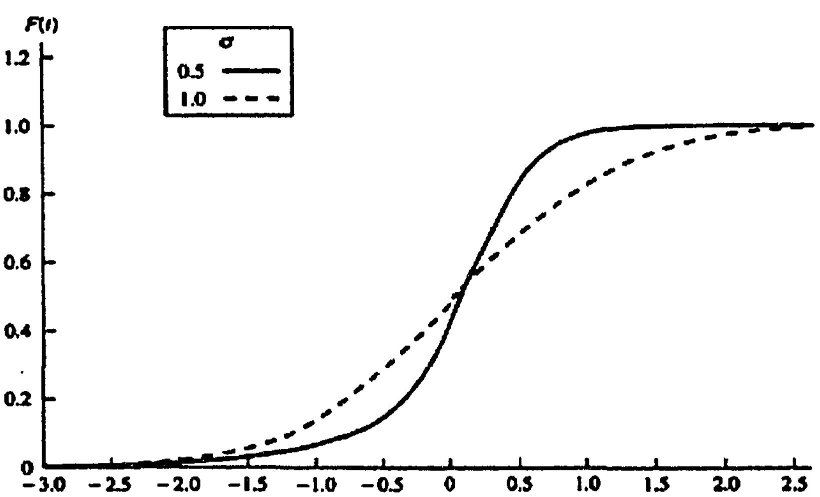
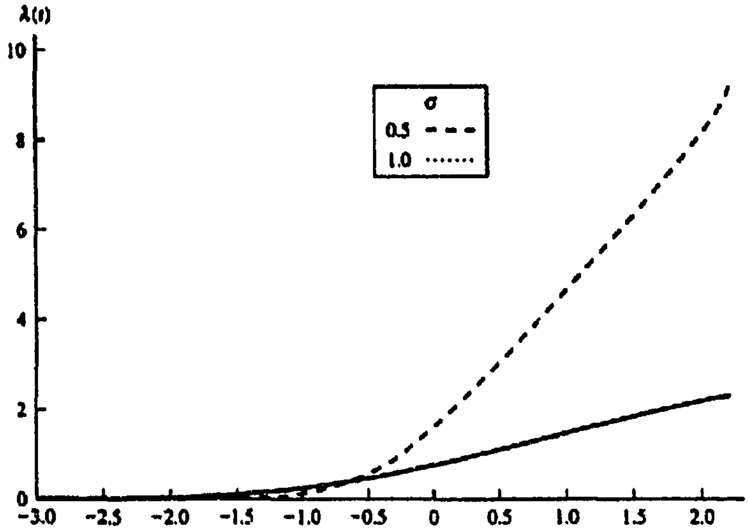


Figure 3.8: The effect of the standard deviation σ on the normal probability density function (Ebling,1997)



(a)



(b)

Figure 3.9: Effect of the standard deviation on
(a) the normal cumulative function
(b) the normal hazard rate curve (Ebeling,1997)

3.1.4 LOG NORMAL DISTRIBUTION

If the random variable T, the time to failure has a lognormal distribution, the logrithm of T has a normal distribution. The density function for the lognormal is

$$f(t) = \frac{1}{\sqrt{2\pi}st}\exp\left[-\frac{1}{2s^2}\left(\ln\frac{t}{t_{med}}\right)^2\right] \qquad t \geq 0 \qquad (3.64)$$

where the parameter s is a shape parameter and t_{med} , the location parametetr, is the median time to failure. The distribution is defined for only positive values of t and is therefore more appropriate than the normal as a failure distribution. Examples of the lognormal probability density function for different values of the shape parameter are provided in Fig 3.10a. Like the Weibull distribution, the log normal can take on a variety of shapes. It is frequently the case that the data that fit a Weibull distribution will also fit a log normal distribution (Ebeling, 1997).

The mean, variance, and mode of the lognormal are

$$MTTF = t_{med} \exp(\frac{s^2}{2}) \tag{3.65}$$

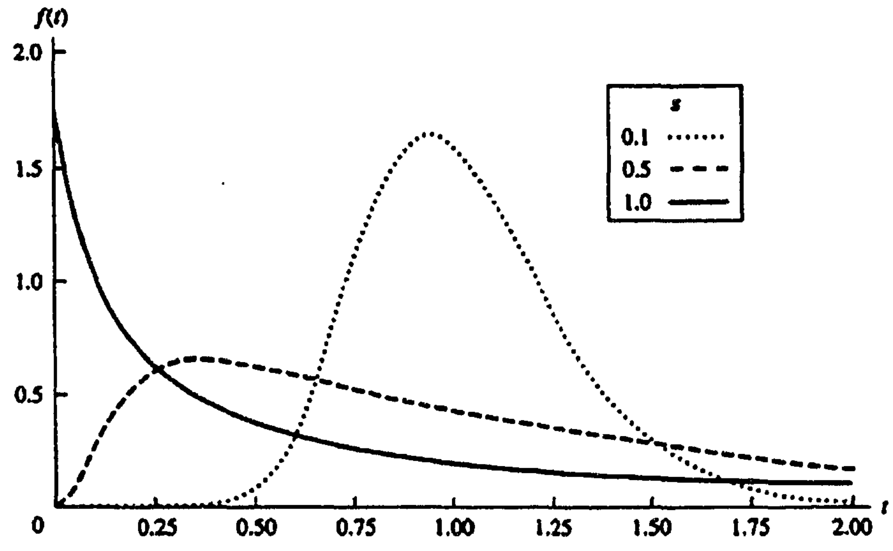
$$\sigma^2 = t_{med}^{\ 2} \exp(s^2)\left[\exp(s^2) - 1\right] \tag{3.66}$$

$$t_{mode} = \frac{t_{med}}{\exp(s^2)} \tag{3.67}$$

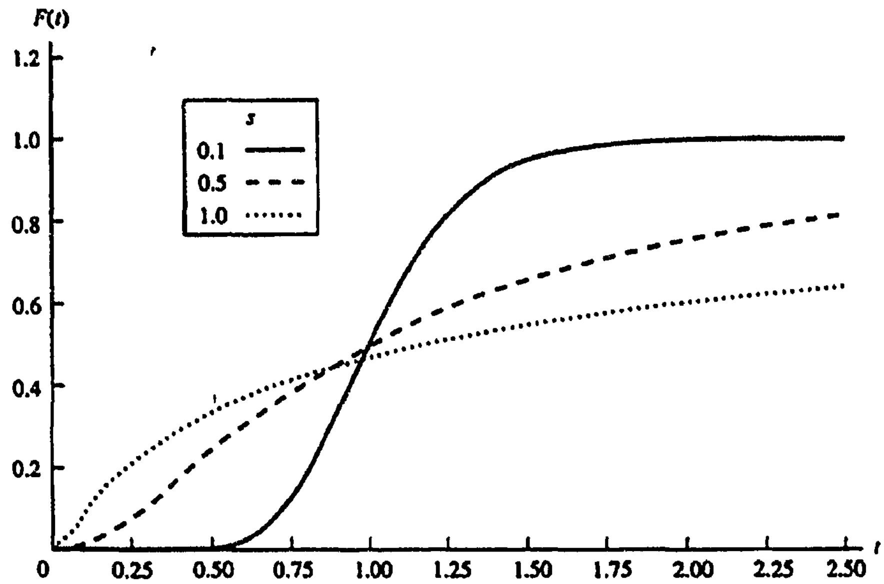
Since the logarithm is a monotonically increasing function

$$F(t) = \Phi\left(\frac{1}{s}\ln\frac{t}{t_{med}}\right) \tag{3.68}$$

Then $R(t) = 1 - \Phi\left(\frac{1}{s}\ln\frac{t}{t_{med}}\right)$ (3.69)



(a)



(b)

Figure 3.10: The effect of the shape parameter s
(a) on the lognormal probability density function
(b) on the log normal cumulative distribution function t_{med}=1.0 (Ebeling,1997)

Figure 3.10(b) is a graph of the CDF for different shape parameters for t_{med}=1.0.The hazard rate for lognormal distribution can not be solved analytically. However the lognormal hazard rate can be calculated numerically selected points in time by finding f(t)/R (t) using equation 3.69. The hazard rate function increases until it reaches a peak and then it slowly decreases. This is an uncommon failure rate of many components.

3.2 IDENTIFYING FAILURE DATA

There are two general approaches to fitting reliability distributions to failure data. The first and usually preferred method is fitting the data to a theoretical distribution such as the exponential, Weibull, normal, or lognormal distributions. The second is to derive directly from the data an empirical reliability function or hazard rate function

3.3. EMPIRICAL METHODS

Empirical methods of analysis are also referred to as non-parametric methods or distribution free methods. The objective is to derive directly from failure data (time), the failure distribution, reliability function and hazard rate function. A brief description is presented below.

The parametric approach consisting of fitting a theoretical distribution is preferred. The empirical method is generally characterized by the collection of a large amount of data before much speculation as to their significance or without much idea of what to expect in contrast to with more theoretical methods in which the collection of data is guided largely by preliminary theoretical exploration of what to expect. The empirical method is only necessary in entering hitherto completely unexplored fields. The empirical method is information derived from the trials and errors of experience. The empirical methods become less empirical as the mastery of the field increases and gives way to theoretical methods.

However there are occasions when no theoretical distribution adequately fits the data and only recourse is to apply the empirical analysis methodology. This empirical analysis is case specific and need only for every specific condition when no theoretical distribution adequately fits the data. When theoretical distributions do not adequately fit the data the empirical methodology is followed. Though this approach is not used in present thesis, a brief description is presented for information.

3.4 UNGROUPED COMPLETE DATA

Given that, $t_1, t_2 \ldots\ldots t_n$ where $t_i \leq t_{i+1}$ n ordered failure times comprised in a random sample the number of units surviving at time t_1, is n-i. Therefore a possible estimate for the reliability function, R (t) is simply the fraction of units surviving at time t_i, or

$$R(t_i) = \frac{n-1}{n} = 1 - \frac{i}{n} \tag{3.70}$$

However Equation (6.70) implies that the estimate for cumulative failure distribution is

$$F(t_i) = 1 - R(t_i) = \frac{i}{n} \tag{3.71}$$

Therefore F (t_n) = n/n =1 and there is zero probability of any units surviving beyond t_n. Since, it is unlikely that any sample would include the longest survival time. Equation 6.70 tends to underestimate the component reliability. It is also reasonable to expect the first and last observations on the average, to be the same distance from the 0 percent and 100 percent observations, respectively. That is they are symmetrical with respect to the 0 percent, 50 percent and 100 percent points (Ebeling, 1997).

An improved estimate of the cumulative failure distribution is

$$F(t_i) = \frac{i}{n+1} \tag{3.72}$$

Then $$R(t_i) = 1 - \frac{i}{n+1} \tag{3.73}$$

3.4.1 PLOTTING POSITIONS

Equations (3.71) and (3.72) are only two of several possible estimates for F (t). These estimates are sometimes referred to as plotting positions since they provide the ordinate values in plotting the cumulative distribution function. That is, the points (t_i, F (t_i)) provide a graph of the estimate of F (t). These same ordinates are used in probability plots.

Equation (3.72) provides the mean plotting position for the ith ordered failure. An alternative plotting position is based on the median. The median is often preferred because the distribution of F(t_i) is skewed for values of *i* close to zero and close to n^3. The median positions are functions of both *i* and *n* and they must be computed numerically. Tables are available to provide plotting positions for $F(t)$ for selected *i* and *n*. The formula $F(t_i)=\frac{i-0.3}{n+0.4}$ (Ebeling, 1997) (3.74)

F(t_i)is often used as an approximation of the median position.

3.4.2 PROBABILITY DENSITY FUNCTION AND HAZARD RATE FUNCTION

An estimate of the probability density function may be obtained using Eq.(3.73) and the relationship between $f(t)$ and $R(t)$ given by

$$f(t)=-\frac{R(t_{i=1})-R(t_i)}{t_{i+1}-t_i}=\frac{1}{(t_{i+1}-t_i)(n+1-i)} \quad \text{for } t_i<t<t_{i+1} \tag{3.75}$$

Therefore

$$\lambda(t)=\frac{1}{(t_{i+1})(n+1-i)} \quad \text{for } t_i<t<t_{i+1} \tag{3.76}$$

An estimate of the mean time to failure is obtained directly from the sample mean

$$MTTF=\sum_{i=1}^{n}\frac{t_i}{n} \tag{3.77}$$

and an estimate of the variance of the failure distribution may be obtained from the sample variance:

$$s=\sum_{i=1}^{n}\frac{\left(t_i-MTTF\right)^2}{n-1} \qquad (3.78)$$

Equation (6.78) defines the sample variance and the square root of the variance is the standard deviation.

3.5 GROUPED COMPLETE DATA

Failure times have been place into time intervals, their original values no longer being retained, are referred to as grouped data. Since the individual observations are no longer available, let $n_1, n_2 \ldots\ldots n_k$ be the number of units having survived at ordered times $t_1, t_2 \ldots\ldots t_k$ respectively. Then a logical estimate for $R(t)$ is

$$R(t_i)=\frac{n_i}{n} \qquad i = 1, 2 \ldots k \qquad (3.79)$$

Where n is the number of units at risk at the start of the test. Because of the larger sample size of the grouped data it is generally unnecessary to obtain more precise estimates by considering plotting positions as before (Ebeling, 1997). Therefore

$$f(t)=\frac{R(t_{i+1})-R(t_i)}{t_{i+1}-t_i} \quad \text{for } t_i < t < t_{i+1}$$

$$=\frac{n_i-n_{i+1}}{\left(t_{i+1}-t_i\right)n} \qquad (3.80)$$

$$\lambda(t)=\frac{n_i-n_{i+1}}{\left(t_{i+1}-t_i\right)n_i} \qquad \text{for } t_i < t < t_{i+1} \qquad (3.81)$$

$$\text{The MTTF} = \sum_{i=0}^{k-1} t_i \frac{-(n_i - n_{i+1})}{n} \tag{3.82}$$

Where $t_i = \dfrac{t_i + t_{i+1}}{2}$

3.6 FITTING THE DATA TO A THEORETICAL DISTRIBUTION

The process of fitting the data to a theoretical distribution can be done either through specially drawn graph papers or through probability plots obtained by analytical methods. The merits of each these procedures and the preferred methods are discussed below.

3.7 PROBABILITY PLOTS AND LEAST SQUARES APPROACH

Probability plots provide an informal method of evaluating the fit of data to a distribution. If the points (t_i, $F(t_i)$) i=1,2,,,,,,n on appropriate graph paper, are plotted, a fit to the distribution would graph an approximate straight line. This is because the vertical scale and possibly the horizontal scale have been modified to linearize the cumulative distribution function. Since straight lines are easily identifiable (Ebeling, 1997) a probability plot provides a better visual test of a distribution than comparison of a histogram with a probability density function. However, because of skewness, convenience of use and the ability to plot multiply censored data using rank adjustment method, approximation to the median plotting positions given by Equation (3.74) will be used.

From a probability plot it may also be possible to obtain initial estimates for the parameters of distribution being fitted. Probability plots may also be used when the sample size is too small to construct a meaningful histogram and may be used with incomplete data.

There are two general methods of parameter estimation. They are least squares approach and maximum likelihood estimation. The former has been a popular choice and is tied to many familiar statistical concepts such as linear regression, sum of square's, proportion variance, and root mean squared deviation. Least squares approach unlike MLE requires no or minimal distributional assumptions and is useful in obtaining a descriptive measure for summarizing observed data.(In Jae Myung, 2003). MLE is a mathematics intense process which will be difficult to adopt in an industrial environment. Therefore, least squares approach is applied to data in this thesis.

Least Squares Approach

Field data is often accompanied by noise. Even though all control parameters (independent variables) remain constant, the resultant outcomes(dependent variables) vary. A process of quantitatively estimating the trend of the outcomes also known as regression or curve fitting therefore becomes necessary. The curve fitting process fits equations of approximating curves to the raw field data. Nevertheless, for a given set of data the fitting curves of a given type are generally not unique. Thus a curve with a minimal deviation from all data points is desired. The best fitting curve can be obtained by the method of least squares. The idea is to obtain a straight line with minimum error. Least squares approach provides such a straight line and hence least squares approach is more accurate than any other method.

At this juncture random error and residuals need to be discussed. A linear model is taken for discussion. Consider two variables 'x' and 'y' and check for the adequacy of the model

$y = a + bx + e$

The variable 'e' denotes a random error. The relationship between x and y is linear.

A model appears to be good when there are no errors. But field data always comes with error. The model can be said to be good if there is no connection between 'e' and a + bx, that is the random error is free of 'x' . Hence for predicting y, this model contains all the information based on 'x'. Now there may be other variables which help in predicting 'y'. These will be contained in 'e'. So the following assumption on a model should be verified.

Model Assumption: The random error component is independent of the 'x' component.To check this assumption plot random error 'e' against a + bx. A scatter would indicate that the errors do not depend on a + bx; the errors are free of a + bx. Thus the model is good. At this point the errors are not known. As 'x' and 'y' are known 'a' and 'b' are estimated. Hence a + bx is known, leading to the predicted value of 'y' which is labelled as '$\hat{y}$'.

The estimate of the error is $y - \hat{y}$. This is called the residual and denoted by '$\hat{e}$' The assumption can be verified by plotting '$\hat{e}$' against '$\hat{y}$'. This is the residual plot. A random scatter indicates that the model is good.

The Least squares method is a mathematical optimization technique which, when given a series of measured data, attempts to find a function which closely approximates the data (a "best fit"). It attempts to minimize the sum of the squares of the ordinate differences (called residuals) between points generated by the function and corresponding points in the data. An implicit requirement for the least squares method to work is that errors in each measurement be randomly distributed. According to Gauss-Markov theorem,Myers,2001) least square estimators are unbiased and that the sample data do not have to comply with, a normal distribution. This is quite significant that the industrial data do not always follow normal distribution and least squares approach is a useful tool to analyse the data. The least squares technique is commonly used in curve fitting. Suppose that the data set consists of the points ($x_{i,}$ y_i) with i= 1,2,3 .....n, a function f is required such that $f(x_i) \approx y_i$. Assuming that $f(x_i) = mx + c$. The values of m and x are not yet known. The values that will minimize the sum of the squares of the residuals need to be found out

$S=\sum_{i=1}^{n}(y_i - f(x_i))^2$ This explains the term least squares.

The primary approach to probability plots is to fit a linear regression (least squares) line of the form y = a + bx to a set of transformed data. The nature of the transform will depend on the distribution. If the failure times fit the assumed distribution, the transformed data will graph as a straight line and the fitted regression line will have a high index of fit r. This approach is more accurate than manually plotting the data on special graph paper. The least-squares fits to the exponential, Weibull normal and lognormal distributions are discussed below.

3.8 EXPONENTIAL PLOTS

The cumulative distribution function for the exponential distribution is $F(t)=1-e^{-\lambda t}$ or

$1-F(t)=e^{-\lambda t}$

Taking natural log on both sides

$\ln[1-F(t)]=-\lambda t$

$$-\ln[1-F(t)]=\ln\left[\frac{1}{1-F(t)}\right]=\lambda t \qquad (3.83)$$

Given failure times $t_1, t_2 \ldots\ldots t_k$, the points $(t_i, F(t_i))$ where $F(t_i)$ may be any of the plotting positions, may be plotted on exponential graph paper. The vertical scale is based on the transformation.

$$F(t) \longleftrightarrow \ln\left[\frac{1}{1-F(t)}\right]$$

Since F (MTTF) = $1-e^{-1}=0.632$, the MTTF of the distribution may be estimated directly from the graph by finding the value of t that corresponds to F(t)=0.632. A more accurate fit to the data may be obtained by performing a least square fit of equation (6.83) using

$$\lambda=b=\frac{\sum_{i=1}^{n} x_i y_i}{\sum_{i=1}^{n} x_i^2} \qquad (3.84)$$

Where, $y_i=\ln[1/[1-F(t_1)]]$ and $x_i=t_i$ this equation is used. The slope is b and the MTTF is 1/b.

3.9 WEIBULL PLOTS

From the Weibull cumulative distribution function

$$F(t) = 1 - e^{-\left(\frac{t}{\theta}\right)^{\beta}}$$

$$\ln\left[\frac{1}{1-F(t)}\right] = \left(\frac{t}{\theta}\right)^{\beta}$$

Applying logarithms again,

$$\ln\ln\left[\frac{1}{1-F(t)}\right] = \beta \ln t - \beta \ln \theta \qquad (3.85)$$

Therefore plot (x, y) will be

$$\left(\ln t_i, \ln\ln\left[\frac{1}{1-F(t_i)}\right]\right)$$

Linear regression (least squares approach) line is of the form y = a + bx

From the least squares fit β = b.

The shape parameter θ is obtained by setting $\theta = e^{\left(\frac{-a}{\beta}\right)}$. Or using Weibull probability plot (t_i, $F(t_i)$).

3.10 WEIBULL GRAPHING

A least squares fit to the data is recommended over a manual plot of the data on probability paper. It is more accurate and less subjective than fitting by a straight line to the data by eye. In addition measures of how well the curve fits the data , such as the index of fit are available. However, a description of the Weibull paper is provided for information. Weibull graph paper is constructed so that data generated from a Weibull distribution will graph as a straight line. The abscissa is a logarithmic scale, and the ordinate, while labeled in terms of the cumulative percentage of failures, F (t) is scaled on the basis of

$$\ln\ln\left(\frac{1}{1-F(t)}\right)$$

Theta, θ, can be estimated from the point on the line that corresponds to 63.2 percent of the failures, since F(θ)= 0.63.2. The 63.2 percent line is often identified on the graph paper. It can be seen from Eq.(3.85) that β can be estimated from the slope of the plotted line. Weibull graph papers are published in different versions and hence care must be taken while finding the slope. The units of abscissa and ordinate may not be the same. The characteristic life θ is found where the fitted line intercepts the 63.2 cumulative percentage lines

3.11 NORMAL PLOTS

For the normal distribution,

$$F(t) = \Phi\left(\frac{t-\mu}{\sigma}\right) = \Phi(z)$$

The inverse of the function can be written as

$$z_i = \Phi^{-1}[F(t)] = \frac{t_i - \mu}{\sigma} = \frac{t_i}{\sigma} - \frac{\mu}{\sigma} \tag{3.86}$$

Which is linear in t. With the appropriate transformation of the vertical scale the points (t_i, F (t_i)) may be plotted. A least squares fit is obtained by setting

$x_i = t_i$ and $y_i = z_i = \Phi^{-1}[F(t_i)]$

The values of z_i may be obtained from standard tables on the basis of corresponding value for $F(t_i)$. From the least squares fit and Equation (3.86),

$$\sigma = \frac{1}{b}, \mu = -a \text{ and } \sigma = -\frac{a}{b}$$

3.12 LOGNORMAL PLOTS

Lognormal probability plots are based on the relationship of the lognormal distribution to the normal distribution. Since

$$F(t) = \Phi\left(\frac{1}{s}\ln\frac{t}{t_{med}}\right) = \Phi(z)$$

Then $z = \Phi^{-1}[F(t)] = \frac{1}{s}\ln t - \frac{1}{s}\ln t_{med}$

and the points ($\ln t_i$, z_i) are plotted or on lognormal probability paper, the points (t_i, $F(t_i)$)are plotted. For a least squares fit, $x_i = \ln t_i$ and $y_i = z_i$. The shape parameter s, is the reciprocal of the slope of the fitted line and t_{med}, the median, is obtained from the y intercept of the fitted line. That is,

$$s = \frac{1}{b} \text{ and } t_{med} = e^{-sa}$$

The various steps in failure modeling are shown in Fig 3:11

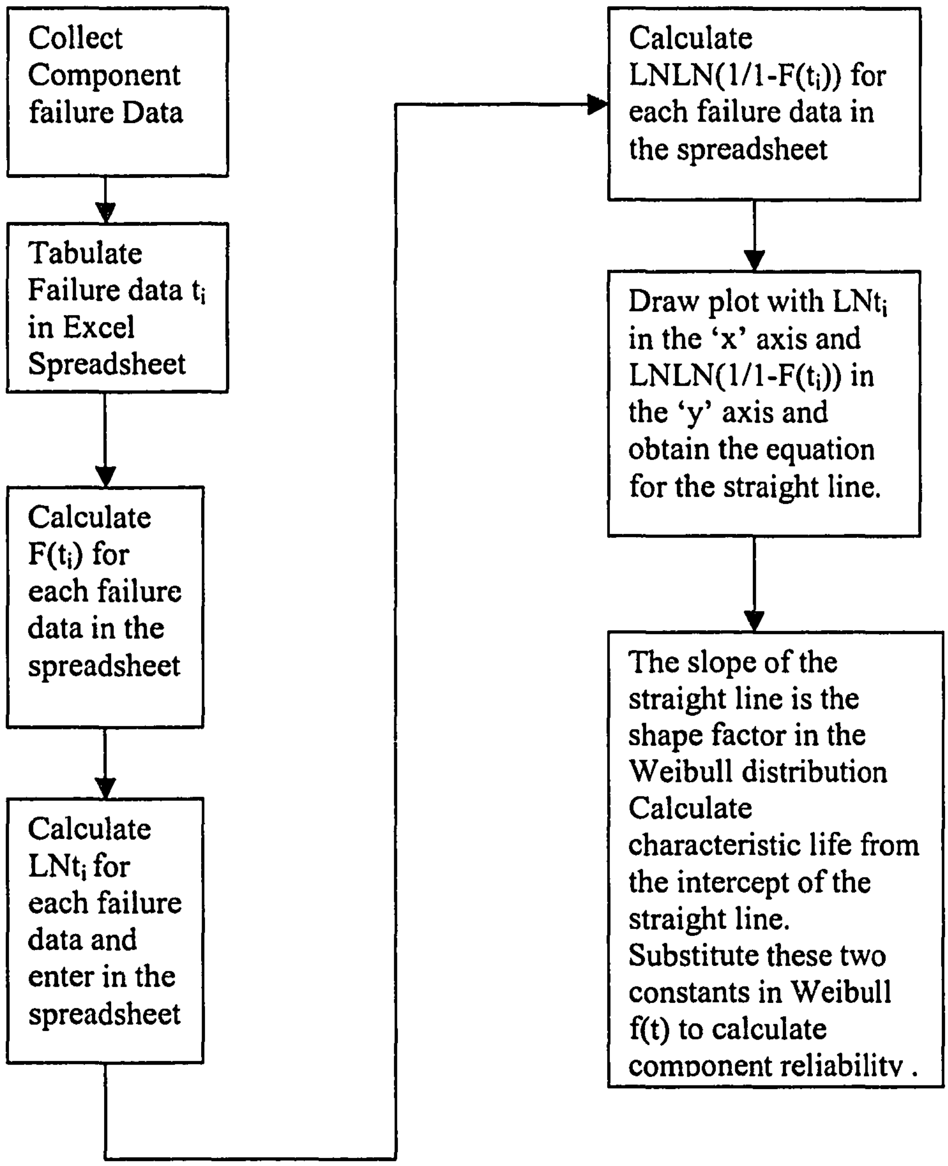


Figure 3.11: Steps in Failure Data modeling

Chapter 4

SYSTEM DEFINITION

System definition is the first step in identifying the components to be inspected. Systems are defined based on the functions they perform. The boundaries of the systems are based on criteria specific to particular needs (i.e. safety aspects, operational requirements, process interactions, jurisdictional constraints, available data, etc.). In the case of fossil plants, the criteria are operational requirement and safety.

4.1 BOILER SYSTEM

Steam generators or boilers are a central element in today's modern thermal power station. They convert the energy in the fuel to a useful form – steam. The generated steam turns turbine – generator sets to produce electric power. Their primary objective is to provide the desired steam flow rate at specified temperature and pressure as efficiently and as cost effectively as possible from the fuel supply. Boilers are made of pressure parts (tubes, headers and cylindrical vessels) which separate the products of combustion (flue gas) from the water while permitting heat transfer to generate steam. This creates two separate flow paths or circuits: the air and gas circuit and the steam water circuit. Two basic designs are used for boiler: the firetube boiler and the water tube boiler. In the fire tube boiler, the hot gases pass through the tubes which are immersed in a cylindrical vessel containing the water. In the watertube boiler, the water and steam flow through the tubes with hot gases passing outside. Cost, size and technical factors tend to limit firetube boilers to smaller low pressure industrial applications while watertube boilers supply the majority of steam used in medium and high pressure applications such as thermal power stations. As a result, water tube boilers are the central focus of this chapter.

4.1.1 COMPONENTS IN THE SYSTEM

The components of the boiler system are water wall tubes, superheater tubes, reheater tubes and economiser tubes. These components are linked in series and failure of one component will shut down the boiler as shown in Figure 4.1.

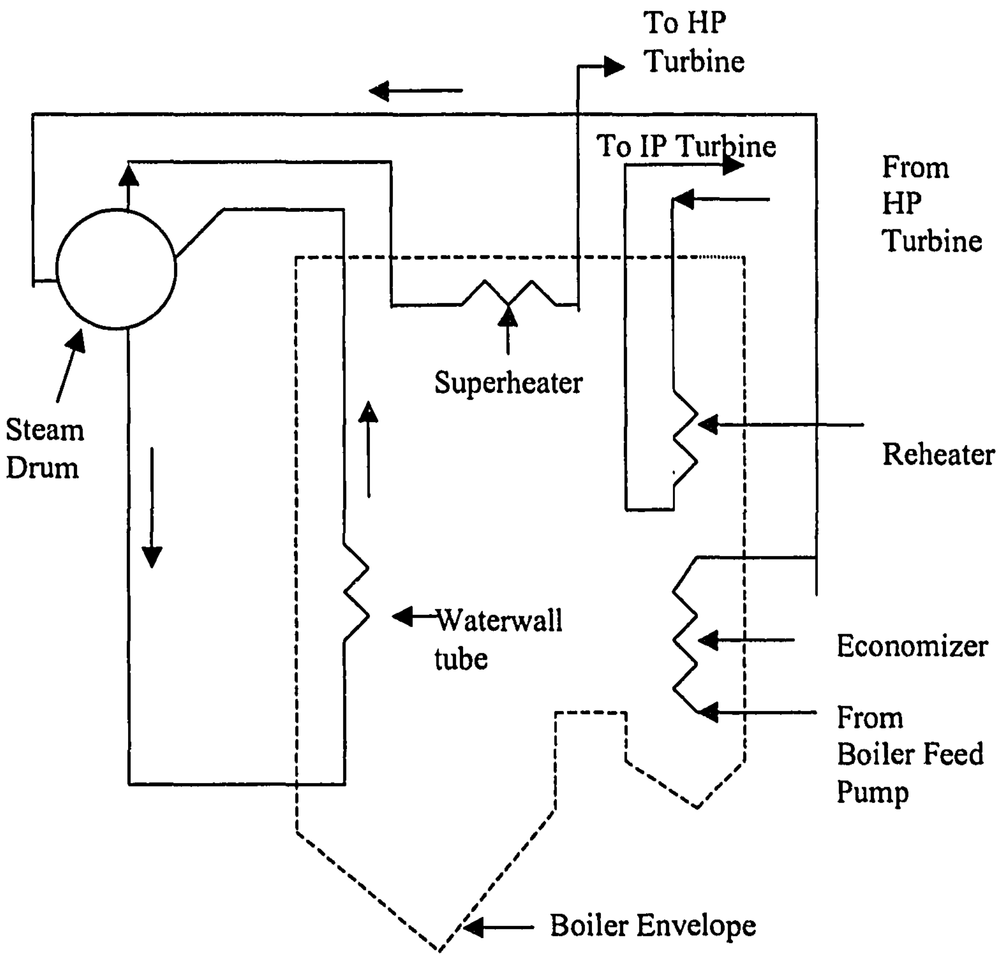


Figure 4.1: Boiler Flow System

A cross section of a water tube power boiler is shown in Figure 4.2 The boiler consists of water wall tubes, superheater tubes, reheater tubes and economizer tubes.The large utility boiler is the waterwall type. A waterwall boiler is basically a box whose walls are made up of tubes through which water flows. The fuel is burned in the 'box' or furnace as it is commonly called. Heat is transferred to the water that flows through the tubes, and thus steam is generated. The flow of water through the tubes is important not only to generate steam but also to keep the tubes cool enough so that they do not become overheated and fail. Some provision must be made for this flow. In most boilers water circulates from a drum at the top of the boiler, through pipes called downcomers to the bottom of the boiler and then up through the waterwall tubes to the drum again. Figure 4.3 shows waterwall tubes on the furnace walls.

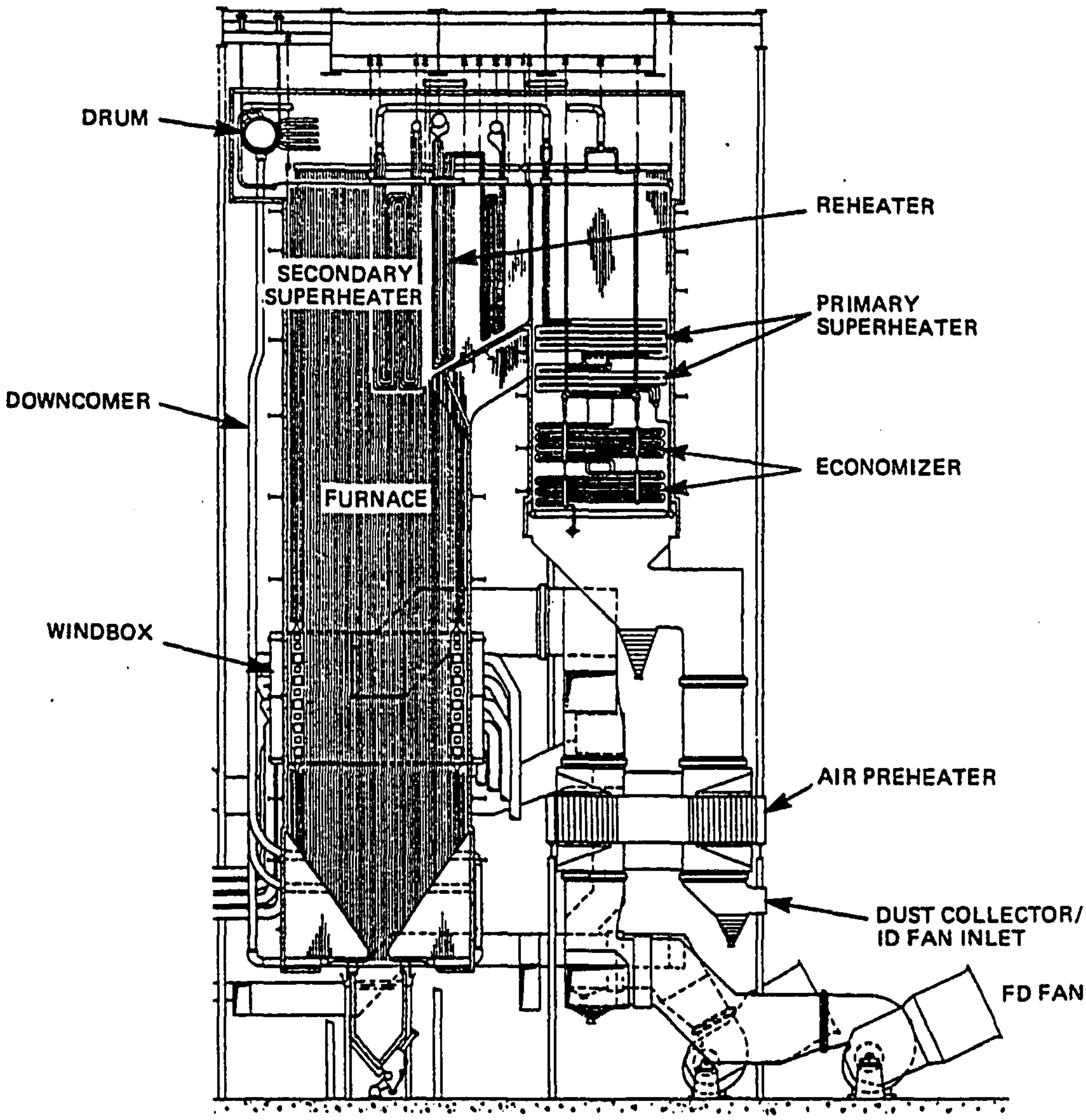


Figure 4.2: Cross Section of a Power Boiler(Combustion Engineering Inc)

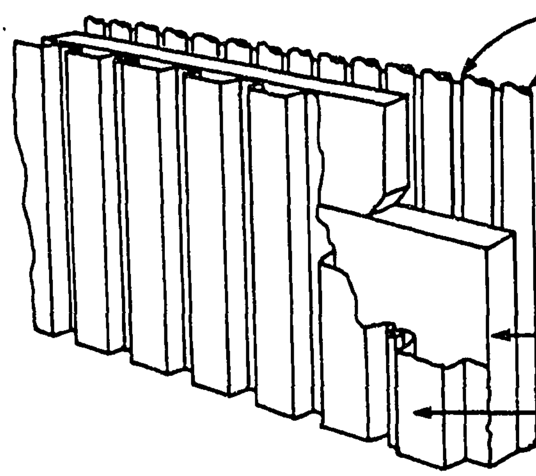


Figure 4.3: Waterwall Tubes(Babcox & Wilcox)

For many boilers the force of natural circulation due to convection provides enough circulation through waterwall tubes for both good heat transfer and adequate cooling of the tubes. Heat is transferred from burning fuel in the furnace to the water in the waterwall tubes. When the water is heated its density decreases and tends to rise in the tubes and flow towards the drum. When it becomes hot enough to reach saturation temperature, steam bubbles are formed that also rise towards the drum because they are so much less dense than the water around them. As the heated water and steam rise in the waterwall tubes cooler water is drawn into the bottom of the bottom of the tubes from the downcomers, which draw water from the boiler drum. The rate of circulation is much greater than the rate of steam generation in boiler of this type. The ratio of number of pounds of water circulated to the number of pounds of steam generated may be as high as 8 or 10 to 1.

The rate of circulation due to convection depends on the difference in density between the heated water and steam mixture in the waterwall tubes and the water in the downcomers. The density can be affected by two parameters. One is the height of the boiler. The greater the height of the boiler, greater the difference in pressure.(pressure at the bottom is higher due to the static head). And thus the density between the bottom and top of the boiler. This is one reason boilers are so high, often as 150 to 200 feet. The second parameter is boiler operating pressure. If the pressure in the boiler increases to what is known as the critical pressure 3206 psia, there is no difference in density between steam and water, so there can be no natural circulation. The operating pressure need not be increased to the critical pressure before the point is reached where natural circulation no longer provides adequate flow through the waterwalls. Boilers with pressures as low as 1800 psia may have inadequate natural circulation. Forced circulation is almost always necessary when operating pressure reaches 2600 psia. When natural circulation becomes inadequate, a boiler must use forced circulation. This arrangement uses pumps, usually located in the downcomer piping, to aid in circulation, which permits higher operating pressures and better control of operation.

The steam in the drum of a drum type boiler is at saturated conditions. If the operating pressure of the boiler is 2600 psia, the temperature is 669^0 F. Modern power plants use temperatures of 950^0 F to 1050^0 F routinely to increase efficiency. Thus it is necessary to add more heat to the steam after it exits the drum before it is piped to the turbine. A special section of the boiler called superheater is used to raise the steam temperature.

The efficiency of the power plant may be increased by reheating the steam after it has passed through part of the turbine. Special sections of the boiler called reheaters are provided for this purpose. Figure 4.4 shows the entry of feedwater to the economizer and then on to the steam drum, waterwalls in the furnace and back to the drum for eventual flow to the superheaters.

Another special heat exchanger portion of the boiler is called the economizer. The economizer uses hot flue gas to heat the water that enters the boiler. This increases efficiency by recovering some of the heat in the flue gas. Also by transferring some heat over a lower temperature difference than in the furnace and in the waterwalls, the heat is transferred more efficiently.

The heating of water and the production and super heating of steam have been discussed to this point without discussing the mechanism of heat transfer from the burning fuel. On the furnace side of the boiler, there are two types of heat transfer that predominate, radiation and convective heat transfer. This is because the fireball from burning fuel is so hot that a tremendous amount of radiant energy (infrared and other radiation) is generated. Radiation is proportional to the 4^{th} power of the absolute temperature difference.

Almost all the heat transferred to the waterwalls of the boiler is by radiation. After the fuel burns the flue gas that remains is still very hot but much less hot than the fireball, so there is negligible radiation. Heat is transferred from flue gas by convection to other tubes in the boiler. Usually the superheater and reheaters are in convection portion of steam generator and the economizer is always in this section.

Heat transfer in the boiler waterwall tubes is also very important. It is complicated by the fact that it occurs as water changes phase to steam. The transformation from water to steam can occur in two distinct ways, nucleate boiling and film boiling. In nucleate boiling steam bubbles grow on the inside of the tube walls and are swept away from the wall by the water.

In film boiling, a thin film of superheated steam covers the inside diameter of the tube either because the water flow through the tube is not great enough, the tube becomes too hot or a combination of the two (the tube may become too hot because the flow is too low). The heat transfer through the film of steam is much less than that through water. This means that when film boiling occurs, the tubes are likely to overheat. This point of transition from nucleate to film boiling is called departure from nucleate boiling often abbreviated as DNB. It is important in steam generator design and operation to limit heat release in the furnace and to provide enough flow so that the point of DNB is never reached. If DNB occurs, serious damage to the tubes will occur due to overheating.

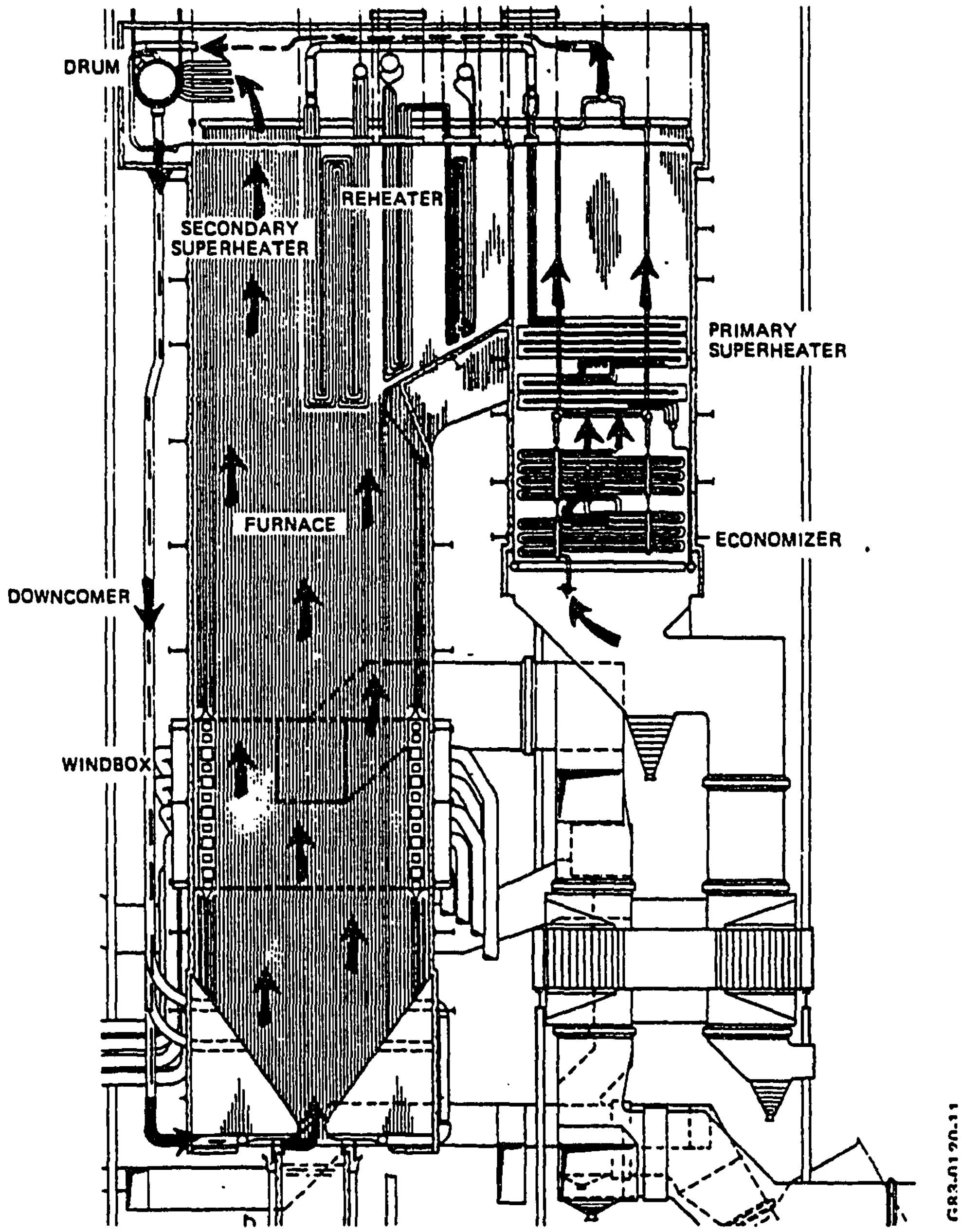


Figure 4.4: Flow Path for Production of Steam(Combustion Engineering Inc)

The efficient combustion of fuel and transfer of heat in the boiler requires that adequate combustion air be provided and that flue gas be removed from the area of combustion. Figure 4.5 shows the flow path of flue gas in a typical boiler.

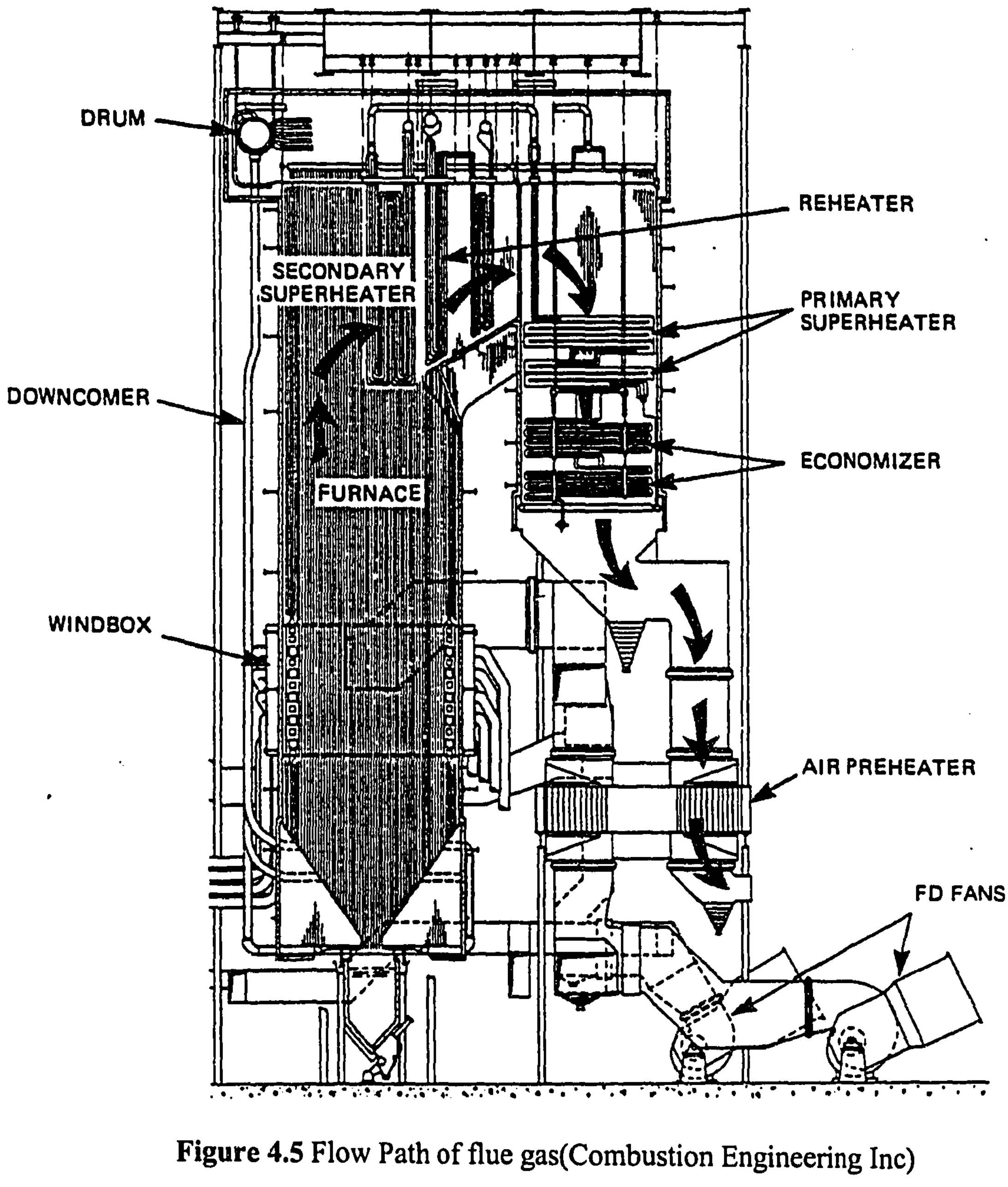


Figure 4.5 Flow Path of flue gas(Combustion Engineering Inc)

In some small or old boilers this is accomplished solely by natural convection or as it is commonly known natural draft. The hot flue gas rises through the stack and draws in cool air for combustion.

As the boilers become larger, however, natural draft becomes inadequate and it becomes necessary to add a fan to blow enough air for combustion into the furnace. If the fan is big enough it will pressurize the boiler furnace and aid in the removal of flue gas also. Such a fan is called Forced Draft Fan. Boiler with only FD Fans are called pressurized furnace boilers because the boiler furnace pressure is above atmospheric pressure. This can be a problem because the flue gas, which is toxic due to the presence of heavy metals and corrosive and fly ash leak out of smallest openings in the furnace, causing maintenance and personnel safety problems. Also, some boilers with considerable convective heat transfer area need more than just a FD fan to move the flue gas.

The solution to these problems is another fan that takes suction on the flue gas exit. Such a fan is called an induced draft fan (ID) fan. Boilers having both FD and ID fans operate at a slightly negative furnace pressure as the ID fans draw the flue gas from the furnace (-0.05 in H_2O). In this way the problem of leaking flue gas and fly ash is eliminated. Such a boiler is called a balanced draft boiler.

Another feature seen in most large utility boiler combustion air and flue gas systems is the combustion air heater. The flue gas that exits from the steam generator is commonly as hot as 600^0 F and represents a major loss of heat and source of inefficiency in the power plant. One way to reduce this inefficiency is to utilize a heat exchanger so that flue gas can heat the combustion air. It is possible to reduce the temperature of the existing flue gas to 300^0 F or less. Such a heater is called an air heater. Tubular air heaters or more commonly rotary air heaters called Ljungstrom after the inventor. The rotary air heater, described later in greater detail later is basically a large porous wheel that rotates from the flue gas duct where it is heated to the combustion air duct where it gives up heat to the air. The major components are described in the following paragraphs.

4.1.1.1 WATERWALLS

The waterwall tube steam generator was described as a box with walls made up of water filled tubes. The construction of those walls is an important feature of the steam generator. A typical cross section of waterwall is shown below in Figure 4.6

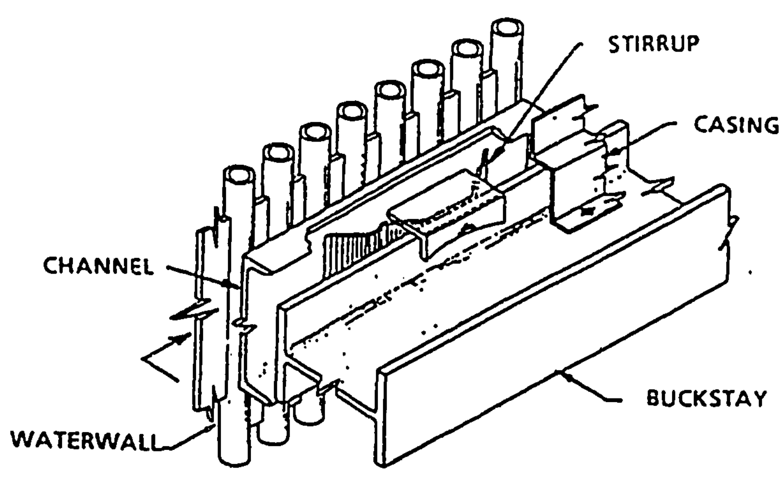


Figure 4.6: Standard Waterwall tube construction (Combustion Engineering Inc)

The above figure shows tubes joined by membrane which is a steel bar welded between adjacent tubes. This construction used in both natural and forced circulation units for all types of firing, has flat wall sections composed of panels of single rows of tubes on centres wider than a tube diameter and connected by means of a membrane bar securely welded to each tube on its centre line. This design results in a continuous wall of rugged, pressure tight construction. The individual panels are of a width and length suitable for economical manufacture and assembly, with bottom and top headers attached in the shop before shipment to for field assembly. Typical furnace wall using membrane construction is shown in Figure 4.7.

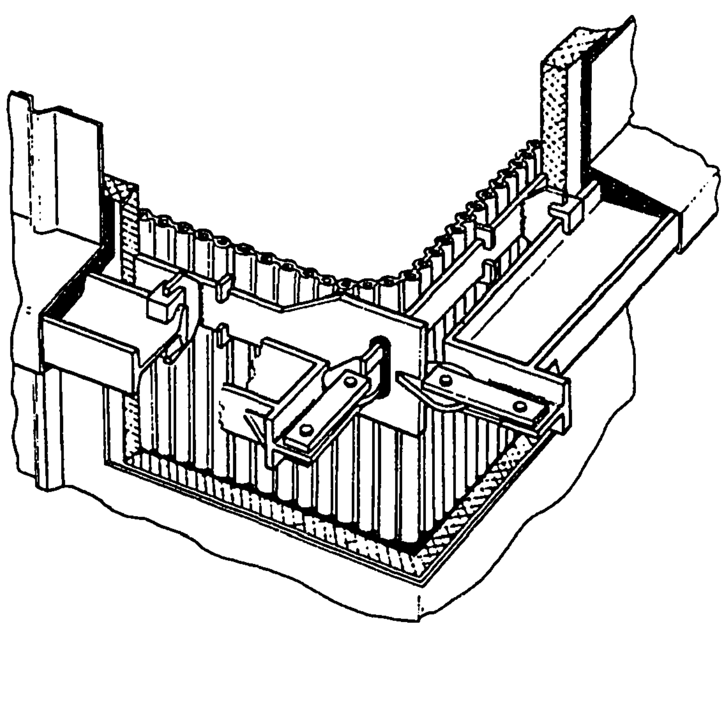


Figure 4.7: Boiler Furnace waterwall (Babcock)

These membrane walls are water cooled walls constructed of bare tubes joined together by thin membrane bars. The walls thus formed are gas tight and require no inner casing to contain the products of combustion. Insulation is provided on the outer side of the wall and metal lagging to protect the insulation.

4.1.1.2 SUPERHEATERS AND REHEATERS

Because the construction of reheaters is essentially the same as that of superheaters the following discussion also applies to reheaters. Except for some special applications, superheaters are located within the steam generator setting at a point where the gas temperatures are high enough to produce the desired steam temperature with a reasonable amount of tube surface and without excessive tube temperature.

There are basically two types of superheaters, the convection type and the radiant type. Either of these superheaters can be further described by its orientation in the furnace or gas path and also by whether it is a primary or secondary superheater. Types of superheaters are described below.

1. Radiant Superheaters – These superheaters are positioned above the boiler furnace at the front of the boiler and are the first superheaters that the gases contact. They receive most of their heat from radiation given off by the firewall.
2. Convection Superheaters – These superheaters are located in the back pass of the boiler gas path, therefore receiving heat from the flow of hot gases over the tubes (convective heat transfer)

The orientations of superheaters are defined as follows:

1. Pendent Superheaters – The term pendent describes a superheater that is hung or suspended in the gas path. The hot gases flow between the tubes in the tube bundle. Pendent superheaters are not drainable.

2. Platen Superheaters – The term platen describes a radiant pendent superheater that is suspended through the furnace roof but oriented parallel to the side walls of the furnace.

These terms apply to reheaters as well as to superheaters . Figure 4.8 shows a drum type steam generator with a radiant pendent type secondary superheater and a convection type primary superheater. Steam flows from the drum first to the primary and then to the secondary superheater. Figure 4.9 illustrates the flow of steam through the pendent reheater in the same boiler.

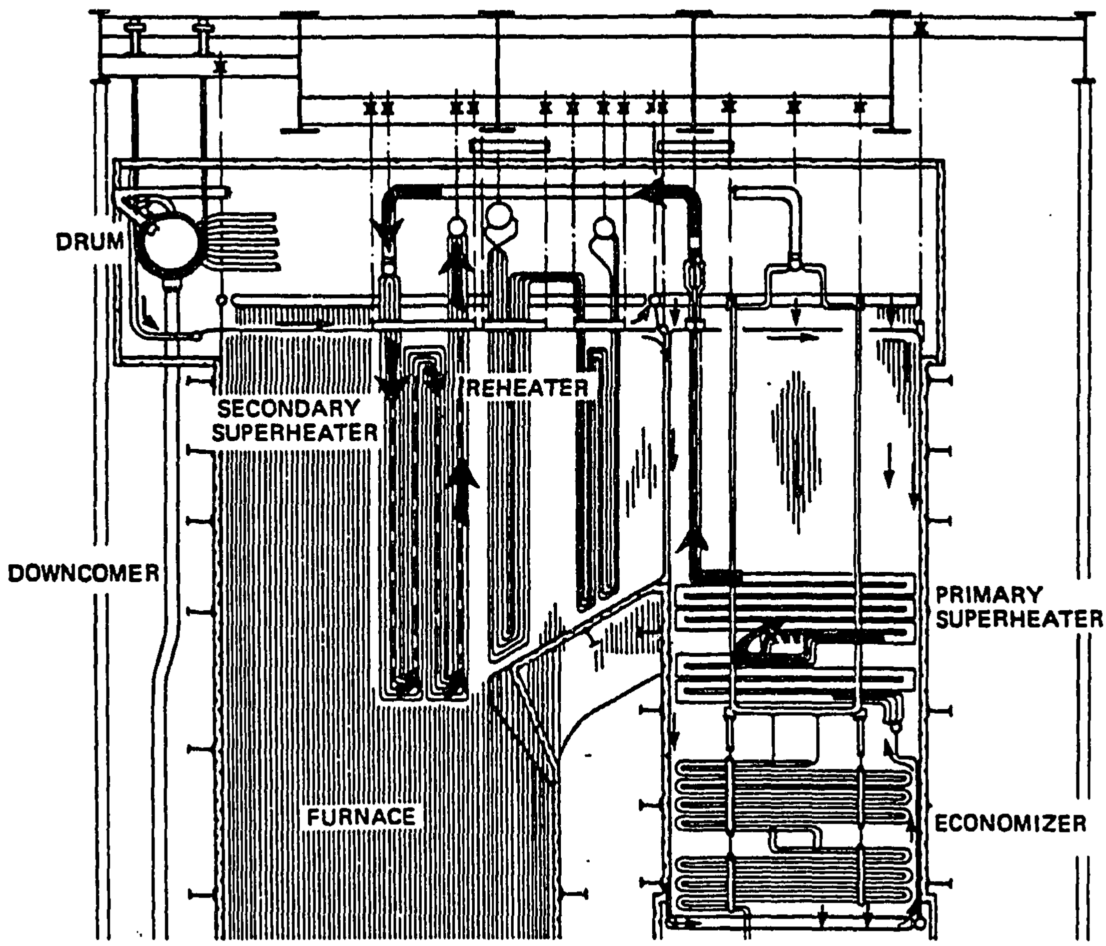


Figure 4.8: Flow Path for Superheated Steam (Combustion Engineering Inc)

Superheater and reheater design considerations are basically the same but reheaters are limited by steam pressure drop. The pressure drop in reheaters is critical because the gain in efficiency can be nullified by too great a pressure drop through the reheater system.

On coal fired units the side-to-side spacing between the tubes is normally governed by the gas temperature and the fouling properties of the ash. On oil-fired units the tube spacing can be closer because the ash percentage is much less.

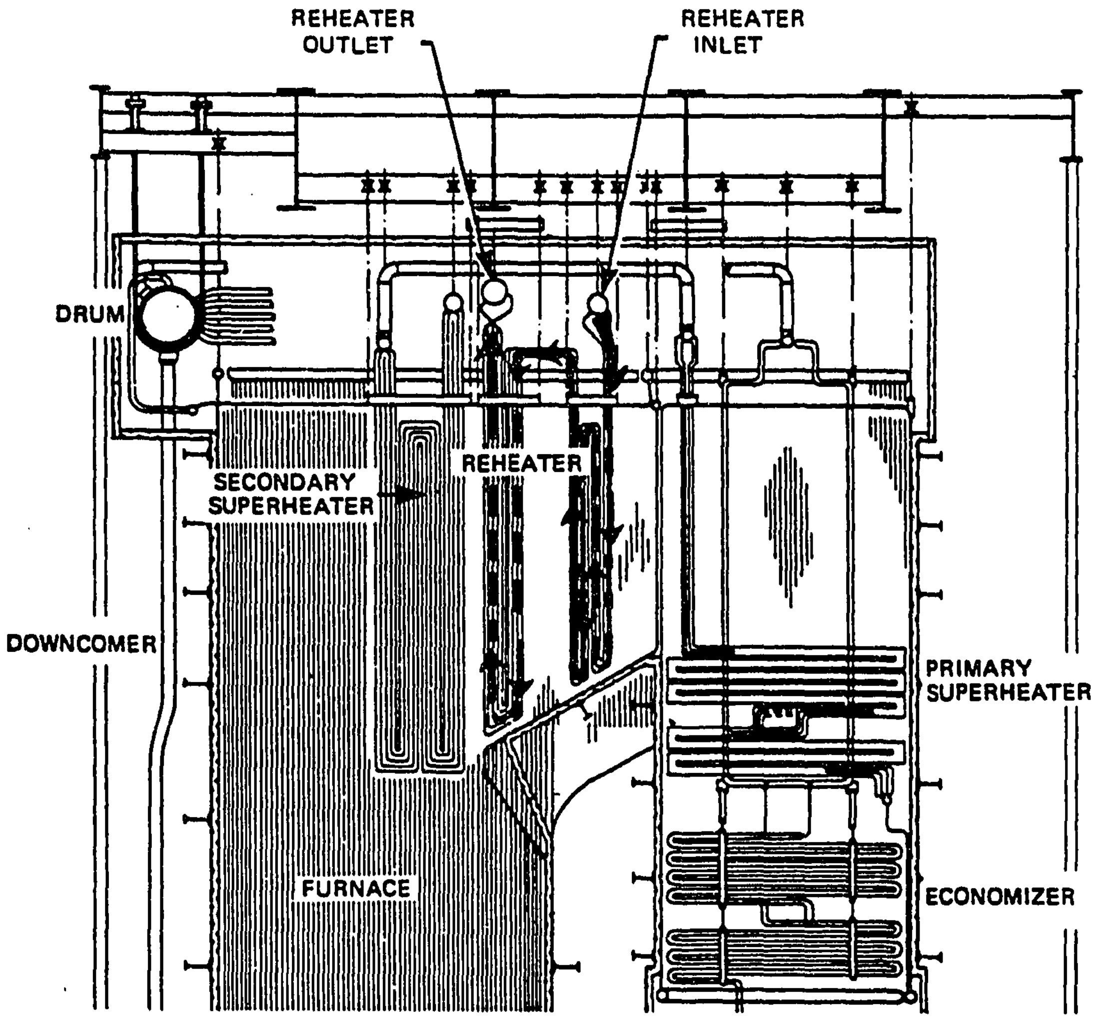


Figure 4.9: Flow paths for reheated steam (Combustion Engineering Inc)

During start up, significant load swings and forced cooldowns, the superheaters and reheaters are subjected to thermal stresses. Consideration must be given to the forced cooling rates because maximum header stresses normally occur during forced cooldowns.

The design of superheater and reheater tubes is normally based on creep rupture properties of the material. Increased temperature will lead to dramatic shortening of life of a typical superheater element. In addition to the reduction in life due to creep rupture properties, intermittent operation above allowable design values will substantially increase thermal stresses and reduce life.

The most important thing the operator can do to ensure satisfactory life of superheaters and reheaters is to limit the furnace exit gas temperature until steam flow is established through both the superheaters and reheater. This is done by adjusting the firing rate during start up of steam generator. Superheat operation at 100^0 F above the material temperature design value results in a tremendous reduction in superheater life.

When choosing materials for superheater and reheater tubes designers must consider the oxidation resistance and economics involved in addition to the maximum allowable stress. The use of carbon steel should be extended as far these considerations permit. Because superheaters and reheaters are located in zones of relatively high gas temperatures, it is preferable to have the tubes themselves carry the major support loads. In horizontal superheaters the load is usually transferred to the boiler or wall tubes by means of lugs, one lug welded to the superheater tubes. In many cases these lugs are made of high chromium –nickel alloy.

4.1.1.3 ECONOMIZERS

The economizer stretches across the exit of the convection pass. It is essentially a counter flow heat exchanger. Figure 5.4 shows the location of the economizer. Economizers are normally equipped with vent and drain valves, a recirculation line and inlet stop check valves.

The vent and drain valves are used during filling and draining of the economizer. The economizer recirculation valve keeps the feedwater from boiling or steaming , the recirculation system is used during startup to ensure flow through the economizer.

The inlet stop check valves prevent the feedwater from flowing in a reverse direction. For example, during shutdown and after the feedwater supply has been secured, the boiler is at a higher pressure than the feedwater system. The inlet stop check valve ensures that the economizer remains full of water.

The economizer tubes can be plain, studded, or finned. Studs and fins help provide additional surface area to transmit heat from the flue gas to the feedwater but they can plug and restrict flue gas flow. Increasing the surface of the tubes on the gas side of the economizer is done because the coefficient for convective heat transfer is low for gases. To offset the low coefficient the area is increased. This makes it possible to use a smaller economizer. On coal-burning units, finned economizer tubes are not always used because the high ash content of the combustion gases leads to plugging. When fins are not used the size of the economizer has to be increased. The economizer tubes face a maximum temperature of 710^{0} F and the heat transfer is 100% convection. At Holyrood Generating station there had been just one failure in 20 years. As heat transfer in the boiler envelope takes place through all the three modes of heat transfer, (conduction, convection and radiation), waterwall tubes are subjected to a temperature of about $1400\ ^{0}$ C and tubes of other components except economizer tubes, are likely to encounter temperatures around $1200\ ^{0}$ F. The economizer tubes are at the tail end of the boiler heat stream and hence are subjected to about 660^{0} F only and this temperature is below the recommended service temperature of 850^{0}F. The economizer tubes are carbon steel SA192. The maximum recommended service temperature for this steel is 850^{0}F (French, 1990). There is no failure of economizer reported from 32 Turbine-Generator units, of capacity 100 to 199MW, in the Generating Availability Data System maintained by North American Electric Reliability Council for the years from 1998 to 2002. As there is only one failure reported for economizer from Holyrood Generating Station in 20 years and with the absence of any economizer failure in the NERC – GADS report, the economizer is not considered for analysis in this thesis.

4.2 BOILER AIR AND GAS SYSTEM

The boiler and gas system provides combustion air and force the products of combustion through the boiler to the stack. This system consists of forced draft fan, steam coil air heater and rotary air heater. Though the largest equipment in the system is the rotary air heater and is also subjected to flue gas temperatures around 710^0 F, it does not fail often enough to cause production loss. The reason being that it rotates at a very low speed of about 3 RPM. Moreover, it consists fabricated plates and seals which are regularly replaced annually. The equipment of concern is the forced draft fan which handles large amount of air, rotating at 1500 RPM. It consists finely aligned components whose failure can bring the fan to fail and result in loss of production. Therefore, in this system forced draft fan is considered. The rotary air heater is a heavy equipment It is a regenerative air heater in which heat is transferred to elements rotating at 3 RPM, when they alternatively come into contact with furnace flue gas and air from forced draft fan. The rotary air heater is important for continuous production and is considered here. The air and gas flow is shown in Figure 4.10 The description of the major components in this system are provided in the following paragraphs.

Typical parameters of Air and Flue gas are given below:

a.	Air to FD Fan Temperature	95^0 F
b.	Air Heater Air inlet Temperature	116^0 F
c.	Air Heater Air Outlet Temperature	480^0 F
d.	Flue Gas Temperature entering Air Heater	675^0 F
e.	Flue Gas Temperature leaving Air Heater	500^0 F
f.	Furnace Pressure	30 psi

4.2.1 COMPONENTS IN THE SYSTEM

a.	1500 HP, 132, 565 cfm Forced Draft Fans	2 units
b.	21 Feet Circumference 5 HP, 3 RPM Rotary Air heaters	2 units

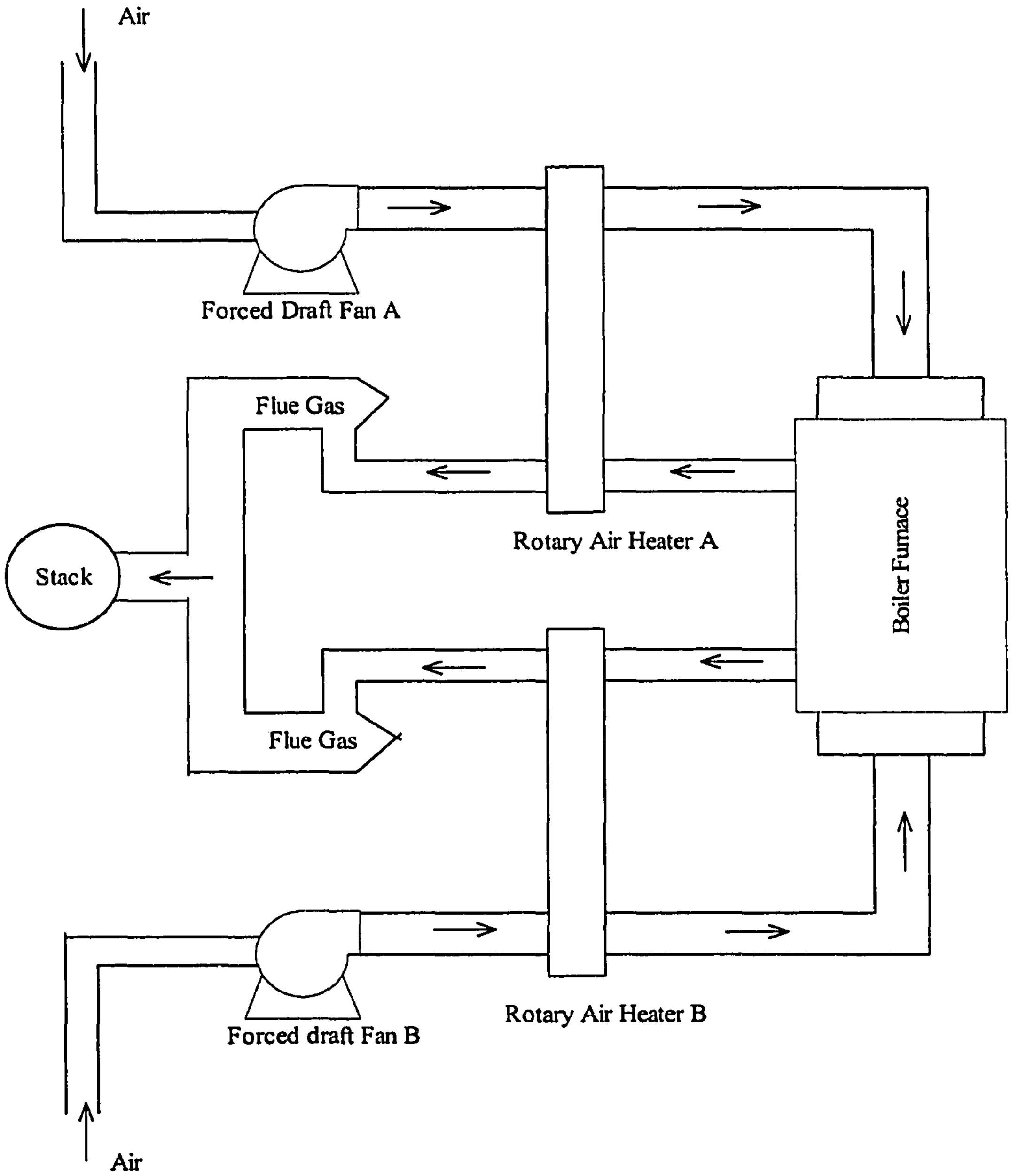


Figure 4.10: Air and Gas System

4.2.1.1 FORCED AND INDUCED DRAFT FANS

As explained earlier, large modern steam generators require fans to provide adequate combustion air and to remove flue gas. All units use FD fans; balanced draft units use ID fans also. Nearly all units have two identical half capacity fans or sets of fans. Both FD and ID fans may be either centrifugal or axial flow. Centrifugal fans are the most common. Figure 4.11 shows a cutaway view of a typical FD fan.

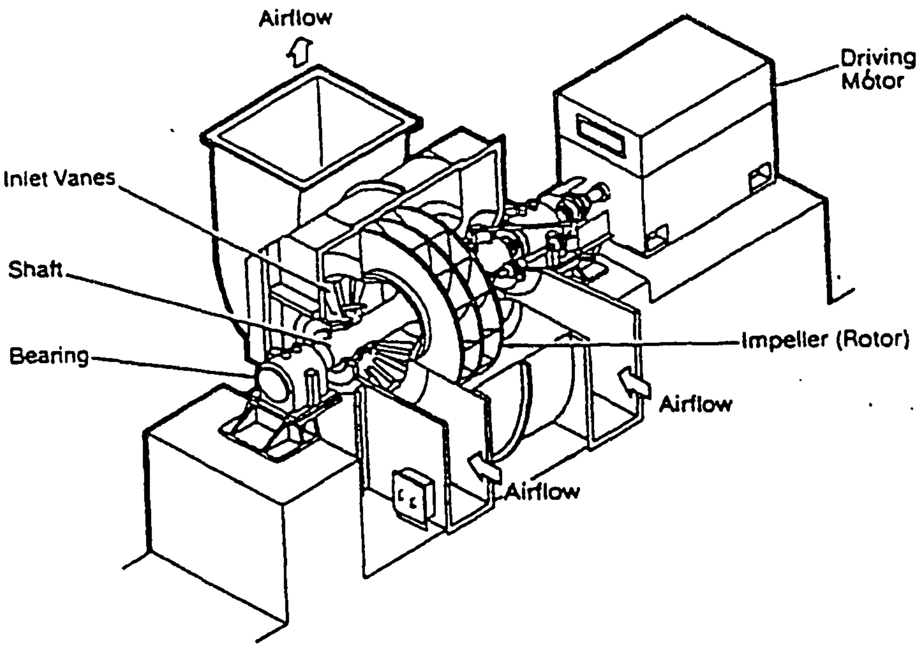


Figure 4.11: Typical Forced Draft Fan

Most FD fan installations have dampers at the air inlet to control the flow of air. Normally, FD fans are constant speed, electric motor driven devices. Some units have two speed electric motors, and occasionally they are driven by variable speed steam turbines. Whether the system is balanced or pressurized the FD fan must supply the entire airflow. As the FD fan in a pressurized system must produce a higher pressure than in the balanced draft system, the motor will be normally larger and more powerful even though the total airflow may be the same for both systems.

ID fans are usually quite similar in appearance to FD fans. They may utilize either adjustable dampers or speed control to control the amount of flue gas through the fan. ID fans are normally larger than FD fans for any given system. These fans must be sufficiently sized to handle the required flue gas flow at maximum boiler firing rate plus any leakage of air past the seals of the rotary air heaters. This leakage is always from the air to the gas side of the air heater and acts to increase the total flow through the fan.

ID fans are powered by either motors or occasionally turbines. Holyrood power plant does not have ID fans.

4.2.1.2 ROTARY AIR HEATER

The rotary air heater heats the air before admitting it to the furnace by using the hot gases leaving the steam generator. Combustion and efficiency improve with the use of an air heating system. The efficiency of the boiler will increase approximately 1% for every 40^0F decrease in exit gas temperature. An air heating system supplying air at temperatures of 300^0F or more achieves a 5% to 10% fuel savings over a unit operating without heated air. The rotary air heater is shown in Figure 4.12

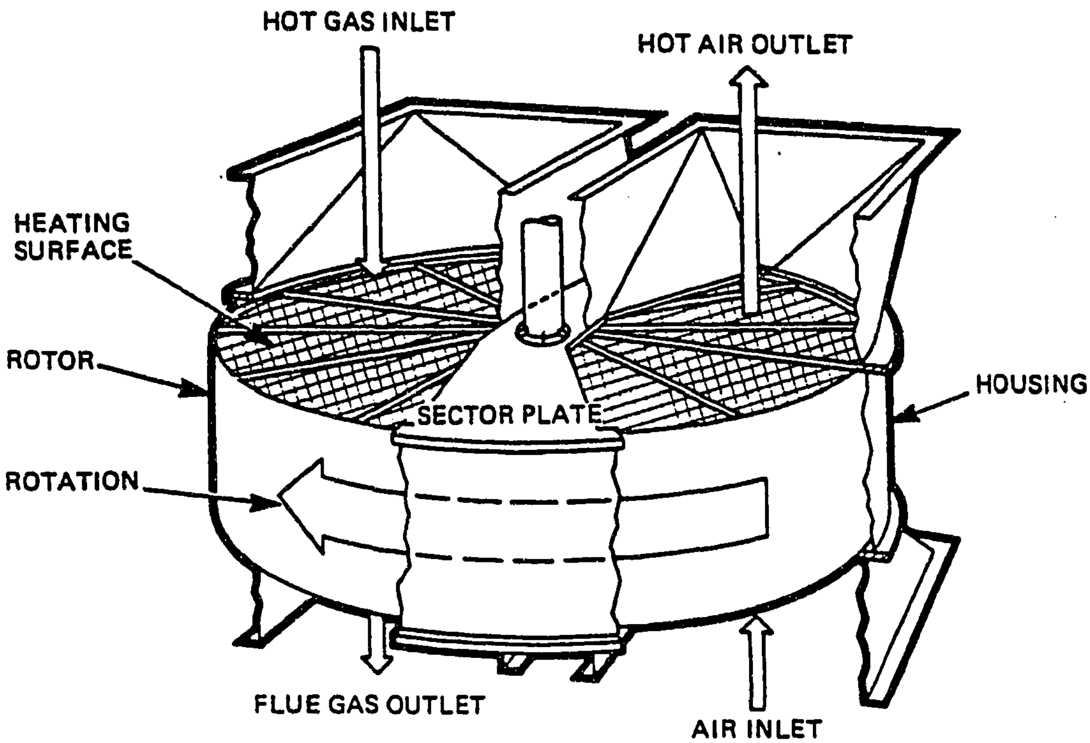


Figure 4.12: Rotary Air Heater(General Physics Corporation)

Heating is usually achieved in two steps. First, the outside air travels through a steam or condensate coil preheater. Some preheaters use glycol, which is heated by steam to prevent condensate freezing inside the coil. Air preheating helps keep the cold end temperature of the air heater above the flue gas dew point. This is important especially when high sulfur fuels are used. If the temperature of the air heater falls below the dewpoint of the flue gas, there will be condensation of moisture on the air heater surface. This moisture will combine with sulfur dioxide and trioxide in the flue gas to form sulfuric acid which can quickly and severely damage the air heater. The air next goes to the air heater. Some steam generators have no coil preheaters. For such units, fans often take their suction from inside the plant to help prevent chilling of the plant.

Air heaters are classified as recuperative or regenerative. The recuperative air heaters are tubular. Tubular recuperative air heaters are basically straight tube and shell heat exchangers. The hot exit gas flows through the tubes and the combustion air flows over the tubes. Because of the size problems recuperative tubular air preheaters are not often used in modern power plant steam generators.

The most frequently used air heater in power plants today is the regenerative, rotating type heater. In this design flue gas heats corrugated metal plates. The corrugated plates are layered and segmented to form a rotor.

The housing surrounding the rotor is provided with duct connections at both ends and is sealed by radial and circumferential sealing members. This forms an air passage through one half of the air heater and a gas passage through the other half. The seals limit the leakage of air into the gas passage and the leakage of air out of the air passage. Figure 5.8 illustrates a rotary air heater.

Each air heater has tight shutoff dampers on the combustion air outlet(hot air) duct and the flue gas inlet (hot gas) duct to allow maintenance and repair of the air heater. A lighted observation port is typically installed at the air inlet for inspecting the cold end elements during operation. To control the accumulation of soot and ash in the air heater elements the air heaters are installed with a cleaning system. The cleaning system includes steam soot blowers and water wash systems.

4.3 BOILER FEEDWATER SYSTEM

The boiler feedwater system supplies feedwater to the boiler. This system consists of feedwater tank, boiler feed pumps, boiler feed pump recirculation valve and high pressure heaters. Of these components feedwater tank and high pressure heaters do not contribute to system failure. There has never been a failure of feedwater tank at Holyrood Generating Station in 30 years. In the 2005 report of the North American Reliability Council(NERC) there is no mention of feed tank failure reported from any of the 1324 Turbine Generator units in the years 2000 to 2004. The feed tank serves the purpose of a holding tank for the boiler feed pumps. It stores condensate obtained by condensing the exhaust steam of the low pressure turbine. The feedtank is not under any stress apart from the expansion caused by the temperature of the feed water. The tank is supported on sliding supports to allow for any thermal expansion. The oxygen in the condensate is stripped by injecting low pressure steam in the opposite direction of the condensate flow. Thus the feed tank is well protected against physical deformation due to thermal and chemical forces. The high pressure heater failure is a rare occurrence. Moreover, individual high pressure heaters can be bypassed if there is heater failure and the system will not have to be shut down. There will be a slight decrease in efficiency but the turbine will have more steam available to produce power, as there will be no extraction steam flowing to the failed heater. In the old units, the common cause of failure used to be stress corrosion cracking within 8 inches from the face of the tube sheet where the tube ends were expanded by mechanical rollers. If excessive pressure had been used during expansion the tube ends would have high residual stresses. If the feed water is dosed with either excessive ammonia or phosphate stress corrosion cracking will take place near the tube ends depending on the tube material. Stainless steal inserts expanded by hydraulic expanders to measured torques at the tube ends, have mostly put an end to High Pressure Heater tube failures. Besides, the NERC report for the years 2000 to 2004 does not mention any high pressure heater failure in the 32 Turbine Generator units, of capacity 100 to 199 MW, belonging to utilities using oil as primary fuel. Therefore, feed tank and high-pressure heater are not considered for analysis in this thesis. The boiler feed pump is 3000 HP equipment pumping at a high pressure of about 2000 psi and also is a precision machine. Its failure is possible and can cause production loss. The boiler feed pump recirculation valve ensures minimum flow through the feed pump during low loads and hence has to reduce 2000 psi to 72 psi to pipe the feed water to feed tank. This valve is subjected to a large pressure differential and high temperature. There is a likelihood of failure of this valve and any failure of this valve can cause a loss in production. The feedwater flow drawing is shown in Figure 4.13. Therefore the boiler feed pump and the recirculation valve are considered. The major components in this system are described in the following paragraphs.

Typical parameters of the system are as below:

a.	Feedwater Tank Pressure	70 psi
b.	Feedwater Tank Temperature	300^0 F
c.	Feedwater leaving Boiler Feed Pump Pressure	2500 psi
d.	Feedwater leaving Boiler Feed Pump Temperature	311^0 F
e.	Feed water leaving HP Feedwater Heater No. 4 Temperature	350^0 F

f. Feedwater leaving HP Feedwater Heater No.5 Temperature 390^0 F

g. Feedwater leaving HP Feedwater Heater No. 6 Temperature 460^0 F

4.3.1COMPONENTS IN THE FEEDWATER SYSTEM

a. Boiler Feed Water Tank

- Design Flow 1,140, 000 Lb/hr
- Operating Pressure 65 psi
- Heater Section 6.5 ft diameter
- Storage Section 12 ft diameter

b. Boiler Feed Pump

- H. P 3000
- Quantity of Flow 1185 US gpm
- Head 5600 ft

c. Boiler Recirculation Valve

d. High Pessure Heaters

i. Number of Tubes 598

ii. Diameter of tubes 5/8 inch

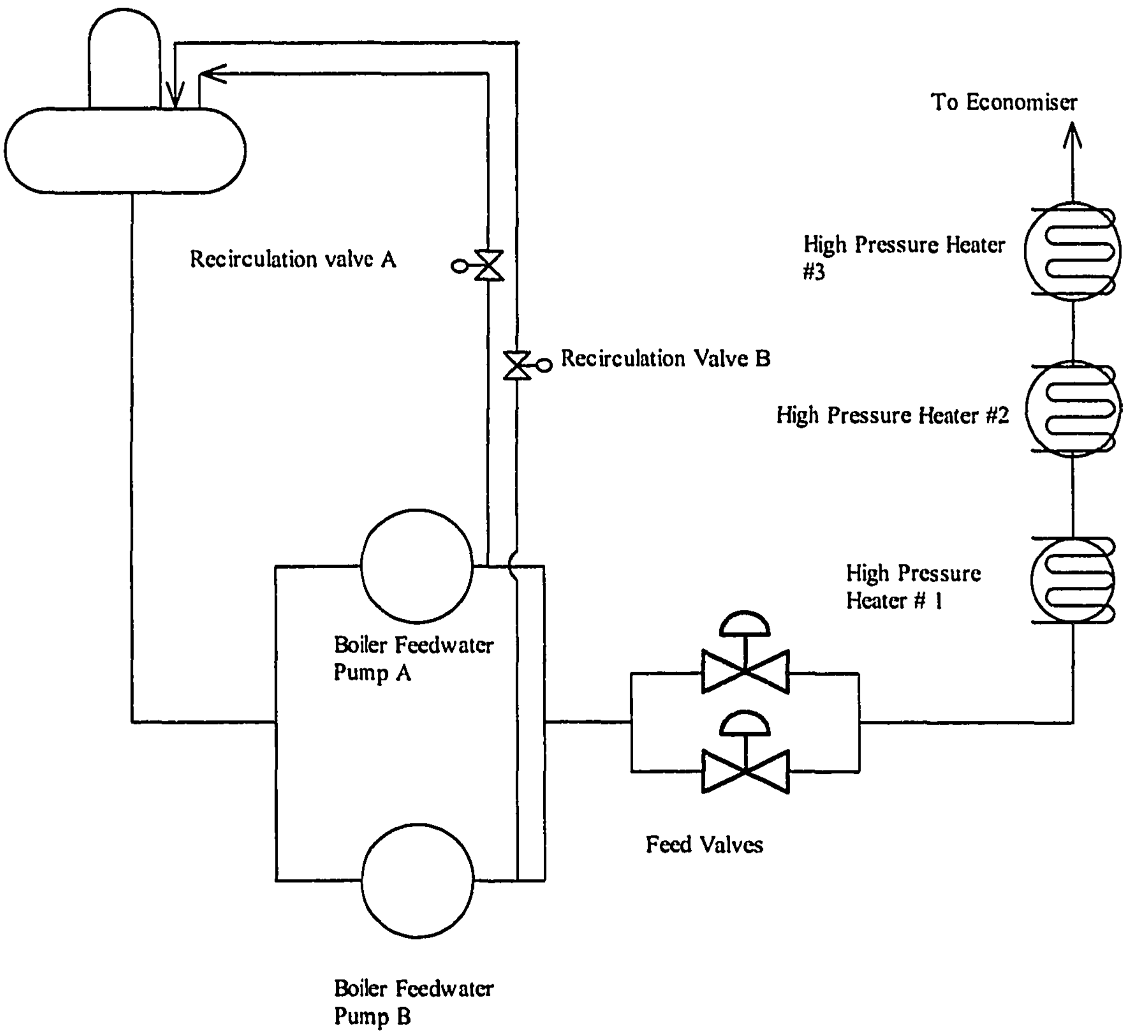


Figure 4.13: Boiler Feedwater System

4.3.1.1 FEEDWATER TANK

The feedwater tank holds the boiler feedwater. The feedwater tank receives the boiler feedwater as condensate from the turbine condenser. The condensate that enters the feedwater tank needs to be stripped of oxygen and hence a deaerator is mounted on the feedwater tank. The feedwater tank is considered as a heat exchanger and is also called a deaerator.

Removal of dissolved gases in boiler feedwater is important because they are corrosive at the elevated temperatures in the boiler. This is particularly true of oxygen, but also of carbon dioxide and ammonia which is present in the boiler water due to chemical dosing of ammonia to maintain high pH. Thus deaerator does not only remove air but also corrosive gases. Open heaters whose effectiveness in oxygen removal approaches about 7 to 5 parts per billion are classed as deaerators. The feedwater exiting the deaerator supplies suction to the boiler feed pump, which then pumps it through one or more high pressure feedwater heaters to the boiler. Heating steam is supplied to the deaerator as to the other feedwater heaters from turbine extractions. A second source of heating steam is the high pressure feedwater heater drains. Generally the high pressure feedwater heater drains are cascaded downstream to the deaerator where due to the elevated temperature of the drains and comparatively low pressure in the deaerator, the water flashes to steam. Figure 4.14 illustrates the arrangement of deaerator and feedwater tank.

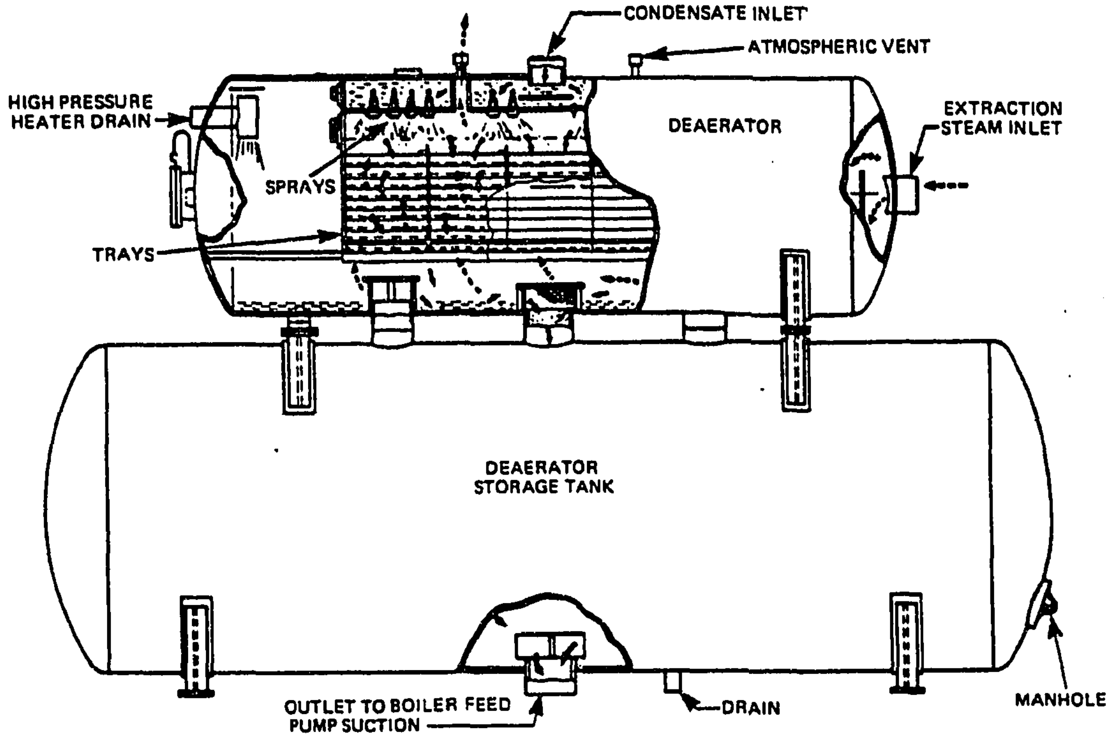


Figure 4.14: Feedwater tank and deaerator(Chicago Heater Co)

Deaerators can be used at a variety of pressures ranging from as high as 800 psi to below atmospheric pressure. Heat balance considerations in most plants however place the the deaerator at an operating pressure of 100 psi. As already noted the deaerator heats feedwater by mixing with steam. There are three mechanisms for accomplishing this mixing. The first is the spray. The water is sprayed in a fine mist into the area of the deaerator that contains steam. Dividing the water into tiny droplets increases the surface to volume ratio of the mass of water, facilitating better heat transfer. The second method is admitting steam to a volume of water. Bubbling the steam through the water also agitates the water, which helps to deaerate it. The third method of heating is cascading the water over trays. This causes the feedwater to form thin sheets from which gas bubbles can easily escape. The deaerator must be vented to carry off non-condensable gases driven off the feedwater.

Use of materials in deaerators is a serious consideration. The feedwater entering the deaerator is highly corrosive. The material in the area where steam and water are mixed must be corrosion resistant such as stainless steel or monel. Another consideration in use of the deaerator in a power plant is that most deaerators supply suction to the boiler feedpumps. The deaerator feedwater tank is generally placed as high in the plant as possible. This placement provides a water head that can be sufficient to satisfy the net positive suction head of the boiler feed pumps and can eliminate the need for booster pumps.

4.3.1.2 BOILER FEED WATER PUMP

The boiler feedpump is a centrifugal pump. The centrifugal pump is a simple machine that contains a rotating impeller within a casing. The centrifugal forces generated by the spinning impeller impart kinetic energy to the fluid. The centrifugal pump then converts kinetic energy into pressure at the discharge side of the pump. Large centrifugal pumps have two or more stages.

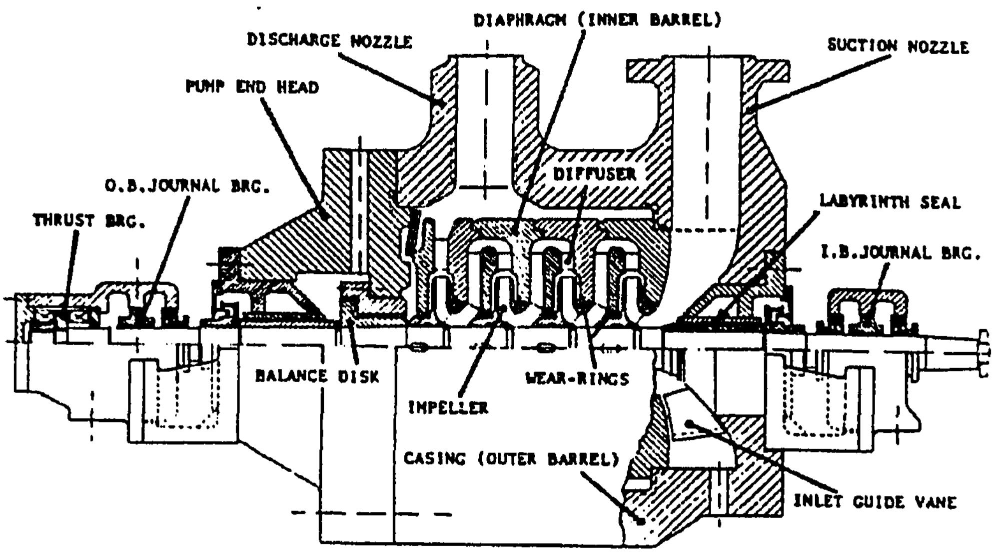


Figure 4.15: Boiler Feed water pump (General Physics)

The discharge of the first stage is directed to the suction of the second and so forth. Multistage centrifugal pumps have wearing and casing rings for each impeller as well as interstage seals. Regardless of how many stages are used the construction and operation do not change. The major pumps in a power plant are all centrifugal pumps. The boiler feed pump is a multistage centrifugal pump. Figure 4.15 shows the cross section of a boiler feed pump.

Generally, the most complex pump in the power plant is the boiler feed pump because of the severe operating requirements, the high total pump head that must be developed and the large capacities involved. Thrust in the boiler feed pump from the discharge to the suction is the result of differential pressure. This pressure is too great to be handled by thrust bearing alone. A balance disc is mounted on the pump shaft at the discharge end of the pump. High pressure water is allowed to leak to the rotating disc and keeps the shaft at fixed position due to the pressure exerted on the disc. The leaked water is piped to the pump suction. This disc is nothing but a water lubricated thrust bearing. Normally the disc does not touch the stationary disc fixed to the casing. The disc can be damaged because of debris in the feedwater. Figure 4.16 shows a cross section of the balance disc arrangement. The mechanical seal at each end of the pump shaft is an area of concern. The mechanical seal can leak if the pump had not been properly warmed up prior to start up. The subject of boiler feed pump design is quite deep. Considerable research on boiler feed pump design in areas other than thrust balancing and seals are in progress. Much of the study of the hydrodynamics and stability of these pumps.

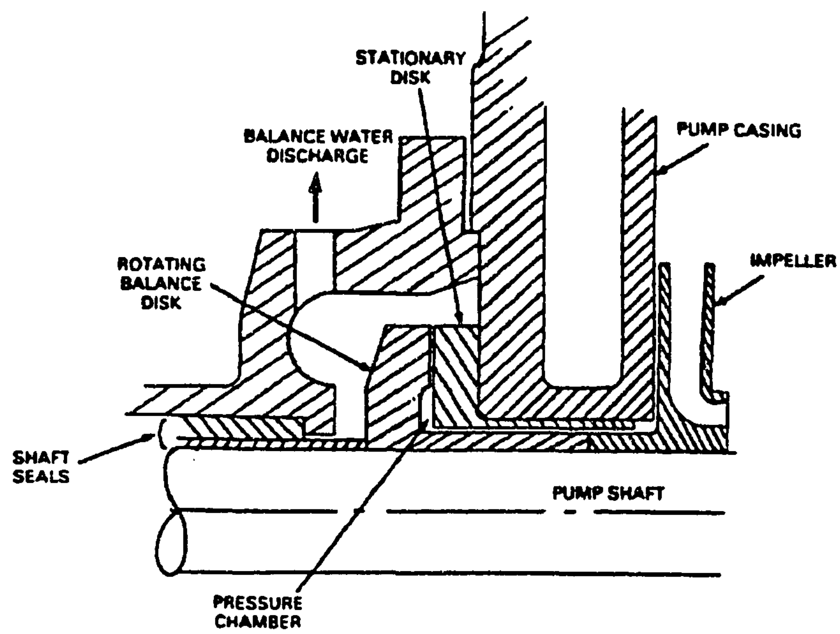


Figure 4.16: Boiler Feedwater pump balance disc arrangement (General Physics)

Overall there has been more emphasis placed on the reliability of boiler feed pumps than on their efficiency. Part of the reason for this trend is that even large changes in feed pump efficiency have a relatively minor impact upon overall plant efficiency. This may be understood by examining two areas.

First the water or steam in the Rankine cycle experiences changes in enthalpy as it passes through the cycle. In some components, the change in enthalpy is large; in the neighbourhood of 1050 Btu/lb in the boiler, 360 Btu/lb in turbine, 1000Btu/lb in the condenser and 40Btu/lb in each feedwater heater. The change in enthalpy across the feed pump is typically only about 10Btu/lb. Therefore the boiler feed pump has a relatively small influence on overall efficiency.

Secondly the boiler feed pump is in the feedwater heating cycle where the objective is to add heat to the feedwater. Pump inefficiency raises the temperature of the water because because of eddies and turbulence. However this heat is not lost to the cycle and so overall efficiency suffers very little.

The reliability of the boiler feed pumps as with all pumps is affected by the design of the piping system in which it operates. The two factors having greatest influence on pump performance and reliability are the NPSH and the sizing of the required recirculation flow. This is intended to reduce the cost of the plant. In practice if the system is not designed with an adequate margin for these two parameters, damage to pump often results. For instance there should be 3% margin above the specified NPSH to ensure that there will be no cavitation.

4.3.1.3 BOILER FEEDWATER PUMP RECIRCULATION VALVE

All boiler feed pumps have recirculation systems. The recirculation system takes part of the pump's discharge capacity and returns it to the suction source. The purpose of the recirculation system takes part of the pump's discharge capacity and returns it to the suction source. The purpose of the recirculation system is to ensure a minimum flow through the pump. A centrifugal pump continues to try to pump fluid even when the discharge valve is closed. The impeller spins the liquid and the discharge pressure rises to its maximum value. This condition is called shutoff head. In this situation, the pump generates heat quickly and some fluid must be recirculated to remove the excess heat and prevent the fluid from reaching saturation temperature in the pump resulting in cavitations. The boiler feed pump recirculation valve ensures minimum flow through the feed pump by diverting the high pressure pump discharge to the feedwater tank. The boiler feed pump recirculation valve has to reduce the pump discharge pressure of about 2000 psi to that of the feed water tank pressure which is 100 psi. Hence the boiler feed pump recirculation valve is subjected to a very high differential pressure across the valve plug. Therefore the plug called trim wears out quickly and the valve fails. A cross sectional view of the valve is shown in Figure 4.17

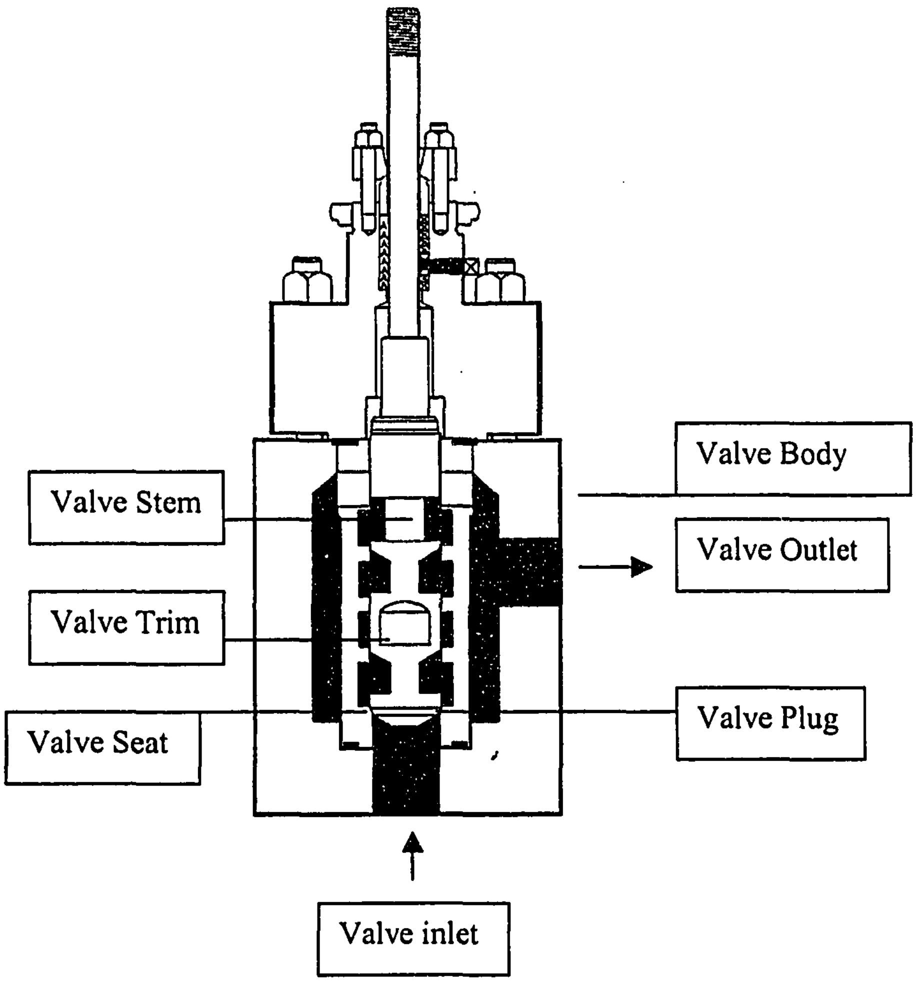


Figure 4.17: Boiler Feedwater pump recirculation valve (Masoneilen)

The valve design is based on the principle of high resistance mutistep axial flow trim. In an axial flow trim, fluid flow is parallel to the axis of the plug and cage. Pressure reduction occurs along the length of the plug. Therefore no individual stage is ever exposed to full pressure differential. As a result trim life is greatly extended.

4.3.1.4 FEEDWATER HIGH PRESSURE HEATER

Feed water heaters are designed to operate over a wide range of pressure and temperature. Heaters utilizing low pressure turbine extraction steam that are in the condensate part of the cycle might operate at a few hundred pounds on the tube side (water) and at less than atmospheric pressure on the shell (steam) side. At the opposite extreme, a heater utilizing extraction steam in the high pressure feed water portion of the cycle might have up to 4000 psig on the tube side and 1200 psig on the shell side.

Essentially all feed water heaters consist of a cylindrical shell into which a tube bundle is inserted. The feed water heater may be mounted vertically or horizontally. A vertical arrangement has the advantage of small floor space requirements, however there must be adequate head room for installation of the heater initially and removal of the tube bundle for maintenance later. Low pressures feed water heaters are usually horizontal partly because it is difficult to design vertical heaters with separate drain coolers and desuperheating sections. However, many high pressure feed water heaters are vertical to facilitate removal of the necessarily heavy tube bundles.

Figure 4.18 shows a horizontal shows a U tube horizontal feedwater heater

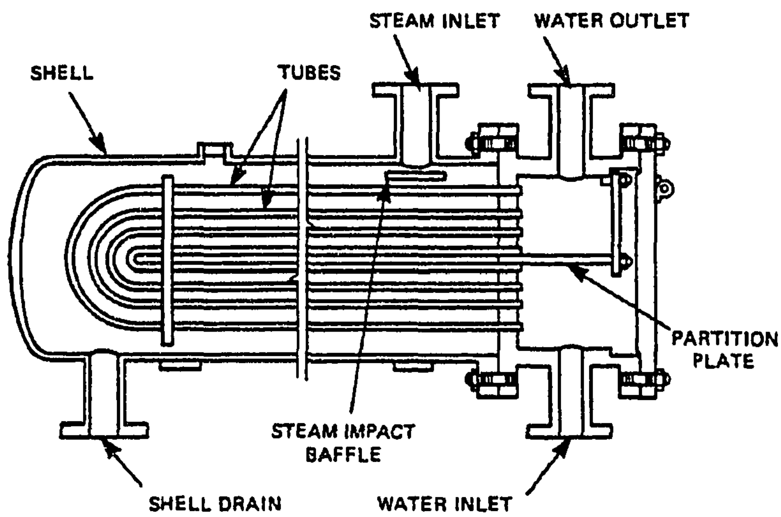


Figure 4.18: Horizontal U Tube Feed water Heater (General Physics)

It is a counter flow heater with feed water entering at the bottom and exiting at the top, while the opposite is true of the heating steam. There is no desuperheating section or drain cooler. There is an impingement baffle at the steam inlet. This baffle helps distribute steam in the heater and protect the tubes from erosion from extraction steam. The feedwater is routed to flow through the lower half of the heater by a partition plate in the waterbox . The feedwater exists at the top of the feedheater. The extraction steam is fed to the shell side of the heater from the turbine through a motor operated valve. The condensed drain flows out of the heater to either the feedwater tank or condenser.

The tube materials in the past were copper and brass alloys. Carbon and stainless steel are more common now because of the higher temperatures used in modern power plants. Current practice calls for use of 304 stainless steel, 90-10 Cu-Ni alloys or admirality brass in low pressure heaters. For high-pressure heaters, 70-30 Cu-Ni alloy and carbon steel are commonly used.

4.4 MAIN CONDENSATE SYSTEM

The main condensate system condenses the exhaust steam from the low pressure turbine and pumps the condensate through low pressure heaters to the feed water tank. This system consists of condenser, condensate extraction pump and low pressure heaters. The condensate extraction pump is an axial flow pump pumping water at 90^0 F. This pump is not subjected any high stress and rarely fail. The low pressure heaters are shell and tube heaters and the heating medium is low pressure steam from the last stages of the low pressure turbine. The remedial measures taken for high pressure heaters were also employed for low pressure heaters. Hence they seldom fail. Moreover in the 2005 report of the North American Reliability Council (NERC) there is no mention of low pressure heater failure reported from any of the 1324 Turbine Generator units in the years 2000 to 2004. The sea water flows through condenser tubes to condense the exhaust steam enveloping them. The condenser is under vacuum and the condenser rattles against their support plates during turbulence in the sea water flow, causing rupture at the point of contact. Therefore the condenser tubes have the potential to fail and result in loss of production. Hence, condenser tubes are considered for analysis. The condensate system flow drawing is shown Figure 4.19. The major components in the system are described in the following paragraphs.

. Typical parameters of the system are as below:

1. Condensate leaving condenser temperature 90^0 F
2. Condensate leaving gland steam condenser Temperature 93^0 F
3. Condensate leaving Low Pressure Heater No 4 Temperature 200^0 F

4. Condensate leaving Low Pressure Heater No 5 Temperature 268^0 F

4.4.1 COMPONENTS IN THE CONDENSATE SYSTEM

a. Condenser

- Number of Tubes 7415
- Tube Diameter 1 inch

b. Condensate Extraction Pumps 2 Nos

- H.P 350
- Quantity of Flow 1770 gpm
- Head 550 ft

c. Low Pressure Heaters 2 Nos

- Number of tubes 520
- Diameter of Tube ¾ inch

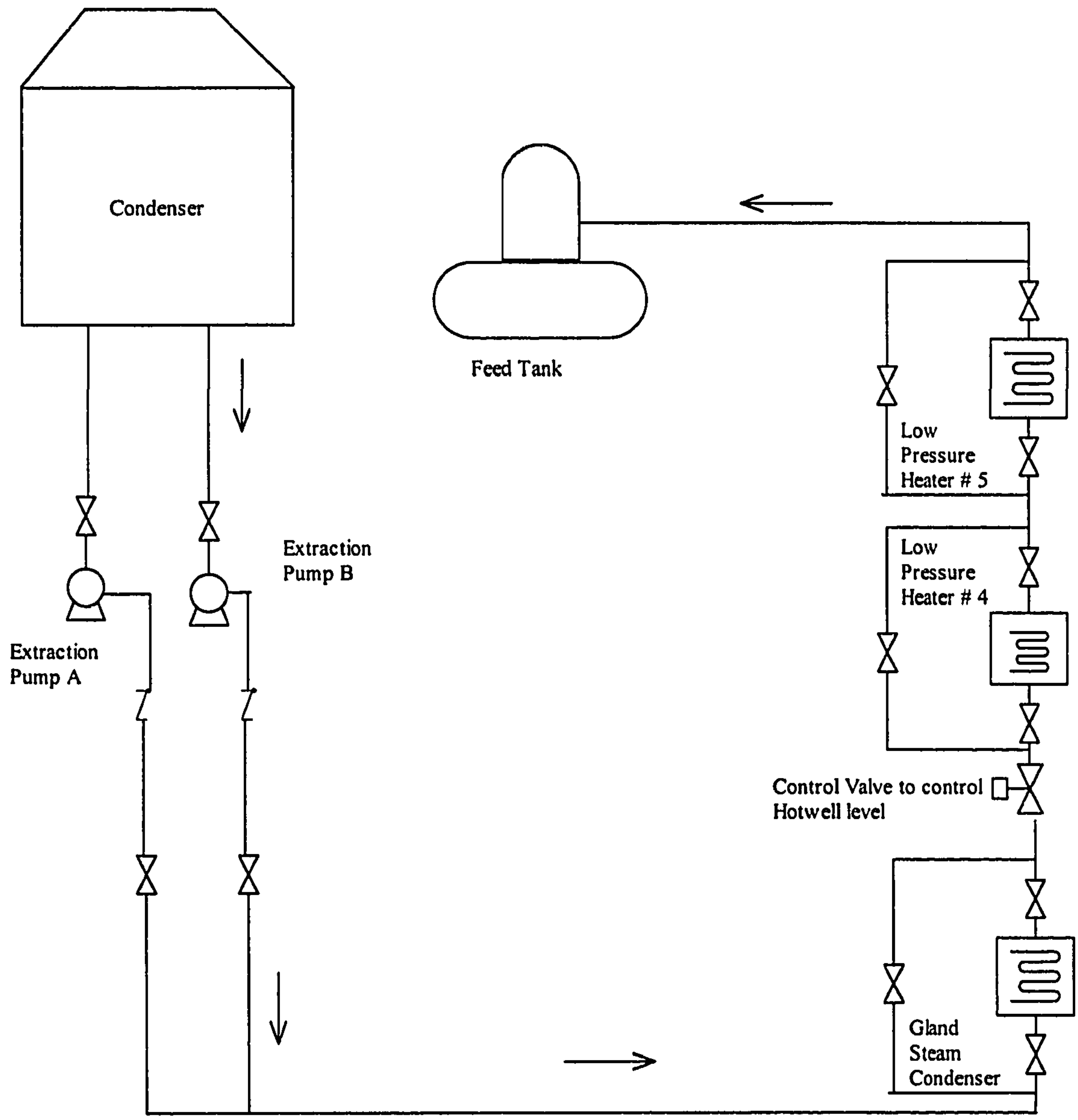


Figure 4.19: Main Condensate System

4.4.1.1 CONDENSER

Condensers in modern power plants are generally rather similar. They usually take the form of a large metal tank beneath the turbine. There are however, number of possible differences in the arrangement of the condenser. Although in most plants the condenser is located directly beneath the low pressure turbine. There are several variations in the shape, arrangement , flow paths, and flow directions. These variations are dictated by cost, space limitations, cooling water quality and availability, efficiency and other plant specific considerations. Variations in type include round, oval and rectangular shaped condensing space, single pass or double pass, circulating water flow through the tubes either parallel or perpendicular to the turbine shaft, and uniform or multipurpose condensing. Each of these has advantage in initial cost, case of erection or efficiency. Most modern plants have rectangular welded steel shell condensers. Where the supply of cooling water is plentiful, the condenser is generally single pass and uniform condensing. with the tubes perpendicular to the turbine shaft. Where the supply of water is limited, and cooling towers are used, condenser characteristics may include double pass circulating water flow, multipressure condensing and tubes parallel to the turbine shaft. Figure 4.20: shows the cross sectional view of a condenser

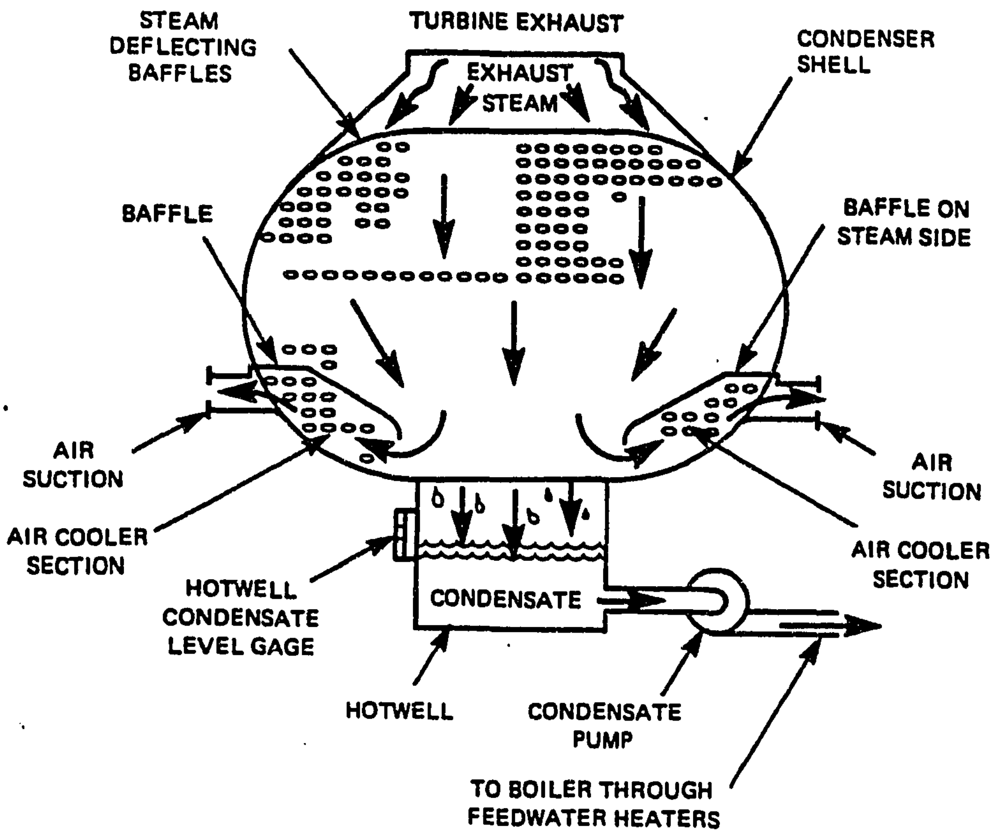


Figure 4.20 Cross section of a typical condenser (General Physics)

The normal range of operating temperatures for the condenser shells is from ambient to approximately 120 ^{0} F. Because of its large size and the fact that it may see temperatures as high as 212 ^{0} F in low vacuum situations it has substantial amount of expansion. Therefore, the condenser shell is either supported on springs or rigidly supported with expansion joint at the top where it joins the low pressure turbine. Baffle plates are installed in the condenser to evenly distribute the steam exiting the turbine. Without these plates the top tubes would receive all the steam resulting in less than optimum cooling water utilization. Steam enters the condenser from the turbine generator low pressure exhaust. At this point steam has a high velocity. Some of the steam will penetrate to the centre of the tube bundle and the moisture can erode the surface of the tubes and can cause tube leaks. The high velocity steam is desirable to strip off any insulating air blankets that may form on the tube surfaces. As steam condenses in the condenser non condensable gases trapped in the steam will come out of solution and accumulate. If these gases are allowed to accumulate in the condenser, the natural vacuum formed when steam condenses into water would be lost and the steam cycle would lose much of its efficiency. If the gases primarily oxygen and carbon dioxide are allowed to remain in the condenser, the condensate in the hotwell will absorb them, which will lead to corrosion in condensate and other systems. Air ejection and removal systems are installed to remove these non condensable gases. Air is removed from the condenser through air collection headers. These headers take suction in a section of the tube bundle that is physically separated from the rest of the tubes by baffle plates. These sections are called the air coolers . The air coolers reduce the volume of the non condensable gases and condense as much steam as possible. The air is then pumped out by air ejectors or vacuum pumps. The condensed water reaches the bottom of the condenser called hotwell.

The most important element in the condenser is the tubes. The tubes carry the cooling circulating water in the inside and the outside provides the heat transfer surface which the steam is condensed. The capacity of a condenser is based on the heat transfer surface available. The greatest heat transfer surface would be provided by thousands of tubes.

Many different materials have been used for condenser tubes: aluminium, admiralty brass (71% copper, 28% zinc and 1% tin), Muntz metal, arsenical copper, aluminium brass, aluminium bronze, 90-10 copper nickel, 70-30 copper nickel, stainless steel and titanium. The heat transfer coefficient for conductance and the initial cost. Aluminium may be the best material from the stand point of initial cost but actual costs are governed by such factors as resistance to corrosion and erosion on both the steam and circulating water sides, costs of installation and the actual effective heat transfer rate. The last factor is especially meaningful when one considers that the wall resistance to heat transfer may account for only 2% of the total. Steam side and water side fouling and film resistance may account for the remaining 98% of total resistance. Therefore materials that tend to resist this fouling and reduce the film resistance tend to have a much better overall heat transfer coefficient.

Resistance to corrosion and erosion is also important because highly resistant materials will not require frequent replacement. Therefore material installation and operating downtime costs are saved. As a result of these considerations many modern condensers are being built or older condensers are retubed with stainless steel or titanium tubes.

4.5 SUMMARY

In this chapter, the boiler, air and gas system, boiler feed water system and main condensate system are described. The specifications of the components, waterwall, superheater, reheater, forced draft fan, boiler feed pump, boiler feed pump recirculation valve and condenser tubes are provided to have an idea of the size of the components. The descriptions of low pressure heater and condensate extraction pump have been omitted as their failures are very rare and are not considered in this thesis. The failure data obtained for these components are provided for analysis in the forthcoming chapters. The failure data of other components in the systems are not provided as these components do not fail often enough to create loss of production and can be maintained during planned shutdowns.

Chapter 5

QUALITATIVE ANALYSIS

Qualitative risk analysis is a screening technique based on plant specific or generic data and assumptions that are used to evaluate accident sequences, frequencies, and consequences. The objective of this part of the process is to identify and rank the importance of the equipment necessary to achieve and maintain safe and efficient operation based on the availability of the plant systems and the impact of their failure during normal operation or on demand. In a qualitative risk assessment process, the most likely failure scenarios (root cause, failure mechanisms, failure modes, and consequences) are identified based on experience and engineering judgment.

5.1 LISTING OF SYSTEMS AND COMPONENTS

The most important systems which have a large failure rate impacting production are considered. They are Boiler, Air and Gas system, Boiler Feedwater System and Main condensate system.

5.2 IDENTIFICATION OF FAILURE CAUSES

Studies of potential degradation mechanisms can help define potential component failure mechanisms and causes. Design and operational experience provides information about component failure modes. This step can provide useful insight into identification and prediction of failures.

5.3 FAILURE DATA

The failure data can be obtained from the plant if the plant has kept a good data acquisition system. In case the plant data is not available, generic data can be used. Generic data can be obtained from North American Electric Reliability Council. The generic data consist of component failure caused by infant mortality, bad design, environmental problems or mal operation. Therefore, the data reflects the worst scenario and the plant failure may not have anything common with the generic data. Generic data may be used only when plant data are not available. The question of adopting generic data for this thesis did not arise as necessary data were available. The water wall failure data and others used in this thesis is plant specific (Holyrood Generating Station).

5.4 WATERWALL

The wall of the boiler furnace is made up of steel tubes. For typical 175 MW power boilers each wall has rows of tubes for a height of 100 feet. The material is SA 210 Gr A1. The diameter is 2 inches and thickness is 0.2 inch. There are 275 tubes on each wall. Failure of any one tube can cause boiler to be removed from service. The water wall tubes face direct furnace fireball. The temperature of the fireball is usually around 1400 ^{0} C. The boiler water that flows through these tubes have a pH of about 9. Table 5.1 shows the failure modes of waterwall tubes

Table 5.1: Waterwall Tube Failure Modes

Failure Mode	Failure Mechanism	Failure Cause
Bulging	Long term overheating	Water formed deposits
Large Fish mouth rupture. Rupture edges are thick. No deposits	Short term overheating	Pluggage or flow related problems
Distinct hemispherical or elliptical depressions filled with corrosion products	Caustic corrosion	Availability of alkaline producing salts, mechanism of concentration
Rupture due to gouging	Low pH corrosion during service	Sea water ingress from leaky condenser tubes
Metal loss on waterwall tubes	Fire side corrosion	Incomplete combustion, Insufficient Oxygen at burner zones
Thick walled window opening	Hydrogen damage	Release of atomic hydrogen due to electrochemical corrosion reactions

5.5 SUPERHEATER

The saturated steam generated in the water walls is routed to be superheated in the Superheaters. The Superheater consists of many rows of tube panels, typically 26 rows for a 175 MW boiler. The tubes are of Stainless steel SA 213 TP 321H. The size of the tubes is 2-inch outer diameter with a 0.2 inch thickness. The Superheaters are located close to the roof of the boiler furnace and see the flame. Therefore the heat transfer is mostly due to radiation. In case of multiple stages, superheating the superheaters are also located in the convection zones of the boiler. Superheater tube failure occurs mainly due to aging creep, erosion, overheating due to soot, temperature excursions, incorrect chemical regime and wrong superheater tube material.

5.6 REHEATER

The function of the reheater is to superheat the temperature of the steam exhausted from the High Pressure Steam Turbine to that of the steam exiting the Superheater. The steam which is superheated in the reheater will enter the intermediate steam turbine. The purpose of reheating is to increase the efficiency of the cycle. The reheaters are located in the convection zones of the boiler. These are tube panels installed in rows. A typical reheater tube size is 2 inch with a thickness of 0.14 inch. The material is SA 213 TP. The reheater tubes can fail due to creep, improper chemical regime, and overheating and wrong tube material. The failure modes of Superheater and Reheater are tabulated in Table 5.2.

Table 5.2: Superheater and Reheater Failure Modes

FAILURE MODE	FAILURE MECHANISM	FAILURE CAUSE
Rupture at bulge with fragmented oxides outside	Long term over heating	Deposits, Improper firing, Improper material, Creep
Longitudinal tear, edges same as tube thickness	Short term overheating	Brief upset operating conditions
Needle Wedge shaped cracks perpendicular to metal surface	Corrosion Fatigue Cracking	Cyclic Tensile stresses, low pH, High dissolved Oxygen
Thick walled fractures with branches	Stress Corrosion Cracking	Presence of tensile strength and corrodants

5.7 ECONOMIZER

The economizer failures are few. However the failure modes of economizers are tabulated in table 5.3, to show the existence of possibilities for failure. Under failure causes, presence of acid is mentioned for all failure modes. The acid comes from the flue gas when the flue gas temperature is lower than the acid dew point. Normally the plant will operate the boiler in such a fashion to avoid the flue gas cooling to the sulfur dew point temperature, which is specified for each type of fuel.

Table 5.3: Economizer Failure Modes

FAILURE MODE	FAILURE MECHANISM	FAILURE CAUSE
Deep gouging filled with laminated iron oxide deposit	Low pH corrosion	Availability of free acid or acid producing salts and means of concentrating them
Poke marked metal surface. Detachment of fins	Cold end corrosion	Corrosive quantities of sufur trioxide in flue gas in the presence of moisture
Irregular pebble like surface. Irregular contour	Dew point corrosion while shut down	Presence of sulfurous ash on the tube surface and low dew point
Thick walled fractures with branches	Stress Corrosion Cracking	Presence of tensile strength and corrodants

5.8 FORCED DRAFT FAN

The table shows the times when failure was observed in FD Fan. The FD Fan failure modes are tabulated in Table 5.4

Table 5.4: FD Fan Failure Modes

FAILURE MODE	FAILURE CAUSE
Insufficient discharge Pressure	Air leaks, damaged rotor, incorrect inlet vane positions, system head greater than design
Overheated bearings	Abnormal end thrust, Aerodynamic instability, Bent shaft, Loose bolts, Damaged wheels, Dirt in bearings, Damaged runner, Foreign substance on runner, Mis- alignment, Heat transmitted from outside, vibration transmitted from outside
Short bearing life	Aerodynamic instability, Bent shaft, Speed too high
Overload on Motor	Improper bearing lubrication, Bent shaft, Fan delivering more than rated capacity, Mis-alignment, Total system head greater than design.
High Vibration	Abnormal end thrust, Aerodynamic instability, Improper bearing lubrication, Bent shaft, Loose bolts, Damaged runner, Dirt on runner, Resonance, Misalignment.

5.9 BOILER FEED PUMP

The boiler feed pump failure modes are described in Table 5.5

Table 5.5: Boiler Feed Pump Failure Modes

FAILURE MODE	FAILURE CAUSE
Low discharge Pressure	Cavitation, clogged impeller, air pockets, Insufficient suction pressure, total system head higher than design.
Insufficient Capacity	Cavitation, clogged impeller, air pockets, suction strainer, clogged, insufficient suction pressure, internal wear, leaks in pipes, vessels, non condensables in liquid
High bearing temperature	Bent shaft, cavitation, worn bearings, misalignment, wrong lubricant, Lube oil temperature high
Short Mechanical seal life	Bent shaft, pipe strain, cavitation, improper mechanical seal, insufficient warm up, misalignment
High Vibration	Bent shaft, pipe strain, clogged impeller, internal wear, misalignment, rotor imbalance,
High Noise Levels	Cavitation, air pockets, insufficient suction pressure,

5.10 BOILER FEEDWATER PUMP RECIRCULATION VALVE

The Boiler Feed Pump Recirculation Valve times are as per. The failure mode of boiler feed pump recirculation valve is tabulated in Table 5.6

Table.5.6: Boiler Feed Pump Recirculation Valve Failure Modes

FAILURE MODE	**FAILURE CAUSE**
Leakage through valve	Excessive wear, Line pressure too high, Mechanical damage to seat

5.11 CONDENSER

The failure modes are tabulated in Table 5.7

Table 5.7: Condenser Failure Modes

FAILURE MODE	FAILURE CAUSES
Tube thinning	Random excitation, Air pockets
Tube failure	Improper tube material
Low vacuum	Unclean tubes, Air pockets

5.12 ESTIMATION OF FAILURE PROBABILITIES

As it is a qualitative analysis, the failure probabilities components will be ranked relative to each other. The probability categories are ' very low', 'low', 'medium', 'high,' and 'very high'. Word definitions and probabilities are as per table 5.8 (ASME 1991).

Table 5.8: Probability Definition

Possible Qualitative Ranking	**Definition**	**Failure Frequency**
Very High	An event that can occur more than once in a components lifetime.	10^{-1}
High	An event that can occur once in a components lifetime	10^{-2}
Medium	An event that is not expected to occur once in a component's lifetime but when integrated over all the system components has the credibility of occurring once	10^{-4}
Low	An event of such low probability that an event in this category is rarely expected to occur	10^{-6}
Very Low	An event of such low probability that an event in this category is considered to be incredible	10^{-8}

5.13 CONSEQUENCE ESTIMATION

The consequence portion has two categories. One is safety and the other is economic consequence. Environmental consequences can be included in either of these categories. or addressed separately. Safety consequences both direct and indirect are not considered in Probabilistic Risk Assessment (PRA) evaluations from a structural integrity point of view. No generally accepted method exists for combining safety and economic consequences. The consequence of economic loss will have to be estimated, but experience usually exists from other related failures that can be utilized for estimation. Economic loss includes the repair or replacement of the component that has failed, the repair or replacement of other equipment that was affected by the failure, the loss of availability of the overall system, business interruption and damage to the public or environment. The dollar values of economic consequences are tabulated in Table 5.9 (ASME 1991).

Table 5.9: Economic Consequence (ASME Risk Based Inspection Development of Guidelines, 1991)

Possible Qualitative Ranking	Definition	Estimated Consequence Cost $
Very High	Failure causes significant potential off-site and facility or system failure costs and potential for significant litigation.	10^9
High	Failure causes indefinite shutdowns, significant facility or system failure costs and potential for litigation.	10^8
Medium	Failure causes extended unscheduled loss of facility or system and significant component failure costs	10^7
Low	Repair can be deferred until a scheduled shutdown, some component failure costs will occur	10^5
Very Low	Insignificant effect on operation	10^4

The safety consequences are not included in Table 5.9 The safety consequences need to be assessed separately according to the Corporate Safety Guidelines.

5.14 QUALITATIVE RISK MATRIX

When the likelihood and consequences of component failures have been determined, graphic methods can be used to organize and illustrate the effects of these two parameters on the system. A qualitative risk based ranking matrix has been adapted from similar approaches used by the U.S. Environmental Protection Agency (EPA 1987) and by Lercari (Lercari 1987) for the state of California Office of Emergency Services. The matrix is arranged in such a fashion that probability increases in the vertical direction upwards and the consequence increases in the horizontal direction to the right. The matrix shows the highest priority items at the upper right hand corner. However, the matrix draws attention to items with least probability and unacceptable consequences as well as items with least consequences and unacceptable probabilities. The risk matrix for components discussed in this thesis drawn as per Figure.5.1

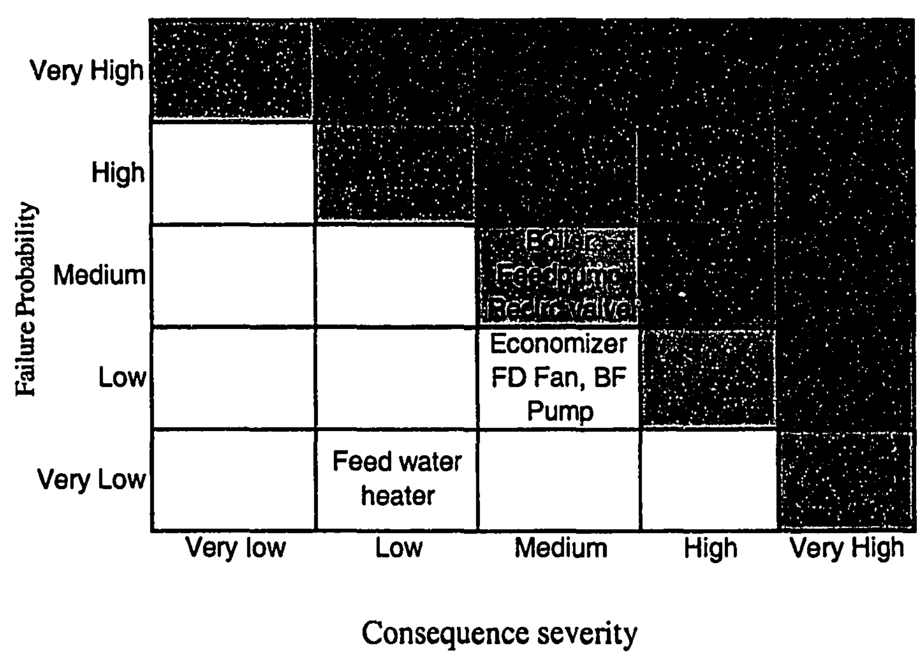


Fig 5.1: Risk Matrix

The risk matrix is drawn in Figure 5.1 shows that the waterwall and superheater tubes have a high probability of failure with the consequential shut down and component expenditure. There is no reason for litigation arising out of this failure. The power guaranteed to the distribution company will be met by running Gas Turbines. There is no failure qualified to a high or very high consequential item in this thesis. A lube oil cooler failure in a Turbo Generator will be a high consequential item. A fuel oil tank rupture will be a very consequential item as such a failure can cause environmental damage resulting in possible litigation. The lubrication oil tank is located always close to the turbine and it is in a high traffic area and hence any problem will with the integrity of the tank will be noticed. Moreover the tank is not pressurized. In fact the vapour extractor of the tank keeps it under a vacuum of about seven centimeters of water.

Chapter 6

QUANTITATIVE ANALYSIS

6.1 ANALYSIS OF FIELD DATA

This chapter is about analyzing field data obtained from a thermal power plant. The data relate to failure times of waterwall tubes, superheater tubes, reheater tubes, forced draft fan, boiler feed water pump, boiler feed water pump recirculation valve , and condenser tubes. The strategy is to fit the data to a theoretical distribution. The preference to a theoretical distribution over an empirical distribution is discussed in chapter-3. The empirical methodology is not acceptable in an industrial set up where strict control is maintained over financial operations and major expenditures have to be justified to stake holders and the Public Utility Board and hence reasons for major expenditures have to be based on sound scientific principles. Therefore, the theoretical distribution that can fit the data with a regression coefficient according to figure 6.1. is selected. Least Squares approach is adopted and Microsoft Excel is used to draw the graphs and calculate the regression coefficient.

6.1.1 WATERWALL

The waterwalls are tubes that form the walls of the boiler furnace as explained in chapter-4. There had been seven failures. The failure times are in hours of operation. The first failure had occurred after 86,256 hours of operation of the boiler. There had been seven failures. They are 86,256 hours, 98,472 hours, 98,640 hours, 101,016 hours, 106,056 hours, 109,656 hours, and 111,816 hours. The data were fitted to Weibull distribution employing least squares approach.

For the least squares approach x =ln t_i and $y = \ln\ln\left(\frac{1}{1-F(t)}\right)$.

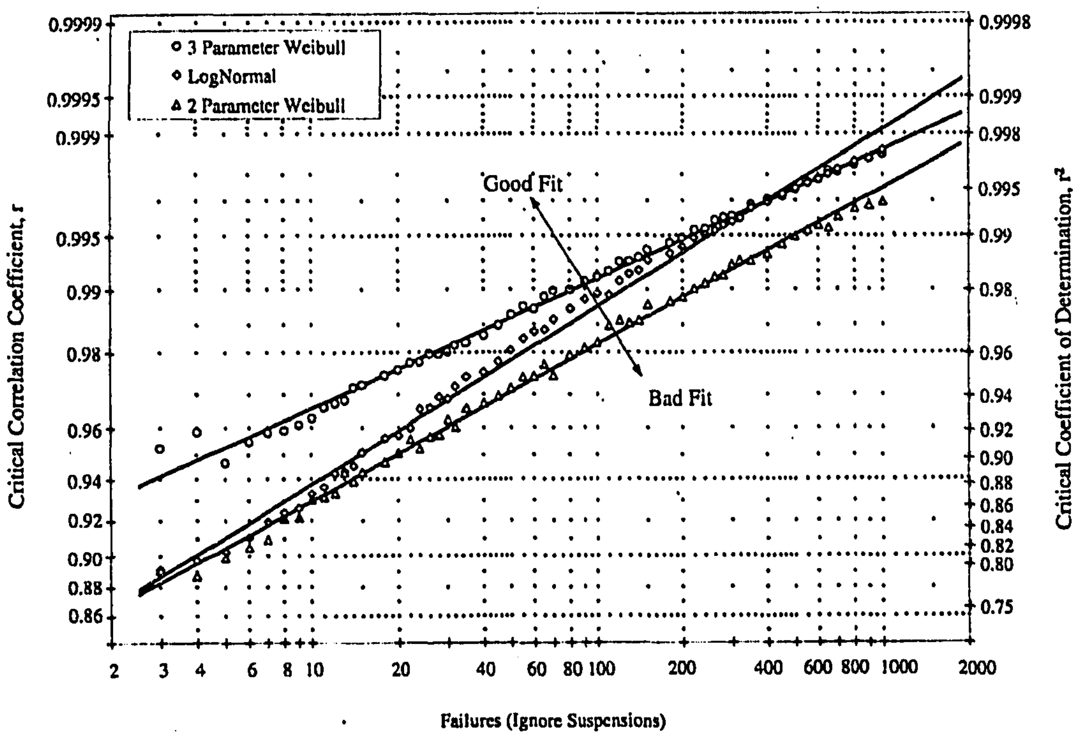


Figure 6.1: Regression Coefficient r and r^2 for goodness of fit (Abernathy, 2000)

The shape factor β is 12 and the characteristic life θ is 112,795. The regression coefficient is 0.95. Please refer to figure 6.1 as the failure data are fitted to Weibull distribution the regression coefficient of 0.95 for seven failures is a good fit. The following table and plot illustrate data fitting.

Table 6.1: Least squares fit of seven failure data of waterwall

i	Failure Times.t_i	$F(t_i)$=i-0.3/6+0.4	$Ln(t_i)$	$LnLn(1/(1-F(t_i)))$
1	86256	0.0945	11.3650	-2.3088
2	98472	0.2297	11.4975	1.3431
3	98640	0.3648	11.4992	0.7898
4	101016	0.5	11.5230	0.3665
5	106056	0.6351	11.5717	0.0081
6	109656	0.7702	11.6051	0.3858
7	111816	0.9054	11.6246	0.8578

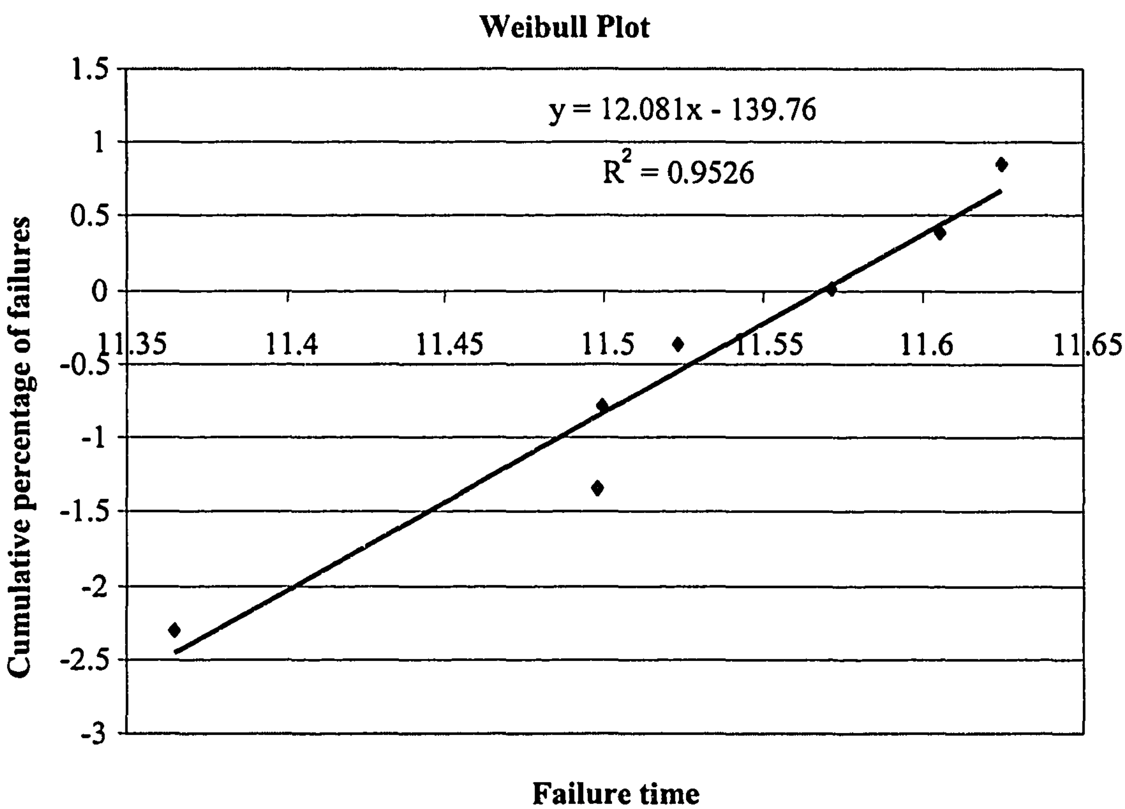


Figure 6.2 :Weibull least squares plot of waterwall failure data

The equation for the Weibull least squares plot is

y = 12x + (-139.76)

Intercept a = -139.76; Slope = β = 12

$\theta = e^{\left(\frac{-a}{\beta}\right)}$

Substituting, θ = 112795

$$R(t) = e^{-\left(\frac{t}{\theta}\right)^{\beta}}$$

Running Hours per year = 7416

Substituting, Reliability R (t) = 0.98

Referring to equation (6.34), Mean Time to Failure = $\theta\Gamma\left(1+\frac{1}{\beta}\right)$

Substituting, MTTF =112795Γ (1 + 0.083) or 108252 hours.

6.1.1.1 SUMMARY OF WATERWALL FAILURE DATA ANALYSIS

The shape factor β is 12. The characteristic life θ is 112795. The mean time to failure is 108252 hours. The reliability for an operation of 8760 hour per year is 1. The reliability for a five-year operation is 0.99. But the last failures had shown hydrogen damage to the tubes indicating a potential increase in tube failures.

6.1.2 SUPERHEATER

The superheaters raise the temperature of saturated steam to super heated. The locations of the superheaters and the various types have been described in chapter-4. The following table 6.2 illustrates the failure data analysis as per least squares approach. The regression coefficient is 0.87 and it is acceptable as a regression coefficient of 0.83 for a six failure will provide a good fit for considering Weibull distribution, according to the chart in Figure 6.1

Table 6.2: Least squares fit of six failure data of superheater

i	Failure Times.t_i	$F(t_i)$=i-0.3/6+0.4	$Ln(t_i)$	$LnLn(1/(1-F(t_i)))$
1	39572	0.1093	10.5858	2.1556
2	57672	0.2656	10.96252	1.1752
3	57792	0.4218	10.96460	0.6015
4	58392	0.5781	10.9749	0.1472
5	71520	0.7343	11.1777	0.2819
6	71616	0.8906	11.1790	0.7943

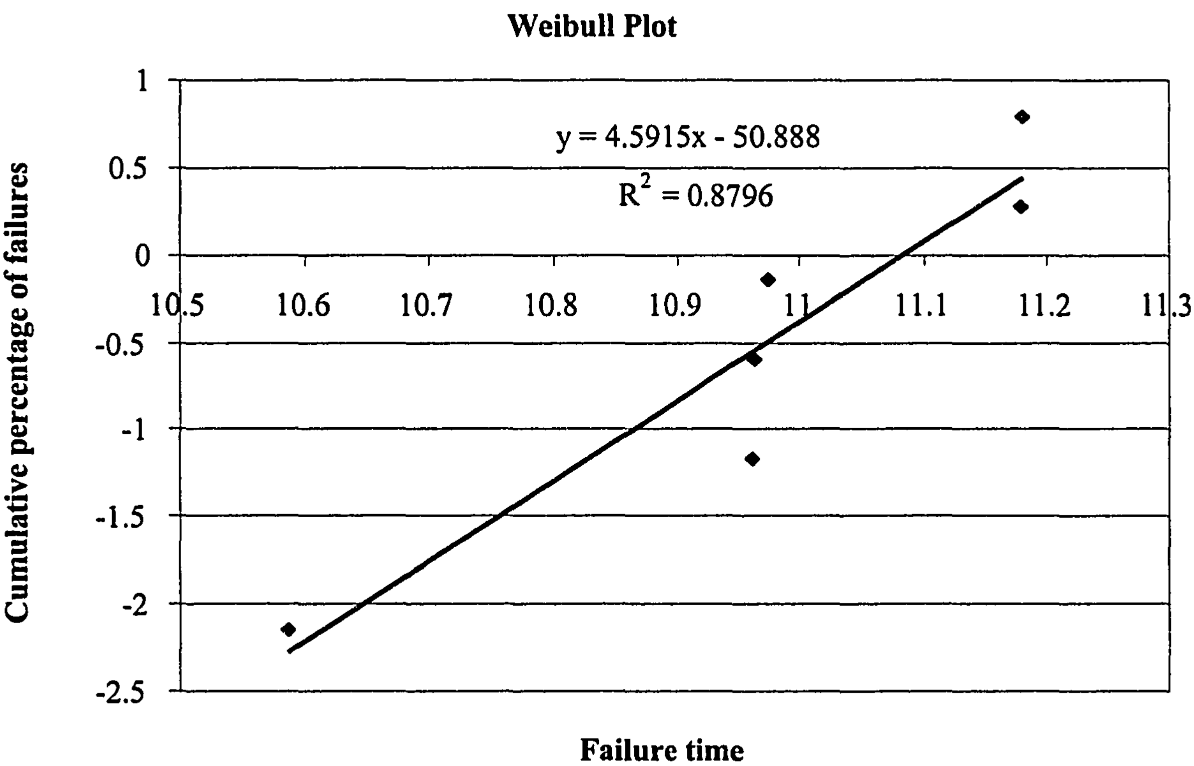


Figure 6.3: Weibull least squares plot of superheater failure data

The equation for the Weibull least squares plot is

y = 4.5915x × (-50.888)

Intercept a = -50.888; Slope = β = 4.5915

$\theta = 65026.67314$

Running Hours per year = 8760

Reliability = 0.99

MTTF = 65026 Γ (1 + 0.217) = 59536 hours.

6.1.2.1 SUMMARY OF SUPERHEATER FAILURE DATA ANALYSIS

The analysis has revealed that the superheater failure data follow Weibull distribution. The shape parameter β is 4.59 and the characteristic life θ=65026 hours. The mean time to failure MTTF is 59536 hours. The reliability for an annual running hour of 8760 hours is 0.99.

6.1.3 REHEATER

The reheater tubes are placed in the convection heat zone in the boiler. The occurrence of tube failure is not frequent. There can be only two reasons for frequent reheater tube failures. One is improper reheater metal . A 2.25% chromium tube being in use where a 9% chromium tube is required due to higher heat flux. Secondly, during boiler start ups the reheater tubes will not have any steam flowing through their tubes due to the turbine being not in service. Turbine is required to be in service as reheater gets its steam from the exhaust of high pressure turbine. Till steam is admitted to turbine, and flow established through the reheater, the boiler firing rate needs to be kept low so as not to allow the furnace exit gas to exceed 800^0F. When firing rate exceeds this limitation, reheater tubes which are located in the convection pass fail. During every annual outage it is usual to see reheater tubes warped and out of alignment. In this case plants replace sections of the reheater where warping has taken place. The fact that there are only three failures does not mean that the tubes in the reheater are reliable. The three failure data were fitted for Weibull, and yielded a regression coefficient of 0.83 whereas the regression coefficient obtained from exponential distribution was only 0.62. In as much as an acceptable regression coefficient is set at 0.75, Weibull distribution is acceptable for analyzing the reheater failure data. The following table 6.3 illustrates the failure data analysis.

Table 6.3: Least squares fit of three failure data of reheater

i	Failure Times.t_i	$F(t_i)$=i-0.3/3+0.4	Ln(t_i)	LnLn(1/(1-F(t_i)))
1	32256	0.2058	10.3814	1.4674
2	88152	0.5	11.3868	0.3665
3	90768	0.7941	11.4160	0.4577

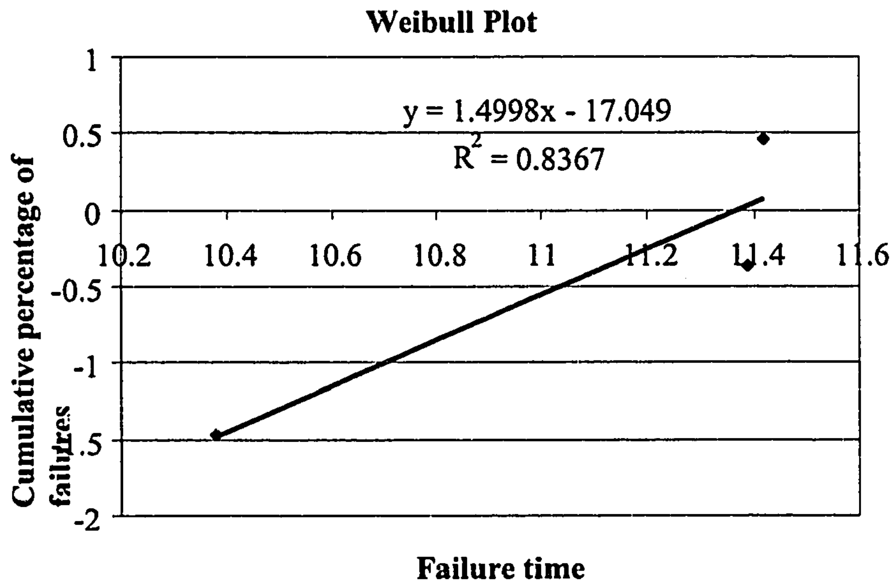


Figure 6.4: Weibull plot of three failure data of reheater

The equation for the Weibull least squares plot is

$y = 1.4998x \times (-17.049)$

Intercept $a = -17.049$; and Slope = $\beta = 1.4998$

$\theta = 83561.09612$

Running hours per year = 8760

Reliability = 0.96

MTTF = 83561 Γ (1 + 0.66) or 75204 hours.

6.1.3.1 SUMMARY OF REHEATER FAILURE DATA ANALYSIS

The failure data analysis yielded a r^2 value of 0.836 for three failures. This implies that 83.6% of the variation in data is explained by the fit of the trend line. The acceptable r^2 value for good fit for a three failure Weibull analysis is 0.774 according to the chart in Fig 6.1. The shape factor β is 1.5 and the characteristic life θ is 83561 hours. The mean time to failure MTTF is 75204 hours. The reliability for annual running hours is 0.966.

6.2 FORCED DRAFT FAN

The forced draft fans blow air for combustion in the furnace. They are huge fabricated equipment running at 1800 rpm. The fan blades develop cracks during service and cause vibration. The lubrication oil system and fan controls cause fan failures too. There are eight failure data are analyzed in this chapter. Table 6.4 illustrates the data analysis.

Table 6.4: Least Squares fit of eight failure data of Force Draft fan

i	Failure Times.t_i	$F(t_i)$=i-0.3/3+0.4	$Ln(t_i)$	$LnLn(1/(1-F(t_i)))$
1	26760	0.0833	10.1946	-2.4417
2	32160	0.2023	10.3784	-1.4866
3	32352	0.3214	10.3844	-0.9473
4	42720	0.4404	10.6624	-0.5435
5	65712	0.5595	11.0930	-0.1985
6	65736	0.6785	11.0934	0.1266
7	88608	0.7976	11.3919	0.4685
8	96168	0.9166	11.4738	0.9102

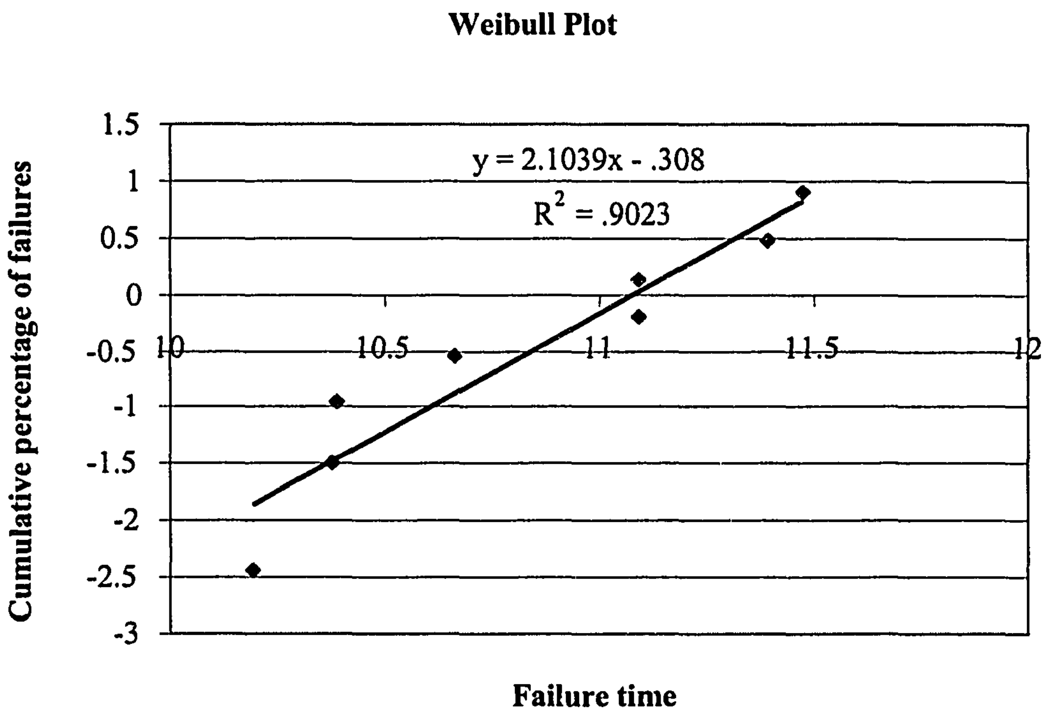


Figure 6.5: Weibull plot of Force Draft fan

The equation for the Weibull least squares plot is

$y = 2.1x \times (-23.3)$

Intercept a = -23.3; and Slope $\beta = 2.1$

θ = 65856 hours

Running Hours per year = 8760

Reliability = 0.98

MTTF = 65856 Γ (1 + 0.476) or 61246 hours.

6.2.1 SUMMARY OF FORCED DRAFT FAN FAILURE DATA ANALYSIS

The analysis of the FD Fan failure data analysis yielded r^2 value of 0.9, which is acceptable for eight failures. The acceptable r^2value for good fit for a eight failure Weibull analysis is 0.85 according to the chart in figure 6.1. The shape factor β is 2.1 and the characteristic life θ is 65,856 hours. The mean time to failure MTTF is 61,246 hours. The reliability for annual running hours is 0.98

6.3 BOILER FEED PUMP

The boiler feed pump provides the feed water to the boiler. Five failures are analyzed. Table 6.5 illustrates the analysis of the failure data by least squares approach.

Table 6.5: Least squares fit of five failure data of Boiler feed pump

i	Failure Times.t_i	$F(t_i)$=i-0.3/3+0.4	Ln(t_i)	LnLn(1/(1-F(t_i)))
1	116208	0.1296	11.6631	-1.9744
2	142296	0.3148	11.8656	-0.9726
3	142632	0.5	11.8680	-0.3665
4	142680	0.6851	11.8683	0.1447
5	167208	0.8703	12.0269	0.7144

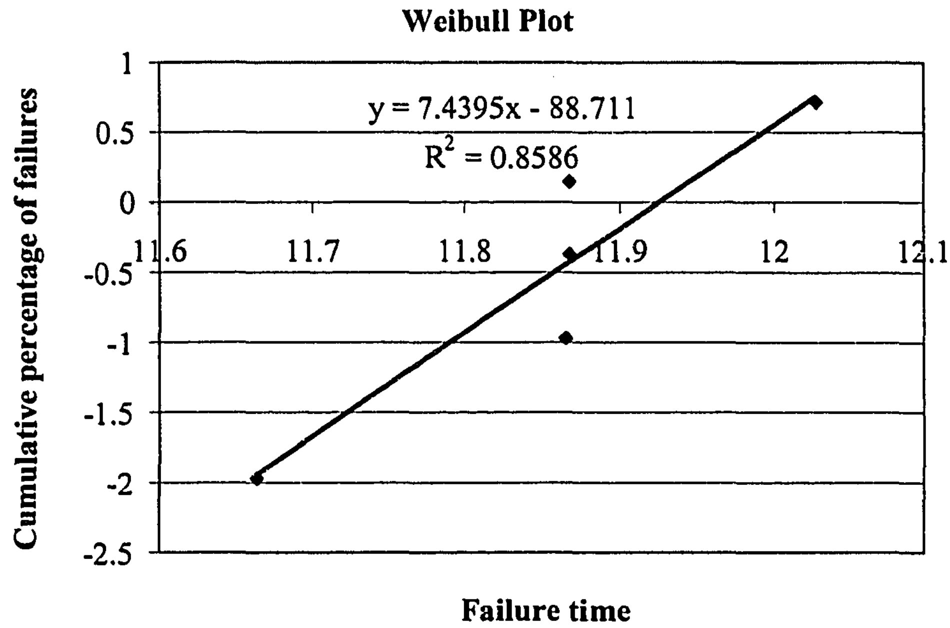


Figure 6.6: Weibull plot of Boiler feed pump

The equation for the Weibull least squares plot is

y = 7.43x × (-88.71)

Intercept a = -88.71; and Slope β = 7.43

θ = 150892 hours

Running Hours per year = 8760

Reliability = 1

MTTF = 150892 $\Gamma(1 + 0.1345)$ = 131276hours.

6.3.1 SUMMARY OF BOILER FEED PUMP FAILURE DATA ANALYSIS

The analysis of the boiler feed pump failure data analysis yielded r^2 value of 0.85 which is acceptable for five failures. The acceptable r^2value for a good fit for five failure Weibull analysis is 0.81 according the chart in Figure 6.11. The shape factor β is 7.43

and the characteristic life θ is 150892 hours. The mean time to failure MTTF is 131276 hours. The reliability for an annual running hour is 1 for a year

6.4 BOILER FEEDPUMP RECIRCULATION VALVE

The boiler feed pump recirculation valve has to reduce the high boiler feed pump pressure of about 2000 psi to about 75 psi and in this process its seat and plug undergo a high differential pressure and the valve slowly begins to deteriorate and eventually fail. Technological advances in the design have steadily improved the performance of these valves. However they do breakdown. Table 6.6 illustrates the analysis of 5 Boiler feed pump recirculation valve failure data.

Table 6.6: Least squares fit of five failure data of Boiler Feed pump recirculation valve

i	Failure Times.t_i	$F(t_i)$=i-0.3/5+0.4	Ln(t_i)	LnLn(1/(1-F(t_i)))
1	27072	0.1796	10.2062	-1.6194
2	54840	0.3648	10.9121	-0.7900
3	61608	0.55	11.0285	-0.2250
4	66096	0.7351	11.0988	0.2842
5	72456	0.92037037	11.190735	0.928365151

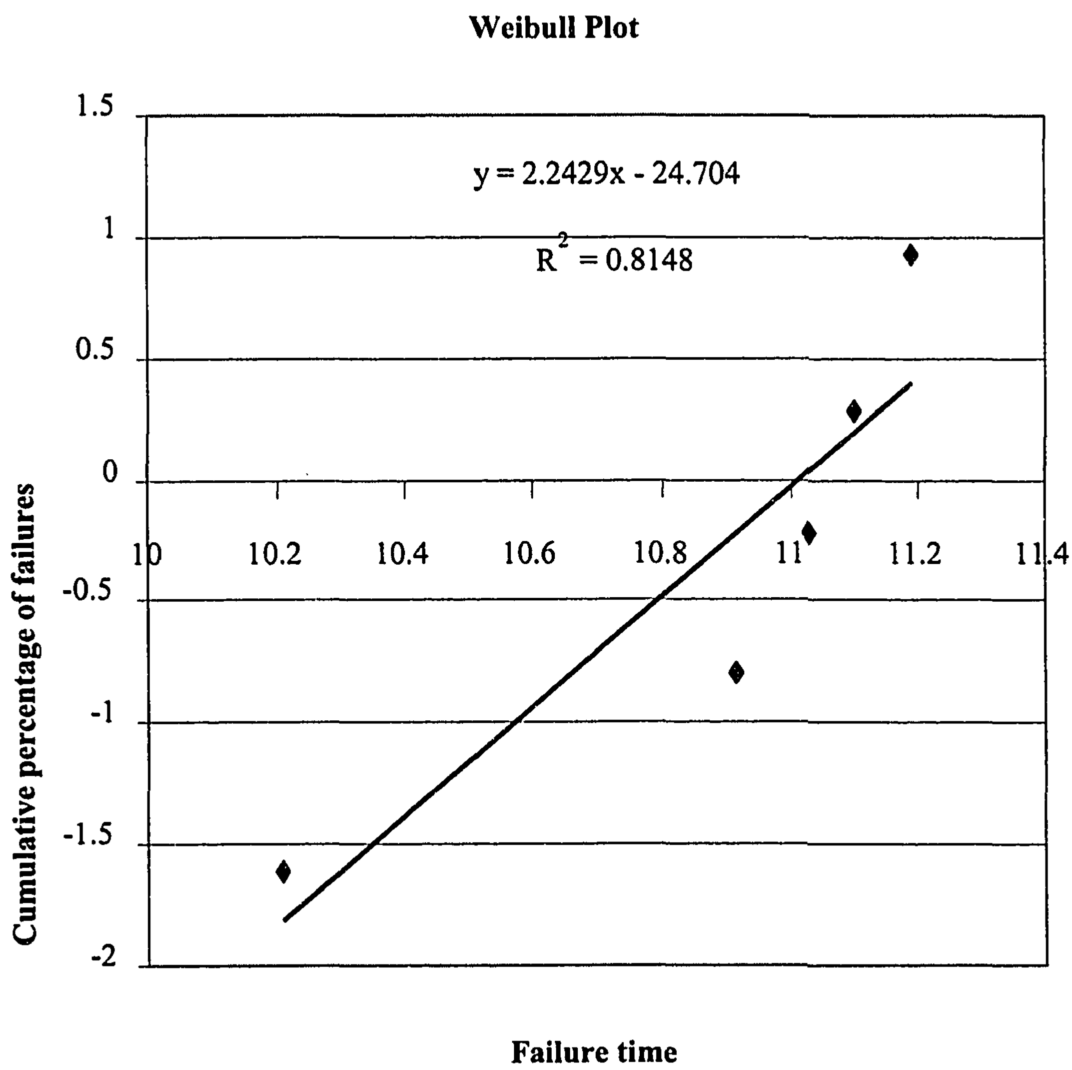


Figure 6.7: Weibull plot of boiler feed pump recirculation valve

The equation for the Weibull least squares plot is

$y = 2.2429x \times (-24.704)$

Intercept $a = -24.704$

Slope = β = 2.2429

θ = 60628.9

Running Hours per year = 8760

Substituting, Reliability = 0.98

MTTF = 60628.98 Γ (1 + 0.4458) = 53696 hr

6.4.1 SUMMARY OF BOILER FEED PUMP RECIRCULATION VALVE FAILURE DATA ANALYSIS

The regression coefficient r^2 is 0.814. As per chart in figure 6.1, for a good fit for a five failure Weibull analysis, the regression coefficient must be 0.81 and hence the regression coefficient is acceptable. The shape parameter β is 2.24 and the characteristic life θ is 60628. The mean time to failure MTTF is 53696 hour.

6.5 CONDENSER TUBES

The condenser tubes develop leaks due to vibrating tubes hitting against the supporting plates, other than corrosion and tube end defects. Such tube failures have been overcome mostly by up grading the tube materials to tungsten. Nineteen tube failures are analysed by means of least squares approach. They are tabulated in Table 6.7.

Table 6.7: Least squares fit of nineteen failure data of condenser tubes

i	Failure Times.t_i	$F(t_i)$=i-0.3/5+0.4	Ln(t_i)	LnLn(1/(1-F(t_i)))
1	27504	0.0360	10.2220	-3.3036
2	28584	0.0876	10.2606	-2.3891
3	30072	0.1391	10.3113	-1.8980
4	30120	0.1907	10.3129	-1.5529
5	39744	0.2422	10.5902	-1.2822
6	40488	0.2938	10.6087	-1.0559
7	42312	0.3453	10.6528	-0.8587
8	42792	0.3969	10.6641	-0.6818
9	42840	0.4484	10.6652	-0.5191
10	43296	0.5	10.6758	-0.3665
11	43464	0.5515	10.6796	-0.2207
12	43728	0.6030	10.6857	-0.0789
13	43920	0.6546	10.6901	0.0612
14	44208	0.7061	10.6966	0.2027
15	44304	0.7577	10.6988	0.3490
16	44688	0.8092	10.7074	0.5049
17	50808	0.8608	10.8358	0.6790
18	58344	0.9123	10.9741	0.8898
19	58728	0.9639	10.9806	1.2005

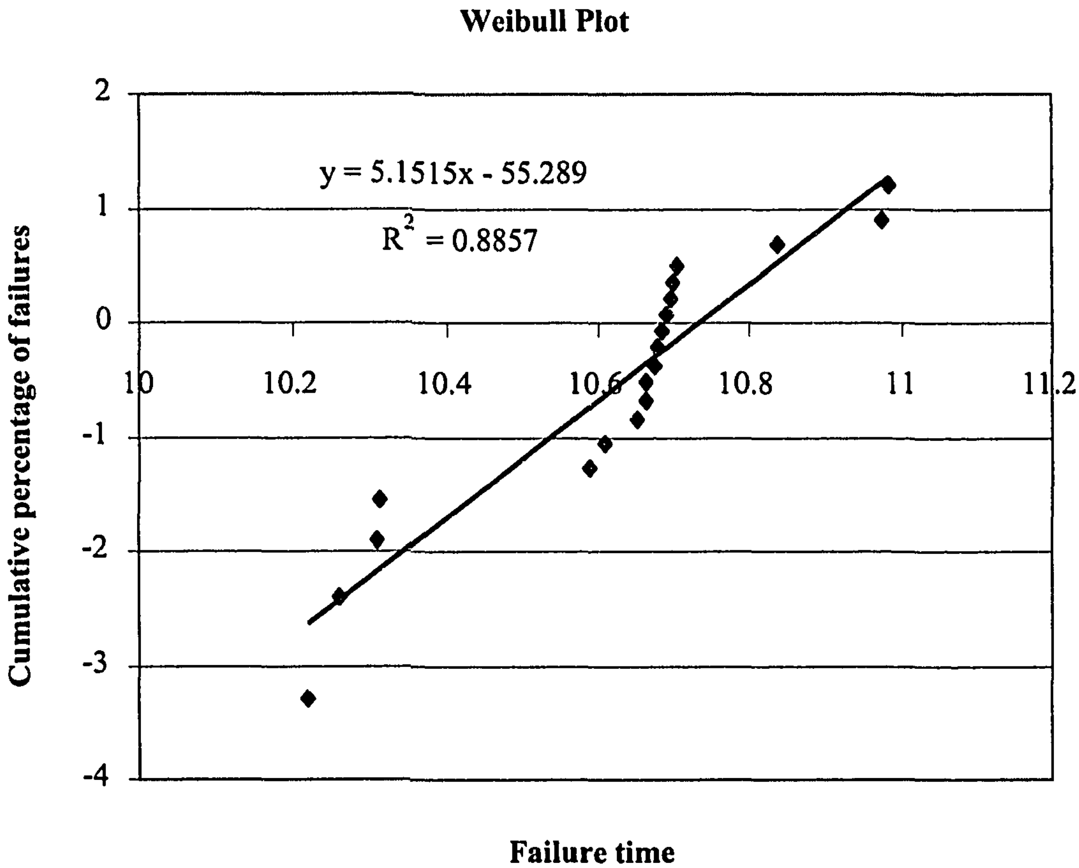


Figure 6.8: Weibull plot of Ccndenser tubes

The equation for the Weibull least squares plot is

y = 5.1515x × (-55.289)

Intercept a = -55.289

Slope = β = 5.1515

θ = 45825

Running Hours per year = 8760 hr

Reliability = 0.99

MTTF = 45825 Γ(1 +0.1941) = 42159 hr.

6.5.1 SUMMARY OF CONDENSER TUBES FAILURE DATA ANALYSIS

The regression coefficient r^2 is 0.8857. The acceptable regression coefficient r^2 for a 19-failure analysis is 0.887 for Weibull according to the chart in figure 6.1. The shape parameter β is 5.15. The characteristic life θ is 45825. The reliability for an operation for a year is 0.99. The mean time to failure MTTF is 42159 hrs.

6.6 SUMMARY OF DATA ANALYSIS

Table 6.8: Summary of Data Analysis

Component	Shape Parameter	Characteristic Life	Running Hours per Year	Reliability for a time of year	MTTF Hours
Waterwall	12	112795	8760	1	108252
Sperheater	4.59	65026	8760	0.99	59536
Reheater	1.5	83561	8760	0.96	75204
FD Fan	2.1	65856	8760	0.98	61246
Boiler Feed Pump	7.43	150892	8760	1	131276
Boiler Feed Pump Recirculation Valve	2.24	60628	8760	0.98	53696
Condenser	5.15	45825	8760	0.99	42159

6.7 AVAILABILITY OF SOFTWARE

American Society of Mechanical Engineers has issued a CD ROM called 'Risk based methods for equipment life management' to do data analysis. This CD ROM is available with ASME International, New York 10016 – 5990.

Chapter 7

CONSEQUENCE ASSESSMENT

In the previous chapter, the failure times of seven critical components were modeled using appropriate reliability model, consequently mean time to failure (MTTF) and reliability for one year operation were assessed. Once failure probability is known inspection interval is decided to check and maintain the component/system. Failure probability is an indicator of the reliability of a component and hence it dictates the frequency of inspections. Thus Inspection planning is the obvious chapter to follow an assessment of failure probability. The consequences of the failure of a component will reflect in dollar revenue lost in production of power. The calculation of consequential lost revenue forms part of the component replacement procedure. However, in this chapter the focus is on the replacement of high risk components rather than optimization of inspection interval. Inspections by themselves are not important but it is the action that follows an inspection has an impact on the plant operation. The action may be either repair or component replacement depending on the findings of the inspection. This chapter provides details of cost based optimization to replace/repair defective components to ensure reliable operation of the power plant. The replacement/repair interval optimization is carried by maximizing NPV (net present value). This step needs to be worked out before considering inspections because inspection program development is a resource intensive process that need not be undertaken until it is known what it will do (ASME, 2003)

In this work the replacement cost will be considered instead of the inspection cost.. This is mainly because inspection cost is smaller compared to the outage and repair/replacement costs. Basing the optimization calculation on inspection costs would lead to inaccurate results regarding what equipment need to be inspected. Therefore the strategy followed in the present work is to:

1. Optimize, based upon replacement cost
2. Inspect using an optimized strategy before the projected component replacement date.
3. Compare the actual component conditions that are found with the projected conditions.
4. Replace the component or calculate a new optimized replacement interval.

However in this thesis, the time to replace is taken as 2007. The well managed companies usually look for a pay back period of five years or some time seven years.

7.1 MAXIMIZING VALUE TO THE COMPANY

The emphasis today is on the "value added". The reason for this is that most companies are owned by stockholders who aspire at maximizing the return on their investment. Maintenance is an area of particular concern because maintenance costs are not perceived to be directly connected to production. When a new plant is built, the costs associated with fuel and the overheads are alone estimated to arrive at the profits. The cost of maintaining the plant is usually not considered at the initial stages partly due to the lack of data and the expectation that there would not any major breakdowns in a new plant. As the plant ages, the yearly maintenance budget increases which is separately prepared and approved. The maintenance budget is a variable quantity. But the cost of fuel and salaries remain do not vary very much and considered as production cost. However maintenance is critically important. Therefore, spending a maintenance dollar in a manner that does not provide maximum return is not making the best use of the stockholder funds nor company resources (ASME, 2003).

Using net present value (NPV) as a decision making criterion is one way to illustrate the "value added" which will accrue as a result of the maintenance program. NPV not only considers the investment of resource but also accounts for cash flow consequences over the service life of the equipment. This is why maximization of NPV is suggested as the decision making criterion for investments (ASME,2003). Maintenance expenditures are investments that are made to receive the benefit of production return in the near, intermediate and long terms.

NPV becomes the common denominator for proposals put forward from different business lines to the corporate decision makers. This puts all corporate entities on the same level with a common communication medium for the corporate decision maker. This is why it is so useful in communications and decision making. All the business are on the same level with regard to proposals for projects because NPV is the unit of the measure for any aspect of the company operation, including maintenance. Maintenance engineering proposals benefit, together with engineering analysis results, have been difficult to quantify for the decision maker. Concentrating on conversion of maintenance and engineering effects into cash flow and NPV terms will allow these to compete with other business lines of the company in a clear manner. The common communication medium of dollars ties directly to the language of the decision maker and to stockholders.

Optimization creates savings by looking at the whole life of the component. The real plan is to operate these components for a number of years; therefore, looking at the financial effects over this whole frame is most realistic.

There is a tendency to use payback periods to make project decisions. The difficulty with that approach is that it only looks at the short range. A financial process that also considers the long range benefit of a project provides a more realistic view of the financial considerations over the service life of the component. This longer range view occurs when NPV is used as the optimization criterion. For this reason NPV will be used.

7.2 ANALYTICAL APPROACH

One of the most important characteristics of the analytical approach to maintenance optimization is its use of NPV as the decision making criterion. The key to a smooth and a successful integration of maintenance and engineering decision making into mainstream corporate decisions is the calculation of NPV by including lost production costs in the failure consequence cost. This is because the corporate decision making criteria are being used to express the need for maintenance resources. (ASME, 2003)

The specific elements of the optimization model are:

1. The replacement or repair cost of the components of concern
2. Realistic constraints such as annual budget costs
3. The production loss consequence if the component is not replaced

4. The production loss consequences if the component is replaced

5. The facility safety constraint

Items 1 and 4 are costs related to the component replacement and implementation costs. Item 4 is the consequence avoided by replacing the component and it is the gross benefit. Item 2 keeps the expenses in check by disqualifying strategies that are unaffordable. Item 5 keeps out any strategy that compromises safety (ASME, 2003).

7.2.1 THE CONCEPT OF NET PRESENT VALUE

Let us assume that a house has burned down leaving the owner with the vacant land worth $30,000 and a cheque for $100,000 from the home insurance company. The owner considers rebuilding the house but he is advised by investors to build an office building to be sold after a year. The advisors expect a shortage of office space and expect that the building could be sold for $300,000. The construction of the office building would cost $200,000 including the insurance pay out and the cost of land which might otherwise be sold for $ 30,000. Thus the owner would be investing 230,000 in the hope of realizing $300,000 in one year from now. The owner must ask himself the question "What is the value of $300,000 (earned one year from now) in terms of today's money (Brealey, 1986).

7.2.1.1 PRESENT VALUE

The present value of $300,000 one year from now is less than $300,000. The reason for this is summed up by the following principle: a dollar today is worth more than a dollar tomorrow, because the dollar today can be invested to start earning interest immediately.

Thus the present value of a delayed pay off may be found by multiplying the pay off by a discount factor that is less than one. If the discount factor was greater than one, a dollar today would be worth less than a dollar tomorrow. If C_1 denotes the expected payoff at time period 1(one year hence), then

Present Value (PV) = discount factor x C_1

The discount factor is expressed as the reciprocal of one plus a rate of return:

$$\text{Discount factor} = \frac{1}{1+r}$$

The rate of return r is the reward investors demand for accepting delayed payment. Considering the real estate investment, assuming for the moment that the \$300,000 pay off is certain, the office building is not the only way to obtain \$300,000 a year from now. \$300,000 can be invested in Federal Government bonds for a year. Assuming that these bonds yield 5% interest, $\frac{300{,}000}{1+0.05}$ has to be invested now to get \$300,000 after a year. The invested amount is \$ 285,714 now. If the owner wants to sell the project just after he has committed the land and started construction on the building, any investor would be willing to pay \$285,714. This is what it will cost the investors to earn \$300,000 in government bonds. Of course, the owner can sell for a lower price. But why should he sell for a less price than the market will bear. Therefore, the present value is also its market value.

To calculate the present value, the expected future pay offs is discounted by the rate of return offered by comparable investment alternatives. The rate of return is often referred to as the discount rate, hurdle rate, or opportunity cost of capital. In this example, the Present value is obtained by dividing $300,000 by 1.05.

Therefore, PV = discount factor x $C_1 = \frac{300,000}{1.05} = 285,714$

7.2.1.2 NET PRESENT VALUE

The office building is worth $285,714. This does not mean that the owner is $ 285,714 better off. He committed $230,000 and therefore his net present value is $ 55,714. Net present value (NPV) is found by subtracting the required investment.

NPV =PV – required investment = 285,714 – 230,000 = $55,714

In other words the office development is worth more than it costs. It makes a net contribution to value. The formula is.(Brealey,1986)

$$NPV = C_0 + \frac{C_1}{1+r} \tag{7.1}$$

C_0 is the cash flow at time 0 (that is today) will usually be a negative number. In other words, C_0 is an investment and therefore a cash outflow. In this example, C_0 = - $230,000 Therefore NPV has to be positive to earn profit.

7.2.2 APPLICATION OF NPV TO COMPONENT REPLACEMENT

Component replacement is also an investment but its usefulness is manifested as an increase in the overall of efficiency of the plant. The losses caused by having one inefficient component can be estimated and expressed in terms of lost power. The power lost represents financial loss. Therefore Eq 7.1 is written in terms of losses and investment.

The reasoning behind the model is this: (ASME,2003).

If the proposed component replacement is not implemented, there will be certain production losses, e.g.; a "Do nothing different" or "Base Case" (ASME, 2003 Risk Based Methods for Equipment Life Management page 159) cost. Let this be C_B

If the proposed component is replaced, there will be lower total production losses.e.g: "With project" or "Alternative Case" cost. Let this be C_A

If the proposed component is replaced, there will be a cost for component and its installation. Let this be C_p

If the sum of the cash flows for the component replacement cost and the Alternative Case production loss cost is greater than the Base Case production loss cost cash flow, then a negative NPV will result. Writing as an equation (ASME, 2003)

$$NPV = C_B - (C_P + C_A) < 0. \qquad (7.2)$$

The component will not be replaced. It is not profitable to replace the component, the component should not be replaced..

If the reverse is true, then the Base Case production loss cost cash flow is greater than component replacement cost plus the Alternative Case production loss cost, then the NPV will be positive. Writing as an equation (ASME, 2003)

$$NPV = C_B - (C_P + C_A) > 0 \qquad (7.3)$$

It is more profitable to replace the component. The component replacement can be approved.

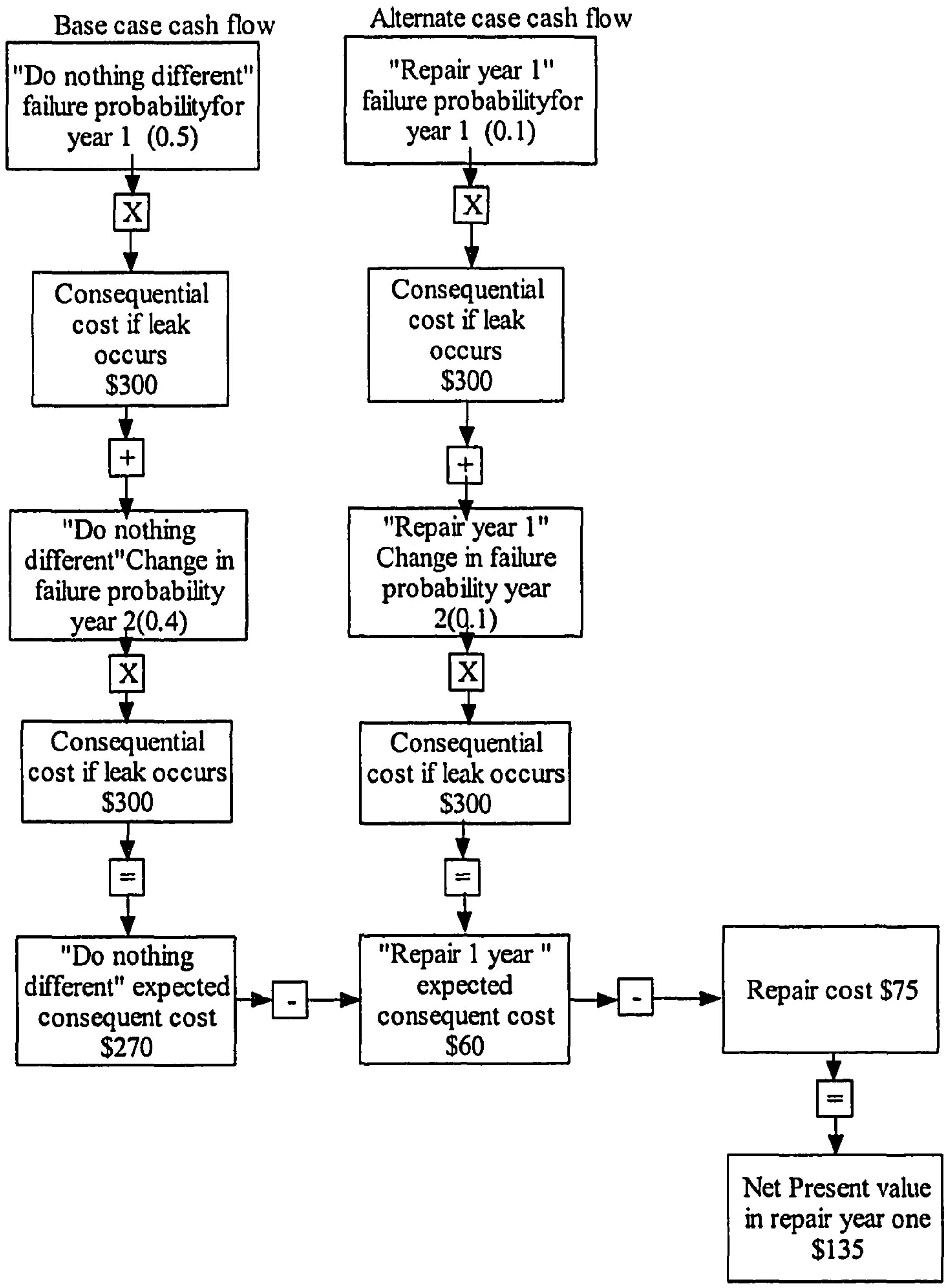
To illustrate the above concepts the following scenario is considered.

1. A house has an old wooden window. The wood has become soft. There is a concern that the window may leak during winter.
2. The owner of the house is contemplating repairing wood that has become soft the at a cost of $75.

. If the owner continues to live with old wooden window the probability of a leaky window is 50% this year and 90% next year.

3. If the owner replaces the window, the probability of leak is 10% this year and 20% next year
4. The consequences of having a leaky window will be higher heating bill by $600 per year.

Should the window be replaced this year or next year?



FIigure 7.1:NPV Calculation for "Do nothing" vs "Repair in year 1"

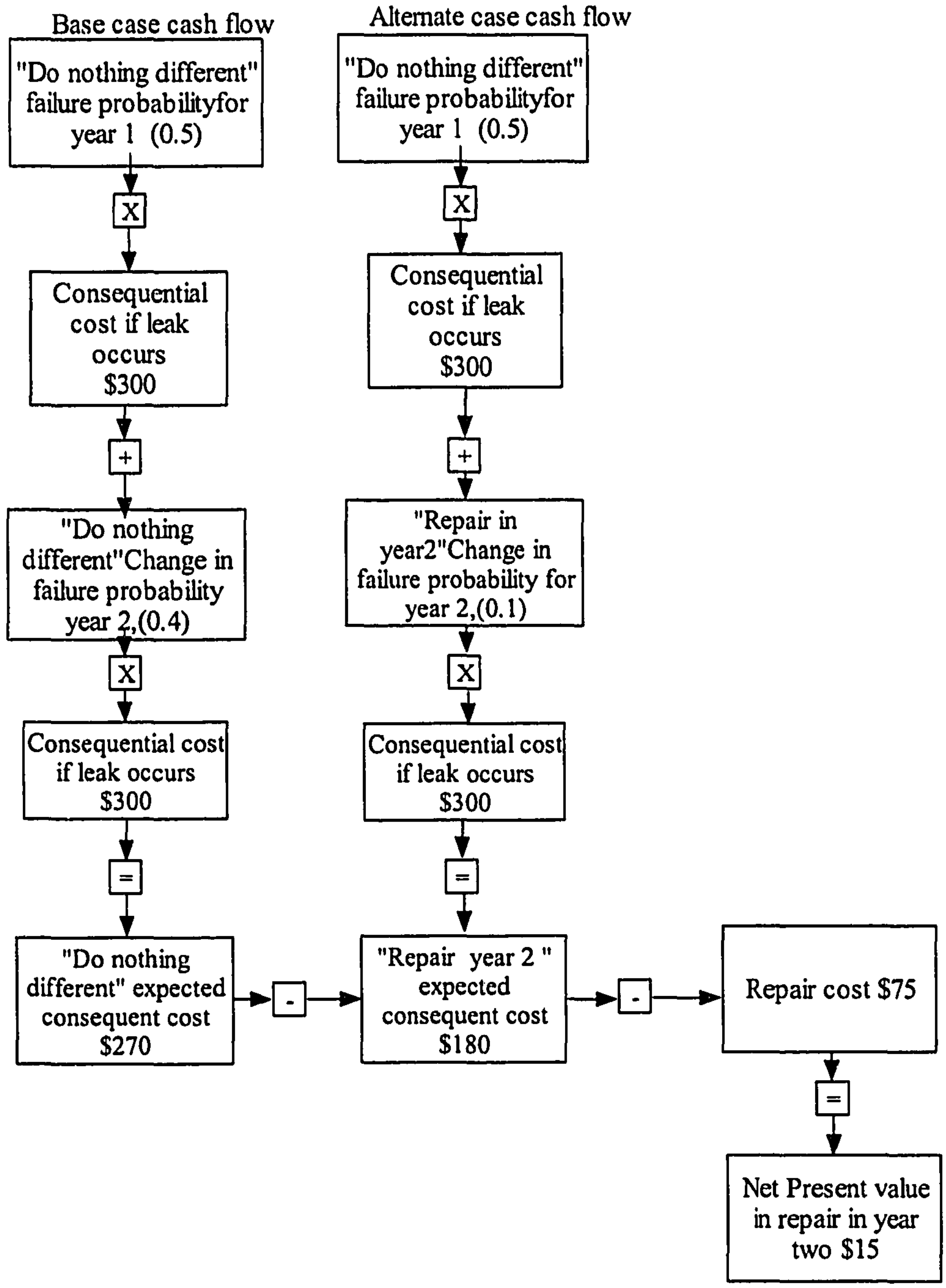


Figure 7.2 NPV Calculation for "Do Nothing vs Repair in Year 2"

The year that produces the highest positive NPV must be chosen. In the example shown in Fig 7.1 and 7.2, the highest NPV is for repair in the first year. Therefore component replacement should be in the year which will produce the highest positive NPV.

7.3 THE MODEL DEVELOPMENT PROCESS

The decision model is best illustrated by the decision analysis influence diagram. An influence diagram graphically represents the relationships that link a decision with its outcomes and their consequences.(ASME,2003).

The purpose of the influence diagram is to link the failure probability and NPV. Engineers have often had difficulty expressing the need for financial resources in a format that communicated with the financial world. The influence diagram is a communication tool that explains the make up of the decision and what influences it. The influence diagram contains no numbers and can be understood by plant personnel and company executives.

The necessary nodes between the decision and the financial outcome are the consequences and relationship information that link them to form a complete model. To construct the diagram, a beginning is made at the node NPV on the right. Then question the information that is needed to arrive at NPV. In this fashion move towards left until the decision node is reached at the left. The engineering state of the component as expressed by the failure probability determines the performance of the component as a result of the decision made. The relationships that convert the failure probability to components of NPV form the bridge between engineering and finance. Fig7.3 is the influence diagram for the window repair example. The real question is "What are the magnitudes of the losses due to a leaky window."

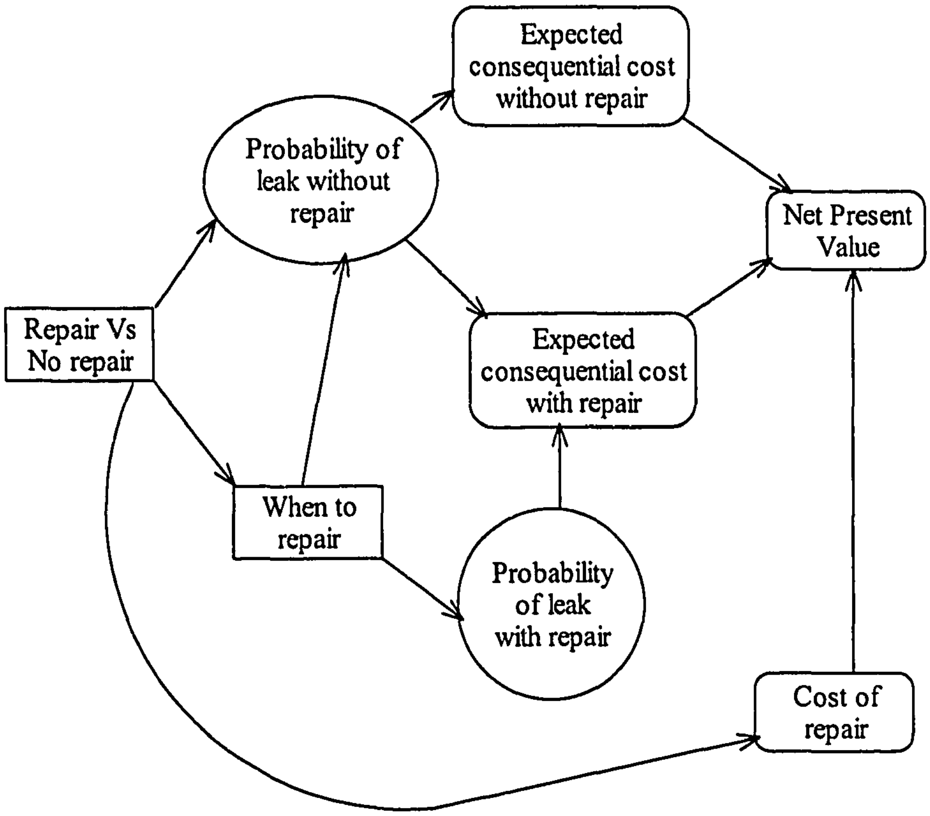


Figure 7.3: Influence Diagram for window repair

7.4 WATERWALL REPLACEMENT

The waterwalls of a boiler forms the walls of the boiler furnace. The waterwall tubes are subjected to a furnace temperature of approximately1400 ^{0}C. The boiler water that flows through the tubes is chemically treated to maintain a pH value of about 9. Waterwall tubes are susceptible to deviations in the chemistry of the boiler water. Both the fire side and feedwater side of the tubes can deteriorate due to combustion excursions like variations in combustion air, fuel oil pressure, steam atomizing pressure and furnace pressure. Under these circumstances waterwall tubes are replaced in aging boilers. A boiler waterwall replacement that took place recently is analyzed. The boiler capacity was 175 MW. When a tube fails, it takes 72 hours to bring the boiler back to service. These hours are required as time is needed for cooling the furnace to enable workers to enter and build access for welders, NDT technicians, and inspectors. During this time, the lost power has to be generated by running the gas turbines. It costs $135 to produce 1 MW using the gas turbine. It costs $65 to produce 1 MW using an oil fired boiler. Therefore the incremental cost is $70 per MW due to a waterwall tube failure. The cost of labour and material needed to repair one waterwall tube failure is $20,000. The cost of fuel needed to start a boiler from a standstill is $45,000, to reach the levels of the boiler parameters to the rated pressure and temperature. The wages to be paid for additional personnel to correct instrumentation and electrical problems that may come up during a boiler start up. The metallurgical laboratories charge $2000 to analyze a failed tube. Therefore, a waterwall tube failure costs $949,000 to the plant. The cost of replacement of a panel or a section of the furnace waterwall where NDT has revealed tube thinning costs $1,000,000. The following calculation shows the validity of incurring an expenditure of $1,000,000 in waterwall replacement.

MTTF for waterwall tubes. Ref Table 6.8	108252 hours
Base year for data	1993
Year of replacement	2007
Number hours of operation from 1993 to 2007	131400

Number of failures expected in 2007	1.2 say 2
Loss of generation due to waterwall failure	175 MW
Time taken to repair waterwall tube	72 hours
Incremental Cost of generating ,175 MW	
By Gas Turbine to make up for the loss @$70.00/MW	$882,000
Cost of Repairing Failed waterwall	$20,000
Cost of Laboratory analysis for failed tube	$2000
Cost of Boiler start up after waterwall repair	$45,000
Cost of one waterwall failure	$949,000
Cost of two waterwall failures, C_B	$1,898,000
Cost of water wall replacement in the failure zone, C_P	$1,000,000
Running Hours for 5 years	43800 hours
Expected failure in 5 years after replacement, C_A	0

The project will be implemented if:

$$NPV = C_B - (C_P + C_A) > 0$$

Substituting for NPV as per Eq 7.3,

$$1{,}898000 - (1{,}000{,}000 + 0) = \$898{,}000$$

As NPV is more than zero, the project will have to be implemented. It is obvious that implementation of the project beyond 2007 will increase losses and hence the year of implementation should be 2007 or earlier. A time ordered waterwall influence diagram is shown in figure 7.5.

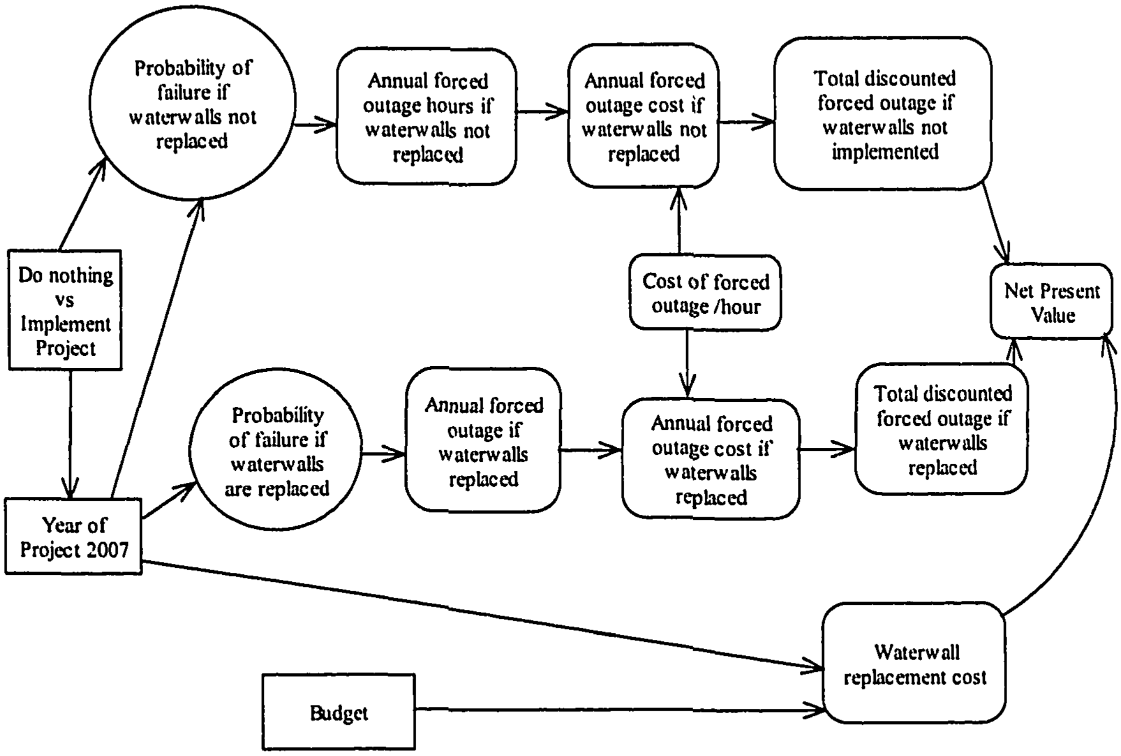


Figure 7.4: Time ordered influence diagram for Waterwall maintenance optimization model

7.5 SUPERHEATER REPLACEMENT

The superheaters are affected by creep in aging boilers and due to temperature excursions. Sometimes the tubes lose their hardness due to overheating in a particular zone. Stress corrosion cracking due to bad water chemistry coupled with high residual stresses can cause tube failures. The expenses of boiler downtime, tube repair cost, boiler start up cost, laboratory cost, and cost of gas turbine power are all the same as for boiler waterwall. The differences are the cost of a superheater replacement panel and the number of failures. As the NPV is positive, the superheater replacement must be carried out.

MTTF for Superheater tubes. Ref Table 6.8	59536 hours
Base year for data	1993
Year of replacement	2007
Number hours of operation from 1993 to 2007	131400
Number of failures expected in 2007	2.2 Say 3
Loss of generation due to Superheater failure	175 MW
Time taken to repair Superheater tube	72 hours
Incremental Cost of generating ,175 MW	
By Gas Turbine to make up for the loss @$70.00/MW	$882,000
Cost of Repairing Failed Superheater	$20,000
Cost of Laboratory analysis for failed tube	$2000
Cost of Boiler start up after Superheater repair	$45,000
Cost of one Superheater failure	$949,000
Cost of three Superheater failures, C_B	$2,847,000
Cost of Superheater replacement in the failure zone, C_P	$1,741,000
Running Hours for 5 years	43800 hours
Expected failure in 5 years after replacement	0.73 Say 1
Cost of one failure, C_A	$949,000

The project will be implemented if:

$NPV = C_B - (C_P + C_A) > 0$

Substituting for NPV as per Eq 7.3,

$$2{,}847{,}000 - (1{,}741{,}000 + 949{,}000) = \$157{,}000$$

7.6 REHEATER REPLACEMENT

The reheater is located in the convection zone and is not subjected to high temperature radiation. However, the tube bundles can distort and break. This is due to uncontrolled furnace exit gas during start up when reheater tubes will have no steam flow due to turbine not being in service. When tube bundles have been found to have mis-aligned and warping, the defective bundle is replaced. The analysis described below belongs to such a reheater panel replacement. The tube repair and other expenses associated with reheater are identical to waterwall and superheater. The cost of a reheater panel including labour and material is $786800

MTTF for Reheater tubes. Ref Table 6.8	75204 hours
Base year for data	1993
Year of replacement	2007
Number hours of operation from 1993 to 2007	131400
Number of failures expected in 2007	1.7 say 2
Loss of generation due to Reheater failure	175 MW
Time taken to repair Reheater tube	72 hours
Incremental Cost of generating,175 MW	
By Gas Turbine to make up for the loss @$70.00/MW	$882,000
Cost of Repairing Failed Reheater	$20,000
Cost of Laboratory analysis for failed tube	$2000
Cost of Boiler start up after Reheater repair	$45,000
Cost of one Reheater failure	$949,000

Cost of two Reheater failures, C_B	\$1,898,000
Cost of Reheater replacement in the failure zone, C_P	\$786800
Running Hours for 5 years	43800 hours
Expected failure in 5 years after replacement	0.58 Say 1
Cost of one failure, C_A	\$949,000

The project will be implemented if:

$$NPV = C_B - (C_P + C_A) > 0$$

Substituting for NPV as per Eq 7.3,

1,898,000 – (786800 + 949000) =\$162,200

As the NPV is positive, the replacement of reheater is justified.

7.7 FORCED DRAFT FAN RUNNER REFURBISHMENT

The Forced draft fan problems are mostly due to cracks in the rotor. The rotor is a fabricated body of welded plates. As the fan pushes the air to the furnace, it sometimes has resistance on the flow path if the rotary air heater is choked due to grit build up on the rotary elements. The fan rotor plates develop cracks. These cracks are welded during annual outages. A stage is reached when the whole rotor needs to be refurbished due excess repairs to the rotor or the cracks are larger and cause fan vibration. Data pertaining to a case when the rotor had to be shipped to the original equipment manufacturer for refurbishment is discussed below. The cost of refurbishing the fan was \$25,000

MTTF for FD Fan. Ref Table 6.8	34731 hours
Base year for data	1993
Year of replacement	2007

Number hours of operation from 1993 to 2007	131400
Number of failures expected in 2007	3.78
Loss of generation due to FD Fan Failure failure	125MW
Power Produced with one FD Fan	50MW
Time taken to repair Refurbish a Fan	504 hours
Incremental Cost of generating,175 MW	
By Gas Turbine to make up for the loss @$70.00/MW, C_A	$4,410,000
Cost of Refurbishing, C_P	$25,000
Cost of four failures, C_B	$17,640,000
Running Hours for 5 years	43800 hours
Expected failure in 5 years after replacement	1.26 Say 1

Substituting for NPV as per Eq7.2,

$NPV = C_B - (C_P + C_A) > 0$

17,640,000 – (25,000 + 4,410,000) =$13,205,000

7.8 BOILER FEED PUMP REPLACEMENT

The boiler feed pump handles high pressure and hot water. The pressure is about2000 psi and temperature about 1000 ^{0}F. The usual problems are vibration, mechanical seal failure and lubrication oil leaks. Most of these problems do not occur often as the pump internals are replaced once in seven years. However boiler feed pumps do fail. The loss of one pump does not bring the generation down to zero, as the high pressure feed water system consists of two 50% duty pumps and one pump can keep the boiler in service at 50% load. The financial loss is much less than that of waterwall, superheater or reheater failures. The cost of replacing one pump is $93,000. The boiler feed pump failure data analysis is as below.

MTTF for Boiler Feed Pump. Ref Table 6.8	71450 hours
Base year for data	1993
Year of replacement	2007
Number hours of operation from 1993 to 2007	131400
Number of failures expected in 2007	1.8 Say 2
Loss of generation due to Boiler Feed Pump failure	90MW
(Boiler Feed Pump 50% Duty in 175 MW Unit)	
Time taken to repair Boiler Feed Pump	64 hours
Incremental cost of generating	175 MW
By Gas Turbine to make up for the loss @$70.00/MW, C_A	$403,200
When two failures occur running the gas turbine cost, C_B	$806,400
Cost of replacing a Pump, C_P	$93,000
Running Hours for 5 years	43800 hours
Expected failure in 5 years after replacement	0.61 Say 1

Substituting for NPV as per Eq 7.2

$NPV = C_B - (C_P + C_A) > 0$

$806400 - (93000 + 403200) = \$310200$

The positive NPV justifies boiler feed pump replacement.

7.9 BOILER FEED PUMP RECIRCULATION VALVE REPLACEMENT

The boiler feed pump recirculation valve diverts the high pressure boiler feed pump discharge to the feedwater tank when the boiler feed pump discharge valve is closed during boiler start up to control water level in the boiler steam drum. Therefore there is a high pressure differential across the valve seat and plug. The seat and plug get eroded. The valve leaks and no longer provided the service it is intended for. Refurbishing a valve costs $7000. When a boiler feed pump recirculation valve fails, the corresponding boiler feed pump can not be operated. Hence the boiler can generate 50% load with available boiler feed pump. It takes 40 hours to get a valve refurbished. The analysis of the failure data is described below. The NPV is calculated and is positive for

MTTF for B F P Recirculation Valve. Ref Table 6.8	53696 hours
Base year for data	1993
Year of replacement	2007
Number hours of operation from 1993 to 2007	131,400
Number of failures expected in 2007	2.4 Say 3
Loss of generation due to Boiler Feed Pump failure	90MW
(Boiler Feed Pump 50% Duty in 175 MW Unit)	
Time taken to repair a Boiler Feed Pump Recirc Valve	40 hours
Incremental Cost of generating,175 MW	
By Gas Turbine to make up for the loss @$70.00/MW, C_A	$252,000
Cost of Repairing a Recirculation Valve	$7000
Total cost for repairing three valves, C_B	$777,000

Cost of replacing by different valve, C_P	\$50,000
Running Hours for 5 years	43800 hours
Expected failure in 5 years after replacement	0.8 Say 1

Substituting for NPV as per Eq 7.2,

$NPV = C_B - (C_P + C_A) > 0$

777,000 – (50,000 + 252000) =\$475,000

7.10 CONDENSER TUBES REPLACEMENT

The condenser tubes fail mostly due to mechanical friction between the tubes and the stay plates, which support the tubes along its length. They also fail at their ends where the tubes are expanded. When a condenser tube fails the condenser section where the tube is located is isolated and the power generation has to be cut by 50%. The cost of retubing is \$500,000. A positive NPV is obtained .

MTTF for Condenser tubes .Ref Table 6.8	42159 hours
Base year for data	1993
Year of replacement	2007
Number hours of operation from 1993 to 2007	131400
Number of failures expected in 2007	3.1 Say 3
Loss of generation due to Condenser tube failure	90MW
(Condenser 50% Duty in 175 MW Units)	
Time taken to repair a Condenser tube	40 hours
Incremental Cost of generating,175 MW	
By Gas Turbine to make up for the loss @\$70.00/MW, C_A	\$252,000

Cost of repairing three failures, C_B	\$756,000
Cost of replacing by Condenser tubes, C_P	\$500,000
Running Hours for 5 years	43800 hours
Expected failure in 5 years after replacement	1.03 Say 1

Substituting for NPV as per Eq7.2,

$NPV = C_B - (C_P + C_A) > 0$

756,000 – (500,000 + 252000) =\$4000

7.11 SUMMARY OF COMPONENT REPLACEMENT

The components that will be replaced in year 2007 are summed up in Table 7.1. The Year 2007 is selected because of increasing failure probability in the following years. The procedure remains the same regardless of the year of replacement. The loss of generation of power will be less if replaced earlier and more if replaced later.

Table 7.1: Component Replacement Optimization Summary

Component	Component replacement/ refurbishment Cost C_P	Increment production cost if the component is not replaced/ Refurbished C_B	Increment production cost if the component is replaced/ Refurbished C_A	Net present value
Waterwall	1,898000	$1,000,000	0	$898,000
Superheater	$1,741,000	$2,847,000	$949,000	$157,000
Reheater	$756,800	1,898,000	$949000	$162,200
Forced Draft Fan	$25,000	$17,640,000	$4,441,000	$13,205,000
Boiler Feed Pump	$93,000	$806,400	$403,200	$310,200
Boiler Feed Pump Recirculatio n valve	$50,000	$777,000	$252,000	$475,000
Condenser Tubes	$500,000	$756,000	$252,000	$4000

Chapter 8

INSPECTION PROGRAM OPTIMIZATION

In the previous chapter, the focus was on identifying components that needed immediate attention and now an inspection program has to be developed to provide proper maintenance to components. A decision analysis requires to be done through a decision model. Decision analysis is "a formal process for organizing the information, including measures of information uncertainty that will influence a future course of action or inaction, mathematically modeling the information and making calculations that will help identify the best decision and/or determine what additional information is necessary." (ASME.2003 Risk Based Methods for Equipment Life Management. Page 216) A decision model is to be developed to link the failure probability versus time to failure data for each inspection program decision that will be considered. An inspection program should be able to detect the failure mode at early stage to prevent a failure. It is not an easy task to develop/select the proper inspection program as data gathering, reliability modelling and decision-making are tedious tasks. The goal of this chapter is to develop a decision model for inspection planning. Prior to developing an optimized inspection program for waterwall tubes, the concept is explained by a simple example. For clarity of the concept, a hypothetical case is assumed.

A pump has a corroded discharge pipe and the pipe runs from the first floor to the fifth floor. There are electrical switchboards located directly under the corroded pipe. The plant can either run the system with the corroded pipe with the risk of a leak or run the system after having replaced the corroded pipe. The following data are assumed.

1.	Failure Probability if run with corroded pipe	70%
2.	Failure Probability if run with replaced piping	10%
3.	Consequential cost if pipe breaks at lower floors	$500
4.	Consequential cost if pipe breaks at upper floor	$1000

The subsequent pages explain the general requirements for an inspection program with an emphasis on the example chosen to bring forth the concept.

8.1 STRATEGY TABLE

The first step is to construct a strategy table. The strategy table consists of the things to do for inspection. These are broad classifications of scope of work and items of interest. They are categories, candidate strategies and damage mechanisms. Table 8.1 illustrates the basic worksheet to form the strategy table.

Table 8.1: Original Worksheet

	Candidate Strategies	Damage Mechanisms	Categories					

8.1.1CATEGORIES

With reference to 8.1, a category can be any of the following or all of the following (ASME, 2003 Risk Based Methods for Equipment Life Management. Page 195)

"A quantity that you need to know before you can estimate the economic decision criteria or

A resource that you will need to choose before you can estimate the economic decision criteria

A value that you need to calculate"

The above definition of categories is explained as below

1. Category is a quantity. This quantity can be the number of tubes in a waterwall planned for inspection. The number of tubes has an impact on the cost

of inspection. If more number of tubes are planned for inspection, it is going to cost more and if less, less economic impact. Hence this quantity is a category. or

2. A resource that has to be chosen before estimating the economic decision criteria. This resource can be either skyclimber Fig 8:1 and 8.2 or scaffolding Fig 8.3 and 8.4. The waterwall tubes are at several levels inside the furnace. To inspect a tube at a height of 80 feet, there is a need for scaffolding to be built from the bottom floor The tube at 80 feet, can also be inspected by a skyclimber which will slide on the waterwall tubes from the bottom floor with a platform for inspectors to ride. A decision has to be made whether to use scaffolding or skyclimber to access the tubes. The skyclimber and scaffolding become categories

3. A value that has to be calculated. There will be money to be spent on inspection of tubes, building a scaffolding,or installing a skyclimber This amount of money that is to be spent in is a value. This value can be Net Present Value. Therefore, NPV is a category.

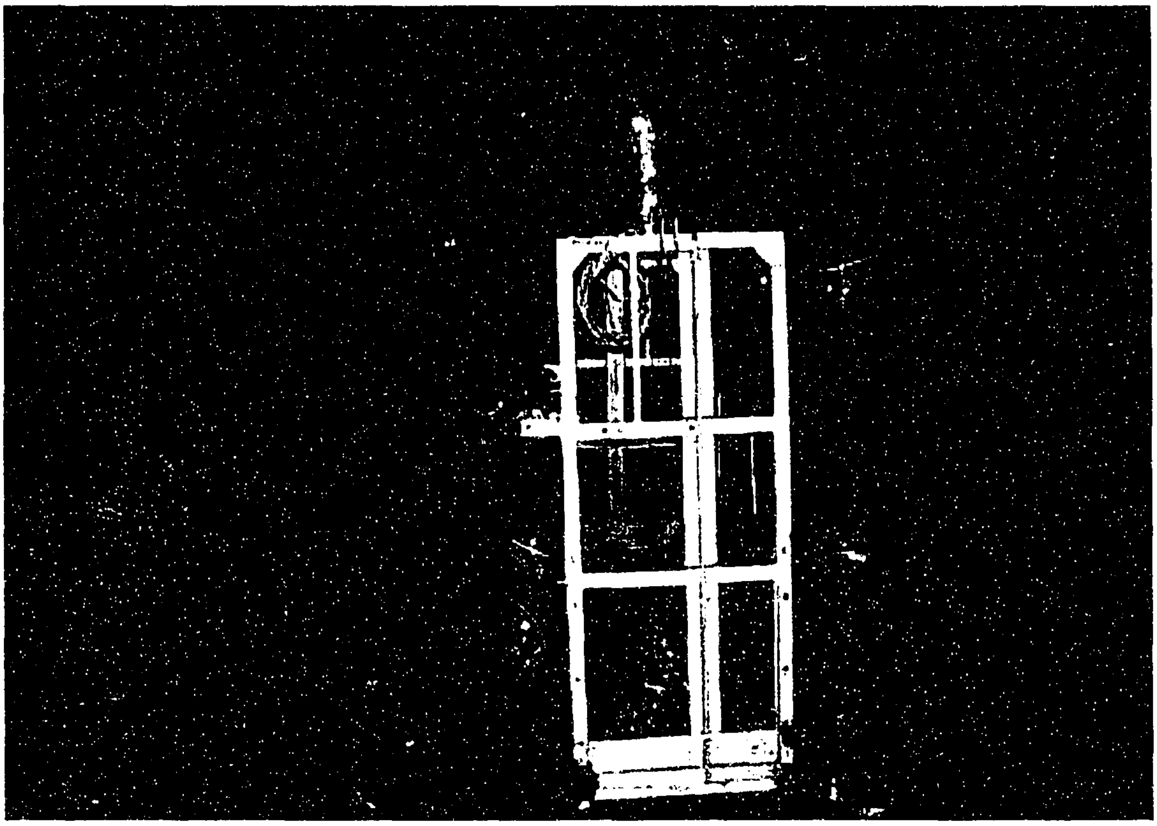


Figure 8.1: Sky climber being assembled inside the boiler furnace (3S Gondala, Division of Ficont Industry Inc. Beijing China)

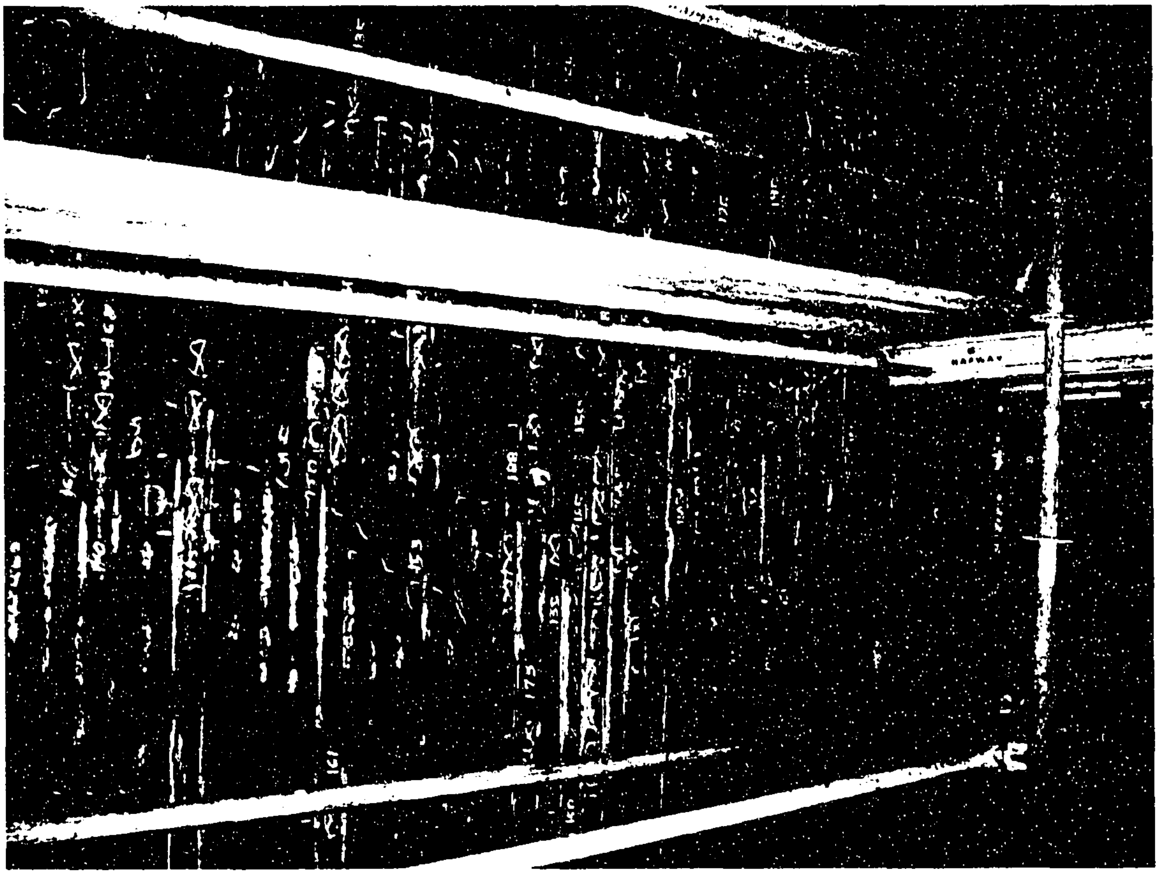


Figure 8.3: Scaffolding inside boiler furnace to inspect water wall. (Holyrood Generating station)

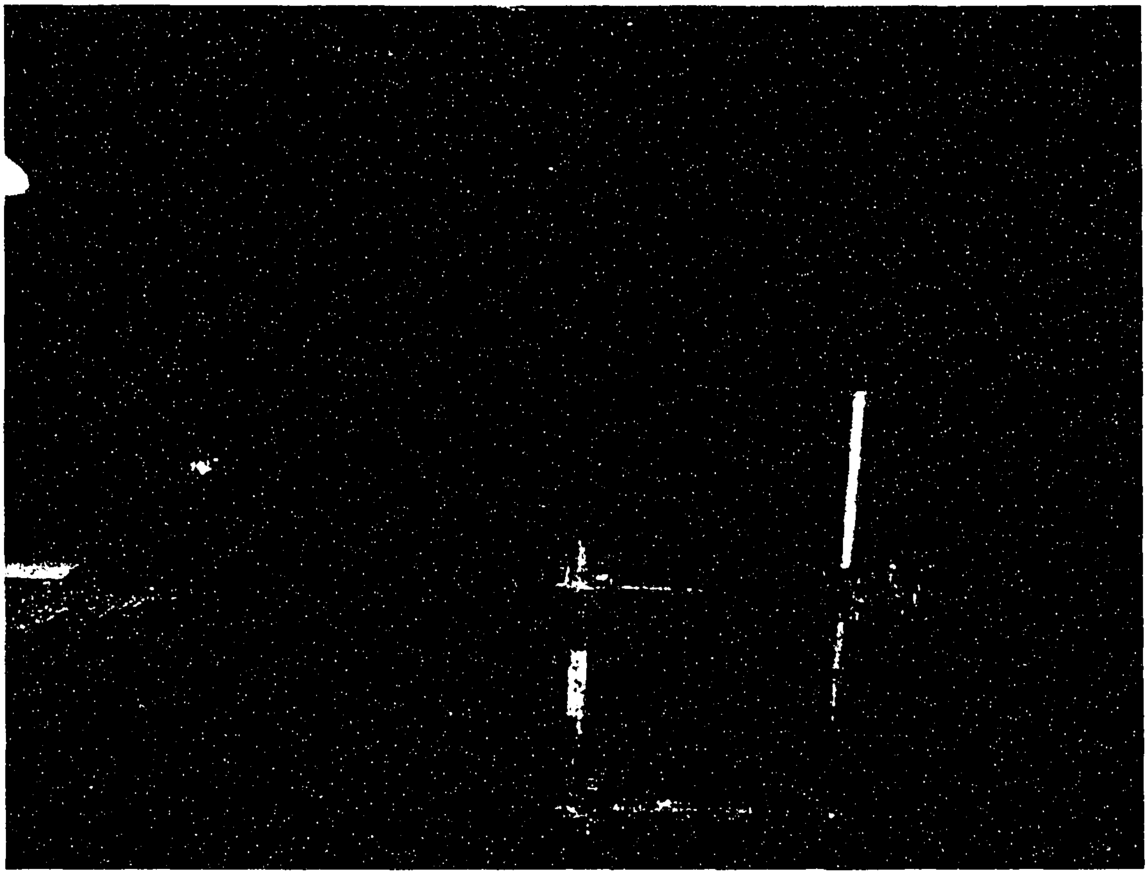


Figure 8.4: Scaffolding at the roof of the boiler furnace for tube inspection(Holyrood Generating Station)

When developing an inspection strategy, the categories will include the decisions that will be required to be made and tools that will be required to perform the inspection. It is preferable to make a list of categories to be considered and their magnitude on plain paper and brainstorm before making a decision. A list for a corroded pipe replacement decision might be:

1. Pipe condition

   Whether the pipe is fit for service or defective or likely to failure

2. Probability of rupture

The probability that the pipe will fail during service

3. Pump use

   The chances of pump being used either for first floor use or for second floor use expressed in terms of percentage

4. Consequent cost of rupture

   The financial loss when the pipe breaks

5. Risk of rupture

   It is the product of probability times the consequential cost of rupture

6. Pipe replacement cost

   The price to be paid if the pipe is replaced

7. Net Present value

   Net Present Value is an amount that expresses how much value an investment will result in. This is done by measuring all cash flows over time back, towards the current point, in present time. The NPV should be positive for a successful investment.

8.1.2 CANDIDATE STRATEGIES

Candidate strategies mean the choices available to the plant. The candidates in this example are "to run" or "replace". In some other situation, it may be "inspect" or "not to inspect" The candidate strategy will be the first column in the excel spreadsheet. As inspection is the aim, all inspection methods will be listed under this column. This is only for brainstorming discussion to decide the appropriate inspection method. Typical inspection methods include:

1.Ultrasonic Thickness measurement

Ultrasonic non-destructive testing characterizing material thickness, integrity, or other physical properties by means of high frequency sound waves is a widely used technique for quality control. In thickness gauging, ultrasonic techniques permit quick and reliable measurement of thickness without requiring access to both sides of the part. The thickness gauge determines the thickness of a part or structure by accurately measuring the time required for a short ultrasonic pulse generated by a transducer to travel through the thickness of the material , reflect from the back or inside surface and be returned to the transducer.

2. Replication for Creep

This method examines the actual microstructure of a suspect metal surface. The metal surface suspected to have undergone creep is polished to a mirror finish using successive grinding and polishing discs, followed finally by a diamond impregnated cloth. The topography of the surface is replicated on a 1inch square cellulose acetate film. The microstructure of the metal surface can be seen when the film is viewed through a portable microscope with a 400x magnification. The degradation of the carbon and iron boundaries will reveal the amount creep.

3. Magnetic Particle Inspection

Magnetic particle inspection is used for the detection of surface and near surface flaws in ferromagnetic materials. A magnetic field is applied to the specimen either locally or overall, using a permanent magnet, electromagnet, flexible cables or hand held prods. If the material is sound most of the magnetic flux is concentrated below the material surface. However if a flaw is present, such that it interacts with magnetic field, the flux is distorted locally and leaks from the surface of the specimen in the region of the flaw. Fine magnetic particles applied to the surface of the specimen are attracted to the area of flux leakage, creating visible indication of the flaw. The materials commonly used for this purpose are black iron particles and red yellow stone iron oxides.

4. Low Frequency Electromagnetic Technique

Very-Low-Frequency (VLF) surveying is a continuous-wave (frequency domain) electromagnetic technique that uses low-frequency radio transmissions as the source. When these intersect a buried deposit they induce eddy currents that generate a secondary magnetic field concentric around the source of the currents. VLF surveys involve measuring the orientation of this field. As the instrument passes perpendicularly over a vertical target the vector orientation changes from a maximum on one side to a minimum on the other side. The method is primarily used in mineral exploration work but has also been successfully applied in finding the size of boiler tube internal deposits

5. Ultrasonic Flaw Detection

High frequency sound waves reflect from flaws in predictable ways, producing distinctive echo patterns that can be displayed and recorded by portable instruments. It utilizes the basic principle that sound energy traveling through a medium will continue to propagate until it either disperses or reflects off a boundary with another material, such as the air surrounding a far wall or found inside a crack. In this type of test, the operator couples the transducer to the test piece and locates the echo returning from the far wall of the test piece, and then looks for any echoes that arrive ahead of that backwall echo, discounting grain scatter noise if present. An acoustically significant echo that precedes the backwall echo implies the presence of a laminar crack or void. Through further analysis, the depth, size, and shape of the structure producing the reflection can be determined.

8.1.3 DAMAGE MECHANISMS

The second column would be 'Damage Mechanisms'. The appropriate damage mechanism for the component under inspection will be entered in this column. The damage mechanism for the hypothetical pump example is corrosion. Typical damage mechanisms are for boiler tubes are described below:

1.Overheating

Overheating may be long time or short time. Long time overheating is a condition in which metal temperatures exceed design limits for days, weeks, months, or longer. A mild steel tube subject to temperatures above 850^0F (450^0C) for more than a few days may experience long term overheating. Short term overheating occurs when the tube temperature rises above design limits for a brief period. In all instances, metal temperatures are at least 850^0F (450^0C) and often exceed 1350^0C (730^0C). Depending on temperature, failure may occur in a very short time.

2.Caustic Corrosion

Two critical factors contribute to caustic corrosion. The first is the availability of sodium hydroxide or of alkaline producing salts. Sodium hydroxide is often intentionally added to boiler water at non corrosive levels. It may also be introduced unintentionally if chemical from a caustically regenerated demineralizer is inadvertently released into make up water. Alkaline producing salts may also contaminate the condensate by in leakage through condensers or from process streams. The second contributing factor is the mechanism of concentration. High pH substances such as sodium hydroxide will dissolve magnetite: (Port, 1991)

$$4NaOH + Fe_3O_4 \rightarrow 2NaFe\,O_2 + Na_2Fe\,O_2 + 2H_2O \qquad (8.1)$$

When magnetite is removed the sodium hydroxide may react directly with the iron:

$$Fe + 2NaOH \rightarrow Na_2FeO_2 + H_2 \qquad (8.2)$$

3. Hydrogen damage

Hydrogen damage may occur where corrosion reactions result in the production of atomic hydrogen. When a tube has failed due to hydrogen damage, the failed portion has the appearance of an open window. Prolonged boiler operation with sea water ingress caused by turbine condenser tube leak leads to accumulation of alkaline producing salts in boiler tubes. This type of damage has recently occurred at Holyrood Generating

Station and resulted in large sections of the waterwall tube replacement. The inspection optimization in this thesis is based on this project. Damage resulting from high pH corrosion reaction or from a low pH corrosion reaction is simply caustic corrosion.

Concentrated sodium hydroxide dissolves the magnetic iron oxide according to the following reaction:

$$4NaOH + Fe_3O_4 \rightarrow 2NaFe\,O_2 + Na_2Fe\,O_2 + 2H_2O \qquad (8.3)$$

With the protective layer destroyed, water is then able to react directly with iron to evolve atomic hydrogen:

$$3Fe + 4H_2O \rightarrow Fe_3O_4 + 8H\uparrow \qquad (8.4)$$

The sodium hydroxide itself may also react with the iron to produce hydrogen:

$$Fe + 2NaOH \rightarrow Na_2FeO_2 + 2H\uparrow \qquad (8.5)$$

If atomic hydrogen is liberated, it is capable of diffusing into the steel. Some of this diffused atomic hydrogen will combine at grain boundaries or inclusion in the metal to produce molecular hydrogen or will react with iron carbide in the metal to produce methane.

$$Fe_3C + 4H \rightarrow CH_4 + 3Fe \qquad (8.6)$$

Since neither molecular hydrogen nor methane is capable of diffusing through the steel, these gases accumulate primarily at grain boundaries. Eventually gas pressure will cause separation of the metal at its grain boundaries, producing discontinuous intergranular microcracks. Accumulation of microcracks cause failure of the tube.(Port,1991)

4.Stress Corrosion Cracking

Stress corrosion cracking could occur wherever a specific corrodent and sufficient tensile stresses coexist. The tensile stresses may be applied by internal pressure or by residual stresses induced by welding. In boiler systems, carbon steel is specifically sensitive to concentrated sodium hydroxide, while stainless steel is specifically sensitive to both sodium hydroxide and chlorides. The combination of sodium hydroxide, some soluble silica and tensile stresses will cause continuous intergranualar cracks to form in carbon steel. As the cracks progress, the strength of the remaining intact metal is exceeded and a brittle thick walled fracture will occur.

8.1.4 NODES FOR EACH CATEGORY

Each category is allotted a node. The nodes are:

1. *Decision Nodes:* -Decision needs to be made as to which of the categories are to be selected. e.g: How many elements to inspect.

2. *Chance Nodes:*-Categories which may produce several different results. e.g.: How sensitive is a measurement to NPV.

3. *Value Nodes:*-Is a number calculated. e.g.: Net Present Value.

8.2 ORDERED CATEGORIES TABLE

In this table, the node types are decided for each category. To decide on the node type, the type of information that would be put into each category should be ascertained. For example a category "Probability of Failure Today Based on Trend." needs a node to be decided. This category needs a single numeric estimation from past data, so this node is a value node. On the other hand the "inspection sensitivity" category requires uncertainty information, so this node is a chance node. Table 8.2 illustrates this stage in the development of the model for the hypothetical pump example.

Table 8.2. Ordered Categories for Pump

Candidate Strateges	Damage Mechanisms	Catagories						
		Pipe Condition	Probability of Rupture	Pump Use	Consequent Cost of Rupture	Risk of Rupture	Pipe Replacement Cost	Net Present Value
Run Replace Node Type	Corrosion							
Decision		Chance	Chance	Chance	Value	Value	Value	Value

8.3 PROVIDING ALTERNATE STRATEGIES

Alternatives need to be provided for each constituent in the table. The alternatives will be developed from the node under each category and each of the candidate strategies. The first step is to look at the node under a 'category' or 'candidate strategies'. A decision node will produce a list of alternative for the item above that node. The node under 'candidate strategy' is 'decision'. This means that a specific decision should be made. In the pump example, in Table 8.3, a decision has to be taken whether to replace the pipe or to run the pump with a corroded pipe. A chance node will mention possible outcomes. A category above a value node in the table will require a numerical value to be calculated and provided.

8.3.1 ALTERNATE POSSIBILITIES

The Table 8.3 lists the alternate choices and the data that are available for each category. Looking at the 'candidate strategies' a decision has to be made whether to run the pump with a corroded pipe or to replace the corroded pipe. Listed under the damage mechanism is corrosion. There is no choice to be made in the damage mechanism. It is a prevailing condition of the pipe. The condition of the pipe is either good or poor, depending upon whether it is a replaced pipe or corroded pipe respectively. Under the 'probability of failure', 0.7 is associated with corroded pipe and 0.1 failure probability is associated with a replaced pipe. 90% of the pumped flow is along the lower floor and 10% of the flow is along the upper floor. This information is provided under 'pump use'. The risk of failure is to be calculated and it is a value node. The cost of replacing a pipe is $100. The net present value is a numerical value and it has to be calculated.

Table 8.3. Alternate Possibilities for Pump

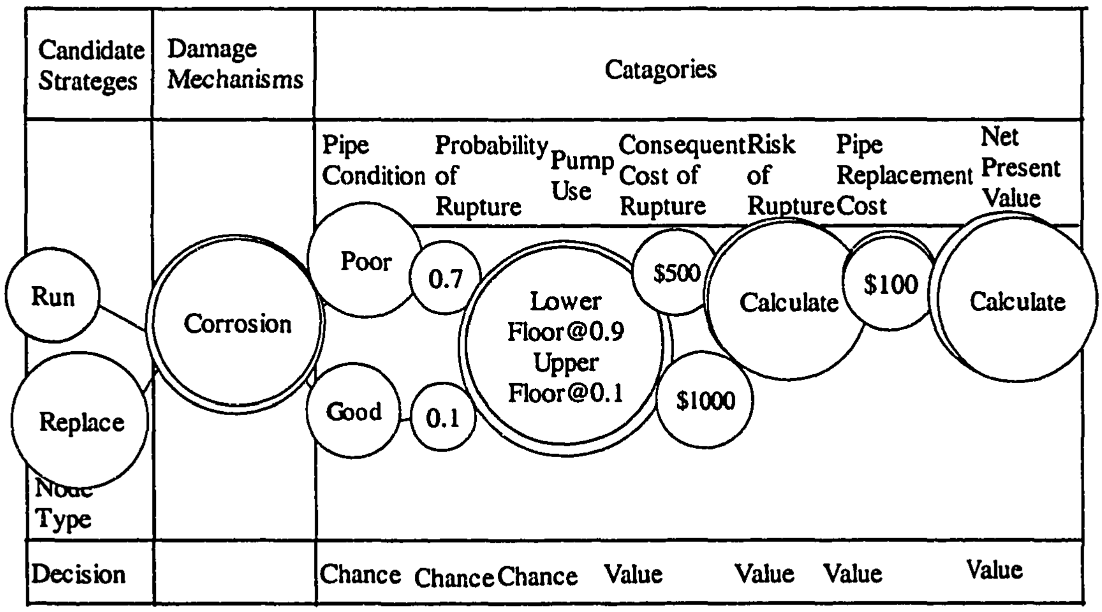
Candidate Strateges	Damage Mechanisms	Catagories						
		Pipe Condition	Probability of Rupture	Pump Use	Consequent Cost of Rupture	Risk of Rupture	Pipe Replacement Cost	Net Present Value
Run	Corrosion	Poor	0.7	Lower Floor@ 0.9	$500	Calculate	$100	Calculate
Replace		Good	0.1	Upper Floor@ 0.1	$1000			
Node Type								
Decision		Chance	Chance	Chance	Value	Value	Value	Value

8.3.2 STRATEGY FORMING

The alternate strategies that are contemplated must be investigated for the outcomes. An alternate strategy selection table is drawn with all the constituents. Starting from the left of the table, a strategy is selected and its associated chain is circled with one color. Similarly the other strategy is selected and its associates are circled in different color. This table will form the basis for drawing the influence diagram. Table 8.4 illustrates the concept. The first candidate strategy 'Run' is circled in green. The damage mechanism associated with this strategy is circled in green. Each successive alternative choice or outcomes associated "run/corrosion/0.7 rupture probability(candidate/failure mechanism/failure probability) are circled in green. Some alternatives apply to both. When all the green circle categories are linked, the "Run" strategy is developed.

Similarly the "Replace" strategy and associated alternatives are circled in red to identify the "Replace" strategy .

Table 8.4. Strategy Alternatives for Pump



8.4 INFLUENCE DIAGRAM

The influence diagram is a layout. It is a relationship picture of strategy alternatives, their outcomes, consequences, the value of the consequences and the financial outcome. The following are the steps to draw the influence diagrams.

1. Draw each node from the strategy table in time ordered fashion from left to right.
2. Start at the right most node which is the financial outcome (NPV) and ask the question what is required to get to this node.

3. If the existing node in the layout to the left is what is required, then connect a line to that node. If any other node is needed bring it in and connect with a line.
4. Keep asking the question 'What is required for this node at each node and connect the related node with a line till the left most node is reached. The left most node will be the strategy alternative.
5. Tip the lines with arrows in the process flow direction which is left to right.

The value nodes are green bordered rectangles. The chance nodes are ellipses. The decision nodes are red bordered rectangles. Figure 8.5 shows a conceptual influence diagram.

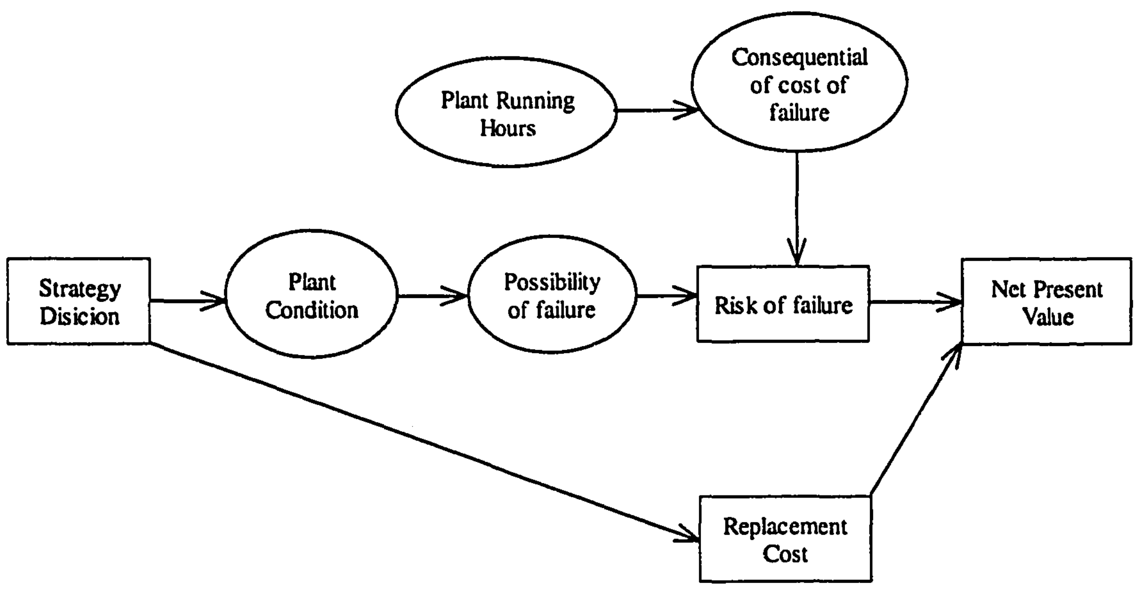


Figure 8.5 Conceptual Influence Diagram

8.5 DECISION TREE

The decision tree describes in a time ordered fashion the choices and the consequences or the outcomes produced by each choice. The influence diagram establishes relationship between categories. The decision tree, Table 8.5 clarifies the time order of the decision/consequence sequences among the categories and alternatives. It is time ordered from left to right showing that the results of the choices made, as the results are not known till they are implemented.

Table 8.5 Decision Tree

Strategy Decision	Pipe Condition	Rupture Probability	Pump Use	Consequential Cost of Rupture

8.6 DECISION MODEL

The decision model is shown in Table 8.6. The relationships and the inputs that were established thus far in the process is used to calculate the present value for each strategy. The basic strategy is no change strategy. This means that the pump is run with the corroded pipe. The probability of failure is 0.9. This is the worst case scenario.

The total consequential cost is $0.9 \times 500 + 0.1 \times 1000 = 550$.

Therefore the risk of rupture is $0.7 \times 550 = 385$

This strategy involves no other cost.

Therefore, the present value = \$385

The alternate strategy is replace the pipe at a cost of $100

The total consequential cost is 0.9 ×500 + 0.1 × 1000 = 550

After pipe replacement the cost is 550×0.1 = 55

Net Positive value must be positive for pipe replacement

NPV is

Loss due to corroded pipe – (pipe replacement cost + Loss due to pipe replacement)

Substituting,

$$385 - (100 + 55) = \$230 = \text{Overall Risk}$$

Table 8.6. Decision Model

Strategy Decision	Pipe Condition	Probability of Rupture	Pump Use	Expected Consequent Cost of Rupture	Risk of Rupture	Present Value	Net Present Value
Run	Poor	0.7		$550	$385	$385	
Alternatives							
Run	Poor	0.7	Lower Floor@ 0.9	$500			
Replace	Good		Upper Floor@ 0.1	$1000		$155	$235
					Pipe Replacement Cost $100		

The net present value indicates that the alternate is good while considering the base case of running the pump with a corroded pipe and its consequential costs. The alternate consists of expenses for replacement and any consequential costs due to replacement. In this case the NPV is positive. If there are several alternatives, then the alternate solution that provides maximum NPV should be selected for implementation.

8.7 INSPECTION PROGRAM FOR WATERWALL

The waterwall failure data was analyzed earlier. The most cost effective way will be determined to check whether the predictions arrived at for the failure probability of waterwalls are true. At Holyrood Generating Station eight blisters were noticed during an inspection of the furnace. A month later there was tube failure due to Hydrogen damage. On further inspection, blisters were noticed on the eastern wall of the furnace. Hence a detailed inspection of the waterwall was decided. An inspection optimization program is developed for the waterwall at a boiler in Holyrood Generating Thermal Power Plant. The following is a real case study.

8.7.1 STRATEGY TABLE

The development of a decision model for the waterwall inspection starts from the strategy table. The waterwall failure is loss of tube thickness due to hydrogen damage caused by internal deposits. There are two items of interest. One is tube thickness measurement and the other is measurement of variation in tube internal thickness. A small "D" meter(digital thickness measuring meter) which is a hand held ultrasonic thickness measuring instrument with a probe and a digital read out, can be used to measure tube thickness or a Low Frequency Electromagnetic Technique can be employed. The variation in tube thickness is measured by a ultrasonic flaw detector. The test locations and who will do the thickness measurement needs to be considered.

8.7.2 CANDIDATE STRATEGIES AND DAMAGE MECHANISMS

The following are the candidate strategies:

1. No Inspection (Base Case).
2. D Meter Thickness Meter.
3. Low Frequency Electromagnetic Technique.
4. Ultrasonic Flaw Detector.

The damage mechanism is hydrogen damage. The aim of the inspection is to find out how much damage has occurred in the waterwalls.

8.7.3 INSPECTION STRATEGY CATEGORIES

The goal of the decision model is to choose the ultimate strategy. The first step is to list the categories as explained in 8.1.1.

The categories (Decision making parameters) in Table 8.7 for waterwall tubes are:

1. Net Present Value
2. Probability of failure
3. Probability of failure if no defect is reported
4. Number tubes for inspection
5. Tube Elevations
6. Waterwall access
7. Contract or in house workforce
8. Boiler outage time
9. Cost of power purchased during boiler outage

Table 8.7 Ordered Categories

Candidate Strategies	Damage Mechanisms	Categories							
		Probability of Failure Today Based on Trend	Inspection sensitivity	Number of Elevations to Inspect	Probability of Failure Given no Defect Reported	Number of Tube Elements	Access to the component	In-house or Contract Inspectors	Consequential Time for Shutdown
No Inspection									
D meter thickness meter	Hydrogen Damage								
LFET									
Node Type									
Decision		Value	Value	Decision	Value	Value	Decision	Decision	Value

8.7.4 DECISION NODES

There are three nodes. They are:

1. Decision Nodes: Defines the category that is to be selected for developing the inspection program. If there are choices in a category, a decision is needed to go ahead in the process. Example: Whether 'D' Meter or Low Frequency Electromagnetic Technique.
2. Chance Nodes: When a category's outcome is uncertain and can not be determined, it is called a chance node. Example: The failure data is a chance node because it is an uncertain parameter.
3. Value Nodes: When a numerical data is needed for a category it is called a value node. Example: Sensitivity of inspection is a value node because there is a numerical value to how far the inspection measurement variations will affect NPV.

8.7.5 ALTERNATIVE CHOICES

A decision is to be made as to which category is chosen and their consequences. The corresponding categories are linked. To differentiate colored lines and borders are used to group them. Refer to Table 8.8. Each colour denotes an option. No inspection is green and therefore there is no NPV for this option. There is no green circle on NPV.

8.7.6 INFLUENCE DIAGRAM

This diagram shows Fig 8.6 how the categories are influenced and by what. It is drawn from right to left. The category on the far right is chosen. In this case the category on the far right is the NPV and the category preceding NPV is drawn to the left of NPV. The category to the left of NPV is arrived at after asking the question, 'What is needed to produce NPV?' Similarly each category is located in the influence diagram and they are linked to the consequent categories.

Table 8.8 Strategy Alternatives

Candidate Strategies	Damage Mechanisms	Categories: Number of Turbe Elements	Probability of Failure Today Based on Trend	Inspection sensitivity	Number of Elevations to Inspect	Probability of Failure Given no Defect Reported	Access to the component	Net Present value
No Inspection D meter thickness meter LFET	Hydrogen Damage	120	20%	50% of Actual 100% of Actual 150% of Actual 90% of Actual 100% of Actual 110% of Actual	1@25% Effective 125 hrs. 2@50% Effective 48 hrs. 4@80% Effective 500 hrs.	Calculate	scaffold @ $32000 skyclimber @ $1,000	Calculate
Node Type								
Decision		Value	Value	Chance	Decision	Value	Decision	Value

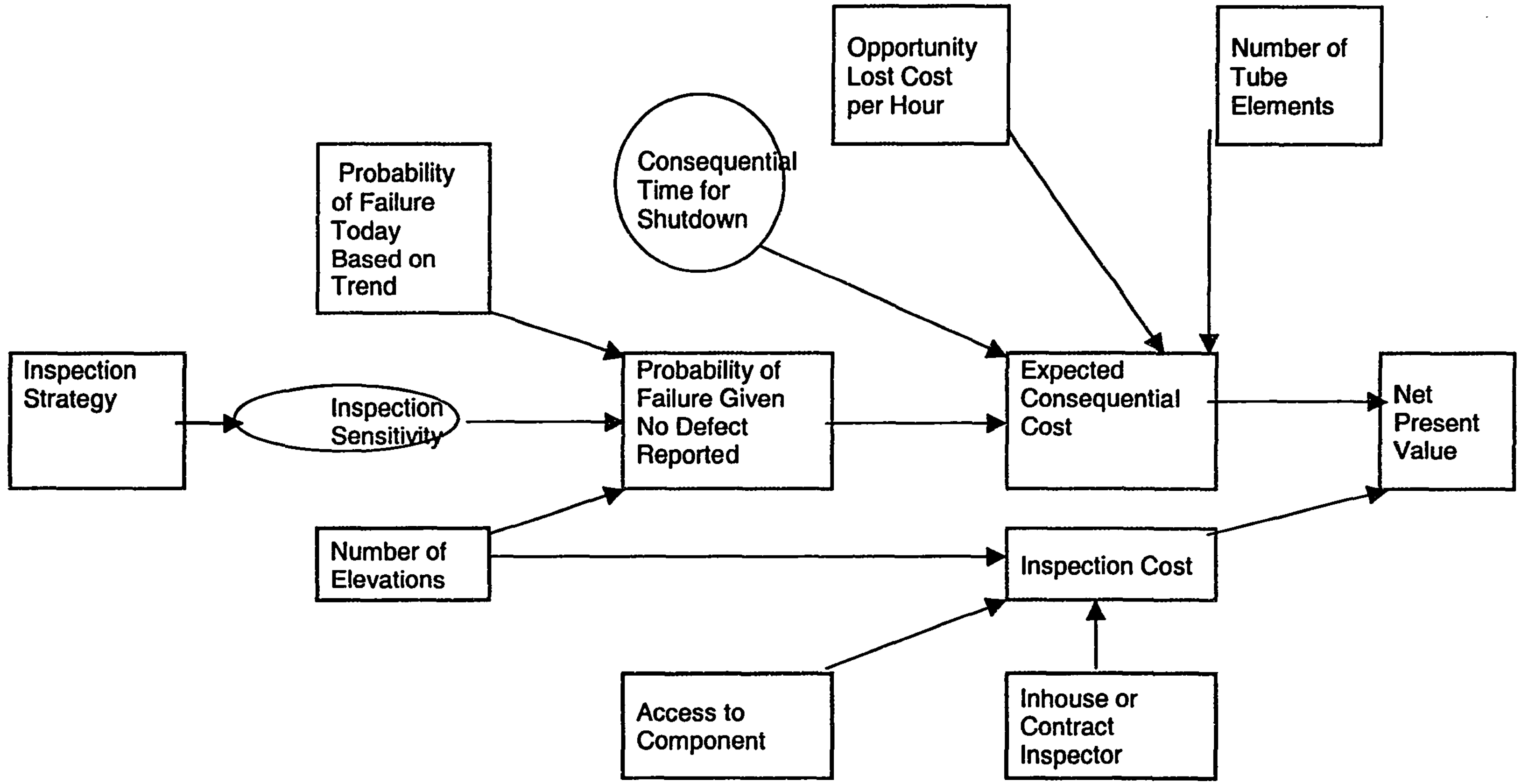


Figure 8.6: Influence Diagram for waterwall

8.7.7 DECISION TREE

The decision tree Table 8.9 consists of chance and decision categories. The categories are tabled in a time ordered fashion. Therefore the strategy decision to go without inspection, or D Meter or LFET is the starting point of the tree. The other categories are placed to the right as the consequence of the preceding decision category. The consequent categories placed on the right are separated from the left by a black line. The vertical length indicates the decision or the decision which causes the consequence.

Table 8.9 Decision Tree for Waterwall

Inspection Strategy	Inspection Sensitivity	Number of Elevations to Inspect	Access to Component	In-house or Contract Inspectors	Consequential Time for Shutdown

8.7.8 DECISION MODEL

The decision model is laid out in an Excel spreadsheet. The cells from left to right contain the categories in the time ordered sequence. The multiple variables for each category is taken from the decision tree. The relationships between the categories are expressed as formulas and the values are calculated. The Decision Model has been developed to find the maximum Net Present Value. The plant has various options with regard to the inspection of the waterwall. The plant may be under the impression that inspecting one elevation only may be cost saving. The plant can also consider engaging contractors using a basic thickness measuring instrument such as a D Meter. Similarly the plant management has other options such as increasing the inspection to second elevation with either contractors being paid on a hourly basis or on a lumpsum basis. In view of the many options available to the plant management Net Present Value for all options should be calculated to obtain the optimum inspection plan. Therefore, Net Present Values for the following options are calculated.

1. D Meter for one elevation.
2. D Meter for two elevations.
3. D Meter for four elevations.
4. LFET for one elevation.
5. LFET for two elevations.
6. LFET for four elevations.

The spreadsheet for the above six combinations are attached in appendices A, B and C. However a sample calculation for using LFET on four elevations is shown below:

8. 8 INSPECTION OPTIMIZATION USING LFET ON FOUR ELEVATIONS

The following steps are calculated in a spreadsheet. A sample calculation for using a LFET instrument at four elevations is explained below:

8.8.1 PROBABILITY OF FAILURE

The probability of failure for waterwalls is obtained from the data analysis of waterwalls. The failure probability for the running hours till the year 2006 is calculated.

Table 8.10 illustrates the parameters.

Table 8.10: Data Analysis for 99100 hours Waterwall Service

Shape Parameter	Intercept	Characteristic life	Running hours	Reliability	Failure Probability
12	-139.6	112795	99100	0.80	0.20

The probability failure is taken as 20% for the waterwalls considering the running hours till April 2006 with the base year as 1995.

8.8.2 SENSITIVITY OF INSPECTION

The effect of sensitivity of inspection on the Net Present Value is taken from ASME Handbook on 'Risk Based Methods for Life Management'

The Sensitivity is as below:

1. For D Meter

- 90% of actual at 25%
- 110% of actual at 50%
- 130% of actual at 25%

2. For LFET

- 90% of actual at 25%
- 100% of actual at 50%
- 110% of actual at 25%

When using D Meter for measuring the thickness of the tubes the sensitivity is calculated for a 20% Failure Probability as

$0.25 \times 0.2 \times 0.9 + 0.5 \times 0.2 \times 1.1 + 1.3 \times 0.2 \times 0.25 = 0.22$

Similarly when using TS-LFET the sensitivity is calculated for a Failure Probability as

$0.9 \times 0.2 \times 0.25 + 1 \times 0.2 \times 0.5 + 1.1 \times 0.2 \times 0.25 = 0.2$

8.8.3 PROBABILITY OF FAILURE, GIVEN NO DEFECT IS REPORTED

The Probability of Failure Given No defect is reported as follows:

When measuring in one elevation only, the Probability of Failure is

$0.2 \times (1 - 0.25) = 0.15$, as the measurement is effective in 25% at one elevation

When measuring two elevations only the Probability of Failure is

$0.2 \times (1 - 0.5) = 0.1$, as the measurement is effective in 50% at two elevation

When measuring four elevations the Probability of Failure is

$0.2 \times (1 - 0.8) = 0.04$, as the measurement is effective in 80% at four elevation

8.8.4 NET PRESENT VALUE CALCULATION

Access to four elevations is $32,000 paid for building scaffolding

Contractor uses LFET instrument to measure tube thickness in four elevations for 120 tubes at a lump sum price of $71,000 for 100 hours.

Therefore Inspection cost is $103,000.

Outage time for a waterwall failure = 72 hours

Additional Cost of running Gas Turbine to make good the lost production 175MW for 72 hours = $ 819,000 at $65 per MWH.

Expected consequential cost for 120 tubes when nothing is done ie no inspection is $120 \times 0.2 \times 72 \times 11375$ = $19,656,000.

When inspection is carried out at four elevations using a LFET instrument, the expected consequential cost is calculated as below:

$120 \times 0.04 \times 72 \times 11{,}375$ = $3,931,200 ($11,375 being the cost of running the gas turbine per hour to produce 175 MW.)

To calculate Present Value the cost of inspection should be added to the consequential cost

Therefore Present Value = 3,931,200 + 103,000 = $ 4,034,200.

Net Present Value = Expected Consequential Cost – Present Value

Substituting, NPV = 19,656,000 – 4,034,200 = $15,621,800.

Similarly NPV for all combinations are calculated. NPV obtained for all combinations are tabulated below:

Table 8.11: Present Value Combinations

Strategy	Present Value		
	1- Elevation	2- Elevations	4 - Elevations
No Inspection	$19,656,000	$19,656,000	$19,656,000
D Meter	$16,268,200	$10,882,800	$4,436,320
LFET	$14,844,300	$9,930,300	$4,033,500

Table 8.12: Net Present Value Combinations

Strategy	Net Present Value		
	1- Elevation	2- Elevations	4 - Elevations
D Meter	$3,387,800	$8,773,200	$15,219,680
LFET	$4,811,700	$9,725,700	$15,621,800

From the above Net Present Value combination table, it is found that the best inspection strategy would be using a Low Frequency Electromagnetic Technique thickness measuring instrument for four elevations as this strategy produces the maximum Net Present Value.

8.9 SUMMARY OF INSPECTION OPTIMIIZATION

The important points of the optimized inspection program as calculated in the preceding sections is as follows:

1. Low Frequency Electromagnetic Technique will be used for thickness measurement of waterwall tubes.
2. The thickness of the tubes from elevation -1 to elevation-4 will be measured.
3. The lumpsum payment of $70,000 is advantageous than contracting on hourly basis.
4. The time taken to measure the thickness of the tubes is less when Low Frequency Electromagnetic instrument is used.

   The optimization arrived at by developing a decision model to calculate the maximum Net Present Value, has provided a direction to choose the most beneficial combination of options for plant. The optimization models in Microsoft Excel Spreadsheets are attached as Appendices A, B and C.

Chapter 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 CONCLUSIONS

Thermal power plants generally, have a preventive maintenance program. Periodically, components in the plants are inspected and either repaired or replaced. When replacement is contemplated, a budget provision is made for a certain year. In this method there is no scientific analysis for either replacement or inspection. The most cost effective time to replace a component is not thought about. The best means of inspection are rarely analyzed.

Many power plants have data acquisition systems which store every trip and start up of equipment. The Power Plants use these data to report on the availability of power generating units. Rarely are these data used for any valuable analysis such as assessment or risk based decision making. This thesis has used the equipment trip and start up data to estimate the risk factor which is later used in component replacement and inspection optimization.

Qualitative Analysis

The failure data of important equipment were qualitatively analyzed. The failure data of components that caused an outage of the generating unit were selected for analysis. The generating units had to be shut down whenever there was a leak in one of the furnace water wall tubes. Similarly, a leak in the superheater tube or the reheater tube contributed to a shut down and unavailability. A forced draft fan failure resulted in a 50% loss of power generation. Similarly, a boiler feed pump failure, boiler feed pump recirculation valve failure and a condenser tube failure also contributed to 50% loss of power generation. The failure data of these components were qualitatively analyzed and a risk matrix was drawn. The risk matrix drew attention to components with least failure probability and unacceptable consequences as well as components with least consequences and unacceptable failure probabilities. Both the failure rate and the consequence of failure for a waterwall tube are high. Both the failure rate of a feedwater heater and its consequence severity are low. The failure rate of a forced draft fan was found to be low with medium consequence severity.

Maintenance Optimization

The failure rates of waterwall, superheater, reheater, forced draft fan, boiler feed pump, boiler feed pump recirculation valve, and condenser tubes were quantitatively analyzed using a least squares approach and a Weibull distribution. Mean time to failure (MTTF) was calculated for each of the above mentioned components. The MTTF provided the number of times a component would fail and this information was used to forecast the economic consequences when the component aged. Though the failure rate forecast was not exact, it did provide a good estimate for the minimum number of expected failures. The concept of Net Present Value was used to determine the most cost effective time for replacing the aging component. Thus, this work has shown that a combined use of the Net Present Value and the failure rate obtained from a Weibull distribution derived from the component failure times can provide information as to the optimum time for the replacement of a defective component.

Inspection Optimization

All the decisions, actions, the financial implications that go into planning an inspection of waterwall tubes were analyzed using, influence diagrams, decision trees and a decision model. An inspection optimization program was developed for waterwall inspection. A decision had to be made whether to choose a digital ultrasonic thickness measuring instrument or a low frequency electromagnetic technique thickness measuring instrument. Similarly, decisions had to be made with regards to employing in plant inspectors or contract inspectors. The question of access to the waterwall tubes had to be decided, whether by means of scaffolding or sky climber. The number of elevations/tubes to inspect was also a question to be settled. Net Present Value was the deciding factor in arriving at a decision for choosing the best option. The Net Present Value was maximum when choosing to inspect four elevations, with scaffolding and contract inspectors using low frequency electromagnetic instrument to measure tube thickness. The Net Present Values were \$15,622,500 for four elevation inspection, \$9,760,500 for two elevation inspection and \$4,864,250 for one elevation. Obviously, the inspection program that yields the maximum NPV is the preferred method for waterwall inspection.

Application of Weibull Distribution

The Weibull distribution was selected from among a number of candidate distributions because of its ability to provide reasonably accurate failure analysis using a small number of data points. This was proven in the case of reheater. The reheater had failed only three times but the regression coefficient r^2 for Weibull distribution was found to be 0.83. The required regression coefficient for a good fit for 2 parameter Weibull distribution with three failure data is 0.78. Thus a methodology to analyze failure data has been established.

ASME Guidelines

The applicability of the ASME Guidelines to risk management has been demonstrated in this thesis by applying simple procedures with the aid of Microsoft Excel.

9.2 RECOMMENDATIONS

The procedure adopted in this thesis can be improved by including the following recommendations in the analysis. The recommendations are:

1. Sensitivity Analysis should be done to ascertain which inputs influence the Decision Model. When such inputs are found care has to be exercised in obtaining this input
2. Human Error Probability should be calculated for every failure and incorporated in the analysis.

3. Possibility of using Bayesian Methodology to remove uncertainty should be explored.

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Appendix A	Inspection Optimization for one elevation				
Categories					
Strategy Decison	Number of Tube Elements	Probability of Failure Today Based on Trend	Inspection sensitivity Effect	Number of Elevations to Inspect	Probability of Failure Given no Defect Reported
LFET	120	20%	20%	1	15%
Alternatives					
No Inspection	120	20%			
			90% of Actual @ 25%	1@25% Effective 125 hrs.	
D meter thickness meter			110% of Actual @ 50%	2@50% Effective 250 hrs.	
			130% of Actual @ 25%	4@80% Effective500 hrs.	
LFET			90% of Actual@25%	1 @ 25% Effective 25 hrs	
			100% of Actual @ 50	2 @ 50% Effective 50 hrs	
			110% of Actual @ 25%	4 @ 80% Effective 100 hrs	

Access to the component	In-house or Contract Inspectors per Hour	Inspection Cost	Consequential Time for Shutdown	Opportunity Lost Cost per Hour	Expected Consequential Cost	Present
$32,000	$133	$49,750	72	$11,375	$14,742,000	[redacted]
scaffold @ $32,000	Contractor @ $160/hr		20@25%			
	for four Technicians		24@50%			
			16@25%			
	Lumpsum for 4 Elevation $71,000					

	Present Value
0	[redacted]

Present Value Combinations

Present Value			Scaffold w/Contractor	
	Number of Elevations	1	2	4
Inspection Strategy				
No		$19,656,000	$19,656,000	$19,656,000
D Meter		$16,268,200	$10,882,800	$4,436,320
LFET		$14,791,750	$9,895,500	$4,033,500

Net Preser

Net Present Value
Inspection Strategy
D Meter
LFET

	Scaffold w/Contractor	
1	2	4
56,000	$19,656,000	$19,656,000
58,200	$10,882,800	$4,436,320
91,750	$9,895,500	$4,033,500

Net Present Value Combinations

Net Present Value			Scaffold w/ Inhouse	
	Number of Elevations	1	2	4
Inspection Strategy				
D Meter		$3,387,800	$8,773,200	$15,219,680
LFET		$4,864,250	$9,760,500	$15,622,500

Appendix B Inspection Optimization for two elevations						
Categories						
Strategy Decison	Number of Tube Elements	Probability of Failure Today Based on Trend	Inspection sensitivity Effect	Number of Elevations to Inspect	Probability of Failure Given no Defect Reported	Acce
LFET	120	20%	20%	2	10%	
Alternatives						
No Inspection	120	20%				
			90% of Actual @ 25%	1@25% Effective 125 hrs.		scaf
D meter thickness meter			110% of Actual @ 50%	2@50% Effective 250 hrs.		
			130% of Actual @ 25%	4@80% Effective500 hrs.		
LFET			90% of Actual@25%	1 @ 25% Effective 25 hrs		
			100% of Actual @ 50	2 @ 50% Effective 50 hrs		
			110% of Actual @ 25%	4 @ 80% Effective 100 hrs		

Access to the component	In-house or Contract Inspectors per Hour	Inspection Cost	Consequential Time for Shutdown	Opportunity Lost Cost per Hour	Expected Consequential Cost	Preser
$32,000	$133	$49,750	72	$11,375	$9,828,000	[redacted]
scaffold @ $32,000	Contractor @ $160/hr		20@25%			
	for four Technicians		24@50%			
			16@25%			
	Lumpsum for 4 Elevation $71,000					

ent Value

Present Value Combinations

Present Value			Scaffold w/Contractor	
	Number of Elevations	1	2	4
Inspection Strategy				
No		$19,656,000	$19,656,000	$19,656,000
D Meter		$16,268,200	$10,882,800	$4,436,320
LFET		$14,791,750	$9,895,500	$4,033,500

Net Present Val

Net Present Value	
	Number Elevatio
Inspection Strategy	
D Meter	
LFET	

				Net Present Value Combinations				
	Scaffold w/Contractor			Net Present Value			Scaffold w/ Inhouse	
1	2	4			Number of Elevations	1	2	4
				Inspection Strategy				
,000	$19,656,000	$19,656,000		D Meter		$3,387,800	$8,773,200	$15,219,680
,200	$10,882,800	$4,436,320		LFET		$4,864,250	$9,760,500	$15,622,500
,750	$9,895,500	$4,033,500						

Appendix C Inspection Optimization for four elevations

Categories						
Strategy Decison	Number of Tube Elements	Probability of Failure Today Based on Trend	Inspection sensitivity Effect	Number of Elevations to Inspect	Probability of Failure Given no Defect Reported	Access t
LFET	120	20%	20%	4	4%	
Alternatives						
No Inspection	120	20%				
			90% of Actual @ 25%	1@25% Effective 125 hrs.		scaffold
D meter thickness meter			110% of Actual @ 50%	2@50% Effective 250 hrs.		
			130% of Actual @ 25%	4@80% Effective500 hrs.		
LFET			90% of Actual@25%	1 @ 25% Effective 25 hrs		
			100% of Actual @ 50	2 @ 50% Effective 50 hrs		
			110% of Actual @ 25%	4 @ 80% Effective 100 hrs		

	Probability of Failure Given no Defect Reported	Access to the component	In-house or Contract Inspectors per Hour	Inspection Cost	Consequential Time for Shutdown	Opportunity Lost Cost per Hour	Expect Conse Cost
	4%	$32,000	$133	$49,750	72	$11,375	$
rs.		scaffold @ $32,000	Contractor @ $160/hr		20@25%		
rs.			for four Technicians		24@50%		
s.					16@25%		
s			Lumpsum for 4 Elevation $71,000				
s							
rs							

					Present Value Combinations			
Consequential Time for Shutdown	Opportunity Lost Cost per Hour	Expected Consequential Cost	Present Value		Present Value			Scaffold w/
72	$11,375	$3,931,200	[redacted]			Number of Elevations	1	
					Inspection Strategy			
					No		$19,656,000	$19,65
					D Meter		$16,268,200	$10,88
					LFET		$14,791,750	$9,895
20@25%								
24@50%								
16@25%								

Model

r	Expected Consequential Cost	Present Value
75	$3,931,200	[redacted]

Present Value Combinations

Present Value			Scaffold w/Contractor	
	Number of Elevations	1	2	4
Inspection Strategy				
No		$19,656,000	$19,656,000	$19,656,000
D Meter		$16,268,200	$10,882,800	$4,436,320
LFET		$14,791,750	$9,895,500	$4,033,500

	Scaffold w/Contractor	
1	2	4
56,000	$19,656,000	$19,656,000
58,200	$10,882,800	$4,436,320
91,750	$9,895,500	$4,033,500

Net Present Value Combinations

Net Present Value			Scaffold w/ Inhouse	
	Number of Elevations	1	2	4
Inspection Strategy				
D Meter		$3,387,800	$8,773,200	$15,219,680
LFET		$4,864,250	$9,760,500	$15,622,500