LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
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SPARE PART MANAGEMENT OF BUBBLING FLUIDIZED BED BOILER

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Docent, D.Sc. (Tech.) Juha Kaikko

Supervisor: M.Sc. Johanna Iivonen

ABSTRACT

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Energy generation industry is very capital-intensive industry. Productivity and availability requirements have increased while competition and quality requirement have increased. Maintenance has a significant role that these requirements can be reached. Even maintenance is much more than repairing faults nowadays, spare parts are important part of maintenance. Large power boilers are user-specific therefore features of boilers vary from project to project. Equipment have been designed to follow the customer's requirements therefore spare parts are mainly user-specific also.

The study starts with literature review introducing maintenance, failure mechanisms, and systems and equipment of bubbling fluidized bed boiler. At the final part spare part management is discussed from boiler technology point of view. For this part of the study science publications about spare part management are utilized also some specialist from a boiler technology company and other original equipment manufacturers were interviewed.

Spare part management is challenging from the boiler supplier point of view and the end user of spare parts has a responsibility of stocking items. Criticality analysis can be used for finding most critical devices of the process and spare part management shall focus to those items. Spare parts are part of risk management. Stocking spare parts is increasing costs but then high spare part availability is decreasing delay time caused by fault of item.

TIIVISTELMÄ

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Energiateollisuus on hyvin pääomavaltaista. Teollisuuslaitteiden tuottavuuden ja käynnissäpidon vaatimukset ovat kasvaneet kilpailun ja laatuvaatimusten kasvaessa. Kunnossapidolla on merkittävä rooli, jotta nämä vaatimukset saavutetaan. Vaikka kunnossapito on nykyään muutakin kuin vikojen korjaamista, varaosat ovat oleellinen osa kunnossapitoa ja laitteen ylläpitoa. Suuret voimalaitoskattilat ovat räätälöity asiakkaan tarpeisiin, jolloin kattilan ominaisuudet vaihtelevat suuresti projektista toiseen. Laitteet mitoitetaan näiden vaatimusten mukaisesti, jolloin laitteiden varaosat eivät ole käytettävissä muissa kohteissa.

Työn alkuosassa tarkastellaan kirjallisuusviitteiden kautta sekä kunnossapitoa ja vikaantumismekanismeja, että kuplaleijupetikattilan osasysteemejä ja niiden laitteistoa. Jälkimmäisessä osassa käsitellään varaosien hallintaa voimalaitoskattiloiden näkökulmasta. Tässä osassa on käytetty materiaalina tieteellisiä julkaisuja aiheesta sekä haastateltu erään voimalaitoskattiloiden toimittajan asiantuntijoita ja muiden laitetoimittajien edustajia.

Kattilatoimittajan näkökulmasta varaosien hallinta on haasteellista ja vastuu varastoinnista on varaosien loppukäyttäjällä. Laitekriittisyysanalyysin avulla voidaan löytää prosessille kriittisimmät laitteet ja näihin varaosien hallinnan tulisi keskittyä. Varaosat ovat osa riskienhallintaa. Varaosien varastointi nostaa kustannuksia, mutta toisaalta varaosien nopea saatavuus alentaa vikaantumisen aiheuttamaa epäkäytettävyyttä.

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Kiitos!

Tampere, May 11th 2016

Nanna Jaakkola

TABLE OF CONTENTS

SYMBOLS AND ABBREVIATIONS

Latin srcipts

A	Availability
K	Criticality index
M	Multiplier
p	time between failures
P	Performance rate
Q	Quality rate
W	Weighting factor

Supscripts

e	environmental risk
p	production loss
q	quality cost
r	repair or consequential cost
s	safety risk

Abbreviations

AHP	Analytic Hierarchy Process
BFB	Bubbling fluidized bed
BHF	Bag House Filter
CFB	Circulating Fluidized Bed
Cl^-	Chlorine ion
EPC	Engineering, Procurement, and Construction
EPCM	Engineering, Procurement, and Constructions Management
ESP	Electrostatic Precipitator
FMEA	Failure Mode and Effect Analysis
FMECA	Failure Mode Effect and Criticality Analysis
FTA	Fault Tree Analysis
HAZOP	Hazard And Operability Analysis
ID	Induced Draft

KPI	Key Performance Indicators
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
MWT	Mean Waiting Time
NO_x	Mono-nitrogen oxides
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer
OMF	Optimizing Maintenance Function
OTF	Operate To Failure
RCM	Reliability-Centered Maintenance
RTF	Run To Failure
SO_4^{2-}	Sulfate ion
SRCM	Streamlined Reliability-Centered Maintenance
TPM	Total Productive Maintenance
VED	Vital, Essential, Desirable

1 INTRODUCTION

A boiler is high-value capital asset which productivity expectations and requirements are high. Maintenance assures that these targets will be reached therefore maintenance is developing side by side with these requirements of capital assets. Since it is typical for high-value capital asset that a part of it is maintained rather the asset itself, spare parts have a significant role for maintenance (Driessen 2010, 3).

1.1 Background

The study is done cooperation with a company which provides technology solutions and services to pulp, paper and energy generation industries. The company is global and it has about 10 500 employees in 30 countries.

The company is providing a spare part package with a new boiler which includes spare parts for first two years operation. Commissioning spare parts are not part of the spare part package but those are including to the boiler delivery. If the customer wants availability guarantee for the new boiler, the spare part package is requirement that the company is able to guarantee an availability of the boiler in first years. The company is developing its spare part business and the study is done as a part of this development process.

Usually a customer, who is investing to the new boiler, chooses a main supplier who manages the whole project on behalf of the customer. This is typical for energy industry and it is called Engineering, Procurement, and Constructions Management (EPCM) form of contracting. The main supplier is managing then also equipment deliveries from other equipment suppliers which not belong to the main supplier’s main knowledge.

The power boiler is a complex system and there are several factors that vary from project to another. Mainly large power boilers are designed to fulfill the customer’s requirements and a detail structure of the boiler differ nearly every delivery project. This affects to spare part management as well that there are several equipment which are not originally supplied by the boiler supplier. These factors make spare part management challenging especially to the boiler supplier since they need to manage their own spare parts but also spare parts of equipment supplied by other suppliers.

1.2 Research execution and targets

The target is to create a methodology for defining the content of a strategic spare part list offered during the new boiler quotation process. The methodology shall create a foundation for fulfilling the availability guarantee and shall be based on for example criticality analysis or risk management. A bubbling fluidized bed (BFB) boiler type was selected for the object of the study. The methodology shall be applied to clarify the content of the spare part package list of the BFB boiler for the first two years operation and justify reasons for each item to be part of the scope. The BFB boiler is delimited to include the boiler itself, daily fuel silos and main saturated steam line at the study. Therefore it is excluding equipment such as a fuel handling equipment before daily silos and steam turbine.

The study is mainly a literature review. Also some main original equipment manufacturers and the company’s own experts are interviewed for the study. Interviewees have been chosen due to get information which spare parts shall be included to the spare part package. It is interesting how original equipment manufacturers are choosing recommended spare parts and they should have a good knowledge of products they are offering. The study is interviewed few equipment manufacturers which one is material handling system supplier, one manufactures fans, two manufacture pumps and two manufacture sootblowers.

1.3 Structure of the thesis

The study has been divided to two parts: theoretical aspects are introduced at the beginning and then spare part management and spare part package are discussed at the final part.

The maintenance chapter is introducing maintenance by different maintenance strategies, key performance indicators (KPI), maintenance frameworks and maintenance services. Maintenance management can use many maintenance strategies to ensure that required functions of the item will be archived and KPI are used to measure performances. Total Productive Maintenance (TPM) and Reliability-Centered Maintenance (RCM) are two well-known maintenance framework and these two frameworks are introduced. This section of maintenance frameworks shows typical aspects and implementing steps are went through shortly of both frameworks. Last topic is maintenance service business at the maintenance management chapter where the possibility to outsource maintenance tasks are introduced.

Next chapter is focusing on failure mechanisms in metal structure components. Focus is on corrosion mainly since it occurs often in metal structures of the boiler. Typically corrosion process induces loss of material and corrosion type can be identified from these chances. Atmospheric corrosion, galvanic corrosion, pitting and erosion-corrosion mechanisms are introduced. In the end of the failure mechanisms chapter also fatigue and wear failure mechanisms are introduced shortly.

Spare parts of the BFB boiler was chosen to the object of the study. The BFB boiler is one type of fluidized bed boilers and it is widely used combustion technology. At the chapter the BFB boiler is reviewed as five parts which are furnace, water-steam cycle, flue gas system, ash handling and sootblowing system. The furnace section is divided to four parts which are fluidized bed, fuel and sand feeding, combustion air and auxiliary fuel system. The chapter introduces main components of the BFB boiler and descripts shortly how it works.

The chapter five starts the final part of the study which discusses some typical features of the boiler spare part management and spare part classification. At the spare part management chapter is discussed about different point of views of the user and the provider of spare parts. Also whether stock or not spare parts for the boiler, is discussed at the chapter.

The spare part package is offered alongside with the new boiler delivery. The purpose of the spare part package is to support availability during guarantee period mainly in first two years. A scope of the spare part package, warranty and spare part classification is discussed and showed at the chapter.

Finally some conclusions of spare part management of the boiler and spare part classification are showed. And in the end are the summary of the study and the references list.

2 MAINTENANCE MANAGEMENT

The European Standard SFS-EN 13306:2010 specifies generic terms and definitions for the technical, administrative and managerial areas of maintenance. The maintenance is specified as: “combination of all technical, administrative and managerial actions during the life of an item intended to retain it in, or restore it to, a state in which it can perform the required function”. As a term the item can consist, for example, a plant, a component, a system or equipment (Manzini et al. 2010, 65).

If earlier maintenance focused mainly on repair a fault in the item, now it is more than that. Nowadays maintenance includes wide range of activities to maintain, adjust and preserve productivity of fixed assets. Every item has to perform the required function or a combination of functions and the target of maintenance is to ensure that this will be archived. (Järviö 2007, 12.)

Productivity can be defined as the ratio of an output to an input of a production system. The output of the production system is products or services delivered while input is resources needed to produce the output. Resources of the input can consist, for example, labour, materials, tools and equipment. With the given input, productivity efficiency is as high as outputs of products or services can be produced. Productivity is a combination of two measures: effectiveness and efficiency. Efficiency usually refers how well something is done while effectiveness refers how useful something is. (Parida & Kumar 2009, 18.)

High productivity efficiency reduce investment need of the company because of the higher productivity efficiency with the lower investments the company can produce the output. This improves profitability and competitiveness of the company. (Järviö 2007, 13.)

The standard SFS-EN 13306:2010 divide maintenance strategies to two main groups: preventive maintenance and corrective maintenance (Figure 1). Actions belong to preventive maintenance are taken place before a detected fault while corrective maintenance is relating to actions after the detected fault. The standard does not take into account a maintenance concept Run To Failure (RTF, also known as Operate To Failure, OTF). This concept means that operation personnel are responsibility of condition monitoring and routine maintenance which are only maintenance tasks needed to be done for item during its lifetime. The item will be repaired or replaced when the item breakdown. RTF are widely used for low value items that do not made an effect to the production during failure. (Järviö 2007, 47-48.)

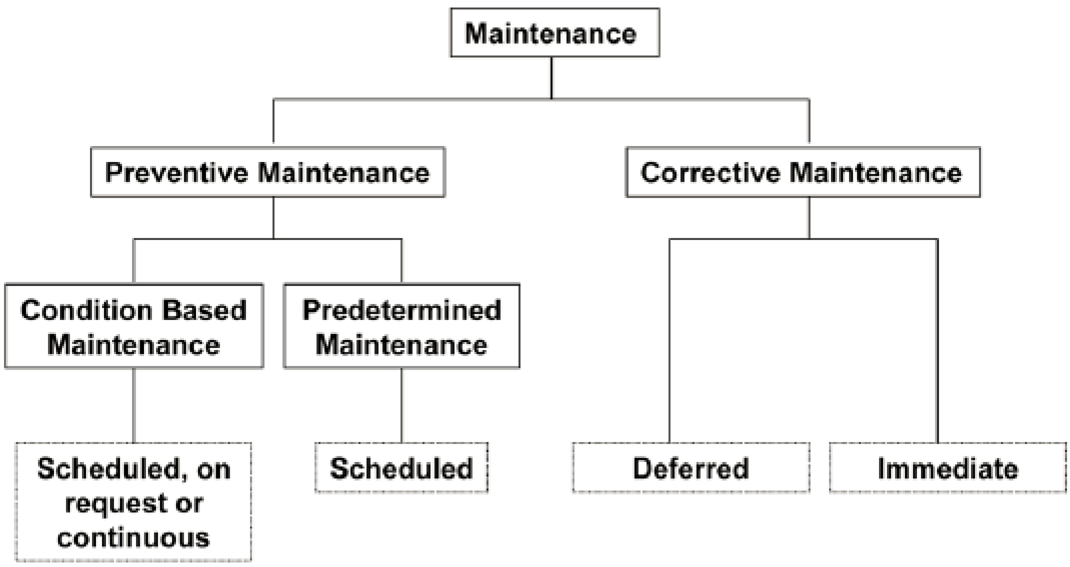

Figure 1 Maintenance strategies overview (SFS-EN 13306:2010).

But why several different maintenance strategies are needed? Expectations around maintenance have been matured and nowadays companies understand that maintenance has an effect to the safety, the environment and the quality of the output. Also companies is striving a high availability to the item. For example, value of the item and its criticality affect to how the item should maintain. Therefore the maintenance has developed many different strategies to achieve these objectives and every item shall not have a same maintenance strategy.

2.1 Key Performance Indicators

Maintenance management characterizes the process of leading and directing the maintenance organization, and consist all activities that relate to maintenance objectives, strategies and responsibilities. These activities can be implemented by maintenance planning, maintenance control and supervisions, also improvement of methods in the organization. Key Performance Indicators (KPI) such as overall equipment effectiveness (OEE), reliability, availability, mean time to repair (MTTR), mean time between failures

(MTBF), failure frequency, and maintenance costs, measure maintenance performances. KPIs can be included to maintenance objectives. (Manzini et al. 2010, 65-66; Márquez 2007, 20; Parida & Kumar 2009, 21.) Few of KPIs are introduced the following.

2.1.1 Availability and Reliability

Availability shows time when equipment is available to perform as required under given conditions. Laine (2010, 108) is introducing availability (Figure 2) trough reliability, maintainability and maintenance supportability, when a plan is to improve availability. Availability is a sum of these three elements and these can be divided to other sub-elements. Like reliability can be improved by develop planning, maintenance frequency, skills of operational personnel and reserve capacity.

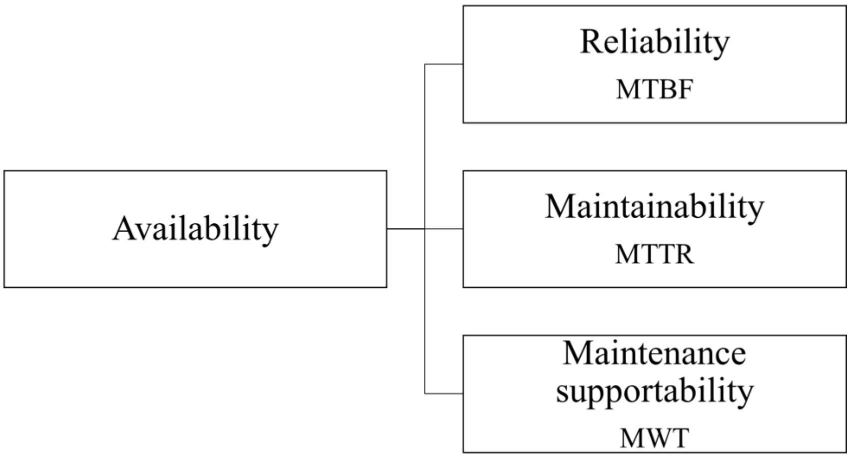

Figure 2 Availability components (Laine 2010, 108).

Reliability can be defined as probability that the item perform as required under given conditions and in given time period without failure. Mean Time Between Failure (MTBF) can be used as a measure to indicate reliability performance. MTBF indicates average time from last failure to a new one. MTBF is the proportion of total failures to given time period. (Márquez 2007, 267; SFS-EN 13306:2010.)

Maintainability indicates the probability that the item is repaired back into required condition after failure. A measure that indicates maintainability is Mean Time To Repair (MTTR) which shows average repair times and technical delays. It is not taking into account logistic delays that a maintenance organization can’t control. (Márquez 2007, 267.)

Mean Waiting Time (MWT) measures maintenance supportability. It shows how long the item needs to wait a repair or an overhaul. Maintenance supportability indicates effectiveness of the maintenance organization to provide the correct maintenance actions in given time frame. (Márquez 2007, 75.)

2.1.2 Overall Equipment Effectiveness

Overall Equipment Effectiveness (OEE) is a rate to review equipment effectiveness and manufacturing productivity. This performance indicator can be used as a very simple tool to review current state of manufacturing process but also a complex tool to understand and notice effects of different issues in the process. (de Souza 2012, 3-4.)

$$OEE = \text{Availability}\,(A) \cdot \text{Performance rate}\,(P) \cdot \text{Quality rate}\,(Q) \tag{1}$$

$$\text{Availability}\,(A) = \frac{\textit{Operating time}}{\textit{Operating time} + \textit{Downtime}} \cdot 100\,\% \tag{2}$$

$$\text{Performance rate}\,(P) = \frac{\textit{Production volume}}{\textit{Nominal production capacity} \cdot \textit{Operating time}} \cdot 100\,\% \tag{3}$$

$$\text{Quality rate}\,(Q) = \frac{\textit{Production} - \textit{Reject}}{\textit{Production}} \cdot 100\,\% \tag{4}$$

OEE is a product of availability, performance and quality (1). Availability, performance rate and quality rate are loss-related factors that provide information which losses categories affect to OEE. Availability A is calculated by operating time and downtime (2). Equipment failure and set-up also adjustment losses are downtime losses which affect to availability rate. Speed losses come from idling, minor stoppage and reduced speed, and these are caused because of running speed is less than optimal operating speed. These losses affect to performance rate P (3). Defects in process and reduced yield cause quality losses in the process. Quality rate Q is calculated by amount of production and reject during operating time (4).

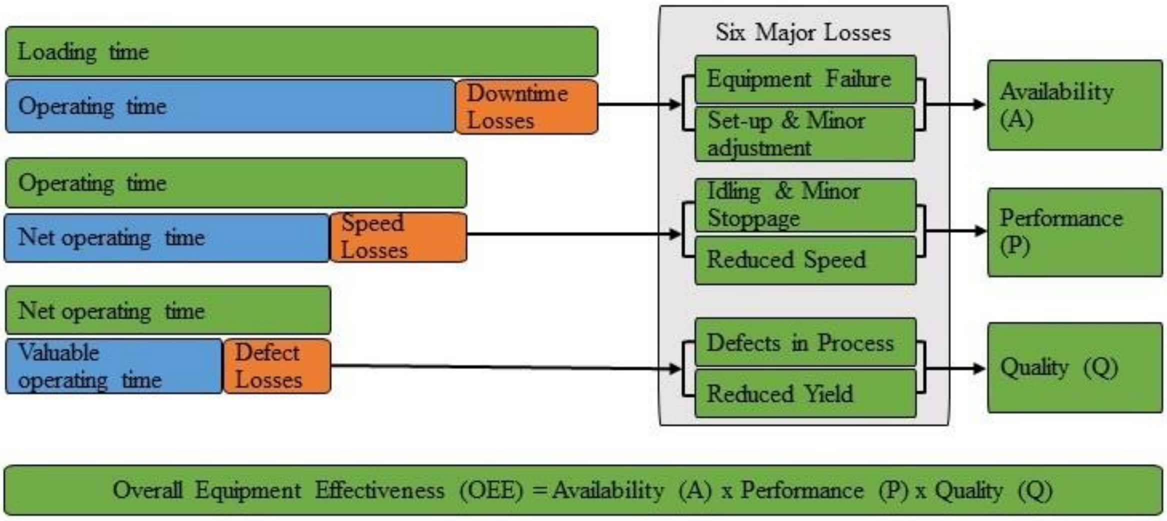

Figure 3 Structure of OEE (Ahuja 2009, 428).

An OEE score of 100 % means that all these three factors has a score of 100 % each meaning that process is always running during planned production time, it is running as fast as possible and only good quality products are being produced (Figure 3). Manzini et al. (2010, 76) says that a world-class OEE rate is between 80 and 85 percentage when the availability rate is about 92-94 percentage, the performance rate is about 90-92 percentage and the quality rate is about 98-99 percentage.

It is good to realize that OEE doesn’t take into account planned disuses of the process. Disuses may be due to overcapacity or lack of orders. Utilization rate indicates time the process is in use annually. It can be calculated by the proportion of utilization time to calendar time (Laine 2010, 21-22; PSK 7501:2010.)

2.2 Maintenance Frameworks

After the Second World War maintenance was mainly restoring and focused on breakdowns. Started in 1950’s, plant managers developed preventing thinking for maintenance. As a conclusion, previous development maintenance frameworks were created. Because of different character of items, usually maintenance policy is a mix of different maintenance strategies. (Manzini et al. 2010, 70-71.) Next two well-known maintenance frameworks are introduced: Total Productivity Maintenance (TPM) and Reliability-Centered Maintenance (RCM). Usually these frameworks are heavy to go through for the whole process. Especially RCM is wide and tough to utilize for whole process and that is why usually it is used for most critical items of the process. Therefore maintenance is a mixture of different maintenance frameworks and strategies in the reality.

2.2.1 **Total Productive Maintenance**

The TPM concept was developed during 1960s originally in Japan to support its lean manufacturing system. The understanding the importance of the maintenance had increased. Expectations to keep and increase availability, product quality, safety requirements, and cost-effectiveness started an interest to develop the maintenance. (Ahuja 2009, 417; Manzini et al. 2010, 73.)

The TPM framework is developed primarily to optimize effectiveness of the item throughout its entire life by participation and motivation of the entire human resources. It is said that TPM is a people-centered methodology. (Manzini et al. 2010, 73.)

The framework underline word “total” in TPM and it may assume three meanings:

- total effectiveness, measured as economic efficiency and profitability
- total maintenance approach, mainly including corrective, preventive and condition based policies
- total participation of all employees, involves every level and function in the organization (Manzini et al. 2010, 73-74).

Developers of the TPM framework wanted that the framework is not only maintenance specific policy; it is a culture, a philosophy, and a new attitude towards maintenance. The key target in TPM is that all items related to the production are kept in optimum condition with maximum efficiency. The target is possible to achieve when operating personnel of items are personally responsible to follow that target will be reached. Therefore TPM is based on teamwork and it involves employees from both production and maintenance organizations through cross-functional teams. The framework provides a method to achieve world class levels of overall equipment effectiveness (OEE) trough people, not only through technology or systems. (Järviö 2007, 111; Ahuja 2009, 418.)

The TPM mainly focuses to reduce equipment losses to improve OEE. Equipment losses may be divided to six major equipment losses categories including time losses, speed losses and defects:

- failure
- set-up and adjustments
- idling and minor stoppage
- reduced speed
- process defects
- reduced yield.

Here failure means any downtime was it scheduled or not. Production time is increasing when losses are decreasing, which improves OEE. Time losses are due to breakdowns and setup activities. Here setting up means a series of operations during product-change until the production of the new item is completely satisfactory. Used time for scheduled shutdowns can be reduced by decreasing shutdown time or by increasing resources of shutdown. All failures should be recorded and discussed afterwards to learn about them. This is how same kind of failures can be avoided or prepared in advance. (Duffuaa & Haroun 2009, 111; Laine 2010, 24-25, 48; Manzini et al. 2010, 74.)

Speed losses are due to micro-stops and speed reduction from nominal value. Micro-stops are caused when production is interrupted by a temporary malfunction or when a machine is idling. One minor stoppage doesn’t affect significantly to OEE but when there are several minor stoppage the sum of them affects. That is why also minor stoppages should be recorded and fixed even few minutes stoppage seems to be irrelevant. Defects occur due to equipment starting and quality defects. Reduced yield is all produced parts from startup until stable production with good quality is reached. (Duffuaa & Haroun 2009, 111; Laine 2010, 24-25, 48; Manzini et al. 2010, 74.)

TPM is based on several fundamental steps. The first step is deletion causes of losses, introduced above, to improve productivity of the process. (Manzini et al. 2010, 74; Laine 2010, 48.) Other steps are introduced briefly as follows.

The second step includes creation of a program of autonomous maintenance. Autonomous maintenance means maintenance by workers and the standard SFS-EN 13306:2010 uses term “operator maintenance” of it. The purpose of the step is to move simple maintenance tasks under operators perform while resources of skilled maintenance personnel is concentrated on maintenance tasks that mostly required technical expertise and more sophisticated techniques for advanced manufacturing. (Manzini et al. 2010, 74-75.)

After step two when operators are able to perform basic maintenance tasks, the maintenance personnel are focusing only nonconventional maintenance task in the third step. They are also able to focus to develop maintenance activities to increase the equipment reliability, maintainability and maintenance supportability. (Manzini et al. 2010, 75.)

The fourth step is focusing to improve all workers capability to perform maintenance tasks. This is done by training personnel continuously to upgrade their skills and reaching well-motivated experts. The idea of TPM is to provide trainings to all personnel in order to reach experts from everyone not only a small amount of workers. This is captured to four phases: “do not know, know the theory but cannot do, can do but cannot teach, can do and also teach”. (Manzini et al. 2010, 75.)

The fifth step of TPM is creating management system for the equipment or the plant to develop and manage those. The plant or equipment are not operating all the time and the time outside of operate time need to manage also. The fifth step is focusing to manage spare parts, design modification and continuous improvement. (Manzini et al. 2010, 75.)

It is important to understand that TPM model cannot be transformed directly from the company to another. Cultural differences need to take an account while implementation of TPM. The whole implementation and to achieve world stage level of OEE, took several years.

2.2.2 **Reliability-Centered Maintenance**

The RCM framework has been developed in support of the preventive maintenance planning. The problem relating to the preventive maintenance is that too many and unnecessary activities are executed under the preventive maintenance when it is neither effective nor efficient. Generally items are opened or dismantled to monitoring a condition for nothing. If possible condition monitoring would be best to do while operating because of every opening increase a possibility of failure. Also maintenance activities are not focused on items that are valuable and really need to be maintained. RCM helps the company to plan maintenance activities and direct the resources reasonable. (Järviö 2007, 123.)

The standard SFS-IEC 60300-3-11:2001 presents RCM as “a method for establishing a preventive maintenance program which will efficiently and effectively allow the achievement of the required safety and availability levels of equipment and structures, which is intended to result in improved overall safety, availability and economy of operation.” The history of the RCM started in the mid-20th century. Federal Aviation Agency started to develop preventive maintenance plan for civil airplanes. As a result of the research the RCM framework was released. Now RCM is a proven and accepted methodology used in industries like nuclear industry and oil refining industry. (Siddiqui & Ben-Daya 2009, 741.)

The RCM process starts with clarifying, which processes need maintenance. When processes has been clarified and put in order, then need to clarify what kind of items processes consist. After this, next step is to figure out how these items can get a fault and what consequences the failure can cause to the process and the item. Then items can be organized following how severe consequences are. Maintenance possibilities and how useful those are, will be examined at the next step. When all these steps have been done, the maintenance plan for the production can be rewritten following the RCM procedure. (Järviö 2007, 124.)

As a part of the RCM process can be used various analysis tools such as Failure Mode and Effect Analysis (FMEA), Failure Mode Effect and Criticality Analysis (FMECA), Fault Tree Analysis (FTA), Optimizing Maintenance Function (OMF), and Hazard And Operability (HAZOP) analysis, to help identifying the functions of items, the causes of failures, and the consequences of the failures. (Ahuja 2009, 421.)

The framework is task-oriented rather than maintenance process oriented. This eliminates the confusion associated with used terminology such as condition monitoring and on-condition. By using a task-oriented concept, it is possible to see the whole maintenance program reflected for the given item. The preventive maintenance tasks that comprise RCM based preventive maintenance program are:

- lubrication and servicing
- operational, visual, and automated check
- inspection, functional test and condition monitoring
- restoration
- discard.

The maintenance program includes also non-scheduled maintenance tasks. (The Standard SFS-EIC 60300-3-11:2001.)

The traditional RCM is tough and expensive to execute because the planning process start from the beginning without any assumes. Therefore Streamlined Reliability-Centered Maintenance (SRCM) has been developed to make it easier and faster. SRCM is like lighter version from RCM and SRCM take into account some well-known assumes. (Järviö 2007, 125.)

2.3 Maintenance service business

Maintenance service business has increased while maintenance task for machines and equipment has not increased in the same rate. This tells the maintenance outsourcing has increased its popularity. Traditionally maintenance service products have been labour and spare parts. (Laine 2010, 169-171.)

A reason for outsourcing maintenance should not be in cost reduction even it has been. When the company buys maintenance services it should pay for productivity. Seems that companies are striving cost reduction by outsourcing maintenance activities even the target should be to improve productivity of production and that way to achieve cost reduction by improving productivity. (Laine 2010, 169.)

Now the understanding is that maintenance activities need to be done by operating and maintenance personnel with good cooperation. If maintenance is outsourced, there is a risk of negligence about maintenance in operating personnel. It is possible that operating personnel start to think that “the maintenance does not belong to under my responsibility” and this can cause problems to condition monitoring of the item and others.

Maintenance services open new business area for boiler suppliers. Customers are interest to outsourcing maintenance task to improve their productivity. This requires supplier to know both operation and maintenance tasks. Maintenance knowledge enable supplier to quote maintenance services and long term service agreements. These stabilize the supplier’s businesses. This also opens an opportunity to offer life-cycle services and maintenance services are also good after sales market for the boiler supplier. In the future may customer pay only for the output and the boiler supplier has a responsibility of delivery, operation and maintenance of the plant. Then the site is supplier’s asset and the customer buys the output.

3 FAILURE MECHANISMS

Failure is a physical event where the item does not archive the required function or a combination of functions. Functions are necessary performances for the item to provide a given service. (Márquez 2007, 43.)

After a failure the item has a fault. The fault can be complete or partial, what means that the item cannot perform any required functions or can perform some of the required functions, but not all. It is good to realize that failure is an event, while fault is a state. There is always a reason to the failure and a cause of failure can be due to mistakes in design, manufacturing, installation, handling and/or maintenance. The cause of failure can be one of these or a combination. (Márquez 2007, 43-44; Järviö 2007, 53.)

Every failure has a mechanism. Failure mechanism means physical, chemical or other processes which may lead or have led to failure (SFS-EN 13306:2010). Failure cause tells “why” the item fails, while failure mechanism tells “how” the item fails to perform the required function (Márquez 2007, 43).

There are several failure mechanisms. Mechanisms vary depending on different variable of items such as item type, function of the item, material, and operating environment. The following sections present some common failure mechanisms in metal structure components.

3.1 Corrosion

Corrosion is a natural and a complex process that occurs as the deterioration of a material being result of chemical or electrochemical reactions. It can exist in different forms and it is affected by numerous chemical, physical, electrochemical, mechanical and metallurgical variables. Corrosion process may produce a protective surface as a corrosion byproduct. The corrosion begins very aggressively but reduces its action as soon as the protective surface film or corrosion deposit is formed on the metal surface. However, if the protective film slit or removed, corrosion proceeds again. (Otegui 2014, 90.)

Typically any corrosive process induces loss of material and the type of corrosion could be identified by the shape of the generated chances over the surface. Corrosion can be divided to general or localized corrosion. General corrosion occurs widely over the surface area of a metal, while localized corrosion results in a localized metal loss or cracks at different small areas over the surface. (Otegui 2014, 40; Khan et al. 2012, 250.) Figure 4 shows how the surface is affected by some common mechanisms of corrosion. Instance of localized corrosion are galvanic corrosion and pitting corrosion.

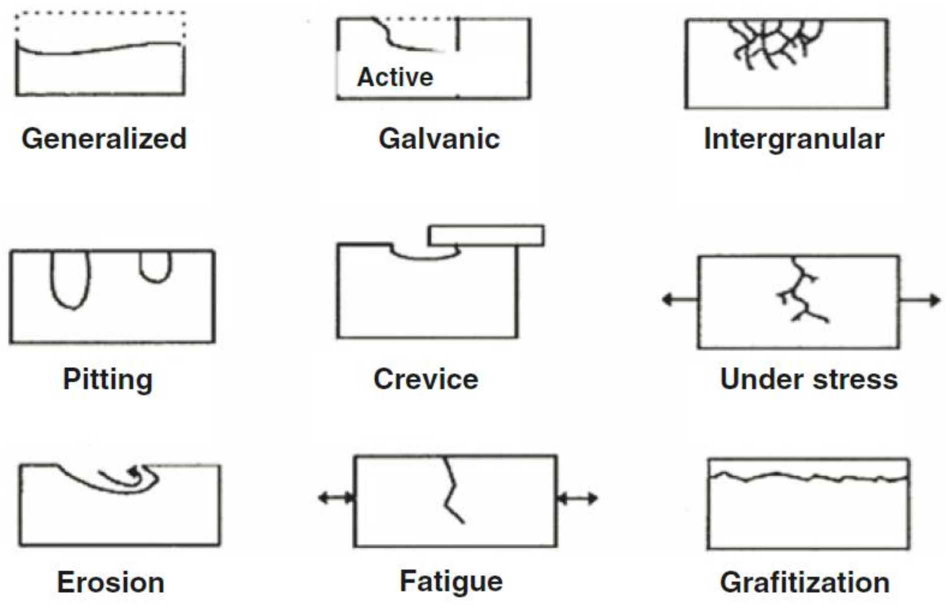

Figure 4 Various corrosion types (Otegui 2014, 91).

Atmospheric (Figure 5) corrosion is one of the most likely forms of generalized corrosion. In this type of corrosion the loss of thickness is uniform. There are few important variables in the process such as the type of atmosphere (industrial, marine), relative humidity, temperature, and the presence of salts, sulfides and dirt. The surface of the metal can be protected by coating. (Otegui 2014, 90-93.)

Galvanic (Figure 5) corrosion occurs when two dissimilar metals are electrically connected by the electrolyte, and it is an impact of the difference in electrochemical potential between the two metals. As a result of galvanic corrosion, the cathodic metal is protected and the anodic metal will corrode faster. The cathodic metal is nobler one of the two metals. The best prevention for the galvanic corrosion is to avoid connection of dissimilar metals. (Otegui 2014, 90-93.)

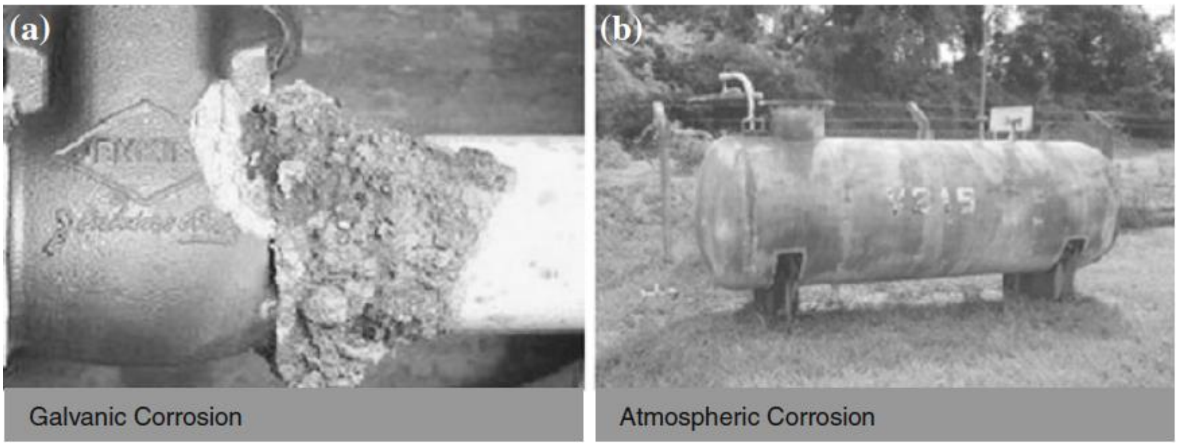

Figure 5 Galvanic and atmospheric corrosion mechanisms (Otegui 2014, 91).

Pitting (Figure 6) is the type of the localized corrosion. Even so it occurs in very small surface areas; the pitting is dangerous form of corrosion and as the attack is very fast. The certain ions such as chlorine (Cl^-) and sulfate (SO_4^{2-}) ions, have the property of locally breaking the protective film on the surface of metal and exposing to the corrosive medium. Pitting can cause perforation of the wall and material with protective films such as stainless steel and nickel alloys, are more susceptible for it. (Otegui 2014, 90-93.)

Erosion-corrosion (Figure 6) is erosion that is increased by corrosion. Erosion itself is the removal of material from the metal surface by the action of numerous individual impacts of solid particles from a fluid. Erosion-corrosion can be identified from the shape of a “horseshoe” on the surface in the direction of flow. The most important factors that influencing the mechanism are speed, size, and shape of the particles, fluid velocity and the active corrosion mechanism. Especially high turbulence areas are exposure to the mechanism. The use of corrosion-resistant alloys and/or altering the process to reduce corrosivity, are possibilities to mitigate erosion-corrosion. (Otegui 2014, 90-93.)

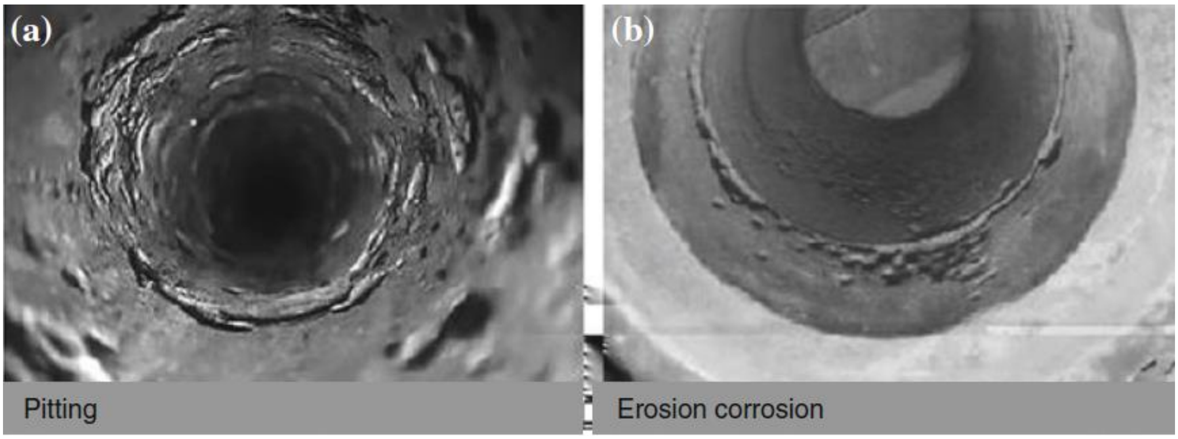

Figure 6 Pitting and erosion-corrosion mechanisms (Otegui 2014, 93).

3.2 Fatigue

Fatigue is a form of material weakening that occurs due to cyclic loading in a period of time. Cyclic loading is due to mechanical loads, thermal cycling and vibration. Causes of fatigue are initiation and growth of cracking. When size of crack is small, crack grows slowly but growth rate is increasing with crack size. In a critical size, the crack grows suddenly and the mechanical structure will fracture. If fatigue cracking will not be noticed in time, it usually causes unexpected failure of the item. (Otegui 2014, 100; Khan et al. 2012, 250.)

3.3 Wear

Wear removes metal surface in mechanical structure and causes deformation of the structure. Worn structures lose their capability to perform as required and worn structures need to be replaced or repaired to reach required perform state.

There are several wear mechanisms such as abrasive, adhesive, corrosive, sliding, rolling and cavitation. Abrasive wear is caused when fine particles in lubricant, fuel or air are lapping mating surfaces. Abrasive materials are sand, dirt, metal particles and other debris. Adhesive wear is caused when operating surfaces are in direct metal-to-metal contacts and adhesive to each other. (Otegui 2014, 36, 86, 230.)

4 BUBBLING FLUIDIZED BED BOILER

Fluidized bed combustion had been used in many industrial applications before it has been begun to use in energy production in the 1970's. Nowadays fluidized bed combustion is widely used combustion technology because as a fuel can be used many different types of fuels with high combustion efficiency. Also emissions control can be done easily by restrict combustion temperature or by injection of lime directly to the furnace. There are two main types of fluidized bed boilers: Bubbling Fluidized Bed (BFB) and Circulating Fluidized Bed (CFB). (Teir 2003, 37-38.)

Depending on the fluidizing velocity the bed reacts differently and gets different types of fluid-like behavior (Figure 7). In the BFB boiler the velocity of air flow is kept so low that the particles of the bed are not carried out with flue gas. Also the size of particles in the bed is bigger that differs from CFB boiler. (Teir 2003, 37-38; BREF LCP 2006, 289.)

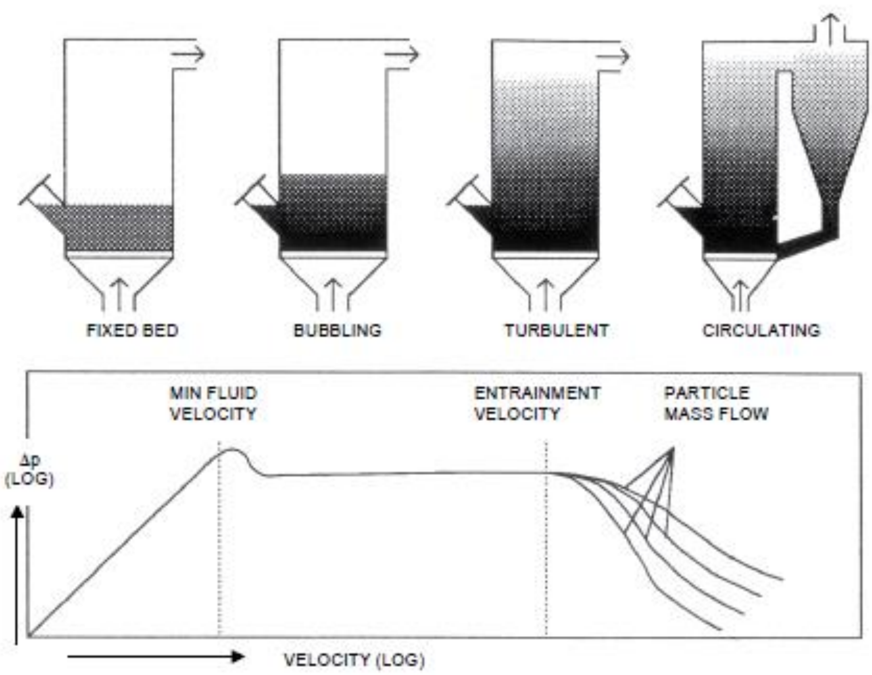

Figure 7 Effects to the bed are depending on the fluidizing velocity (Teir 2003, 37).

Hereafter only the BFB boiler is enlarged. A process of the BFB boiler and its equipment are introduced in this chapter. Also some of the typical failure causes is introduced. The Figure 8 introduces the typical side view of the BFB boiler.

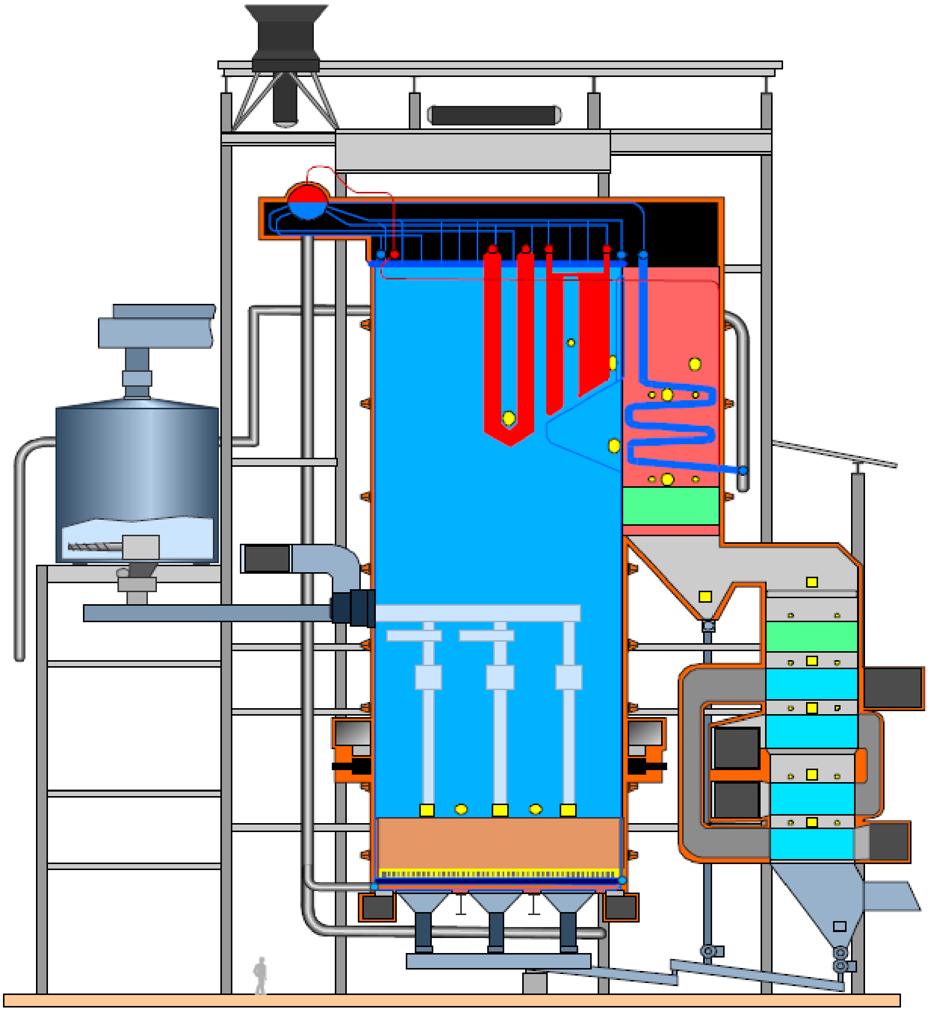

Figure 8 Typical side view of the BFB boiler (Vakkilainen 2011).

4.1 Furnace

The furnace is a part of the boiler, where heat is generated and fuel is combusted. Combustion of the fluidized bed boiler is based on fluidizing sand bed that is fluidized with the combustion air. The fuel is fed to the bed, where it is mixed with bed material and combusted. Materials can be used in the bed are sand, minerals and ash. (BREF LCP 2006, 289.)

The structure of the furnace of the BFB boiler has been represented on Figure 9. In the study the furnace system of the BFB boiler is introduced in four sections, which are fluidized bed, combustion air, fuel and sand feeding, and auxiliary fuel system. Water-steam system is introduced separately later in the chapter.

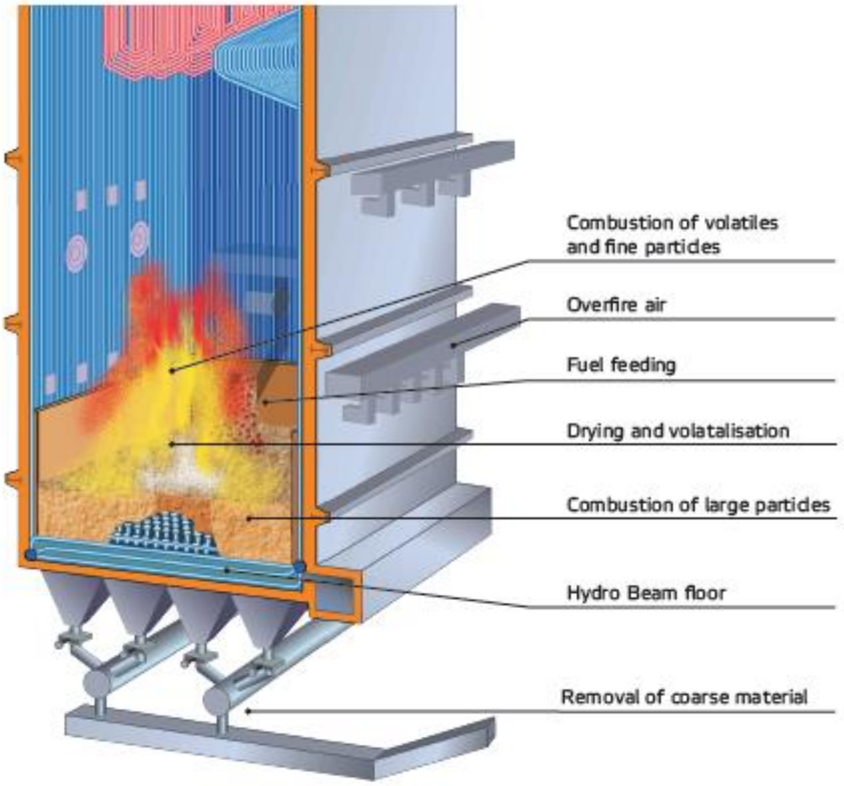

Figure 9 Cutaway of a bubbling fluidized bed furnace with Hydro Beam grate (Valmet Corporation).

The furnace walls are made up vertical membrane design tubes. The membrane design is a structure of carbon steel tubes and fines. Tubes are connected each other with all way welded fines and the structure is gas-tight. (MyAcademy 2014.)

Like previous was said in the BFB boiler can be combusted a wide variety of fuels. The high heat capacity of the bed enable to use fuels that quality and composition can vary a lot. Fuel consists harmful components and the type and amounts differ widely between different fuels. These impurities such as alkalines, chlorine and trace metals, can cause problems in the boiler as follows:

- bed sintering
- slagging of the furnace walls
- fouling of heating surfaces and
- corrosion.

Slagging, fouling and corrosion are consequence of lower melting point of ash, which is the effect on chlorine and alkali metals. Potassium and Sodium can react with silica in the bed material, which forms low melting-point silicates and this cause sintering. (MyAcademy 2014.)

Like it is said, the alkali metals in the fuel, causes bed sintering. Sintered bed material particles have stuck together and this disturb fluidization. This causes local hot spots in the bed and accelerating the bed sintering. The problem can be avoided by lowering the bed temperature with flue gas recirculation, changing the bed material sufficiently often or using inert bed material. (MyAcademy 2014.)

Partially molten ash particles become sticky and if these particles impact the furnace walls, it causes slagging. The thick slagging deposit disadvantage to steam cooling in the tubes and eventually the outer surface of the slagging deposit reaches the temperature of the flue gas. Then the slagging melts and runs down the tubes. Good fuel and air feeding design keeps the fuel away from the furnace walls and this way the slagging can be avoided. (MyAcademy 2014.)

In the fouling, partially molten ash particles stuck to the heating surfaces, causing the fouling deposits. The fouling reduces heat transfer which may reduce availability of the boiler. The fouling of heating surfaces depends on the composition and melting behavior of the fuel ash. To minimize the superheater fouling the tubes of superheaters shall be spaced wide, flue gas and metal temperatures shall be controlled, and sootblowing shall be executed efficiently. (MyAcademy 2014.)

Especially the high-chlorine fuels at high steam temperatures cause corrosion of the boiler tubes. Factors such as the flue gas temperature, the steam temperature, the air factor in the boiler, the composition of the ash, the ash melting temperature, and the amount of the smelt in the ash, affect corrosion of superheaters. The corrosion rate is increased radically by ash melting and fouling of heat transfer surfaces. To minimize corrosion of the furnace, to the lower part of the furnace can be built the refractory lining. To minimize corrosion of the superheaters, the used material of the superheaters shall be corrosion resistant and the flue gas temperature before the superheaters shall be kept below the melting point of the fly ash. (MyAcademy 2014.)

4.1.1 **Fluidized bed**

The bottom of the furnace is composed of air nozzles and water cooled tubes. The example of the structure of the bottom is shown in Figure 10. This bottom structure is one type for the BFB boiler and it vary depending on the manufacturer.

Primary air, that fluidizes the bed, comes through these air nozzles. When bed particles start to fluidize and they are no longer in constant contact with each other, the minimum fluidizing velocity has been reached. In this point the bed has begun to act like a fluid. In BFB combustion bed particles are wanted to keep in the bed and avoided them to escape by gas flow from the furnace. This restricts fluidizing velocity in BFB boilers and this limit value of the velocity is specified as the maximum fluidizing velocity. Typically, the minimum fluidizing velocity is about 0,8 m/s and under normal operating conditions the velocity is about 1,2 m/s. (MyAcademy 2014.)

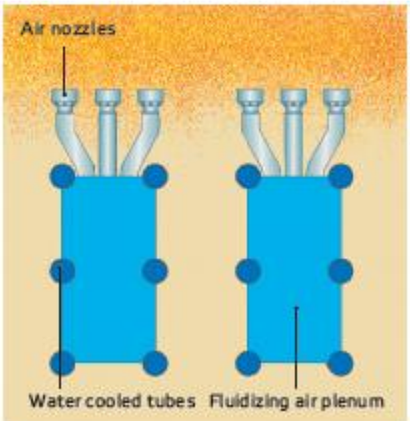

Figure 10 Bottom structure of the BFB boiler (Valmet Corporation).

Temperature of the bed is kept usually between 800 to 900 degrees Celsius but it can vary from 600 to 1000 degrees. These temperatures are low for combustion but because of high heat capacity of the bed, combustion efficiency is good in BFB boilers. (MyAcademy 2014.)

Operating problems may be caused by bed sintering or agglomeration, or the deterioration of the components of the bed. These cause changes to the fluidizing flow that causes changes to local temperature areas. The bottom of the furnace consists temperature measuring components that the temperature changes can be observed.

4.1.2 Fuel and sand feeding

Fuel is needed to pretreat before it is fed to the furnace. The particle size cannot be too small when it will escape by gas flow from the furnace. If the particle size is too large, the particle will not fluidize and it can cause local temperature raising that have effect to the bed agglomeration. Pretreating is also mixing the solid fuel to ensure stable and efficient combustion. (MyAcademy 2014.) The fuel is pretreated, also stored, usually outside of the boiler house and it is done before the daily fuel silos.

The purpose of the fuel feeding is to ensure required fuel flow from silos to the boiler. Fuel feeding system is assembly of a silo, a silo reclaimer, a conveyor, a balancing hopper, metering screws and fuel chutes. The silo reclaimer is feeding the fuel from the silo to the conveyor. The conveyor is moving the fuel to the balancing hopper in which the metering screws are dividing the fuel to the fuel chutes. The fuel chutes are feeding the fuel to the furnace and those are equipped with rotary valves. The rotary valves are prevented backfire from the furnace. The fuel chutes can be located on the front wall or site walls of the furnace depending of the size of the boiler. (MyAcademy 2014.) The principle structure of the fuel feeding equipment can be seen on Figure 8.

The purpose of the sand feeding is to store and periodically to supply sand to the boiler. The assembly of the sand feeding is similar to the fuel feeding system. (MyAcademy 2014.)

Impurities of the fuel shall be separated from the main fuel stream because of the impurities may cause damages to fuel feeding equipment. Sometimes these impurities pass the sieving system and for instance the large metal pieces may cause the blockage or the damage to the feeding system. These failures are usually unexpected and may cause unavailability or even a breakdown of the boiler.

Components of the fuel feeding equipment are wearing under operation. For instance worn flights of the screw decrease the conveying capacity when the screw does not achieve the required fuel flow. This causes reduction both to the fuel flow to the boiler and to the generated heat.

The dust of the fuel may dirt areas around the fuel feeding equipment. It is important to keep process areas clean because the dust may cause overheating of components and faster wearing.

4.1.3 Combustion air

The combustion air system provides the required air flow to the furnace. Usually the combustion air is fed to the furnace from different sections of the boiler. The primary air is fed to the boiler from the bottom of furnace. The secondary air and, when applicable, the tertiary air are fed to the furnace from upper part of the furnace. With combustion air the combustion of the fuel is efficient and can be controlled. (MyAcademy 2014.)

The primary air is supplied to the furnace by a high-pressure primary air fan. Radial air fan is most used fan type (Figure 11) in the steam boiler plants. The primary air flow is approximately 30-75 percent of the total air flow. For optimum combustion, air ducts and registers are equipped with dampers and different air control devices to obtain correct air distribution and air pressure. (Vakkilainen et al. 2003, 92-93; MyAcademy 2014.)

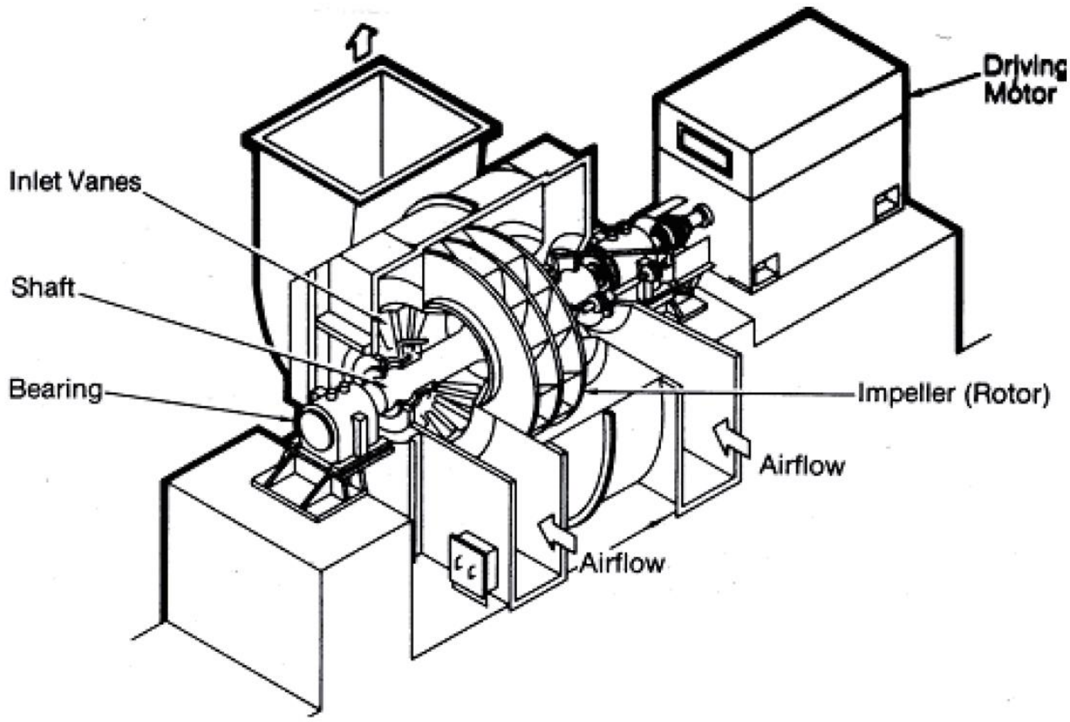

Figure 11 Radial air fan (Vakkilainen et al. 2003, 93).

Secondary and tertiary airs are used for finalize combustion. The secondary air fan supplies the air to the secondary air nozzles, the burners and, when applicable, to the tertiary air nozzles. The secondary air fan can be controlled by a variable frequency drive. Tertiary air is used when low mono-nitrogen oxides (NO_x) emissions are required. (MyAcademy 2014.) The combustion air feeding stages can be seen at Figure 9.

The combustion air is preheated in two stages. At the first stage the primary, secondary and tertiary air flows are heated in steam-coil or feedwater air preheaters before entering the flue gas air preheaters at the second stage. In the preheaters the combustion air is heated to approximately 100-350 degrees of Celsius before feeding to the boiler. (MyAcademy 2014.)

4.1.4 Auxiliary fuel system

The auxiliary fuel system consist oil or gas fired start-up burners and load burners. The purpose of the start-up burners is to heat the sand bed and create the required conditions for safe solid fuel firing. Before the solid fuel firing can be started also the steam pressure in the boiler need to be raised. Load burners are used for support to produce the required steam flow. (MyAcademy 2014.)

4.2 Water-Steam cycle

In water tube boilers the water-steam mixture flows inside the tubes and is heated by external heat source. The water tube boilers can be classified by the way of water-steam circulation. In natural circulation water from the steam drum flows through the downcomer tubes coming to a header. From the header, also called mud drum, the flow continues to the riser tubes and saturated water partially evaporates by an effect of the external heat. Water-steam mixture flows back to the steam drum where water and steam are separated. The separated water flows back to the downcomer tubes and the steam flows to the superheaters. The circulation occurs by naturally without water circulation pumps and that is why the type is called the natural circulation boiler. The circulation due to the water-steam density differences between the downcomer and riser tubes. (Teir & Kulla 2003, 54-55.)

The water-steam cycle equipment consist of boiler pressure parts and feedwater system. The boiler pressure parts are the furnace, the steam drum, superheaters and economizers. Some boilers are equipped with the generating bank that is also the pressure part. The feedwater system consists of the feedwater tank and feedwater pumps. (MyAcademy 2014.)

The feedwater system assures proper feedwater amount for the boiler at all loads rates. The feedwater tank stores feedwater reserve that is need for safety shutdown of the boiler. The tank collects streams such as condensate, fully demineralized makeup water and low-pressure steam, and the inputs are fed through the deaerator, where gases are removed and the needed chemicals are fed, before the feedwater tank (Figure 12).

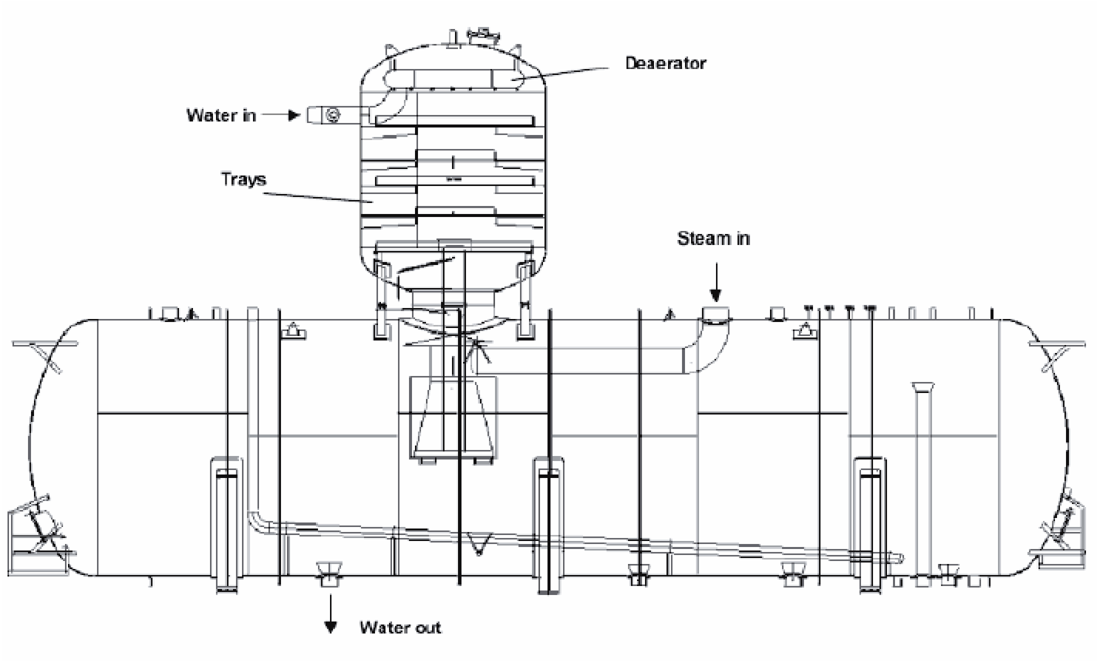

Figure 12 Feedwater tank (Teir & Kulla 2003, 78.)

The purpose of the feedwater pumps is to lead the feedwater from the feedwater tank to the boiler pressure parts and to pressurize the feedwater to the boiler pressure level. To secure required feedwater flow to the boiler, there are usually at least two similar and parallel connected feedwater pumps. Both pumps have enough individual power to singularly supply the required feedwater flow, in case one was damaged. (Teir & Kulla 2003, 78.) The Figure 13 shows an example of the feedwater pump provided by the KSB Group.

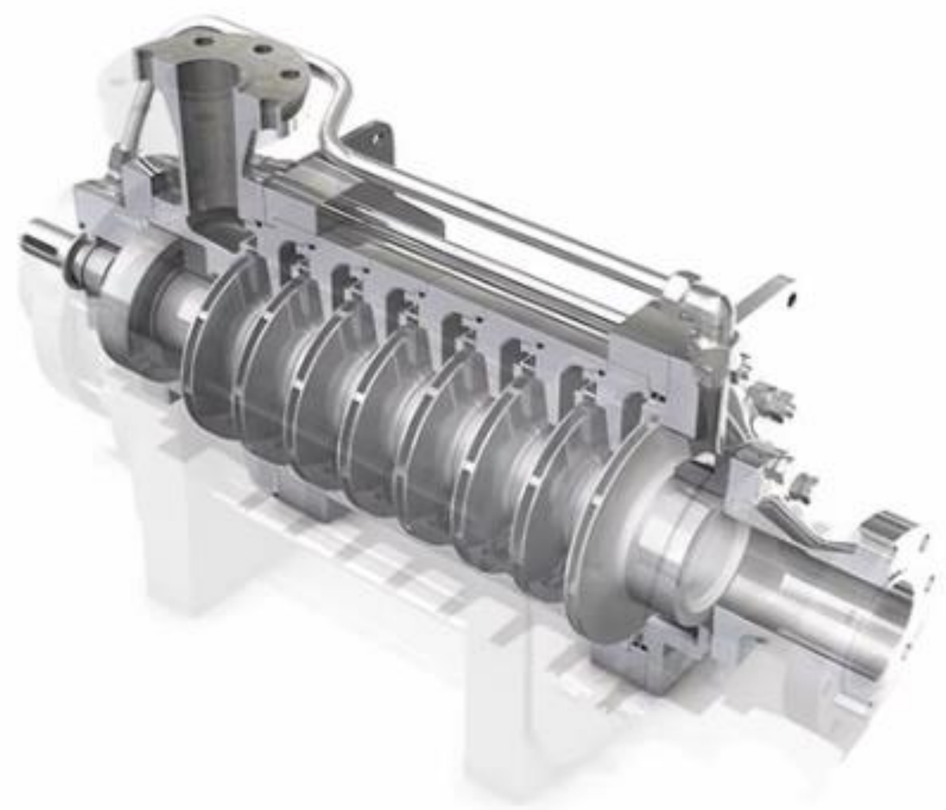

Figure 13 HGM Boiler Feed Pump by KSB (KSB Company 2015).

Economizers preheat feedwater by absorbing heat from flue gas before it is fed to the drum. The economizers both utilize the heat content of flue gas and cooling flue gas. (MyAcademy 2014.)

The steam drum can be called for the heart of the water-steam cycle because it is a key component in boilers. After the feedwater has been preheated by economizers the water flow arrives to the steam drum. The steam drum has several functions in the water-steam cycle. The purpose of the steam drum is to mix the feedwater with the circulating boiler water, supply the boiler water to the evaporator through the downcomers, receive water-steam mixture from the evaporator, separate water and steam, remove impurities, control water chemical balance, supply saturated steam, store water for load changes, and act as a reference point for feedwater control. (Teir & Kulla 2003, 73-74.)

The separated steam is fed to the superheaters where the saturated steam is superheated by absorption of heat from the flue gas. There are usually three superheater stages: the primary superheater stage, the secondary superheater stage, and the tertiary superheater stage. Attemperators spray feedwater into the steam between the superheater stages to obtain the correct leaving temperature of the steam. After the last superheater stage the superheated steam continues to the main streamline. (MyAcademy 2014.)

The components of pressure parts are exposed to slagging, fouling and corrosion. These can be minimized by using corrosion resistant alloys, reducing temperature of the flue gas, spacing tubes wide and sootblowing tube surfaces.

4.3 Flue gas system

Flue gas is generated from the combustion of fuel in the furnace. Hot flue gas is removing from the furnace impact of negative pressure produced by induced draft (ID) fan. (Vakkilainen et al. 2003, 92.)

The purpose of the flue gas system is to utilize the heat content of flue gas, remove dust particles from flue gas, and remove flue gas to the stack. The heat content of flue gas is utilized by heating feed and boiler water, and superheat steam with flue gas. (MyAcademy 2014.)

Flue gas system consists the flue gas induced draft (ID) fan, a flue gas recirculation fan, emission control systems such as an electrostatic precipitator (ESP) and a bag house filter (BHF), and the stack. Fflue gas flows over the heat absorbing surfaces releasing most of its heat content. After the heat absorbing surfaces flue gas passes through the emission control system. The ID fan is located after the emission control and it feed flue gas to the stack. With the recirculation fan can be controlled the bed temperature by recirculated back part of the flue gas to the furnace. The recirculation fan is positioned after the ID fan. (MyAcademy 2014.)

4.4 Ash handling

The ash handling system consists the coarse removal from the bottom of the furnace and the fly ash handling system. Almost all ash in the fuel is leaving from the furnace as the fly ash and the fly ash is removed from flue gas in the second and third pass ash hoppers and in the electrostatic precipitators or bag house filters. Particles that are too coarse for fluidizing do not leave with flue gas from the furnace. The coarse material such as oversized sand, stones and other impurities in the fuel, is removed with bottom ash removal equipment. (MyAcademy 2014.)

Ash hoppers collect the bottom ash and pneumatic dampers and rotary valve feeders collect ash from the second and third pass. These are removed to a bottom ash container by a chain conveyor and a screw conveyor. The bottom ash conveyor includes the sieving system to separate the coarse material and the reusable bed material. The fly ash that is separated from flue gas in the electrostatic precipitators or the bag house filters, is conveyed to a fly ash silo. The fly ash silo is equipped with a wet or a dry discharge system. (MyAcademy 2014.)

In the ash handling system problems may be caused by impurities in the fuel. For instance metal pieces in the sieving system may cause a blockage of the screens and even the damage of the screens.

4.5 Sootblowing system

The purpose of the sootblowing system is to keep the heat exchanging surfaces clean, which improves heat transfer and keeps the flue gas passages open. The sootblower use high-pressure steam injection to remove deposits from the surfaces. (Vakkilainen et al. 2003, 97.)

There are various types of steam sootblowers such as a retractable sootblower, multi-nozzle part-retractable sootblower, rake-type sootblower, and high-pressure steam jets. The chosen sootblower type depends on the position of the sootblower. (MyAcademy 2014.)

Retractable sootblowers are used for the secondary and tertiary superheaters, and positioned between the superheater stages because of this sootblower type is well suited to high temperature conditions. The retractable sootblower consists of a rotating lance that is pushed into the boiler when the sootblower is activated. The working end of the lance consists of two opposing nozzles through the steam is injected. After the executed operation the lance is pulled out from the furnace and the lance remains fully outside of the boiler during it is not in service. (Vakkilainen et al. 2003, 97; MyAcademy 2014.) The retractable sootblower is presented on Figure 14.

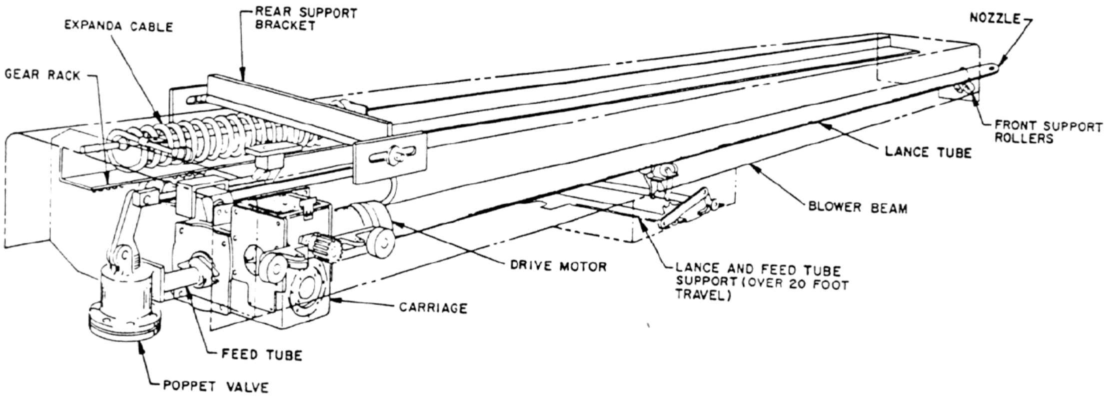

Figure 14 The structure and components of retractable sootblower for kraft recovery boiler (Vakkilainen et al. 2003, 98).

Places where the temperature is not that high, sootblower or part of that may be left inside of the boiler. The used sootblower types in that condition are multi-nozzle part-retractable sootblower or rake-type sootblower. The multi-nozzle part-retractable sootblower can be used for removing deposits on the primary superheaters, economizers and air preheaters at second and third pass. Rake-type sootblowers are used for the finned-tube economizer sections. (MyAcademy 2014.)

5 SPARE PART MANAGEMENT AT BOILER TECHNOLOGY AREA

Power boilers are high value capital assets and high availability of the boiler is important. Downtime of the boiler may cause other things lost revenues, end user of the output dissatisfaction and safety risk, and usually cost of downtime is very expensive. Maintenance is playing significant role to reach high availability of the boiler and availability of spare parts affect directly to maintenance delay. (Driessen 2010, 1-2.) The standard SFS-EN 13306:2010 defines the spare part as an "item intended to replace a corresponding item in order to retain or maintain the original required function of the item".

Spare parts can be divided roughly into two groups: business specific and standard parts. The business specific parts are used only of one or two business plants, while the standard parts are used more than two different business plants. Difference between the business specific and standard parts are that the business specific parts are high valuable slow moving parts, while the standard parts are less valuable but rotation rate is higher. (Molenaers et al. 2011, 572.)

From maintenance point of view spare parts can be divided to repairable parts and non-repairable parts or consumables. Repairable parts will be repaired after taken out and sent to the stock to wait next usage. Non-repairable parts or consumables also called wear parts, are not possible to repair technically or economically therefore non-repairable parts are discarded after taken out and the part was replaced by a new part. (Driessen 2010, 3.)

The power boiler is a complex system and there are several factors that vary from project to another. Mainly large power boilers are designed to fulfill the customer requirements and the detail structure of the boiler differ nearly every delivery project. Several factors have an effect to the boiler design and the structure such as:

- used fuel or fuels
- combustion technology
- dimensions of the boiler
- used construction materials
- the scope of auxiliary equipment

- operating time
- availability requirement, and
- maintenance productivity.

Therefore spare parts are mainly user-specific, or in the other words business specific, parts and the spare part management is complicated due to the large number of different items from many vendors.

5.1 Different point of views of spare part management

The point of view for spare parts depends on what is operator location at the supply chain. The end user of spare part hereafter the customer has other interests than the supplier of spare part has.

It depends on the customer’s maintenance strategy how they manage spare parts. For some customers availability of the process is really important therefore they are strongly focusing to improve their operation and maintenance functions continuously. These customers are planning their maintenance and using different maintenance strategies depending on how the failed item affects to the process. Maintenance is using spare parts to get item back to requested condition therefore availability of spare parts effects to downtime of the item. The issue to stock or not spare parts is discussed later on this chapter. Conversely some customers are not focusing that much to maintenance and they try to operate the boiler as minimum resources as possible. They only maintain the item when failure occurs. There are also differences in customers’ knowledge to operate and maintain the boiler which has an effect to maintenance levels and needed support from the outside of the organization.

The boiler supplier and probably the original EPC (Engineering, Procurement, and Constructions) main contractor hereafter the boiler supplier, has a challenge to manage all spare parts for the boiler since it consist various equipment from different manufacturer. When the customer chooses to invest a new boiler and chooses EPC main contractor to the boiler project, this main contractor start to be a link between the customer and the equipment or system manufacturer. This how the boiler supplier begins to be an agent and supply spare part also from other manufacturer not only their own spare parts. The boiler supplier wants to serve the customer as well as possible but stocking of spare parts is risky since user-specific design and intermittent demand.

The boiler supplier may have a problem if their company has separate a new capital project organization and a service organization, which do not cooperate with each other. If the new project organization only focuses to handle each boiler projects without life cycle thinking or standard way to operate, these may cause problems to the service organization later. Spare part sales mainly belong to after sales, where the service organization operates, but spare parts are also needed during the new boiler commissioning and warranty period in first years. Spare parts are easily only expense item for a sales team while a project execution team wants as much spare parts to the project site as possible to reach given availability of the new boiler. The service organization benefits if the project organization uses standard designs from boiler project to next ones. If this not happens every boiler has the own design and spare parts are user specific for each boiler. Because of large number of factors of the power boiler the same design is not possible to use every project and these characteristics make the spare part management challenging for the boiler supplier.

The original equipment manufacturer (OEM) has knowledge of its own products therefore the OEM's opinion of recommended spare parts impacts which spare parts the boiler supplier recommends to the customer to purchase and which spare parts the customer probably is going to purchase. Also the OEM decides which spare parts need to be purchased with the machine that their availability warranty holds. Spare parts are cheaper to manufacture same time with the machine so the OEM usually recommends to purchase spare parts via equipment purchase. When the equipment has already been delivered spare parts belongs to aftermarket and prices are higher than in manufacturing phase. Since the OEM has influence to recommended spare parts, they could use that for selling more spare parts than needed. Also the OEM may see the boiler supplier as a competitor at spare part sales market and they want to sell their own spare parts directly to the customer. Even the OEM and the boiler supplier are competitor for each other, they could cooperate and find the way to operate that satisfy both. When the boiler supplier has effective sales organization for spare part sales, probably the OEM does not need their own active sales organization to those areas and they will be benefit for the boiler supplier's work.

The OEM may recommend whole reparable units such as a screw for screw reclaimer, a bearing housing and a rotary valve feeder, as a spare part when possible. They justify these by faster replacing time than replacement of separate spare parts. The idea is to keep the whole reparable unit in the stock and when some part of these operating unit fails, the whole unit will be replaced and failed unit will be maintain later on to the stock waiting next replacement. This way the whole failed unit doesn't need to dismantle and assemble again during downtime of the process but the existing unit can replace the failed unit and then the failed unit is maintained after the process is back in operation. It is true that this way replacing time is shorter than other way but then the unit need to be kept in stock and this causes expenses to the stock keeper.

5.2 Stocking

The capital-intensive industry like energy generation industry strongly depends on availability of its technical equipment as it ensures the continuity of production flow. Therefore availability and continuous operability of the production system depends strongly on availability of spare parts. (Molenaers et al. 2011, 571; Manzini et al. 2010, 70.)

Factors of spare part such as value and delivery time, differs a lot. Because large scale boilers are usually customer specific, spare parts are also customer specific mainly. When spare part is not standard part which may be used in several boiler plants, spare parts are usually expensive and lead time is long. The effect is that spare parts will be manufactured only for need and lead times are long. Manufacturing cost is also higher because of the cost is split only for few items instead of several items. Since spare parts are mainly user-specific and intermittent demand, spare parts provider hardly stock items and the lead time of parts is usually several weeks from order. Therefore the end user of spare parts hereafter the customer, has a responsibility to decide to keep the stock or not to keep. However the stocking is increasing operating cost and then it affects to the cost of finished goods (Diallo et al. 2009, 191).

When planning spare part stocking the decision maker need to take into account different factors of the spare part such as:

- lead time
- price of the spare part
- probability of part failure
- cost of downtime
- other consequences of downtime
- repairability and
- self-life.

Even downtime is expensive the stocking causes also costs, decision maker need to find balance between spare part availability, working capital and operational costs. (Driessen 2010, 3-8.)

If spare part is decided to not keep in the stock, it is not meaning that lead time of spare parts is equal to availability of spare part. Then the condition monitoring is important operating and maintenance task and signal to purchaser need to come on time if the item needs to be replaced. Long lead times need to be take into account in maintenance planning and the demand of the part needs to be forecasted.

The decision whether stock the item or not can be made before or after the first need of the part. If the decision is made before the first need, it is possible that the part is never needed during its lifetime when the stocking only causes unnecessary work and cost. When the decision of stocking is made after the first need it is possible that the supplier does not exist anymore or then the supplier is still available but the lead time is long. Detailed information such as technical details, lead time, value, of the part is needed to collect if the part is decided to keep in the stock. Collecting these information may increase the lead time of the part if it is not kept in the stock and it need to be purchased. (Driessen 2010, 7.)

The possibility that the item is never needed during its lifetime, that has been decided to keep in the stock, affects to decision making. All stoking items are increasing cost of finished goods due to holding cost such as cost of stocking space, cost of item management and cost of stocking system. When price of spare part is low, the risk that the stock keeper lost money is lower in case that this spare part is never needed. If the price of the spare part is high, for example more than 50 000 euros, the risk losing money is higher if the spare part is never needed and decision to keep this spare part at the stock shall be make carefully.

Even the spare part would be extremely critical to the process availability and its lead time would be several weeks or even months, but probability of failure is low or other words part is very reliable, it is more likely that the stocking causes more costs in long time period than downtime in unforeseen breakdown. Especially when the price of the spare part is really high. Therefore the item criticality shall not been used as an only factor when decide which spare parts shall be available at the stock.

6 STRATEGIC SPARE PART PACKAGE

In the industry, it is typical that spare parts are cheaper to purchase via the equipment delivery. Later when the equipment has been already delivered and in service, the spare parts belong to after sales market and prices of spare parts are higher. The price of the spare part could be even two or three times higher at the after sales market. The reason is that the spare part is just cheaper to manufacture as a same time with the equipment, which spare part belongs to. The spare part package is sold via the new equipment delivery. It is a combination of recommended spare parts that are needed to assure the required productivity during a guarantee period. The purpose of the spare part package is to back up the guarantee period by shorting unplanned shutdowns and to achieve the required availability of the boiler.

The value of the spare part package is approximately 0,5-2 percent from the contract price of boiler delivery. Commissioning spare parts exclude to the spare part package. The commissioning spare parts are part of the boiler delivery and these parts secure a successful testing and start-up of the new boiler (MyAcademy 2014).

It is typical for energy industry to use Engineering, Procurement, and Constructions Management (EPCM) form of contracting to new boiler projects. A client, who is investing to the new boiler, chooses the main supplier who manages the whole project on behalf of the client. The main supplier is managing then also equipment deliveries from other equipment suppliers which not belongs to the main supplier’s main knowledge.

The power boiler system is a combination of different subsystems. The functional tree of the BFB boiler is shown in Figure 15. The boiler delivery project usually consist several equipment suppliers and spare parts are originally from the equipment suppliers. Naturally the main equipment supplier or here the boiler supplier manages its own spare parts but needs to handle also other spare parts from the auxiliary equipment suppliers. When the boiler supplier manages and collects the spare part package most spare parts are not its own articles due to EPC form of contract.

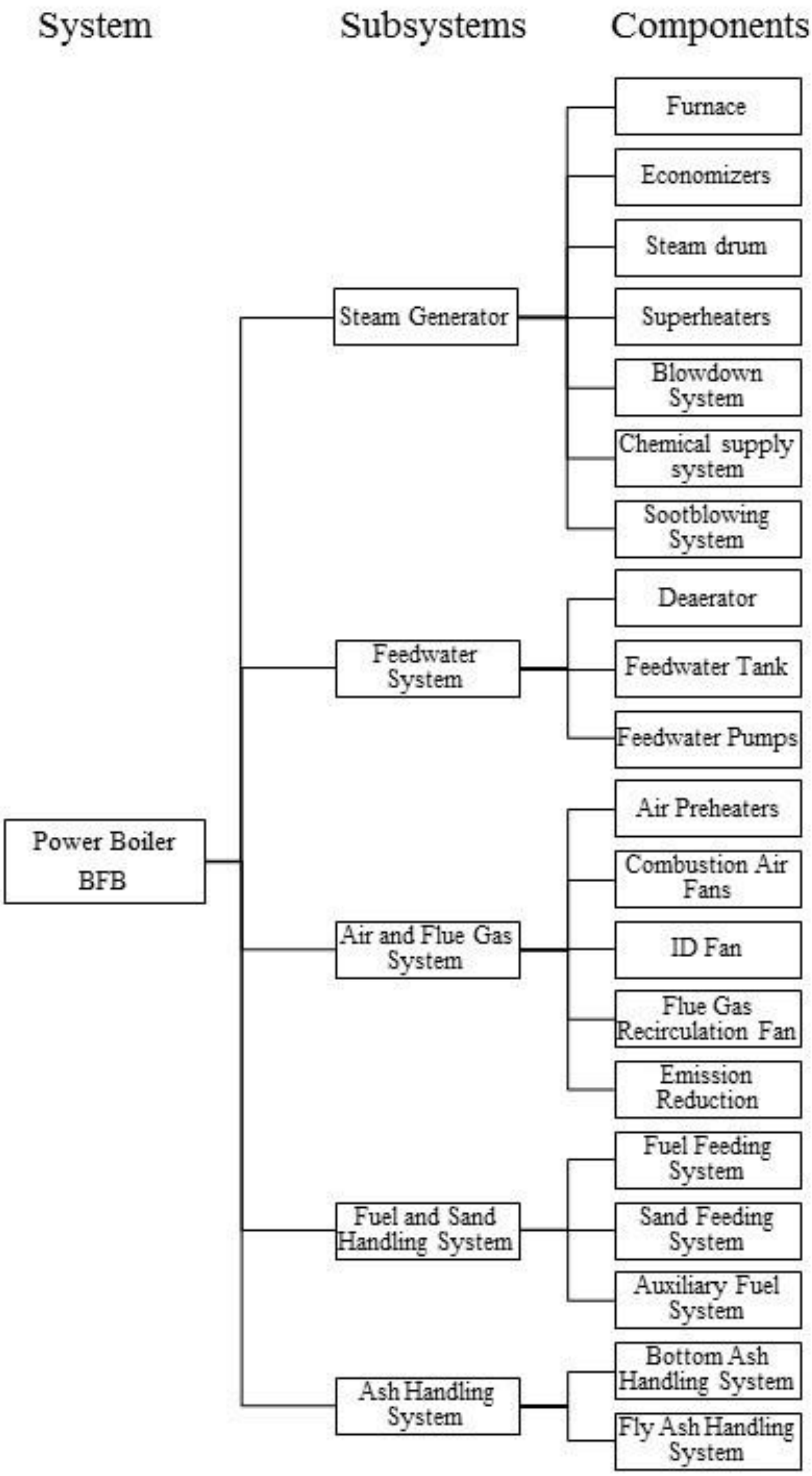

Figure 15 The functional tree of BFB boiler

It is significant to notice when spare parts are user-specific and origin of most spare parts are from sub-suppliers, spare part management is challenging. Therefore, for instance, spare part pricing includes a risk and a comprehensive spare part catalogue could not be prepared before the detail design is completed. Because of this sales phase of the spare part package is a challenge if the customer wants the final spare part list and unit prices for spare parts before a purchase decision. The detail design is finished usually after the sales has been confirmed in the boiler business area.

6.1 Scope of spare part package

The scope of the spare part package is combination of spare parts of various equipment. It could include only needed wear parts for planned shutdowns or then wide range of spare parts that cover high availability of the boiler plant.

Figure 16 is presenting relationship between the spare part package scope and the accepted risk level during first two years after the commissioning. The buyer of the new power boiler decides the required productivity of new installation. Then the seller, here the boiler supplier, defines needed spare parts for the guaranteed period that the required productivity is possible to assure.

The scope of the spare part package number 1 has been reduced and may include only wear parts needed during the guarantee period. Then the customer accept higher risk level that influence to the guaranteed availability of the new installation. At the next level the scope of spare part package number 2 is wider and the guaranteed availability is higher. The spare part package includes the wear parts and the high critical spare parts. The scope of spare part package number 3 is the widest and the spare part package includes the wear parts and wide range of critical spare parts. This means basically that the lower acceptable risk level the wider scope of spare parts and the other way around.

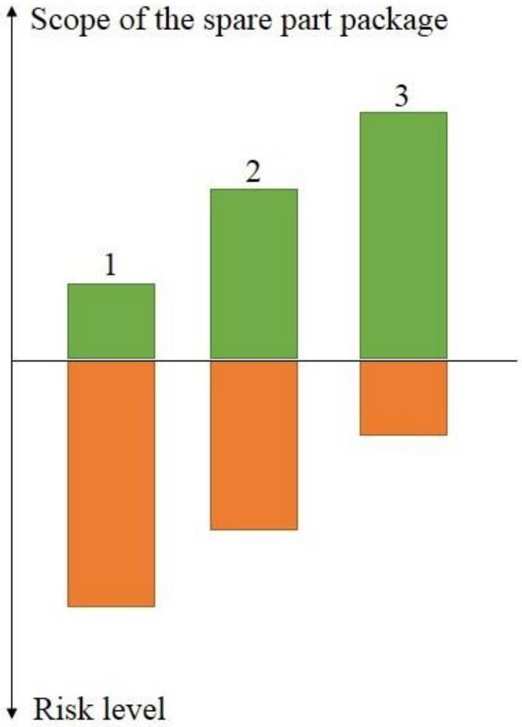

Figure 16 How the scope of the spare part package relating to the risk level.

The spare part package contract assures that there are spare parts at the new power boiler plant and therefore the boiler supplier has a possibility to guarantee the required availability to the new installation. It may be said that the spare part package is the value of the guaranteed availability of boiler.

The location of boiler needs to be taken into account when the scope of spare part package is defined. The accessibility of the boiler plant affects to delivery time of the spare part and it could have a significant impact to lead times of spare parts. It affects also to value of spare parts since transportation costs may increase because of a challenge location of the site. Transportation takes about one week inside of Europe from the spare part supplier to the customer’s site. Even large spare parts can be delivered in short period. If the customer’s site is in middle of a jungle or in an island, the transportation takes much longer. Then the role of stocking comes more important to reach high availability of the boiler.

The situation is more critical when critical equipment for the process is not doubled. Good example of doubled machine are feedwater pumps which the process has normally at least two pieces. Both feedwater pumps can be reach a full capacity by themselves or then the process is designed that a one pump can reach for example 75 percent capacity. If one of the two pumps occur a failure the process does not stop while other pump still can perform as required. If feedwater pump is not doubled and it faces a failure, the process does not get feedwater and the whole process will break down immediately.

Amount of spare parts in the spare part package is usually based on recommendations of original equipment manufacturer or other expert. Amounts can be based on calculations or simulations also. (Diallo et al. 2009, 192-193.) For some equipment only one quantity of spare part per type is needed, like spare parts such as rotary feeder or fan. But it is harder to identify how many pieces of, for example, primary air nozzles of the BFB furnace need to be kept in the stock. The furnace of the BFB boiler may consist several hundred pieces of primary air nozzles and it is more likely that if one is need to be replaced then there are others need to be replaced also. Then the amount of spare part, here primary air nozzles, is not that easy to identify beforehand.

6.2 Warranty

During a warranty period the seller of new installation has a responsibility to assure the required functions and then to repair or replace a failed item back to proper condition (Manzini et al. 2010, 406-407).

Usually the supplier gives the warranty that the new installation achieves the required performance values. This warranty is called a performance guarantee and it takes place in the performance guarantee test period after the commissioning. There the supplier shows that the boiler achieves the required performance values, such as the capacity of boiler, the certain heat output, the good total efficiency, low emissions and/or acceptable noise level (Vakkilainen 2013). After the succeed performance guarantee test period the boiler will be relinquished to the customer and after that the boiler is owned and managed by the customer.

Added to this the contract of the new boiler may include the warranty for availability or unavailability. This guarantee period lasts usually year or two years after the takeover of boiler. For instance, the guaranteed availability may be between 97 to 99 percent. Usually time where availability will be calculated does not include planned shutdowns and the supplier reserve annually about two weeks for the planned shutdowns that excluded to the availability guarantee.

Unavailability of the boiler causes expenses due to production losses and maintenance cost come from fault correction. The amount of expense caused by unavailability, depends on, for instance, the function of boiler, the downtime and the causes of the fault. If the function of the boiler is to produce process heat to wider production process, like pulping process, unavailability may affect to the whole process and therefore expenses can increase heavily. When the boiler is part of bigger complex of boilers, like district heat system or as a reserve power, it is possible that unavailability of one boiler does not affect that much to the total production.

If the supplier does not achieve the guaranteed availability the supplier will be pay the penalty to the buyer. The maximum amount of penalty usually is restricted to 10 percent of the value of main contract.

The assumption is that there is no need for unlikely spare parts in first couple of years when equipment run like should to and there are no mistakes in design or manufacturing. Some wear parts may be needed to replace in first of years like gaskets and these should be kept in the stock or then purchased on time before planned shutdown. A reason to keep some strategic spare parts in the stock even those should not be needed during first years, is that a lead time for most parts is that long and down time of the equipment is expensive, that if the equipment face a failure it can be get back in the required condition faster when spare parts are available in the stock. The cost of down time is then smaller than value of the spare part in the stock, but if there is no spare part available and it need to purchase after failure occurs, it is more likely that the cost of down time is multiple than value of the spare part. The situation is the same for the supplier during warranty period when they assure the availability than for the customer when it is under their control after warranty period.

6.3 Spare part classification

The spare part classification helps to understand which spare parts are more important than others and to divide different spare parts to groups. The groups can be based on criticality of spare parts or other factors. Here the focus is on criticality of spare parts. The impact of a shortage of a high critical part may be a multiple of its commercial value. It is important to identify which spare parts have significant effect to the process and which not. This can be done by classification. Criticality can mean different things and it can be viewed as risk of loss of production, environmental safety, personnel safety, lead time, purchase cost, maintenance cost, or demand time.

Traditionally the spare part classification has been done by ABC analysis which is rough but also quick and easy to implement. It can be based on single or multi criterion. (Molenaers et al. 2011, 571.)

Molenaers et al. (2011) implemented a practical spare part classification method based on item criticality in a petrochemical company. The case study was part of the spare parts improvement project in the company. They used a logic decision diagrams and analytic hierarchy process (AHP) to solve multi-criteria classification approach. AHP solved the multi-criteria sub-problems when a decision node integrates several attributes but mainly the logic decision diagrams were used.

The following spare part classification is modification from the study case made by Molenaers et al. (2011). It is simpler than the original one and has been done by using the logic decision diagram (Figure 17) and AHP was left out. The equipment criticality was selected the most important factor in classifying spare parts and that is why the decision diagram starts with this node. The answer for the equipment criticality is leading to the next node in the diagram, which is probability of item failure. The third factor in the analysis was selected the delivery time of spare part. The Table 1 presents the criticality criteria and decision levels for each criticality criteria.

Table 1 Categorical measurements of criticality criteria.

Criticality criteria	Categories Vital	Essential	Desirable
Equipment criticality	Failure causes immediately production losses	Failure causes production losses but not immediately	Failure does not cause production losses
Probability of item failure	≥ 1/year	≥ 1/5 year but < 1/year	< 1/5 year
Lead time (in working days)	> 10	≤ 10 but ≥ 5	< 5

The equipment criticality criteria have been categorized to three classes by using the VED approach. These classes are Vital, Essential and Desirable. Here criticality is the main rule and spare parts are classified to classes 1-4 by following VED decision levels and the logic decision diagram.

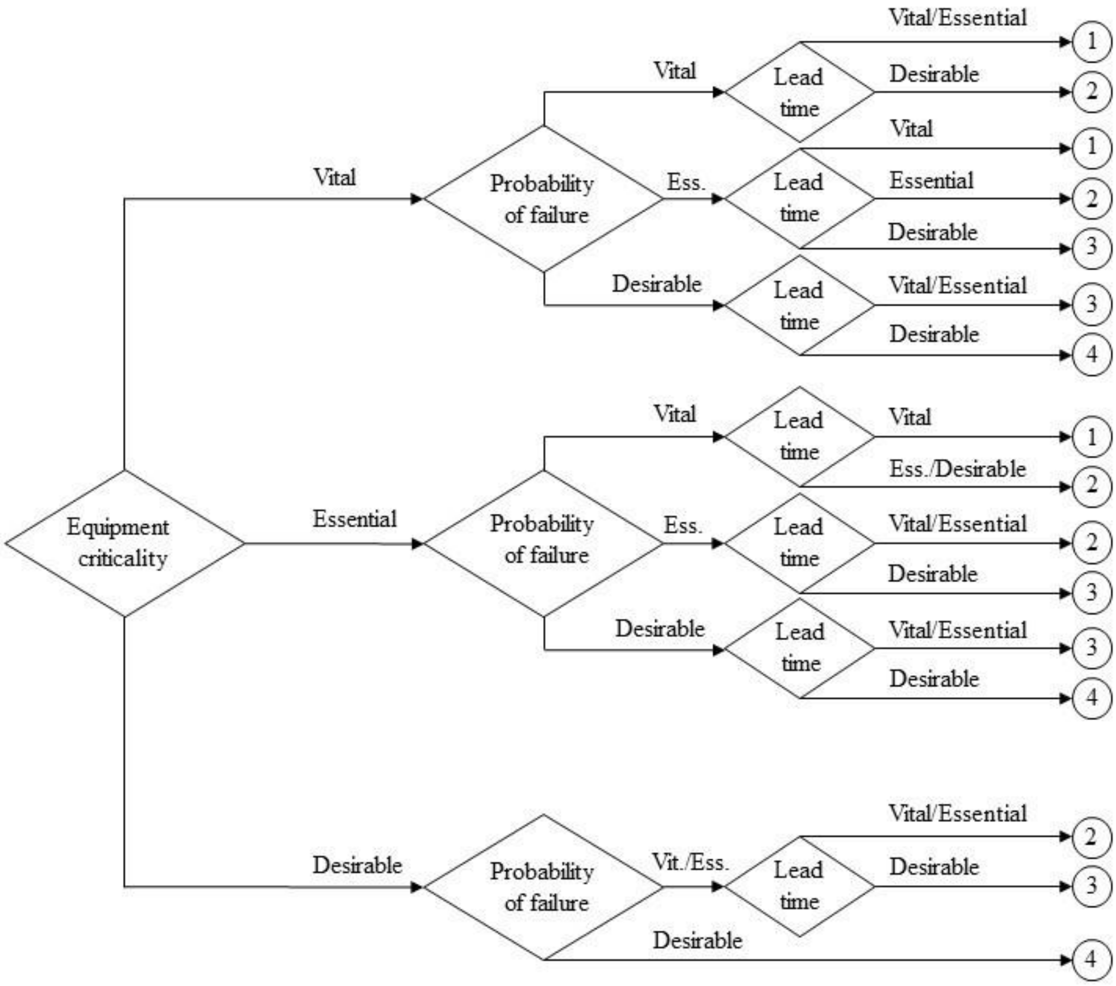

Figure 17 Spare part criticality classification decision diagram.

As a result the spare part criticality has been divided to four classes. The class 1 is high critical level. Items in this class are for critical equipment which causes production losses when failure and probability of failure is plausible in five years. Usually the lead time for the spare part is long in this class. The class 2 is medium and the class 3 low critical levels. The spare parts in these classes can belong to any equipment but the probability of failure and/or the lead time are in the vital or the essential categories. In the class 4 the spare parts are not critical because of possibility of failure is unlikely and the lead time for these spare parts is short.

The knowledge of equipment criticality shall be added to the spare part criticality analysis. The good criticality analysis consist the practical experience of operating and maintenance personnel, and the realized failure data from the plant. Therefore the comprehensive criticality analysis shall not base on one person opinion to avoid subjective result from the analysis. VTT's research report No VTT-R-03718-07 introduces how the risk analysis shall be done in order to reach a risk analysis of good quality. This research report can be used as a framework for criticality analysis as well. The report introduces good working methods when implementing risk analysis. According to the report, follow elements need to be as good as possible to reach quality risk analysis:

- definition of target
- define the subject
- suitable method or methods
- quality of initial information
- competence of analysis manager
- reserve resources
- documentation
- results and execution according to targets
- notification of results.

The standard PSK 6800:2008 is for equipment criticality analysis and it is made for industry uses. The purpose of analysis method that the standard is introducing, is to offer initial information for maintenance planning by analyzing equipment of process. The method is focusing mainly to economic impacts but it is also taking into account personnel safety and environmental impacts to determine critical equipment. As a result of criticality analysis, method calculates the criticality index *K* for a piece of equipment.

$$K = p \cdot \left(W_{\mathrm{s}} \cdot M_{\mathrm{s}} + W_{\mathrm{e}} \cdot M_{\mathrm{e}} + W_{\mathrm{p}} \cdot M_{\mathrm{p}} + W_{\mathrm{q}} \cdot M_{\mathrm{q}} + W_{\mathrm{r}} \cdot M_{\mathrm{r}} \right) \qquad (5)$$

where *K* criticality index

p time between failures

W weighting factor

M multiplier

Subscripts refer to object of impacts: safety risk (s), environmental risk (e), production loss (p), quality cost (q) and repair or consequential cost (r) at the equation 5.

The criticality analysis method starts with definition a scope of analysis and definition of production loss weighting factor. Then other weight factors estimated or at least checked are weight factors given at the standard, usable for studying equipment. Next phase is to choose multipliers which are given at the standard but those are only informative and can be modified. After these the criticality index or its sub-indices can be calculated and equipment will be arranged into order by its criticality index.

7 CONCLUSIONS

Maintenance management has developed and productivity requirement has increased during few decades. High productivity efficiency level requires the process works as well as possible therefore maintaining the process needs to be at good level. Since every processes have own specialites, those need different maintenance strategies. Spare parts are important part of maintenance therefore spare part management has significant role of reach required availability level of the equipment. Since the maintenance outsourcing has increased its popularity, the spare part management would be good business to the boiler supplier.

Power boilers are complex systems and the process includes many different equipment. Detail design of the boiler is done case by case when boilers are mainly different from project to project. Every machine has its own spare parts therefore the whole power boiler system has a large number of different spare parts. Since a demand of the item is hard to forecast and demand cycles are intermittent, spare part management is challenging for the boiler.

Since many spare parts of the power boiler are user-specific and intermittent demand, the stocking policy is not clear. Decision making whether stock spare parts or not, require to taking into account many varies. The factor that the spare part is very critical is not meaning directly that the spare part need to stock or that it is recommended to stock. Stocking is always increasing cost of finishing goods and there is always a risk that the spare part is never needed during its lifetime. The stock keeper needs to find optimal level of the spare part stock by balancing spare part availability, working capital and operational cost.

Maintenance planning of good quality creates spare part recommendation for planned maintenance tasks and these spare parts should be available at the site when needed. For critical spare parts with long lead time that have been decided to not keep in the stock, condition monitoring should indicate replacing needs on time. Spare part demand for unforeseen breakdown is most difficult to forecast. These can be studied beforehand by making criticality analyses but probability of failure affects how those are prepared. If preparing means stocking an expensive spare part, the cost of stocking will be compared to the cost of unavailability of the spare part. If the stocking cost seems to be higher than the unavailability cost, then the spare part is not decided to keep in the stock.

Since the knowledge of equipment criticality for the process is the base of the spare part classification, at the first phase of the classification the focus is on equipment criticality. The boiler consist several subsystems, therefore it is important to put in order all equipment to see which equipment are most important to the process. If the target is to reach all spare part for the boiler at the same time it consist so much work to be done that it is not effective and needs much resources to be done. The better way is to begin from most important equipment and then start to research spare parts of those. Then the spare part business gets results faster than the research of all spare parts for all equipment of the boiler.

It is recommendable to make criticality analysis case by case for equipment of the boiler because of factors of boilers usually varies from project to another. Of course one study case may show guide lines which equipment are more critical than others generally for boilers but individual criticality analysis shows specialties of the specific boiler. Also it is easier to analyze one case at the time when factors are not varying than to try creating an overall analysis generally for the boiler type. Factors are varying so much for different boilers therefore it is hard to create the general criticality analysis which covers all these variations. The result from a case study analysis would be good to compare to others case study analysis to find common repeating results even when factors are not the same.

Since a starting point, resources and analysis object varies for all cases, it is hard to say which criticality analysis model suit best for power boilers. Also criticality analysis methods can be modified to come up expectations. For example, the criticality limit at the standard PSK 6800 is not calculated but it is decided to suit for the objects level. Then the criticality analysis author decides which items are above of criticality limit and which are not. The criticality analysis needs to be suited for the objects properties but this also makes possible to affect the result of criticality analysis. Because of this the criticality analysis shall be done as good quality as possible. The best is that authors are well motivated and manager has a good knowledge of criticality analyses. Also the target need to be define at the beginning and it need to be followed during the criticality analysis. The documentation and information others of the result is significant to review how the analysis succeed and compare the analysis for other objects in future.

It is as important to find most critical equipment as to review results of the criticality analysis. The boiler supplier shall cooperate with customers to get operating data and failure details of boilers. Realized operating data and the result of critical analysis shall be reviewed and compared to each other to see which equipment cause most critical faults to the process and are these same as the criticality analysis. This how it is possible to see was the criticality analysis useful and how truthful the analysis was.

When weight has been at the equipment criticality analysis at the first phase on the spare part classification, the focus moves to spare parts of the most critical equipment at the next phase. Lead time and price of the spare part is easy to define with OEM and sub-suppliers. Spare parts reliability is harder to define but if the timeframes of the probability of failure is wide enough it should be possible to define with well experience personnel. Used timeframes could be for example at least one failure at the year, at least one failure during five years but not more than one failure per year and one failure more than five years.

The spare part classification is easy to make by following decision diagram after the equipment criticality, probability of failure and lead time are defined. These factors are only for example and other factors can be added to decision diagram if needed. Other useful factors are price of the spare part, cost of downtime, specificity, shelf life and repairability.

Full criticality analysis as same kind of equipment criticality analysis but for spare parts would be too heavy to implement and/or it took too much time and resources. Benefits of full criticality analysis barely meet with used resources to go through the full analysis at least at the boiler supplier point of view. Since the base of the spare part classification is equipment criticality, lighter analysis tool would be specific enough to analyze spare parts when equipment criticality analysis is good quality.

Even the target of the study was to create a methodology for defining a scope of strategic spare part package offered during the new BFB boiler quotation phase; the target was not fully reached. The biggest problem is that the scope of new boiler is not totally decided at the quotation phase. Also there is not much time to define the scope of spare part package at the quotation phase which limits how the process can be done. It is not possible to make a criticality analysis of equipment or spare parts at the given timeframe during quoting the spare part package therefore it cannot be used. However it is recommendable to make the criticality analysis for some already delivered boiler to see if there are equipment which usually are critical to the process. This how the spare part business gets guidelines which equipment shall be focusing and then defines spare parts for those.

The original equipment manufacturers could have some requirements for available spare parts at the site during availability warranty period. Requirements force the boiler supplier to have these spare parts at the site and also in the scope of spare part package. At the beginning the thought was to collect these requirements by interview OEMs so at least these spare parts are in the scope. The problem was that mainly these requirements vary case by case and that is why OEMs could not give those.

The study contained OEMs interviews but the inputs of those were not success. Interviews were open discussion events and they did not have a strict structure. A target was to improve knowledge of spare parts and get more information of maintenance related factors to help spare part management. As a result, OEMs did not give any new information rather the same information was given as a quotation phase normally. This may mean that the suppliers have not focus on spare parts either and they do not have the information like time between failures and most typical failure causes, or then they are not willing to share the information with others.

If the boiler supplier works as a link between the customer and OEMs and they want to develop the spare part management overall, the boiler supplier should find the way to get more information from OEMs’ spare parts. The way could be some kind of cooperation between the boiler supplier and OEMs which benefit both operators. When the boiler supplier find the way to help OEM’s work and give more sales to both party, the OEM could see the reason to share its knowledge of spare parts.

The customer may wonder why they should contact to the boiler supplier instead of OEM, but the boiler supplier can justify their position between the customer and the OEM by offering better spare part management solutions and easier way to operate for the customer.

This helps a lot of the customer’s work to manage spare parts when they are able to contact only one operator instead of several spare part operators.

It can be said that spare part management is way to handling risk levels. If the risk level is wanted to keep at low level, spare part availability need to be higher than in the situation when higher risk level is acceptable. The low risk level is more expensive to keep than the high risk level while more spare parts need to be available. Some risks are not highly probable when it need to be carefully defined should these risks need to be prepared. The boiler supplier needs to define which risk level is acceptable for them during they are responsible for the boiler while the customer needs to define which risk level is acceptable for them during the lifecycle of boiler. The acceptable risk level varies case by case.

8 SUMMARY

Energy generation industry is very asset-intensive industry. Productivity and availability requirements have increased while competition and quality requirement have increased. Maintenance has a significant role that these requirements can be reached. Large power boiler are user-specific therefore features of the boiler varies from project to project. Equipment have been designed to follow the customer’s requirements therefore spare parts are mainly user-specific also. Since the asset-intensive industry strongly depends on the availability of its technical equipment, availability and continuous operability of the production system depends strongly on availability of spare parts.

The study is mainly a literature review. It was done cooperation with a company which provides boiler technology solutions and the company’s own experts were interviewed for the study. Also some main original equipment manufacturers were interviewed. The study is in two parts: theoretical aspects are introduced at the beginning and then spare part management and the spare part package are discussed at the final part.

Topics in the theoretical review are maintenance, failure mechanisms and a bubbling fluidized bed (BFB) boiler. Expectations around maintenance have been matured and nowadays companies understand that maintenance has an effect to the safety, the environment and the quality of the output. Also companies is striving high availability to the item. Therefore the maintenance has developed many different strategies to achieve these objectives.

There is always a reason why item is injured and a cause of failure can be due to mistakes in design, manufacturing, installation, handling and/or maintenance. Failure is physical event and it has a mechanism. There are several failure mechanisms and mechanisms vary depending on different variable of items such as item type, function of the item, material, and operating environment. Corrosion is one of the most common failure mechanisms that occurs in metal structures.

Today BFB combustion is widely used combustion technology because as a fuel can be used many different types of fuels with high combustion efficiency. Also emissions control can be done easily by restrict combustion temperature or by injection of lime directly to the furnace.

Spare part management is way to handling risk levels. If the risk level is wanted to keep at low level, spare part availability need to be higher than situation when higher risk level is acceptable. The low risk level is more expensive to keep than the high risk level while more spare parts need to be available. Some risks are not highly probable when it need to be carefully defined should these risks need to be prepared.

Usually the customer, who is investing to the new boiler, chooses the main supplier who manages the whole project on behalf of the customer. The main supplier is managing then also equipment deliveries from other equipment suppliers which not belong to the main supplier's main knowledge. Spare part management is challenging especially to the boiler supplier since they need to manage their own spare parts but also spare parts of equipment supplied by other suppliers.

The end user of spare part hereafter the customer has other interests than the supplier of spare part has for spare part management. It depends on customer's maintenance strategy how important high availability of spare parts is. For some customers availability of the process is really important therefore they are strongly focusing to improve their operation and maintenance functions continuously. Conversely some customers try to operate the boiler as minimum resources as possible. They only maintain the item when failure occurs. There are also differences in customers' knowledge to operate and maintain the boiler which has an effect to maintenance levels and needed support from the outside of organization.

For customer it is easy to use the boiler supplier as a contact to original equipment manufacturers (OEM). The boiler supplier is an agent for the customer and supply spare part also from other manufacturer not only their own spare parts. The boiler supplier wants to serve the customer as well as possible but stocking of spare parts is risky since user-specific design and intermittent demand. The OEM has knowledge of its own products therefore the OEM's opinion of recommended spare parts impacts which spare parts the boiler supplier recommends to the customer to purchase and which spare parts the customer probably is going to purchase. Also the OEM decides which spare parts need to be purchased with machine that their availability warranty holds.

Spare parts can be divided roughly into two groups: user-specific and standard parts. The user-specific parts are used only of one or two business plants, while the standard parts are used more than two different business plants. From maintenance point of view spare parts can be divided to repairable parts and non-repairable parts or consumables. Repairable parts will be repaired after taken out and sent to the stock to wait next usage. Non-repairable parts or consumables also called wear parts, are not possible to repair technically or economically therefore non-repairable parts are discarded after taken out and the part was replaced by a new part. Factors of spare part such as value and delivery time, differs a lot. Because the large scale boilers are usually customer specific, spare parts are also customer specific mainly. When spare part is not standard part, it is usually expensive and lead time is long. The effect is that spare parts will be manufactured only for need and lead times are long.

Downtime of the equipment is expensive in the asset-intensive industry but the stocking causes also costs and decision maker need to find balance between spare part availability, working capital and operational costs. There is always a possibility that the spare part is never needed during its lifetime, that has been decided to keep in the stock. If spare part is decided to not keep in the stock, then the condition monitoring is important operating and maintenance task and it forecast when the spare part needs to be replaced. Long lead times need to be take into account in maintenance planning and the demand of the part needs to be forecasted.

Even the spare part would be extremely critical to the process availability and its lead time is really long, but probability of failure is low or other words part is very reliable, it is more likely that the stocking causes more costs in long time period than the downtime in unforeseen breakdown. Especially then the price of spare part is really high. Therefore the item criticality shall not been used as an only factor when decide which spare parts should be available at the stock.

The boiler supplier is offering a spare part package via the new equipment delivery. It is a combination of recommended spare parts that are needed to assure the required productivity during a guarantee period by high availability of spare parts. The purpose of the spare part package is to back up the guarantee period by shorting unplanned shutdowns and to achieve required availability of the boiler.

The spare part classification helps to understand which spare parts are more important than others and to divide different spare parts to groups. The groups can be based on criticality of spare parts or other factors. The focus was on criticality of spare parts in the study. The impact of a shortage of a high critical part may be a multiple of its commercial value. It is important to identify which spare parts have significant effect to the process and which not. This can be done by classification.

The knowledge of equipment criticality shall be added to the spare part criticality analysis. The boiler consist several subsystems, therefore it is important to put in order all equipment to see which equipment are most important to the process. The good criticality analysis consist the practical experience of operating and maintenance personnel, and the realized failure data from the plant. Therefore the comprehensive criticality analysis shall not base on one person opinion to avoid subjective result from the analysis. Since a starting point, resources and analysis object varies for all cases, it is hard to say which criticality analysis model suit best for power boilers. Also criticality analysis methods can be modified to come up expectations.

Full criticality analysis as same kind of equipment criticality analysis but for spare parts would be too heavy to implement and/or it took too much time and resources. Benefits of full criticality analysis barely meet with used resources to go through the full analysis at least at the boiler supplier point of view. Since the base of the spare part classification is equipment criticality, lighter analysis tool would be specific enough to analyze spare parts when equipment criticality analysis is good quality.

One of the biggest problems is that the scope of new boiler is not totally decided at the quotation phase. Also there is not much time to define the scope of spare part package at the quotation phase which limits how the defining a scope can be done. It is not possible to make a full criticality analysis of equipment or spare parts at the given timeframe during quoting the spare part package therefore it is not recommended to use. However it is useful to make the criticality analysis for some already delivered boiler to see if there are equipment which usually are critical to the process. This how the spare part business gets guidelines which equipment shall be focusing and then defines spare parts for those.

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