LAPPEENRANTA-LAHTI UNIVERSITY OF TECHNOLOGY LUT
LUT School of Engineering Science
Master's Program in Biorefineries

Hannareetta Aalto

RECLAMATION HANDLING PROCESS IN SMELT SPOUT DAMAGE CASES AND MECHANISM BEHIND THE DAMAGES

Examiners: Professor, D. Sc (Tech) Tuomas Koiranen
Master of Science (Tech) Johanna Iivonen

ABSTRACT

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Reclamation handling process in smelt spout damage cases and mechanism behind the damages

Master’s Thesis

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89 pages, 25 figures, 16 tables and 4 attachments

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Keywords: smelt spout, reclamation, continuous improvement

The purpose of this Master Thesis was to establish descriptions about the most common damage types on smelt spouts and to recognize circumstances which lead to damages. Events causing premature damages and events firing the reclamation process were identified. In this thesis purpose is to improve reclamation process flow in the client company by making observations about the events which lead to reclamations, and purpose is to describe reclamation handling in the company.

Process descriptions are based on the results presented in written studies and information gathered for the client company, which has been presented in the reclamation reporting. Analysis tools are used in conjunction with segmentation and tabulation to handle of reclamation and damage types. Handling of reclamations is studied also by using the most common root cause analysis tools such as Fishbone diagram, Issue Tree and A3-tool.

It can be found out from the analyzed data that the most common reason for smelt spouts failures is a cracking which is caused by thermal fatigue. It covers over 70 % of the smelt spout failure cases. The procedure how to handle smelt spouts related reclamation process from receiving customer claim to the closing reclamation case was created. The guidelines how to utilize continuous improvement and lessons learned features on the reclamation cases was added to the reclamation process description.

TIIVISTELMÄ

Lappeenrannan-Lahden teknillinen yliopisto LUT
LUT School of Engineering Science
Master's Program in Biorefineries

Hannareetta Aalto

Reklamaatiprosessi sulakourujen vauriotapauksissa ja mekanismit vaurioiden takana

Diplomityö

2021

89 sivua, 25 kuvaa, 16 taulukkoa ja 4 liitettä

Tarkastajat: Professori, Tkt Tuomas Koiranen
DI Johanna Iivonen

Hakusanat: Sulakouru, reklamaatio, jatkuva parantaminen

Tämän diplomityön tarkoituksena on laatia kuvaukset yleisimmistä vauriotyypeistä sulakouruissa ja tunnistaa niiden syntymiseen vaikuttavat olosuhteet prosesseissa, jotka johtavat sulakourun vaurioitumiseen ennakoitua nopeammin ja laukaisevat reklamaatioprosessin. Diplomityössä on tarkoituksena myös parantaa reklamaatioprosessin kulkua toimeksiantajayrityksessä tekemällä huomioita yleisimmistä reklamaatioon johtavista tapahtumista ja niiden käsittelystä yrityksessä.

Prosessikuvaukset pohjautuvat kirjallisissa tutkimuksissa esitettyihin tuloksiin ja yritykselle kertyneeseen tietoon, joita on esitetty reklamaatioraportoinnissa. Reklamaatio- ja vauriotyyppien käsittelyssä käytetään hyväksi analysointityökaluja yhdessä segmentoinnin ja taulukoinnin kanssa. Reklamaatioiden käsittelyä tutkitaan myös yleisimpien juurisyyanalyysityökalujen kuten kalanruoto -diagrammi, päättelypuu ja A3-työkalujen avulla.

Analysoidusta datasta voidaan päätellä, että yleisin sulakourun vauriotilanne on halkeama tai pinnan säröily, jonka on aiheuttanut lämpöväsyminen. Tällainen vaurio kattaa yli 70 % tutkituista sulakouruvaurioista. Reklamaatioiden käsittelyyn sulakouruihin liittyvissä tapauksissa luotiin ohjeistus, joka kattaa prosessin vaiheet reklamaation saapumisesta toimeksiantajayritykseen aina reklamaation sulkemiseen asti. Lisäksi reklamaatioiden jatkokäsittelyyn jatkuvan parantamisen ja oppimisen kautta luotiin prosessikuvaus.

PREFACE

I would like to thank all representatives of Valmet Technologies, who has been involved in this process of doing this Master Thesis and give their knowledge to this work. Specially I like to thank my supervisors Johanna Iivonen and Hanna Niittyniemi about their support during this process. I would also like express my gratitude towards professor Tuomas Koiranen from LUT University about supervising and examining this work.

Thanks to all my team members in Energy Spare Parts team, who has supported and cheered me up during this tight scheduled Fall. Specially thanks to Susanna Kirjava about grammar checking and to Niko Liiri and Sara Heikkilä about their Word support. Finally, I want to thank my husband and family about all their endless support during my Master studies in Lappeenranta.

Tampere, January 5th, 2021

Hannareetta Aalto

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a	$a_1 + a_2 T$
a_1	0.3176
a_2	0.002268
b	$b_1 + b_2 T$
b_1	-0.01394
b_2	-0.003069
η	Dynamic viscosity
$\boldsymbol{\lambda}$	Thermal conductivity
μ	Viscosity
ρ	Density
S	Sulfidity
X	the dry solids concentration

A3	Root cause analysis tool on A3 size
aq	aqueous solution
ASME	American standard
BFB	Bubbling fluidized bed boiler
CFB	Circulating fluidized bed boiler
EMEA	Europa, Middle East, Africa
EN	European standard
HSE	Health, safety, environment
ISO	Internal Organization for Standardization
KMW	Krauss-Maffei Wegmann
MSM	Mill Sales Manager
MT	Magnetic particle inspection
NDE	Non- destructive Evaluation Techniques
OPERA	Root cause analysis tool
PDCA	Plan, do, check, act
PT	Liquid penetrant inspection
RT	Radiographic inspection
s	solid
UT	Ultrasonic inspection
VT	Visual inspection

1. INTRODUCTION

This section introduces the background of this Master Thesis and the main objectives and methods of this research.

1.1 Background

This Master Thesis has been made together with Valmet Technologies Oy's Technology Unit, Energy Spare Parts. Also, other Technology Units have been given lot of help and expertise about smelt spouts. The subject for this Master Thesis was chosen because smelt spouts are very important parts of the chemical recovering process in the pulp mills and any damages of spouts can cause serious profit losses and possible danger situations. Smelt spouts are one of the key technologies in Valmet's Energy Business. Usually smelt spouts are changed in every 12 months in regular yearly shutdowns. If a smelt spout gets damaged, it must be replaced which leads to unexpected shutdown of whole pulp mill. That can create 1-2 days loss of pulp production. In bigger pulp mills couple days production loss can cost multiple millions. Smelt spouts are a critical component for pulp mills but also for companies who produce and design them. In designing of smelt spouts even the slightest changes can make a huge difference in the customers production mill and that is why this product needs extra attention.

Recovery boilers are nowadays driven with heavy load and dry solid matter of black liquor has been increased when evaporators are been developed at the same time. Also, other circumstances in the pulp mills are varying a lot. Such as driving methods, content of the raw materials and the structure of the boilers all affecting to chemical recovering process. Also, renovations and upgrades of the boilers are affecting the smelt spouts because the smelt flow to the smelt spout can be different compared to old circumstances. All these things are creating unique circumstances to every boiler.

One target of this Master Thesis is to collect all the available data of received reclamations which are related to smelt spouts and create a material which will help in the future with similar reclamation cases. Target is also to develop reclamation process in the company and create a standard process, which will be followed in every reclamation case concerning smelt spouts.

1.2 Research Objectives

The purpose of this Master Thesis work is to recognize the most important factors inflicting damages in recovery boilers' smelt spouts and thus shortening the lifetime of smelt spouts. Those damaging factors will be categorized, and root causes will be analyzed. Purpose of this analysis is to create material and templates, which will help reclamation handling in the future cases which have similar problems. These materials will be shortening the time and lowering effort which is used to handling reclamations with similar failures.

The idea is to improve and define more detailed structure for reclamation handling process in the company. There is a couple general of guidance's for reclamation handling process in the company's quality system but not specific one for the smelt spouts' reclamation handling. It has been noticed that there is a need for separate, item specific, reclamation handling process for smelt spouts because they are of the key products in the Energy Business.

1.3 Research Methods

Main research methods are segmentation and tabulation of the collected reclamation material from the archive. Reclamation material is collected from the archives and analyzed with the help of client company's smelt spout experts. Data is handled and collected only from the past 10 years which is helping to limit of the available information. This kind of definition is mandatory to be made because there is so much material available for the smelt spouts.

In this Master Thesis it is not purposed to introduce any specific case or damaging mechanism particularly precisely, the purpose is to create data which, will help with reclamation cases in the future. The research will go through the root cause analysis tools which are in use in the company. The idea is to compose the most useable method handling the reclamations. The presented root cause analysis methods are Pareto-analysis, Fishbone diagram, 5x Why-method, PDCA-method and Issue Tree-method.

1.4 Thesis Outline

The client company, where this Thesis has been made, is first presented in the theory section. Section two focuses on recovery boilers and recovering process. The main chemical and mechanical processes will be presented together with recovering cycle of pulp mill chemicals. The most important chemical substances, black liquor and smelt, are handled in the separate sections.

There is a complete section about the smelt spouts, where the general structures and functions together with the types are presented. Each main cause factor for smelt spout damaging area presented in separate sections as well as theories behind the events. Some examples about typical places for each damage are also presented.

In the reclamation section, the phenomenon itself is first presented and then the key process steps to handling it is introduced. Pareto-analysis and Fishbone diagram are presented as theories or tools. These are common in reclamation analysis phases. Tools and models for the root cause analysis are presented and examples how to utilize those are given. Common reclamation handling process description is used as a reclamation handling tool for creating a new model for specially smelt spout related reclamations.

Collected data is analyzed through the main categories of root causes by using segmentation and Pareto-analysis. Examples about root cause analysis by using presented tools are given with all main failure reasons. Specific reclamation process for smelt spouts and needed organization together with responsibilities, will be presented. Finally, the concept of continuous improvement is presented and general rules how to proceed with that on the business line level are introduced.

2. VALMET

This section provides a general introduction to the client company and introduces the main solutions and services what they provide to their customers.

2.1 In General

Valmet is a Finnish based worldwide company which has been notified in Helsinki stock. Valmet's Headquarters is in Espoo, Finland. Valmet has four business lines and five areas which serving customers around the globe. Business lines include Automation, Paper, Pulp & Energy and Service business lines. Areas are EMEA, Asia Pacific, China, South America and North America (Valmet 2020c). Valmet provides services for paper, pulp, tissue and board industries and it is one of the leading companies in its business field. Valmet services includes technologies, automation, maintenance, plant improvements and spare parts for paper, pulp, tissue and board industries. Valmet delivers complete mills which are customized for meeting their customer's needs (Valmet 2020c). Valmet's roots are in Finland and company's roots are more than 200 years old. Valmet as it is known nowadays was reborn in 2013 when demerging from Metso. Valmet is Finnish based global company which has employees in over 30 countries worldwide and it has been merged with several companies during the years. (Valmet 2020c).

2.2 Energy business in Valmet

Pulp and Energy Business line is one of the four main business lines in Valmet. Pulp and Energy Business line provides technologies for customers in energy and pulp production, biomass conversion and emission control. Valmet's Pulp and Energy Business line delivers worldwide their solutions for complete pulp mills and power plants for the customers, who are mainly pulp, heat and power producers around the globe (Valmet 2020a). Energy related portfolio in Valmet includes boilers, environmental systems and rebuilds. Other products for pulp customers are solutions for wood and pulp handling, recausticizing technology, evaporation systems, lime kilns technology and lignin extraction systems. Other solutions for energy customers are flue gas cleaning for boilers, marine emission control, different kind of burners and pyrolysis plants (Valmet 2020a).

Service Business line in Valmet serves customers with existing boilers with maintenance, field service, mill improvements and spare part services. Over the years Valmet has merged with many boiler manufacturing companies such as Götaverken, Tampella, KMW and Noviter and it is now serving also customers with those boiler solutions (Valmet 2020b).

2.3 Valmet boilers

Nowadays Valmet has three main types of boilers which they are designing and supplying; recovery boilers, circulating fluidized bed and bubbling fluidized bed power boilers. Recovery boiler is an important part of kraft pulp mills, and the main purposes of a recovery boiler is to recover pulping chemicals and generate power to the whole mill complex. Recovery boiler and its main functions are introduced later in this Master Thesis. BFB and CFB are power boilers designed for combustion of mainly bio-based materials. Power boilers can generate power or heat to the mill. Generated power can be utilized to the local community or to the customers. Valmet also provides boilers for burning waste to the energy for community (Valmet 2020a).

BFB is an abbreviation for a bubbling fluidized bed. A BFB boiler has a sand bed which also includes fuel ash. Bed height is between 0,4-0,8m. Fluidizing air is supplied to the bottom of the bed which creating bubbling effect in the furnace. BFB is suitable for wet fuel combustion such as wood and bark wastes. Fuel is crushed and fed to the boiler from the top of the bed. Bed temperature is usually between 700-1000℃ but that depends on the load and fuel. Furnace is cooled with water circulation and fluidized air is distributed evenly to maximize the combustion reaction (Huhtinen & Hotta 1999, B233). In Figure 1 is presented the general view about the BFB boiler and is introduced boiler's most important parts.

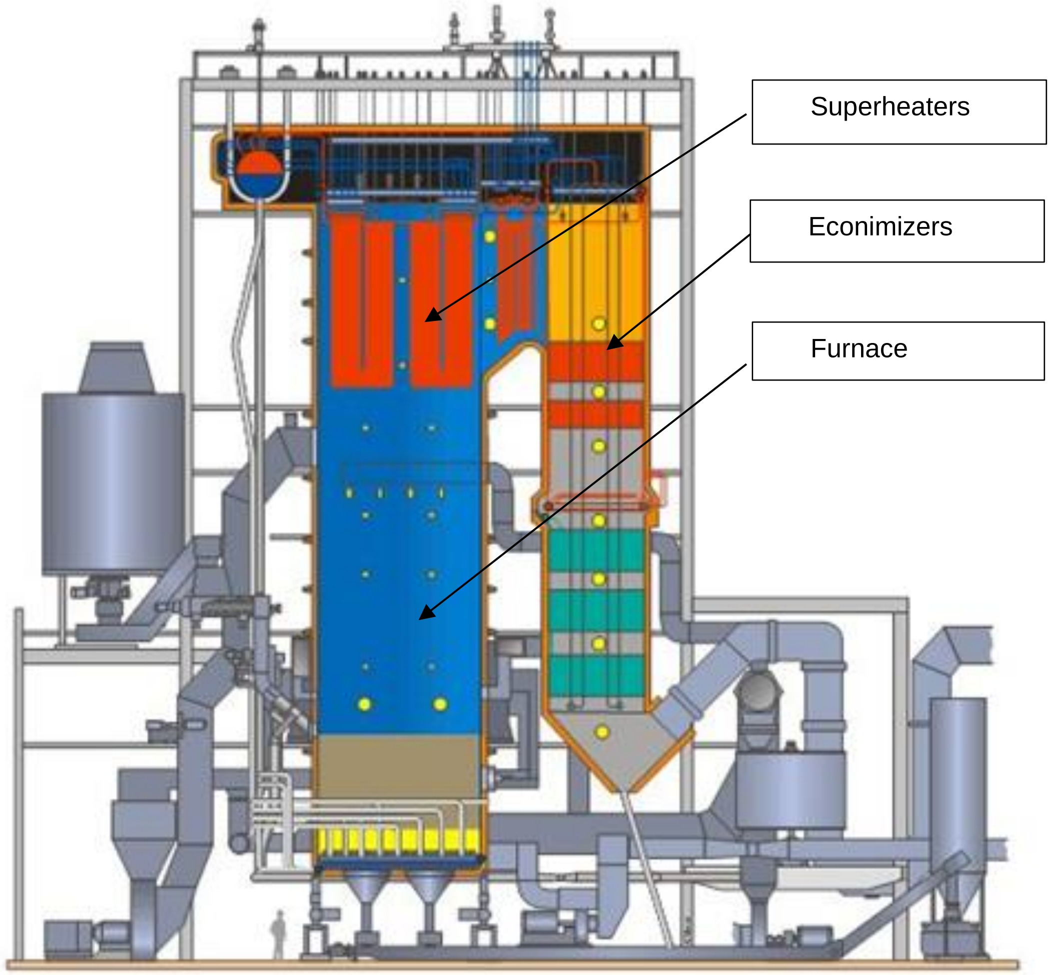

Figure 1. BFB boiler. Adapted and modified (Metso 2010)

CFB is an abbreviation for circulating fluidized bed. Main components in a CFB boiler are a furnace and a cyclone unit, which captures bed material, unburned fuel and other particles and returns those back to the furnace. Basically, bed material is constantly circulating and ensuring the even combustion in the furnace. Fuel feeding system in CFB boilers is similar to BFB boilers and furnace walls are cooled with water circulation as well. Good heat capacity and solids loading ensure stable combustion of moist fuels like sludge (Huhtinen & Hotta 1999, B234).

Valmet and Tampella has manufactured close to 600 boilers over the years and Götaverken has manufactured over 1000 steam boilers in over the years. Typical use age of boiler is nowadays 30-40 years. Together with other merged boiler manufacturers and their boiler models, Valmet has wide scope of boilers which need maintenance, spare parts and support with their yearly shutdowns (Valmet 2020b).

3. RECOVERY BOILER

Recovery boiler is an important part of a sulfate pulp mill's chemical circulation. The main functions of the recovery boiler are producing of steam by burning black liquor, reduction of chemicals from pulp production and minimizing waste streams in the mill (Vakkilainen 2008, 86). The typical lifetime of a recovery boiler is 30-40 years nowadays and because of quite a long lifecycle the development and installation of new technologies for recovery boilers is relatively slow. Recovery boilers became more common in sulfate pulp mills during 1930's and recovering technology was revolutionized around Second World War (Vakkilainen 2014). Nowadays the capacity of pulp mills has become big enough to cost effectively collect of pulping chemicals. The chemical recovery efficiency of sulfate pulp mill has improved compared to the old sulfide method which was previously used as the main method. The amount of sulfate pulp mills and recovery boilers did increase significantly in the middle of 20th century when technology was evolving rapidly (Vakkilainen 2014, 19–22.)

Recovering technology has a long history. High prices of needed chemicals in pulping process have increased the interest towards chemical recovering. Early recovery technology was only focusing on the chemical recovery. The electricity generation came along with the modern technology relatively recently. Nicholas LeBlanc discovered a process, where soda was produced at reducing furnace. After that discovery, recovering technology started to evolve (Vakkilainen 2014). In the first recovery boilers, fouling was a major problem. Technology improvements such as soot blowing system and wider spacing innovations in superheaters changed the situation with fouling. Later, technologies such as Electrostatic precipitators were introduced to control chemical loses in recovering process and to the make process more cost efficient (Vakkilainen 2014).

Improvement of evaporation technology has made it possible to reach higher dry solid content, which has increased the maximum design capacity of recovery boilers. Main principle is that combustion of black liquor, which is organic matter, generates steam which is utilized in other parts of pulp mill. The biggest impact to recovery boiler development in recent years has been the demands with environmental and efficiency requirements (Vakkilainen 1999, B96). Today's modern recovery boiler is an energy generator and a chemical recycler, which also provides sellable energy to the mill. New processes such as additional firing, lignin recovery and hemicellulose removing will create new technology improvements also in recovery boilers (Vakkilainen 2014, 14). In Figure 2 is presented the general structure of recovery boiler and names the most important parts of the recovery boiler.

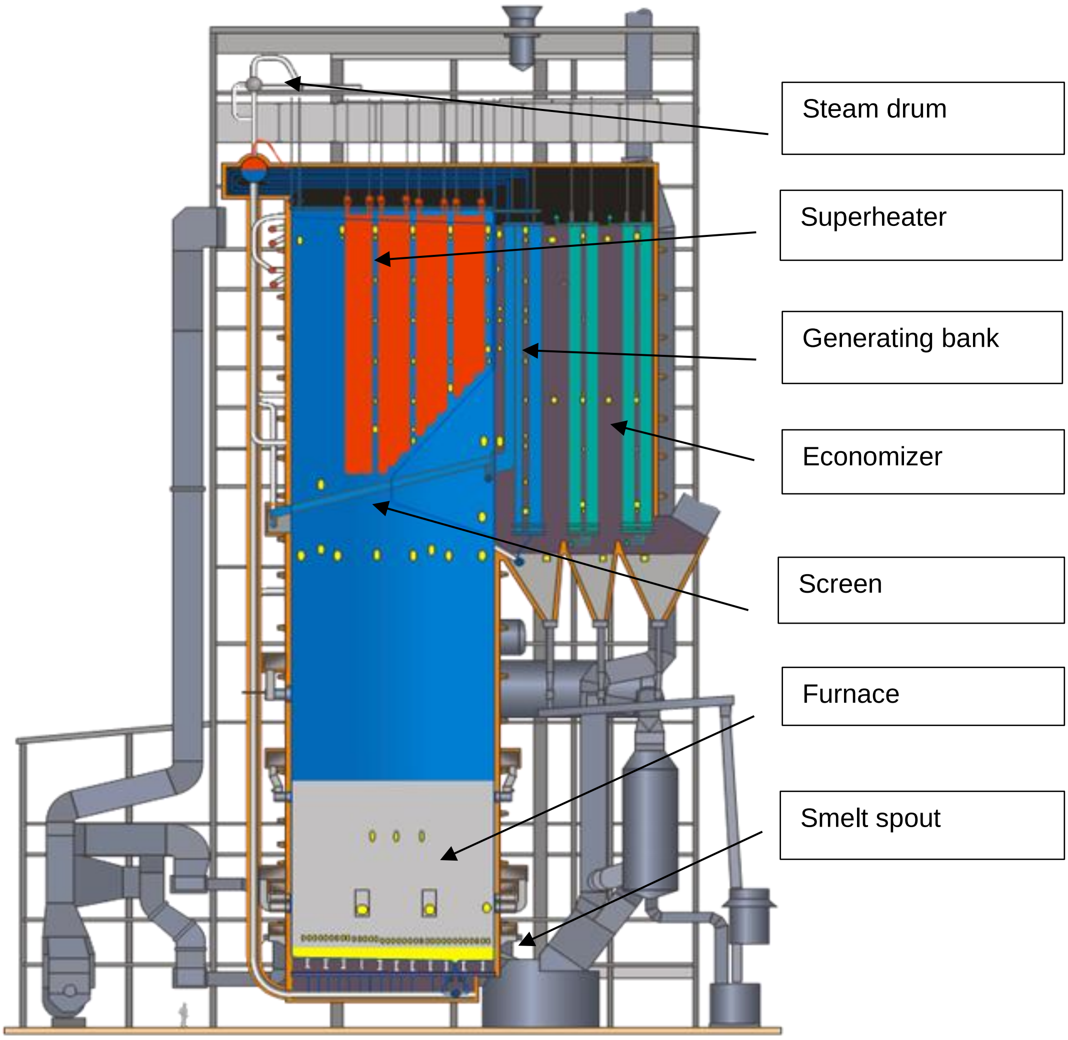

Figure 2. General structure of recovery boiler. Adapted and modified (Välimäki et all. 2010).

3.1 General structure of recovery boiler

Today's recovery boilers are usually two drum design and typical designing values are steam pressure 85 bar and temperature 480°C. Because the long lifetime of a recovery boiler, two drum design is still predominant model in the world, but the new boilers are designed with one drum model. In recovery boiler, there is typically three level air intake and stationary firing system. Also, four level air intakes in recovery boilers are common ones. This type of boiler has a screen, which protects superheaters from carry over and radiation of the furnace (Vakkilainen 1999, B97). The main components of a recovery boiler are a furnace, a screen, superheaters, a generating bank, economizers and a steam drum. Air enters the recovery boiler via air ports which are in different levels of the boiler. Air levels have different functions in the recovery boiler process. Black liquor enters to the recovery boiler furnace via black liquor guns and smelt together with combustion residue exits from furnace via smelt spouts (Vakkilainen 1999, B97).

In the future recovery boilers steam pressure and temperature will keep increasing. In the future the designing of superheaters will allow optimum heat transfer and superheaters are protected by bullnose. When recovery boilers' pressure and temperature are increasing the needed amount of air ports is decreasing at the same time (Vakkilainen 1999, B99). In Figure 3 is presented the main structure of upper part of the recovery boiler.

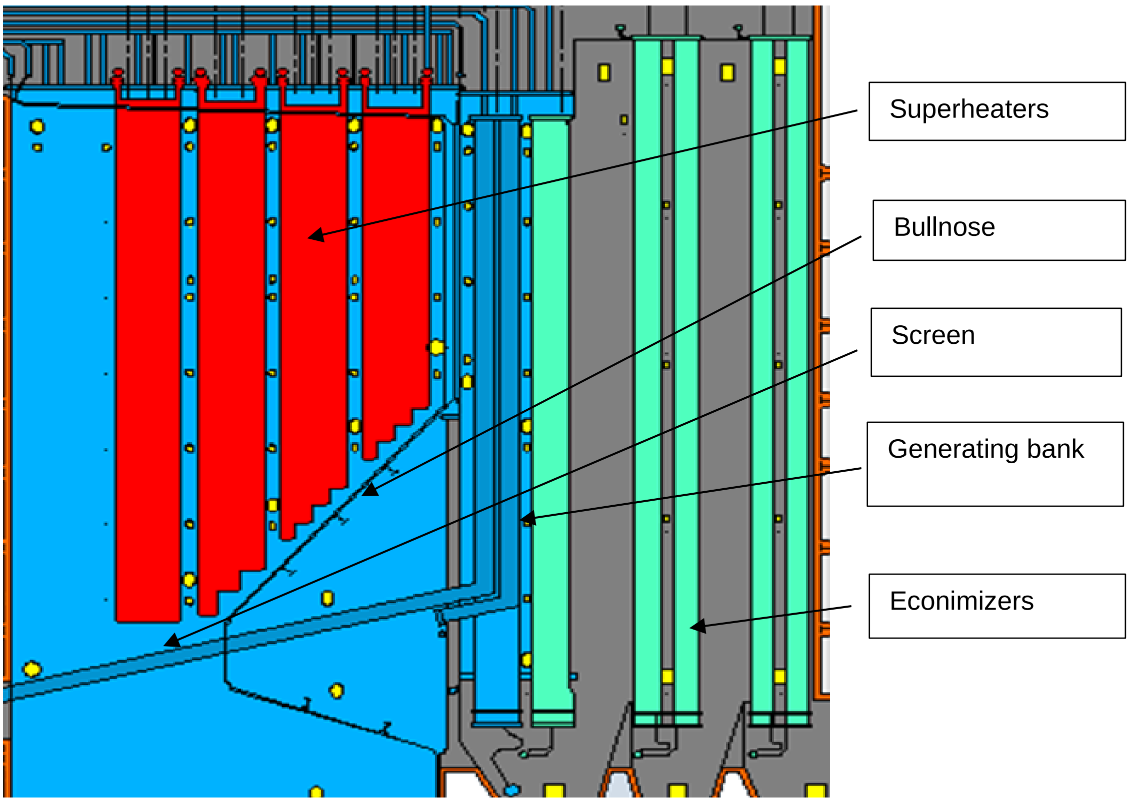

Figure 3. Upper part of recovery boiler. Adapted and modified (Aikio 2014a)

Effective air circulation is key element to successful combustion. Air system in recovery boilers including ducts, air heaters, dampers, blowers and measuring devices (Aikio 2014b). Those control air inlet to the boiler. Flue gas system is used to transfer combusted material out of the furnace through the emission control devices. Flue gas system usually includes ducts, dampers, scrubbers and an electrostatic precipitator. Nowadays all flue gases are cleaned before exiting to the sky and stronger gases are burned by using specific burners (Vakkilainen 1999, B122).

In recovery boilers, water and steam circulation’s main functions are cooling floor tubes and creating energy. Feed water system starts from feed water tank which feeds low oxygen water through pumps, valves and the deaerator to the economizers (Aikio 2014a). In the economizers water is heated almost to the boiling point. Then it flows through the sweet water condenser to the steam drum. After that downcomers are feeding water to the furnace walls where most of the evaporation is happening. In the steam drum steam is separated from the water. Saturated steam goes from the drum to the superheaters and after that to the steam turbine creating energy (Vakkilainen 1999, B123).

Limiting factor in recovery boilers is fouling which happens because of the inorganic salts, char fragments and liquor particles are enter the upper furnace and accumulate to the parts which are colder than flue gases temperature. Layers of unwanted particles on the surfaces on the upper part of the boiler block the flue gases free exit way and cause the fouling (Huhtinen & Hotta 1999, B278). Soot blowing system prevents the fouling in the boiler. In modern boilers there is automatic control system which takes care of soot blowing operation. Soot blower uses steam or compressed air to clean superheaters. Soot blowing is normally constant and for that purpose compressed air is expensive alternative. Steam is mainly used because it is available from the steam generating system (Huhtinen & Hotta 1999, B278).

Typical design and dimensioning values for a recovery boiler in the designing phase are dry solids capacity, gross heat value of black liquor, main steam conditions, feedwater inlet temperature and flue gas outlet temperature. The main key design criteria are black liquor’s dry solid flow because that tells the required boiler size (Vakkilainen 2016, 341). In a recovery boiler there is a risk for a safety hazard which occurs when even a small amount of water is mixed to the char bed. If that happens, water evaporates too fast creating pressure wave between 10-10000 Pa, this is called smelt-water explosion. Furnace walls are not designed to handle this kind of sudden pressure difference, so in any possible leakage of water situation, immediate shutdown is the only option to prevent explosion (Vakkilainen 2016, 334)

3.1.1 Modern recovery boiler

The most important purpose of a recovery boiler is to utilize the energy from black liquor. When increasing electricity production of recovery boilers also, pressure and temperature need to be increased at the same time. Nowadays new recovery boilers are usually designed with pressure over 100 bar and temperature of steam over 500 ℃ (Vakkilainen 2014, 26–28.) Also typical for modern recovery boiler is that strong and weak odorous gases are burned in the recovery boiler by using specifically designed burner. New recovery boilers have one drum design and a vertical steam generating bank. The first single drum boiler was delivered in 1984 and was manufactured by Götaverken (Vakkilainen 2014, 5).

Nowadays all new boilers are made with single drum design except very small boilers. The advantages of the single drum design are capacity for higher pressure and need for less tube joints. In one drum design the possibility of water leaking to the furnace is lower because the drum is placed outside of the furnace and water circulation is separated. In the first recovery boilers walls of the furnace were made from carbon steel. In 1972 the first recovery boiler with furnace made from compound tube material was delivered. Nowadays in all modern recovery boilers lower furnace area is made from compound material because it resists better against corrosion problem, which is caused by high pressure, high temperature and aggressive chemical conditions in the furnace (Vakkilainen 2014, 16). Vertical steam generating bank have similar design than with vertical economizer. Advantage of this design is easier cleaning when dust load is high. In modern recovery boilers spacing between superheaters and economizers is increased to minimize fouling (Vakkilainen 1999, B98).

3.2 Revovering process

The cooking chemicals in the kraft pulping process are commonly known as white liquor. White liquor is mainly composed of sodium hydroxide and sodium sulfide compounds. During the pulp cooking process, white liquor is transformed to black liquor. Black liquor is combusted in the recovery boiler's furnace and as a result, is formed inorganic smelt.

Smelt consists of sodium carbonate, sodium sulfide and sodium sulfate. Smelt is lead out of the furnace via smelt spouts. Smelt is dissolved with water in the dissolving tank and that compound is called green liquor. Green liquor is caustized with lime and converted from sodium carbonate back to sodium hydroxide. After this recovering cycle the white liquor is available to be utilized again in the cooking process (Alen 1999, 62). When concentrated black liquor is burned, generated energy is covering the whole internal energy need of a pulp mill.

Efficient recirculation of cooking chemicals is the main goal in the recovering process. After pulping process, pulp is washed with watery solution. The purpose of the washing is to separate used cooking chemicals and dissolved organic compounds from the pulp. The liquor cycle in pulp mills contains following phases: pulping, evaporation of black liquor, recovering black liquor chemicals in recovery boiler combustion, causticizing and lime cycle where calcium oxide is produced from lime mud (Vakkilainen 2016, 330).

There are several advantages in recovering black liquor chemicals. In addition to them, recovery boiler is generating energy from pulp mills waste steam (Vakkilainen 1999, B7). In addition to producing needed chemicals for pulping process, recovery boiler is producing several other chemical compounds which can be utilized in chemical production. Examples of these by-products are tall oil and soap. Additional make-up chemicals, such as sodium sulfate, are added to the process to keep the sodium-sulfate balance and remove ash fly (Vakkilainen 2016, 331). In Figure 4 is presented the simplified structure of liquor cycle in the recovery boiler. In Figure 4 is described the main processes of liquor cycle and how the liquor calls in each stage.

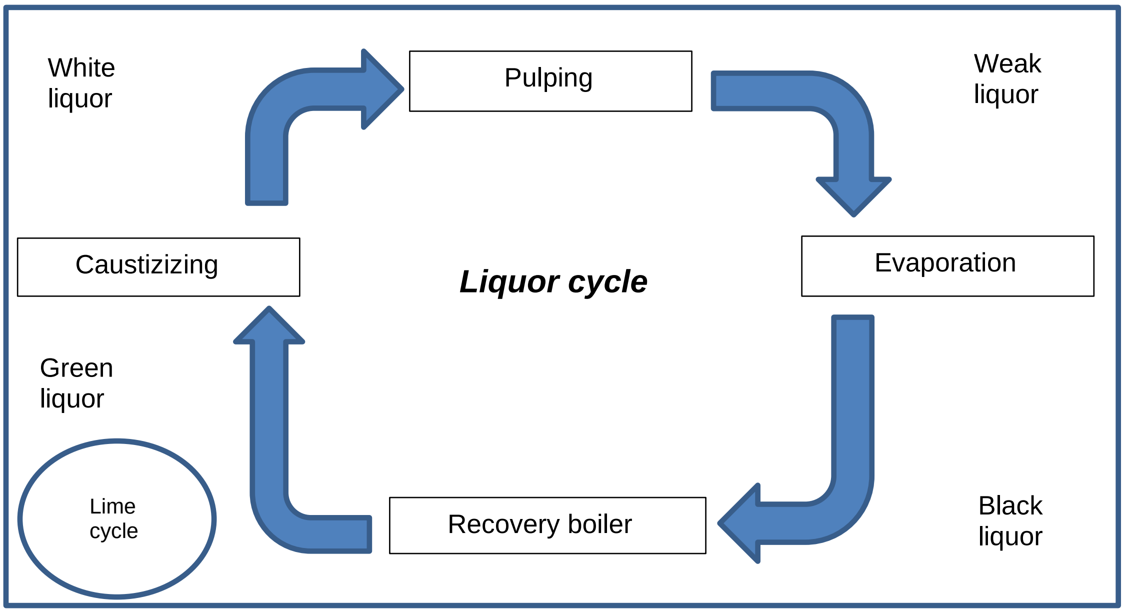

Figure 4. Kraft liquor recovering cycle

In the evaporation process, the aim is making concentration of black liquor high enough to make most efficient burning in the recovery boiler. After washing black liquor from pulp, the concentration of black liquor is usually between 12-20% and it is called weak liquor. Basic principle of evaporation to separate water and soap from the black liquor (Vakkilainen 1999, B8). Weak black liquor contains too much water for the efficient burning process and evaporation process is therefore mandatory.

In the evaporation process there are heat transfer units which cause vaporization of the water in the evaporator. There are usually multiple heat transfer units on the series (Holmlund & Parviainen 1999, B40). If there is soap on the liquor, then liquor is usually sweetened which means increasing concentration by feeding heavier intermediate to feed liquor. Feed liquor is usually sweetened to 18-22% concentration of dry solid. Hardwood liquor contains less or not at all soap, so in those cases sweetening isn't done at all (Holmlund &Parviainen 1999, B69).

Black liquor is after final stages of evaporation in concentration 75-85% of dry solids. If water content is above 80% in black liquor, it has a negative net heating value. Black liquor is stored in a pressurized tank before pumping into a recovery boiler. Black liquor is entering to the furnace through black liquor guns in a pre-heated temperature between 125-150 °C (Holmlund & Parviainen 1999, B70). After entering the furnace black liquor is combusted in the recovery boiler where it becomes smelt after burning reactions. Smelt will be removed from the bottom of the boiler furnace by using smelt spouts. Via smelt spouts smelt is ends up in the dissolving tank where smelt is dissolved with ash and water.

The main goals in causticizing process are to produce clean and strong white liquor, with low sodium carbonate content which doesn't include much unreactive chemicals, and to produce clean dry mud, which will be utilized in the lime kiln process (Arpalahti et all 1999, B135). The main compounds of green and white liquor are sodium sulfide, sodium sulfate, sodium hydroxide and sodium carbonate. Green liquor is converted into white liquor in the recausticizing process, where reburned lime is reacting with sodium carbonate. In causticizing process sodium carbonate is converted into sodium hydroxide (Arpalahti et all 1999, B135).

There are impurities in the liquor which are separated from the green liquor before causticizing process. These impurities are mostly carbon and lime mud particles, some metal hydroxides and sulfides are also possible impurities. In the causticizing process, there are two reactions that occurs simultaneously; slaking and causticizing. In the slaking process, green liquor is mixed with calcium oxide and the following exothermic reaction will happen (Arpalahti et all. 1999, B136)

$$CaO + H_2O \rightarrow Ca(OH)_2 + 65kJ/mol \tag{1}$$

At the same time, following causticizing reaction happen, which is an equilibrium reaction

$$Ca(OH)_2(s) + Na_2CO_3(aq) \leftrightarrow 2\ NaOH(aq) + CaCO_3(aq) \tag{2}$$

Lime mud and white liquor are products of the recausticizing process. These products will be separated from each other with clarification and filtration processes. After these processes, white liquor is ready to be used in the cooking process in the kraft pulp mill. Lime mud is transferred to lime kiln process. Lime kiln process is side stream process, but it has an important role of drying lime mud and calcining calcium carbonate. Lime reburning is a part of the lime cycle, where calcium carbonate is converted into calcium oxide. Reburned lime is used in converting green liquor into white liquor. In lime reburning process following reaction occurs (Arpalahti etc. 1999, B136).

$$CaCo_3 \rightarrow CaO + CO_2 \tag{3}$$

In Figure 5 is presented simplified circle structure of recovering the most important chemicals of the pulping process.

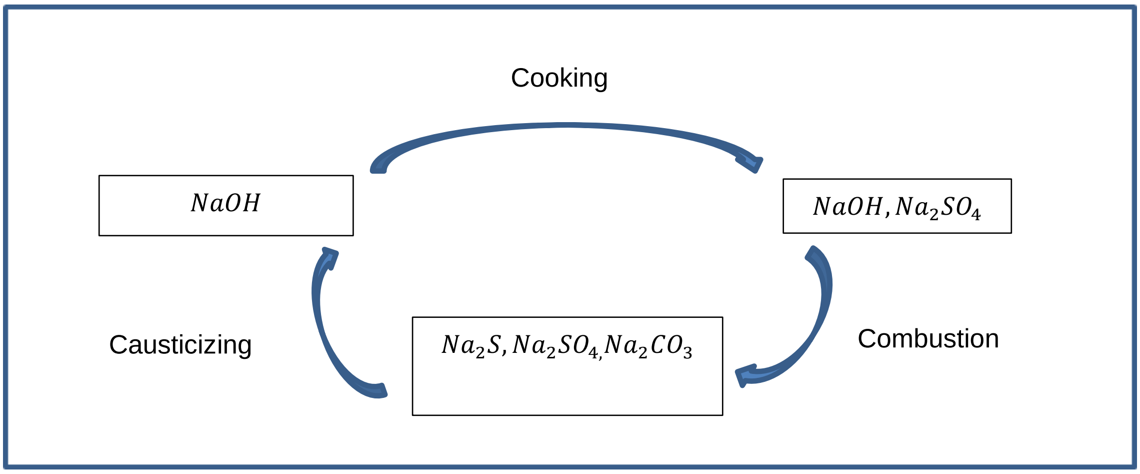

Figure 5. Chemical recovering cycle

When comes it to designing recovery boilers, it is always a compromise because there are so many aspects which need to be considered. Recovery boiler needs to be efficient in both reduction and combustion processes, which are opposite processes. Other requirements for a recovery boiler are high thermal efficiency, low fouling, environmental process and low emissions to nature. Chemical processes in the furnace are complex and optimizing those is rather difficult. Other factors which need to be taken into account are the use of the boiler, maintenance and safety aspects.

3.3 Chemistry in recovery boiler

An important factor in combustion reaction is that the air flow is matching the fuel flow because that ensures steady combustion reaction. Black liquor's heating value depends on the water content and that affects the need of air. Typical fuel contains carbon, oxygen, nitrogen, sulfur, hydrogen, potassium, chlorine and sodium. Black liquor heat treatment separates non-condensable gases from combustible material. The organic material is burned in the recovery boiler and inorganic material is recovered into smelt. Sulfur compounds of the black liquor react with sodium during the combustion and produce sodium sulfate and sodium carbonate. Important part of recovering process is to reduce sulfur emissions (Vakkilainen 2016, 331).

Black liquor is sprayed to furnace through black liquor nozzles and average droplet size entering the furnace is between 2-3mm (Vakkilainen 1999, B108). Black liquor gun will spray droplets with similar size in order to the unburned char to reach the char bed. During the combustion, black liquor droplets are going through several stages. The most important and relatively unique feature is swelling behavior of black liquor. Because of the swelling behavior, there are different combustion speeds and stages at the same time in the furnace (Vakkilainen 1999, B108).

Table 1. Stages combustion of black liquor droplets in recovery boiler furnace (Vakkilainen 1999, B109)

Stage	Characters	Timeframe in furnace
Drying	Evaporation of water, constant diameters of droplets	0.1-0.2 s
Devolatilization	Ignition and swelling of droplets	0.2-0.3 s
Char burning	Reduction reaction	0.5-1s
Smelt reactions	Reoxidation	Long

In Table 1 is presented the combustion stages of black liquor droplets. In the drying stage, heat of the furnace creates a fast evaporation process, in which water evaporates from black liquor droplets. Diameter of black liquor droplets is increasing and at the same time density is decreasing. All the moisture doesn’t evaporate, there are usually circa 5 % of moisture left after this first stage. In the devolatilization stage, black liquor droplets continue to dry, and temperature increases while swelling continues. In this phase, black liquor droplets have a foam like structure. The main reaction during devolatilization phase are sulfur releasing dimethyl sulfides and methyl mercaptans, hydrogen sulfides are forming decomposition reactions and char oxidation begins (Vakkilainen 1999, B110).

The swelling behavior affects black liquors' behavior in the furnace. Swelling also affects the dryness of the droplets. A droplet which has been swelled notably, is flowing to the bed slower than a droplet which hasn't swollen that much. That kind of droplet is also drier and includes less carbon than a droplet which has swelled less. Spraying technique of black liquor droplets has a significant effect to the size of the black liquor droplets. If droplets are too small, they flow away easily from the furnace and will end up surface of superheaters. If droplet is too large, it will land to the bed too soon without drying complete and bringing moisture to the bed which causes temperature of the bed to drop. Optimal size for the black liquor droplet is when the droplet will dry before landing to the bed but the most of it is still on unburned stage (Frederick & Hupa 1997, 149-152).

There have been studies of the relationship of main compounds of black liquor and how those are affecting different stages in the combustion. Aliphatic acids have strong influence on drying rate, swelling behavior and pyrolysis time. Lignin is affecting on swelling behavior and char burning time. Extractives and hemicellulose are also affecting the swelling behavior of black liquor (Alen 1999, 77). In Figure 6 is presented relationships of main organic compounds.

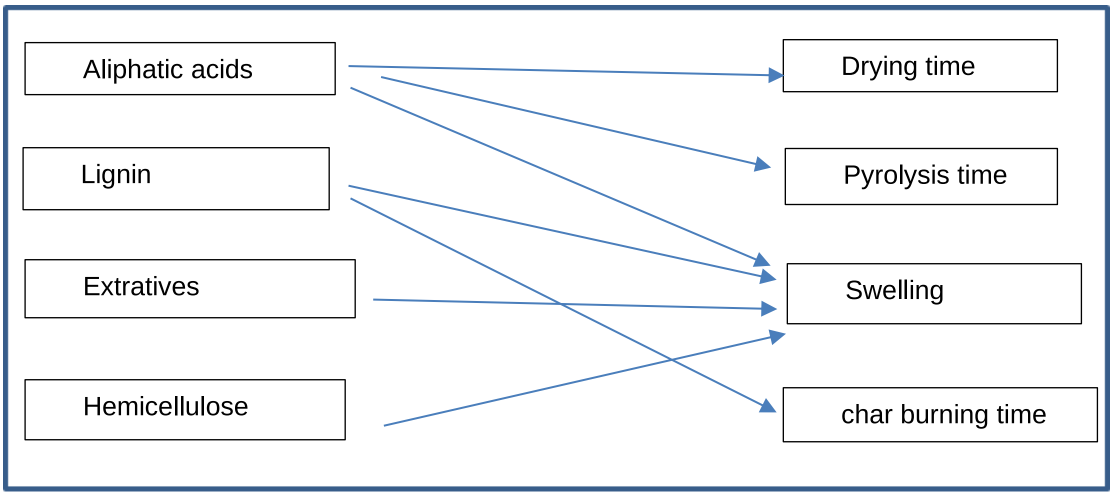

Figure 6. Relationship of main organic compounds and black liquor combustion stages (Alen 1999).

When char combustion starts, combustion residue size is large, but the structure is porous. Large portion of inorganic matter remains on carbon char and it consists of three inorganic salts: sodium carbonate, sodium sulfate and sodium sulfide. At this point of combustion, there isn't organic oxygen present in the carbon and reduction rate is close to 50%. In the reduction reaction sodium sulfate is reacting with carbon and forms sodium sulfide. Reduction of sodium is caused by burning carbon. Following reactions are present at this stage (Vakkilainen 1999, B111).

$$Na_2S + 2O_2 \rightarrow Na_2 + SO_4 \tag{4}$$

$$Na_2SO_4 + 2C \rightarrow Na_2S + 2CO_2 \tag{5}$$

$$Na_2So_4 + 4C \rightarrow Na_2S + 2CO \tag{6}$$

At the end of the combustion of black liquor, final reactions are happening in smelt. If there is remaining oxygen in the smelt, reoxidixing is occurring to sodium carbonate, and sodium sulfate. This is something to avoid in the recovery boiler. Reduction of inorganic sulfur and sodium sulfide is happening in the smelt (Vakkilainen 1999, B113).

Potassium and chloride are the main reasons for recovery boiler fouling and small amounts of them in the dust can cause congestion of superheaters. Dust in the recovery boiler is containing sodium carbonate, sodium sulfate and some amounts of chloride and potassium. These components are creating a carry-over phenomenon in the upper part of the boiler (Vakkilainen 1999, B128).

Char bed is in the bottom of the furnace and char bed mainly includes inorganic compounds. Bed is consisting of layers which are: active top layer, reductive smelt layer, liquid layer and solid layer. The shape of the furnaces' bottom is also affecting bed's characters. In the top layer reduced sodium sulfite is reacting with oxygen and forming sodium sulfate. Sodium sulfate is reduced when it is reacting with carbon. In the reduction layer reduced sulfide can't react with oxygen and it stays in the reduced form (Grace & Frederick 1997, 163-179). In Figure 7 is presented bed layers in the recovery boiler furnace.

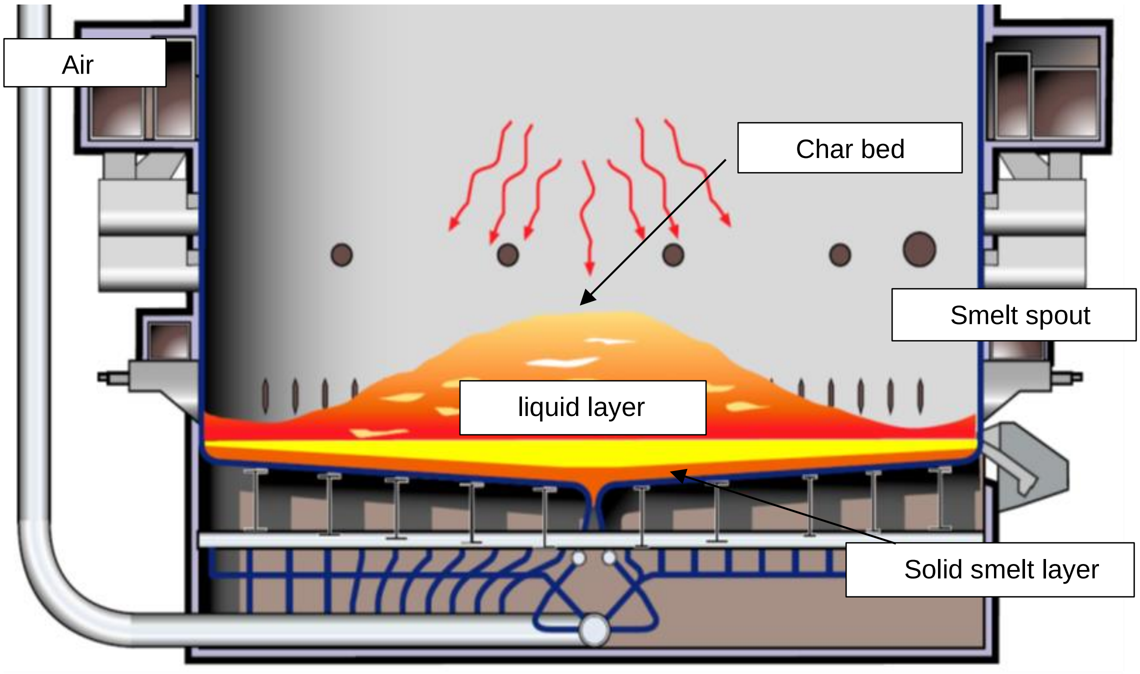

Figure 7. Furnace floor, Adapted and modified (Aikio 2014c)

3.3.1 Black liquor

Content and properties of black liquor depend on used pulping raw materials, conditions of the pulping process and treatment method of black liquor after pulping. Usually raw material contains mixture of hard- and softwoods and main variables are with chemical concentrations (Vakkilainen 1999, B13). Studies have shown that black liquors which are hardwood based, have shorter combustion time and more swelling behavior than soft-wood based black liquor (Alen 1999, 76).

Black liquor contains water, organic and inorganic matter. Organic matter includes lignin, hemicellulose and cellulose from the trees. Cellulose consists of linear homopolysaccha-rides with glycosidic bonds and hemicellulose consists of hexoses, pentoses, xyloses, and deoxyhexoses. The hemicellulose content and constituents of softwoods' and hardwoods vary, the wood raw material used also affects composition of black liquor. Lignin is an amorphous polymer (Alen 1999, 38). The most important organic compounds in black liquor are polysaccharides, carboxylic acids and extractives. Inorganic matter includes pulping chemicals like natrium and sulfur compounds (Alen 1999, 38). Black liquor is separated from the pulp by washing.

Dry matter content of black liquor has been increased remarkably during the decades of the 20th century. In the 1950s it was circa 50% and nowadays 80-85% (Vakkilainen 2009, 10–11). In today's recovery boilers increase of dry matter content made it possible to decrease of Sulphur emissions. Emissions can be reduced when dry matter content of black liquor is over 75% (Vakkilainen 2014, 24–25). The properties of black liquor are varying specially in viscosity, heating value and boiling point. In Table 2 is presented typical composition of black liquor.

Table 2. Typical composition of black liquor (Vakkilainen 1999, B15).

Element	**Pine**	**Birch**	**Eucalyptus**	**Mixed tropical wood**
Carbon	35	32.5	34.8	35.2
Oxygen	33.9	35.5	35.5	35.5
Sodium	19.0	19.8	19.1	18.8
Sulfur	5.5	6.0	4.1	3.0
Hydrogen	3.6	3.3	3.5	3.6
Potassium	2.2	2.0	1.8	2.3
Chlorine	0.5	0.5	0.7	0.8

Black liquor thermal conductivity depends on dry solids content and temperature. Equation for thermal conductivity of black liquor is following

$$\lambda = \lambda_{H_2O}(1 - X)aX + bX^2 \tag{7}$$

where:

X = the dry solids concentration

a = $a_1 + a_2T$

b = $b_1 + b_2T$

$a_1 = 0.3176$

$a_2 = 0.002268$

$b_1 = -0.01394$

$b_2 = -0.003069$

Black liquor's density depends on the shear rate and typically it is non-Newtonian fluid. When temperature of black liquor increases at same time, viscosity decreases. (Vakkilainen 1999, B23). Dynamic viscosity of black liquor can be calculated by following equation.

$$\eta = \mu\rho \tag{8}$$

Black liquors viscosity depends on cooking methods, thermal treatment and wood species. It is function of concentration and temperature. When solids dry content increased also viscosity of black liquor is increased (Holmlund & Parviainen 1999, B38)

3.3.2 Smelt

Smelt is a product of the combustion process in the recovery boilers furnace. Important properties of smelt are heat capacity, heat of formation and melting heat. Smelt contains primarily sulfur compounds, sodium carbonate and sodium sulfide (Vakkilainen 2006). When black liquors composition is changing, that also affects smelt behavior. Reaction which occurs in the smelt is reduction. Reduction is measured at the reduction rate by the following equation, which is molar ratio.

$$reduction\ rate = \frac{Na_2S}{Na_2S + Na_2SO_4} \tag{9}$$

Reduction rates between 95-98 % are quite typical in well operated boilers. The higher the reduction rate, the higher the amount of reusable sodium. When the temperature of the bed is increased, reduction rate is also increased. There are very small amounts of sodium oxides and thiosulfates in the smelt. Another important measure of smelt is sulfidity. Sulfidity is a molar ratio of sodium sulfide. If the sulfidity is too high, it causes problems in process (Vakkilainen 2006). Sulfidity can be measured by following equation:

$$Sulfidity = \frac{S_{tot}}{Na_2 + K_2} \tag{10}$$

Temperature of smelt is typically between 750-850℃. In newer boilers temperature is naturally closer to 850℃ temperatures. In overall the smelt's composition is quite similar in all recovery boilers. An amount of different compounds depends on the black liquor's origin. In Table 3 is presented the typical compounds of smelt in the softwood and hardwood.

Table 3. Smelt compounds in soft- and hardwoods (Vakkilainen 2006, 68)

Amount %	Softwood	Hardwood
Na_2S	25-28	19-21
Na_2CO_3	66-68	72-75
Na_2SO_4	0,4-1	0,6-1,4
$Na_2S_2O_3$	0,3-0,4	0,2-0,4
Others	5-6	3-5

From the Table 3 can be seen that main components of smelt are sodium carbonate and sodium sulfide. The amount of sodium sulfate is small when reduction rate is good. Reduction of sodium sulfate requires sulfur and usually that is the limiting factor in reduction process (Vakkilainen 2006, 68).

Smelt's viscosity affects smelt flow to dissolving tank. Smelt's viscosity is inversely proportional to smelt's fluency. If viscosity is high, it will cause uneven flow to smelt spouts and can cause the plugging of the smelt spouts. Viscosity of smelt increases when smelt is closer to pour point (Tran et al 2006, 182). Composition of smelt has a significant influence to pour point temperature. When sulfidity is circa 40% the pour point is at the lowest. Steady smelt flow without interference is the best operational environment for smelt spouts.

If smelt reacts with water and it will cause a smelt-water explosion. When smelt reacts with the water will vaporize too fast and it will cause the explosion. This phenomenon known as vapor explosion happens when hot liquid is interacting with colder liquid. (Jin et all. 2020). In dissolving tank smelt is reacting all the time with water but it is important to keep the incoming smelt in small droplets with using shattering steam nozzle. Then explosions are tiny and don't create any trouble in the process. With the hot smelt the risk for the damages is high. Possible risk situations occur when plugged smelt is opened, sudden smelt rush and water leakage in the smelt spout.

3.4 Finnish recovery boiler committee

The purpose of this committee is to promote safe, environmentally friendly and economic operations in Finnish recovery boiler mills. Committee was founded in 1964. The members of this committee are Finnish pulp mills, manufacturers who are making recovery boilers, engineering companies which are working with recovery boilers and universities which are providing education and research on the fields which are close to recovering technology. There are also members in this committee from insurance companies and inspection companies (Soodakattilayhdistys 2020).

The committee publishes material and arrange education which are promoting its targets. Committee is organizing gatherings and meetings; also, international connections are important with committees in different countries. Committee is collecting information about damages and danger situations in recovery boilers and based on those send valuable information to members of the committee, so similar situations can be prevented in the future. Committee funds studies and projects whose objectives are close to those of the Committee (Soodakattilayhdistys 2020).

In Sweden there is similar committee than in Finland, which is called Sodahuskommitten, that is a Committee for Swedish and Norwegian companies close to recovery boilers. The purpose of this Swedish Committee is similar than the Finnish one; preparation of recommendations and spread the information related recovery boiler operation to its members. Sodahuskommitten has been founded in 1965 (Sodahuskommitten 2020).

Black liquor recovery boiler advisory committee is internal trade association which is publishing safety guidelines and recommendations to the pulp mills. The committees of the various countries are represented on this committee and work closely with the national committees of each country (BLRBAC 2020). American paper and pulp association has founded TAPPI which is foundation to promoting pulp, paper and packaging industries. It is focusing on funding scholarships on these fields. TAPPI publishes lot of studies and education material from these specific fields of engineering and machines (TAPPI 2020).

4. SMELT SPOUTS

Smelt spouts are a crucial part of recovery boiler's structure and their smooth function is essential for recovery circle in pulp mills. The basic function of a smelt spout is to lead smelt, which has been evolved in the boiler bottom, away from the boiler. Smelt spout is located between smelt spout opening on the boiler wall and dissolving tank. Mainly nowadays smelt spouts are cooled with cooling water circulation but there are un-cooled versions of smelt spouts available (Vakkilainen 2006, 120). There are usually three parts in the smelt spout; upper part which is attached to the boiler and smelt enters to the spout, banked flute where smelt is flowing and bottom part which is attached to the dissolving tank and smelt exists from the spout.

Other equipment connected to the smelt spouts are a cover for the smelt spout which prevents smelt from spreading out from the spout, a cover to the dissolving tank and a shattering steam nozzle which is scattering smelt to droplets before entering dissolving tank. The smelt flow behavior in smelt spouts is varying a lot due to boiler operating conditions. Also, congestion of one smelt spout is quite common situation and that is affecting flow to other the smelt spouts. In the newer boilers smelt spouts load is on average higher than in older ones. Regular cleaning of the smelt spout is important because otherwise smelt spout can be plugged and as a result a powerful smelt rush through the smelt spout can occur (Soodakattilayhdistys 2018). In Figure 8 is presented the general structure of smelt spouts and related equipment's.

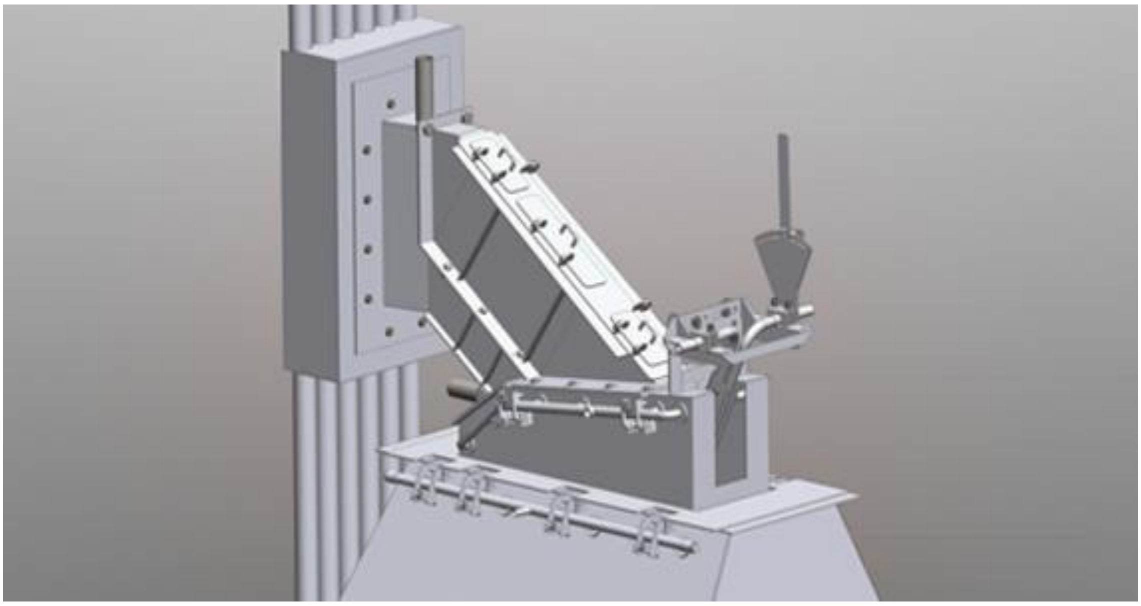

Figure 8. Smelt spout and equipment’s (Valmet 2020d)

Small explosions are constantly happening in the dissolving tank when hot smelt is flowing from smelt spout to the cooler liquid in the dissolving tank. The temperature of the liquid in the dissolving tank is between 90-100℃. If a bigger explosion happens in the dissolving tank, there are many possible scenarios what could be the reason for such an incident. Black liquor’s quality is may have changed and then dissolving of the smelt isn’t functioning as it has been designed. If the amount of organic matter is low in the black liquor or white liquor’s sulfidity level is low both reasons are creating functional issues into the dissolving process. If washing water is led to the causticizing process that is creating major risk to the process. It is better to use furnace’s washing water as a weak white liquor or lead the washing water to the wastewater system (Soodakattilayhdistys 2018).

When superheaters are swept using the soot blowers, salt can gather also in the furnace bottom and can end up in the smelt. Powerful smelt rush can create a pile of undissolved smelt in the bottom of the dissolving tank which will disturb the process. Also, if surface of the liquid in the dissolving tank is too high and shattering isn’t functioning as it should be that can create problems in a smelt spout (Soodakattilayhdistys 2018).

4.1 Types

Smelt spouts are divided to uncooled and cooled ones. In the cooled one's water is used for cooling without exceptions. Inlet water temperature is circa 60°C when entering the smelt spout and, in the outlet, temperature is maximum 80°C. Quality of water which is cooling the smelt spout has a great matter; oxygen in the water can cause corrosion on tubes and impurity layers on the pipes. Water which is used for cooling smelt spouts needs to be demineralized or condensate water from the process (BLRBAC 2012, 59). Temperature of cooling water needs to be kept close to given value, otherwise it can create troubles to the function of smelt spouts. Too low water temperature can create condensation of water to the surface of the smelt spout and explosions can happen. Also, corrosion is possible if water temperature is too low. Too high temperature of the cooling water can cause vaporization of water, which will disturb water circulation and weakens the heat transfer and cooling effect in the smelt spouts (BLRBAC 2012, 59-60).

Cooled smelt spouts can be divided to two groups depending on the circulation flow of the water. In once-through smelt spouts water goes in from the other end and out from the opposite side of the smelt spout. In multipass smelt spouts water is divided to several flow channels which are separated with plates (Reid 2011). In Figure 9 is presented the basic principles of the two different types of flowing channels.

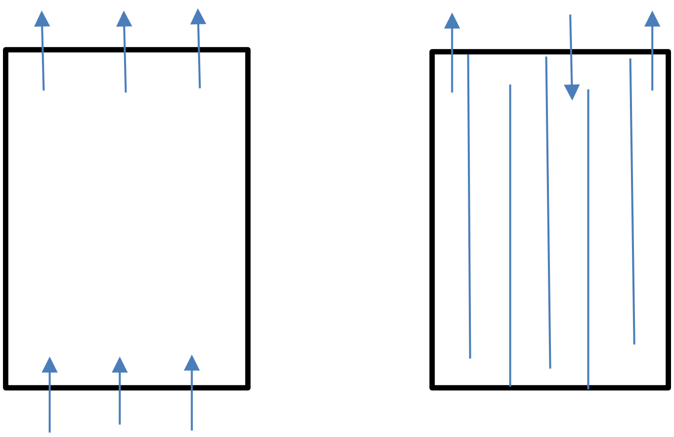

Figure 9. On the left once-through spout, on the right multipass smelt spout

Cooling system can be designed in multiple ways. Preferred way is the model where water is circulating in the channels under pressure. That prevents the risk of water getting inside the boiler in possible spout damage situations. Typical ways to create the water circulation are pump circulation, pump circulation with valves and ejector circulation. To monitor the circulation of the water, there needs to be flowmeters in the cooling circulation tubes (BLRBAC 2012, 61-68).

Uncooled smelt spouts are rare and for example in Finland there aren't those models in use. Benefits in uncooled spouts can be the following factors; no risk of explosion when water is missing, overall cost is lower than cooled spouts because uncooled spouts doesn't need to be changed yearly and use age is longer than in cooled spouts (Hollenbach & Morrison 2001). In practice it has been noticed that driving periods aren't necessarily long enough to cover expensive material cost. Uncooled spouts have been manufactured for example nickel-chrome mixture (Reid 2011).

Smelt spout material is usually carbon steel and it can be overlay welded from the bottom and/or the top. Smelt spouts can be overlay welded with stainless steel or with nickel-based mixture. Smelt spouts can be also manufactured from compound material where there is stainless steel on the top of carbon steel (Soodakattilayhdistys 2018). Table 4 presents most common materials in smelt spouts and material characteristics.

Table 4. Smelt spouts materials (Matmach 2020. Aalco 2020. Thyssenkrupp-materials 2020. Goncalves & Bresciani 2017)

Material	Chemical compound	Characteristics	Strength
Carbon steel	Iron with carbon (0.05-2.1%)	Three categories; low, medium and high according to carbon content	Depends on the category. Low-carbon steels have relatively low strength, high ones very wear-resistant

Table 4 (Continues)

Material	Chemical compound	Characteristics	Strength
Stainless steel	Iron based alloys with minimum 10.5% Chromium	High corrosion resistance	Higher strength and hardness
304L / 1.4307	Low carbon version of 304, stainless steel with 18% Chromium and 8% Nickel	Improved weldability, excellent corrosion resistance, stress cracking can occur	High strength
Nickel- Chrome mixture	Nickel and Chrome, usually with 80/20	Hardness and elastic features	Depending on the mixture

Recommendation is that smelt spouts are changed yearly, usually during the annual shutdown. Old smelt spouts are not allowed to be repaired or modified for reuse. Leakage test is mandatory before adoption of smelt spout. These actions prevent the risk of possible damage situations (BLRBAC 2012, 63-64).

4.2 Damages

In general, it can be said that the main damage in smelt spouts is that material will be corroded or cracked. Recognized damage types in smelt spouts are manufacturing error, designing error, problems with water circulation, mechanical damage, corrosion, erosion, thermal fatigue and damages which are affected from properties of smelt. Most common manufacturing errors are with poor welding quality. Water circulation problems are usually with water flow, poor quality of water and deposition on pipes. Cooling water can be also vaporizing on the spout which create damages to the spout. Most common mechanical damage is a spout material damage which happens during the welding of smelt spout (Signbeil et al. 2014). In Table 5 is presented the most common smelt spouts damage reasons.

Table 5. Smelt spout damages

Type of damage	Description
Manufacturing phase	Manufacturing error, designing error, welding defects
Operational	Thermal fatigue, water circulation prob-lems
Chemical properties	Corrosion, erosion, water quality, proper-ties of smelt

When installing smelt spouts there are several risks which can create a possible smelt leakage to the boiler room. When a smelt spout is refracted it is important to ensure the proper drying time and condensation for the refractory mass. If a spout is clogged and it is opened, there is a risk for smelt-water explosion which can cause damage to the spout and dissolving tank.

4.2.1 Manufacturing errors which can cause corrosion

Tension corrosion can happen when a spout is in the corrosive environment and there is tensile stress directed to the spout. Tensile stress can be caused by inner or outer tension. The most important actions which create inner stress to the spout are cold modification and welding (Siitonen 2004, 117-120). Salts in the smelt create tension corrosion and that enable tension corrosion on the spouts. Typical smelt spout material strength is 235 or 265 MPa (Soodakattilayhdistys 2018) and in challenging circumstances tension corrosion can appear when tension is over 10% bigger than the limit of the material. (Siitonen 2004 118-119).

Sulfur compounds in the smelt can create spot corrosion, which can be a starting point for tension corrosion. In the smelt, there is a low amount of thiosulfate which can remove or weaken the effectiveness of corrosion protection products. Sodium sulfide forms in aqueous solutions hydrogen sulfide compound which is corrosive compound. Hydrogen sulfide causes spot corrosion on alkali conditions (Ahlers 2004, 410). If alkali content and temperature are high, carbon steel can’t be used as a smelt spout material. In these conditions carbon steel can be exposed to alkalic tension corrosion, which is called lye fragile.

Mechanic corrosion can be prevented in the designing and manufacturing phase. Quality control in the manufacturing phase is important because cracks can develop even before the spout has been used. Every manufacturer has strict inspection methods which are followed and documented carefully. Effect on the mechanical corrosion when the spout is in use, is harder and that is the reason why spouts need special inspection. Spouts are inspected by external inspection company before smelt spouts are sent to the customer.

4.2.2 Chemical corrosion

Smelt on metals can create corrosion and the solid metal material can become brittle. If the metals melting point is low, it is possible that liquid metal can interact with solid metal and create compounds. That affects the metal by lowering the strength and when subjected to tension the metal can crack. Metals with low melting point are for example aluminum, copper, sodium and potassium (Nikula 2004, 188). These metal compounds come to the recovering cycle from wood and even though contents are low, those enriched in the closed loop of liquor cycle. In a recovery boiler both sodium and potassium are common elements and can create corrosion to the smelt spout. In Table 6 is presented the main chemicals which can cause corrosion to the smelt spouts when these chemicals interact with spouts surface.

Table 6. Main chemicals which can affect corrosion

Chemical	Source of chemical
Aluminum (Al)	Wood
Copper (Cu)	Wood
Sodium (Na)	Pulping Chemical
Potassium (K)	Pulping Chemical
Sulfur (S)	Wood
Chlorine (Cl)	Pulping chemical

Protection against chemical corrosion is based on a phenomenon, where smelts is freezing to the bottom of the spout. That frozen smelt layer protects smelt spout from the liquid smelt and keeps the temperature lower on the surface of the spout (Tran 1997, 298-302).

Corrosion fatigue happens when the corrosive environment weakens the materials fatigue strength. In corrosive environment this cause stress cracking. Typical corrosion forms are galvanic corrosion, spot corrosion, crack corrosion and hydrogen embrittlement (Nikula 2004, 179).

If the corrosion is in the bottom of the spout, reason usually is, that steam from the dissolving tank is raising to the spout or washing waters are condensing to the surface of the spout. Smelt and moisture together can create erosion and cavitation explosions in the spout. In these problems the corrective actions can be done in the dissolving tank area as for example lowering the surface of the liquid in the dissolving tank. When technical designing is done by designing coating to spouts edge that can help to prevent these problems (Soodakattilayhdistys 2018).

Using weak white liquor for washing showers for the spout that can cause NaOH corrosion if shower ends up to the hot surfaces. The reasons behind the corrosion-erosion on the edge of the spout outlet are usually material, structure of the spout, irregularities on the surface and temperature on the spout end. Also, properties of the smelt such as quantity, viscosity and stream velocity affect the corrosion in the spout outlet end. It is recommended that spout outlet ends are designed to be as smooth as possible, so Sulphur compounds can't cause corrosion to the irregularities on the spout edge surface (VTT 2020).

4.2.3 Thermal fatigue

Thermal fatigue cracks are formed to the material as a result from temperature changes and can occur without mechanical load in the material. Local temperature changes cause thermal fatigue in the material. Cracking develops from constantly cooling and heating the material (Xin 2013). Smelt flow changes create the temperature changes in the surface of the smelt spout and that causes thermal fatigue. Temperature difference between cooling water and surface of the spout is only few tens of degrees. If a smelt spout is clogged, then the temperature of surface can drop down close to cooling water temperature. Also smelt flow rushes create changes on the temperatures in the spout surface (Siitonen 2004, 123). If smelt enters the cracks, it can accelerate growth of the cracks and corrode spout material inside the cracks (VTT 2020).

Corrosion on the top of the smelt spout, is usually caused by local problems with thermal transferring. In these cases, the corrective actions are made to cooling water system. Technical designing solution, which will also protect the top of the spout is the covering the top part of the spout (Soodakattilayhdistys 2018). If thermal load is varying a lot during the process, that can create cracking effect to the spout. Because of the cracking behavior of the spout, it is recommended to keep steady flow to the spouts (Soodakattilayhdistys 2018). The design and the material of the spout contribute to the possibility of cracks in different parts of the spout. Also design of the cooling circulation ducts influences cracking (VTT 2020).

4.2.4 Cooling circulation

Problems with cooling water circulation include multiple factors that can reduce smelt spout's lifetime. Spout material temperature can increase too high if there are disruptions in the cooling circulation. Impurities in the cooling water can create layers to the pipes and cause damages on the spout (Busby 2014). One possible damaging factor is the vaporizing of cooling water during the smelt flow rush. Cooling water is usually in the vacuum pressure and supercooled before entering the smelt spouts' cooling circulation ducts.

Forming of steam bubbles requires that surrounding material is in higher temperature than water's vaporizing point. In supercooled water, the first steam bubbles are collapsing close to the wall and heat transfer is more effective and wall material's temperature is dropping (Kind & Schröder 2010, 804).

Because of the cooling water's flow in the circulation duct, the possible scenario in the ducts is flow boiling. The most important factor in the smelt spouts is boiling of supercooled water. If the heat flux is high enough, boiling can start before saturated temperature. Leakage in cooling water circulation can cause water to end up to the furnace bottom or to the smelt flow thus causing a smelt-water explosion. Possible reasons for the leakage are premature wearing of the spout, breaking of water circulation, manufacturing mistake and flawed installation (Soodakattilayhdistys 2018). If there is leakage in the water circulation, the boiler is needs to shutdown and smelt spout must be changed.

Problems with cooling circulation can cause corrosion to the inner part of the spout. This kind of corrosion is usually caused by impurities of water or problems with oxygen removing. Also, deposits can cause corrosion inside the spout (Soodakattilayhdistys 2018).

4.2.5 Smelt flow

There are several reasons for smelt rush. Common reasons for smelt rush are opening of the plugged spout, low sulfidity of black liquor and collapsing of the char bed. Smelt flows which are bigger than in the normal process create specially problems in the dissolving tank. If smelt flow is too big shattering steam nozzles can't break the whole flow to the small droplets and that will cause explosions in the dissolving tank. Also, this scenario can create possible problems to the other phases of the recovering process (Tran et al 2014, 197-210). In Tran et al. (2014, 202) study the average smelt flow in the single smelt spout is 0,96l/s and the variation for the flows was between 0,44-1 l/s. Powerful sudden rush of smelt is easiest to be notice from the automation system from the raising temperatures of the cooling water.

Other way to monitor the smelt flow is to follow mass balance in the dissolving tank. Using this method, the following of the mass flow in single spouts isn't possible, it will only measure the overall smelt flow variance. Also, it needs to be noticed that dissolving tank balances the mass flow (Tran et al 2014, 203). Usually these bigger smelt flow rushes won't last longer than 30 minutes.

Smelt flows freely due to gravity. In practice, the exact calculation of flow amount isn't easy because the char bed characters vary a lot. The possible extra smelt in the furnace affects the hydrostatic pressure, which the smelt is creating to the smelt spouts. Furnace bottom design is affecting the hydrostatic pressure influence on the smelt spouts. In the boilers with banked bottom, lesser increase of smelt in furnace creates the same effect as in a boiler with flat bottom (Tran et al 2014 205-207).

Also smelt viscosity affects the flowing behavior of the smelt. The lower that viscosity gets, the more flowing the smelt is. In these situations, powerful smelt flows don't happen so easily and smelt is easy to break down into droplets. Sulfidity of the smelt is affecting the viscosity and freezing temperature. Freezing temperature is at the lowest when sulfidity is less than 40 %, so it is possible to decrease the smelts freezing sensitivity by increasing the sulfidity (Tran et. al 2014, 208). Layers which are dropping from the upper parts of the furnace, can cause changes on the smelt flow. If the sulfidity is low on these layers, it will cause sulfidity lowering on the char bed when layers are melted. This will weaken the viscosity of smelt (Tran et all. 2014, 208).

4.3 Inspection and standards in smelt spout manufacturing

Manufacturer of smelt spouts and all subcontractors must fulfill requirements from quality assurance systems ISO 9001, ISO 9002, EN 3834 or equivalent quality standard. Materials which are used to smelt spout manufacturing are inspected in accordance to standard EN 10204 type 3.1 or 3.2 Inspection certificate. Also, other equivalent quality standards can used, such as ASME standard. Non-destructive evaluation techniques are used to monitor welding quality after the welding and during the welding (Ghaffari 2010). In Table 7 is presented different inspection method standards and acceptance criteria's for smelt spouts which used commonly used in smelt spouts final inspection.

Table 7. NDE methods

NDE method	What can be measure	What can be revealed
RT (radiographic inspection)	Demanding welding seams	Pores and interfaces on the material
UT (Ultrasonic inspection)	Material thickness, manufacturing and material errors	Interface, pores, cracks
MT (Magnetic particle inspection)	Only for ferromagnetic materials	Detecting surface and near surface
PT (Liquid penetrant inspection)	Can reveal cracks on width 0,1µm	Cracks and pores on the surface
VT (Visual inspection)	Everything which can be seen with barren eye	Cracks, pores

Extensive visual inspection and liquid penetrant test for every manufactured smelt spout need to be performed in manufacturing workshop (Soodakattilayhdistys 2018). If welds on the smelt spout need to be repaired, the following procedure is fulfilled; Visual Inspection (VT) is made to 100% for weld repairs and after that Liquid Penetrant Inspection (PT) for weld repairs is performed. If repairs have been made, Non-Destructive Evaluation (NDE) report should contain a map about the repairs and traceability of smelt spouts (Weldinginspections 2020). Every time before installation of smelt spout, the spout shall be leak tested with air in test pressure 2 bar and holding time 10 minutes on that pressure (Soodakattilayhdistys 2018).

5. RECLAMATIONS

Reclamation is a situation between the company and a customer, where the customer experience doesn't fulfill the expectations. Typically, a reclamation situation happens in customer service situations, there is a late delivery or when there is a mistake in the product. The customer can also make a reclamation if given promises have been broken. In majority of the cases, the reason for a reclamation is a broken or wrong item.

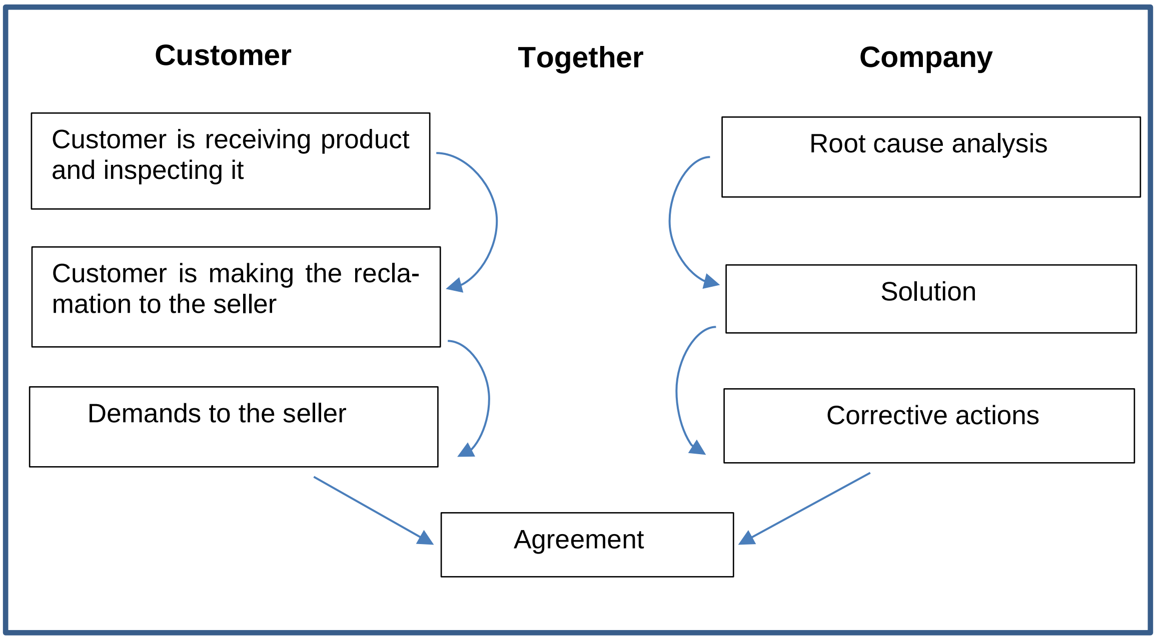

Figure 10. Reclamations basic steps

In Figure 10 is presented a rough model for the reclamation handling process. When a customer receives the product, it needs to be inspected and if there is a mistake, reclamation process needs to be started immediately. The same rule is applied if there is a warranty issue with products, or a product breaks down before its assumed lifetime (Kuluttajaneuvonta 2020). When making the reclamation to the company, customer needs to present the best possible description about the fault; what kind of fault, when it has been noticed and when it could possibly have happened. In the end, the customer presents their demands against the seller. For the customer, the most important thing is continuous communication and cause for the mistake. If there are any delays to the customer, those need to be communicated to the customer in timely manner. To the company, the root cause analysis is the most important thing in reclamations, because that will prevent the same mistakes from happening again and maybe even develop processes or products further.

Learning from reclamations has a positive effect on a company's results in the long and short term. Controlling the reclamations, the goal can be to keep the customer relationship or learn inside the organization. Reclamations can reveal bad working methods in the company and create improvements. Reclamation can also have an effect in longer time period when company is improving their processes, based on lessons learned (Ylimaz et all 2015). From the customer point of view, companies want to act fast in reclamation situations, but on those cases, there aren't necessarily enough time for learning about reclamation. If the learning needs interaction, it is time consuming (Vos et all 2008).

5.1 Key Process steps in reclamation handling

The basic key process steps which are followed when the reclamation process is ongoing in the company, are presented in the following Figure 11.

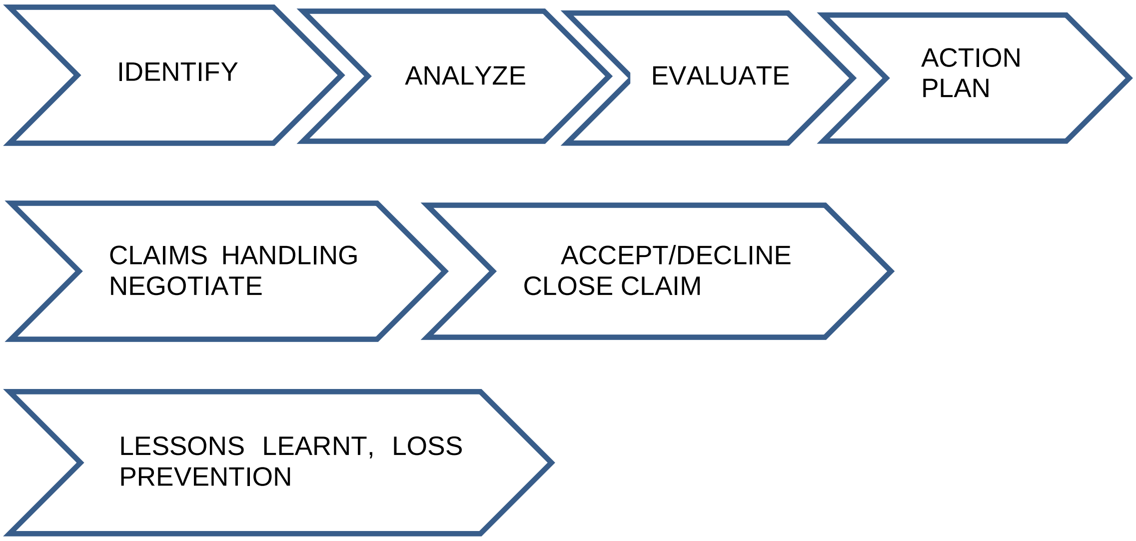

Figure 11. Key process step in reclamation handling

These steps are presented from the point of view of business to business and not all steps are suitable when it comes to normal customer business. The general targets in every company in the customer claim handling process are fast response time, minimizing financial liability and securing customer satisfaction. When reclamation is received, the company needs to be proactive when handling the case. First step is to identify and collect all the relevant documents. If photos can be taken that is beneficial and possible inspection or survey must be made. It is important to take notes during the phone calls, meetings and verbal conversations where reclamation case is discussed.

When all the available data is collected from the reclamation case, it is time to analyze the case within the company and decide who is the responsible person for handling the reclamation. It is important to confirm that is the reclamation a warranty reclamation that meets the definitions and analyze facts, obligations and liability of the case. If there is a contract with the customer, that needs to be reviewed together and find out who is liable in this case.

If needed, a special team will be selected to handle the reclamation based on their expertise. The next step is to determine further actions in the reclamation handling process, evaluate critical risks and risks which are related to the reclamation. If there is a need for internal communication in the company, that is evaluated at this point. In action plan phase, are to be reviewed already taken actions as well as all collected documentation. The responsible person decides if any internal functions of the company needs to be called in and evaluates the functions' responsibilities.

An action plan is created and that is defines continuous reclamation handling process and communication with customer. Immediate actions are decided and secured to prevent further loss, damage, liability or cost. After action plans have been decided the proceeding actions will take place according to the action plan. If there is a contract with the customer, then there is a possibility to negotiate with the customer. Negotiate is the possibility also, when reclamation is against project or product with high value.

The next step is either to accept or decline the reclamation and to close it. All the agreed decisions are communicated to the customer and confirmed in writing. For any financial transactions, it is usually proceeded with standard procedures for settlement. Before closing the case, everything needs to be clear and confirmed that the settlement is full and final. The final step for the reclamation handling is the reporting summary, including loss prevention and feedback for internal use. If needed, a special team is collecting lessons learned actions and presenting actions in the company.

In the next chapters the root cause analysis tools which are all in use on the client company will be presented. The selected tool or method will be depending on the initial data and it will be selected by the team members who are doing the analysis.

5.2 Pareto-analysis and Fishbone diagram

Pareto-analysis is known as 80-20 rule method, where in many events about 80% of problems is caused by 20% of causes. Idea is to focus on the most important root causes and not spend time on the minor reasons. Combination of line and bar chart will be prepared, and main problems can be identified. Pareto-analysis helps to identify causes that lead to resolving 80% of the problems (Karuppusami& Gandinathan 2006).

Fishbone diagram is a tool which identifies root causes of problems and influencing factors. This diagram is also called Ishikawa diagram according the inventor of this method. The idea behind the diagram is to recognize the correlation between the causes and events. Fishbone structure is a systematic process and it helps effectively to reach to the root cause of the problem (Shinde et all 2018). The Fishbone diagram contains typically predefined aspects and groups of causes belong together. Fishbone tool can be used together with 5 x Why-method.

Table 8. Fishbone diagram guidelines

Basics	**Steps**
- Analyze and organize primary causes and sub-causes - Helps demonstrate the complexity and interactions - Helps create potential solutions - Clarify ownership and responsibilities	1. Describe the problem 2. Start from top level 3. Continue to primary and sub-causes 4. Review constantly
Tips	**Common categories**
- Use 5 x Why-method when building fishbone diagram	- People - Methods - Measurements - Materials - Equipment’s - Environment

In Table 8 is presented the general guidelines of 5 x Why-method. The table presents the basic guidelines and tips for the use of Fishbone model. In Figure 12 is presented an example template of Fishbone diagram. This template can be filled out when using this diagram on root cause analysis. The bigger template about Fishbone diagram can be found from the Appendix 1.

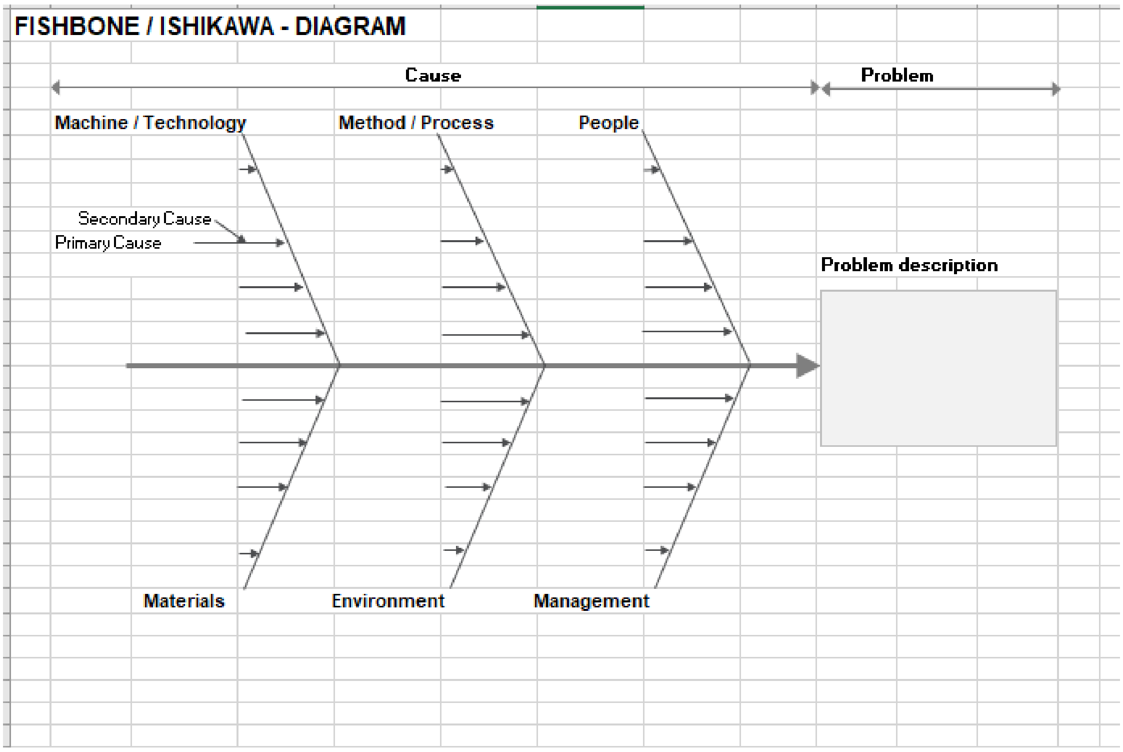

Figure 12. Example of the Fishbone diagram (Valmet 2019)

5.3 Root cause analysis with 5 x Why-method

The 5 x Why-method is a simple brainstorming tool which will help to identify root cause of the problem. Asking 5 whys allows to move beyond obvious reasons and move towards less obvious. In Figure 13 is presented the flowing process of root cause analysis. The presented model is a rough version and in real life the process can be more complex and demand more stages.

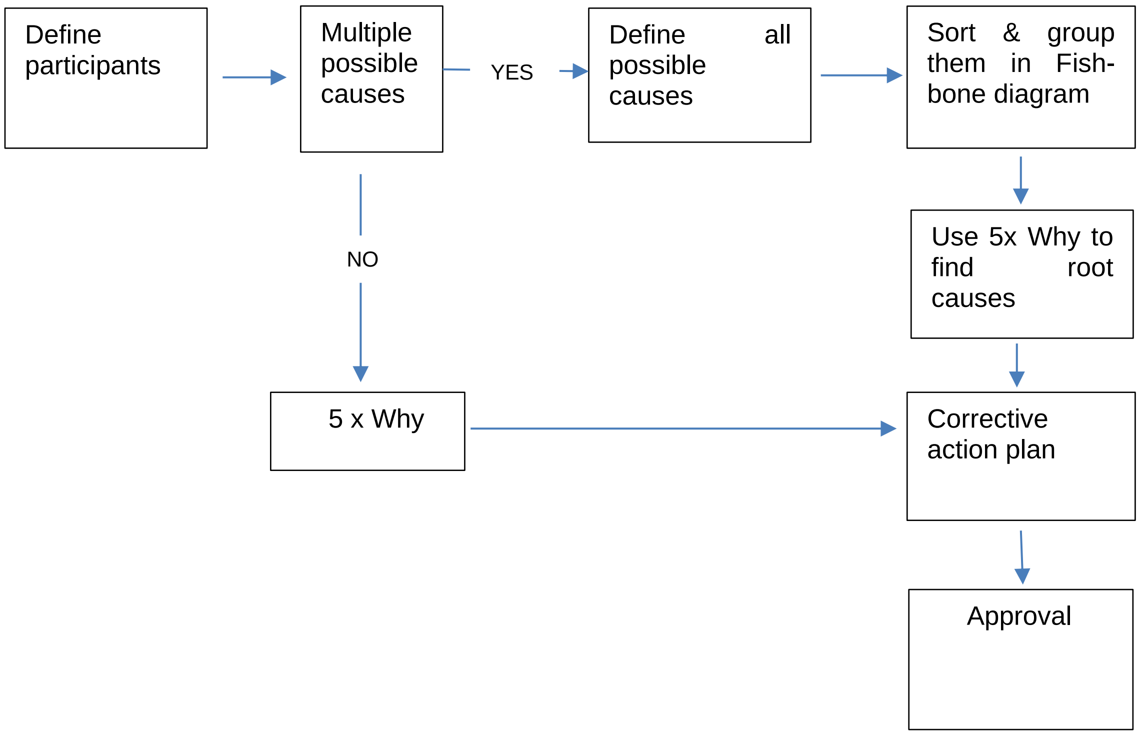

Figure 13. Root cause analysis diagram

First, the participants to the root cause analysis will be selected. Preferably there will be people with different backgrounds in the group and the team leader will be selected from the nominated people. If there are multiple possible reasons, the defining, sorting and grouping of the reasons will be done by using Fishbone diagram. 5 x Why-method is used, when the actual root cause, covering all relevant aspects, need to be determined. Example template about 5x Why-method can be found from Appendix 2.

In more complex cases for the root cause analysis, the OPERA approach is used to answer the question “how do we solve the root cause?”. In OPERA approach, every letter is staging some action. “O” is for own individual ideas. “P” is for par discussion and suggestions of solution ideas. “E” is for explanation of solutions ideas. “R” is for ranking the solutions by efficiency. “A” is for arranging the further evaluation or action planning. This approach helps to limit possible root causes and limits the possible factors behind the main root cause. In Table 9 is presented the general guidelines for using 5x Why-method.

Table 9. 5 x Why- method guidelines

Basics	**Objective**
Steps in 5 x Why 1. Describe the problem and write it down. This will help everybody understand it same way 2. Write down why problem happens 3. If answer do not provide the root cause go to step 1 again 4. Loop until root cause has been identified	- Once general problem has been recognized, “Why” questions help to find a root cause
Tips	**Benefits**
- Choose right people - Give responsibility - Keep the focus on why questions - Utilize together with Fishbone diagram	- Helps to identify the root cause - Helping the initiate thinking process - Leads to the deeper understanding of the problem - Determine the relationships between reasons

5.4 PDCA method and A3-tool

The name PDCA comes from the basic principles of the method; “Plan, do, check and act”. PDCA is a tool for continuous improvement planning. Using it will help to maintain focus to the problem. There are only four steps in PDCA approach, and it can be used together with A3 tool.

The current situation, actions and preferred outcome are described in one A3 paper sheet. Example template of A3 method can be found from Appendix 3. In Table 10 is presented the general guidelines of PDCA-method.

Table 10. PDCA method guidelines

Basics	Implementation model
1. Plan 2. Do 3. Check 4. Act	- Identify and analyze the problem - Develop and implement solutions according to the plan - Evaluate results and re-plan if needed - Implement the full-scale solution
Tips	**Benefits**
- Keep it simple - Fulfil the basic standards of PDCA	- Simple and pragmatic method - Maintain focus

5.5 Issue Tree

The Issue Tree is tool to identify the root causes. It is functioning the same way than 5 x Why-method, but the problems are broken into sub-problems and then even further to smaller parts. With this approach, the Issue Tree becomes detailed and that will help the root cause determination. In Table 11 is presented the general guidelines of using Issue Tree method on root cause analysis.

Table 11. Issue Tree-method guidelines

Basics	Objectives
1. Main problem is written down 2. Problem is broken down 3. Perform analysis	When using this tool, the predominate problem is broken down to the sub-problems and these are broken down even further.
Tips	**Benefits**
- Issue tree resembles Fishbone diagram, but it is more detailed - It addresses the problem similar way than in 5 x Why-method	- Addressing the root cause is the efficient way to solve problems - The root cause is not always easy to understand

In Figure 14 is presented the example template of the Issue Tree. The main idea is to split the problems to smaller ones. The bigger example template about Issue Tree can be found from Appendix 4.

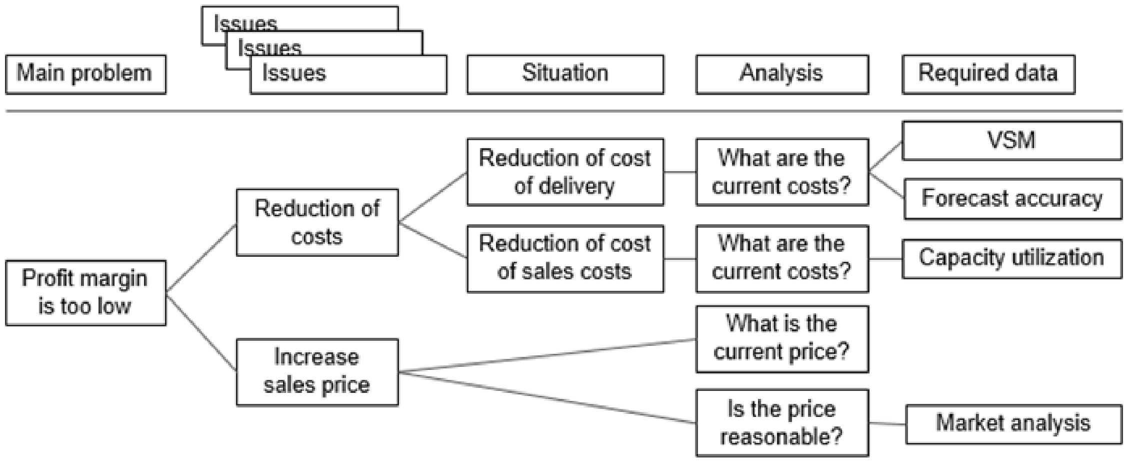

Figure 14. Example about Issue Tree (Valmet 2019)

6. SEGMENTATION

In Table 12 is presented Table analysis about root causes behind the smelt spouts related reclamations. Material of the spout is given on the table because that is very important information on smelt spout related cases. Description of the damages on the spouts is describing only the main issues. Main failure tells the main reason for the reclamation and root causes are based on the analysis of all the collected data. Root cause analysis has been done by a specified team, who have expertise on their field. The main study method has been presented on the table, that indicates different methods which can be used, when searching the root causes behind the failure.

Table 12. Root causes of failures

Material of the spout	**Description about the failure**	**Main failure reason**	**Determined root cause**	**Main study method**
Carbon steel, overlay welded	Cracks on inlet area and corrosion	Cracking	Thermal fatigue	Examination of cracks
Carbon steel, overlay welded	Material loss in outlet part, erosion	Erosion	Erosion caused by smelt	Failure examination of outlet part
Carbon steel, overlay welded	Cracks	Cracking	Thermal fatigue	Examination of cracks
Carbon steel, overlay welded, thermal spray	Cracking in overlay welded area and erosion on outlet	Cracking and erosion	Thermal fatigue	Examination of damages

Table 12. (Continues)

Material of the spout	**Description about the failure**	**Main failure reason**	**Determined root cause**	**Main study method**
Carbon steel, overlay welded	Waterside corrosion, oxygen corrosion, cracks	Corrosion and cracking	Thermal fatigue, impurities on inlet water	Examination of leaks
304L	Cracks, heavy deformation, smelt leak	Smelt leak	Thermal fatigue	Visual examination
Carbon steel, overlay welded	Cracking on outlet	Cracking	Thermal fatigue	Examination of cracks
304L	Cracking and leakage	Cracking and leakage	Weld defects	Examination of cracks
Carbon steel, overlay welded	Cracking and waterside corrosion	Cracking	Thermal fatigue	Examination of cracks
304L	Cracking	Cracking	Thermal fatigue	Examination done by other company
Carbon steel, overlay welded	Erosion, micro cracks	Erosion	Erosion	Examination of eroded parts
Austenitic steel, overlay welded	Cracking, erosion	Cracking	Thermal fatigue	Failure analysis

Table 12 (Continues)

Material of the spout	Description about the failure	Main failure reason	Determined root cause	Main study method
Stainless steel	Cracking on inlet	Cracking	Thermal fatigue	Examination of inlet area
304L	Cracking on inner inlet plate	Cracking	Thermal fa-tigue	Failure examination
304L	Cracking	Cracking	Thermal fa-tigue	Failure examination
Carbon steel	Cracking on smelt side, wa-ter side corro-sion	Cracking, cor-rosion	Thermal fa-tigue, poor quality of cool-ing water	Failure analysis
Carbon steel	Transversal cracking, wa-terside corro-sion	Cracking, cor-rosion	Thermal fa-tigue, poor quality of cool-ing water	Failure analysis
Carbon steel	Deformation, waterside cor-rosion, over-heating	Deformation, corrosion	Lack of cool-ing water	Failure analysis
Carbon steel	Cracking	Cracking	Thermal fatigue	Failure analysis
Composite	Leakage due to cracking	Cracking	Thermal analysis	Examination of cracks
Carbon steel, overlay welded	Erosion, corro-sion, material loss, cracking	Cracks, material thinning	Thermal fatigue, smelt properties	Metallographic examination

Table 12. (Continues)

Material of the spout	**Description about the failure**	**Main failure reason**	**Determined root cause**	**Main study method**
Carbon steel	Cracking	Cracking	Thermal fatigue	Metallographic examination
304L	Cracking on inlet plate, heat affection	Cracking	Thermal fatigue	Metallographic examination
Carbon steel, overlay welded	Cracking	Cracking	Thermal fatigue	Metallographic examination
Carbon steel	Leaking spout due to cracking	Cracking	Thermal fatigue	Examination of cracks
Carbon steel, overlay welded	Longitudinal cracking and corrosion on spout end	Cracking and corrosion	Smelt properties	Failure analysis
Carbon steel	Transverse cracking through spout	Cracking	Smelt properties	Examination of cracks
Carbon steel, overlay welded	Collapsed cooling water space, erosion, cracks on inlet	collapsed cooling water space	Operational reasons	Analysis of operational data
Carbon steel, overlay welded	Leaking spout, burned when water turned off	Leaking	Operational reasons	Analysis of operational data

Table 12. (Continues)

Material of the spout	**Description about the failure**	**Main failure reason**	**Determined root cause**	**Main study method**
Carbon steel, overlay welded	Leaking spout	Corrosion	pH value of cooling water	Analysis of cooling water

From the Table analysis the main analyzed root cause reason behind the failures can be easily noticed. There are a lot of similarities on the descriptions, main failure reasons and root causes behind the failures. In the Table analysis the main reason for the failure has been the cracking on the spout. The examinations have been shown that the main root cause behind the cracking of the spout has been the thermal fatigue. Based on Table analysis the Pareto-analysis can be done. Pareto analysis presents the main root causes behind the smelt spout failures.

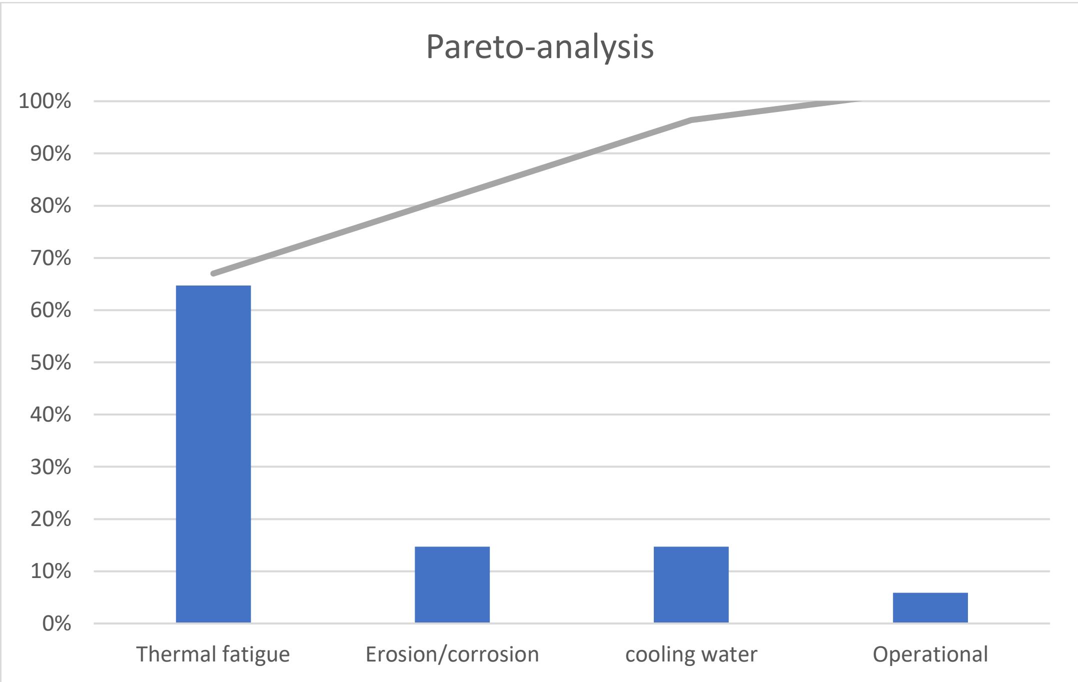

Figure 15. Pareto-analysis about root causes on smelt spout failures

It can be seen from the Figure 15, that thermal fatigue as a root cause covers almost 70 % of reclamation cases. Together with corrosion and erosion as root cause or with problem on cooling water, these causes cover over 80 % of all cases. Based on the Pareto-analysis, it can be said that there are three main root causes which, cause shortened lifetime on the spouts. Those are thermal fatigue, corrosion/erosion and problems with cooling water circulation. Based on the Pareto-analysis those three root causes are the ones where the main interest should be focused on.

7. ANALYSIS OF RECLAMATIONS

The Table analysis and Pareto-analysis showed the main root causes behind the smelt spout failures. Here, the root causes are more analyzed by using the before presented tools which are suitable for root cause analysis. The cases are examples and to show how these tools can be utilized in the actual process of root cause analysis. The order follows the before presented order of main failure reasons and root cause analysis tools.

7.1 Thermal fatigue

On this example, case there is single crack on the bottom of the spout. Cracking in the different locations of the spout can be explained with different structures of the smelt spout and with different materials. Every pulp mill has their own specified design and material for smelt spouts which has been decided based on the boiler and operation conditions. On the Figure 16 can be seen an example about a single crack on a smelt spout.

Figure 16. Cracked bottom of a spout (Valmet 2016)

When starting the root cause analysis using Fishbone analysis diagram, the problem statement must be defined well. Once the problem has been clearly defined all the collected data related to this exact case will be processed. That makes the processing of the possible causes more efficient. Next step is to draw a Fishbone diagram and include all the possible causes under the six standard problem causes. With every problem source the team who is doing the root cause analysis must think through all the possible causes and hypothesis. When possible, root cause has been determined, the hypothesis must be checked with support of other functions. In Figure 17 is presented an example about root cause analysis by using the Fishbone diagram.

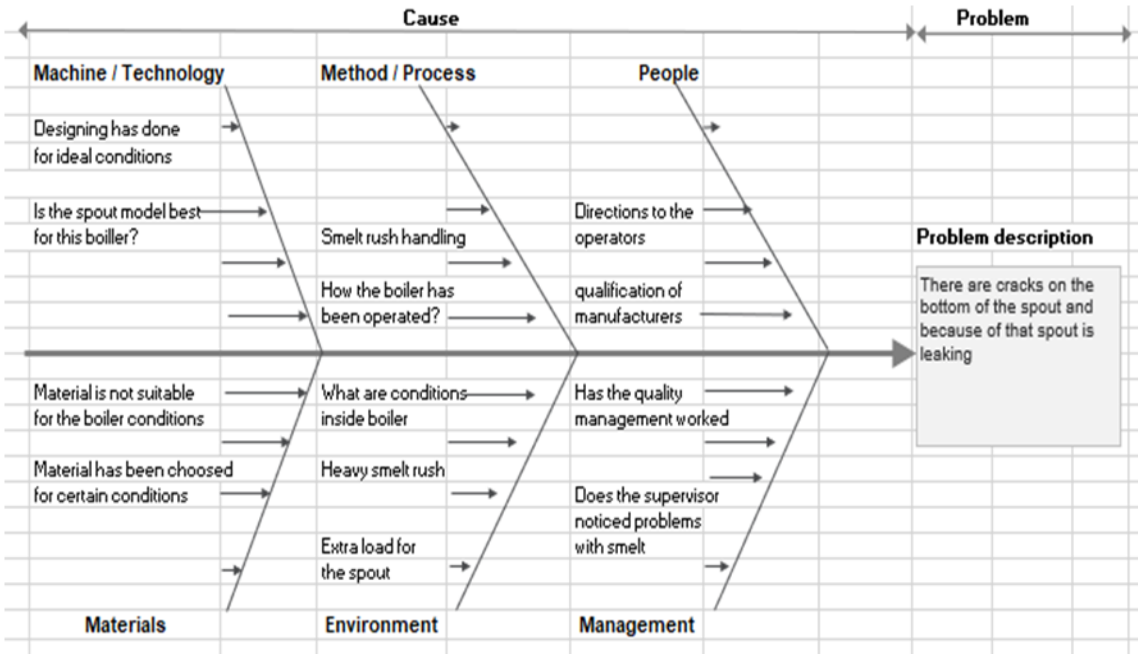

Figure 17. Example about use of Fishbone diagram

In this case, the root cause would be thermal fatigue on the spout. The collected operational data showed that there has been disruption on the cooling water flow, which indicates smelt rushes from the boiler furnace. The micrograph examination confirmed that there was indication about a centralized overheating with extreme spout surface temperatures that has resulted in failure after repetitive expanding and constricting of metal under these conditions. In this case root cause analysis doesn't support switching to another material of the spout because that doesn't help with centralized overheating problem.

Recommendation is to continue operating with the standard carbon spouts, review the cooling water system setup, and take safeguards to ensure proper cooling water conditions such as flow and temperature are maintained all the time.

7.2 Corrosion/erosion

On this example case the main failure and the reason for reclamation is easy indicate. As can be seen from the Figure 18, the main failure on this spout is with spot corrosion on the surface on the smelt spout. Usually the place of the corrosion on the spout and the type of the corrosion indicate the root cause behind the appearing of corrosion.

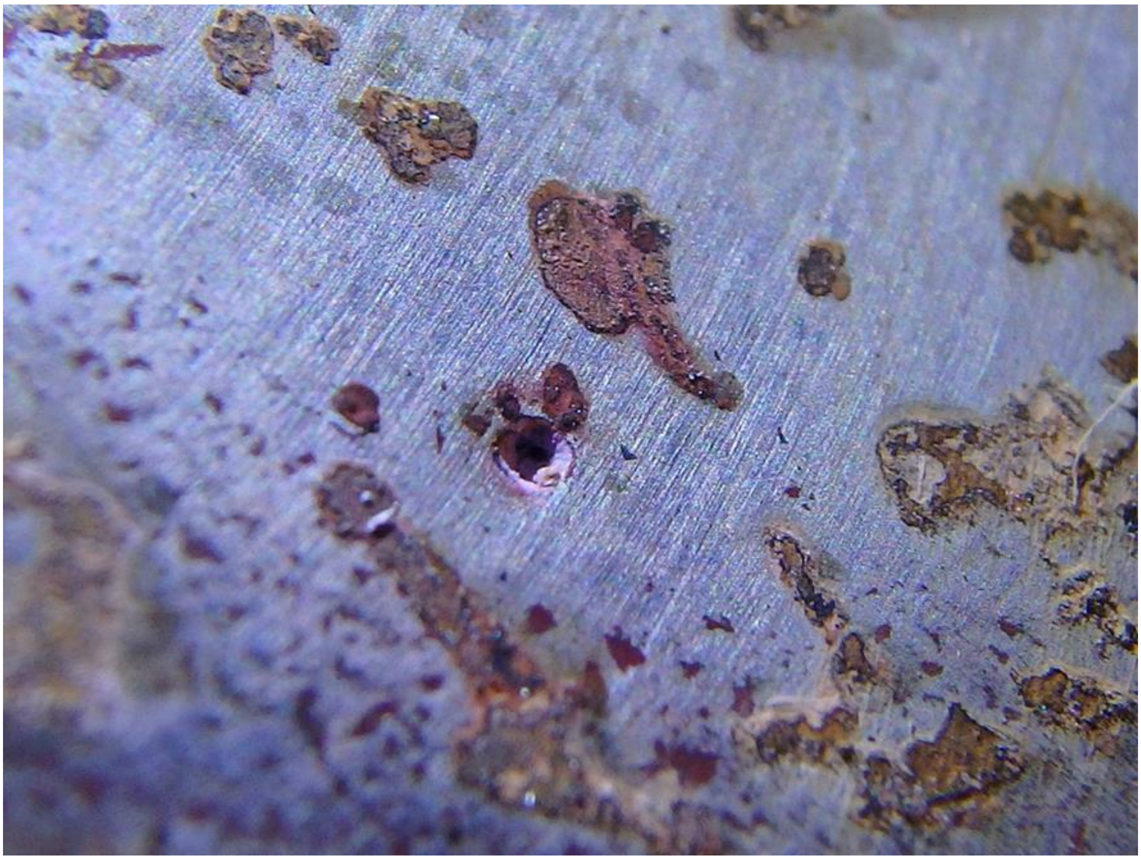

Figure 18. Spot corrosion (Valmet 2017)

Because the main failure reason is obvious in this case and the root cause, which has been led to this situation, needs to be determined, the root cause analysis method is chosen to be 5 x Why-method. First the problem description is written down in order to make the problem defined. Then root cause analysis starts with asking what is causing the problem and answers will be written down. Team who is analyzing the root cause will be looping and asking why until the root cause has been identified. Finally, a simple description about the corrective actions can be presented. That description can be further evolved more with support from other functions. In Figure 19 is presented an example about the 5 x Why-method on root cause analysis.

Define the Problem:
There is spot corrosion on the surface of the spout

What is causing the problem?

1. Operational data is showing high pressure on the collar show- ers

Why

2. Operators are driving with higher pressure, but corrosion risk is lower better at lower water pressure

Why

3. Significant risk for water mist, spatters etc.

Why

4. It is almost impossible to see wetness from under the running smelt.

Why

5. It is important to keep spout dry and avoid any water contact

Why

Corrective actions for eliminating the cause (from the box above):
When keeping the spout as dry as possible and avoiding any water contact, corro- sion risk can be reduced

Figure 19. Example about use of 5 x Why-method

On this case the root cause analysis shows that the problem is with water collar showers which are leaving water to the spout when pressure is too high. Collected operating data shows the high pressure on collar showers and examination of smelt spout verifies the root cause. Root cause analysis supports continuation of operation at the lower pressure of the collar showers on the smelt spouts.

7.3 Cooling water circulation problem

On this example there is collapsed cooling space on the smelt spout and that lead to the reclamation process. Process data from the boiler is the key factor when searching the root cause for cooling circulation problems. Data about cooling water inlet and outlet temperature, cooling water flow and cooling water pressure are the most valuable data for the root cause analysis.

For the root cause analysis, the PDCA method together with A3 tool is used. This method is chosen because the problems with cooling water circulation system are quite complex. The A3 tool is basically presenting the problem and how to solve it on one page. The thinking process is the following; first the problem and the background of the problem will be defined. Then will defined the customer, who is getting benefit from the fixing the problem and success criteria will be determined. Project scope and hypothesis are determined and then the suggested solutions can be presented. Risk analysis is done, and deliveries will be decided. In Figure 20 is presented the example about root cause analysis which has been done from cooling circulation problem.

Purpose
Root cause analysis of reclamation case

Background

Collapsed water cooling space, cracking both ends of the spout. Spout tip facing furnace has a deep cracks which indicated problems with cooling water circulation.

Customer (who shall benefit from this project)
Customer who has done the reclamation and product team of smelt spout s

Success criteria (KPIs/PPIs, Including financials if possible)
Finding the proper root cause and corrective actions for that. Actual results which can be presented to the customer when negotiations about settlement will be started

Project scope
Product team, Hydraulics team. Supported by manufacturing quality team and design engineering team

Hypothesis / Root Cause Analysis
There isn't enough cooling water on the system, collected data from the mill is proving that root cause

Suggested solution/Activity plan

New model of individual cooling water isolation valves installed

Flow modelling is done

Checking the temperature of cooling water outlet

Deliveries

New valves will be promoted to the customer and installed at the site.

Risk analysis

	Risk What is currently the biggest threat to the success of project?	Mitigation What actions needs to be taken to mitigate this risk?	Responsibility Who? By when?
A	Flow modelling	Conditions of the boiler and cooling water circulation	Hydraulics team
B	New design of valves	Calculations	Design engineer
C	Operating principles	Manuals to the operators	Installation group
D	manufacturing	Quality	Manufacturing

Figure 20. Example about use of A3-tool on root cause analysis

When root cause analysis has been done by using A3-tool then the PDCA-method can be utilized. On the Figure 21 the PDCA-method has been implemented to the A3 page. At planning stage, the problem is identified and analyzed. The goals are set, and hypothesis is formulated. At the "do" stage the solution is developed and implemented as planned on the previous stage. On the checking stage, the results will be evaluated and re-planned if needed. On the acting stage the full-scale solution will be implemented.

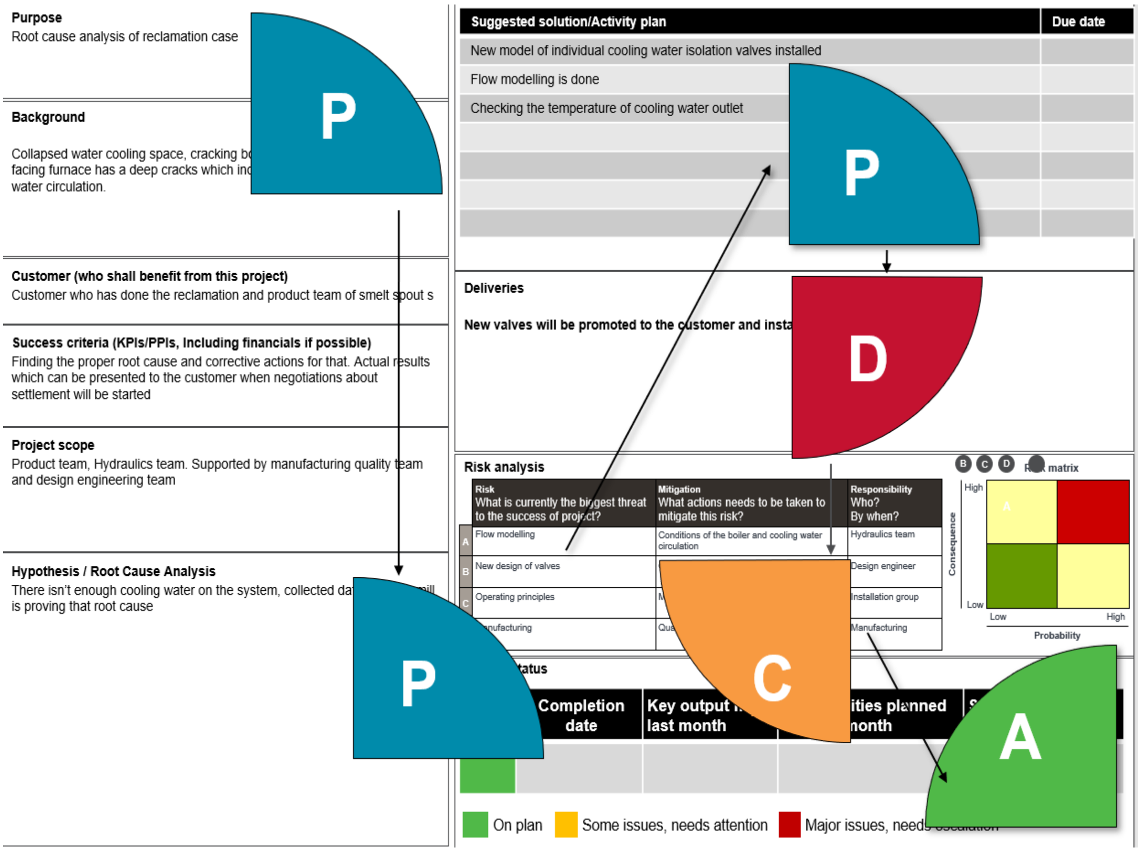

Figure 21. Example about PDCA-method together with A3-tool

The root cause analysis showed that the root cause was the lack of cooling water. The collected data was showing that there were problems with the valves controlling the water flow. These valves are designed to control the spouts cooling water outlet temperature and were installed to address heavy smelt runoffs that had previously resulted in high temperature spikes in the spouts cooling water temperatures. A temperature set point of the cooling water is selected by the operator. The control valves increase or decrease the cooling water flow to maintain the temperature set point. There is also a minimum flow limit of water installed on these valves to prevent the valves from closing off too far resulting in low cooling water flows to the spouts. The examination also shows that there are cracks which are located at both ends of spouts. Spout tip facing furnace has a deep crack which indicated problems with cooling water circulation and this way confirming the root cause analysis.

Another example case about a problem with cooling water circulation was with a leaking spout. The cooling water flow was closed by the operator according to the operational instructions of the mill and because of that action a spout was burned. That makes root cause analysis more complicated. On the Figure 22 can be seen the burned spout.

Figure 22. Burned spout (Valmet 2017)

Issue Tree analysis was used on this example case to find the root cause. Issue Tree is a good tool when root cause needs to be identified and the problem-solving process needs structure. First the main problem is written down and then the problem is broken down by asking question why and how. Then the current situation can be clarified, and the same time can be determined which kind of data and analysis is needed. On the Figure 23 there is an example about using of Issue Tree in root cause analysis.

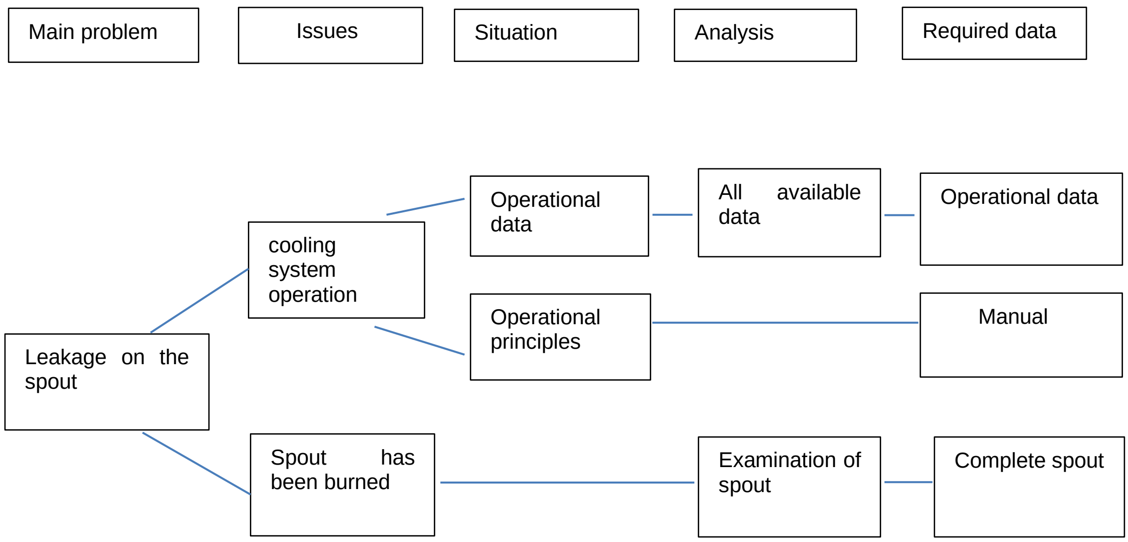

Figure 23. Example about use of Issue Tree

The root cause analysis was made, and it was given two possible scenarios. One of them was the problems with cooling system operation. The collected data was analyzed, and cooling system was working well at the time and there wasn't any interruption of water flow. Condition of spout did not allow make full examination of the spout and because of that the root cause analysis didn't reveal the root cause of this failure. In this case more investigation is needed if reclamation process will be continued.

7.4 Operational damages

When root cause analysis indicates that the failure of the smelt spout has been affected by operational actions, the operation principles will be collected and analyzed. In this example case, the examination showed cracks and mechanical damages on the spout trough surface. This kind of damage can be the result of aggressive rodding practices. Data about how often spouts are rodded and how often spouts get stuck are valuable information on this case. Some of the operators were reported to be chipping the smelt build up in the trough with the rod instead of using a sweeping motion in the trough to remove the deposits. On this case root cause analysis showed that main failure reason was the rodding practices and new instructions were given to the operators.

8. RECLAMATION HANDLING PROCESS

There are five main phases in reclamation process which have been determined in the Valmet Service handbook; receiving the claim, immediate actions, root cause analysis, approval of claims and closing the claim. It has been determined in the Service Handbook that general targets of the customer reclamation handling procedure are fast response time, minimized financial liability and secured high customer satisfaction.

8.1 Receiving the claim

Person who is receiving the claim in a smelt spout related cases is usually a Project Engineer from the spare part team. Project Engineer is the person who has sold and determined the correct parts for the customer. Project Engineer is obligated to inform Mill Sales Manager and Product Manager about the claim case. Mill Sales Manager is responsible about the customer's mill and needs to be updated in all cases related to the named customer. Product Manager is the person who is responsible for a specific product, in this case Product Manager of smelt spouts.

Most issues with reclamation cases can be handled with normal communication between customers and suppliers by emails or meetings. In case addressing the issue in this way doesn't work, client company needs to take more official approach. In these cases, sending official notification is the next step. Notification gives parties a clear message that issue is important and actions are needed to avoid claims. It is the Product Manager's responsibility to send an official notification to the customer and oversee that the notifications have been sent to the suppliers. An official notification is always delivered in writing and is signed by client company's representative. The communication is the most important part of the reclamation process. It is important to answer the customer immediately when claim has been received and inform when the official notification will be sent to the customer. The person who receives the claim will answer to the customer that claim has been received and then immediately informs all the relevant people about the situation.

Table 13. Communication responsibilities

Status	Responsible person	Where to communicate
Receiving the claim	Whoever is the customer’s first contact	Mill Sales Manager, Product manager
Immediate response to the customer	Whoever is the customer’s first contact	Towards customer. Relevant internal distribution, MSM is the most important
Official notification	Product Manager or Mill Sales Manager	Towards customer

Product Manager, or in some cases Mill Sales Manager, will clarify together with the customer the urgency of the issue. In smelt spout related reclamation cases, the case urgency is the most critical thing. Boiler can’t be driven without smelt spouts and if customer hasn’t substitutive ones in the stock, substitutive spouts need to be delivered urgently. If new spouts are manufactured and delivered to the customer, the boiler is on shutdown during that period. Immediate communication is the key factor on those cases. At the same time the possible safety risks and financial losses are clarified. The possible safety risk is taken seriously, and support is offered to the customer immediately.

The reclamation case is opened by Product Manager to the Spotlight which is internal continuous improvement tool. The whole reclamation documentation and conversation will be handled and saved via Spotlight. Product Manager or Mill Sales Manager will inform customer about client company claim handling procedure’s next steps and making clear to the customer if there are any financial liabilities which need to be approved by client company at this first stage of reclamation process. On the following Table 14 the responsibilities at the first stage are presented.

Table 14. Responsibility matrix at the first stage of reclamation process

Action	Project Engineer	Product Manager	Mill Sales Manager
Receiving claim	x		x
Informing other responsible persons	x		x
Clarifying customer urgency		x	(x)
Documenting claim to Spotlight		x	
Informing the customer		x	(x)

8.2 Immediate actions

The Product Manager of smelt spouts gathers all documents, photos and relevant facts and saves those to the Spotlight. Product Manager forms a team, which has necessary expertise to perform an immediate action plan. Immediate action plan is decided together with Project Engineer, Product Manager and Manager of Spare Parts. Director of Spare Parts will be informed about the claim and if new parts need to be manufacture, then manufacturing team will be involved in the discussion. Spare Part Specialist is handling the delivery of the goods to the customer. If there are deliverables at this stage, they are designed to minimize financial losses of customer. Preliminary costs are estimated and approved by Director of Spare Parts or Manager of Spare Parts. After immediate actions and costs approval, Product Manager will communicate the immediate action plan to the customer and implementation of this plan will start as soon as mutual agreement with customer has been reached. Director of Spare Parts will support Product Manager with communication towards the customer if needed and will sign needed documents.

Table 15. Responsibility matrix, immediate actions

Action	Project Engineer	Spare Parts Specialist	Product Manager	Manager, Spare Parts	Director Spare Parts	Manufacturing
Gathering facts to Spotlight	(x) helps if needed		x			
Communication towards customer			x		x	
Actions on ERP system	x	x				
Delivery		x				
Manufacturing						x
Approval of actions				x	x	
Approval of cost				x	x	

In Table 15 is presented responsibilities in the immediate actions phase. In this second phase it is crucial that everyone knows their responsibilities because that makes immediate actions faster. Time is the most important thing when it comes to smelt spout reclamation where the boiler has been forced shutdown. Every minute the boiler is shutdown is costing to the customer. Smelt spout manufacturer needs to act as fast as possible to minimize customer’s loss. The key persons at this stage are Product Manager and Project Engineer together with Spare Part Manager.

8.3 Root cause analysis

In this third stage is important to do the analysis of the reasons which have caused the problem. Product Manager is responsible for implementation of analysis. Mandatory fields in this analysis are solid understanding of likely causes and proposal of corrective actions. Also, possible improvements need to be present at this point. First root cause analysis is done by using Pareto-analysis and creating Fishbone diagram from the case. By using Pareto-analysis, it is possible to determinate the most likely root cause. In this Master Thesis presented previously Pareto-analysis from the causes behind the smelt spout reclamations. That can be used as a base when evaluating the upcoming reclamations. When root cause has been clarified, the Fishbone diagram can be made. If only one clear root cause has been determined, then 5x Why- method can be used for evaluating.

Product Manager, with support from Technology Unit will select the correct team to do the fundamental analysis. This is the team that does the fundamental analysis about the root cause and presents corrective actions which include the possible improvements. Smelt spout reclamations are usually service business-related cases but support be given by product team from Pulp & Energy Business. Pulp & Energy Business line has their own product team for recovery boiler’s smelt spouts and Product Manager who can support smelt spout related reclamations.

There are different roles with different root cause scenarios. Product team is always involved in every stage and usually an appointed person from the design engineering team is involved into the reclamation process. Product team includes Product Manager and the supervisor of Product Manager, Product Manager from Pulp & Energy Business line, representatives from spare part team and if needed Head of the Business unit will support the team. From design engineering team the supporting representative has usually been working with that specific customer before and knows the features of this customer.

In Table 16 is presented different teams and possible root causes in the responsibility matrix. The team that are investigating the root cause is based on expertise and product team is involved in every stage. Other important support functions which are involved all the time in the root cause analysis phase are design engineering team and manufacturing.

Table 16. Responsibility matrix, root cause analysis

Problem area	Product team	Metallurgist team	Flow modeling team	Manufacturing	Design engineering team
Cooling circulation	Support		Flow models, calculations	Support	Support
Corrosion	Support	Calculations			
Thermal fatigue	Support	Calculations			Support
Mechanical damages	Data collection				Support, calculations
Manufacturing errors	Data collection			Documentation	Support
Wrong delivery	Support			Documentation	Support

When problem is related to material and corrosion of that, the metallurgist team will do the necessary calculations and process the available data in order to find the root cause. If the problem is related to cooling circulation, the flow modelling team will do the flow models and calculations. Manufacturing team will provide all the documentation and investigation if problem is related to manufacturing. If manufacturing is done by using a supplier, there is a specific document which will be sent to the supplier. That document demands them to do their own root cause analysis.

If reclamation is related to mechanical damage, the study of the reclamation is done by using the collected data and a specialist if needed. With cases of wrong delivery, spare part team will handle the root cause analysis of the case with support from engineering and will inform the rest of the product team.

8.3.1 Corrective actions

Corrective actions are decided separately in every reclamation case. To the customer, the corrective action is usually a new product or if the problem in smelt spout has occurred because of the boiler driving conditions, seller company isn't obligated to cover those losses to the customer. If root cause analysis shows that there is a need to improve smelt spouts, that will be evaluated together with the design engineering team.

Sometimes the customer is demanding changes to the spout material or changes to the overlay welded area. Those demands will be evaluated together with design engineers, product team and metallurgist team. Also, a member from the quality team and manufacturing team will be involved if these kinds of changes are planned to the design.

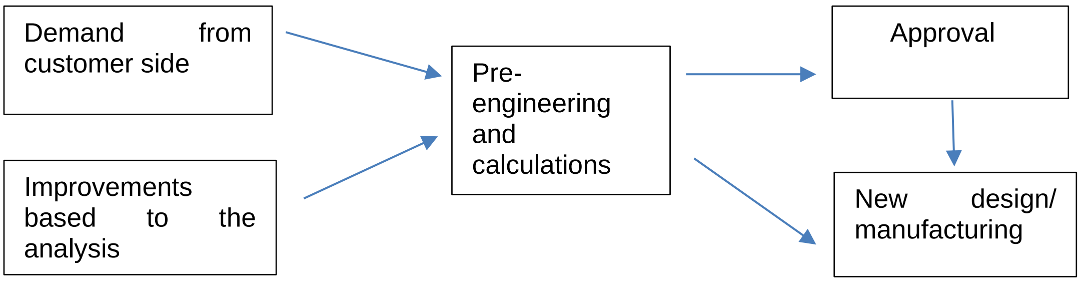

Figure 24. Corrective actions to the smelt spout design

In Figure 24 is presented the way of working when the design changes are made. All changes are made due to the need for improvement, and demand for the changes comes from supplier or own team after thorough investigation. Pre-engineering stage is making sure, that presented changes are possible to execute. At this stage the costs are calculated. After pre-engineering the changes are mandatory to approve. The person who is doing the approving depends on the cost and size of the changes. Before approval, it is mandatory to present pre-engineering results to the people who are responsible about smelt spouts. After approval, the new design can be implemented, and manufacturing of newly designed product can be started.

8.3.2 Preparation to customer negotiation

Before entering the customer negotiations regarding the received reclamation, there needs to be solid understanding of the likely causes behind the failure and proposal for the corrective actions from company's side. If reclamation is regarding an item which has been manufactured by supplier, the root cause analysis with the supplier needs to be on going, when entering the customer negotiations. It is important to know what the customers' expectations regarding the liabilities are, if those are present on the case, before negotiations. Internal agreement about the possible cost split is done internally before customer negotiations. Also, the clear proposal to customer is prepared before entering the negotiations.

8.4 Approval of claims

When the reclamation from the customer will be approved, the work with continuous improvement will be started. Depending on the reclamation type, approving the reclamation can be usually done after the root cause behind the failure is located. Before this stage, every action has been done in order to minimize loss on the customer side. At this point, focus must be on preventing these kinds of failures from happening again. There is a separate process for handling the cases in the continuous improvement tool and that will be presented later this Thesis.

8.5 Claim closing

Claim closing can be done when possible deliverables are in the customers site and final settlement has been agreed with the customer. Retaining of the good customer relationship and minimizing the cost impact are the main goals in final settlement agreement. Product Manager with the support from Mill Sales Manager will participate in the negotiations of the final settlement with the customer. Also, the Head of Technology Unit can be a part of the negotiations if needed. Reclamation can't be closed before the root cause analysis is ready and actions have been internally agreed. Before closing the reclamation, all documentation and approved actions are collected to the internal continuous improvement tool, Spotlight. If reclamation is concerning an item which has been manufactured by supplier, the root cause analysis and settlement needs to be agreed between parties before closing the reclamation.

8.6 Continuous Improvement

In Figure 25 is presented the continuous improvement process, which is linked to the reclamation handling process and root cause analysis.

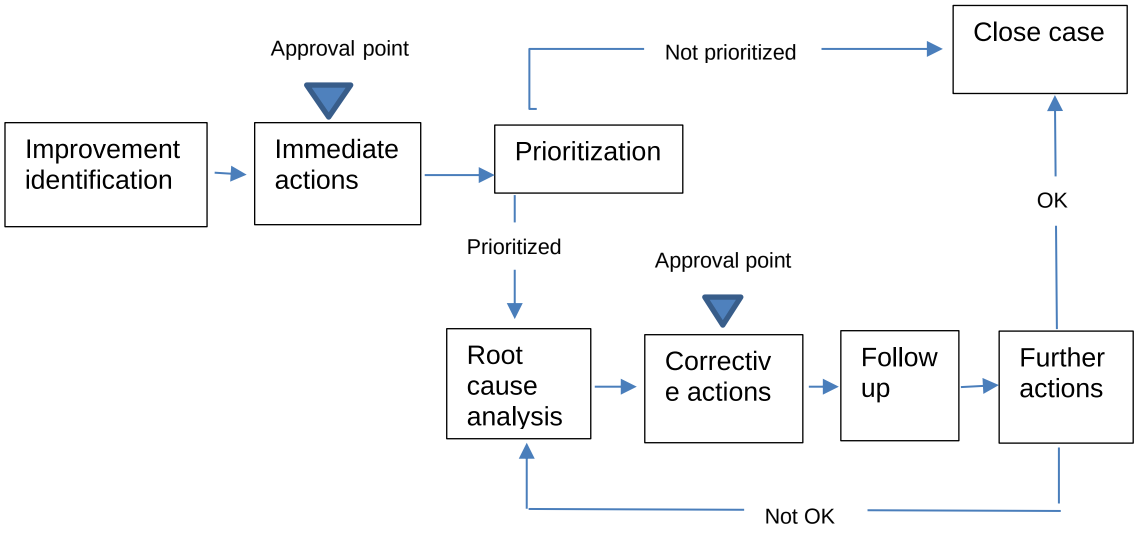

Figure 25. Flow chart of continuous improvement process

Documentation of all steps of continuous improvement is done in a tool called Spotlight. That tool is presented in a later chapter. When the identification of improvement is done, there are several potential inputs for continuous improvement. Potential inputs that are related to reclamations are customer satisfaction, customer claims, cost of poor quality, supplier claims and improvement ideas. There are two approval points in this process when immediate actions and corrective actions are made. Which means that in continuous improvement tool system those actions need to be approved by a person who has set been as an approver. Usually that person is the Head of the Technology or Business Unit.

Prioritizing the cases is important, because it is must be made sure, that the most important cases will be handled immediately. This prioritizing is done by operative forums in Spot-light tool and it is always considering the impact of the matter and estimated efforts which is required put into the case handling.

Root cause analysis in continuous improvement stage is usually done by using 5x Why-method. Other possible methods for root cause analysis are Fishbone diagram, PCDA and Issue Tree. Usually these different methods are the best when they are used together with each other. At first participants for the root cause analysis will be defined and “What is the problem” is clearly defined for the root cause analysis. Corrective actions are done according to previously presented methods.

8.6.1 Spotlight

Spotlight is a global system of quality and HSE system used by client company. All HSE and continuous improvement actions are documented to this tool. All cases that are related to products, services and processes are reported to continuous improvement tool. Named process users are making sure that the cases are investigated, corrective actions are determined, and lessons learned will be shared.

8.7 Lessons learned

Purpose of the lessons learned is to conclude how to utilize results of the improvement on future cases. Lessons learned is performed after final acceptance and settlement has been agreed with the customer. Product Manager invites people who would benefit from the lessons learned meeting. In this session reclamation handling process, cost estimation and corrective actions are presented. The experiences and improvement possibilities will be reviewed together with involved people.

9. CONCLUSIONS

One of the main targets in this Master Thesis was to collect all the available data which relates to smelt spout reclamation cases from the past 10 years and do the analysis about that data. In overall, data collection was successful and there was enough available data for the reliable root cause analysis. However, the available data was scattered in many different databases. Data collection has been done using various different templates during the years, therefore it is possible that some of the data was not found and that information is missing from this Thesis.

It was possible to recognize from the collected data the most important factors behind the smelt spout failures. Chosen segmentation tools, Table analysis and Pareto-analysis, supported in finding the most important factors. It is presented in the theory section the main factors which are usually causing smelt spouts failures and lifetime shortening. These factors are: thermal fatigue, corrosion and erosion in smelt spout surface, cooling circulation problems, unexpected smelt flows and mechanical damages. All these factors were found from the collected smelt spout reclamation data, and the hypothesis behind the failures was correct.

The reason for smelt spout reclamation data collection was to create material and templates which support and save time in future smelt spout reclamation cases. In the theory section it is presented root cause analysis tools which are all in use in the client company of Valmet. Those tools were used in the example analysis to investigate the root causes behind the smelt spout failures. Based on the example cases, all presented root cause analysis tools were suitable for smelt spout related cases. Choosing the correct tool for each case depends on the initial data and preferences of the investigation team. The aim of this thesis was not to introduce any specific reclamation case and its solution. Example cases were used instead to present selected analysis tools.

One of the main targets was also to create standard handling process for the smelt spout related reclamation cases and to develop current reclamation handling process further. The standard process was created based on the combination of existing guidelines which can be found from the business line related handbook of the client company. The created standard process is a mixture of each business line specific procedure because this core product is supported by many Technology Units from different business lines.

During this Master Thesis, reclamation handling process related to smelt spouts was already developed further, as many issues had not been formally recorded and agreed. Currently, the detailed structure is described for each step of reclamation handling process, and it will be further tested and changed if there is still need for modifications.

The smelt spouts reclamation handling process is created to the written form and the next step will be implementation of detailed process to the action. Because there is usually lot of people involved to these reclamation cases, the good communication and clear responsibilities are the most important issues which ensure the fast response time and the best support for the customer. These actors ensure cost minimization in reclamation handling.

The reclamation handling process, systematic approach towards customer in responding and processing the reclamation are very important factors in good co-operation. When reclamation is well handled and process is clear, it will give an opportunity to good customer relationship. In addition, reclamation cases often enable improve company operations and quality. Continuous improvement and lessons learned play an important role in reclamation handling process.

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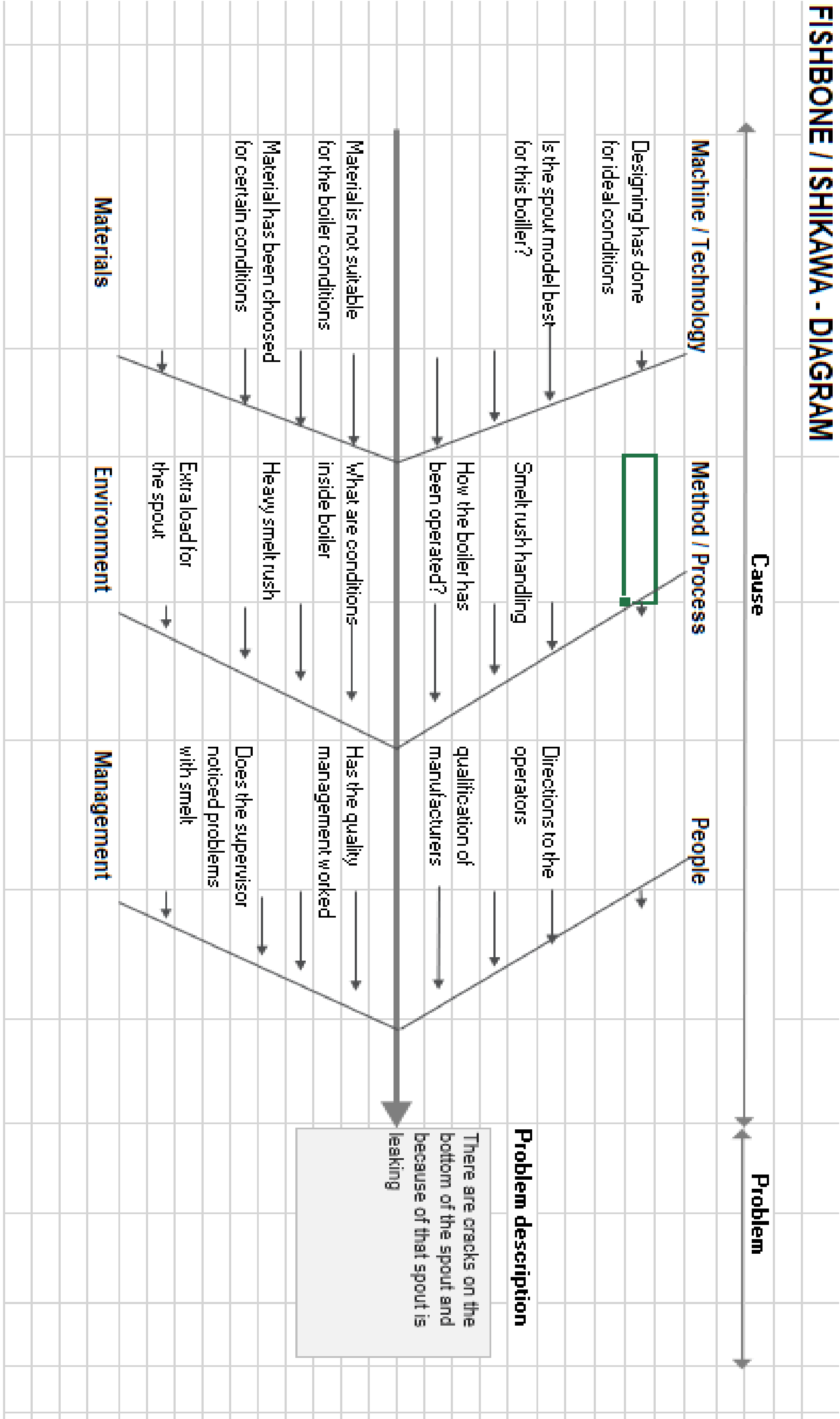
APPENDIX 1. FISHBONE DIAGRAM MODEL



APPENDIX 2. 5 WHYS WORKSHEET

5 WHYs Worksheet

Define the Problem:

Why is it happening? *(Identify each as a concern, influence or control.)*

1.

Why is that?

2.

Why is that?

3.

Why is that?

4.

Why is that?

Loop back until the team is in agreement that the problem's root cause is identified. This may take fewer or more times than five Whys.

5.

Why is that?

Corrective actions for eliminating the cause (from the box above):

APPENDIX 3. A3-TOOL TEMPLATE

A3 Project / tas	Name of A3 project / task	**A3 Team membe**	**Start** :
Owner:	Name of owner		**Revision/date:**
Coah:	Name of coach		

CURRENT STATE, PROBLEM STATEMENT, GOALS & METRICS

Current Condition:

Problem Statement:

Goals and metrics:

Metrics	Goal
1.	
2.	
3.	
4.	

PLAN

Identify & Analyze the Problem

What: Formulate problem statement, set goals & metrics, identify stakeholders and plan communication
Why: Map the process, collect and analyze data, brainstorm cause, formulate hypothesis and verify or revise problem statement

DO

Develop and implement solutions as planned

Develop solutions, design experiments to test solutions and implement the experiments/pilots.

CHECK

Evaluate results, replan or Act

Gather and analyze pilot (DO), validate hypothesis, re-plan if necessary or go back to Plan or continue to Act

ACT

Implement full scale solution and adjust as needed

Implement solution and its standardized process, metrics, daily management & continuous improvement practices.

SPONSORS:

APPENDIX 4. ISSUE TREE TEMPLATE