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Effects of Different Fuels on Combustion Boiler Processes

The analysis of alternative fuel mixtures

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Abstract

The objective of this study is to investigate the effect of different fuels on two fluidized bed boiler systems at the energy company Söderenergi's site in Igelsta, called IKV and IGV P3. Today, recovered waste wood (RWW) is the major fuel share fed into the boilers. However, with an insecure fuel supply in the future, other fuel types must be considered. Based on knowledge from previous fuel usage in the boilers, an evaluation of how other potential fuel mixtures may effect the operation is conducted. The additional fuels considered in the fuel blends are; stem wood chips, cutter shavings, solid recycled fuel (SRF) and rubber.

With elemental analysis of the fuels and established key numbers, the previous fuel mixtures are evaluated. The indications by the guiding parameters are compared with experienced problems and the former condition of the boilers, and the risk limits for the key numbers are adjusted to a suitable level. The potential mixtures are evaluated with the key numbers and the updated limits. In addition to the key numbers, the heavy metal concentration, the heating value, the moisture content and the ash content of the fuel blends are included in the evaluation. The considered damages in the boilers caused by the fuel blends are corrosion, sintering and fouling.

The damage level from the current fuel usage for IKV and IGV P3 is fairly low. The results from the analyzed fuel mixtures show an increased damage risk in the boilers. Additionally, adjustments of the boiler systems are required by some of the analyzed fuel mixtures. In general, the corrosion risk and the heavy metal content will increase in comparison with today's fuel. The fouling and slagging are as well expected to increase for the assessed fuel mixtures. Moreover, the result illustrates an increased ash generation, which demands a reconstruction of the ash cooling system for IKV. Furthermore, the increase of LHV in the assessed fuel mixtures to IGV P3, is likely to require an increased capacity of the flue gas recirculation pump.

In the analysis of the potential fuel mixtures it is found that the corrosion risk expressed by the key numbers is reduced with a higher share of rubber. The heavy metal content is, however, increased, leading to e.g. an enhanced risk for formation of eutectic salts, which as well are corrosive. On the contrary, the fuel mixtures with a high risk expressed by the key numbers, have the lowest concentrations of heavy metals. Due to the results are conflicting, a balance between the risk indicated by the key numbers and the heavy metal concentration must be considered in the evaluation. The fuel mixtures considered causing least damage to IKV are a mixture of 42% RWW, 48% wood fuel and 15% SRF, and a mixture of 70% wood fuel, 20% SRF and 10% rubber. The fuel mixtures considered causing least damage to IGV P3 are a mixture of 85% RWW and 15% rubber and a mixture of 70% RWW and 30% SRF.

Keywords: Fluidized bed boiler; Sintering; High Temperature Corrosion; Used-wood Fired Boilers; Cl-induced Corrosion; Combined Heating Plant

Sammanfattning

Syftet med studien är att undersöka bränslets påverkan på två fluidbäddpannor, IKV och IGV P3, hos energiföretaget Söderenergi. Idag är det huvudsakliga bränslet till dessa pannor returträ (RT). Med en ständigt rörlig bränslemarknad krävs kunskap för alternativa bränslen. Baserat på tidigare bränsleanvändning, är påverkan från potentiella bränsleblandningar på pannan undersökt. Utöver returträ är stamvedsflis, spån, papper-plast-trä (SRF) och gummi med i de analyserade mixarna.

Med elementaranalyser på bränslena och etablerade nyckeltal utvärderas de tidigare använda bränslet. Indikationen från nyckeltalen är jämförd med upplevda problem och risknivåerna för nyckeltalen är ändrade till passande nivåer. De framtida bränsleblandningarna är analyserade med hjälp av nyckeltalen och de uppdaterade risknivåerna. Utöver nyckeltalen analyseras tungmetallhalten, värmevärdet, fukthalten och askhalten i bränslemixarna. De pannskador orsakade av bränsleblandningarna som är undersökta är korrosion, sintring och påslag.

Det nuvarande bränslet till IKV och IGV P3 ger en relativt låg skadenivå. Resultaten från de analyserade bränsleblandningarna visar att skaderisken i pannorna kommer öka och förändringar av pannan kan komma att krävas. Generellt kommer korrosionsrisken och tungmetallinnehållet öka i jämförelse med dagens bränsle. Ökat påslag och slaggning är också förväntat. Vidare visar resultatet att askproduktionen kommer öka, vilket göra att IKVs kylsystem för bottenaskan kommer behövas byggas ut. LHV för de analyserade bränsleblandningarna för IGV P3 ökar, varför troligtvis kapaciteten måste ökas för returgasfläktarna.

I jämförelsen av de olika bränslemixarna är det sett att korrosionsrisken, förutspådd av nyckeltalen, är minskad med en högre andel gummi. Däremot, ökar tungmetallinnehållet, vilket leder till en ökad risk för bildning av eutektiska salter, vilka också är korrosiva. Tvärtemot, bränsleblandningarna med en indikerad hög risk av nyckeltalen, har den lägsta koncentrationen av tungmetaller. Eftersom resultaten är motsägande, krävs en avvägning mellan riskerna indikerade av nyckeltalen och tungmetallshalten. De bränslemixar som är ansedda att vara minst skadliga för IKV är; en blandning av 42% RT, 48% trädbränsle and 15% SRF, och en mix av 70% trädbränsle, 20% SRF and 10% gummi. De bränslemixar som är ansedda att vara minst skadliga för IGV P3 är; en blandning av 85% RT och 15% gummi, och en mix av 70% RT och 30% SRF.

Nyckelord: Fluidbäddpanna; Sintring; Högtemperaturkorrosion; Returträ
Förbränningspannor; Klor-inducerad korrosion; Kraftvärmeverk

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Contents

Terminology and Abbreviations

ar	as received
APH	Air PreHeater
BFB	Bubbling Fluidized Bed
CFB	Circulating Fluidized Bed
CHP	Combined Heat and Power
Conv	Convection
COD	Cross Over Ducts
ds	dry substance
ECO	ECOnomizer
FB	Fluidized Bed
MC	Moisture Content
MCR	Maximum Continues Rating
PWP	Paper Wood Plastic
RWW	Recovered Waste Wood
SH	SuperHeater
SRF	Solid Recycled Fuel
SNCR	Selective Non-Catalytic Reduction
TDF	Tire Derived Fuel

1 Introduction

The usage of biomass as fuel in Sweden is increasing along with the desire to minimize the climate changes. The European Union's 2020 target with the desire to reduce greenhouse gases and increase the renewable energy to 20%, is as well contributing to the increase. [1] Using biomass is a preferable alternative since it is considered carbon neutral [2, 3]. Meaning, the tree absorbs as much carbon dioxide during its life time as it emits when being combusted. The chemical energy in the biomass is converted to thermal energy in boilers to generate heat and electricity. The fuels fed to the boilers are typically forest residuals, recovered waste wood and municipal solid waste. The advantage of using waste wood and other solid wastes is mainly the lower costs compared to virgin wood [3]. Moreover, due to the Swedish law prohibits the waste deposition, incineration is an attractive alternative for materials not suited for further usage. However, there exist drawbacks with using recovered waste, due to it contains damaging substances for the boilers, e.g. alkali metals and heavy metals. These compounds are highly corrosive which can generate high maintenance costs and production losses for the energy plants. It is estimated that 10% of a plant's annual turnover is due to corrosive related maintenance [4]. Other common damages in boilers are sintering, erosion and fouling. Generally, the problems increase with the decrease in fuel quality. E.g. plants using municipal fuels as paper, plastic and rubber, encounter problems with contaminated ashes and gas emissions, as well as ash depositions in the boilers [5].

1.1 Purpose

This Master Thesis investigates the effects of different fuels on two boilers at the energy company Söderenergi's site in Igelsta. The boilers are used for generation of electricity and heat for the district heating network. The different technologies used in the boilers are circulating and bubbling fluidized bed. To each boiler a certain fuel or fuel mix is fed. Effects from the current and the historical fuel feed to the boilers will be evaluated by analyzing several parameters in the fuel, and by established key numbers and indices for fuels and ashes. In other words, an analysis of the fuel and running parameters of the boilers is conducted and conclusions are drawn about caused wear and tear. The thesis also focus on finding suitable levels of the identified key numbers for the two boilers in Igelsta based on the historical scenario. The main objective for the thesis is to evaluate potential fuel blends, based on the analysis of the previous fuel usage.

1.2 Scope

The scope can be described by the following questions.

- What is indicated by the key numbers for the fuel usage during 2013-2017?
- Is the indication by the key numbers consisting with experienced problems?
- Can the value for the risk limit for the key numbers be adjusted?
- What problems can be anticipated for the selected fuel mixes?
- What fuel mixtures show least damage for the boilers?

1.3 Limitations

The project is limited to investigate two out of the four existing boilers at Söderenergi in Igelsta. The boilers are; IKV, the steam boiler for combined heat and power, using a circulating fluidized bed and IGV P3, the hot water boiler for district heating using bubbling fluidized bed. Many possible damages in a boiler may be analyzed, however, the study will be limited to some of these. Only problems related to the gas flow side of the boiler will be considered. Initially the review will focus on fouling, corrosion, erosion and sintering. The heating value, moisture content and ash generation are as well considered. Regarding the recommendations for potential mixtures, only given mixtures from Söderenergi will be evaluated.

1.4 Background

Söderenergi is producing heat to the district heating network in the south of Stockholm, in the Södertälje region. The company is owned by Telge AB and Södertörns Fjärrvärme AB, two companies owned by the municipalities of Huddinge, Södertälje and Botkyrka. The district heating from Igelsta heating plant provides 100 000 households with heat through the district heating network owned by Telge Nät and Södertörns Fjärrvärme AB. Söderenergi also exports heat to a cooperation partner located nearby. The district heating network is one of the biggest and most complex nets in the world. Söderenergi has several plants to produce heat and power. In Igelsta, Södertälje, Söderenergi owns two plants, called Igelsta combined heat and power plant (CHP) and Igelsta heat-only plant, together called Igelsta heating plant (Igelstaverket). Additional plants are Fittjaverket in Botkyrka, Huddinge Maskincentral in Huddinge and Geneta Panncentral in Södertälje. Söderenergi has an annual heat production of 2900 GWh. [6]

1.4.1 The Boilers at Igelsta Heating Plant

The three hot water boilers at the heat-only plant are named IGV P1-3. The boilers were built in 1982 to use coal powder but were later during the 90's rebuilt to use biomass and recovered material as fuels. The CHP plant was built in 2009 and has a steam boiler called IKV. A brief description of the boilers is found below.

IGV P1 is fed with mostly recovered fuel, which means used wood from demolition and packaging from construction, industry and offices. Additionally, milled waste from offices and industry containing paper, plastic, rubber and wood are used in IGV P1. IGV P1 is a grate boiler which means, fuel is introduced on a moving solid bed.

IGV P2 is a pulverized fuel boiler and fed with wood pellets and tall oil pitch. The tall oil pitch oil, is a byproduct from the pulp industry and produced from tall oil. IGV P2 is only used at peak loads and during shut downs of other boilers.

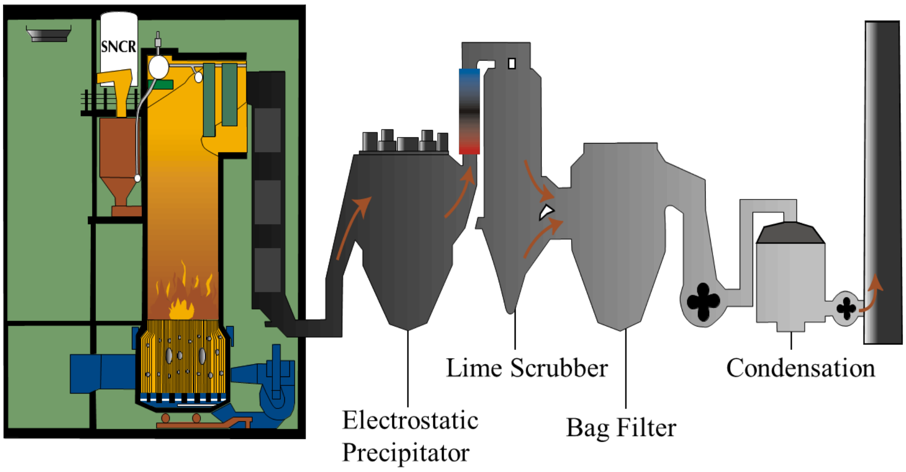


Figure 1: Design of IGV P3 at Igelsta, Söderenergi.

IGV P3, seen in Figure 1, is a bubbling fluidized bed (BFB) boiler and is fed with recovered waste wood chips. Sand and fuel are mixed forming a bed that bubbles when introducing the combustion air. The bed temperature is normally 850°C. IGV P3 also has a flue gas condensation to improve the efficiency. The boiler is in operation approximately 3700 h/year.

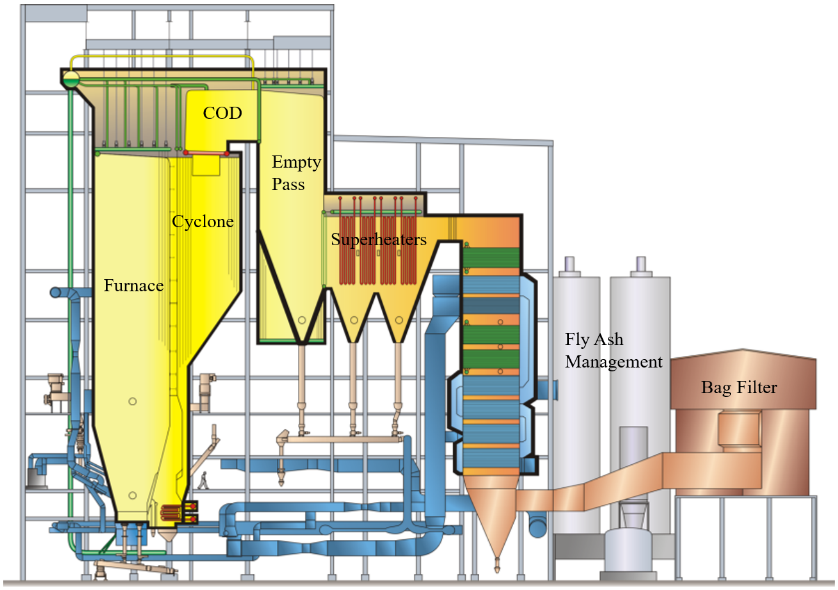


Figure 2: IKV at Igelsta, Söderenergi

IKV, is a circulating fluidized bed (CFB) steam boiler from Foster Wheeler, seen in Figure 2. The technology is similar to the bubbling fluidized bed but here a higher air flow is used causing circulation of the bed. IKV is in operation 8000 h/year. The fuel in this boiler is a energy mix between 70% recovered wood waste chips and 30% wood fuel, which is mix of cutter shavings and chips from stem wood.

Table 1 depicts the power for each boiler.

Table 1: The maximum capacities for the boilers.

Unit	**Power**
IGV P1	85 MW
IGV P2	120 MW
IGV P3	100 MW
IKV	210 MW heat, 85 MW electricity

2 Theory

2.1 Boiler Technologies

The boiler technologies described in this chapter are steam boilers and hot water boilers. Furthermore, the technology of the circulating and bubbling fluidized bed boilers are described, along with the general combustion principles.

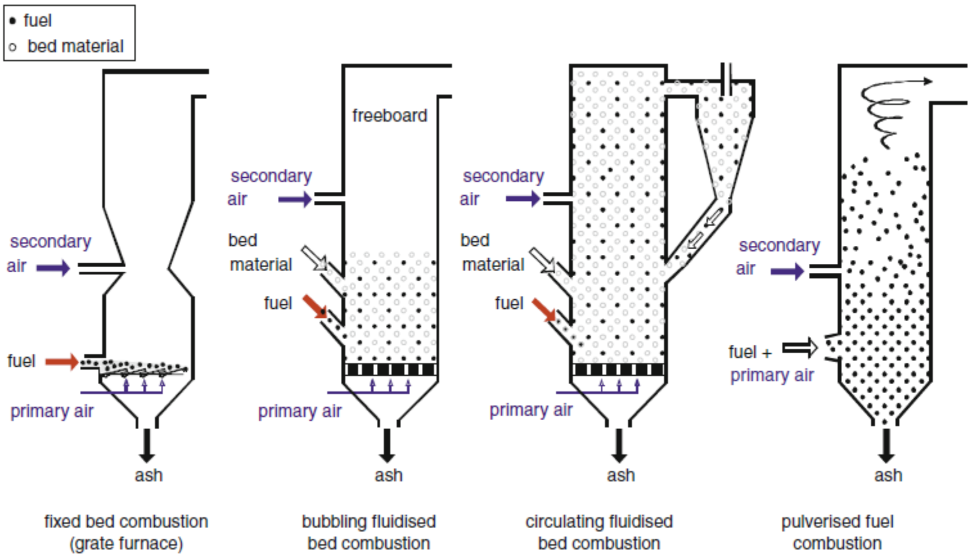


Figure 3: Schematic of common furnace technologies. [7]

Boilers are defined as pressurized vessels designed to transfer heat to a fluid. The fluid is typically liquid water or steam. The water is heated by the hot flue gases generated in the combustion process. The boiler contains a combustion chamber, also called *furnace*, where the fuel is combusted. [8] Different furnace technologies can be used in both steam and hot water boilers. In Figure 3, the principles of the four most common combustion technologies are shown, the fixed bed, the bubbling and circulating fluidized bed and combustion of pulverized fuel.

2.1.1 Steam Boilers

Steam boilers are used for combined heat and power generation. It is a way to produce electricity and at the same time utilize the generated heat for other applications as district heating. In this way the total efficiency increases. [3] Steam boilers are also used in the industry when steam is needed, e.g. the forest industry. Further, steam boilers are utilized for centralized heat production to the district heating network.

The general principles of steam boilers used for CHP are here described. Depicted in Figure 4 is an example of a steam boiler. In the steam boiler, superheated steam is produced to be used to generate electricity in a turbine. To reach this state of the steam, water is heated in different stages by combusting a fuel, turning chemical energy into thermal energy. The hot produced flue gas flows all through the boiler. Highly pressurized water at low temperatures is pumped by a feed water pump to the first heat exchanger. It enters the so called economizer, see Figure 4, where the temperature of the water is increased slightly. The water is then led to the steam drum. In the steam drum the water is heated further and is later led to the bottom of the furnace, through the down comers. The water is then flowing in small tubes in the walls of the furnace from the bottom to the top. The walls of the furnace are called *water walls* [10]. During the time in the water tubes, the water converts to steam. However, the final product from the water walls is a mix of steam and water droplets. The steam and water droplets are separated when again entering the steam drum. From the drum the steam is saturated, however, to

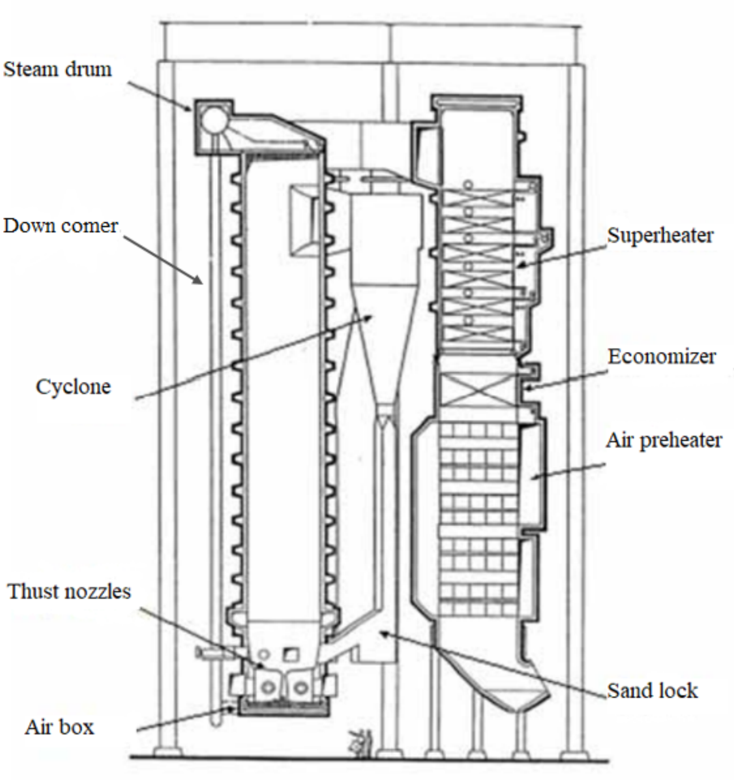


Figure 4: A schematic of a circulating fluidized bed steam boiler. [9]

increase the efficiency of the plant, higher steam temperatures are beneficial. The temperature of the steam is increased in the superheaters, which are also reducing the moisture content in the steam. The superheated steam is then led to the turbine. Due to temperature restrictions on the turbine blades, the steam temperature cannot be higher than 600℃. After the first expansion the temperature of the steam decreases, why, it is interesting to increase the temperature again in a reheater before the next expansion. The two expansions are beneficial when a high electricity production is desired. The excess heat left after the turbine can be utilized in a heat exchanger to the district heating network. [9] As seen in Figure 4 the circulating fluidized bed boiler additionally has a heat exchanger for air preheating. This is a way to utilize the remaining heat of the flue gas and improve the efficiency in the boiler.

2.1.2 Hot Water Boilers

Hot water boilers are commonly used for local small scale heat production or in industry. Hot water boilers are also funded on the principal of flue gases generated by combustion of fuel are heating water in tubes, similar to the steam boiler, however, the water is never heated to exceed the transition stage to steam. Hot water boilers are defined heating water to a temperature of over 120℃. The water is as well pressurized by feed water pumps and to reduce formation of steam the flow of cold water must be controlled. The advantages with hot water boilers, in comparison with steam boilers, are the lower cost, the longer life time and the lower heat losses. [11]

2.1.3 Bubbling Fluidized Bed Boilers

Generally, in a fluidized bed (FB) boiler, the fuel is mixed with a bed material. Sand, typically silica and dolomite, is a common filling material for the bed [12]. In FB boilers 95-99% of the mass fraction in the mix of fuel and bed material, is bed material. [13] As seen in Figure 3 second from the left, air is let in from the bottom of the boiler, passing through the bed and creating a bubbling fluidized surface. A nozzle system at the bottom is providing an even distribution of air in the boiler. The space above the attained surface is called *freeboard*. The fuel is commonly let into the bed or above of the bed. [12]

An advantage with FB boilers in general is the increased possibility to control the bed temperature. It can be held between 800-950℃, and with this temperature the NO_x formation is avoided [12]. However, in the BFB boiler, parts of the combustion is occurring in the freebord, giving a higher temperature in this area [9]. Why it can be necessary with a NO_x reduction system. Additional disadvantages of the BFB are the high investment cost and the high operating costs. Moreover, the BFB boiler has high flexibility concerning moisture content, this due the heat conserved in the sand can improve the drying of the fuel. The heat capacity of the bed material is increasing the stability in the boiler. Meaning a varying fuel feed is not interfering with the boiler performance [13]. More about fuel properties to the BFB in Table 2. [12]

2.1.4 Circulating Fluidized Bed Boilers

Another version of a fluidized bed boiler is the circulating fluidized bed boiler, as previously shown in Figure 4. In the schematic in Figure 3 second from the right, the principles of fuel and bed material are demonstrated. The fuel is let into the lower part of the furnace and together with the bed material the fuel is entrained in the gas flow. Due to the high air velocity, parts of the sand are exiting with the flue gases, why the bed material is captured with a cyclone and reintroduced into the boiler [12, 13]. The temperature of the bed is stable, and can be held around 800-900℃[9]. Additionally, a high amount of finer particles results in more fly ash [13]. The temperature on the bed material from the cyclone has almost the same temperature as in the furnace. In some boilers the bed material is cooled before entering through the sand lock into the reactor. It is an utilized technology due to the high heat transfer between steam tubes and the sand. [9] A finer particle size is required for the CFB than in the BFB due to particles tend to hit the walls, form clusters and fall down into the furnace. Thus, a gradual size distribution in the CFB. [13]

Fuels generating ashes with low melting point should be avoided in FB boilers. Ashes tend to form larger agglomerates and disturb the flow pattern in the fluidized bed. [12] The agglomerates and other incombustible materials will fall to the bottom of the reactor and are ejected along with the ash through openings between the nozzles. The FB boiler can only handle a certain amount of incombustible parts in the fuel since these can get caught in the bottom and disturb the fluidization. The fuel needs to be separated from e.g. metals and larger stones to reduce the risk for disturbances. However, the problem is common although separation is performed. [9] Further important fuel properties for the FB combustion are listed in Table 2. One of the best features of the CFB boiler is the fuel flexibility, different fuels can be utilized simultaneously [13].

Table 2: Important fuel properties for the CFB and BFB boiler. [5]

Property	**Fuel characteristics for fluidized bed**
Heating value	BFB: 5-18 MJ/kg. CFB: 5-30 MJ/kg.
Moisture content	High contents are tolerated, BFB: 20-65%. CFB: 5-65%.
Ash content	Insensitive to ash with high melting point, ash with low melting point can cause problems.
Particle size	50-100 mm is preferable.
Particle shape	Can affect how the fuel is distributed on the bed.
Feeding properties	Should not break and give high portion of finer particles.
Density	Affects the fuel handling. Affects if the fuel burns inside the bed or on the surface.
Alkali content	High content is a risk for fouling and bed sintering.
Chlorine and sulfur level	Possibility for an efficient sulfur capture in the bed.

2.1.5 Combustion Principles

In ideal cases, combustion is a full conversion of organic matter with oxygen to H_2O and CO_2, i.e. an oxidation reaction. The combustion reaction is seen below.

$$C_xH_y + O_2 \longrightarrow H_2O + CO_2$$

The oxygen level affects the conversion rate and is a way to control the combustion reaction. The conversion starts with drying of the solid organic, followed by pyrolysis, gasification and the final oxidation of charcoal and fuel gases. The chemical reactions are found below [13].

Combustion reaction:

$$C_xH_y + O_2 \longrightarrow H_2O + CO_2$$

Pyrolysis:

$$\text{Feedstock} \xrightarrow{\text{heat}} \text{char} + \text{tar} + CO_2 + H_2O + CH_4 + CO + H_2 + C_2{-}C_5$$

Gasification:

$$C + CO_2 \longleftrightarrow 2\,CO$$

$$C + H_2O \longleftrightarrow H_2 + CO$$

$$C + 2\,H_2 \longleftrightarrow CH_4$$

Oxidation of char and fuel gases:

$$C + \frac{1}{2}\,O_2 \longrightarrow CO$$

$$C + O_2 \longrightarrow CO_2$$

$$C + H_2O \longleftrightarrow H_2 + CO$$

$$CH_4 + H_2O \longleftrightarrow CO + 3\,H_2$$

$$CO + H_2O \longleftrightarrow CO_2 + H_2$$

The access of air is an optimization challenge. Too much air cools down the process and insufficient supply gives an incomplete oxidation. In practice the theoretical optimal level is hard to obtain, why typically an excess of air is used. The oxygen surplus can be lowered by separation into combustion stages in the boiler. The different zones increases the retention time and control. [7] The zones are defined from the air distribution in the boiler. In Figure 5, the so called *staged combustion* and the different areas in a BFB boiler are depicted. The air entering from underneath is first drying the fuel, secondly gasification and pyrolysis take place, where the fuel volatilizes and char forms. This is followed by the combustion of

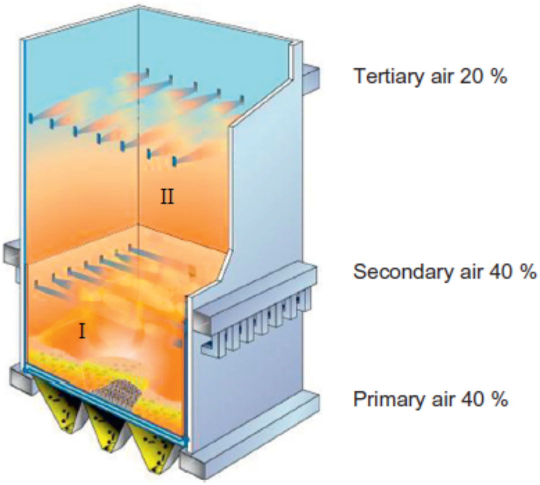


Figure 5: Depicts the different combustion zones in a BFB furnace. [13]

char. All these stages occur in the primary combustion zone (I) which is in the dense bed, between the primary and secondary air inlet. In the secondary combustion zone (II) the complete combustion of the fuel gas takes place due to the inlet of the secondary air. The second combustion area is from the second air inlet to the top of the furnace, in the freeboard. Tertiary air may be needed if the NO_x emissions are to be kept at a low level. [13]

In CFB, the bed is working at sub-stoichiometric oxygen conditions, first when the secondary air is introduced the oxygen level approaches sufficient levels. Parts of the char formed at the first combustion stage (I), can leave the furnace without being combusted. However, they are recirculated into the furnace again together with the bed material from the cyclone and can then be combusted. Thus, the combustion rate is rather long in a CFB boiler. [13]

2.2 Common Problems in Boilers

Some of the common problems in boilers are sintering, erosion, fouling and corrosion. In this chapter they are further described.

2.2.1 Sintering

Sintering indicates solid material fuse together forming larger particles at high temperatures. The melting point of the material is not necessary reached. Sintering is also referred to as bed agglomeration. This problem occur in the bed material, specially for boilers fed with fuels generating ashes with low melting points [9]. Fuels with high alkali levels infer a risk for sintering [5]. The alkali compound decreases the melting temperature of the bed material and a too high concentration can cause the whole bed to fuse or sinter. The sintering may come as a surprise for the operator since it is a rapid phenomenon. To control alkali related problems the alkali levels should be monitored, as well as, to avoid a bed temperature above 900°C. [13] Moreover, changing the bed material reduces the risk for bed sintering.

2.2.2 Erosion

Erosion is another problem in waste wood fed boilers, it appear at tubes and furnace walls. Erosion is a removal of material from a surface through a flow of matter. Erosion damages caused by sand is common in FB boilers. Damages may appear on prominent parts or dimension changing areas in contact with the flow of sand. The tubes in the furnace as well as the central pipe in the cyclones are threatened by erosion. Also the superheaters are exposed to erosion by the sand. [9]

2.2.3 Fouling

Fouling occurs when a layer of particles deposit on a convection heat surface in the boiler. The deposition is due to vaporization of volatile inorganic elements when at cooler temperatures condense on ash particles and heat surfaces. This decreases the thermal efficiency and reduces the heat transfer. It is also bringing about a lower temperature on the water in the tubes, alternatively causing a higher fuel consumption to keep the same temperature. As previously mentioned, fouling of ashes and molten salts are a common problem in boilers fed with recovered material. To reduce and remove fouling sootblowing is used. Another associated problem is slagging. Slagging is considered to be molten or partly fused deposits on furnace wall or convection surfaces exposed to radiant heat. Slag is melted or soften ash particles not cooled down to solid phase when reaching a heating surface.

2.2.4 Corrosion

Corrosion is another problem for biomass fed boilers, here it is referred to as corrosion that can occur on the flue gas side between the feeding and the stack. Corrosion can occur on all metallic components in contact with the flue gas, combustion air, ashes and fuel. The corrosion risk is associated with the fuel's chemical properties. Corrosion infers to the dissolving process of a metal to a more stable compound. The process proceeds due to electrochemical reactions, an oxidation and a reduction reaction, involving ions and electrons, forming an oxide. Three different categories of corrosion are here described; furnace corrosion, superheater corrosion and low temperature corrosion. [5] The corrosion on the furnace and the superheaters is also refereed to as high temperature corrosion.

Low Temperature Corrosion

Low temperature corrosion occurs at economizers, air preheaters, dust filters and flue gas ducts. Problems due to high moisture content in the fuel and low combustion temperatures have been reported. [5]

Superheater Corrosion

Corrosion attacks on superheater surfaces are common. Alkali compounds with low melting points present in reductive environments and at high temperatures cause superheater corrosion. Main conditions causing corrosion attack reported in [5] are; low initial melting point of the ash, low efficiency of the final combustion, high surface temperature of superheater tubes and unbalance between the steam and flue gas sides. The surface temperatures depend on the steam temperature and the design of the boiler. [5]

A known type of corrosion is the *coal ash corrosion*. The name comes from coal firing but the same type of corrosion occurs in biomass fed boilers. High sulfur content is required for coal ash corrosion to occur. Deposits of sodium and potassium sulfates melt and attack the passivating oxide film on the metal and exposes the metal surface to corrosion. This corrosion occurs at 566-732℃. If chlorine is present the scenario becomes worse since Cl reduces the melting point of the ashes. [5]

Additionally, NaCl and KCl are specially corrosive. It has been shown that both the halogen (Cl) and the alkali compound (K or Na) must be present for the corrosion to initiate [3]. KCl is found to specially cause pitting on superheaters [9]. Pitting is a type of corrosion creating small holes in the surface.

Furnace Corrosion

Combustion in stages can bring about locally reducing conditions, this is a risk for the furnace corrosion called *CO corrosion*. The name is due to the high amount of carbon monoxide (CO) in the gas caused by the lack of oxygen. The most important reaction is the carbon reacting with the metal surface. The carbon can be in form of CO or other carbon containing molecule. It becomes absorbed on the surface and through the reaction pure carbon is formed. The carbon diffuses into the metal and reacts, forming inclusion carbides. Carbides are compounds consisting of carbon and metal e.g. Fe_3C, Cr_23C_6 and Ni_3C. The problem with inclusion carbides is the grain formation in the metal alloy. These grains gradually burst the surrounding metal matrix. [5]

In the fluidized bed the corrosion varies over the bed dependent on the partial oxygen pressure. An overall excess of oxygen is not a guarantee against the corrosion since locally deficits may occur. The corrosion risk increases when sulfur absorbents are added, this due to the equilibrium between $CaSO_4$ and CaO may release corrosive sulfur in the oxygen-low zones. This may lead to sulfuration of the metal components in the bed. [5]

Table 3: Melting and boiling points for salts and the lowest expected melting point for salt mixtures. [3, 14]

Single compound	**Melting point, ℃**	**Boiling point, ℃**
$ZnCl_2$	318	732
$PbCl_2$	501	954
$FeCl_2$	677	1026
KCl	771	1407
NaCl	801	1465
$CrCl_2$	845	
PbO	886	1472
K_2SO_4	1076	
$PbSO_4$	1170	

Salt mixture	**Melting point, ℃**
KCl-$ZnCl_2$	230
$ZnCl_2$-$FeCl_2$	300
NaCl-$FeCl_2$	378
KCl-$PbCl_2$	406
NaCl-$PbCl_2$	408
$PbCl_2$-$FeCl_2$	421
NaCl-Na_2CrO_4	592
KCl-NaCl	657
KCl-K_2CrO_4	658

Molten salt corrosion is another type of corrosion occurring at high temperatures. The corrosion is caused by low temperature melting alkali chloride compounds. Mixtures of salts may have a melting point as low as 230℃. Table 3 shows the temperatures of melting points for salts and eutectic mixtures. An eutectic compound is a mix of two or more salts that together have a lower melting point than the compounds by them self. The melted salt deposits on the surface and can transfer the metal oxide into the salt. The extension of corrosion depends on the metal alloy utilized in the furnace and the type of salt melt deposited. [3] The molten salt corrosion is known to have high corrosion rate [9].

2.3 Fuels

In this chapter the fuels used at Igelsta will be described, as well as the effect of the elemental composition of the fuels. Additionally, guiding parameters and key numbers are described. Today Söderenergi use recycled and renewable material as much as possible for the heat and electricity production. The recycled material is material that no longer can be utilized and the energy in the material is recovered by incineration in the boilers. The fuels used at Söderenergi's facility can be divided in three categories; biofuels, recovered fuels and other fuels [6].

Biofuels are made of renewable organic matter and consists of:

- Forest fuel which is forest residues from harvesting as tops, branches and bark that are chipped.
- Wood fuel as wood chips from stem wood, cutter shavings and pellets, which is a refined fuel made from powder from sawmills and planing mills.
- Tall oil pitch, an oil made from a byproduct from the pulp mills.

Recovered fuels are material that cannot be utilized in other ways. The two main fuels are:

- Used wood from industry, construction and commercial operation processed into wood chips. Also called recovered waste wood (RWW) or demolition wood fuel.
- Municipal solid wastes are waste from offices and industry, consists of plastic, paper, rubber and wood, that been milled, separated from sand, metals and other contamination.

Other fuels

- Heating oil, only used to start the boilers or in special occasions during insufficient fuel feed in order to maintain steady state operation. Contributes less than one percent of the fuels used at the plant in Igelsta.

A further description of the different fuels is given with the aim to understand and clarify the properties and problems associated with each fuel.

2.3.1 Wood and Forest Fuel

According to the statistics from the trade organization for energy companies in Sweden, Energiföretagen, the use of wood fuel has been rather stable the last five years and 2016 the national level was at 15000 GWh [15]. Statistics for prices for biomass fuels are administrated by the Swedish Energy Agency. The price for wood chips used for district heating is approximately 190 SEK/MWh, for solid by-products the average price is 160 SEK/MWh and for densified wood fuels (pellets) the average price is 280 SEK/MWh [16].

The forest fuel consists of tops and branches and are left overs from the forest industry. Bark and stumps are other residues included in the forest fuel. In the mix used by Söderenergi, chips from stem wood and shavings are included as well, these are considered as wood fuels. The forest residues cannot be used directly due to the high moisture content. The stumps, tops and branches can e.g. be left and dried at place after felling to reduce the moisture content. The moisture content is, however, still as high as 40-60% in the forest fuel when it is used. [5]

Problems related to firing forest fuels can arise if the moisture content in the forest residues is very high or has a high variety. Furthermore, the finer fractions of the fuel can cause problems in the boiler. These fly up in the boiler and are combusted in the higher part of the reactor which is causing increased corrosion. The corrosion occurs due to higher temperature, fouling and the reductive environment caused by a high carbon monoxide level and low presence of oxygen. In the long run this may lead to tube damages and leakage. The risk is higher for the BFB since the temperatures are higher in the superheater region than for CFB. Comparing the ash melting point between forest and wood fuels, it is typically lower for forest fuels than for wood fuels. [5] In wood fuels calcium is the main ash forming element [7]. The typical elemental composition of wood and forest fuel is listed in Appendix A.

2.3.2 Recovered Waste Wood

To the category recovered waste wood fuel, no forest residues are considered, only wood used for previous commercial applications without the possibility for reuse or recycling are included. According to the statistics from Energiföretagen, the use of demolition wood has increased the last years and 2016 the national level was 3600 GWh [15]. The average price for the recovered wood is approximately 90 SEK/MWh, reported by the Swedish Energy Agency [16].

Since RWW has been used for other purposes before, it is generally contaminated; e.g. with plastic and metal, and chemically with e.g paint. In general the demolition wood creates more problems in the boilers than pure biofuels. The increased levels of zinc and chlorine cause corrosion and surface deposition in the boilers. Additionally, the high levels of sulfur, potassium, copper, arsenic and chrome in demolition wood, are a significant difference compared to wood and forest fuels. The content of these elements leads to formation of a problematic ash. The impregnation contributes mainly to contamination of copper, chrome and arsenic. While the contamination from surface treatment with paint is mostly zinc and lead. The distribution of contamination agents is also reported, typically the majority of RWW is surface treated wood and about 5% is impregnated wood. [5] The typical elemental composition of RWW is listed in Appendix A.

Many problems with RWW are reported. One of the reported problems when using recycled wood, is the influence from the finer fractions, as previously is mentioned [5]. Another difficulty with the finer fractions is the incomplete combustion, leading to the emission of unburned particles exiting with the ash. Further problems with RWW are caused by the metals in the fuel increasing clogging of the combustion air inlets and thrust nozzles. The need to change the sand in fluidized bed boilers is also increased when using recycled wood due to the contamination in the fuel is lowering the melting point of the sand and ash forming sticky particles. Boilers with flue gas condensation using demolition wood fuel may find heavy metals in the water, depending on the origin of the fuel. This can give a demand for a water treatment facility which can require a large investment. [5]

2.3.3 Municipal Solid Waste

The municipal solid waste is in general a mix of paper, wood and plastic, but other combustible wastes may as well occur, as textiles and metals. Impregnated wood can also be a part of the municipal solid waste. The proportions of each component varies, however, according to Strömberg et al. [5], at least 20% wood is needed in order for the fuel preparation to function. The more wood the easier is it to crush the mix. The quality of the fuel mix depends on how the separation of the material sections has been executed. Generally, the customers have demands regarding the maximal size, the size distribution and heating value of the fuel. The heating value of the solid waste varies depending on the composition, but often the heating value is relatively high. The fuel can be delivered in separate fractions or be mixed together. As well the processing to smaller parts may be done at the site of the fuel consumer or at the fuel provider's facility. [5] At Söderenergi two types of municipal solid waste are used. They are categorized in; solid recycled fuel (SRF) and paper-wood-plastic (PWP). SRF is shipped in packages while the PWP arrives lose in trucks. Moreover, the SRF contains no or low amount of wood.

Furthermore, the inhomogeneity of the fuel can generate problems for the boiler since the content of metals, chlorine and other damaging components affect the combustion and the ashes. The chloride level is normally around 0.5% of dry substance. The humidity varies but is often around 30% and the ash content is around 13%. Problems with this fuel corresponds partly to the high chlorine content which gives rise to corrosion and deposits. In addition, the finer fractions creates problems since they burn high up in the boiler or in the cyclones. This generates carbon monoxide which makes it difficult to keep the emissions below the legal restrictions. [5]

2.3.4 Rubber

The rubber mainly comes from old tires, cut and cleaned from metal wires. The fuel is typically called tire derived fuel and is abbreviated TDF. The TDF can have varying composition depending on the origin of the rubber. The general characteristics for rubber are the high ash content, high zinc content and relatively high levels of sulfur. The ash content is around 10-15%, partly due to the steel wires. The zinc content is high due to zinc oxide, ZnO, is used as a catalyst in the vulcanization. It also functions as a filling material. Other fillers are silica and kaolin. The calcium content is relatively high. In some types of rubber the chlorine content is high, especially when using neoprene. The existing high sulfur content origins from the vulcanization of the elastomer. [5]

The zinc and chlorine in the TDF can cause problems to the boiler. At temperatures of 120°C, zinc and zinc chlorides condensate, which gives rise to corrosion in the colder parts of the boiler. In addition to those substances, the metal wire in the tires can interfere with the ash removal. The sulfur content can have a positive effect on the corrosion and fouling when using fuels high in alkali and chlorine compounds. However, if the sulfur content is too high, desulfurization may be neededin the flue gas cleaning. The metals in the TDF are transported in the flue gas which can lead to formation of dioxin if the temperature is close to 400°C. This temperature can be found in the convection package by the heat exchangers. The time of stay at this temperature in the boiler is crucial. [5]

2.4 Fuel Sampling

In order to reduce damage in boilers, the quality of the fuel is analyzed. However, the quality control is critical due to the difficulty to collect representative samples. E.g. 1 gram sample can be used to analyze a fuel delivery at 1000 tonnes. According to Strömberg et al. [5] the error depends up to 80% on the sample taking, 15% on the sample treatment and 5% on the analysis. The different steps in the sampling procedure are described in an European standard. In the standard different sampling situations, tools and methods are described. Additionally, equations are provided to reach a specific accuracy with the sampling. In general it is better to collect several small samples and mix these, than taking few larger samples. Additionally, different analyses requires different amounts of sample, e.g. 500 gram for moisture content and 30 kg for bulk density. Interesting parameters to analyze in the fuels are; the ash content, moisture content, the heating value, the elementary composition where nitrogen, sulfur and chlorine are important parameters. In the ash analyses it is advantageous to measure the level of aluminum, calcium, iron, magnesium, manganese, potassium, phosphor, silicon, sodium and titanium. If a fuel mix is utilized at a heating plant, the composition of the components are preferably measured separately. This to control the levels of dangerous substances in the fuels. [5]

2.5 The Effect of the Elemental Composition in Fuels

The carbon, oxygen and hydrogen affect the heating value of the fuel. The effect of nitrogen being a part of the fuels, is the undesired NO_x emissions. The occurrence of chlorine in a fuel affects the hydrochloric acid (HCl) formation, enhances the corrosion, increases the risk for formation of dioxins and furans and lowers the ash melting point. The sulfur in fuels give rise to SO_x emissions and corrosion. Cl and S may cause ash depositions on boiler tube surfaces, this ash mainly consists of alkali salts as KCl and K_2SO_2. Additionally, the presence of S and Cl interferes with the dew point of the flue gas which impacts condensation in heat exchangers and in flue gas cleaning. [7]

The Cl can fluctuate between HCl and salts. It can also, as mentioned before, form part of harmful organic compounds. This transformation to larger compounds, depends on how Cl is bound in the incoming fuel. The toxic compounds have low volatility and are therefore found in the ash, principally in fly ash. In addition, copper causes problems in presence of chlorine since it catalyzes the synthesis of toxic chlorinated aromatics. [17]

Sulfur, however, has low tendency to form toxic organic compounds. Sulfur can form hydrogen sulfide (H_2S) upon lack of oxygen, a sub-stoichiometric combustion. H_2S can be bound to alkaline ash during sulfide (S^{2-}) formation. Conditions for this formation are a reducing environment and a strong alkaline ash, alternatively metal ions in the ash. The metal ions need to have a high affinity to H_2S, e.g. Cd, Hg, Pb and Zn. In oxidizing conditions, mainly SO_2 is formed and smaller portions of SO_3. Both compounds can form salts with alkali metals. SO_2 is a weaker acid, thus binds more loosely the alkali. If the fuel contains a high amount of sulfur a desulfurization stage is required, this usually removes the HCl as well. The sulfur can be removed if oxidized to SO_3. The sulfur is typically removed from the flue gases after the boiler. [17]

Alkali chlorine compounds are one of the most corroding elements present in the fuel. This corrosion can be reduced by adding sulfur since alkali metals have a higher affinity to sulfur. [9] The sulfur alkali salts are preferred since these have a higher melting point then the chloride salts [5]. The concentration of Cl in the fly ash decreases when the sulfation reaction occurs. As seen in the reaction below, SO_2 and KCl or NaCl react and HCl is formed. [18]

$$2\,\mathrm{MCl} + \mathrm{SO}_{2(g)} + \frac{1}{2}\,\mathrm{O}_{2(g)} + \mathrm{H_2O}_{(\mathrm{g})} \longrightarrow \mathrm{M_2SO}_{4(s)} + 2\,\mathrm{HCl}_{(\mathrm{g})}$$

In the reaction M stands for K or Na, the state of the alkali chloride compound is not agreed upon [18]. The hydro chlorine acid is a famous corrosive acid but in gaseous phase it is less corrosive than the alkaline chlorides, why this reaction is favourable [9]. However, the liquid HCl is still rather corrosive and can cause damage on steel pipes and cause problems for the flue gas treatment [3].

As mentioned, fuels containing potassium or sodium may have problems with corrosion in heat exchangers and superheaters. The presence also lowers the melting point temperature for the ashes. Additionally, the aerosol formation is increased. [7] An aerosol is a fine particulate matter with a particle size of $<1\mu$m [19]. The elements forming most aerosols are primary K, Na, Pb and Zn. A higher concentration of these in the fuel generates more ash, leading to more ash vapors and depositions. However, the formation of aerosol is not proportional to the concentration of the elements. This due to other chemical reactions with the gas phase and other elements e.g. Si, may interfere. [7]

When a fuel containing K is combusted, the potassium can either retain in the ash or be released into the gas phase. In the condensed phase K_3PO_4, K_2SO_4 and KCl are found. With temperatures over 727°C(1000 K), the common species released to the gas phase are KCl, KOH and K, since these are stable in the gas phase at such temperatures. Measurements have shown low amounts of K released from biomass for temperatures under 1000 K. The vapour pressure of KCl and KOH increases rapidly over 1000 K. [20]

If the fuel contains fluor, it may lead to hydrofloric acid (HF) emissions and corrosion. Magnesium and calcium increase the ash melting point temperature. Phosphor causes ash melting and aerosol formation. The elements forming ash can be divided upon their volatility. Al, Ca, Fe, Mg and Si are nonvolatile elements, while Mn and P are semi-volatile. K and Na are rather volatile and Cl, CO_2 and S are especially volatile. The minor ash formation elements as As, Cd, Cu, Cr, Hg, Mo, Ni, Pb, Sb, Tl and Zn are interesting to reduce due to avoiding high heavy metal emissions and regarding the usage of the ash. If the heavy metals form compounds with chlorine the melting point of the ashes reduces drastically, which can be seen in Table 3, causing increased depositions and corrosion. [7]

2.6 Key Numbers and Guiding Parameters

Guiding parameters and key numbers for solid fuels are preferably utilized to analyze the fuels damaging tendencies. The indices and key numbers give an idea of the corrosive and fouling characteristics of the ashes. The key numbers are often empirical and based on experience. The purpose is to function as a guideline and not an absolute prediction. The key numbers can be calculated from element analysis of the fuel and ashes, giving an indication on what can happen or what may have happened.

The common foundation for the key numbers, guiding parameters and indices, is the acid and base concept applied to ashes, called the *Lewis-concept*. The concept is funded on acids being electron pair acceptors and bases being electron pair donators. Common examples of donators are O^{2-}, OH^-, SO_3^{2-}, SO_4^{2-} and $S_2O_3^{2-}$. Typical basic ash compounds are CaO, MgO, K_2O, Na_2O and Fe_2O_3. Example of acid ash components are SiO_2, HCl, S, S_2O, P_2O_5 and TiO_2. When an acid and a basic ash component react, a salt or a mineral is formed. These salts and minerals have different corrosive and clogging characteristics. [7]

The guiding parameters are derived from the chemical compositions of different solid biofuels. When S and Cl are combusted the formation of alkaline (K, Na) sulfates and chlorides are favored. If the present of K and Na is low, gaseous compounds as HCl and SO_x will be formed. This is why the parameter (2S+Cl)/(K+Na) is important. If the molar ratio is lower than 1 the alkaline salt formation is benefited. If the ratio is above 1 the HCl and SO_2 emissions will be increased. [7] The ratio is called *Salt ratio 1* [5].

Additionally, the ratio 2S/Cl is interesting to analyze. When 2S/Cl >1 the formation of alkaline sulfates is increased. A molar ratio <1 indicates a larger formation of alkaline chlorides. [7] The key number is called *Sulfating number*. It can only be used when the amount of free alkali is lower than the quantity of sulfur and chlorine (Salt ratio 1 >1). In other words, the chlorine and sulfur are assumed to compete about the same alkali metal ions. Moreover, it is important that the chlorine and the sulfur have the same way in the combustion process. [5] According to Strömberg et al. [5] the most predictive values are below 1, in these cases sulfur cannot force out the chlorine. Reported in [19] a 2S/Cl ratio over 4 indicates a minor corrosion risk. Furthermore, in Table 4 additional key numbers are presented.

Table 4: Key numbers for fuels and ashes. The key numbers are calculated with the relative molar mass. [17]

Key number	**Denomination**	**Predicts**
$\frac{2Ca+3Fe+Na+2Mg+K}{2Si+Al+3P+3Ti}$	Alkalinity number 1a	<1: Shortfall of alkalinity. >1: Excess alkalinity. Hazardous area when FB firing with quartz sand: >1.
$\frac{Na+K}{2Si+Al+3P+3Ti}$	Alkalinity number 1b	<1: Shortfall of alkalinity. >1: Excess alkalinity. Very hazardous area in FB firing with quartz sand: >1. Moderately hazardous in FB also for >0.5.
$\frac{2Ca+Na+2Mg+K}{2Si+Al+3P+3Ti}$	Alkalinity number 2	<1: Shortfall of reactive alkalinity. >1: Excess of reactive alkalinity. Hazardous area roughly as alkalinity number 1a.
$\frac{Na+K}{2Ca+K+2Mg+Na}$	Alkali proportion	Proportion of strong alkaline substances in total alkalinity (always<1). Very hazardous area >0.5. Hazardous area from >0.3.
$\frac{Cl+2S}{K+Na}$	Salt ratio 1	>1: All free alkali metal can be bound as chloride or sulfate. <1: All chlorine and sulfur can be bound to alkali (if all alkali are free). Values <0.7: hazardous for alkaline sintering. Values >1: hazardous for salt stickiness, formation of deposits and free corrosive acidic gases. Values in between: moderately hazardous. Non-hazardous zones: unfortunately none.

$\frac{Cl+3P+2S}{K+Na}$	Salt ratio 2	>1: All free alkali metal can be bound as water-soluble salt. Values <1: hazardous for alkaline sintering. Values >1: hazardous for deposit formation or sintering by salt melt.
$\frac{Cl}{K+Na}$	Vaporization ratio	>1: All free alkali can be vaporized as chloride (shows the proportion of alkali that can easily be vaporized as volatile chloride). >0.3: high risk of the formation of corrosive chlorine-rich deposits. >1: high risk of the formation of other volatile chlorides than with Na and K. Also high risk of homogeneous chloride-induced corrosion or low-temperature corrosion with Cl admixture by excess HCl.
$\frac{2Si}{Al}$	Feldspar number 1	<6: all silicate can be present as or form aluminosilicate or feldspar. >6: parts of the silicic acid may form alkali silicate with low melting point. <6: generally good. >6: often poor, but not always.
$\frac{Al}{K+Na}$	Feldspar number 2	>1: All alkali is bound or can be bound to the aluminosilicates of feldspar type and with relatively high melting point. >1: Often good. <1: Often poor.
$\frac{2(K+Na)}{3Si}$	Vitrification number (soda lime glass number)	0.5 – 1: High risk of the formation of glass phases with low melting points (melting point around 750°C). 0.2 – 0.5 and >1: minor risk. <0.2: small risk (low proportion of melt).
$\frac{Na}{K+Na}$	Eutectic number 1	Close to 1 or close to 0: good. 0.2 – 0.8: poor.
$\frac{Ca}{Ca+Mg}$	Eutectic number 2	Close to 1 or close to 0: good. Close to 0.5: poor.

The *alkalinity number 1a* is the ratio between the basic and acid ash components. It is used mostly for anticipate sintering in fluidized beds. A surplus of basic components can attack bed material made of SiO_2 and form a melt in the bed. *Alkalinity number 1b* can be used for predicting bed sintering as well, a value >>1 is an indication for this. Great differences between alkalinity number 1a and *alkalinity number 2* is a prediction for rust in the boiler. *Alkali proportion* expresses the portion of the easy moving basic alkali elements of the total basic alkali compounds present in the fuel. Values over 0.5 should be seen as a warning, specially if the alkalinity number 1a and 1b are high. [5]

For fouling and bed sintering, chlorides and sulfates have a huge impact. Salt ratio 1 shows the maximum portion of the alkali metals that can form chlorides and sulfates. A value over 1 is rare for virgin biofuels since the amount of alkali is typically higher than the portion of S and Cl. For used wood the typically value is 0.5, in these cases there is a surplus of alkali metals which can react with P, Al, Si and Ti. *Vaporization ratio* indicates the vaporization of the alkali metals. At 800-900°C, in a FB the only volatiles are Na and K. If the ratio is >1 the alkali is bound to chlorine. If the parameter is over 0.5 it should be seen as a warning. [5]

Feldspar is a compound consisting of a silicate and aluminum together with Na, K or Ca. A silicate is Si and O together with a metal atom and sometimes also hydrogen. *Feldspar number 1* is showing if highly reactive alkali oxides can react with the aluminum silicates. A number <6 is preferable since it indicates the aluminum being a part of the feldspar. This feldspar has a higher melting point than the feldspar without aluminum. A number over 6 implies a surplus of silicon, this is a risk for soda lime glass formation. In FB boilers a feldspar number 1, higher than 6 is common due to the bed material. If the alkalinity number as well is high it is a guarantee for sintering. Recovered material can appear to have low feldspar number 1, this due to metal aluminum in the mix, however, the metal form cannot react and form feldspar. A high *feldspar number 2* (>1) is favorable if the aluminum is in non-metallic form. [5]

lime-soda glass is formed from a mix of potassium carbonate, sodium carbonate and quarts sand. At temperatures at 850-900°C, the alkali carbonates transforms to their oxides that attack the silica in the sand and silicates are formed. At 540°C, the lime-soda glass is created. The *vitrifaction number* is showing how much lime-soda glass that will form. A low number (<0.25) indicating a low formation of glass in the ashes. A high value (>0.5) implies a possible high formation of glass creating a sticky ash. The start of the glass formation is around 750°C. [5]

Eutectic compounds are common in ashes and infer the melting interval of the ash being undefined. The two key numbers, *eutectic number 1* and *2*, show how the two most frequent alkali and respectively rare earth metals are interrelated. The eutectic number should be used with care and not be seen as the absolute truth since the real ash is much more complex than the model used for this key number. [5]

In Table 5 a selection of the key numbers are shown together with values indicating a risk for the boiler.

Table 5: Significance of key numbers and the risk limit. [5]

Key number	**Significance**	**Risk**
Alkalinity number	Risk for alkali attack on silicatic bed material.	>0.8
Alkali proportion	Level for melting points for salts and silicates.	>0.3
Salt ratio	Formation of salt mixtures with low melting points	0.2-4
Eutectic	Lowering of melting points of salt mixtures.	0.2-0.8
Feldspar	Formation of light metal alumina silicates.	>6
Vitrification number	Risk for formation of soda lime glass with low melting point in the ash.	0.2-1

The ratio Ca/S give a indication if self absorption of sulfur by the bed material is to be expected. For fuels with low sulfur content a high value increases the risk of forming alkali chlorides. The ratio Ca/(S+1.5P) is also taking into account the ability of phosphor to react with calcium. P/(K+Na+1.5Ca+1.5Mg) shows if there is enough phosphor to replace the chlorine in the alkali compounds. If the chlorine content in the deposits are to be reduced by adding sulfur, a high Ca/S could indicate a lowered effect of the added sulfur. A high Ca/S in a FB boiler requires a high value of the S/Cl ratio to remain the positive effect. The sulfating number can be used to confirm if there is enough sulfur to reduce the chlorine initiated corrosion. [5] In Table 6 a summery of the previous mentioned molar ratios are given. Reported in [13], when CaO is added to the bed to absorb sulfur a Ca/S ratio of 2 or less is required for a 90% sulfur removal in a CFB boiler. For BFB the ratio is close to 3. However, the sulfation of CaO can be hindered by a formation of a outer layer of sulfate on the particle. An unreacted core of CaO is often found in the ashes. [13] In Table 6 a summery of the previous mentioned molar ratios are given.

Table 6: Sulfur and phosphor molar ratios. [5, 13]

Key number	**Preferred values**
$\frac{Ca}{S}$	<1 <2 for CFB <3 for BFB
$\frac{Ca}{S+1.5P}$	<1
$\frac{P}{K+Na+1.5Ca+1.5Mg}$	>1

Indices for characterizations of biofuels are as well available. One of the indices is the alkali index by Miles. The *Miles index* is calculated from the content of potassium and sodium, Na_2O+K_2O, in the ash (kg on dry basis), divided by the energy content, the high heating value, in the fuel (GJ, on dry basis). The criteria is shown in Table 7. [17]

Table 7: Miles index. [17]

Miles index, kg alkali/GJ	**Interpretation**
0-0.17	Low slagging fuels
0.17-0.33	Slagging fuels
>0.34	Highly slagging fuels

Another index forecasting the level of depositions in boilers, is named *Fouling index*. The Fouling index is calculated though the ratio between the base to acid in oxide form in the ash, multiplied with the sodium oxide content in the ash, see Equation 1 [21, 17]. The fouling criteria is showed in Table 8.

$$RF = mNa_2O\frac{mFe_2O_3 + mCaO + mMgO + mK_2O + mNa_2O}{mSiO_2 + mTiO_2 + mAl_2O_3} \tag{1}$$

Table 8: Fouling index. [17]

Fouling index	**Interpretation**
RF <0.2	Insignificant deposits
RF = 0.2-0.5	Intermediate deposits
RF = 0.5-1.0	Heavy deposits
RF >1.0	Critical deposits

2.7 General Advises

When using a problematic fuel with risk of causing corrosion and fouling, additives can be used to reduce the damages. Problems occurring when using RWW can be reduced by introducing an additive to the fuel or the flue gas. The additive can in different ways obviate the problematic compounds before they deposit on the boiler surface. Positive results have been reported when adding sulfur to the fuel. It has been done through using peat, TDF, digested sludge and pure sulfur as well a water solution of sulfur that can be added above or directly into the grate. Moreover, additives containing silica have given positive results when firing RWW. [5]

How much sulfur necessary to add to reduce the alkali chlorides can be calculated by using the ratio S/Cl. A molar ratio of 0.5 is theoretical enough, however, it depends on how the sulfur is added. If it is in form of sulfates, salts of sulfur acid, or in other fuels as e.g. peat. Furthermore, the calcium content in the fuel can affect, since Ca is competing for the sulfur. If sulfur is added in form of ammonium sulfate after the combustion it is enough with a molar ratio of 0.5-1. By experience the ratio must be higher if the sulfur is added in form of another fuel or as elementary sulfur. This due to the reaction with alkali chloride is through the formation of SO_3. SO_3 forms easier from sulfate that is introduced in the upper part of the boiler than in the fuel. [5]

The fuel quality of biofuels and waste fuels can be improved by using a sieve to separate the finest fuel fractions. The finest fractions have been shown to contain increased levels of undesired compounds. If these are removed the level of deposit related compounds can be decreased. The finer fraction also have a high ash content why it can be extra interesting to reduce these. [5]

3 Description of Boilers and Methods Used at Söderenergi

3.1 IKV and IGV P3

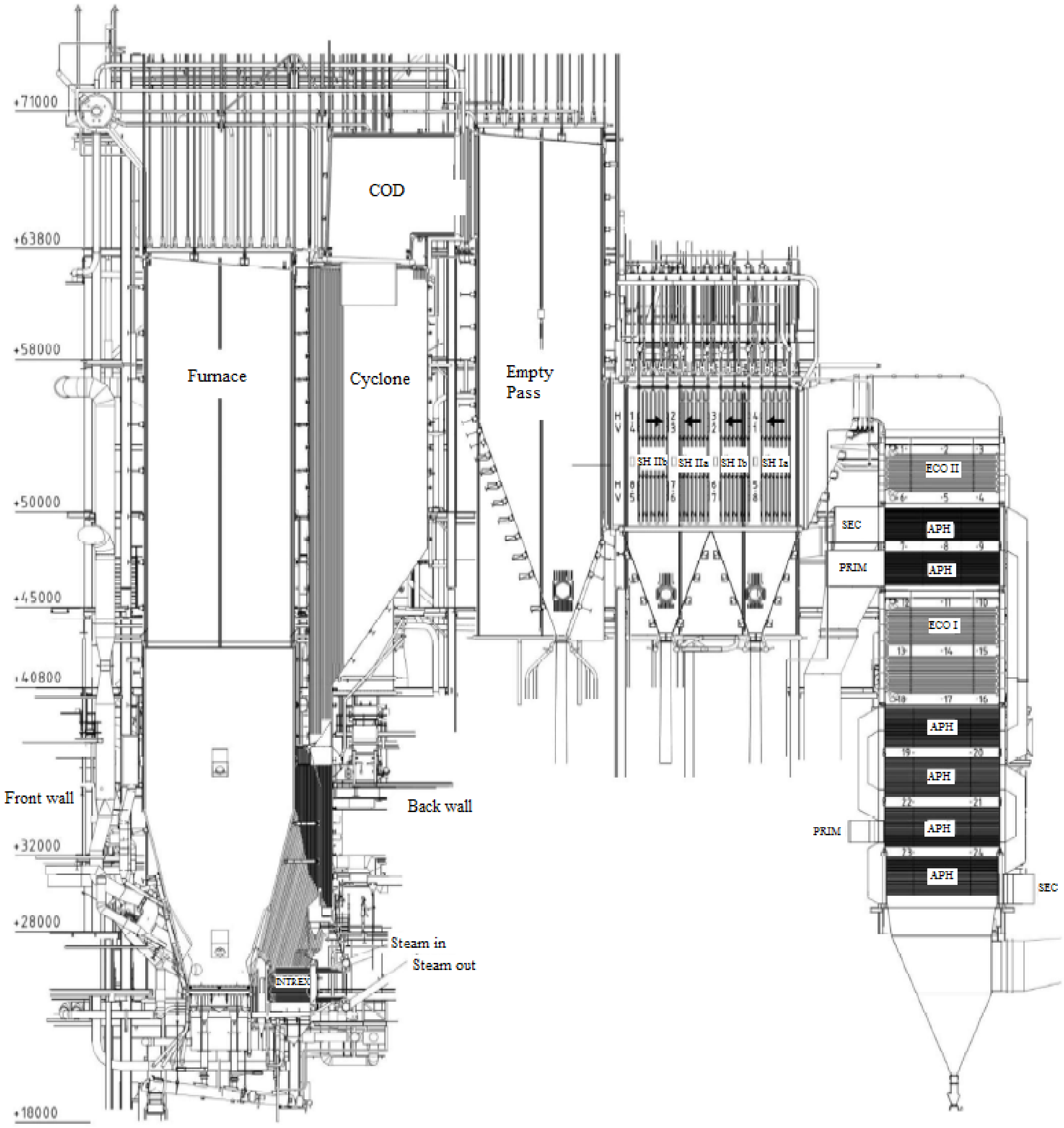


Figure 6: Schematic of IKV at Söderenergi.

The steam data for IKV is 90 bar and 540°C. The sand used in the boiler is 0.5 mm quarts and feldspar. Silo, scraper, feeding screw and cell feeders are used for the fuel feeding to the fluidized bed. The gas cleaning system for IKV includes a bag filter and flue gas condensation. The excess air during combustion is 3-5%. [22]

In Figure 6 the design of IKV is shown. The largest section is the furnace, this is connected to the two cyclones which are recirculating the sand. The flue gas passes the cross over ducts (COD) to the empty pass, to continue to the superheaters (SH) IIb, IIa, Ib and Ia. After the superheaters, the flue gas is passing a number of heat exchangers, starting with the economizer (ECO) II, followed by two air preheaters (APH) and ECO I. Finally to several APHs. In the APH the primary and secondary air is preheated. IKV has in total four SHs, the III and IV are located at the bottom of the furnace and are called Intrex. The flue gas temperatures are found in Appendix B. [23]

The boiler is designed to have a radiation section, the empty pass, to lower the flue gas temperature before being in contact with the superheater. This to reduce the high temperature corrosion risk. In the empty pass only water wall tubes are located, no heat exchangers. [24]

The Intrex are placed in a sand lock and air is used to transfer the sand back to the bed. The sand where the SHs are placed has a temperature of 850°C, creating a high heat exchange efficiency. [23] For SH II which encounter the hottest flue gas, the flow of steam in the heat exchanger is co-current. Meaning, the coldest steam meet the hottest gas. This for cool down the flue gas and mitigate the corrosion attack. SH I is a counter-current heat exchanger which maximizes the heat exchange between the gas and steam. [23]

The way for the boiler water and steam starts from the feed water tank. By one of the two feed water pumps the water is pumped to a high pressure preheater and continues to ECO I and II. The water is led to the steam drum and down to the bottom of the furnace. The water is heated in the water tubes in the furnace and the cyclone walls. The steam is led to the steam drum and continues first to SH Ia-b and secondly to SH IIa-b. The steam is further superheated in Intrex III and Intrex IV and is later led to the turbine. Between the superheaters cooling water is added to reduce the temperature of the steam to keep the final temperature to 540°C. [23]

Ash and sand following with the flue gas, are partly separated from the gas along the way. Hoppers are placed in the empty pass, in the superheater area and by the last heat exchangers to catch the ash.

The design of IGV P3 is shown in Figure 7. As seen in the schematic there are several heat exchangers, here denoted as Convection (Conv), starting with IA and IB. After these the flue gas is passing the back and front wall screen tubes followed by the Conv IIIA and B. Further in the schematic are the superheater and the air preheater, these are however not in use. The flue gas then passes the Conv IVA-C and the upper and lower ECO. From Conv I to the water box after Conv IIIB water tubes are placed in the walls. The stars in the schematic denotes where the steam sootblowers are located.

The boiler water enters from the lower ECO and goes through the upper ECO, Conv IV, Conv III and finally to Conv I. After Conv IA the water is entering the water tubes in the furnace walls to go to the steam drum. The steam drum is used for security reasons to always ensure water in the pipes. Without it the risk for melting of the tube is high. From the drum the water is led to the heat exchanger for the district heating network. [23]

The pressure and temperature of the boiler water are 15 bar and 200°C. The sand used in the boiler is 0.9 mm quarts, SiO_2 and feldspar. Silo, scraper, feeding screw and cell feeders are used for the fuel feeding to the boiler. The cleaning system consists of an electrostatic precipitator, sulfur scrubber, bag filter and flue gas condensation as seen in Figure 1. The excess air during combustion is 3-5%. [22]

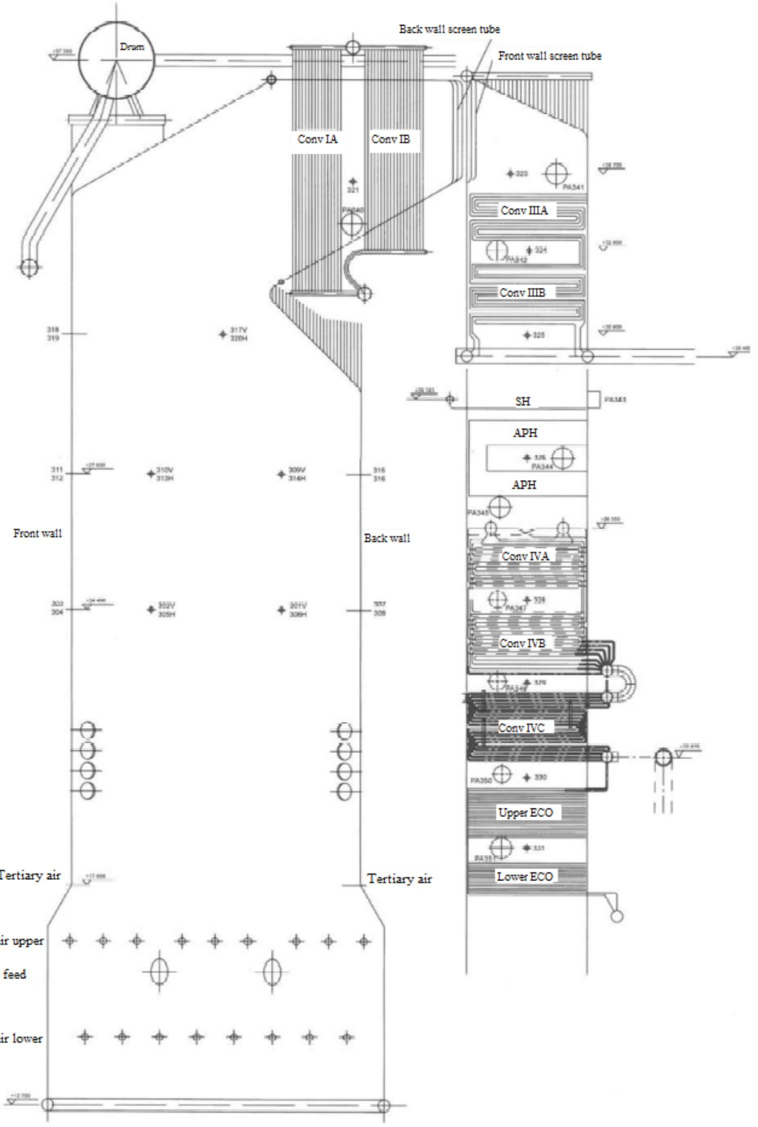


Figure 7: IGV P3 at Söderenergi.

3.2 Additives to the Boilers

Additives to IKV are active carbon, ammonia (NH_3), lime ($CaCO_3$), lye (NaOH), sodium bicarbonate ($NaCO_3$), sulfuric acid (H_2SO_4) and sulfur granulate. To IGV P3 ammonia, lime and lye are added. The active carbon, sulfur granulate and ammonia are added to the furnace, the rest of the additives are used in the gas clean up. The purpose for active carbon is to absorb mercury, dioxins and furanes. During normal running conditions the emissions are kept low without need for the active carbon. The ammonia is added as a selective non-catalytic reduction (SNCR) of NO_x. The lime is used for desulfurization, it reacts with HCl, SO_2 and NO_x. The sodium bicarbonate has the same function as lime, to clean acid compounds from the flue gas. However, it functions better at lower moisture contents and higher temperatures. The lye, NaOH, is added to the condensate from the flue gas condensation to neutralize the acid compounds in the condensate. It also reacts with the SO_2 in the flue gas as an extra cleaning step. Additionally NaOH is added to remove the ammonia from the condensate via a gas membrane. The addition of sulfur is to reduce the risk for corrosion by alkali chlorides at the superheaters and in the furnace. [25]

3.3 Historical Issues

3.3.1 IKV

In the overhaul reports of IKV made during the summer stops 2013-2017 earlier damages are stated. In short, erosion and corrosion are found locally in the boiler. Fouling is found in general all over the boiler, however, before inspection most of it is removed. Damage on the primary air nozzles are reported in several overhaul reports. A summery of the reported damages are provided below.

Erosion in the furnace, specifically at:

- Tubes at the back and side walls, see Figure 6
- At the top of the furnace where the flue gas leaves
- The corner pipes

Additional erosion damages on:

- The air preheaters, specifically secondary air preheater close to the sootblowers
- The sand return pipes
- The edges of ECO I and II toward the front wall
- The benders on Intrex SH III

Corrosion on:

- Side walls tubes in empty pass, close to the horizontal flue gas pass to SH I and II. The corrosion was found 2015 on the tube side not facing the gas flow.
- On the wall between SH Ia and b
- Screen tubes, first found 2015
- Low temperature corrosion on the lowest rows of the air preheater

Refractory lining damages at:

- Mid outlet canals in the back wall
- Cyclones

In a study conducted by SP Sveriges tekniska forskningsinstitut [26] 2013, depositions and bed material from IKV were investigated. Three different deposits at Intrex during February and March 2013 were analyzed. Two of the deposits were thicker and appeared to be sintered sand and ash. The other sample was a thinner deposition. The results show different elemental composition of the thicker and thinner deposits. The thinner tube deposition contained higher concentrations of Pb and S while the thicker had higher concentrations of Si. Zn was present in the depositions as well as K, these have a effect of lowering the melting point of the ash. The thicker deposition was explained to be caused by sintering of alkali and Si. The Fe content in the depositions was low why the corrosion of the tubes appear to be low. In general the Cl content was low and the fouling problems rather seemed to be related to S, due to the high S content. [26]

3.3.2 IGV P3

For IGV P3 overhaul reports from 2015-2017 exist. These show corrosion, fouling and erosion damages in the boiler. Hard and thick depositions were found on furnace walls and at Convection IA, the other heat exchanges did not experience fouling. The refractory lining at the furnace walls was damaged. Further locations with experienced problems are here described.

Erosion on:

- Primary air nozzles
- The tubes in upper part of the water walls
- Screen tubes
- Tubes in Conv IB

Corrosion on:

- Primary air nozzles
- Sootblowers

According to [27], pitting corrosion have been found at the Eco, this damage was reduced by increasing the incoming water temperature. Erosion have been found at the floor by Conv IA and IB. It is thought to be caused by sand flying up and sliding down the tilting floor. The problem has been reduced by covering the floor with a layer of refractory. Additionally, erosion was found at the screen tubes, at the part closest to the ceiling. The loss of refractory lining in the furnace was caused by a damaged nozzle used for injecting pre wash, a water used for cleaning in other processes. However, the general damage rate is low for IGV P3. [27]

3.4 Sampling Method at Söderenergi

3.4.1 Fuel Samples

Samples of fuel are collected from the deliveries to Söderenergi. Deliveries come by ship, trucks and train and the sampling method depends on the delivery type.

For samples from ship deliveries, a high amount of samples are collected due to the large cargo. Every 20 minutes three digs with a spade are collected from different locations from the scoop that is unloading the fuel. The humidity of the sample is kept by storing the sample in a resealable container. Samples gathered during one hour are mixed and separated with riffling. A stationary riffle is shown in Figure 8. Samples are divided to have final mass of 1.5 kg. An alternative method for dividing is by making a square 5-10 cm high, dividing it in four squares. Taking every other square and making a new square with these. Removing the other squares. Performing the same procedure until desired mass is obtained. [28]

Fuel samples from trucks are collected randomly, only the deliveries from two of the suppliers are analyzed every time. A software tells the driver when it is time to leave a fuel sample. The truck is then driving to the fuel reception and a mechanical probe is used to take the sample. The probe is lowered down into the load and a sample is collected. For one truck five samples are collected, from different places, these are gathered in a bucket. The sample in the bucket is later separated into a smaller volume. This is performed manually by spreading out the sample on a table, making lines in the mass, separating the fuel. Volumes are later randomly chosen from the lines and placed on a metal tray. The final fuel sample is weighted and placed in an oven where it is dried over 20 hours. When the fuel sample is dry and weighted again, it is stored in a plastic bag. Each supplier has separate plastic bag for the random samples gathered during a month. Each month the bags are sent for analysis to an external laboratory

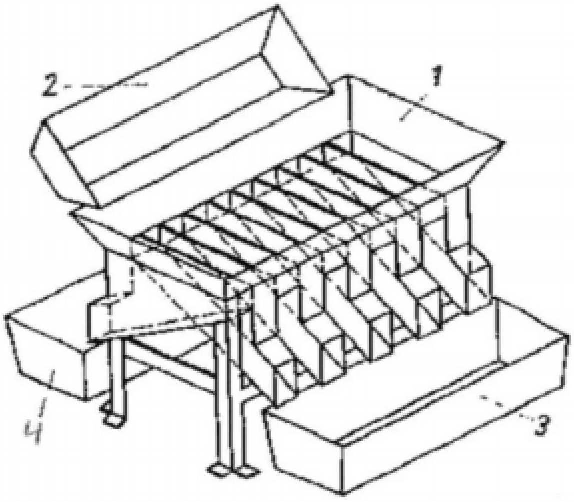


Figure 8: A schematic of a riffle used to separate fuel samples. [28]

called Eurofins. The fuel reception orders the analysis for each supplier and can make changes in the orders, e.g. adding elements to be analyzed.

Regardning the number of fuel suppliers, it varies for type of fuel. Rubber is only delivered by one company. Recovered waste wood is delivered by many suppliers. Meaning, the number of samples for each type of fuel each month is different. Recovered waste wood and solid recycled fuel are delivered by boat. The ship deliveries are analyzed every time and the samples are sent to the laboratory twice a week. [29]

Additionally, what is analyzed depends on the type of fuel. RWW, rubber and SRF are analyzed on the most parameters. In addition to the elementary analysis of C, H, N, Cl and S (% of ds), the heating value, moisture content and ash content, which are analyzed for every fuel type used at the plant, content of Al, As, Cd, Co, Cr, Cu, Hg, K, Mn, Na, Ni, Sb, Tl, V and Zn (mg/kg ds) are analyzed. A reason to why the trace elements are only analyzed for the recovered materials is the high contamination. In virgin wood and forest residuals the levels of these species are lower and do not vary as for e.g. the used wood. Moreover, it is a way for Söderenergi to control the quality of the fuel towards the suppliers.

3.4.2 Ash Samples

Ash samples are collected every week from the bottom ash and the fly ash from the boilers. The fly ashes from IGV P1-3 are mixed. However, the bottom ash from IGV P3 is kept separately. The fly ash from IKV is stored in two silos. When these are emptied the driver performs the sampling, taking a volume of 0.5 liter from each silo. Samples of the fly ash from IGV P1-3 are collected once a week and are performed in a similar manner. The driver is using a scoop to take the sample from the truck, gathering one liter. For the bottom ashes the personnel at Söderenergi perform the sampling. The sample is collected with a shovel, approximately one liter for each ash. The ashes are stored separately in named closed containers. The bottom ash samples collected during a month are mixed and sent to analysis, the same procedure is for the fly ashes. The metal analysis is performed at an accredited laboratory called Eurofins. The metals analyzed for the bottom and fly ashes are: Al, As, Cd, Co, Cr, Cu, Hg, K, Mn, Na, Ni, Pd, Sb, Tl, V and Zn (mg/kg dry ash). Additionally, for the fly ashes S and Cl (% of dry ash) are analyzed.

4 Method

Data from Söderenergi's historical fuel analyses are assessed, among these is the elemental analysis of the fuels RWW, shavings, wood chips, rubber and SRF. The elemental composition of the fuel is compared with literature values and Söderenergi's in-house rule of thumb limits. With the historical fuel analyses and additional analyses required by the thesis, key numbers for IGV P3 and IKV are calculated for the fuel usage during 2013-2017. The predictions from the key numbers are evaluated together with overhaul reports, ash analyses and a deposit analysis in IGV P3. From this, the risk level of the key numbers are evaluated. The adjusted risk levels are used to evaluate potential fuel mixtures for IKV and IGV P3. Furthermore, a comparison of the elemental composition of the mixtures with the in-house rule of thumb limits is performed for the potential fuel mixtures for IKV. The increased ash generation is as well considered in the analysis. From the evaluation, a recommendation for potential fuel usage for IKV and IGV P3 is given.

The following key numbers are considered in the thesis; alkalinity number 1a, 1b and 2, alkali proportion, eutectic number 1, feldspar number 1 and 2, salt ratio 1, sulfating number, vaporization ratio, vitirification number and the ratios Ca/S, Ca/(S+1.5P) and P/(K+Na+1.5Ca+1.5Mg). These key numbers are elected due to being most relevant for the FB technology. The key numbers are calculated from elemental analyses of the fuel used at Söderenergi. The number of historical analyses varies for the different types of fuel. The number of analyzed parameters is also dependent on the type of fuel. To have a complete set of analyzed parameters for all fuel types, additional analyses are made.

The historical data from the RWW fuel analyses is used to calculate the key numbers; salt ratio 1, eutectic number 1, feldspar number 2, vaporization ratio and sulfating number. For all analyzed deliveries only these key numbers are calculated, this due to lack of analyzed parameters in the fuel samples preventing the calculation of the remaining key numbers. Since the data is reported in mass base (mg/kg ds) in the analyses, the concentrations are recalculated with the molar mass for each substance, to molar basis (mole/kg ds). How this is done is shown in Appendix C. The key numbers are calculated with the molar fractions in each delivery and the equations in Table 4. Each delivery has a different weight, why weighted values for the molar fractions are calculated for each analyzed parameter. The weighted values take into account the percentage of the delivery's weight of the total weight.

Forest fuels and wood fuels are not analyzed on as many parameters as RWW, why the additional elemental analyses are necessary. However, additional analyses of elements are required for RWW as well to calculate the remaining key numbers. Three extra elemental analyses of shavings, stem wood chips, RWW, SRF and rubber are acquired from the same laboratory, Eurofins, performing the historical elemental analyses. The fuel analyses are compared with the in-house rule of thumb levels for each fuel and mixtures. Examples on compared parameters are the heavy metal composition, moisture content (MC) and LHV. The rule of thumb values are valid for IKV.

Ashes from IKV, IGV P1 and P3 are as well sent to the accredited laboratory for analysis, this to calculate ash indices and key numbers for the ash. The same key numbers are calculated to compare with the fuel.

An elemental analysis of fouling in IGV P3 is performed. Samples of depositions are collected from several locations in the boiler during the annual overhaul. The analysis are performed to find where the corrosive elements can be found. The samples are sent the same accredited laboratory as the fuel samples.

5 Results and Discussion

In this chapter the results from historical elemental analysis, key numbers, comparison with in-house rule of thumb values are presented and discussed. An evaluation of previous fuel usage in IKV and IGV P3 is performed to have a base line for the evaluation of the potential fuel mixtures for the boilers. The potential fuel mixtures for IGV P3 and IKV are as well evaluated in this chapter.

5.1 Elemental Analysis of Fuel

A comparison with literature values of the elemental composition of the fuels is performed to review the quality of the fuels used at Söderenergi.

5.1.1 Wood Fuel

In Table 9, the content of trace elements in the three additional analyses of stem wood chips and shavings from Söderenergi are compared with reported literature values. No elements exceed the reported intervals. However, Co, Cr, Cu, Fe, K, Mg, P, Pb and V are measured to be lower. A lower concentration of these elements is favourable for the combustion and tear of the boiler.

Table 9: Fuel analysis of stem wood chips and shavings from Söderenergi compared with wood chips [30].

Specie	**Stem wood chips** mg/kg ds	**Shavings** mg/kg ds	**Wood chips [30]** mg/kg ds
Al	17	83	79-580
As	0.05	0.07	0-1.5
Ca	1540	1155	2900-7000
Cd	0.03	0.08	0.06-0.4
Cl	71	138	50-100
Co	0.04	0.08	0.1-0.7
Cr	0.1	0.8	1.6-17
Cu	0.4	0.9	0.3-4.1
Fe	20	46	64-340
Hg	0.02	0.02	0.01-0.17
K	845	552	910-1500
Mg	188	160	310-800
Mn	120	97	63-900
Na	52	64	20-110
Ni	0.1	0.3	1.7-11
P	73	68	97-340
Pb	0.07	0.5	0.3-2.7
S	168	260	70-1000
Si	525	673	440-2900
V	0.05	0.06	0.6-1.4
Zn	20	19	7-90

5.1.2 Recovered Waste Wood

The chemical composition for the RWW used at Söderenergi during 2013-2017 is summarized in Table 10 together with reported values from the literature. The weighted average showed in the table is based on 687 fuel samples from Söderenergi between the years 2013 and 2017. How large the analyzed weight of RWW is of the total delivery weight declines every year, starting from 87% 2013 to 44% 2017. An explanation to this is the increased delivery of recovered waste wood and an introduction of a random sampling method, i.e. how representative the values are, may decrease over the years. In comparison with the additional analyses, the historical analyses of RWW are more representative.

Comparing the values with the literature, the majority of elements in the fuel used at Söderenergi have lower values than the reported literature levels. However, the Pb content is found particularly high for the fuel used at Söderenergi. Cu and Ni are other elements having a higher content in the RWW used at Söderenergi. The lower levels of Na and K for the RWW used at Söderenergi are noted in the table. The lower levels of K and Na are preferable for low corrosion and formation of glass in the bed along with other related problems.

Table 10: Used RWW at Söderenergi compared with values reported in [5]. * from the three additional analyses.

Specie	**RWW** mg/kg ds	**RWW[5]** mg/kg ds
Data points	*687*	*460*
Al	619	1778
As	23	30
Ca	3559*	4039
Cd	0.6	0.3
Cl	894	800
Co	1.6	1.6
Cr	46	56
Cu	91	56
Fe	765*	1855
Hg	0.06	0.1
K	690	1110
Mg	470*	748
Mn	100	103
Na	483	946
Ni	5	3
P	97*	381
Pb	178	54
S	812	1700
Sb	2.5	
Si	5203*	7577
Ti	36*	1039
V	1.5	3
Zn	345	515

When comparing the results from Söderenergi for recovered waste wood and wood fuel, the metal content in RWW is in general higher. The content of Al, As, Cd, Cr, Cu, Ni, Pb, Sb, V, Zn and Fe is over ten times higher than the content in forest fuel. This shows the effect of the surface treatment of the wood. Specifically the composition of Pb, As, Cr and Cu are found to be significantly higher. The Na content is as well higher in RWW, whereas the K concentration is at similar to the forest fuel. Based on this and increase of RWW in the fuel mixture may have negative effects on the boiler system. A higher content of wood fuel is expected to improve the quality of the fuel mixture and the ash.

5.1.3 Solid Recycled Fuel and Rubber

Table 11: Weighted elemental analysis values for SRF and rubber used at Söderenergi.

Specie	**SRF** mg/kg ds	**Rubber** mg/kg ds
Data points	*10*	*70*
Al	10489	5308
As	1.3	4.0
Ca	37922	15593
Cd	1.6	12.7
Cl	9391	10549
Co	3.8	21.0
Cr	57	153
Cu	929	3984
Fe	2335	5183
Hg	0.05	0.6
K	1018	478
Mg	1579	2634
Mn	213	145
Na	2027	567
Ni	16.7	86.2
P	473	504
Pb	112	332
S	2554	3920
Sb	20.1	27.6
Si	23339	18118
Tl	0.03	0.05
Ti	57	60
V	5.9	25.2
Zn	395	4263

In Table 11 the chemical composition of SRF and rubber used at Söderenergi is listed. In Appendix D further information is listed. Comparing the elemental concentration to RWW, the fuels are more harmful since the heavy metal content, as well as the sulfur and chlorine content, is higher. Comparing the SRF to RWW, the content of Cl, Al, Cu and Ca is more than ten times higher in SRF. The content of Cl, Cd, Cu, Hg, Ni, Sb, V and Zn is more than ten times higher in rubber than in RWW. The K and Na content in SRF is higher than in RWW. For rubber the K content is lower than in RWW, the Na content is slightly higher than in RWW. Meaning, the more rubber or SRF used in the future fuel blends the more damaging elements will be present in the boilers.

5.1.4 Comparison with In-House Limits

To control if the fuels to IKV meet the in-house requirements a comparison with the historical data is performed. The in-house rule of thumb limitations for specific elements in fuels and in fuel mixtures are presented in Appendix E. These are used to evaluate the historical fuel data summarized in Table D1 and D2, found in Appendix D. The different types of biofuels used at Söderenergi are called, blended chip, stem wood chips, fuel wood, forest residuals, forest fuels and bark. For the biofuels, the carbon, hydrogen, oxygen, nitrogen, sulfur, ash and chlorine content as well as the moisture content and LHV are compared with the in-house rule of thumb limits. These levels are reported in an interval in Table E1. For SRF and RWW, additional elements are monitored. The maximal levels for disadvantageous elements and heavy metals as Hg, Cu, Co, Cr, Zn, Cd+Tl and Na+K, are depicted in Table E2.

Forest Residues and Wood Chips
The forest residues and forest chips are compared with the in-house rule of thumb intervals for forest

residues. The blended chips, stem wood chips and fuel wood used at Söderenergi are compared with the rule of thumb values for wood chips. For both the fuels compared with forest residues and wood chips, the LHV and MC are within the accepted interval. The C, H, N, S, Cl and ash content is as well within the accepted interval.

Shavings
For shavings the LHV and MC are within the interval. The C, H, N, S, and ash contents are as well within acceptable levels. The Cl content is lower than the typical range.

Bark
All parameters are within the interval.

RWW
For the recovered waste wood the LHV and MC are within the in-house rule of thumb interval. The C, H, N, S, ash content is as well in acceptable levels. Cl, Hg, Cu, Co, Cr, Zn, Cd + Tl and Na + K are lower than the maximum level. However, Pb is significantly higher than the recommended maximum value.

SRF
The MC and LHV for the solid recycled fuel are not coinciding with the in-house rule of thumb intervals. The MC is higher which gives rise to LHV being lower than the rule of thumb value. Regarding the elemental composition all parameters are within the range including the heavy metals.

In general the historical levels are within the in-house recommendations. For the biofuels all levels are within the rule of thumb intervals, except the Cl level for shavings which is lower. For the recovered fuel, the elemental composition of SRF has been within the range. For RWW only the Pb content was too high. Due to the composition of all fuels generally has been within accepted levels, the previous used fuel mixtures are expected to show acceptable results in the key number analysis and when comparing the fuel mixtures with the in-house limits.

5.2 Previously Used Fuel to IGV P3

5.2.1 Key Numbers

During 2013-2017 the fuel for IGV P3 has been 100% recovered waste wood. The variation of the composition of RWW each year is taken into account for some of the key numbers for IGV P3. The following historical key numbers are calculated for each year for RWW; eutectic number 1, feldspar number 2, salt ratio 1, sulfating number and vaporization ratio. The key numbers are presented in Table 12. All key numbers are found in the reported risk zone. The calculated weighted average over the five years is as well showed in the table. Calculated key numbers for each analyzed delivery during 2013-2017 are depicted in Figures 9-13 together with the reported risk zone [5]. Additional key numbers are calculated with molar ratios from three separate analyses of RWW from 2018, where the extra required components are analyzed. These key numbers are alkalinity number 1a, 1b and 2, alkali proportion, feldspar number 1, vitrification number and the ratios Ca/S, Ca/(S+1.5P) and P/(K+Na+1.5Ca+1.5Mg), these are presented in Table 13.

Table 12: Weighted key numbers for RWW used at Söderenergi each year and a weighted average for all years. Marking indicates risk.

Year	**Eutectic number 1**	**Feldspar number 2**	**Salt ratio 1**	**Sulfating number**	**Vaporization ratio**
2013	0.58	0.69	1.86	2.01	0.62
2014	0.54	0.62	1.89	2.57	0.53
2015	0.51	0.58	1.96	2.02	0.65
2016	0.53	0.52	2.01	1.79	0.72
2017	0.53	0.50	2.16	1.74	0.79
Total	0.54	0.59	1.96	2.01	0.65
Risk zone	0.2-0.8	<1	0.2-4	<4	>0.3

The calculated key number eutectic number 1 for all tested deliveries of RWW during 2013-2017 are plotted in Figure 9. The majority of the key numbers are found in the risk area, indicating the melting point of the ashes being lowered. The weighted values of the key number in Table 12, are between 0.51-0.58, implying both Na and K are present, meaning salt mixtures with low melting point can be formed. Seen in the graph the key numbers are fairly concentrated and coincide with the weighted average. Based in the result eutectic salts are expected to have been formed each year.

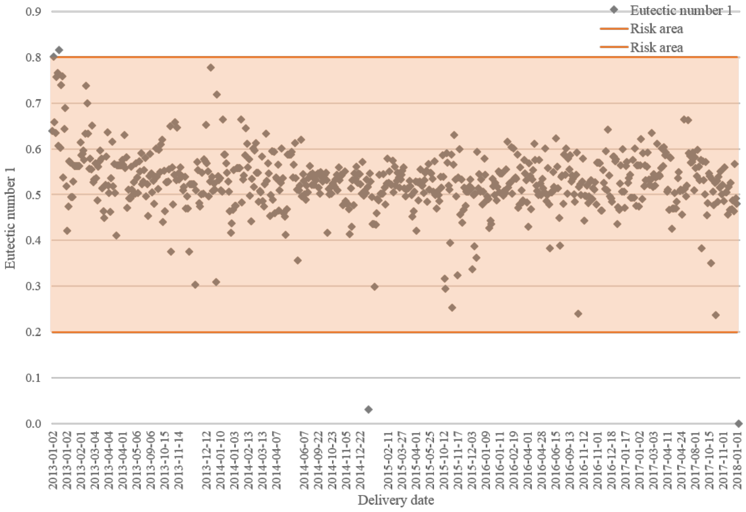


Figure 9: Eutectic number 1

The result for feldspar number 2 is shown in Figure 10 together with the risk area. The majority of the values are in the risk zone. The weighted values in Table 12 show an interval between 0.5-0.7. Seen in the graph the distribution over the years is rather concentrated around these values. At 0.5 the molar mass of Na and K is double the amount of Al. Meaning the amount of Al is not enough to bond the alkali metals to the silicate and silicates with low melting points are expected to have been formed in the bed material. This may have led to an increased consumption of bed material.

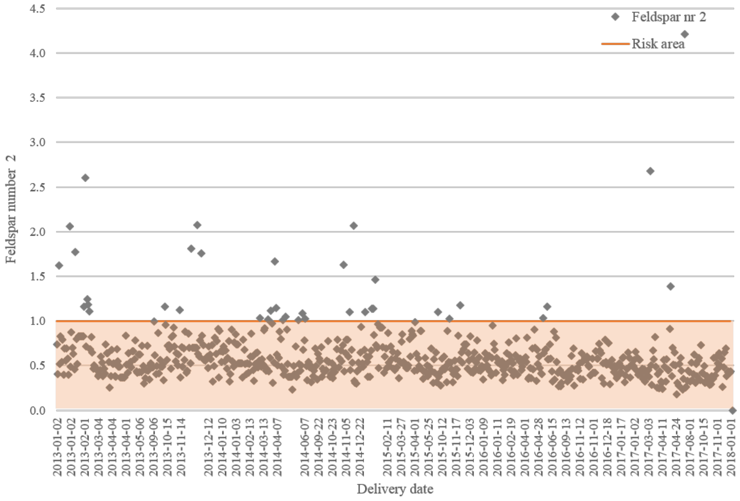


Figure 10: Feldspar number 2

Salt ratio 1 for each tested delivery of demolition wood is shown in Figure 11. The risk area is denoted in the graph. As seen, most of the values are in the risk area. Few key numbers are <1 and the weighted values for salt ratio 1 in Table 12 are close to 2, indicating the potential to bind all the alkali metals to Cl and S atoms. In other words, there are less Na and K atoms present than Cl and S. This also infers a risk for formation of corrosive gases and chlorine and sulfur salt formation with other elements than Na and K.

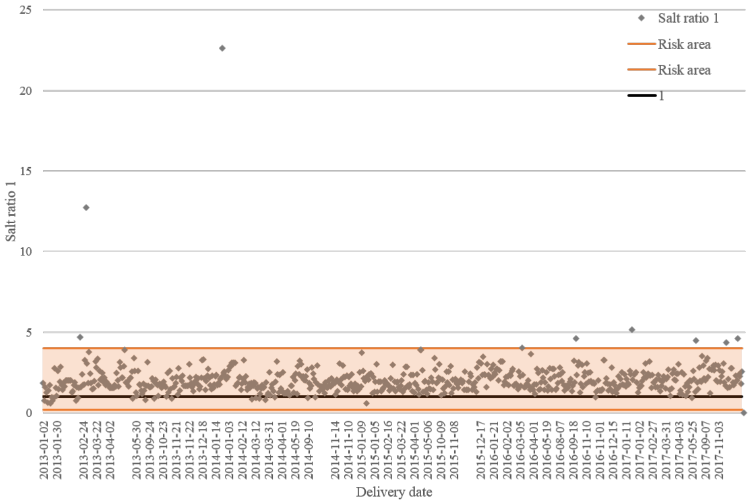


Figure 11: Salt ratio 1

The calculated sulfating numbers during the five years are depicted in Figure 12. Seen in the graph, the key number values varies. Values over 1 (black line), indicate an increased formation of alkaline sulfates. The weighted values for the sulfating number are close to 2. This indicates the amount of substance is similar for Cl and S. To control if the interpretations from the sulfating number are valid, the salt ratio 1 must be over 1, which the majority of the numbers are. Due to the increased alkaline sulfate formation, the corrosion in the boiler is expected to have been rather low, since the sulfates are less corrosive then the alkaline chlorides.

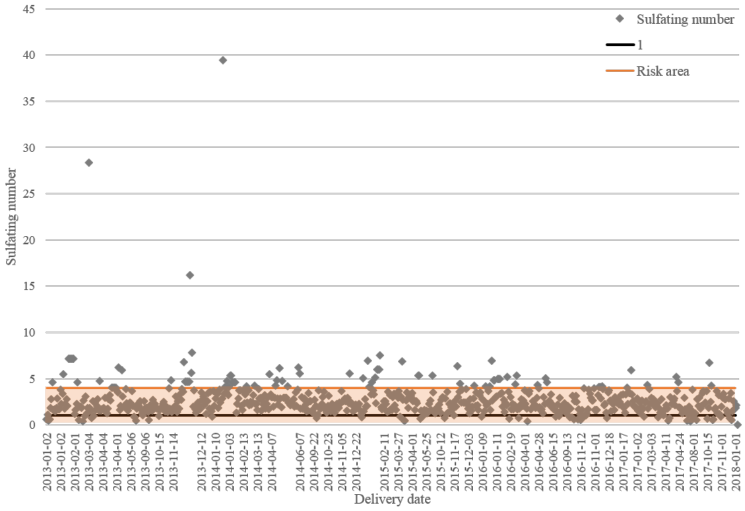


Figure 12: Sulfating number

Vaporization ratio for demolition wood is shown in Figure 13. The majority of the values are over 0.3 which indicates a risk of corrosion. The key numbers over 1 are indicating the alkali being bound to chlorine which gives a risk for low temperature corrosion and volatile chlorine salts. In the figure it is seen that only few key numbers are over one which as well indicates the corrosion rate has been at a reasonable level. Seen in Table 12, the weighted values are in the range of 0.5-0.8, this indicates the sum of amount of substance for K and Na is higher than Cl.

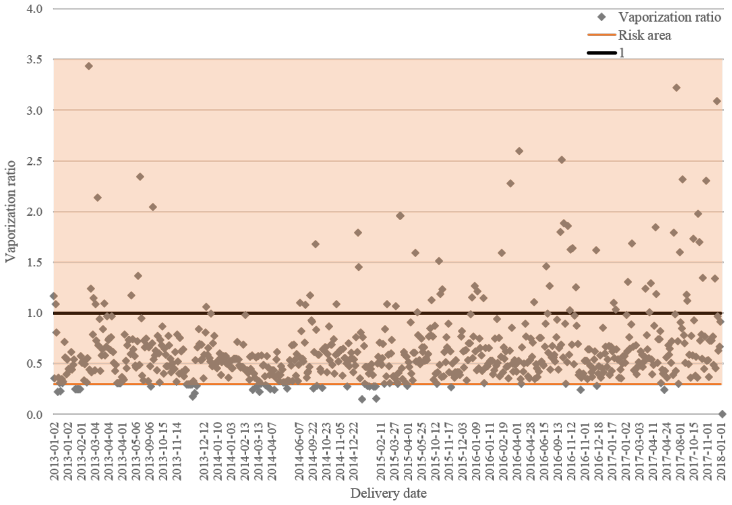


Figure 13: Vaporization ratio

In general the key numbers are found to be stable over the years. Inferring, the average elemental composition over the five years to be representative for RWW in the calculations for the key numbers for the potential fuel mixtures.

Calculations of additional key numbers are made from three samples from RWW deliveries from 2018. In Table 13, the additional key numbers are categorized and depicted. The marked key numbers are in the risk zone.

Table 13: Additional key numbers for historical use of IGV P3.

Key number	**Weighted value**	**Risk zone**
Sintering		
Alkalinity number 1a	0.73	>1
Alkalinity number 1b	0.10	>0.5
Alkalinity number 2	0.63	>1
Alkali proportion	0.15	>0.3
Glass formation		
Feldspar number 1	16.14	>6
Vitrification number	0.14	0.5-1
Alkali chloride & Corrosion		
Ca/S	3.51	>3
Ca/(S+1.5P)	2.95	>1
P/(K+Na+1.5Ca+1.5Mg)	0.02	<1

Alkalinity number 1a, 1b and 2 are not in the risk area, meaning there is a shortfall of reactive alkalinity. The key numbers indicate a low risk for sintering. Alkali proportion is under the risk limit, implying the portion of K+Na of all alkali metals is low.

Feldspar number 1 is in the risk area, the overshoot is rather high. It is indicating a feldspar with low melting point may be formed and in addition a risk for soda glass formation. The high formation of feldspar may have resulted in an high consumption of bed material. Vitrification number is under the risk area. Implying a low risk for formation of glasses with low melting point and no risk for lime-soda glass formation.

The ratio Ca/S is over the risk limit, showing a risk of Ca absorbing S which generates a risk for forming corrosive alkali chlorides. Ca/(S+1.5P) is in the risk area. Implying, the amount of P is not enough to take the S place with Ca, consequently there is a risk for alkali chloride formation. P/(K+Na+1.5Ca+1.5Mg) is as well in the risk zone. Inferring, the amount of P is not enough to replace Cl with the alkali compounds. The risk for alkali chloride formation is predicted.

Comparing the result form salt ratio 1 and vaporization ratio, the impact of the present sulfur is illustrated. Since the substance amount of Cl is lower than K and Na, all Cl can be bound to Na and K and the rest of the alkali can be bound to S. However, S has higher affinity to the alkali than Cl, meaning the sulfur may bind to the alkali first. This can lead to other salts with Cl are formed. However, the presence of Ca is interfering with S absorbing the alkali, showed by the ratio Ca/S. In general the key numbers indicate a risk for corrosion, eutectic salt formation and partly glass formation in the bed. No risk for sintering.

5.2.2 Analysis of Depositions in IGV P3

During the overhaul in April 2018 several deposition samples were collected from IGV P3. At the time the fuel was composed of an energy mix of 90% RWW and 10% rubber. The analysis of the fouling in IGV P3 was conducted to understand where and what the corrosive elements, introduced with the fuel, could be found. Six samples of depositions found at different locations in IGV P3, see Figure 14, were collected and sent for elemental analysis. The locations where the fouling samples were collected are denoted 1-5 and 7 in Figure 14.

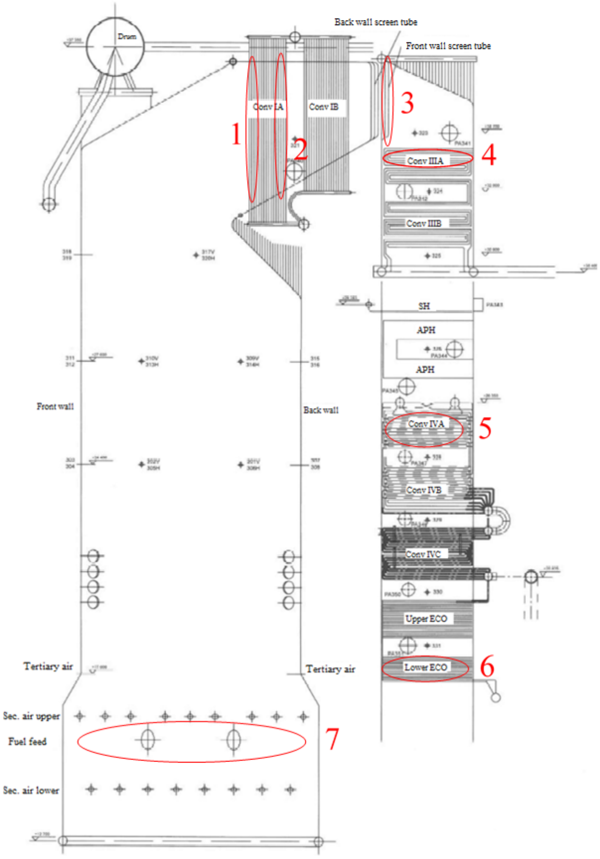


Figure 14: Locations for deposition sampling in IGV P3.

The local state at 1-7 in IGV P3 was documented with photos seen in Figure F1 and F2 found in Appendix F. Together in the figures are the samples sent for analysis. The largest depositions were found at the Conv IA (sample 1). The deposition was found at the wind side of the tubes. Fouling was also found at the screen tubes, and at the tube side facing the gas flow. Further down the convection package the fouling decreases. At the Eco, no fouling was found, why no samples were collected from this place. In the furnace no depositions on the water wall tubes were found. However, a layer of what seemed to be mostly sand was found at the lower part of wall by the grate, at the refractory.

The result from the analysis is showed in Figure 15. The thirteen elements with the highest concentrations are presented in the diagram. The analysis show the fouling on the tubes are similar for samples 1-5. In general the S and Ca content is high in all samples, except the furnace sample (7). High concentrations of Na and K are as well found in the tube samples. The Cl content is low for all samples. The lowest concentrations of Cl are found in sample 1 and 2, which were taken from Conv IA. Thus, the Cl content is low, the alkali is assumed to be bound to S and not Cl. Zn and Pb are found in the samples, indicating a possible formation of eutectic salts. The Cl found downstream in the convection package, and not on Conv I, is an indication for eutectic salts. This since the boiling point of the eutectic salt is lower than the material temperature of Conv I and the salt will first deposit when the material temperature is lowered. Compounds with higher melting point deposits on Conv I.

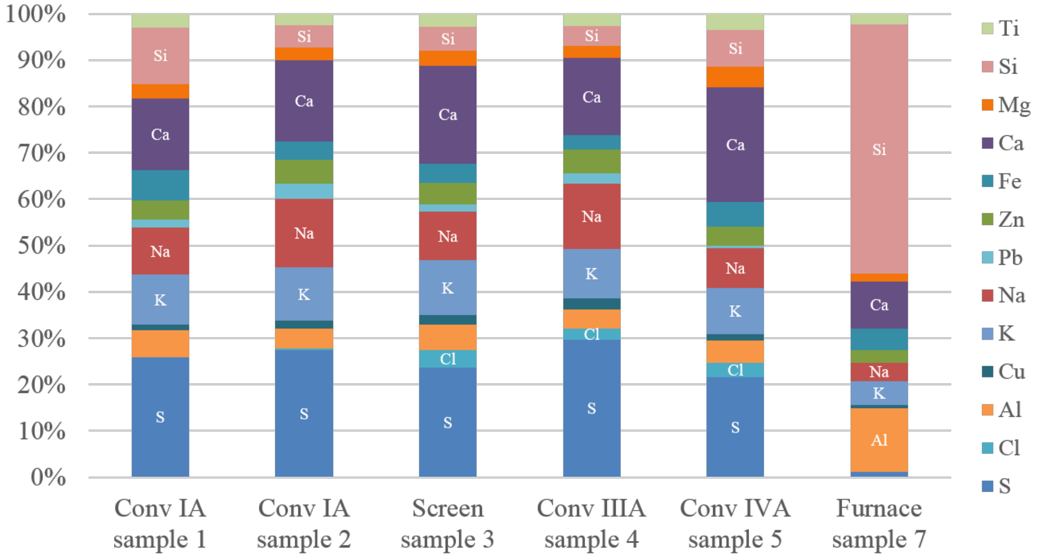


Figure 15: Composition of slag and fouling in IGV P3, based on mass concentration (mg/kg ds).

Corrosion cannot be disregarded since Fe is present in the depositions. However, since it is found in sample 7, which is taken from refractory not a tube, the Fe can be suspected to come from the fuel and is not due to corrosion of the tube. The Fe can also be a part of the salt mixtures. Highest concentration of corrosive elements are found in sample collected from Conv IIIA, however, the concentration is also high in the screen sample and sample 2 from Conv IA. In sample 2 the S and Na+K content is the highest. In sample 1 the Si content is higher, indicating sand particles may have followed the flue gas up in the boiler. The analysis of location 7, in the furnace, showed a high content of Si and Al. It confirms the prediction of the deposit consisting mostly of sand.

5.2.3 Evaluation of Risk Zone for Key Numbers for IGV P3

The reported risk zones for the key numbers are evaluated. If a problem indicated by a key number is not experienced in the boiler, the risk level for this key number is changed to the calculated historical value. This new level is used for the evaluation of the key numbers for the potential mixes for IGV P3. If the present condition in IGV P3 is in line with the indication from the key number, the reported risk limit is kept.

The historical key numbers for IGV P3 are inferring no risk for sintering. According to the overhaul reports and personnel at Söderenergi, sintering is not a experienced problem. Why the reported risk limits for the alkalinity numbers and the alkali proportion are considered reasonable and kept at the same level for the potential fuel mixes. Regarding glass formation, the key numbers indicate a risk of feldspar. Formation of lime-soda glass is, however, not a risk. By a visual inspection of the bottom ashes from IGV P3 the agglomeration appeared to be low. No larger clumps could be seen with typical colours of feldspar or soda lime glass. However, one inspection is not enough to judge if these formations are a common problem since the condition of the bottom ash changes. Due to this the limit for feldspar 1-2 and vitrification are kept the same.

The formation of eutectic salts is presumed to be high according to the key numbers. With the result from the analysis of the fouling, the eutectic salt formation cannot be excluded, why the risk zone for salt ratio 1 and eutectic number 1 are kept the same. The corrosion is as well anticipated by the key numbers. The corrosion rate in IGV P3 is, however, reported rather low in the overhaul reports. Only primary air nozzles have experienced corrosion in 2015-2017. Low temperature corrosion was found in 2016. However, it was prevented by increasing the water temperature and no corrosion have been found during the latter year. The analysis of the fouling cannot exclude corrosion. However, since the current situation is acceptable, the risk limit for vaporization ratio, the sulfur and phosphor ratios and sulfating number are adjusted to the historical calculated values for IGV P3 for the evaluation of the potential mixes.

5.3 Previously Used Fuel to IKV

In IKV a fuel mixture between recovered waste wood and forest fuels has been used. The composition of the mixture is varying over the years. The fuel usage in IKV during the years 2013-2017 is illustrated in Figure 16. The usage of recovered wood fuel has increased, starting from a energy share of 36% to 65% 2017. Simultaneously, the share of wood and forest fuel has decreased. Each year a small amount of firing oil is used, however, the share is negligible in the context and not considered in the calculations. With the increase of the recovered waste wood, a deterioration of the scenario showed by the key numbers is expected.

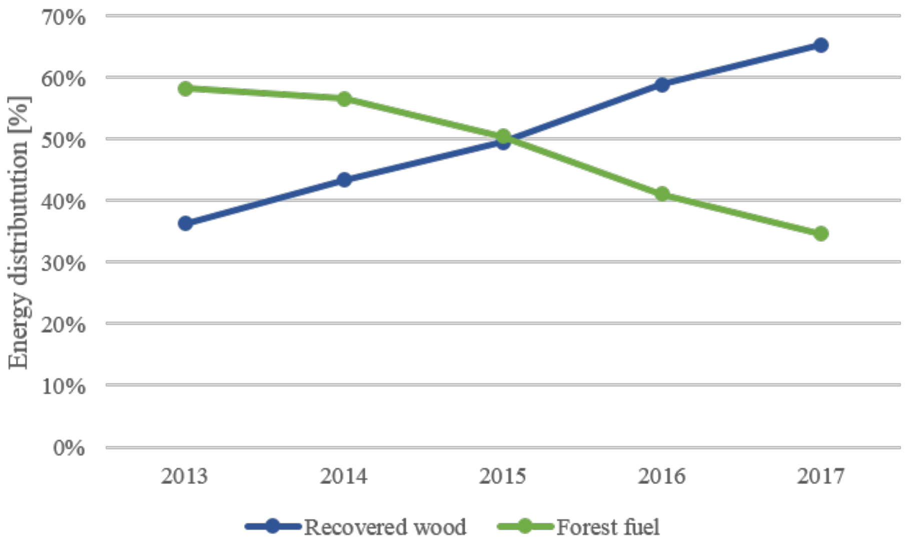


Figure 16: The fuel usage for IKV presented per energy-%.

In Figure 17 the detailed fuel content is presented. Seen in the figure, the share of forest chips is decreasing whereas the share of shavings is rather stable. A trend to use less types of fuels in the mix is as well visible. During 2017 the large weight proportions of fuels to IKV were RWW, stem woods chips and shavings. The historical composition for each year is considered for the key number calculation for IKV. The weight percentages presented in the graph are used to calculate key numbers and elemental composition of the historical fuel usage. The trace element content for blended chips, fuel wood, forest chips and forest residues is represented with the weighed values from the additional analysis of stem wood chips. This since these fuel types are not used at the site any longer and stem wood chips are assumed to be most representative. However, the LHV, moisture content, S and Cl content is used from the weighed values from the historical fuel analyses of each fuel type, showed in Table D2 in Appendix D. The added sulfur to IKV each year is included in the key number calculations.

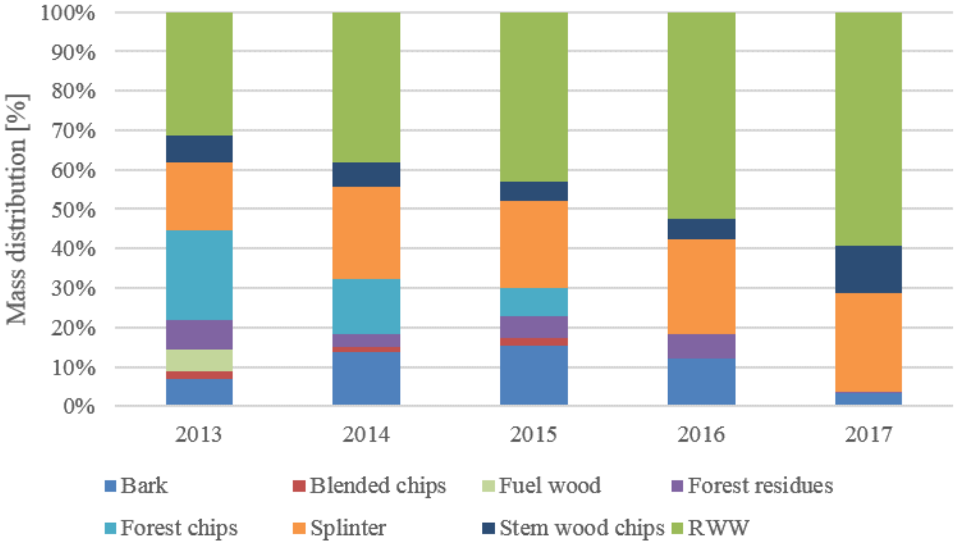
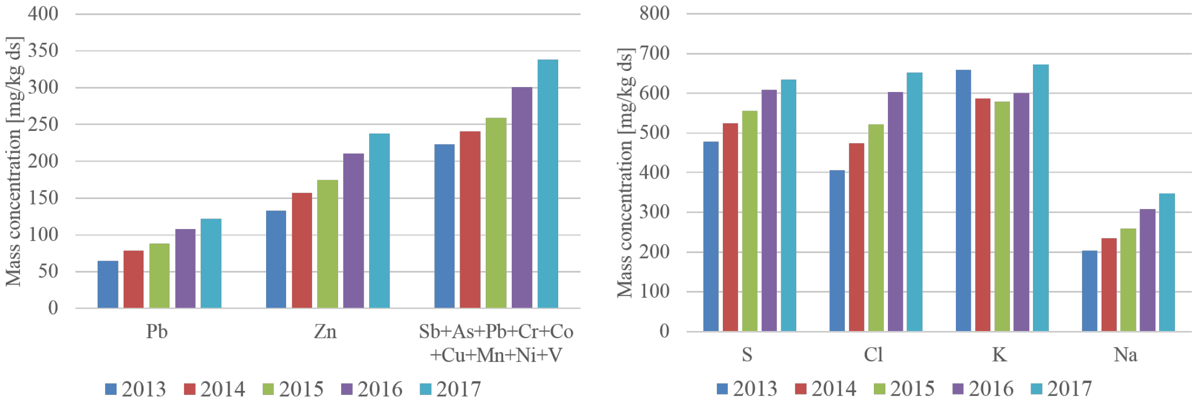


Figure 17: The historical fuel mix for IKV presented in weight-%.

5.3.1 Comparison with In-house Limits

In Figure 18a the Pb and Zn concentrations are illustrated, it highlights the expected increase of contamination when using more RWW in the fuel mix. In the same figure the sum of heavy metals are plotted, an increase of the content is as well seen. Depicted in Figure 18b, are the concentrations of S, Cl, K and Na. The content of Cl, S and Na are increasing, this due to the higher levels in RWW than in the wood fuel. The content of K is varying over the years and is not linear as for the other elements.



(a) (b)

Figure 18: The elemental composition in the fuel used in IKV over the year 2013-2017.

Comparing the elemental composition of the fuel blends used in IKV during 2013-2017 with the in-house rule of thumbs values, seen in Table 14, the only element exceeding the limit is Pb. This due to the high concentrations of Pb in RWW. For the other elements the levels are acceptable. For all years the elemental concentration increases which is expected due to higher concentration in RWW.

Table 14: Comparison with in-house rule of thumb max values and the historical level. Marked numbers indicate over-ride of maximum limit. [22]

Element	**Max**		**2013**	**2014**	**2015**	**2016**	**2017**
Cl	1200	mg/kg ds	406	475	521	604	652
F	50	mg/kg ds	-	-	-	-	-
S	2000	mg/kg ds	478	524	556	608	635
N	1.5	% ds	0.7	0.8	0.9	1.1	1.1
Hg	0.15	mg/kg ds	0.03	0.04	0.04	0.04	0.05
Cd+Tl	0.8	mg/kg ds	0.2	0.3	0.3	0.4	0.4
Br	10	mg/kg ds	-	-	-	-	-
Pb	50	mg/kg ds	64	78	88	108	122
Sb+As+Pb+Cr+ Co+Cu+Mn+Ni+V	700	mg/kg ds	223	241	259	301	338
Zn	300	mg/kg ds	133	157	175	211	238
Al metallic	1000	mg/kg ds	-	-	-	-	-
Na+K	0.2	% ds	0.09	0.08	0.08	0.09	0.10

In Table 15 the LHV and moisture content are shown. Comparing with the the load limitations in Table E4, IKV has been able to operate at 100% MCR until year 2016. 2017 the fuel becomes dryer. However, the boiler has been used at 100% MCR during 2017 as well. The flow of ash is as well shown in the table, is stable at 1.6 ton/h.

Table 15: Additional fuel properties for the used fuel to IKV.

		2013	**2014**	**2015**	**2016**	**2017**
Moisture content	% ar	39.5	39.5	38.8	37.3	35.2
LHV	MJ/kg ar	10.4	10.3	10.4	10.7	11.0
Ash	ton/h	1.5	1.6	1.6	1.6	1.6

5.3.2 Key Numbers

In Table 16 the key numbers for the annual fuel blend to IKV are presented together with the risk zone. The key numbers are categorized after damage type. Marked cells indicate risk. Seen in the table eutectic number 1, the feldspar numbers, salt ratio 1, sulfating number, vaporization ratio and the Ca and P ratios are marked to be in the risk zone. Whereas the alkalinity numbers, the alkali proportion and vitrification number are not indicating risks. The over all outcome for IKV is similar to IGV P3 regarding which key numbers indicating risk or not, i.e. the same risks are presented for IKV as for IGV P3 and the same interpretations can be made for the result; the sintering risk is low, partly glass formation in the bed, risk for formation of both alkali chlorides and eutectic salts, which pose a risk for corrosion attacks. The vaporization ratio is less than one and sulfating number is over one, indicating an increased formation of alkaline sulfates, which may have reduced the corrosion rate in IKV. The Ca/S ratio is, however, in the risk zone, indicating the S may have been absorbed. On the other hand, the exceed is low which may have led to a low S absorption.

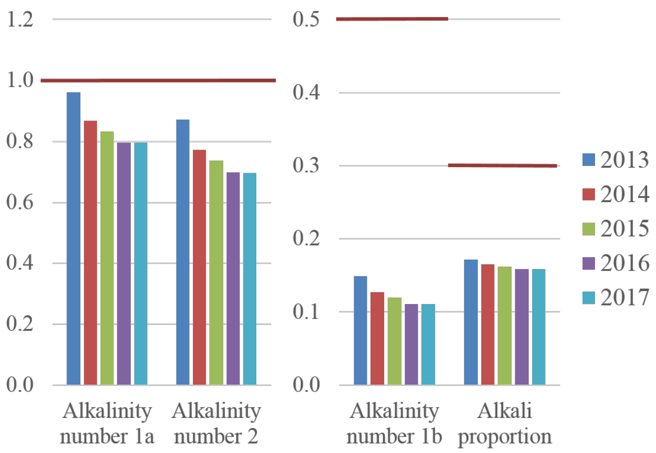
Notable is the similar scenario showed by the key numbers for IGV P3 with 100% RWW and 2013 for IKV with a composition of 35% RWW and 65% wood fuel. The key number value is different but the risks are the same. This may be due to the elemental composition used in the key number calculations are rather similar for RWW and the wood fuel. However, the heavy metal content is different for the compared fuels.

Table 16: Key numbers for IKV during the years 2013-2017. The marking is indicating the key number being in the risk zone, no color indicates no risk.

Key numbers	**2013**	**2014**	**2015**	**2016**	**2017**	**Risk zone**
Sintering						
Alkalinity number 1a	0.96	0.87	0.83	0.80	0.79	>1
Alkalinity number 1b	0.15	0.13	0.12	0.11	0.11	>0.5
Alkalinity number 2	0.87	0.77	0.74	0.70	0.70	>1
Alkali proportion	0.17	0.16	0.16	0.16	0.16	>0.3
Glass formation						
Feldspar number 1	17.35	16.68	16.52	16.31	16.32	>6
Feldspar number 2	0.35	0.43	0.46	0.50	0.50	<1
Vitrification number	0.22	0.19	0.18	0.16	0.16	0.5-1
Eutectic salts						
Eutectic number 1	0.34	0.40	0.43	0.47	0.47	0.2-0.8
Salt ratio 1	1.61	1.83	1.90	1.91	1.79	0.2-4
Alkali chloride & Corrosion						
Sulfating number	2.60	2.44	2.36	2.23	2.15	<4
Vaporization ratio	0.45	0.53	0.56	0.59	0.57	>0.3
Ca/S	3.43	3.22	3.19	3.30	3.56	>2
Ca/(S+1.5P)	2.77	2.66	2.66	2.75	2.93	>1
P/(K+Na+1.5Ca+1.5Mg)	0.02	0.02	0.02	0.02	0.02	<1

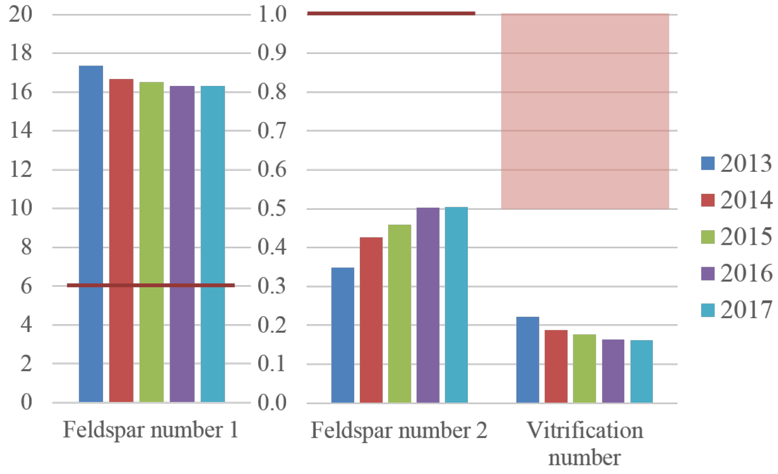
In Figure 19 and 20 the key numbers are plotted together with the risk zones. Considering the trend of the key numbers in Figure 19a, the values for the alkalinity numbers and the alkali proportion are decreasing over the years, implying being further away from the risk zone. I.e. the sintering risk is increased with reduced biofuel.

Seen in Figure 20a, feldspar number 1 is reducing over the years, changing towards the risk free zone. For feldspar number 2 the value is increasing over the years, which is in the direction towards the risk free zone. The vitrification number is decreasing over the years, implying being further away from the risk zone. In Figure 20b no trend can be seen for salt ratio 1. The values for eutectic number 1 are increasing towards the center of the risk zone, with a stabilization for the last year. In Figure 20c, no linear trend can be seen for vaporization ratio, Ca/S and Ca/(S+1.5P). For P/(K+Na+ 1.5Ca+1.5Mg) the level is stable. Sulfating number has a negative trend implying the state being worst every year, i.e. the risk for corrosion is increased.

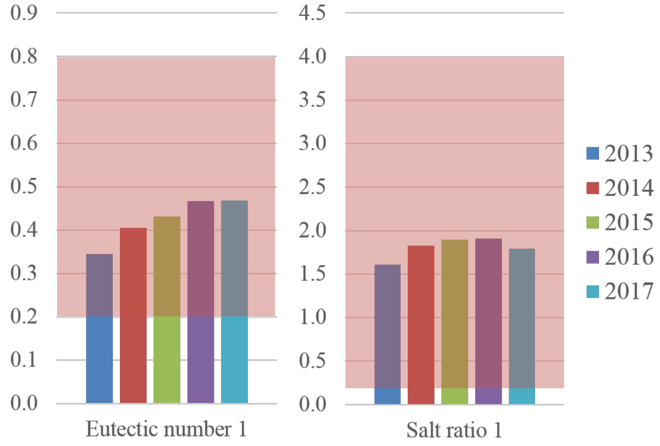


(a) Sintering

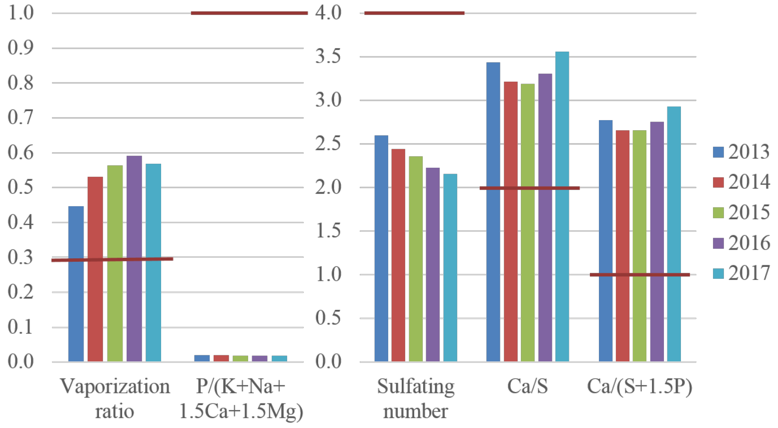
Figure 19: Key numbers for IKV during 2013-2017.



(a) Glass formation



(b) Eutectic salts



(c) Alkali chloride and corrosion

Figure 20: Key numbers for IKV during 2013-2017.

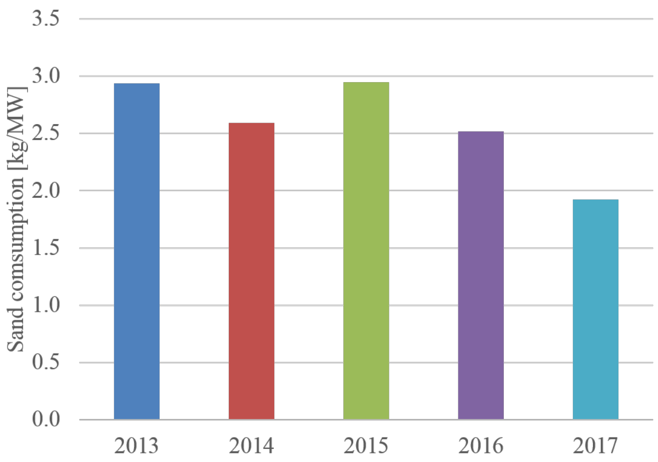


Figure 21: Sand consumption in IKV.

The key numbers feldspar 1 and 2 are improving over the years, however, still being in the risk zone. An indication of the improvement is seen in the history by the reduced consumption of bed material, seen in Figure 21. From 2013 the sand usage was reduced by 1 kg/MW to 2017 which is a reduction of 34%. With the improvement of feldspar number 1 and 2, the tendency for forming agglomerations in of the bed material is reduced and the bed material can be used longer.

5.3.3 Estimation of Fouling in IKV

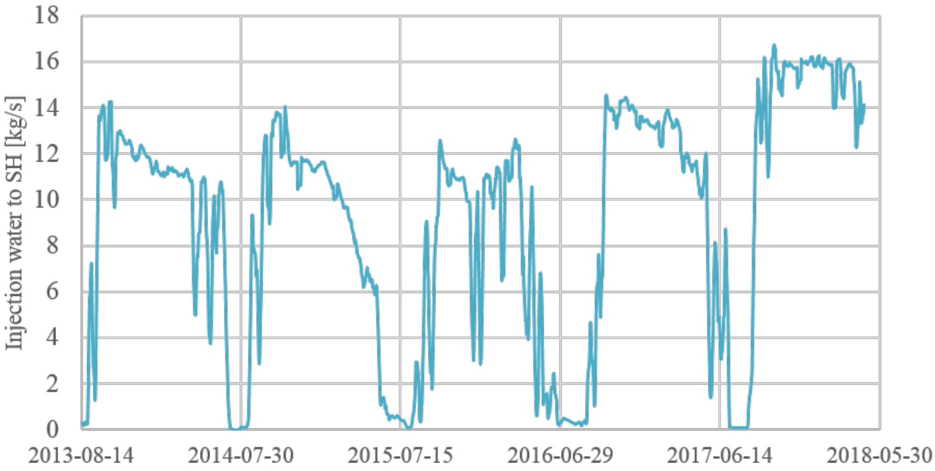


Figure 22: Flow of injection water to SH I-II, SH II-III and SH III-IV.

In Figure 22 the total flow of water injected into the steam flow between the superheaters I and II, SH II and III and between SH III-IV is illustrated. The water injection graphed for several seasons between 2013-2018. The water is injected to control and keep a steady final steam temperature in IKV. In the graph a reduction trend of the water flow is seen from October to July for the seasons 2013-2014, 2014-2015 and 2016-2017. This indicates an increase of fouling on the superheaters during the seasons. When the deposition layer becomes thicker the heat transfer capacity from the flue gas to the steam is reduced and less injection water is required. During June-August IKV is used at reduced capacity and is stopped for overhaul why the flow is zero. During the overhaul the fouling at the superheaters is removed why a higher water flow is required to cool the steam in the beginning of the new season. During the winter 2015-2016 IKV was stopped why the graph is different for this season. 2018 the flow of injection water is stable and higher. This indicates the flue gas being hotter and no fouling tendencies over the season. In other words, with the increased usage of RWW the fouling was reduced. From further analysis of the steam temperatures before and after injection, seen in Appendix G, indications of the location for the fouling is found. 2013-2014 the fouling was increased over the season on SH II and III (Intrex). During the season 2016-2017 on SH III (Intrex).

5.3.4 Evaluation of Risk Zone for Key Numbers for IKV

The evaluation of the risk zone for the key number is performed similarly as for IGV P3. No risk of sintering is indicated by the historical key numbers for IKV. According to the overhaul reports and personnel at Söderenergi, sintering is not a experienced problem. Why the reported risk limits for the alkalinity numbers and the alkali proportion are considered reasonable and kept at the same level for the potential fuel mixes. Regarding glass formation, the key numbers indicate a risk of feldspar. Formation of lime-soda glass is however, not a risk. By a visual inspection of the bottom ashes from IKV the agglomeration appeared to be low. No larger clumps could be seen with typical colours of feldspar or soda lime glass. However, one inspection is not enough to judge if these formations are a common problem since the condition of the bottom ash changes. Due to this, the limit for feldspar 1-2 and vitrification are kept the same. A potential explanation to why feldspar formation not is an experienced problem may be due to a high consumption of bed material. As previously seen, the consumption is reduced with the improvement of the key numbers.

The formation of eutectic salts is predicted to be high according to the key numbers. On the contrary, the result from the report conducted by SP [26], is presuming the eutectic salt formation to be low. This since the depositions analyzed from IKV contained low amounts of Cl. The risk zone for salt ratio 1 and eutectic number 1 are changed to the calculated levels. Corrosion is as well anticipated by the key numbers. The general corrosion rate in IKV is, however, reported in the overhaul reports to be rather low. Still corrosion is found locally at several places in the boiler. E.g. the side walls tubes to the horizontal pass by the superheaters have experienced high temperature corrosion in 2015-2017. Moreover the screen tubes have experienced corrosion. The report by SP claims, however, no corrosion on the Intrex since no Fe could be found in the deposits. Additionally, the other superheaters (SH I and II) do not show any indications of corrosion. To summarize, corrosion exists in the boiler, however, it is not damaging the tube packages why the reported levels are changed. The risk limits for vaporization ratio, the sulfur and phosphor ratios and sulfating number are changed to the historical calculated values for the evaluation of the potential fuel mixtures.

5.4 Ash Analysis

Fly ash from IKV, IGV P1 and P3, are analyzed to compare with fuel key numbers and to calculate ash indices. The ash from IKV was collected in April 2018 and the fuel had a energy composition of 30% wood fuel and 70% RWW. The fly ash from IGV P3 was collected when the fuel consisted of 100% RWW. The ash for IGV P1 is analyzed for comparison and as an anticipation for the future fuel blends. The fuel to P1 at this time was 35% SRF, 35% PWP and 30% rubber, procentages based on energy content.

5.4.1 Ash Indices

Miles index and the Fouling index are calculated to anticipate the slagging and fouling characteristics of the used fuels in IKV, IGV P1 and IGV P3. The evaluation is performed with the ash analyses found in Appendix H and the criteria in Table 7 and 8.

Table 17: Ash indices for fly ashes.

	Miles		**Fouling**	
Fly ash	**Value**	**Interpretation**	**Value**	**Interpretation**
IKV	2.70	Highly slagging fuel	0.25	Intermediate deposits
IGV P1	5.02	Highly slagging fuel	0.12	Insignificant deposits
IGV P3	2.94	Highly slagging fuel	0.01	Insignificant deposits

In Table 17 the result for the indices for the fly ashes are illustrated. According to Miles index, the fuel to all boilers are highly slagging. While the indication by the Fouling index shows insignificant to intermediate deposits. The indices appear to be contradicting. However, considering the definition for fouling and slagging, the deposits have different locations. Slagging is considered deposits on furnace wall or convection surfaces exposed to radiant heat. Fouling is defined as deposition on convection heat surfaces as e.g. heat exchangers.

Comparing Miles index, IKV is fed with the least slagging fuel and IGV P1 is fed with the most slagging fuel. This is in line with the fuel quality reduction. For Fouling index, IGV P1 and P3 have insignificant deposits while IKV have intermediate deposits. Considering the great difference of the values of the Fouling index between IKV and IGV P3, the difference of 30% wood fuel in IKV has a noteworthy effect on the fouling. The results show 100% RWW is reducing the fouling. Notable as well, is the insignificant deposit with a fuel of 35% PWP, 35% SRF and 30% rubber.

The indications from the indices are consisting with the visual inspection of IGV P3 performed during the deposit sampling. Slagging was found by the grate at the refractory and by experienced personnel at Söderenergi, the fouling found in the boiler was considered low.

According to the results for the water injection to the superheaters in IKV, the fouling appeared to be low for the same season as the analyzed ash sample. The Fouling index is showing intermediate deposits in IKV. The results are considered to coincide.

5.4.2 Ash Key Numbers

Table 18: Key numbers for fly ashes. The marking is indicating the key number being in the risk zone, no color indicates no risk.

Key number	**IKV**	**IGV P1**	**IGV P3**	**Risk zone**
Sintering				
Alkalinity number 1a	14.30	1.79	0.41	>1
Alkalinity number 1b	0.76	0.37	0.07	>0.5
Alkalinity number 2	13.13	1.62	0.34	>1
Alkali proportion	0.06	0.23	0.21	>0.3
Glass formation				
Feldspar number 1	3.66	4.69	9.61	>6
Feldspar number 2	0.23	0.41	1.22	<1
Vitrification number	1.59	0.70	0.11	0.5-1
Eutectic salts				
Eutectic number 1	0.64	0.76	0.60	0.2-0.8
Salt ratio 1	3.61	1.98	0.96	0.2-4
Alkali chloride & Corrosion				
Sulfating number	4.79	0.85	3.19	<4
Vaporization ratio	0.62	1.07	0.23	>0.3
Ca/S	3.82	3.20	4.09	>1
Ca/(S+1.5P)	3.64	2.85	3.33	>1
P/(K+Na+1.5Ca+1.5Mg)	0.00	0.01	0.01	<1

The key numbers calculated for the fly ashes are depicted in Table 18. IKV has in total ten key numbers in the risk zone, P1 has eleven and P3 has seven key numbers in the risk zone. The key numbers for the fly ash from IKV indicate risk for sintering, eutectic salts, glass formation and corrosion. The results for IGV P1 are similar. The sulfating numbers are however different. It being >4 for IKV indicates low risk for corrosion. The sulfating number for IGV P1 being <1 indicates a higher formation of alkali chlorides. The vaporization ratio for P1 is >1, indicating all free alkali metals can be vaporized as chloride. Notable is the difference between the ash key numbers for IKV and IGV P3, the increased amount of RWW appears to enhance the ash properties. However, considering the ash from IGV P1, the reduced quality of the fuel mix is shown by the key numbers. Based on this, fuel mixes with more SRF and rubber are expected to produce difficult ashes.

Comparing the historical key numbers for IKV with the ash key numbers, the difference is the high values for the alkalinity numbers. The high alkalinity numbers for the ash is due to high Ca content in the ash. The high presence of Ca may be due to the gas clean up. Another difference between the elemental composition of the historical fuel and the ash affecting the alkalinity, is the Si content. The Si content in the ash is low whereas in the fuel it is high. Furthermore, feldspar number 1 is affected by the Si content. The great difference between the key number for the fuel and the ash is explained by this. The Si and Ca may also come from the bed material. Ca reacts with the Si in the sand and can fly with the flue gas and be ejected with the fly ash.

For the fly ash from IGV P3 the result is similar to the historical key numbers for the boiler. No risk for sintering, low risk for glass formation and high risk for eutectic salts and corrosion. Vaporization number is below one, indicating all alkali cannot be vaporized as chlorides. Salt ratio 1 is <1, indicating all Cl and S can be bound to free alkali metals. The alkaline salt formation is benefited over gases with Cl and S. The salt ratio 1 being less than one interferes with the interpretation of sulfating number and which alkaline compound is favoured. The prediction of an increased formation of alkaline sulfate is not justified. Comparing the ash analysis with the analysis of the depositions from IGV P3, the results are similar. Indications for eutectic salts and alkali sulfates are found in both analyses. The historical key numbers for the fuel to IGV P3 are similar to the key numbers for the ash, except for salt ratio 1, feldspar number 2 and vaporization ratio. No risk is showed for feldspar 2 for the ash, salt ratio 1 is lower and vaporization ratio shows no risk for the ash.

5.5 Potential Fuel Mixtures for IGV P3

A set of fuel mixes for IGV P3 are evaluated. The fuel blends consist of different portions of RWW, SRF and rubber. The assessed mixtures are shown in Table 19. The evaluation is based on the historical analysis. The increased ash flow is considered in the evaluation along with the key numbers and the heavy metal content.

Table 19: Potential fuel mixes for IGV P3, based on energy content.

		M1:85/15			**M2:70/30**			**M3:60/40**		
		M1A1	M1A2	M1A3	M2A1	M2A2	M2A3	M3A1	M3A2	M3A3
RWW	%	85	85	85	70	70	70	60	60	60
Rubber	%	0	7.5	15	0	15	30	0	20	40
SRF	%	15	7.5	0	30	15	0	40	20	0

5.5.1 Key Numbers

The calculated key numbers for IGV P3 are shown in Table 20 and 21. The key numbers are marked with yellow and pink to highlight the key numbers being close to the limit of the risk zone or in the risk zone. Key numbers being within 10% from the limit of the risk zone are not marked. From 10% to 20% the key number is marked with yellow and from 20%, the key number is marked with pink. The adjusted risk limits are shown in the tables. The historical key numbers for IGV P3 are shown in Table 20. The portion of RWW is reduced for each mix (from M1 to M3), while the portion of rubber and SRF increase. The key numbers are expected to worsen for each mixture M1-M3.

Considering all mixtures in Table 20 and 21 the risk for sintering is low. Lower risk for glass formation compared to the reference is as well showed. The low sintering risk and risk of forming glass in the bed is a prediction for a lowered consumption of bed material. Salt ratio 1 is over 1 for all mixtures, inferring all free alkali metal can be bound as chlorine or sulfate. This also legitimates the interpretation from sulfating number. The results for sulfating number is varying for the mixtures affecting the prediction for the forming alkali compound. Vaporization ratio is over 1 for all mixes, indicating all free alkali metal can be vaporized as chloride.

Table 20: Key numbers of potential fuel mixtures for IGV P3. The marking is indicating the key number being in the risk zone, no color indicates no risk. The mix marked *Ref.* is for the previous fuel usage of 100% RWW in IGV P3.

Key numbers	**Ref.**	**M1A1**	**M1A2**	**M1A3**	**Risk zone**
Sintering					
Alkalinity number 1a	0.73	0.88	0.83	0.77	>1
Alkalinity number 1b	0.10	0.08	0.08	0.07	>0.5
Alkalinity number 2	0.63	0.80	0.73	0.64	>1
Alkali proportion	0.15	0.10	0.10	0.11	>0.3
Glass formation					
Feldspar number 1	16.14	7.68	8.95	11.33	>6
Feldspar number 2	0.59	1.44	1.29	1.07	<1
Vitrification number	0.14	0.12	0.12	0.11	0.5-1
Eutectic salts					
Eutectic number 1	0.54	0.61	0.59	0.56	0.2-0.8
Salt ratio 1	1.96	2.86	2.49	3.24	0.2-4
Alkali chloride & Corrosion					
Sulfating number	2.01	1.16	1.23	1.33	<2.01
Vaporization ratio	0.65	1.16	1.27	1.39	>0.65
Ca/S	3.51	6.15	4.74	3.39	>3.51
Ca/(S+1.5P)	2.95	5.05	3.93	2.84	>2.95
P/(K+Na+1.5Ca+1.5Mg)	0.02	0.01	0.01	0.01	<0.02

The result for M1A1 and M1A2 is similar. The key numbers indicate no risk for sintering and partly risk for glass formation. Feldspar number 1 is in the risk zone, which is an indication for parts of the silicic acid may form alkali silicate with low melting point. Furthermore, the key numbers show a risk for formation of eutectic salts and corrosion. The sulfating number is over 1, inferring an increased alkaline sulfate formation. However, the Ca/S ratio is high, threatening to absorb the sulfur. Seen in the results, M1A3 has less key numbers in the risk zone than the other M1 mixtures. The Ca/S ratio is lower which reduces the probability for the sulfur being absorbed by the calcium.

As seen in Table 21, M2A1 has a low risk for sintering and glass formation in the bed. Nevertheless, the fuel mix possesses risk for corrosion and formation of eutectic salts. M2A2 has one key number indicating risk for glass formation in the bed. Corrosion and eutectic salt formation are as well a risk for the fuel mix. The sulfating number for M2A1 and M2A2 is under 1, inferring a larger formation of alkaline chlorides. The result for M2A3 is similar to M1A3. The difference is salt ratio 1 not being in the risk zone. This makes M2A3 to one of the mixtures with least key numbers indicating risk. The sulfating number is >1 indicating a larger formation of alkaline sulfates, simultaneously as the Ca/S ratio is in the risk free zone. Thus, M2A3 appears to form alkali sulfate which are cause less damage than the chlorides.

The result for M3A1 is similar to M2A1. The key numbers indicating sintering are not in the risk area, however, the risk has increased with the higher share of SRF. The mix of rubber and SRF in M3A2 appears to improve the quality of the fuel blend since the number of key numbers in the risk zone decreases. The salt ratio 1 is increased, indicating a reduced risk for eutectic salts. The sulfating number is below 1, forecasting an increased formation of alkaline chlorides. M3A3 is one of the potential fuel mixtures with the fewest key numbers in the risk zone, the result is similar to M2A3. The key numbers indicate risk for glass formation, eutectic salts and corrosion. The glass formation risk is lower than for the other A3 mixtures. Generally, the fuel mixtures with the highest rubber content are showed to possess less risks.

Table 21: Key numbers for potential fuel mixes to IGV P3. The marking is indicating the key number being in the risk zone, no color indicates no risk.

Key numbers	**M2A1**	**M2A2**	**M2A3**	**M3A1**	**M3A2**	**M3A3**	**Risk zone**
Sintering							
Alkalinity number 1a	0.96	0.89	0.79	0.99	0.91	0.81	>1
Alkalinity number 1b	0.07	0.06	0.06	0.06	0.06	0.05	>0.5
Alkalinity number 2	0.88	0.78	0.65	0.92	0.81	0.65	>1
Alkali proportion	0.08	0.08	0.09	0.07	0.07	0.08	>0.3
Glass formation							
Feldspar number 1	5.95	7.04	9.37	5.42	6.43	8.58	>6
Feldspar number 2	2.04	1.89	1.59	2.34	2.21	1.99	<1
Vitrification number	0.11	0.10	0.09	0.11	0.09	0.08	0.5-1
Eutectic salts							
Eutectic number 1	0.66	0.63	0.57	0.69	0.65	0.58	0.2-0.8
Salt ratio 1	1.75	3.57	4.64	3.05	3.98	5.68	0.2-4
Alkali chloride & Corrosion							
Sulfating number	0.90	0.99	1.10	0.81	0.91	1.02	<2.01
Vaporization ratio	1.51	1.80	2.20	1.69	2.08	2.81	>0.65
Ca/S	7.94	5.51	3.32	8.83	5.85	3.29	>3.51
Ca/(S+1.5P)	6.41	4.53	2.78	7.06	4.79	2.75	>2.95
P/(K+Na+1.5Ca+1.5Mg)	0.01	0.01	0.01	0.01	0.01	0.02	<0.02

In Figure 23 the key numbers are plotted together with the adjusted risk areas for each key number. Mixtures M1 are colored in green, M2 in blue and M3 in purple. The darker colored bars contain the same fuels, RWW and SRF, in different proportions. The brightest colored bars contain RWW and rubber. Seen in the figure is the mixture of RWW, rubber and SRF always having a key number value between the two other blends.

Since SRF is considered more detrimental than RWW, the key numbers are expected to worsen for A1 from M1 (green) to M3 (purple). For alkalinity number 1a and 2, sulfating number, vaporization ratio and the S and P ratios the theory coincide with the result. However, for alkalinity number 1b, alkali proportion, eutectic number 1, salt ratio 1, feldspar number 1 and 2 the result is improving with increased share of SRF. The same trend is seen for the other mixtures A2 and A3. Comparing the different fuel compositions within one color, i.e. comparing A1, A2 and A3, the following is seen in Figure 23.

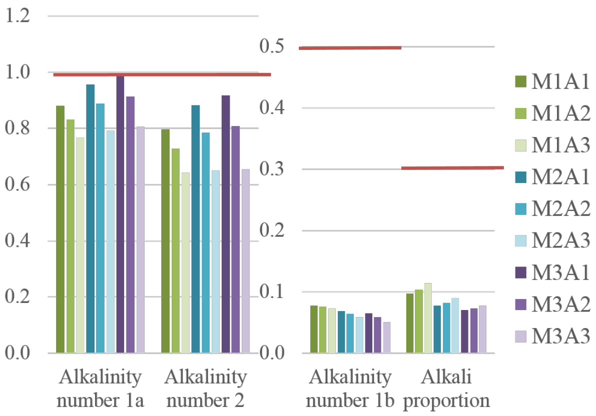
For the key numbers in the risk free zone:

- A1 is closest to the risk area for alkalinity number 1a, 1b, 2 and vitrification number.
- A3 is closest to the risk area for alkali proportion.

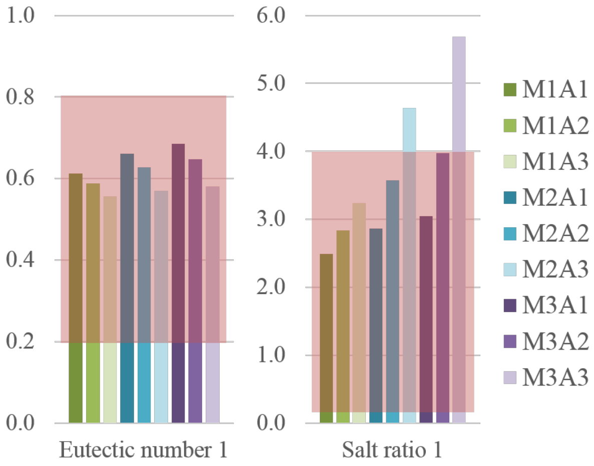
For the key numbers in the risk zone:

- A1 is furthest from the risk free zone for Ca/S, Ca/(S+1.5P), feldspar number 2, P/(K+Na+1.5Ca+1.5Mg), salt ratio 1 and sulfating number.
- A3 is furthest from the risk free zone for eutectic number 1, feldspar number 1 and vaporization ratio.

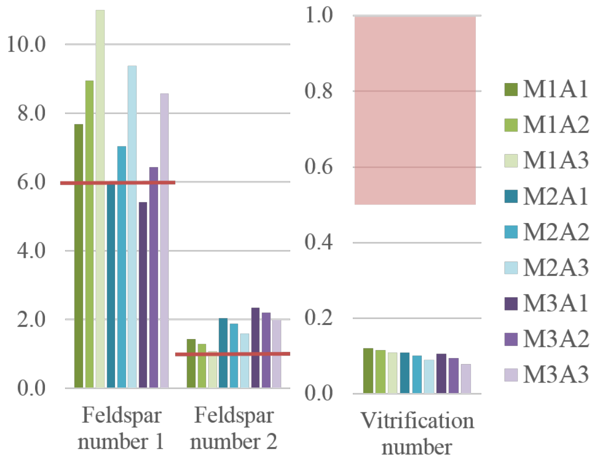
From this analysis, A3 appear to be the least damaging alternative, i.e. the fuel mixtures with the highest portion of rubber reduces the risk predicted by the key numbers.



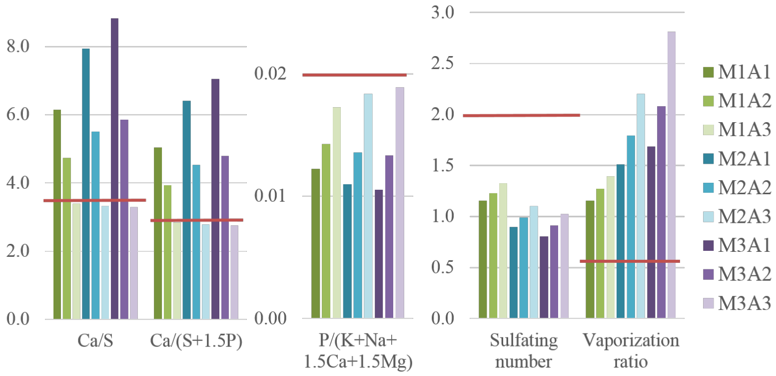
(a) Sintering



(b) Eutectic salts



(c) Glass formation

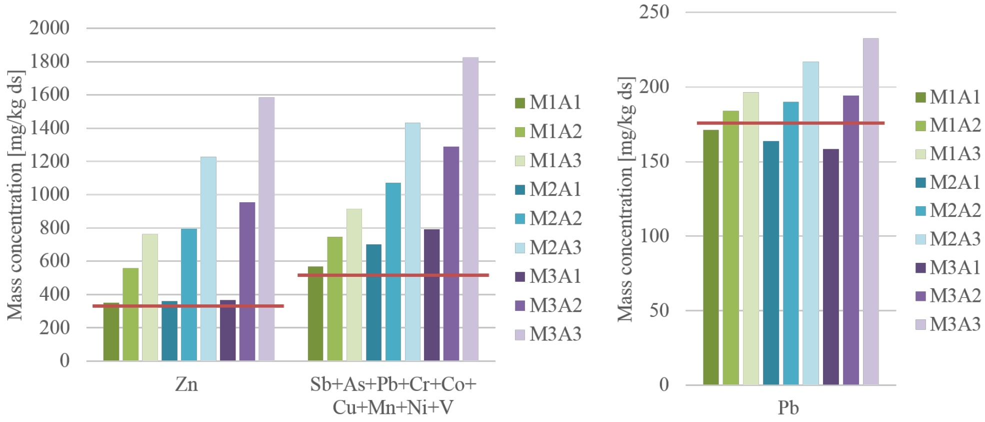


(d) Alkali chloride and corrosion

Figure 23: Key numbers for IGV P3 together with the adjusted risk zones.

5.5.2 Additional Fuel Parameters

In Figure 24 the heavy metal composition in the potential fuel mixtures to IGV P3 are plotted together with the historical levels in the RWW used at Söderenergi. A higher Zn level is acquired when rubber is added to the fuel mix. For the mixtures only containing RWW and SRF, the Zn content is stable. For the sum of heavy metals, the concentration is increased for all mixtures. The highest content has M3A3. Regarding Pb, the concentration in the used RWW have been rather high and the concentration in the potential fuel mixtures is not changed significantly. The Pb concentration is reduced with a higher content of SRF. Seen in the figure, the A3 fuel mixtures (the brighter bars) has the highest values, i.e. a higher rubber share increases the heavy metal content.



(a) (b)

Figure 24: Heavy metal composition in potential fuel mixtures to IVG P3.

In Figure 25, the expected ash flows for the potential fuel mixtures for IGV P3 are illustrated together with the reference of 100% RWW, marked green. The percentages in the figure show the increase of the total ash flow in comparison with the reference. An introduction of 15% of SRF or rubber brings about a 40% increase of the ash flow. M3A1 has the highest ash generation of about 2.5 times higher than the reference case. No limitations for the ash handling system is experienced today. However, problems with scrap metal from the fuel, blocking the ash ejection, exist. With an increase of ash the problem may evolve. The fouling and erosion are as well expected to increase with the increased ash flow. More particles in the convection package tend to cause both wear of the tubes and an increase of deposit. According to the key numbers, the bed material consumption will decrease in IGV P3. However, the increased ash generation poses a risk for an increased formation of sticky ashes which may demand a high bed material consumption.

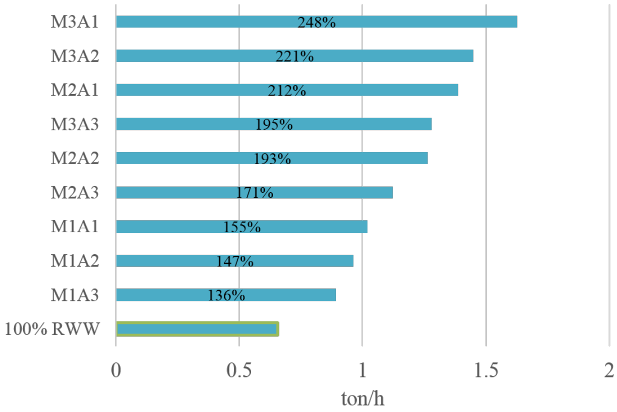


Figure 25: Generated ash from IGV P3 with 90 MW power.

Illustrated in Table 22 are the moisture content and LHV for the potential fuel mixtures to IGV P3, together with the reference of 100% RWW. The moisture content is lower for the assessed fuel blends than for the historically used fuel. The LHV is consequently higher for all potential mixtures. This may bring about higher flue gas temperatures in the boiler. An established maximum limit of LHV to have 100% of MCR for IGV P3 does not exist. However, the maximum level is suspected to be around 15 MJ/kg ar [23]. An increase of the recirculated flue gas is probably required to keep the desired temperature in the boiler.

Table 22: Moisture content and lower heating value for the assessed fuel mixtures to IGV P3.

		100% RWW	**M1A1**	**M1A2**	**M1A3**	**M2A1**	**M2A2**	**M2A3**	**M3A1**	**M3A2**	**M3A3**
MC	% ar	26.3	25.7	25.6	25.5	24.9	24.7	24.5	24.4	24.1	23.8
LHV	MJ/kg ar	12.7	13.2	13.4	13.6	13.7	14.1	14.5	14.0	14.6	15.2

5.5.3 Resume of Potential Fuel Mixtures for IGV P3

Short; the two fuel mixtures with least key numbers in the risk zone are M2A3 and M3A3. The two mixtures with the lowest heavy metal compositions are M1A1 and M2A1. The two fuel mixtures with lowest ash flow increase are M1A3 and M1A2. The fuel mixtures with the most similar moisture contents and LHV to the historical fuel, are M1A1 and M1A2.

The analysis of potential fuel mixtures show an increase of rubber in the fuel mix lowers the risks inferred by the key numbers. However, an increase of rubber increases the heavy metal concentration. To conclude, the results are conflicting why a balance between the risk indicated by the key numbers and the heavy metal concentration must be considered. When introducing more fuel parameters as ash flow and LHV, the weighting becomes more complex. To give a recommendation for potential fuel mixtures the site's capacity must be regarded. However, if the maximum capacity is unknown the evaluation becomes more complicated and uncertain. With no precise limits for heavy metals or LHV for IGV P3, assumptions must be made. The ash handling system is considered not being a restricting parameter since it can be rebuilt for an increased ash generation. The effect of the lower moisture content and increased LHV of the fuel mixtures is regarded as a solvable problem, why the key number predictions and the heavy metal concentration are the reaming defining parameters.

Considering the key number predictions, the fuels containing the highest levels of heavy metals pose the lowest risk for sintering and corrosion. However, the increase of heavy metals may as well increase the eutectic salt formation and corrosion, why a prediction of low corrosion from the key numbers is not necessarily correct. Furthermore, since the fuel mixtures having the lowest heavy metal concentrations have the highest numbers of key numbers indicating risk, these fuel mixtures are neither recommended. The balance between the parameters is considered in the recommendation for the fuel mixtures.

Considering the two parameters, key numbers and heavy metal concentration, the fuel mixtures M1A3 and M2A1 are the least damaging fuel mixtures. M1A3 (85% RWW and 15% rubber) is an acceptable fuel mixture on the basis of having fairly low heavy metal composition, low increase of ashes, similar moisture content and a reasonable key number prediction. M2A1 (70% RWW and 30% SRF) has a higher number of key numbers indicating risk but a lower concentration of heavy metals. The MC and LHV are as well acceptable, the ash generation is doubled. The sulfating number for M2A1 is indicating an increased formation of alkaline chlorine, why sulfur preferably can be added before the combustion to reduce the corrosion risk.

5.6 Potential Fuel Mixtures for IKV

A set of fuel mixes for IKV are evaluated. The fuel blends consist of different portions of RWW, SRF, rubber and wood fuel, which is a 1:1 energy mix of shavings and stem wood chips. The assessed mixtures are shown in Table 23. M1 is the fuel mix used today in IKV. In the evaluation key numbers, ash flow, moisture content, LHV and heavy metal composition are considered. To all mixtures an average amount of the added sulfur during 2013-2017 is included to respect the current combustion conditions.

Table 23: Potential fuel blends for IKV, based on energy content.

		Ref. mix: in-house			**Ref. mix: fuel data**		
		M1A1	M2A1	M3A1	M1A2	M2A2	M3A2
RWW	%	70	0	42	70	0	42
Wood	%	30	75	48	30	75	48
Rubber	%	0	0	0	0	0	0
SRF	%	0	25	10	0	25	10

		M4:30/70			**M5:40/60**	
		M4A1	M4A2	M4A3	M5A1	M5A2
RWW	%	0	20	50	0	0
Wood	%	70	50	20	60	60
Rubber	%	10	10	10	20	10
SRF	%	20	20	20	20	30

The *Ref. mix: in-house* is only used for key number analyses and in the comparison with in-house rule of thumb limits for elemental composition. The difference between the *Ref.* mixtures is the elemental data the key numbers are calculated from. The *Ref. mix: in-house* is based on the in-house rule of thumb values in Table E1 and E2. However, not all elements have a value and for the remaining elements the fuel data presented in Table D1 are used. For the *Ref. mix: fuel data* mixes, the data in Table D1 are used for all elements. The M4 mixes represent a mix of 30% rubber and SRF with different compositions of RWW and wood. For M5 the wood share is 60% and the portion of rubber and SRF is changed. For all these mixtures data from Table D1 in Appendix D are used.

5.6.1 Comparison with In-House Limits

In Table 24 the sulfur and chlorine content in the two reference mixes are shown. Cl and S, marked in bold, are the only elements based on the rule of thumb values for the *Ref. mix: in-house* mixtures. Comparing A1 and A2 for S, the rule of thumb values (A1) give a slightly higher content than for the measured data (A2). For Cl the rule of thumb values are lower than the historical data. Specially the M2A1 and M2A2 mixes are different. The high Cl content for M2A2 is due to the almost double measured Cl content in SRF than for the respective rule of thumb value.

Table 24: Comparison with in-house rule of thumb max values for the reference mixtures to IKV. Marked numbers indicate over-ride of maximum limit [22].

Element	**Max**		**M1A1**	**M2A1**	**M3A1**	**M1A2**	**M2A2**	**M3A2**
Cl	1200	mg/kg ds	**545**	**306**	**453**	625	2100	1206
F	50	mg/kg ds	-	-	-	-	-	-
S	2000	mg/kg ds	**767**	**730**	**759**	629	718	659
N	1.5	% ds	0.8	0.3	0.6	1.1	0.2	0.8
Hg	0.15	mg/kg ds	0.03	0.06	0.05	0.05	0.03	0.04
Cd+Tl	0.8	mg/kg ds	0.4	0.4	0.4	0.4	0.4	0.4
Br	10	mg/kg ds	-	-	-	-	-	-
Pb	50	mg/kg ds	24	34	29	123	24	84
Sb+As+Pb+Cr+ Co+Cu+Mn+Ni+V	700	mg/kg ds	233	815	484	344	378	356
Zn	300	mg/kg ds	282	79	204	241	100	185
Al metallic	1000	mg/kg ds	291	506	453	-	-	-
Na+K	0.2	% ds	0.08	0.07	0.08	0.10	0.12	0.11

The remaining elements in the table are based on partly rule of thumb vales and partly historical data. The Pb content is higher for the historical data than for the rule of thumb values. For M1A2 and M3A2 the maximum limit is exceeded. Indicating the Pb being too high for the mix used today. With the rule of thumb values the sum of heavy metals for M2A1 is significantly higher than for the respective fuel mix based on only measured data. The Br and F contents are not presented due to lack of data. The Al content is not showed since the analysis data is not indicating the the state of the aluminum. The N content is similar for the reference cases and are below the maximum limit for all mixes. The highest content of N is for the fuel mix used today (M1A2). The Hg and Cd+Tl contents are similar for A1 and A2. The Zn content is higher for the rule of thumb values, however, all values are below the maximum limit. The Na+K content is higher for the measured historical data, however, still within accepted levels. To summarize, the corrosion risk would be lower if the fuel had the in-house rule of thumb values, however, the total amount of heavy metals would be higher.

In Table 25 the calculated elemental composition in fuel mixtures M4 and M5 are presented together with the maximum rule of thumb levels. Comparing with Table 24, the maximum limits are exceeded for more parameters for M4 and M5. The Cl content is increasing from M4A1 to M4A3. For M5, the Cl content in A1 is higher than in A2. All fuel mixtures exceed the maximum accepted Cl content. For S, all mixtures are within the accepted levels, the highest S content is for M4A3. Similar result is seen for the N content. The Hg content is as well below the max, the highest content has M5A1. The maximum level of Cd+Tl is exceeded for all mixtures.

Table 25: Comparison with in-house rule of thumb max values and mix M4 and M5. Marked numbers indicate over-ride of maximum limit [22].

Element	**Max**		**M4A1**	**M4A2**	**M4A3**	**M5A1**	**M5A2**
Cl	1200	mg/kg ds	2488	2624	2916	3323	3276
F	50	mg/kg ds	-	-	-	-	-
S	2000	mg/kg ds	895	1007	1212	1184	1089
N	1.5	% ds	0.3	0.6	1.1	0.4	0.3
Hg	0.15	mg/kg ds	0.07	0.08	0.09	0.12	0.07
Cd+Tl	0.8	mg/kg ds	1.2	1.3	1.5	2.2	1.4
Br	10	mg/kg ds	-	-	-	-	-
Pb	50	mg/kg ds	44	80	138	69	53
Sb+As+Pb+Cr+ Co+Cu+Mn+Ni+V	700	mg/kg ds	664	717	845	1017	762
Zn	300	mg/kg ds	388	438	560	703	411
Al metallic	1000	mg/kg ds	-	-	-	-	-
Na+K	0.2	% ds	0.12	0.13	0.14	0.12	0.14

The Pb level is exceeded for all mixtures except for M4A1. M4A1 contains no RWW why this content is lower. The highest Pb content of M4 and M5 has M4A3 which has a RWW content of 50%. To compare, the mixture M1A2 with a share of 70% RWW, has an even higher Pb content. Regarding the sum of heavy metals, the level is exceeded for all but one mix. The M4 mix with the highest content of wood (M4A1) is not exceeding the maximum. The highest heavy metal content do not coincide with the highest Pb content since M5A1 has the highest sum of heavy metals. An explanation to this is due to M5A1 has the highest portion of rubber. The Zn content is over the maximum accepted level for all M4 and M5 mixes. The highest Zn content has the M5A1. The high Zn content in rubber is an explanation to this. The Na+K content is below the maximum limit for all M4 and M5 blends.

The M5A1 has the highest values for the majority of the parameters exceeding the maximum, for all except Pb. The highest Pb value of all the mixtures has M1A2. To conclude, for all potential fuel mixtures the Cl content will increase and exceed the maximum limit. The heavy metal content is as well increased for the majority of the fuel mixtures. This pose an increased risk for formation of salt mixtures with low melting points and corrosion. According to the in-house rule of thumb limits non of the assessed fuel mixtures are acceptable. However, if an increased level can be a tolerated the M1A2-M3A2 are the fuel mixtures with the lowest values and the mixtures considered least damaging. The maximum acceptable limit of these elements in the fuel to IKV must be revised to totally exclude fuel mixtures from potential usable fuel mixtures to IKV.

In Table 26 additional fuel properties for the potential fuel mixtures as ash content and heating values are shown.

Table 26: Fuel properties for potential fuel mixes to IKV.

		M1A2	**M2A2**	**M3A2**	**M4A1**	**M4A2**	**M4A3**	**M5A1**	**M5A2**
Moisture content	% ar	34.1	42.8	37.8	42.4	37.9	30.9	40.0	40.0
LHV	MJ/kg ar	11.3	10.1	10.8	10.6	11.3	12.7	11.3	11.1
LHV	MWh/ton ar	3.2	2.8	3.0	2.9	3.1	3.6	3.1	3.1
HHV	MJ/kg ds	17.1	17.6	17.3	18.2	18.2	18.4	18.8	18.4
Ash	% ds	2.7	5.0	3.6	5.5	6.0	6.9	6.9	7.1
Ash	ton/h	1.5	2.8	2.0	2.9	3.2	3.6	3.6	3.8

In Figure 26, data from Table 26 and limitations in Table E4 are compared. The moisture content of the fuel mixtures are graphed together with colored fields indicating the restrictions. Green indicates 100% of the MCR is possible. Yellow is indicating fuel load limitations and red is signaling an unusable fuel mix. Seen in Figure 26, the boiler load is limited for fuel mix M1A2 and M4A3. For the other blends it is possible to have 100% of MCR. The restricted M1A2 is the fuel blend used today in IKV. Söderenergi is not restricting the load today but they are experiencing problems with the re-circulation fans for the combustion air, due to the fans are run on maximum capacity. If the fans are not functioning correctly the temperature in the boiler cannot be kept. A temperature increase brings about higher risk for sintering, high temperature corrosion and higher emissions. The problem with reducing the load due to a dryer fuel is a reduced power generation, this since less fuel generates a lower flow of flue gas and humidity which reduces the heat transfer. The moisture content of the fuel mixture could be adjusted by considering injecting water to the boiler or increasing the moisture content of the fuel before combusting the fuel.

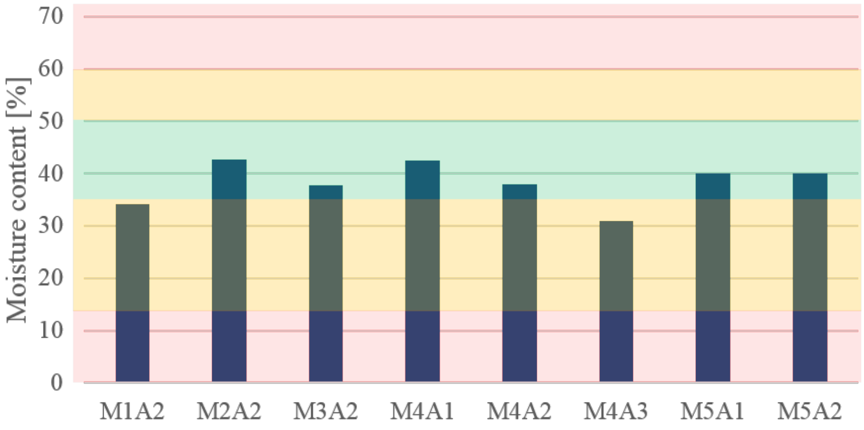


Figure 26: The moisture content for the potential fuel mixtures to IKV.

Furthermore, the ash content is another parameter restricting the fuel usage. Seen in Table 26 the ash flow is increased for M4 and M5. Comparing with M1A2, the blend used in IKV today, the ash content is more than doubled for the mixes containing more rubber and SRF. With a higher ash flow the erosion in the boiler can be expected to increase as well as the fouling. There is no capacity limit for the fly ash for IKV. However, the flow of bottom ash is a limiting factor due to the cooling of the ashes [22]. No precise limit of the capacity exist but the state today is strained. An increase of 50% of the bottom ash flow is assumed to be the maximum capacity of the current system. To handle a higher bottom ash flow the ash handling system must be rebuilt. In Figure 27 the ash flow for both the fly ash and the bottom as is shown. The percentages indicates the increase from the reference state of today (M1A2, marked with green). The bottom ash flow is assumed to be 25% of the total ash flow. This approximation is based on an average bottom ash share from IKV during 2015-2017.

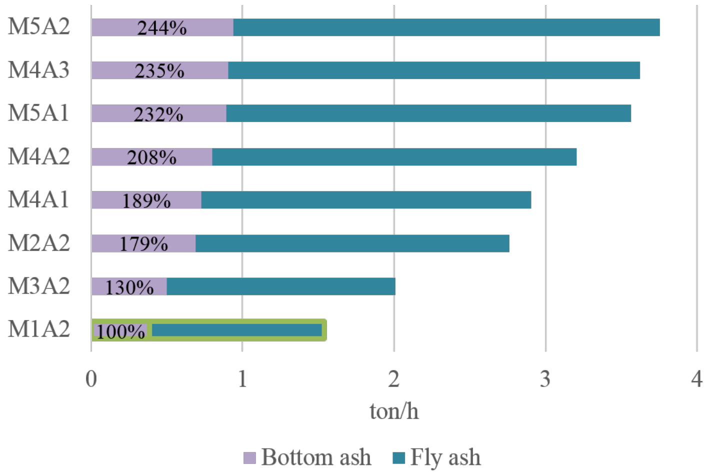
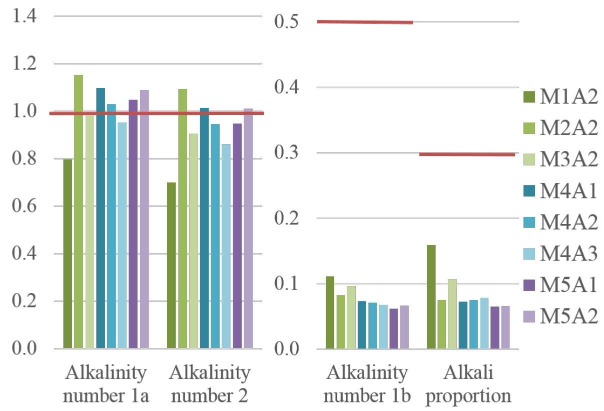


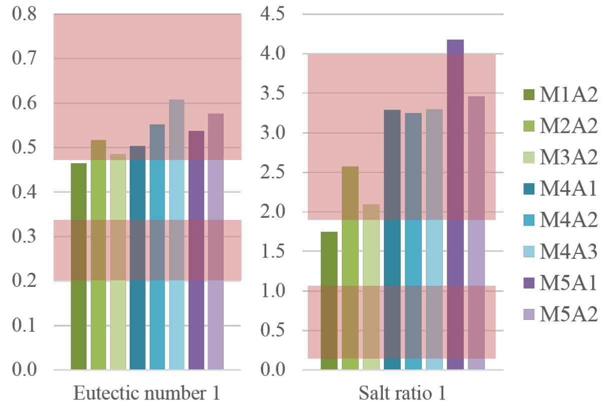
Figure 27: Ash flow for the potential fuel mixtures for IKV.

5.6.2 Key Numbers

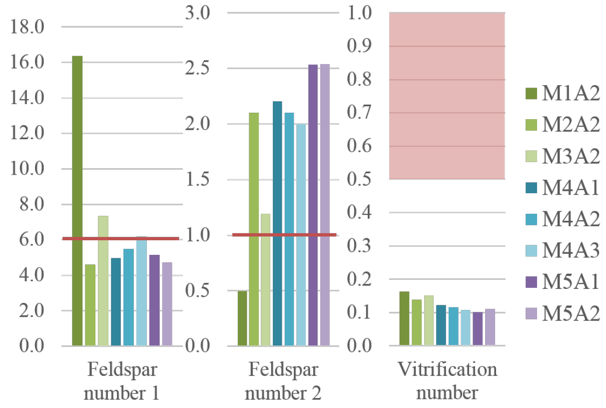
In Figure 28 the key numbers for the fuel mixtures M1A2, M2A2, M3A2 and the M4 and M5 mixtures are presented together with the adjusted risk zone. Comparing the key numbers for the potential fuel mixtures with the historical fuel usage in IKV, the vitrification number is lower (0.1) for M4 and M5 than the historical scenario (0.2), indicating a reduced risk for formation of glass phases with low melting points. The reduced glass formation seen in M4 and M5 may decrease the sand consumption in IKV. The vaporization ratio being over 1 indicates the vaporization of alkali chlorides, all alkali metals can be vaporized with Cl. Additionally, there is risk for other volatile chlorides with other elements as Zn and Pb. This is different from the results from the previous fuel usage where the ratio was below 1. The sulfating number for M2A2, M4 and M5 are below 1, differing from the earlier fuel usage where the values been approximately 2. The prediction is changed from an increased sulfur formation to an increased chlorine formation. The benefit from the added sulfur to the potential fuel mixtures is not acquired. With these fuel mixtures a higher amount of sulfur is required.



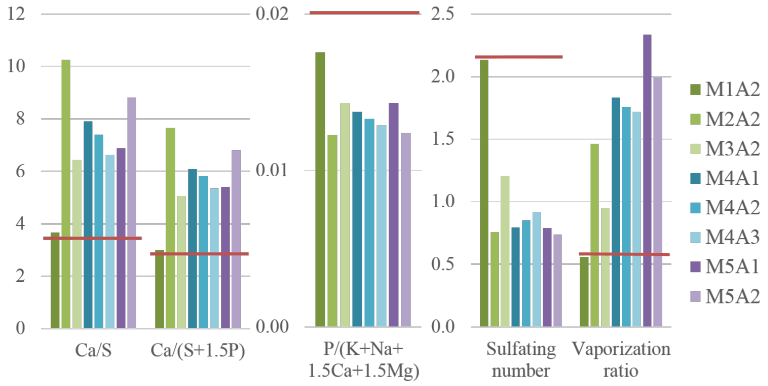
(a) Sintering



(b) Eutectic salts



(c) Glass formation



(d) Alkali chloride and corrosion

Figure 28: Key numbers for IKV together with the adjusted risk levels.

The key numbers in Table 27 and 28 are marked with yellow and pink to highlight the key numbers being close to the limit of the risk zone or in the risk zone. Key numbers being within 10% from the limit in the risk zone are not marked. From 10% to 20% the key number is marked with yellow and from 20% from the risk limit, the key number is marked with pink.

Table 27: Key numbers for potential fuel mixes for IKV. A1 is based on in-house rule of thumb values and A2 on historical fuel data. The marking is indicating the key number being in the risk zone, no color indicates no risk.

Key numbers	**M1A1**	**M2A1**	**M3A1**	**M1A2**	**M2A2**	**M3A2**	**Risk zone**
Sintering							
Alkalinity number 1a	0.73	1.08	0.91	0.80	1.15	0.98	>1
Alkalinity number 1b	0.10	0.05	0.07	0.11	0.08	0.10	>0.5
Alkalinity number 2	0.63	1.02	0.83	0.70	1.09	0.90	>1
Alkali proportion	0.15	0.05	0.09	0.16	0.08	0.11	>0.3
Glass formation							
Feldspar number 1	16.14	4.28	6.93	16.37	4.60	7.36	>6
Feldspar number 2	0.59	3.40	1.65	0.50	2.10	1.19	<1
Vitrification number	0.14	0.09	0.12	0.16	0.14	0.15	0.5-1
Eutectic salts							
Eutectic number 1	0.54	0.77	0.63	0.46	0.52	0.49	0.2-0.34, 0.47-0.8
Salt ratio 1	2.37	2.22	2.31	1.75	2.57	2.10	0.2-1.16, 1.91-4
Alkali chloride & Corrosion							
Sulfating number	**3.11**	**5.27**	**3.70**	2.13	0.76	1.21	<2.15
Vaporization ratio	0.58	0.35	0.49	0.56	1.46	0.95	>0.59
Ca/S	2.56	8.88	5.02	3.66	10.25	6.44	>3.56
Ca/(S+1.5P)	2.25	7.31	4.30	3.00	7.65	5.06	>2.93
P/(K+Na+1.5Ca+1.5Mg)	0.02	0.01	0.01	0.02	0.01	0.01	<0.02

In Table 27 the key numbers for the in-house rule of thumb values (A1) and the measured fuel data (A2) are shown. Marked in bold is the key number only calculated with the rule of thumb values (the sulfating number for the in-house rule of thumb values). Seen in the table, these are not in the risk area. Comparing with the key numbers based on the fuel data, the key numbers for the rule of thumb values are higher and not in the risk zone for corrosion. For the fuel mixes M2A1 and M3A1, the sulfating number indicating no risk, is not a guarantee for no corrosion. This since the Ca/S is in the risk zone, meaning the sulfur can be absorbed and not able to replace the chlorine with the alkali. With the rule of thumb values M1 is more damaging than what is showed with the analysis of the historical data.

The result for M1A2 is similar to the historical scenario for IKV 2017, however, due to the changed risk areas the number of key numbers in the risk zone is differing. This mix is used as a reference towards the others fuel mixes.

For fuel mix M2A2, the alkalinity numbers 1a and 2 are in the risk zone, increasing the risk for sintering of the bed. The alkalinity number 1a is marked yellow. Alkalinity number 2 is within the 10% difference and not marked in Table 27. The feldspar and vitrification numbers are indicating a low risk of glass formation. Regarding the eutectic salt formation, the risk is present for M2A2. The risk for corrosion is as well expressed by the key numbers. The sulfating number for M2A2 is <1 which indicates an enhanced formation of alkaline chlorides. The vaporization ratio for the same fuel mix is >1, indicating all free alkali metals can vaporize as chloride. The Ca/S ratio is particularly high for M2A2, inferring a higher risk of the sulfur being absorbed by the Ca. It can be concluded that M2A2 poses high risk of chlorine induced corrosion, if this mixture is to be used in IKV additional sulfur is preferably added.

The sintering risk appears to be lower for M3A2 than for M2A2 and rather similar to the reference case M1A2. However, the glass formation risk is lower for M3A2 than for the reference case. Moreover, the M3A2 mix encounter risk for forming eutectic salts, the risk is higher than for the present fuel mix. The corrosion risk exists for mixture M3A2, however, the risk is higher for M2A2. This since the Ca/S ratio is lower for M3A2 and the vaporization number is <1 and sulfating number is >1. M3A2 poses less risk of forming alkaline chlorides why this mixture is considered less damaging than M2A2.

Table 28: Key numbers for potential fuel mixes M4 and M5 for IKV, all based on fuel data. The marking is indicating the key number being in the risk zone, no color indicates no risk.

Key numbers	**M4A1**	**M4A2**	**M4A3**	**M5A1**	**M5A2**	**Risk zone**
Sintering						
Alkalinity number 1a	1.10	1.03	0.95	1.05	1.09	>1
Alkalinity number 1b	0.07	0.07	0.07	0.06	0.07	>0.5
Alkalinity number 2	1.02	0.95	0.85	0.95	1.01	>1
Alkali proportion	0.07	0.08	0.08	0.07	0.07	>0.3
Glass formation						
Feldspar number 1	4.97	5.48	6.19	5.14	4.74	>6
Feldspar number 2	2.20	2.10	2.00	2.54	2.54	<1
Vitrification number	0.12	0.12	0.11	0.10	0.11	0.5-1
Eutectic salts						
Eutectic number 1	0.50	0.55	0.61	0.54	0.58	0.2-0.34, 0.47-0.8
Salt ratio 1	3.29	3.25	3.30	4.18	3.46	0.2-1.16, 1.91-4
Alkali chloride & Corrosion						
Sulfating number	0.80	0.85	0.92	0.79	0.74	<2.15
Vaporization ratio	1.83	1.76	1.72	2.34	2.00	>0.59
Ca/S	7.91	7.39	6.63	6.87	8.82	>3.56
Ca/(S+1.5P)	6.08	5.81	5.34	5.40	6.81	>2.93
P/(K+Na+1.5Ca+1.5Mg)	0.01	0.01	0.01	0.01	0.01	<0.02

The result for the mixtures M4 and M5 are shown in Table 28. The result for M4 is expected to worsen from M4A1 to M4A3 due to the RWW portion is increased. However, the decrease in fuel mix quality is not clearly seen in Table 28. The total number of key numbers in the risk zone, both yellow and pink, is the same. However, the highest number of parameters in the pink risk zone has M4A3. Comparing the Ca/S ratio though, the value is better for M4A3. In other words, a smaller portion of RWW is not necessarily improving the result.

Comparing M4A1 with the reference mix M1A2, glass formation risk is significantly lower for the M4 mix. However, the corrosion risk is higher. M4A1 as well possesses a slightly higher risk for sintering and forming eutectic salts than M1A2.

M4A2 is possessing a higher risk for corrosion and formation of eutectic salts in comparison with the reference scenario. The risk for glass formation is, however, significantly lower. The risk for sintering is low, similar to M1A2.

Comparing M4A3 to the reference scenario, the result is similar to M4A2. The risk for forming eutectic salts are slightly higher for M4A3. M4A3 is over the risk limit for feldspar number 1, the exceed is small and as stated in Table 4; "over six is poor, but not always". The key number is not marked in the table since the exceed is less than 10%. For all M4 mixtures the sulfating number is indicating an increased formation of alkali chlorides why additional sulfur may be added to reduce the corrosion risk.

Comparing M5A1 with M1A2, the reference mix, the risk for glass formation is lower and the risk for forming eutectic salts and corrosion is higher for M5A1. The sintering risk is low for both mixtures. For M5A1 the salt ratio 1 is not in the risk zone, this is different from the other M4 and M5 mixtures. According to the number of key numbers in the risk zone, M5A1 appears to be the safest fuel mix, if not considering the current mix M1A2. However, the vaporization ratio is highest for M5A1, indicating the highest Cl/(Na+K) ratio of all mixtures. Bringing about the risk of forming volatile chlorides with other elements than Na and K which is a risk for eutectic salts and corrosion. Additionally, as previously showed M5A1 exceed various in-house rule of thumb limits, projecting a high damage risk.

Seen in Table 28, M5A2 has the same key numbers in the risk zone as M4A3. Comparing with the reference scenario, the corrosion risk and the risk for eutectic salts is increased. The glass formation risk is reduced and the sintering risk is similar, indicating a lower demand of changing the bed material in IKV. The lowest sulfating number has M5A2, indicating the highest risk for forming alkaline chlorides of all assessed mixtures. The indication of a high damage rate is as well indicated by the analysis of the elemental composition of the mix. The high portion of rubber and SRF together with wood fuel is shown to posses high damage risk.

5.6.3 Resume for Potential Fuel Mixtures for IKV

In Table 29 a summery of assessed fuel mixtures is shown. Seen in the table, the lowest number of key numbers in risk zone, with exception for the reference mix M1A2, has M5A1. The highest number of key numbers in total in the risk zone has M2A2. The highest number of elements exceeding the in-house rule of thumb values have M4A2, M4A3, M5A1 and M5A2. The highest concentrations of the heavy metals has M5A1. The lowest number of elements exceeding the rule of thumb values, except the reference scenario, has M2A2. Regarding the ash flow increase, only M2A2 has an acceptable level for the current ash handling system. M4A3 is the only mix with load limitations.

In the evaluation of the fuel mixtures, the reconstruction of the ash handling system is considered essential since it is required for the majority of the fuel mixtures. The limitation of the boiler load is considered a strict parameter and the fuel mix strained by this is not recommended. Both the chemical composition compared with the in-house limits and the key numbers are considered in the evaluation.

Table 29: Summery of the potential fuel mixtures to IKV. Marked in bold indicates the highest parameters.

	M1A2	**M2A2**	**M3A2**	**M4A1**	**M4A2**	**M4A3**	**M5A1**	**M5A2**
Key numbers marked pink	2	**6**	6	5	5	6	5	6
Key numbers marked yellow	-	**2**	1	2	2	1	1	1
Elements exceeding rule of thumb limits	1	1	2	3	5	5	**5**	5
Ash flow increase >50%	-	No	Yes	Yes	Yes	Yes	Yes	**Yes**
Load limitation	No	No	No	No	No	**Yes**	No	No

M3A2 (42% RWW, 48% wood fuel and 10% SRF) and M4A1 (70% RWW, 10% rubber and 20% SRF) are considered to be the least damaging fuel blends since these are the fuel mixes with the least parameters exceeding the limitations and risk areas. For M4A1 the sulfating number is indicating an increased chlorine formation. To reduce this, sulfur (more than the current level) can with benefit be added to IKV to reduce the risk for chlorine induced corrosion.

6 Conclusions and Future Work

6.1 Conclusions

The following conclusions are made from the results:

- The key numbers indicate that the previous fuel usage in IGV P3 may have generated high feldspar formation leading to a high bed material consumption. The key numbers as well infer risk for corrosion, however, the increased formation of alkaline sulfates is showed, why the corrosion rate is expected to have been rather low. The low corrosion rate is as well emphasized in the overhaul reports. The deposition analysis is also supporting the thesis by showing a high content of sulfur. The key numbers for the used fuel in IGV P3 indicate formation of eutectic salts which normally it is an guarantee for corrosion. However, since the Cl content was showed to be low in the fouling analysis, the formation of eutectic salts is expected to be low. However, it is not completely disregarded due to Zn, Pb and Cl is found in deposition on the heat exchangers.
- The previous fuel usage in IKV show similar results as for IGV P3. The same risk are indicated by the key numbers for the two boilers and the same conclusions can be drawn. Regarding the evaluation of risk levels for the key numbers, different from IGV P3, the eutectic salt formation is assumed to be negligible for IKV. The previous high content of wood fuel in IKV appears not to decrease the risks. The heavy metal content is, however, increased with higher share of RWW. From the analysis of water injection, the fouling is showed to decrease with an increase of RWW in the fuel. The analysis from the Fouling index is another indication for this. Considering the great difference of the values between IKV and IGV P3 for the Fouling index, the difference of 30% wood fuel in IKV has a noteworthy effect on the fouling. The results show 100% RWW is reducing the fouling.
- As previously mentioned, the current fuel usage for IGV P3 and IKV has a fairly low damage tendency. The results from the study show a fuel change will increase the damage risk in the boilers. In general, the corrosion risk and the heavy metal content will increase in comparison with today's fuel. The increase of fouling and slagging are as well expected based on the ash indices. Moreover, the higher ash generation from the mixtures infers an increased risk for erosion and fouling.
- The sintering risk and the risk for forming glass in the bed are showed to be lowered for the potential fuel mixtures to both IKV and IGV. This infers a lower demand of changing the bed material. However, the increased ash generation may interfere with a decrease of the sand consumption. Additionally, based on the analysis of the ash key numbers, the assessed fuel mixtures are expected to produce difficult ashes.
- The study has relieved that parts of the boilers may require adjustments. Due to the increased ash generation, the ash cooling system for IKV will require a reconstruction for any of the assessed fuel mixtures. The increase of the lower heating value of the assessed fuel mixtures to IGV P3 are likely to require an increase of the capacity of the flue gas recirculation pump.
- The majority of the potential fuel mixtures to IKV and IGV P3 are shown to have a favoured formation of alkaline chlorides why extra sulfur must be added in the boilers.
- In the comparison of the different fuel mixtures, it is found that the corrosion risk expressed by the key numbers is reduced with a higher share of rubber. The heavy metal content is, however, increased, leading to e.g. an enhanced risk for formation of eutectic salts, which as well are corrosive. On the contrary, the fuel mixtures with a high risk expressed by the key numbers, have the lowest concentrations of heavy metals. Due to the results are conflicting, a balance between the risk indicated by the key numbers and the heavy metal concentration, must be considered in the evaluation.
- The fuel mixtures considered causing least damage to IGV P3 are, M1A3, a mixture of 85% RWW and 15% rubber and M2A1, a mixture of 70% RWW and 30% SRF. The fuel mixtures considered

causing least damage to IKV are, M3A2, a mixture of 42% RWW, 48% wood fuel and 15% SRF, and M4A1, a mixture of 70% wood fuel, 20% SRF and 10% rubber. To M2A1 (IGV P3) and M4A1 (IKV) sulfur may be added to the boilers with the fuel to reduce the risk of chlorine induced corrosion.

6.2 Future Work

Recommendations for further work are stated below.

- Since the key numbers are guiding parameters and not an absolute prediction the risk limits for the individual boilers may be evaluated further. All boilers are individual and what levels of damage that are acceptable for each boiler differ.
- The restriction for the concentration of heavy metals to IGV P3 may be analyzed further. Additionally, all the potential fuel mixtures to IKV exceed some of the maximum in-house rule of thumb limits regarding corrosive elements and heavy metals. The maximum limits must be revised.
- In future studies the damage in IGV P1 may be considered to anticipate the fuel change. Specifically, regarding the corrosion.
- Moreover, a model for optimization of fuel mixtures may be developed, where the risk levels of the key numbers and heavy metals may be set and the model provides a set of possible fuel mixtures meeting these requirements.
- Additionally, an optimization of required sulfur to the boiler may be investigated. Where e.g. the uptake of sulfur, type of additive and the proportion Cl/S are considered.
- Further, preforming more analyses of the fuel, may be beneficial to improve the certainty and the representativity of the weighted average. Specifically, analyzing more fuel parameters, including the elements used in the additional fuel analyses.

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Appendix

Appendix A - Literature Values for Elemental Analysis of Fuel

Table A1: Content analysis of forest residue, recovered waste wood and wood chips reported in [5] and [30].

Specie	**Forest residue [5]** mg/kg ds	**Recovered wood [5]** mg/kg ds	**Wood chips [30]** mg/kg ds
Al	540	1778	79-580
As	0.08	30	0-1.5
Ba	73		
Ca	5186	4039	2900-7000
Cd	0.2	0.3	0.06-0.4
Co	0.2	1.6	0.1-0.7
Cr	2.7	56	1.6-17
Cu	2.7	56	0.3-4.1
Fe	225	1855	64-340
Hg	0.03	0.1	0.01-0.17
K	2059	1110	910-1500
Mg	566	748	310-800
Mn	430	103	63-900
Mo	0.1		
Na	231	946	20-110
Ni	0.7	3	1.7-11
P	463	381	97-340
Pb	1.5	54	0.3-2.7
Sb			
Si	3053	7577	440-2900
Ti	29	1039	
Tl			
V	0.5	3	0.6-1.4
Zn	54	515	7-90

Table A2: Elemental analysis of several biofuels reported in [5].

Specie	**Forest residue** % dry ash free	**Recovered wood** % dry ash free	**Wood fuel** % dry ash free
C	53.1	51.7	50.8
H	6.0	6.3	6.2
O	40.6	41.1	
S	0.04	0.07	0.01
N	0.31	0.84	0.05
Cl	0.02	0.05	0.01

Appendix B - IKV and IGV P3 with Temperature

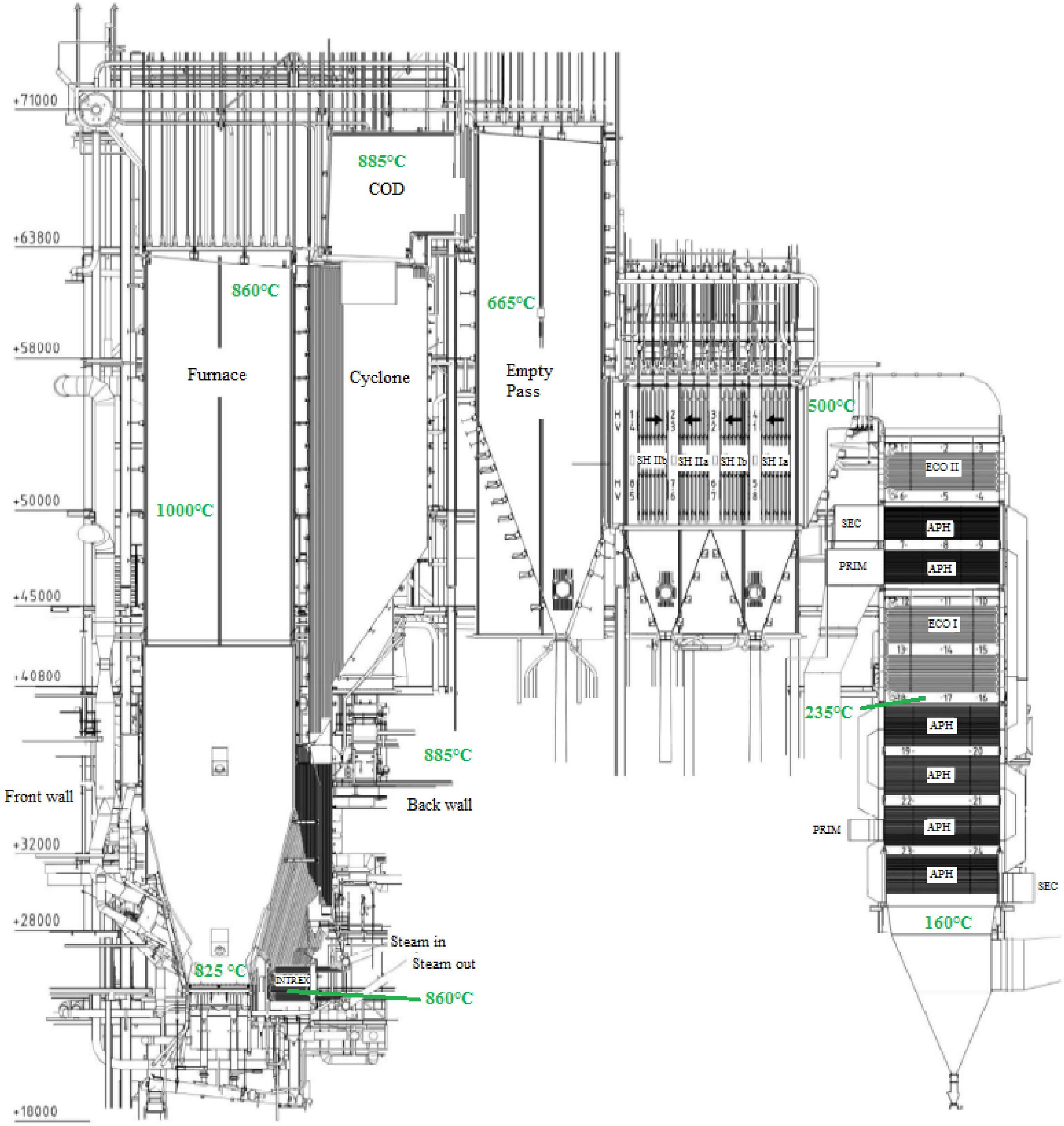


Figure B1: The design of IKV with the flue gas temperatures marked.

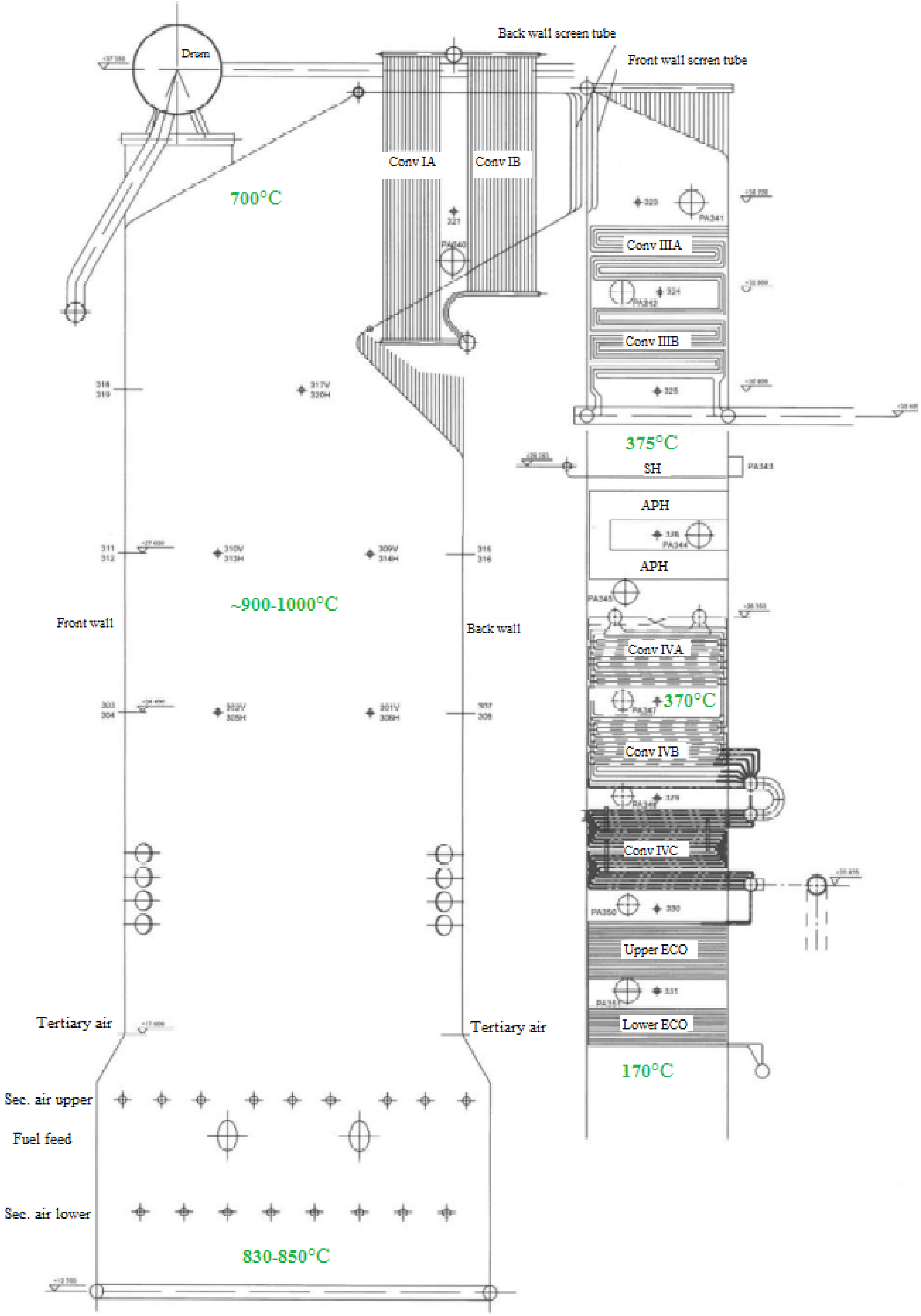


Figure B2: The design of IGV P3 with the flue gas temperatures denoted.

Appendix C - Molar Calculations

An example how to recalculate the sulfur content in the fuel from percentage of dry substance to kmole S/kg ds is here shown. Where X stands for value of sulfur content and the molar mass of sulfur, M_{S} is 32.06 kg/kmole.

$$X\%S = 0.01 \cdot X \frac{\text{kg S}}{\text{kg ds}}$$

$$0.01 \cdot X \frac{\text{kg S}}{\text{kg ds}} \cdot \frac{1}{M_{\mathrm{S}}} \frac{\text{kmole S}}{\text{kg S}} = 0.01 \cdot \frac{X}{M_{\mathrm{S}}} \frac{\text{kmole S}}{\text{kg ds}}$$

Further, an calculation example of the mass ratio to molar fraction of Na. Where Y stands for value of sodium content and the mass fraction, M_{Na} is 22.99 kg/kmole.

$$Y \frac{\text{Na mg}}{\text{kg db}} \cdot 10^{\text{-}6} \frac{\text{kg}}{\text{mg}} \cdot \frac{1}{M_{\mathrm{Na}}} \frac{\text{kmole Na}}{\text{kg Na}} = \frac{Y \cdot 10^{\text{-}6}}{N_{\mathrm{Na}}} \frac{\text{kmole Na}}{\text{kg ds}}$$

Appendix D - Fuel Elemental Analysis from Söderenergi

Table D1: Weighted elemental analysis values for fuels used at Söderenergi.

		Shavings	**Wood chips**	**RWW**	**SRF**	**Rubber**
Data points		*51*	*46*	*687*	*10*	*70*
Data points		*3*	*3*	*3*	*3*	*3*
Moisture content	% ar	53	38	26	21	17
LHV	MJ/kg ar	7.6	10.6	12.7	16.5	21.7
LHV	MWh/ton ar	2.1	2.9	3.6	4.6	6.0
HHV	MJ/kg ds	18.9	18.7	18.3	21.4	26.7
Ash content	wt% ds	0.9	0.9	3.5	19.9	18.0
S	wt% ds	0.03	0.02	0.08	0.26	0.39
N	wt% ds	0.1	0.1	1.6	0.6	1.5
C	wt% ds	50.7	50.4	49.0	50.7	60.3
H	wt% ds	6.1	6.2	6.0	6.9	7.5
Cl	wt% ds	0.01	0.01	0.09	0.94	1.05
Al	mg/kg ds	83	17	619	10489	5308
As	mg/kg ds	0.07	0.05	23.4	1.3	4.0
Cd	mg/kg ds	0.08	0.03	0.6	1.6	12.7
Co	mg/kg ds	0.05	0.04	1.6	3.8	21.0
Cr	mg/kg ds	0.8	0.1	45	57	153
Cu	mg/kg ds	0.9	0.4	91	929	3984
Hg	mg/kg ds	0.02	0.02	0.06	0.05	0.6
K	mg/kg ds	552	845	690	1018	478
Mn	mg/kg ds	97	120	100	213	145
Na	mg/kg ds	64	52	483	2027	567
Ni	mg/kg ds	0.3	0.1	4.9	16.7	86.2
Pb	mg/kg ds	0.49	0.07	178	112	332
Sb	mg/kg ds	0.2	0.2	2.5	20.1	27.6
Tl	mg/kg ds			0.02	0.03	0.05
V	mg/kg ds	0.06	0.05	1.5	5.9	25.2
Zn	mg/kg ds	19	20	340	395	4263
Ca	mg/kg ds	1155	1540	3559	37922	15593
Fe	mg/kg ds	46	20	765	2335	5183
Mg	mg/kg ds	161	188	471	1579	2634
P	mg/kg ds	68	73	97	473	504
Si	mg/kg ds	673	525	5203	23339	18118
Ti	mg/kg ds	11	11	36	57	60

Table D2: Weighted elemental analysis values for biofuels used at Söderenergi.

		Bark	**Blended chips**	**Forest chips**	**Forest residues**	**Fuel wood**
Data points		*76*	*32*	*185*	*55*	*6*
Moisture content	% ar	49	42	42	46	42
LHV	MJ/kg ar	8.7	9.8	8.9	9.5	10.1
Ash content	wt% ds	3.4	3.3	3.5	2.8	0.9
S	wt% ds	0.05	0.03	0.04	0.04	0.01
N	wt% ds	0.4	0.1	0.4	0.4	0.1
C	wt% ds	52.0	50.0	50.4	50.8	50.3
H	wt% ds	5.8	6.1	6.1	6.1	6.2
Cl	wt% ds	0.03	0.01	0.01	0.02	0.01

Appendix E - In-House Rule of Thumb Values

Table E1: In-house rule of thumb values for IKV for forest residues, wood chips, shavings and bark. [22]

Fuel, ar		**Forest residues**		**Wood chips**		**Shavings**		**Bark**	
		Average	Design variation	Average	Design variation	Average	Design variation	Average	Design variation
LHV	MJ/kg	8.3	6-13	8.4	6-13	8.4	6-13	7.7	4-11
MC	%	50	30-60	50	30-60	50	35-60	50	40-70
Analysis, ds									
C	wt%	50	45-55	51	45.9-56.1	50.6	45.5-55.7	52.6	47.3-57.9
H	wt%	5.8	5.2-6.4	5.9	5.3-6.5	6.2	5.6-6.8	5.8	5.2-6.4
O	wt%	38.3	34.5-42.1	40.8	36.7-44.9	42.6	38.3-44.7	37.1	33.4-40.8
N	wt%	0.5	<1	0.2	<1	0.2	<0.3	0.7	<1
S	wt%	0.05	0.01-0.2	0.03	0.01-0.2	0.02	0.03-0.07	0.03	0.01-0.2
Ash	wt%	4	2-12	2	1-6	0.4	<1	4	2-10
Cl	wt%	0.02	0.01-0.05	0.02	0.01-0.05	0.02	0.02-0.04	0.02	0.01-0.05
Na+K	wt%		<0.15		<0.15		<0.15		<0.15
Ash analysis									
SiO_2	wt%		1.5-30		1.5-30		1.5-30		0.5-22
TiO_2	wt%		0-0.1		0-3.4		0-3.4		0-1-6
Al_2O_3	wt%		0.9-4.4		0.9-4.4		0.9-4.4		0-7.5
FeO_3	wt%		0.4-13.5		2-7		2-7		0.3-7.1
MgO	wt%		3-10		1.4-8.5		1.4-8.5		3.6-6.4
CaO	wt%		30-52		9-46		9-46		36-52
Na_2O	wt%		0.1-1		-		-		-
K_2O	wt%		0-10		-		-		-
P_2O_5	wt%		2.5-7		0.6-6.5		0.6-6.5		2-6

Table E2: In-house rule of thumb values for IKV for SRF and RWW. [22]

		SRF/PWP		**RWW**	
Fuel, ar		Average	Design variation	Average	Design variation
LHV	MJ/kg	19.1	17-21	12.9	10-18
MC	%	5	3-12	26	5-40
Analysis, ds					
C	wt%	50	45-55	47.3	43.2-52.8
H	wt%	6.8	6.1-7.5	6	5.5-6.7
O	wt%	26.8	24.1-29.5	39.7	35.8-43.8
N	wt%	0.7	0.6-0.8	1	<2
S	wt%	0.25	0-0.4	0.1	0.1-0.3
Ash	wt%	15	10-20	5	2-20
Ash analysis					
SiO_2	wt%		0.6-17.6		1-55
TiO_2	wt%		2.2-15.9		1-11
Al_2O_3	wt%		2.2-10.6		3.2-9.8
FeO_3	wt%		2.7-28.1		2.7-46
MgO	wt%		2.1-33.1		1.4-9.8
CaO	wt%		1.8-6.3		max 25
Na_2O	wt%		1.4-7.9		1-4.4
K_2O	wt%		1.7-32.9		1.7-22.0
P_2O_5	wt%		1-22.6		0.6-6.7
Heavy metals			Maximal		Maximal
Cl	wt%	0.5	1	0.07	0.2
Hg	mg/kg	0.3	0.5	0.5	0.1
Cd+Tl	mg/kg	2	5	0.8	5
Pb	mg/kg	160	250	35	75
Cu	mg/kg	3100	4000	50	150
Co	mg/kg	3.1	5	1	5
Cr	mg/kg	60	100	70	250
Zn	mg/kg	300	500	400	550
Na+K	mg/kg	3000	4000	900	2000

Table E3: In-house rule of thumb max values for elements in fuel mixes to IKV. [22]

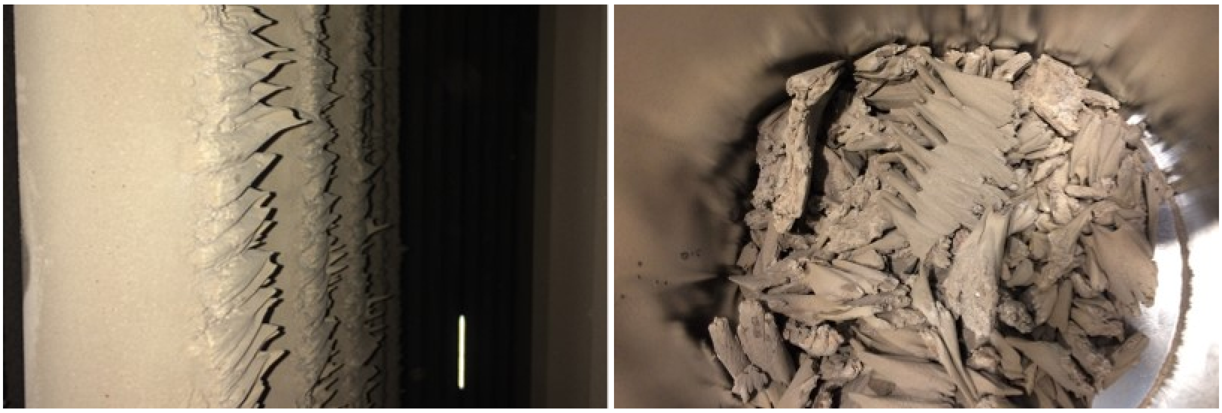
Element	**Max**	
Cl	1200	mg/kg ds
F	50	mg/kg ds
S	2000	mg/kg ds
N	1.5	% ds
Hg	0.15	mg/kg ds
Cd+Tl	0.8	mg/kg ds
Br	10	mg/kg ds
Pb	50	mg/kg ds
Sb+As+Pb+Cr+ Co+Cu+Mn+Ni+V	700	mg/kg ds
Zn	300	mg/kg ds
Al metallic	1000	mg/kg ds
Na+K	0.2	% ds

Table E4: In-house load limits for IKV. Where MCR is Maximum Continues Rating. [22]

Load limit		**The driest fuel**	**Fuel with 100% MCR**	**The most moisture fuel**
Boiler load	% of MCR	32 - 70	32 - 100	32 - 94
LHV	MJ/kg db	16.1 - >11	11 - 8.3	<8.3 - 6
Moisture content	%	14.3 - <35.6	35.6 - 50	>50 - 60

Appendix F - Photos of Deposition in IGV P3

(a) 1. Conv IA (b) 2. Conv IA



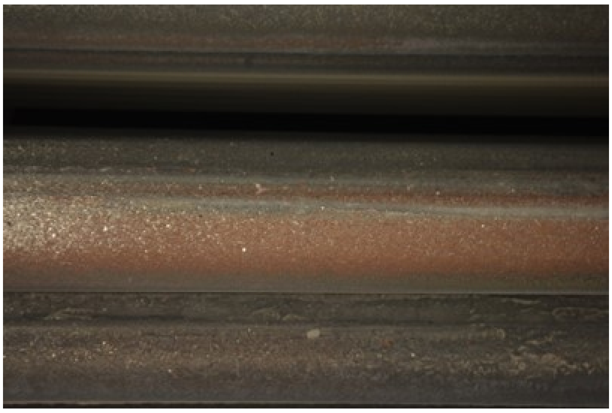
(c) 3. Screen (d) 3. Screen sample

(e) 4. Conv IIIA (f) 4. Conv IIIA sample

Figure F1: Fouling in IGV P3 and deposition samples.

(a) 5. Conv IVA

(b) 5. Conv IVA sample



(c) 6. Eco

(d) 7. Water wall tubes and refractory

(e) 7. Furnace sample

Figure F2: Fouling in IGV P3 and deposition samples.

Appendix G - Injection Water to the Superheaters to IKV

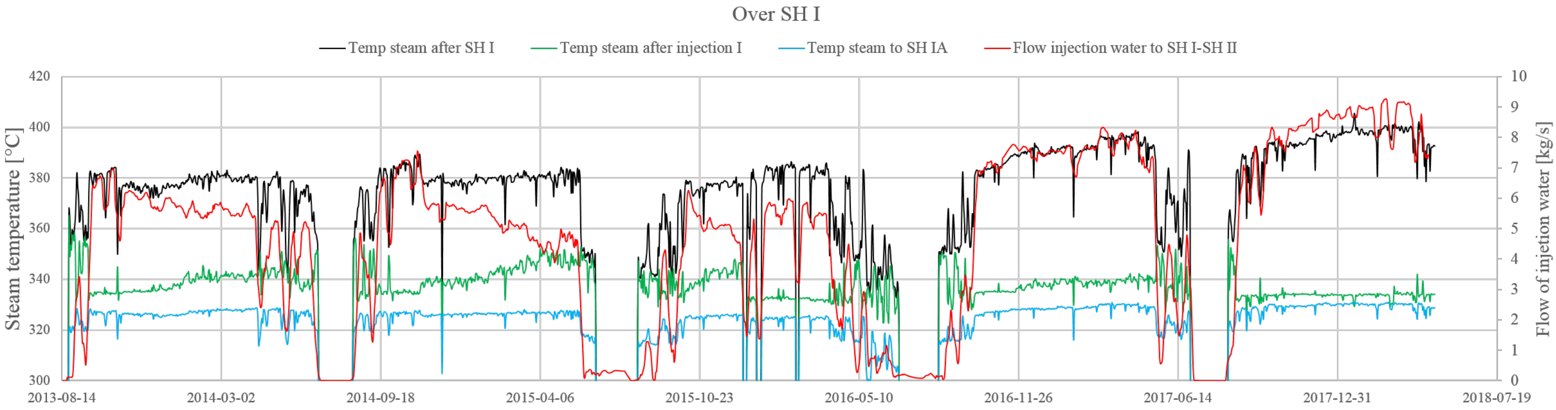


Figure G1: Shows the injection water to the superheater I and the temperature of the superheated steam.

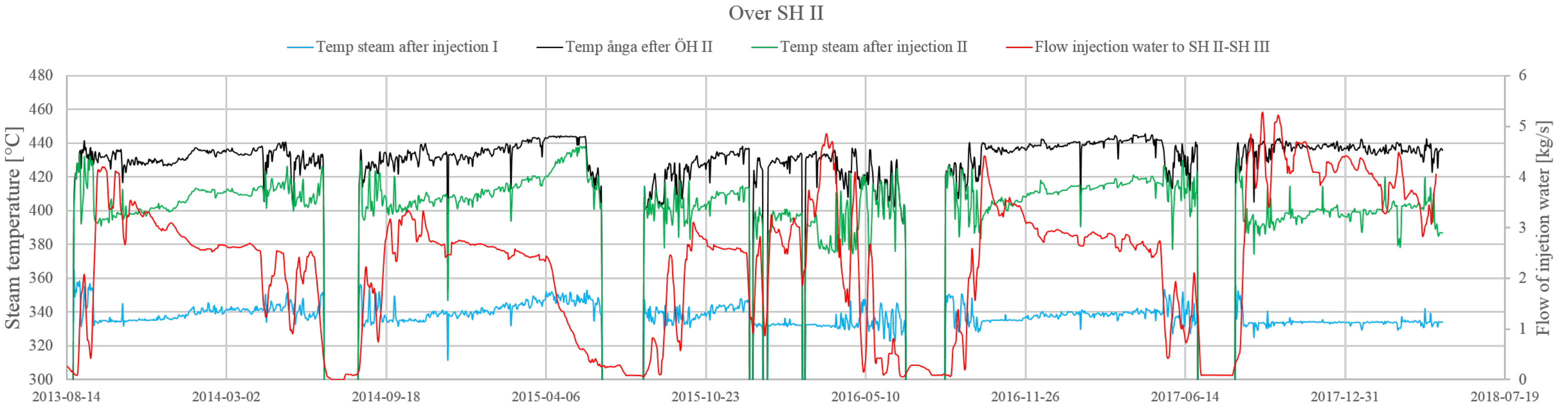


Figure G2: Shows the injection water to the superheater II and the temperature of the superheated steam.

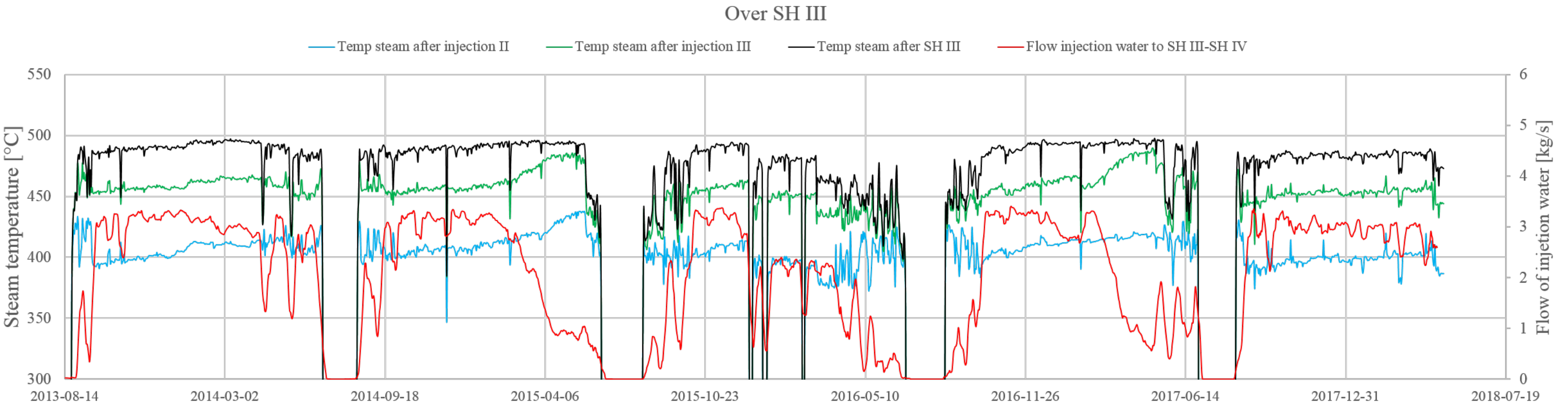


Figure G3: Shows the injection water to the superheater III and the temperature of the superheated steam.

Appendix H - Fly Ash Analyses

Table H1: Analysis result from fly ashes from IKV, IGV P1 and P3.

		IKV	**IGV P1**	**IGV P3**
S	% ds	6.50	4.50	1.70
N	% ds	<0.11	<0.11	<0.11
C	% ds	3.00	2.80	0.90
H	% ds	0.90	0.10	<0.1
Cl	% ds	3	11.73	1.18
Al	mg/kg ds	8 400	34 000	48 000
As	mg/kg ds	38	86	500
Cd	mg/kg ds	60	260	22
Co	mg/kg ds	6	48	35
Cr	mg/kg ds	87	330	620
Cu	mg/kg ds	420	2800	2100
Hg	mg/kg ds	6	5	1
K	mg/kg ds	19 000	29 000	23 000
Mn	mg/kg ds	240	660	2200
Na	mg/kg ds	20 000	54 000	20 000
Ni	mg/kg ds	50	140	110
Pb	mg/kg ds	1 400	7 900	2 900
Sb	mg/kg ds	770	2 800	140
V	mg/kg ds	14	87	64
Zn	mg/kg ds	9 100	37 000	17 000
Ca	mg/kg ds	310 000	180 000	87 000
Fe	mg/kg ds	39 000	27 000	28 000
Mg	mg/kg ds	82 000	17 000	15 000
P	mg/kg ds	2 000	3 500	
Si	mg/kg ds	16 000	83 000	240 000
Ti	mg/kg ds	2 400	13 000	26 000
SiO_2	mg/kg ds	35 000	180 000	510 000
TiO_2	mg/kg ds	4 000	22 000	44 000
Al_2O_3	mg/kg ds	16 000	64 000	90 000
MgO	mg/kg ds	14 000	29 000	25 000
CaO	mg/kg ds	430 000	250 000	120 000
Na_2O	mg/kg ds	27 000	73 000	26 000
K_2O	mg/kg ds	23 000	35 000	28 000
P_2O_5	mg/kg ds	4 600	8 000	5 800
Fe_2O_3	mg/kg ds	5 500	38 000	39 000
MnO_2	mg/kg ds	390	1 000	3 400

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