FINE PARTICLE EMISSIONS OF WASTE INCINERATION

Prepared for
IEA BIOENERGY AGREEMENT - TASK 36

Carl Wilen, Antero Moilanen, Jouni Hokkinen,
Jorma Jokiniemi

PREFACE

This report is a summary report compiled for the IEA Bioenrgy Agreement Task 36 – Energy Recovery from MSW. The report is based on results obtained in a 3-year research project financed by Finnish Funding Agency for Technology and Innovations (TEKES, the FINE Research Programme), VTT and companies involved in energy-to waste businesses.

Complete results will be published in VTT publication series in 2007.

The authors

CONTENTS

ABBREVIATIONS

BLPI	Berner Low Pressure Impactor
C	Concentration
D_{50}	Cut-off diameter in cyclone or impactor
dm	Difference in Mass
Dp	Particle diameter (aerodynamic diameter)
ELPI	Electric Low Pressure Impactor
ESP	Electrostatic Precipitator
FF	Fabric Filter
FTIR	Fourier Transform Infrared Spectrometer
IC	Ion Chromatography
ICP-MS	Ion Coupled Plasma Mass Spectroscopy
m	Mass (of particles)
N	Number (of particles)
NTP	Standard temperature and pressure, 0°C, 101 kPa
P	Power
P	Penetration of particles through filter
ppm	parts per million
SRF	Solid Recovered Fuel
Stk	Stokes number
T	Temperature
TG	Thermogravimetric analyser, thermobalance
U	Velocity of gas
UM	‘Urban Mill’ rejection from processing of SRF

1 INTRODUCTION

Negative health effects of fine particles have gained extensive publicity, energy production being one of the largest producers of fine particles. EU's Waste Incineration Directive (200/76/EC, WID), which come into full force in the beginning of 2006, defines clearly what kind of emissions incineration plants can release. The limits also apply to co-combustion e.g. in coal or biomass plants. The directive outlines the total particle emissions of flue gases to 10 mg/Nm^3 and heavy metals regarding 12 elements, respectively. The WID does not make a stand on possible fine particle emissions; it limits the total dust emissions.

Current energy use of waste in Finland has been mainly co-firing of Solid Recovered Fuels (SRF) in biomass or coal fluidized boilers. Current waste utilization targets in Finland an EU landfill limitations calls for increasing waste utilization in Waste To Energy (WTE) applications.

Waste originating fuels contain typically higher amounts of certain elements, e.g. trace metals, which are also typically more unevenly distributed than in conventional fuels. As they are readily released to the gas phase during combustion, their concentrations in fine particles may be significant. In order to avoid large trace metal emissions, the behavior of the trace metals needs to be understood in waste combustion. The particulate cleaning devices used in WTE plants need to have high collection efficiencies in the whole fine particle range.

The aim of the project was to study formation of fine particle emissions, especially the effect of waste quality on fine particle formation and the amounts and distribution of harmful substances (like heavy metals and chlorine) in particles. The project was implemented in three parts. The first part includes incineration tests in a pilot-scale test rig. In second part, emissions at full-scale waste incineration plants and co-combustion plants were measured. The third part concentrates on studying direct dependency of fuel quality and fine particle formation with laboratory scale investigations and modelling.

2 HEALTH EFFECTS

Increasing the degree of waste utilisation sets requirements also to wastes' energy utilisation. EU's waste incineration directive, which comes into force from the beginning of 2006, defines clearly what kind of emissions incineration plants can release. Fine particles born in waste incineration and fine particle purification have been studied in Tekes' FINE technology programme. Fine particles are particles, their aerodynamic diameter of which is below 2.5 µm (PM2.5). Fine particles penetrate deep into lungs when inhaled and they have been proved detrimental for health in many studies. According to estimation of health effects conducted in CAFE programme (Matti Vainio, Kansanterveys 5/2005), PM2.5 particles shorten the average statistical life expectancy in Europe with about nine months, which is caused by premature death of over 300 000 people in a year.

Negative health effects of fine particles have gained extensive publicity, energy production being one of the largest producers of fine particles. Health effects of fine particles are especially related to incineration originated particles, such as traffic and power plants' particles. The most significant fine particle sources are small-scale combustion of wood at fireplaces in homes and sauna stoves. Fine particle emissions of small-scale combustion were studied in PIPO research project funded by Tekes and companies (University of Kuopio, final report: http://www.uku.fi/laitokset/ifk/publications.shtml). Emissions were also studied in power plant scale and in industrial boilers in a research project called PIHI-RAME lead by VTT and Finnish Meteorological Institute. (Jokiniemi et al., VTT Research Notes 2258/2004).

3 BOILERS, FUEL PREPARATION AND AIR POLLUTION CONTROL SYSTEM

Tests were performed in four different commercial plants and in one pilot plant. Two waste incineration plants were situated in Sweden, Figure 1 and Figure 2 . The co-combustion plant, Figure 3, and the district heating plant, Figure 4, and the pilot plant were situated in Finland. Specific performance data of the commercial plants are given in Table 1.

3.1 NORRKÖPING, HÄSSELHOLM, KAUTTUA AND SIILINJÄRVI POWER PLANTS

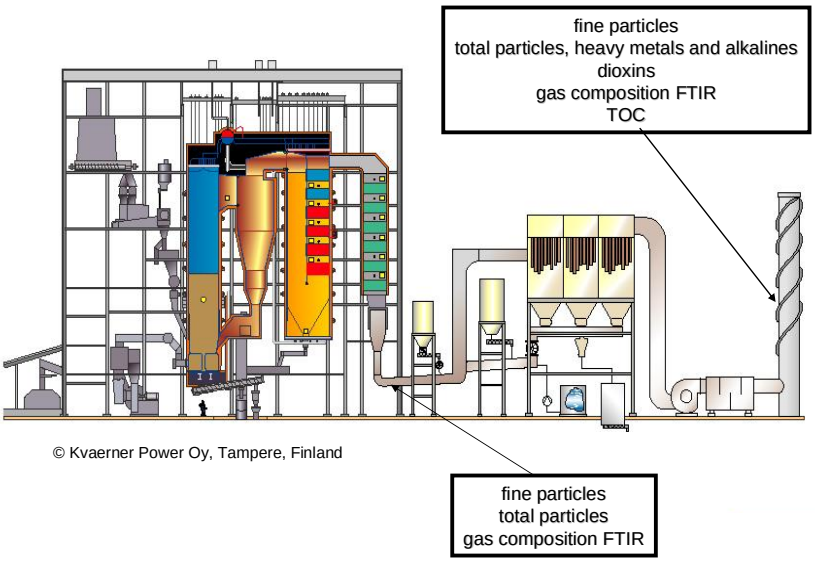

Figure 1. The Norrköping CFB boiler and performed measurements.

Plant	Norrköping	Hässleholm	Kauttua	Siilinjärvi
Owner	Sydkraft Östvärme AB	Hässelholm municipality	Fortum Heat and Power Oy	
Commissioned	2002	2003	1981	
Boiler output	75 MW	20 MW	65 MW	10 MW
Electricity output	11 MWe	1,7 MWe to own use	7 MW	-
Heat output	65 MWth	18 MWth	26 MW process steam, 4 MW district heat	10 MW
Boiler supplier	Kvaerner Power Oy	Babcock & Völund	Ahlström Pyroflow	Wärtsilä
Boiler type	Circulating fluidised bed	grate fired	Circulating fluidised bed	Rotating grate boiler
Fuel	waste; 30-50% household, 50-70% industrial	waste; 70% source separated household, 30 % presorted industrial	42% wood and construction waste wood , 30% peat,10% Solid Recovered Fuel,9% Coke	sawdust, bark, construction wood waste

Table 1. Data on the test plants.

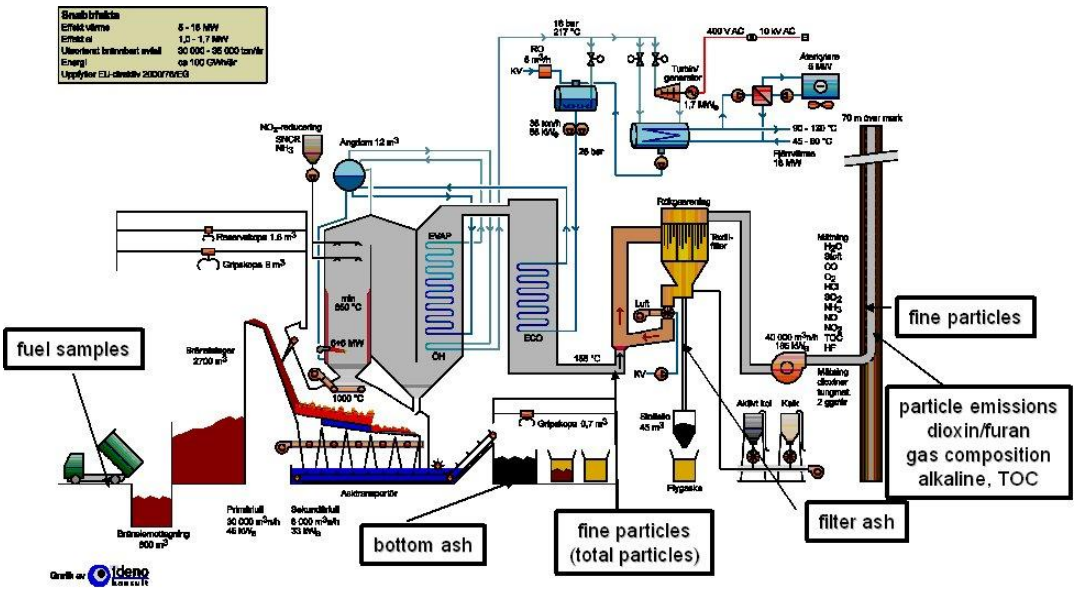

Figure 2. Flue gas cleaning for the grate boiler at the Hässleholm district heating plant.

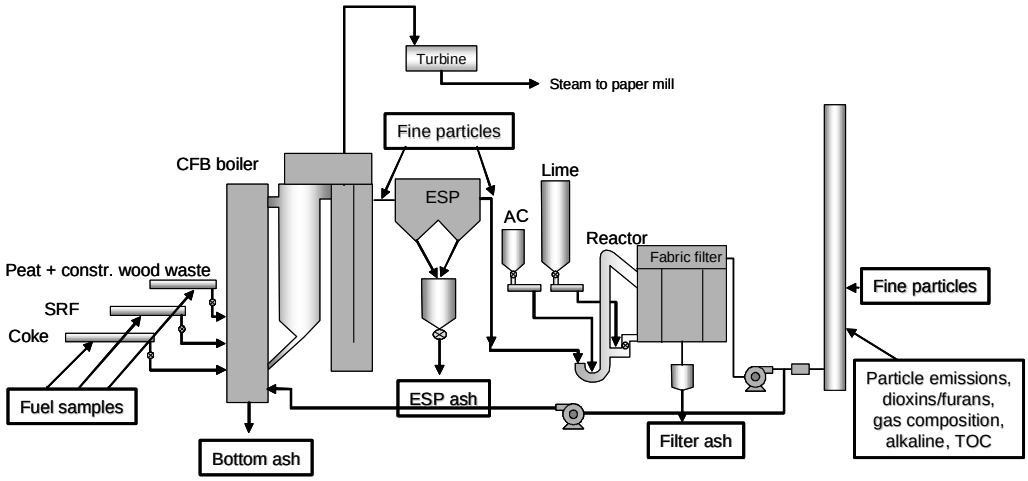

Figure 3. The Kauttua CFB boiler and performed measurements.

The flue gas cleaning systems in all three plants (Norrköping, Hässleholm, Kauttua) are essentially the same. Activated carbon was used for Hg and dioxin absorption in NID, and lime feed was used for HCl and SO_2 reduction. In Kauttua the baghouse filter is installed after the original ESP and was commissioned a few months before the time of the measurements. At Siilinjärvi the flue gas cleaning is carried out with the cyclone and the electrostatic precipitator (ESP).

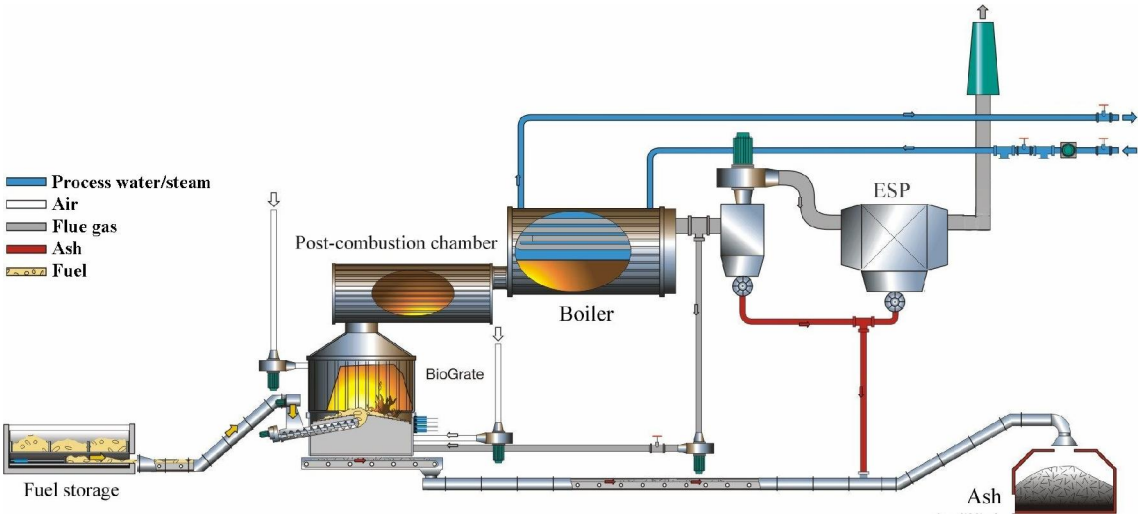

Figure 4. The Siilinjärvi process chart.

In Norrköping plant fuel is crushed in a primary shredder. After magnetic separation fuel is cut with hammer mills. The shredded fuel is stored in a barn-type intermediate storage before conveying to the plant. At the plant an Eddy Current system is used to separate non-ferrous metals from the feed. Figure 5 shows the shredded fuel as fed into the boiler.

Figure 5. The shredded fuel as fed into the boiler at the Norrköping waste-to-energy plant.

The waste in Hässleholm is delivered by trucks to the plant and unloaded into the waste bunker. The fuel is fed by a crane to an intermediate bunker, and from that directly to the grate, Figure 6. Because of an efficient source separation scheme the waste contained little organic residues.

Figure 6. Waste fuel sample from Hässleholm.

At Kauttua fuels are fed to the plant by three separate conveyers. The peat and wood residues are mixed on the courtyard. The mixture is fed to a disc screen before conveyed to the boiler. Metals are also separated by a magnet. The paper and plastic waste is fed to an on-site crusher producing a course fuel fraction, Figure 7. This is fed to the boiler by a separate conveyor and third conveyor is feeding the relatively small amount of crushed coal/coke to the boiler. The fuel mix during the measurements was the one mentioned in Table 1.

Figure 7. Waste wood (left, containing occasionally also paper and plastics) and SRF fractions at the Kauttua plant.

Two different fuel mixes were used in Siilinjärvi plant during tests. In the first day/set-point, the fuel was the bark and sawdust 50/50 mixture, which is normally used in the boiler. On the second day/set-point the intension was to add 30% construction wood to the bark – sawdust mixture.

3.2 KARHULA CFB PILOT PLANT

Combustion tests with five different kinds of waste fractions were performed in December 2003 at the Foster Wheeler Energia Oy´s 1 MW fluidised bed pilot plant in Karhula, Finland. These waste fractions are presented in Table 2. The main objectives of the test were to study the effect of waste quality on fine particle emissions, in particular the concentrations of detrimental substances (mainly heavy metals) they contain and the distribution of the substances in different particle sizes. Important topics were also other waste related gaseous emissions like HCl and mercury.

Table 2. Fuel material used in the pilot plant tests.

Type of waste	**Delivery**	**Composition**	**Abbreviation**
Construction wood waste	Lassila & Tikanoja, Kerava	Construction (mainly) and demolition waste wood	Construction wood waste
Solid recovered fuel, class I	Lassila & Tikanoja, Kerava	Commercial and package waste (mainly paper, board and plastics)	SRF I
Solid recovered fuel, class III	Loimihämeen Jätehuolto, Forssa	Produced from the dry fraction of source separated household waste	SRF III
Solid recovered fuel, class I, reject after fibre removal: Urban Mill process reject	Metso (origin: Loimihämeen Jätehuolto, Forssa)	Commercial and package waste, fibres removed in a pulping process	SRF I UM
Solid recovered fuel, class III, reject after fibre removal: Urban Mill process reject	Metso (origin: Loimihämeen Jätehuolto, Forssa)	Produced from the dry fraction of source separated household waste, fibres removed in a pulping process	SRF III UM

The pilot circulating fluid bed boiler is equipped with a bag house filter with a possibility for additive injection and a scrubber. The scrubber was by-passed during the tests. The fuel amount for a 24 hour set point was estimated to be 4-5 tons, a sufficiently large and representing fuel amount considering the inhomogeneous nature of waste fuels. The combustion equipment has been proven to correspond to a real boiler and its conditions.

4 SAMPLING AND MEASUREMENTS

During the particle measurement campaigns in the power plants, the fuel sampling was arranged so that the fuel quality matched with the particle samples collected at the filter inlet. From the fuel samples, the ordinary fuel characteristics and trace element content were determined. Also, ash samples were analysed for their elemental content. Ash samples were taken both from fly and bottom ashes.

4.1 FUEL AND ASH SAMPLES

In *Siilinjärvi*, fuel samples were taken at every 30 minutes, and the sampling was matched with the time when the particle measurements were carried out for the filter inlet and outlet. Ash samples were also collected during the test. For the analysis, the ash samples taken from the multi-cyclone and electrostatic precipitator (ESP) were combined to one fly ash sample and two ashes from the grate were combined to a bottom ash sample.

In *Norrköping*, fuel samples were taken every 30 minutes when the particle measurements were carried out for the filter inlet and outlet. Ash samples were taken approximately each hour or two hours.

During the two-days measuring campaign in *Hässleholm*, fuel samples were taken twice a day by lifting a 1-2 m^3 batch of waste to the floor of the receiving station, where it was divided by coning-and-quartering method and taking a 100 liter fuel sample for preparation of the final sample for analysis (Figure 8). Ash sampling was carried out so that bottom ash samples were taken from the ash containers and the fly ash samples were taken after the bag house filter by means of a sampling device.

Figure 8. Fuel sampling at Hässleholm

In *Kauttua*, the fuel samples were taken at approximately 1 hour intervals from all the fuel components: SRF, peat-wood waste mixture and coke. Ash samples were collected from bottom, ESP and filter ash.

At Siilinjärvi, for the analysis, the ash samples taken from the multi-cyclone and ESP were combined to a fly ash sample and two ashes from the grate were combined to a bottom ash sample.

4.2 GAS ANALYSIS

During the measurement campaign, the following components were measured using the following methods or standards.

O_2 was measured with electrochemical cell. Calibration was made with ambient air (20,9 %). Method is accredited VTT Processes Measurement Method PRO320202 and it follows the principle of EPA Method 3A.

H_2O, CO_2, CO, CH_4, NO, NO_2, N_2O, NH_3, SO_2, HCl and HF were measured. In Hässelholm also TOC was measured. At Siilinjärvi H_2O, CO_2, CO, NO, NO_x, SO_2 and HF were measured.

In some plants the stack gas composition was followed with FTIR, Fourier Transform Infrared Spectroscopy, which is a continuous online gas analyzer. Infrared spectroscopy is based on the ability of all gases to absorb infrared radiation with a wavelength specific to the gas. Only exceptions are noble gases and biatomic molecules with the same nuclei (N_2, O_2 etc.) which can't be measured with FTIR. The measurement result with FTIR is a spectrum, from which the components of the sample gas are determined. The quantities are calculated from the intensity of the absorption lines. The sample gas was filtered from particles and the temperature of FTIR and sample lines was kept at 150°C.

The process data were collected from the process control system.

Standard method EN 14385 was used to determine trace element concentrations in particles and in gas phase both in the stack and filter inlet. From filter inlet only Hg concentration was determined from the gas phase samples. Hg was analyzed with CVAAS, Tl with GFAAS and other trace metals with ICP-AES.

4.3 FINE PARTICLE MEASUREMENTS

Fine particle samples were taken both before and after flue gas cleaning. At Kauttua particles were also measured between ESP (Electro Static Precipitator) and fabric filter.

BLPI, Berner Low Pressure Impactor, is an eleven stage cascade impactor used to measure particle mass size distribution and mass concentration. In an impactor the sample flow runs through a thin nozzle with a certain velocity. After the nozzle the flow is forced to turn 90°. The particles larger than the cut-off diameter D50 impact on the particle collection substrate, while smaller particles follow the stream to the next impactor stage with a smaller cut-off diameter. The flow rate through BLPI depends only on the inlet pressure and BLPI and the sample flow temperature and is 19 l/min (NTP) at 140°C and normal pressure. The cut-off diameter on the finest stage is 0.022µm and on the coarsest stage 16.22µm. In these measurements a pre-cutter cyclone was used before impactor to collect the coarse particles usually larger than Dp>5µm.

The particle collection substrate material was poreless Nuclepore polycarbonate filter. The polycarbonate filter is especially good for chemical analysis of particles because it contains very little other elements but carbon. The substrates were die-cut to the desired size and shape and greased with Apiezon L ultra high -vacuum grease. After greasing the substrates were baked in a 150°C oven for 4 to 16 hours to evaporate the grease solvent before weighing. Greasing reduces the particle bouncing from the substrate when they hit it. The repeatability in weighing of the substrates is approximately ±4µg per weighing. For the best results 1mg of particles should be collected on a substrate.

ELPI, Electric Low Pressure Impactor, is a twelve stage cascade impactor similar to BLPI. The main difference is that the particles are charged with a needle charger at impactor inlet. The charge is measured separately from each stage with electrometers and the particle number size distribution is calculated from the charge distribution. The particle size distribution can be monitored in real time. The lowest stage was a filter, which collected the particles smaller than 30nm. On the coarsest stage the cut-off diameter was 10µm.

The particles collected with BLPI were analyzed to determine their chemical composition. The water soluble anions and cations were analyzed with Ion Chromatography, IC. One quarter of each BLPI substrate was cut and dissolved in 1ml methanol and 9ml water. Pre-cyclone samples were distilled in 10ml water. If

The trace metals were analyzed with ICP-MS, ion coupled plasma-mass spectroscopy. A quarter of each BLPI substrate was cut and dissolved in 2%HF and 10% HNO_3.

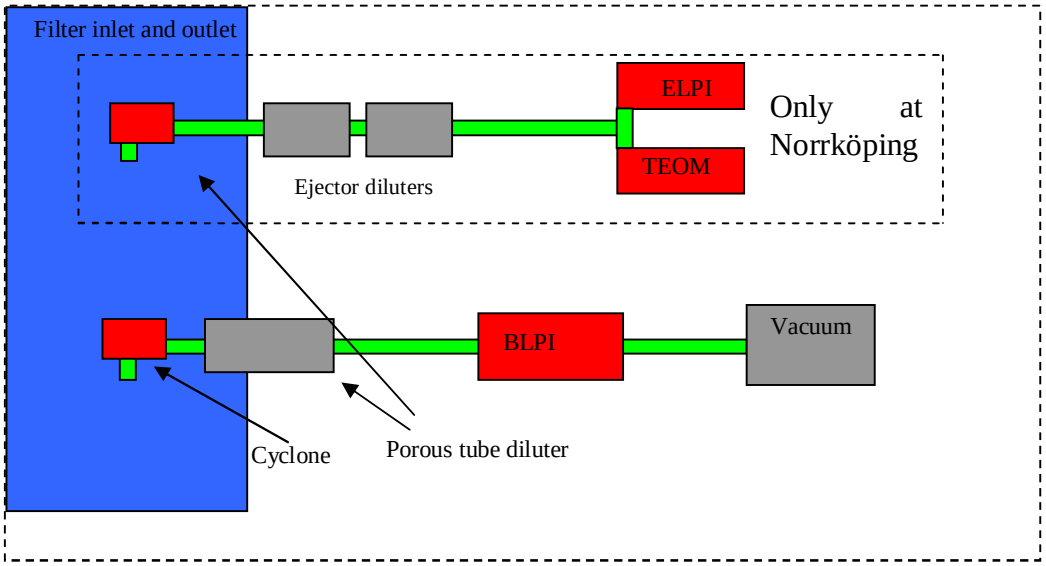

Figure 9. The experimental set-up in BLPI measurement and ELPI and TEOM measurements.

The experimental set-up for particle sampling was made as similar as possible in all field measurement sites (Figure 9). A pre-cutter cyclone was placed inside the duct to collect the coarse particles, typically particles with Dp>5µm, which otherwise would have had heavy losses in the sampling. After the cyclone the sample flow was diluted with a porous tube diluter, which was located partially inside the duct. BLPI was placed right next to the diluter. In BLPI measurements the dilution air and BLPI were pre-heated to 120°C-140°C. The dilution air flow was controlled with a critical orifice. BLPI and ELPI are intrinsically critical orifices and their flow rates are known. The TEOM flow rate is adjusted with a mass flow controller. Maximum temperature was 140°C, because the Nuclepore polycarbonate substrates used to collect the particles in BLPI melt at higher temperatures.

The experimental set-up in ELPI measurements was similar to BLPI measurements except that the sample flow was quenched to 20°C-50°C in the porous tube diluter and the sample line length between the diluter and ELPI was 1m-3m. ELPI operated at ambient temperature, typically 20°C, and. The dilution rate was monitored with a CO_2 analyzer.

All equipment inner surfaces, the pre-cyclone, the porous tube diluter, BLPI and ELPI, were made of stainless steel. The sampling lines were 1cm in diameter and either stainless steel or Tygon tubing.

At Norrköping ELPI and TEOM measurements were also performed. Set-up in Norrköping is also demonstrated in Figure 10.

At Siilinjärvi experimental set-up included BLBI measurements from both filter inlet and outlet and ELPI and TEOM measurements from filter outlet. Set-up was slightly different from other plants since the pre-cutter cyclone was placed outside the duct and the 4mm nozzle was bent 90°.

Figure 10. Fine particle measurement from duct between filter and stack at Kauttua (on left) and from the stack at Norrköping (on right).

4.4 SAMPLING AND MEASUREMENTS AT KARHULA PILOT PLANT

Figure 11 shows the Karhula pilot test rig setup and the sampling points of fine particles, gaseous emissions and solid fuels and ashes.

Fuel samples were taken during the set points with 20 minutes intervals. During the time span of the fine particle sampling the fuel samples were taken with 10 minutes interval for Construction wood waste and SRF I and with 5 minutes interval for the rest of the fuels to be able to trace possible emission peaks in the fine particle samples to the corresponding fuel sample when particle sample was taken at the inlet of the filter. Ash samples were collected at the bottom of the reactor and the boiler and in the bag house filter.

The gaseous components measured before the filter were O_2, CO, SO_2 and NO_x . O_2, CO, SO_2, NO_x, CO_2, N_2O and HCl were measured after the filter in addition to the on-line measurement of mercury. Control measurements of Hg, HCl and heavy metals of the flue gas were carried out during a SRF III set point by gas sampling and laboratory analysis.

All online measurements including process data were collected from the process control system. The feed rate of fuels and additives were controlled manually by weighing the batches.

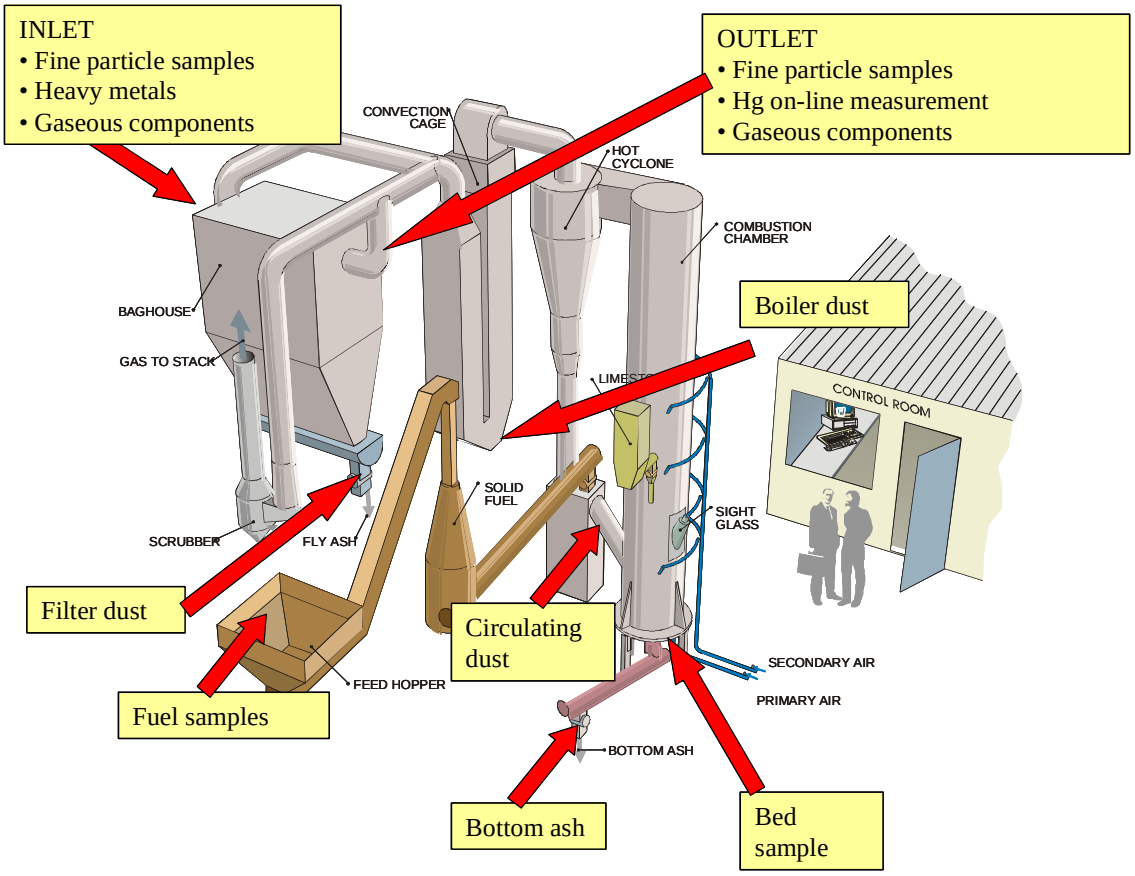

Figure 11. Figure Sampling and measurements at Karhula test rig.

4.5 FUEL ANALYSIS METHODS

For the elemental analysis, dried fuel samples were dissolved in a microwave oven with the mixture of acids (HNO_3 + H_2O_2 + HF). Small amount of insoluble matter remained from all the samples, but the uncertainty was assumed to be insignificant. From the solutions concentrations of As, Cd, Ni, Sb and Tl were measured by the graphite furnace atomic absorption spectrometry (GFAAS), concentrations of Co, Cr, Cu, Mn, Pb, Sn, V and Zn were measured by the inductively coupled plasma atomic emission spectrometry (ICP-AES) and concentrations of Hg were measured by the cold vapour atomic absorption spectrometry (CVAAS). Chlorine and bromine in ashes were analysed in VTT by INAA. Ash samples were analysed by The Geological Survey of Finland (GTK).

5 FUEL AND ASH COMPOSITION

5.1 FUEL ANALYSES

The average compositions of fuels are presented in Table 3, and the variation for element contents in Figure 12. The variation was determined by the difference between maximum and minimum. This variation (as relative, % on the average) in single samples during a test campaign was obtained from the pilot plant tests. The relative difference for trace elements was above 10% and for the ordinary fuel characteristics it was less than that. The variation determined for all fuels followed the same pattern as in the pilot plant test. For metals it was quite large, highest for Cu, then Cd and Ni, about 3 times the average value. The worst behaving element was copper, for example in Norrköping the Cu concentration was 130 mg/kg at its lowest and 11500 mg/kg at its highest.

Table 3. The average fuel compositions.

	dry conc.	Hässleholm Waste	Norrköping Waste	Kauttua SRF 1	Kauttua Peat-wood waste	Kauttua Coke	SRF 1	SRF 1 UM	SRF 3	SRF 3 UM
Fraction		100%	100%	~24%	~68%	~8%	100%	100%	100%	100%
Mercury (Hg)	mg/kg	0.11	0.32	<0.03	0.04	0.04	0.04	0.06	0.07	0.12
Metallic (Al) aluminium	mg/kg	3900	4200	800	2200		-	-	-	-
Arsenic (As)	mg/kg	4.3	10	0.9	74	4.1	6	17	14	7
Cadmium (Cd)	mg/kg	0.8	2.5	0.06	0.4	0.4	1.9	3.3	5.1	21.3
Cobalt (Co)	mg/kg	11	8.8	0.9	1.7	5	1.4	1.3	3.9	5.2
Chromium (Cr)	mg/kg	220	90	6.1	84	83	42	110	157	230
Copper (Cu)	mg/kg	376	4500	22	69	22	320	30	770	1590
Manganese (Mn)	mg/kg	166	260	22	84	87	36	42	230	240
Nickel (Ni)	mg/kg	144	34	3.0	7.5	40	16	8.5	32	39
Lead (Pb)	mg/kg	247	170	4.9	77	19	46	43	110	140
Antimony (Sb)	mg/kg	13	52	15	1.6	0.65	91	39	33	52
Tin (Sn)	mg/kg	45	37	1.2	3.7	1.1	16	41	12	18
Thallium (Tl)	mg/kg	<1	<1	<1	<1	<1	<2	<2	<2	<2
Vanadium (V)	mg/kg	9.6	9.4	<3	5.3	40	<5	<5	5.9	14
Zinc (Zn)	mg/kg	1160	760	30	300	68	730	270	420	620
Fluorine (F)	mg/kg	60	67	<50	<50	<50	<50	<50	63	140
Chlorine (Cl)	%, d.	0.94	1.0	0.08	0.17	0.1	0.39	0.68	1.0	1.7
Soluble Na+K	%, d.	0.5	0.6	0.07	0.07	0.01	-	-	-	-
Sulphur (S)	% d.	0.26	0.40	0.06	0.16	0.58	0.08	0.06	0.14	0.15
Nitrogen (N)	% d.	0.6	1.0	0.7	0.8	1.4	1.1	0.63	0.90	0.57
Carbon (C)	% d.	48	47	56.6	48.5	82.1	59	61	51	60
Hydrogen (H)	% d.	6.6	6.5	8.2	5.6	3.4	8.0	8.4	7.3	8.8
Volatile matter	% d.	71	72	85.9	73.6	18.3	83	85	75	78
Ash	% d.	20	18	6.9	6.8	9.9	7.3	4.1	15.6	13.7
H_2O	%	26	42	7.3	36.3	16	-	-	-	-
Higher heating value HHV	MJ/kg dry	21.1	20.9	26.3	19.8	31.4	26.9	28.0	23.4	29.0
Lower heating value LHV	MJ/kg dry	19.7	19.5	22.6	11.0	25.4				
Lower heating value LHV	MJ/kg ar.	14.0	10.4							

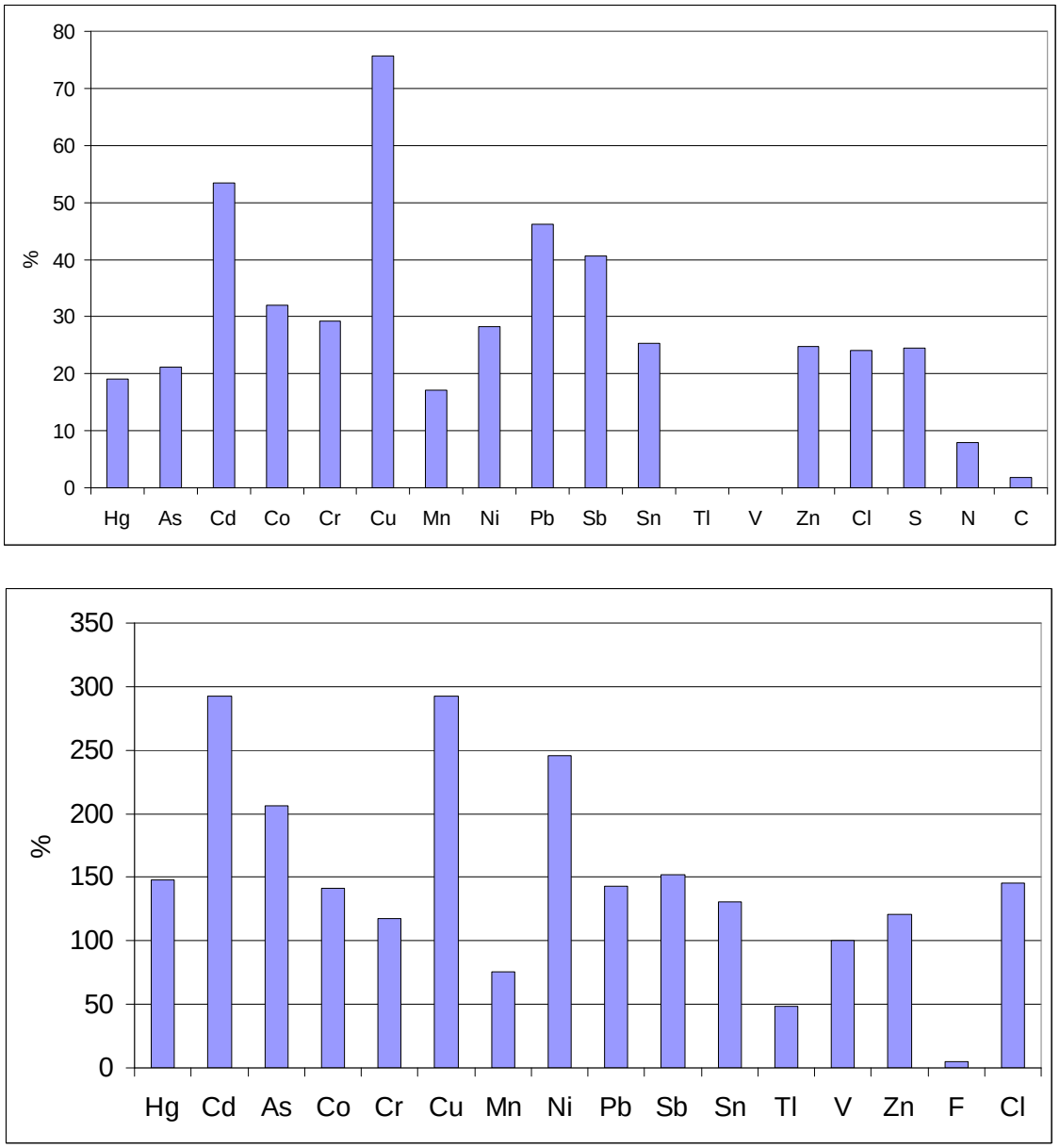

Figure 12. Variation of each element, % on average; pilot plant fuels upper graph and all fuels lower graph.

As results from Norrköping mixed fuel sample analyses, average moisture was 42%, volatile matter 72% and ash contents 18% in dry fuel. The concentration of Cu varied significantly as mentioned above, but all other element concentrations were surprisingly even between the samples. An overall estimate of the "cleanness" of the Norrköping waste fuel would rank the fuel similar or a somewhat more contaminated than the typical SRF III waste derived fuel used in the pilot tests in Karhula in December 2003.

High chlorine contents of average 70 g/kg were measured for fly ashes, from the samples taken each day. Copper content was high both in fly ash and bottom ash, average 6 g/kg. Lead content was 3.4 g/kg in fly ash and 1.4 g/kg in bottom ash.

The ash samples taken in each day at Hässelholm were combined and analyzed as well. Chlorine content in fuel was 1% in average, the main component in fly ash with 21% and only 0.4% in bottom ash. Zinc concentration in fly ash was quite high, 1.7%, in the fuel it was 0.1% and 0.4% in bottom ash. Although copper (chloride) should evaporate in relatively low temperature, more of it is left in the bottom ash than other volatile elements. Copper may exist in larger pieces, which don't stay long enough in furnace to evaporate entirely.

In the fuels, metallic aluminium content at Kauttua was also high in the peat and wood waste mixture, although visually there seemed to be plenty of aluminium in SRF. Arsenic chromium and lead contents were unexpectedly high in the peat and wood waste mixture compared to other SRF and wood waste analysis. Antimony content was high in one of the SRF samples (SRF 2). In coke, the chromium and sulphur contents were relatively high. In ashes, arsenic, cadmium, manganese, lead, antimony, thallium, vanadium zinc and fluorine contents were higher in the ESP ash than in the other ashes, while cobalt, chromium, copper, nickel and tin contents were both high in the ESP and in the bottom ash. Mercury, chlorine (Cl about 12 %) and bromine were clearly higher in the baghouse filter ash than in the others.

The 'dirtiest' fuels with the highest concentrations of the WID trace elements and Chlorine were SRF 3 UM and the waste fuel in Norrköping and Hässleholm. The 'cleanest' fuel was SRF 1 in Kauttua, even including Kauttua coke and peat-wood-construction waste wood mix.

5.2 ASH ANALYSES

Following ashes were analysed in this study:

- Pilot test SRF I bed material, circulating material and filter ash
- Pilot test SRF III bed material, circulating material, fly ash from the boiler bank and filter ash.
- Siilinjärvi sawdust + wood waste, combined multi cyclone and electrostatic precipitator (ESP) ash, bottom ash
- Norrköping filter and bottom ash
- Hässleholm filter and bottom ash
- Kauttua ESP, filter and bottom ash

The content of the following elements were determined: Hg, As, Cd, Co, Cr, Cu, Mn, Ni, Pb, Sb, Sn, Tl, V, Zn, F, Cl and Br.

According to the results, the high content of arsenic and thallium was striking in the combined ash sample collected from the multi-cyclone and electrostatic precipitator in

Siilinjärvi, although wood waste was mixed to untreated wood only 30. The As content in the feedstock was low and much lower than that in Kauttua. Mn content was also much higher in Siilinjärvi ashes (also in the bottom ash) compared to others, although the content in the feedstock was not higher than that of SRF III, SRF III UM, Norrköping or Hässleholm.

Hässleholm filter contained high amounts of Cd (159 mg/kg), Ni (400 mg/kg), Zn (17 g/kg ash), F (3 g/kg ash), Br (1.5 g/kg ash) and Cl (213 g/kg ash). The source for F can be the Teflon containing materials (or coatings) and that for Br the fire retardants. In SRF I filter ash the Br content was significantly higher (almost 1 g/kg ash) than in SRF III. This could indicate the relatively high share of plastics (e.g. a mono-fraction from industrial waste) in SRF I which contained Br based fire retardants. Pb content was in Hässleholm 2.7 g/kg, and it was high also in Norrköping 3.5 g/kg ash; it was also relatively high in Kauttua ESP ash, about 2 g/kg ash. In Kauttua the element contents were higher in ESP ashes than in filter ash, except Hg, Br and Cl. The As content was clearly highest in Kauttua ESP ash. Br content was highest in Kauttua filter ash (2 g/kg ash).

In the filter ashes, the added chemicals (lime and activated carbon) may have a diluting effect on the concentration of an element.

High contents of Cu, Co, Cr and even Ni in the bottom ashes indicated that these existed in metal form in the fuels.

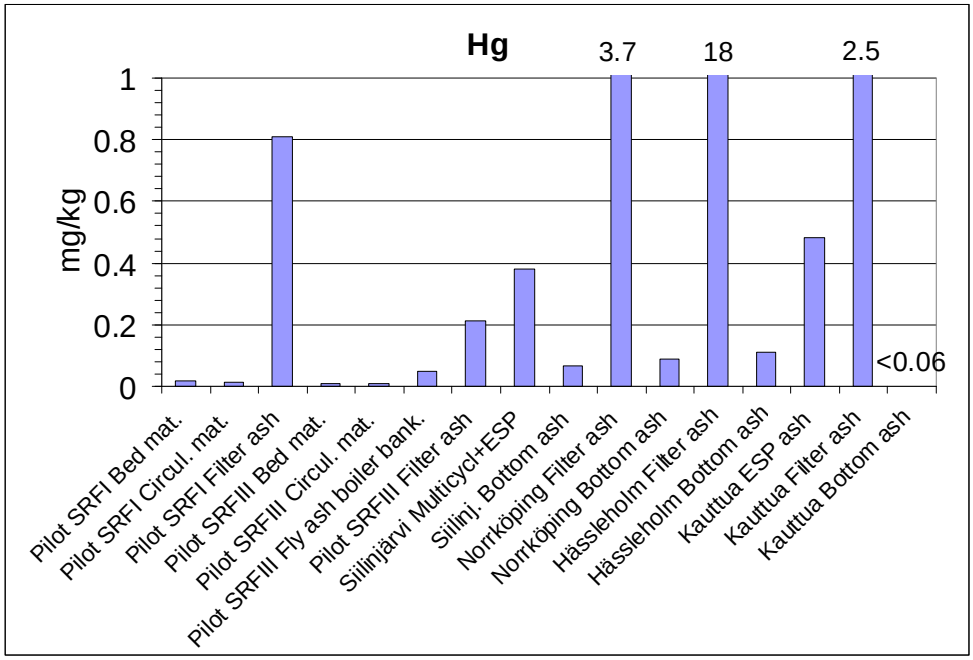

Figure 13. Mercury content in the ashes (< is below the limit).

6 PROCESS MEASUREMENTS

The process data from Kauttua and Norrköping were examined using the multivariate analytical tool Simca – P version 10.0.2.0. In Figure 14, an example of the statistical representation is shown of the Kauttua measurements. Accordingly, the processes operated relatively smoothly. Some of the points deviated from the average, for which the strongest reason was the fluctuation in the temperature and steam flow. This, however, had no effect on the results of the measurements.

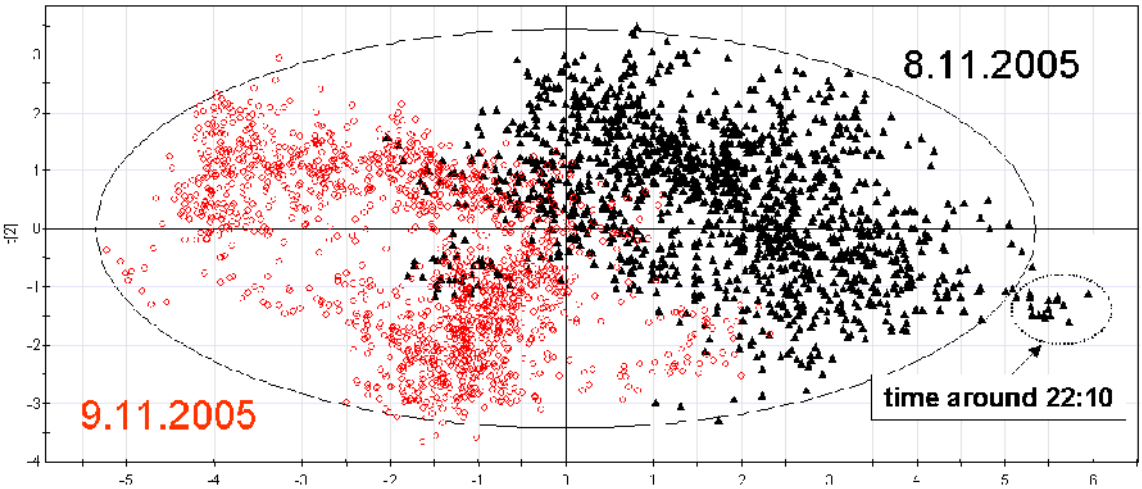

Figure 14. The score plot describing the process data of Kauttua (both boiler and flue gas) collected during the measurement campaign. The black color indicates the data collected during 8.11.2005 and the red one during 9.11.2005.

The combustion processes were running at normal performance values and was stable during the measurements. As an example bead temperatures during measurements at Norrköping are presented in Figure 15.

Process performance assessment of Hässleholm is based on daily plant reports and manually collected data from process control system. Due to the relatively warm weather conditions, 11-12 ^{o}C outside temperature, the plant was not operated at full load. Some additional cooling was used to maintain reasonable operation. The operation was, however, stable during the whole measurements campaign.

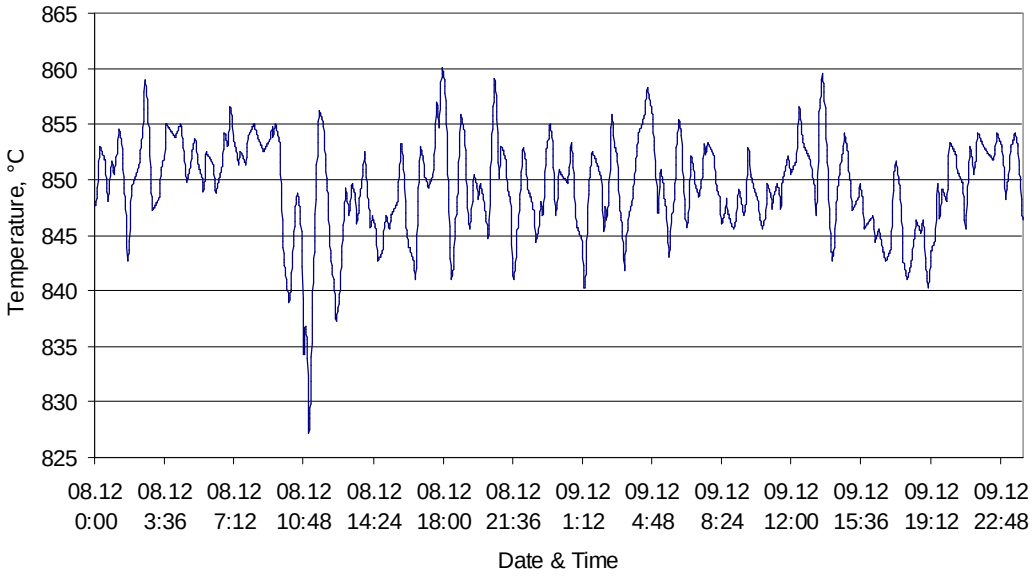

Figure 15. Variation of the bed temperature of the boiler during the measurements (Norrköping).

6.1 FLUE GAS MEASUREMENTS

Emissions of several gaseous components were measured with FTIR. Table 4 presents average gas concentrations during particle measurements. The pollution control systems in the waste combustion plants were quite effective in removing HCl and SO2. The daily average WID limits of HCl emissions is 10 mg/m3 and SO2 emissions 50 mg/m3. The emissions in all plants were below these limits. NOx emissions are generally limited to either 200 or 400 mg/m3 depending on the plant nominal capacity.

Table 4. Average gas compositions during particle measurements.

	O_2	CO_2	H_2O	CO	SO_2	HCl	NOx
Filter inlet	[%]	[%]	[%]	[mg/Nm^3] dry 11% O_2	[mg/Nm^3] dry 11% O_2	[mg/Nm^3] dry 11% O_2	[mg/Nm^3] dry 11% O_2
Hässleholm	-	-	-	-	-	-	-
Norrköping	7	-	25	-	9	870	-
Kauttua	9	9	12	20	90	100	360
Siilinj Bio	-	-	-	-	-	-	-
Siilinj CCW	-	-	-	-	-	-	-
Filter outlet							
Hässleholm	7	11	18	10	3	6	90
Norrköping	7	10	20	7	0.1	4	40
Kauttua	9	9	10	20	30	1	340
Siilinj Bio	5	13	24	30	46	-	67
Siilinj CCW	5	13	21	15	34	-	220

Flue gas composition at Norrköping was monitored continuously with the plant instruments and checked both on the inlet and outlet side by means of VTT:s FTIR measurements. No significant differences were observed between these measurements. The HCl of the flue gas before and after the filter is shown in Figure 16. The HCl emission is well below the 10 mg/Nm^3 WID threshold value. Total organic carbon TOC was both days < 1 mg/Nm^3, WID threshold value is 10 mg/Nm^3.

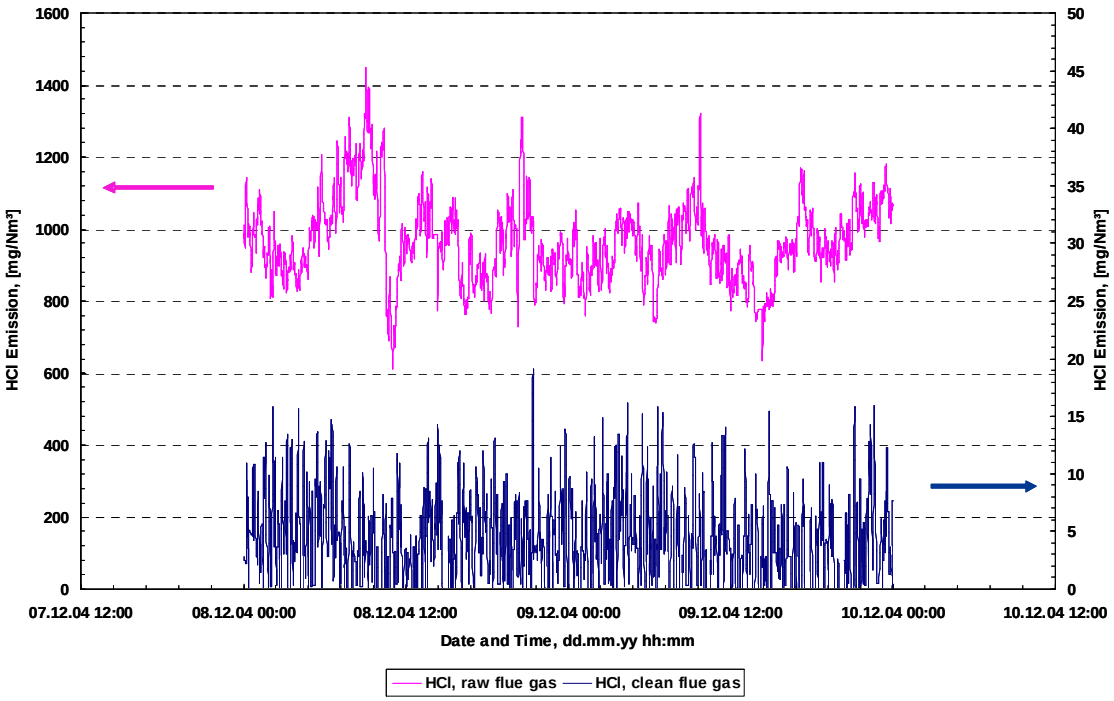

Figure 16. HCl content of the flue gas at Norrköping, process data (wet gas, ab. 4% O2).

Various gas components were measured from filter outlet at Hässelholm. Emissions measured by VTT are well in line with the on-line plant emission measurements. As an example HCl and SO_2 emissions are presented in Figure 17.

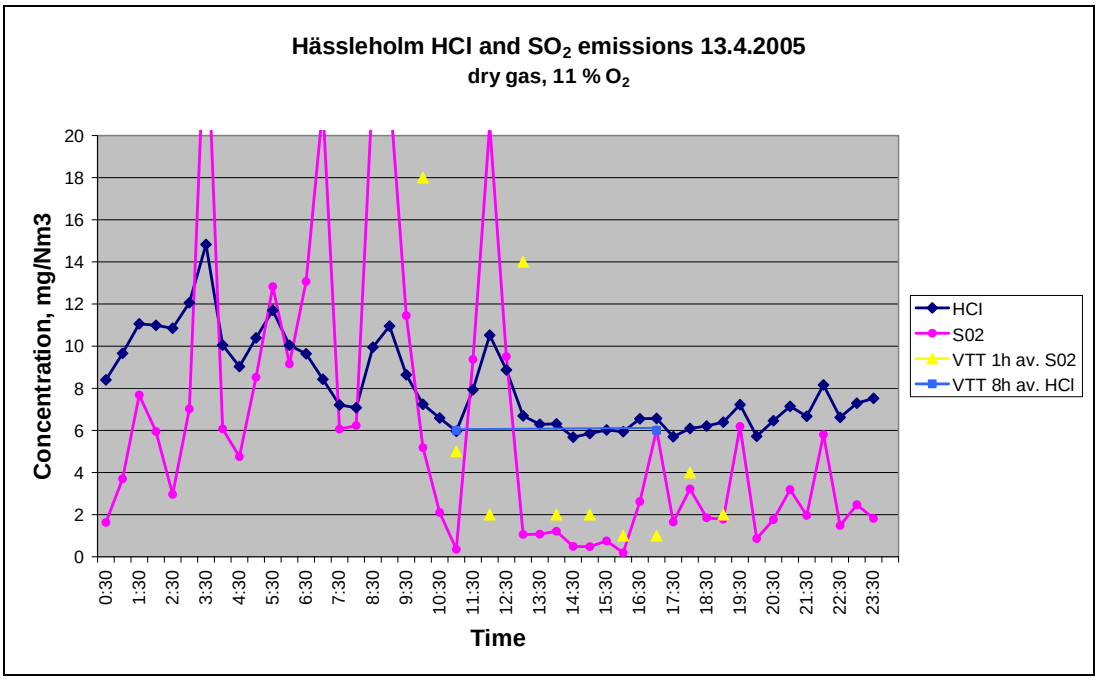

Figure 17. Hässleholm emission measurements 13.4.2006, including VTT measurements.

The HCl of the flue gas before and after the filter is shown in Figure 18, plant measurements. The yellow areas mark the time intervals of the VTT measurements. The HCl emission is well below the 10 mg/Nm3 WID threshold value. A significant increase of the HCl concentration in flue gas before the baghouse filter was observed during the first measurement day. No adequate explanation to this has been found by analyzing a restricted number of fuel samples. The most probable reason is a variation of the chlorine content of either the SRF or the peat/waste wood fuel fraction.

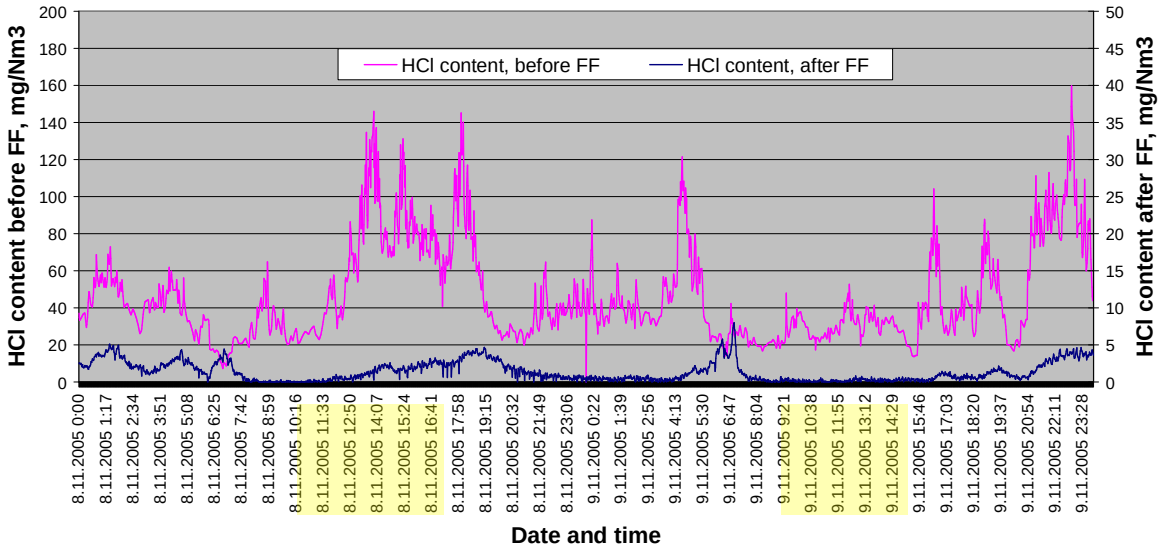

Figure 18. HCl content of the flue gas before and after the baghouse filter at Kauttua, process measurements. Reduced to 11% O2.

6.2 RESULTS FROM KARHULA PILOT PLANT

The process data points were recorded every five seconds during the set points. This data has been used as the basis for mass and energy balance calculations, which give theoretical fuel mass flow, air flow and flue gas mass flow rates. These can be used to estimate the theoretical measurement error, which sums up uncertainties in fuel and ash analyses, and process measurements.

Table 5. Examples of measured gaseous emissions in different unit at Karhula pilot plant

Test	O_2	CO	SO_2 theoretical	SO_2 measured	NO_x	HCl theoretical	HCl measured
	%, wet	ppm, wet	ppm, wet	ppm, wet	ppm, wet	ppm, wet	ppm, wet
10 CWW	6.83	41.8	31.4	40.5	135.4	34.5	26.9
20 REF I	6.77	733.0	50.7	54.1	113.5	210.3	116.6
30 REF III	7.28	227.3	71.6	34.4	117.7	733.8	383.4
40 REF I UM	8.23	380.8	56.3	41.9	99.6	387.9	231.4
45 REF I UM	7.36	421.5	87.9	33.9	70.2	530.0	213.9
50 REF IIII UM	6.21	294.7	31.5	19.1	95.1	315.5	143.6

The process data were examined using the multivariate analytical tool Simca – P version 10.0.2.0. With this tool all the data can be examined simultaneously. The PLS

modelling tool (Partial Least Square) was used to study the correlations between different parameters.

Compilation of setpoints

In Figure 19, all the set points are presented in the same graph. This graph was produced by Simca where the data table was examined row wise. Accordingly, the set points resembled well each other. The good resemblance can be deduced from the fact that the scattering (i.e. standard deviation) of the measured points (5 second interval) are mainly inside the elliptic circle which describes the statistical probability of 95 %.

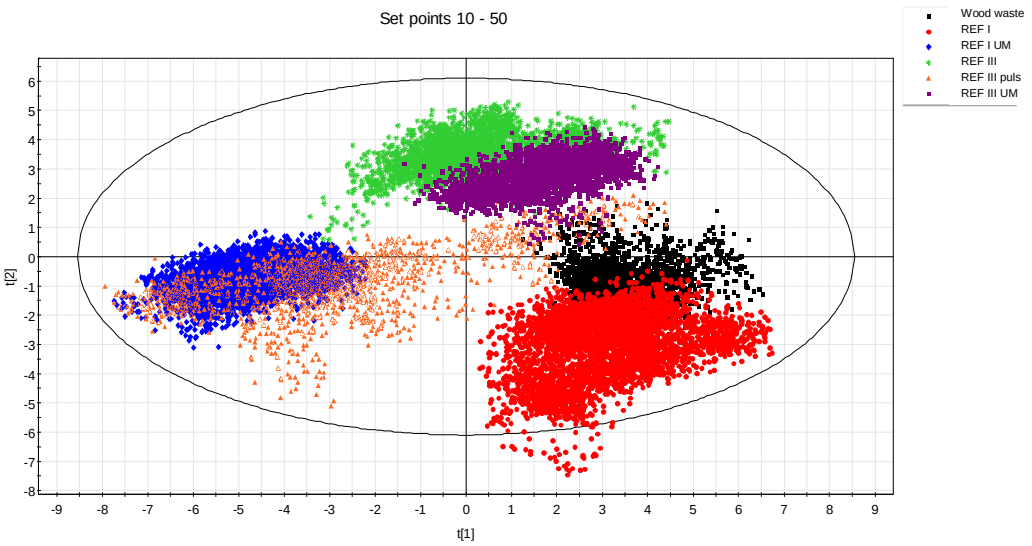

Figure 19. Compilation of the set points – the score plot describing the measured points in each set points presented by colors representing the fuels.

The feed rate was adjusted so that the bed temperature could be kept as even as possible and between 850 and 900 ^{o}C. Some fluctuation had to be accepted due to variations in the waste fuel quality and feeding properties.

Figure 20 presents the Hg measured for all the fuels. Accordingly the peak mercury contents were measured for SRF III 39 µg/m3. Typically, the gas components varied widely especially in the SRF set points. In the results, it was observed that the variation correlated well with the CO content measured in the furnace.

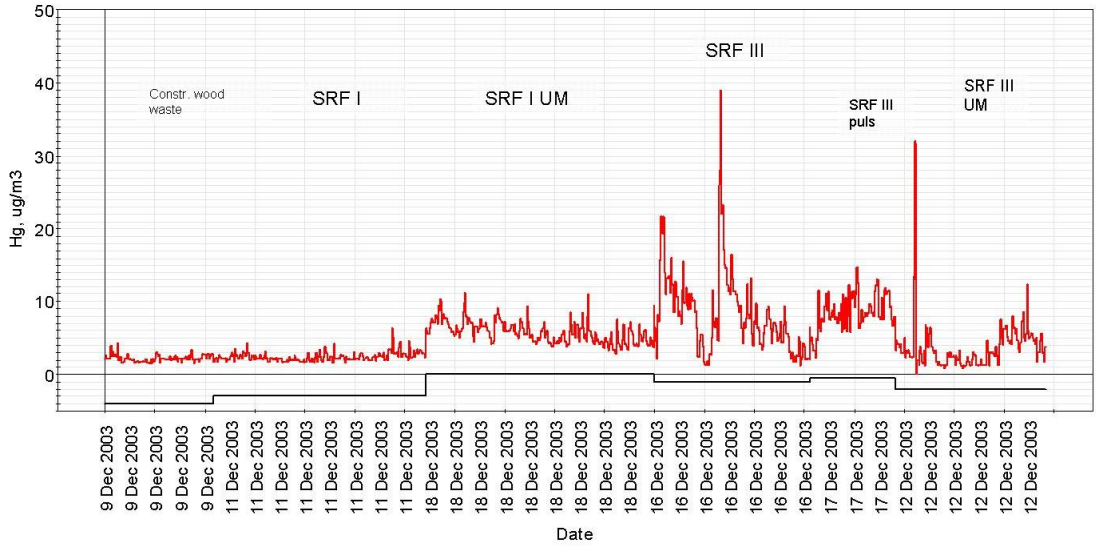

Figure 20. Mercury content measured in the flue gas after the filter in all the set points.

Fuel and ash analyses

An example of the variation in the analysis results of the single fuel samples is given in Figure 21. It can be seen that there was a quite high variation of chlorine and some metals like copper in the single fuel samples taken before the inlet particle sampling. There was even a high variation between the duplicate samples used in the analysis of the metals. In the relationship between the amount of an element fed into the furnace and the amount found in the fine particles a large variation was also found. The main reason for this variation is the inhomogeneity of waste based fuels. These results will be reported in the later stage when the leaching and electron microscopic fuel analysis are available.

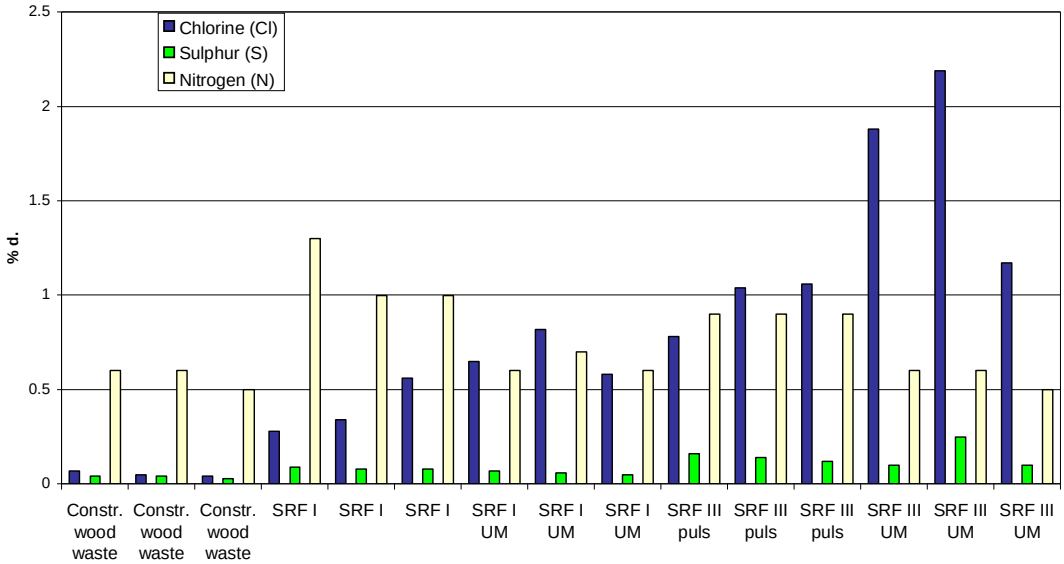

Figure 21. Variation of chlorine, sulphur and nitrogen content in the single samples

When the concentrations of the heavy metals and halogens are compared in the ash samples collected during the tests of SRF I and SRF III, the fly ash contained higher amounts of heavy metals and halogens than bed material (which contained fuel ash) and almost the same amounts than in the fuel ashes (calculated from the fuel analysis data). In the fly ashes, also halogen contents were in measurable amounts and striking was the high Cl content of 4.4 % in the fly ash of SRF III.

The laboratory studies of this project will support the elaboration of the reasons for the observations.

Lime injection into flue gas

Three set points were carried out with each waste fraction using three different limestone types: Sorbalite (containing 10 % activated coke), a commercial lime stone and a “research” limestone (Nordkalk), always in this order. Only gaseous emissions were measured during these set points.

The limestone feed was adjusted so that the HCl content of the flue gas was about or below 10 ppm. The SO_2 content usually dropped to about zero. The additives were fed by a small screw feeder placed on a balance into the flue gas line before the filter. Same feeding rate setting was used for all limestone qualities during the same set point. Between the set points the feeding was adjusted according to the procedure mentioned above.

The quantity of lime fed into the flue gases was calculated based on the weight of the additive batches added to the feeder. The feed rate varied quite substantially from set

point to set point, and also within each set point, due to the inaccurate feeding procedure. Therefore it was not possible to optimise the lime feeding with respect to emission control and no definite conclusions regarding lime quantities may be drawn.

When no additives were injected to the flue gases, the SO_2 emissions after the filter were in the range of 30-40 ppm except for SRF I UM, when the emission was about 15 ppm. Before the filter the measured SO_2 content was usually 30-35 % higher. Limestone addition to the bed did not significantly influence the SO_2 concentrations (less than 10 ppm). When lime was fed into the flue gases before the filter, the SO_2 content dropped to zero as presented in Figure 22.

The HCl was highest for the SRF III waste fraction. Comparing the chlorine content, of the SRF and SRF UM samples shows an almost doubling of the chlorine content of waste fractions which have gone through the washing (defibering) process. The washing process separated but the fibres also fines and heavy fractions like sand, stones, glass and metals. The results indicate that most of the chlorine in the waste is bound to the plastic fraction, probably in the form of PVC.

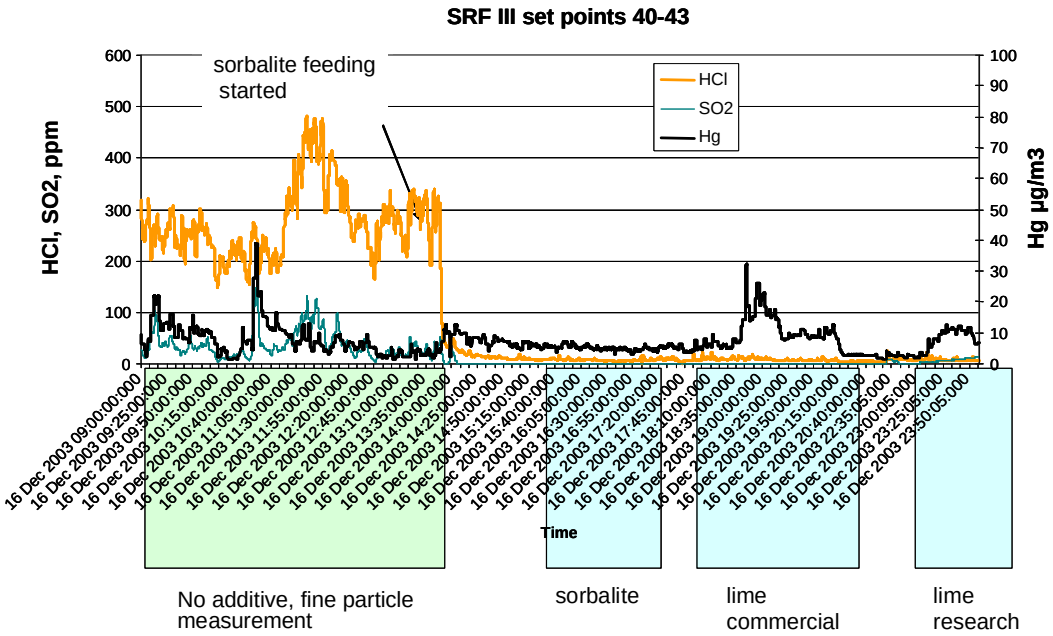

Figure 22. Hg, HCl and SO_2 content after filter measured SRF III set points with lime addition.

6.3 FINE PARTICLE CONCENTRATIONS AND SIZE DISTRIBUTIONS

6.3.1 Mass concentrations and mass size distributions

The particle mass concentration and mass size distribution were measured with BLPI from every plant and from the filter inlet and outlet. In some locations the mass concentration was also measured according to standard EN 13284-1:2001, their results are shown in Table 6 and Table 7 along with BLPI results.

Table 6. Filter inlet mass concentrations.

Filter Inlet	Mass concentration [mg/m^3] NTP, dry gas, 11% O_2	PM 2.5 [mg/m^3] NTP, dry gas, 11% O_2	PM 1 [mg/m^3] NTP, dry gas, 11% O_2
Hässleholm, BLPI	1100 – 1600	1000 – 1400	1100 - 1500
Hässleholm, STD	-	-	-
Norrköping, BLPI	3800 – 5300* (10 300* – 14 800)**	430 – 490	250 - 310
Norrköping STD	4600	-	-
Kauttua BLPI	2400 - 4300	140 – 220	22 – 41
Kauttua STD	-	-	-
SRF 1, BLPI	3800	340	240
SRF 3, BLPI	3700	460	340
SRF 1 UM, BLPI	2200	210	140
SRF 3 UM, BLPI	3200	290	190

* Isokinesis overestimation corrected (Figure 23)

** Actual overestimated result due to bad isokinesis in sampling

Table 7. Filter outlet mass concentrations.

Filter Outlet	Mass concentration [mg/m^3] NTP, dry gas, 11% O_2	PM 2.5 [mg/m^3] NTP, dry gas, 11% O_2	PM 1 [mg/m^3] NTP, dry gas, 11% O_2
Hässleholm, BLPI	0.13	<0.1	<0.1
Hässleholm, STD EN 13284-1:2001	0.2 – 0.4	-	-
Norrköping, BLPI	0.6	0.04, 0.08	0.03, 0.06
Norrköping STD	0.5 - 0.7	-	-
Kauttua BLPI	0.3	0.04	0.03
Kauttua STD	0.2 – 0.4	-	-
SRF 1, BLPI	0.1	0.03	0.04
SRF 3, BLPI	0.1	0.05	0.05
SRF 1 UM, BLPI	0.1	0.02	0.03
SRF 3 UM, BLPI	0.1	0.03	0.04

The two combustion techniques produced very different particle mass size distributions. The grate boiler produced almost solely fine particles 0.1µm < Dp < 2µm, while from the fluidised bed the coarse particle mode is dominant, as seen in Figure 23. The rectangle is a histogram presentation of the pre-cyclone collected particles, and the breakline presents the mass size distribution measured with BLPI. The total mass concentration, shown in Table 6, is the sum of the surface area under these two lines. The pre-cyclone had slightly different cut-off diameters at different locations.

The pilot scale studies showed that the generated fine particle concentration depended on the fuel. The fine particle concentration was the highest with SRF 3 and it was reduced by the urban mill (UM) treatment of the fuel.

The filters in each plant were highly efficient, the fine particle concentrations at filter outlet were well below 0.1 mg/m3. Due to low concentrations extremely small particle masses were collected on the substrates and the measuring accuracy remained poor, approximately ±100% on each stage. For the same reason the weighed masses were below the limit of identification for the data unavailable in Figure 24. At the filter outlet the majority of the particle mass concentration was in the coarse mode and no actual fine particle mode could be detected, regardless of the combustion technique or fuel.

In Norrköping filter inlet BLPI measurements the stack flow velocity was higher than the velocity in the sampling nozzle. Therefore the measured mass concentration was too high. The overestimation can be calculated from /1/:

$$C/C_0 = 1 + (U_0/U - 1)\,(1 - 1 / (1 + (2 + 0.62\,U/U_0)Stk)) \qquad (1)$$

where C is the measured mass concentration, C_0 the real concentration, U the gas velocity in the nozzle and U_0 the flow velocity in the duct. Stk is the Stokes number of the particle, which is related to the size of the particle. The mass concentration overestimation in function of the particle size in Norrköping filter inlet measurements is presented in Figure 25. There is no correction needed in the fine particle mode, but the coarse particle concentration is overestimated up to 3.6 times too high. Norrköping mass size distributions presented in Figure 23 have been corrected according to (1).

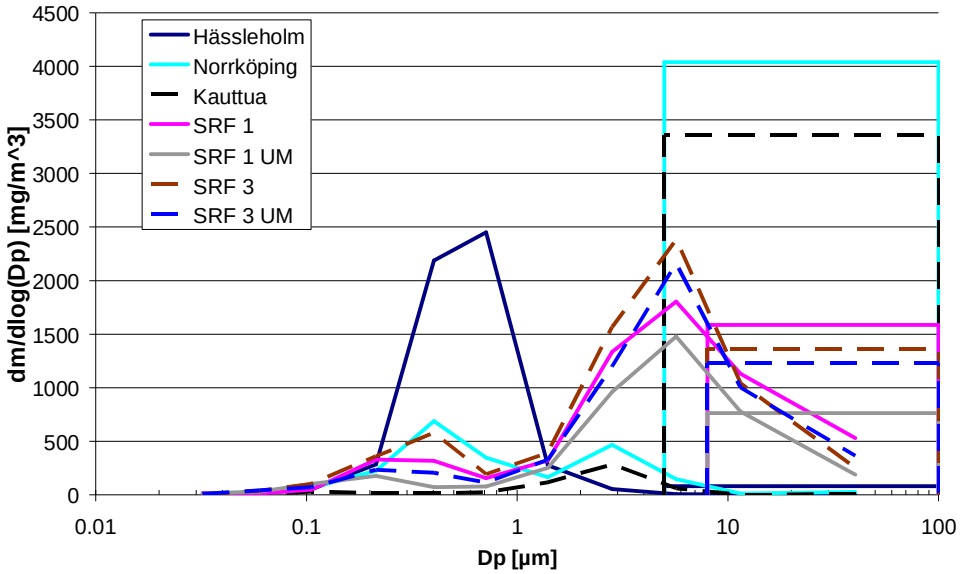

Figure 23. Mass size distributions at filter inlet. The rectangle at right is a histogram presentation of the pre-cyclone collected particles, and the break line presents the mass size distribution measured with BLPI. The total mass concentration is the sum of the surface area under these two lines.

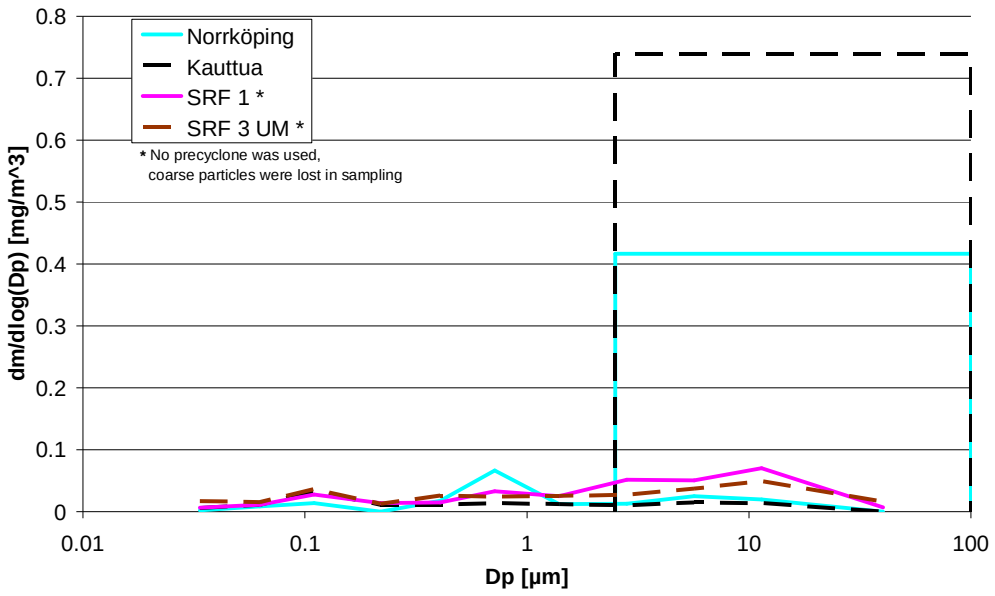

Figure 24. Mass size distributions at filter outlet. No pre-cyclone was used in the pilot plant measurements, coarse particles were lost in the sampling.

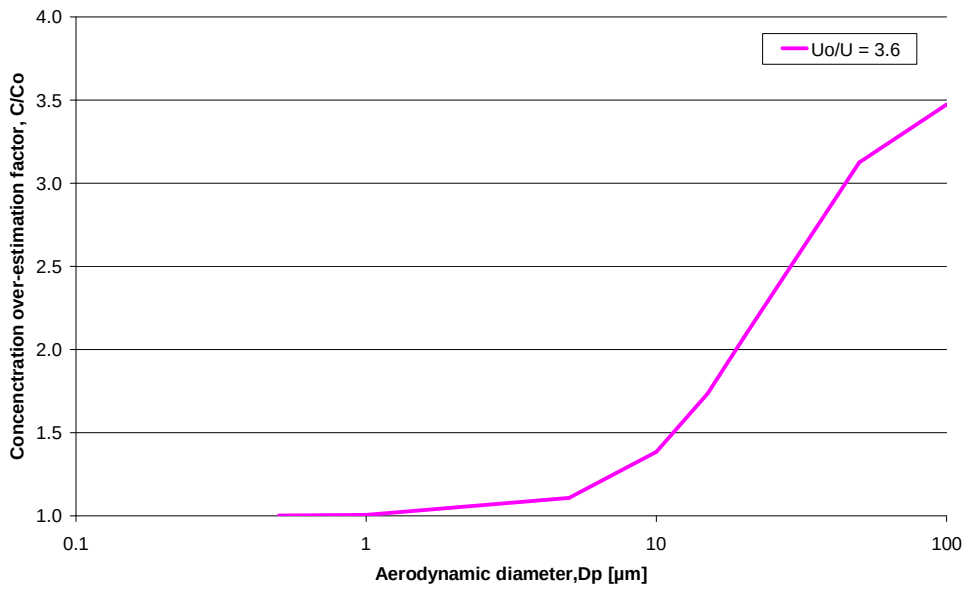

Figure 25. Concentration overestimation in function of particle size in Norrköping BLPI measurements from the filter inlet because of the bad isokinetic sampling, calculated from (1).

6.3.2 Number size distribution

The number size distribution was only measured at Norrköping. Figure 26 presents the number size distribution at the filter inlet and outlet during normal boiler operation and at the outlet during sootblowing. At the filter outlet the number concentration was very small, only ~20000 particles/cm^3. When the sample was heavily diluted, the signal/noise ratio was low.

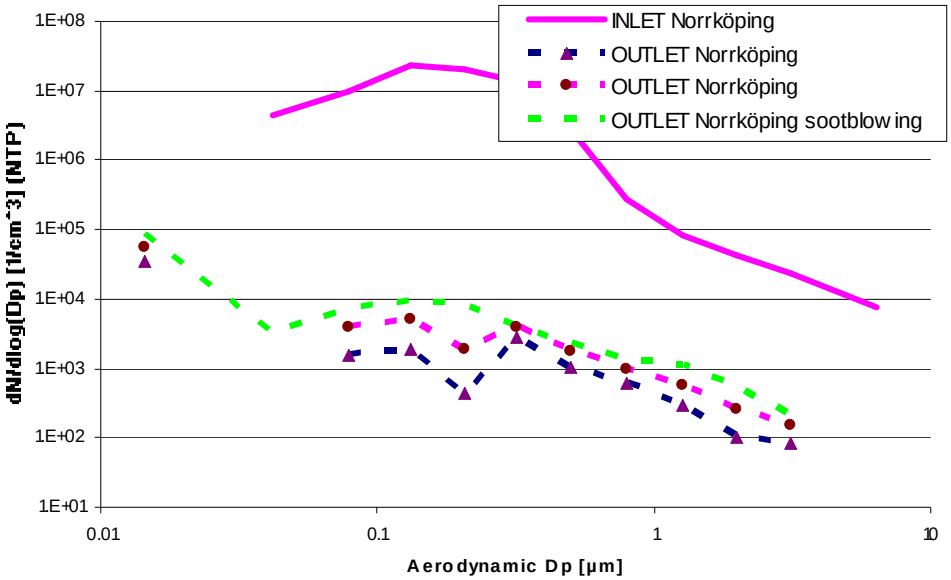

Figure 26. Number size distributions at Norrköping at the filter inlet and outlet during normal operation and at the outlet during sootblowing.

6.3.3 Elemental composition of particles

The elements regulated by EU directive and other selected elements were analyzed from particles with ICP-MS and IC. The analysis was made from BLPI collected particles to acquire the element mass concentrations and size distributions. In some locations the element mass concentration measurements were made also with a standardized method EN 14385.

The EU waste incineration threshold (WID) for emissions of Cd+Tl is 50 µg/m^3 and As+Co+Cr+Cu+Mn+Ni+Pb+Sb+V 500 µg/m^3. The studied emissions were significantly lower than the WID. The emissions of these elements presented in Table 8.

Some element concentrations were below the limit of identification, in which case the identification limit is added to emissions, but '<' is added.

With the existing effective filters the WID limits are easily achieved, and they make the limits seem unnecessary high.

Table 8. Concentrations of WID limited elements in particle emissions.

	Particle emissions [µg/m3]	Cd, Tl [µg/m3]	As,Co,Cr,Cu,Mn, Ni,Pb,Sb,V [µg/m3]	Hg Particle/gas phase [µg/m3]
WID threshold	10 000	50	500	50
Hässleholm BLPI	100	0.001	9*	-
Hässleholm EN 14385	300	0.02	<2.2	<0.01 / 0.05
Norrköping BLPI	600	0.01	32*	-
Norrköping EN 14385	600	<1.5	<17	1.5 / 4.9
Kauttua BLPI	300	0.1	19*	-
Kauttua EN 14385	300	<0.006	<0.8	<0.004 / <0.04
Hässleholm PM1, BLPI	<100	0.02	1*	
Norrköping PM1, BLPI	50	0.005	2*	
Kauttua PM1, BLPI	30	0.001	4*	-

* Includes some Cr contamination from BLPI

The mass size distribution of manganese at filter inlets is presented in Figure 27 at filter outlets in Figure 28. Similarly the mass size distribution of lead at filter inlets is presented in Figure 29 and at filter outlets in Figure 30. Mn is concentrated mainly in coarse particles Dp> 1µm, while Pb is mainly in fine particles, Dp<1µm. The relative abundance of a compound in the fine particles indicates that the element was readily released from the fuel to the gas phase, and that the gas-to-particle conversion mainly occurred by vapor condensation mechanism. The occurrence in the coarse mode particles indicates that the element was not released from the fuel to the gas phase during combustion, or that if it was released, the gas phase compounds reacted with the coarse mode particles by chemical surface reaction. Cl, Cd, Cu, Pb and Tl are typically volatile and thus abundant in the fine particles, while for example As, Co, Mn, Sb and V are usually almost entirely present in the coarse particle mode.

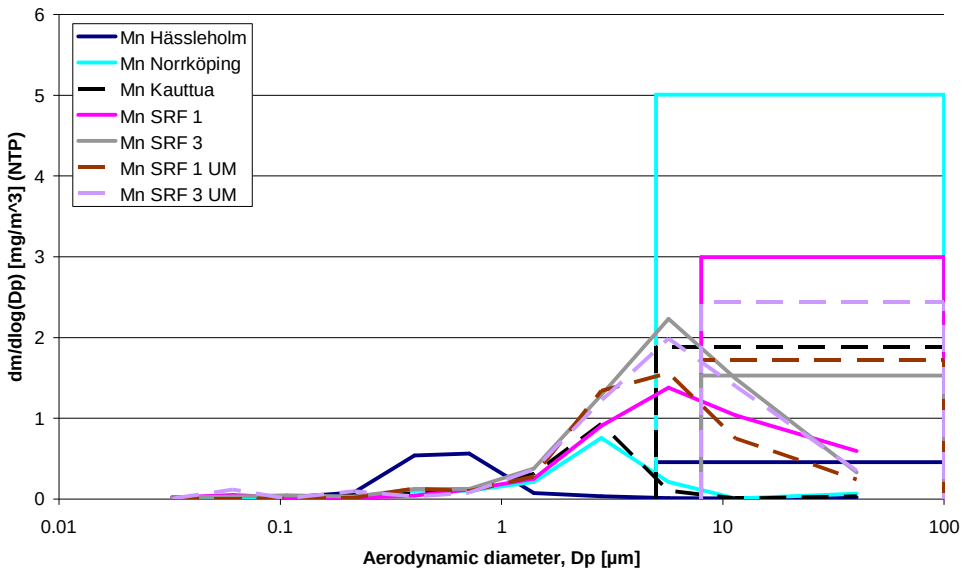

Figure 27. Manganese mass size distribution at filter inlet.

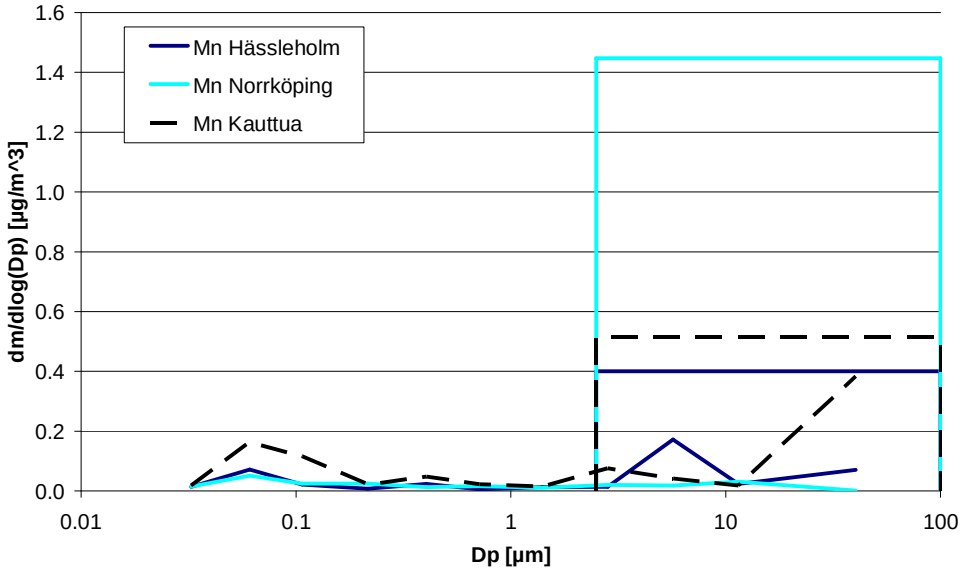

Figure 28. Manganese mass size distribution at filter outlet

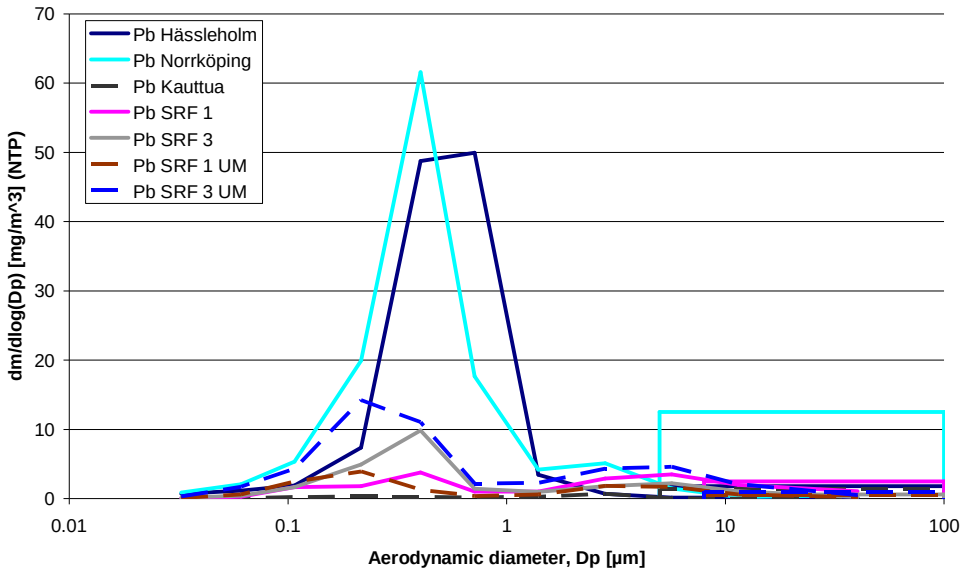

Figure 29. Lead mass size distribution at filter inlet.

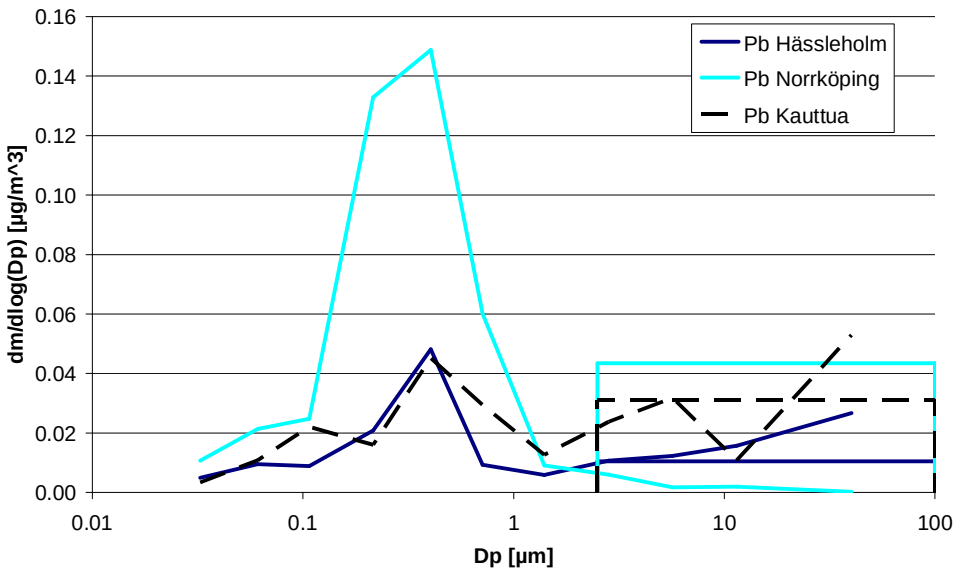

Figure 30. Lead mass size distribution at filter outlet

The pilot scale experiments indicated that the fuel only had a minor effect on the relative abundance of the elements in the fine or coarse mode particles, i.e. certain elements were found mainly in the fine or coarse mode particles for all the fuels. However, for the elements present in the fine particle mode, trends between the element concentrations in the fuel and in the fine particle mode could be found. The concentration of a certain element in fine particle mode depended on both the element and Cl concentrations in the fuel.

On the other hand the combustion technique was an important factor in the fine particle formation. In grate boilers the maximum temperatures are typically higher than in fluidised beds, which causes more elements to be more volatile. This leads to larger fine particle fraction in grate boilers. Also in fluidised bed boilers the volatile elements are found in large concentrations from the coarse particles as the vapours interact with the bed material and other coarse particles reducing the fine particle concentration. For example manganese requires higher temperature than lead or copper to significantly evaporate and is generally found solely from the coarse particle mode in the fluidised beds. However in the Hässleholm grate boiler Mn was found also in the fine particle mode.

The pilot scale studies showed that the waste quality has a significant effect on the fine particle concentration and composition. SRF 3 UM and SRF 3 fuels consisted more chlorine and volatile trace elements leading to larger fine particle concentrations

The combustion of mixed fuels, coke, peat, construction wood waste and REF in Kauttua produced significantly low concentration of fine particles. The chlorine concentration in the Kauttua fuels was low and sulphur concentration high, which result to lower evaporation. Peat consists large amounts of silicon and also aluminium, which react with the volatile trace metals further reducing the fine particle concentration. Silicon and aluminium form insoluble compounds with the trace metals as opposed to soluble metal chloride compounds. In disposal of the filter or bottom ashes the solubility is a cost factor.

The element distribution at filter outlet was very different from that of filter inlet. While the main components, of the analyzed elements, at the inlet were Cl, K, Na, SO4, Pb, Cu and Zn, the main components at the filter outlet were Fe, Al and Cr. It was detected with electron microscopy that after fabric filters there were coarse iron oxide particles, which may be fragments of the duct walls or other structures located after the filter. With such a small particle mass concentration it is significantly increased by few collected rust fragments.

6.3.4 Efficiency of air pollution control systems

The particle penetration through the fabric filter, *P*, is:

P = 100 - Collection Efficiency (%) = 100 (outlet mass concentration / inlet mass concentration)*

The penetration of particles through filters was calculated from simultaneous filter inlet and outlet BLPI measurements. The penetration in function of particle size is presented in Figure 31. The fabric filters removed the fine particles so effectively, that very small masses were collected and the weighing accuracy of the filter outlet BLPI substrates remained poor. Therefore the error in the penetration for individual data points is approximately ±100%. The efficiencies of the fabric filters designed for the waste combustion were significantly better than ESPs or two other FFs in a biomass and a coal

plant. Fabric filters don't have similar penetration window that ESPs have between particle size 0.1µm and 1µm, but the efficiency seems to slightly worsen towards the finer particles.

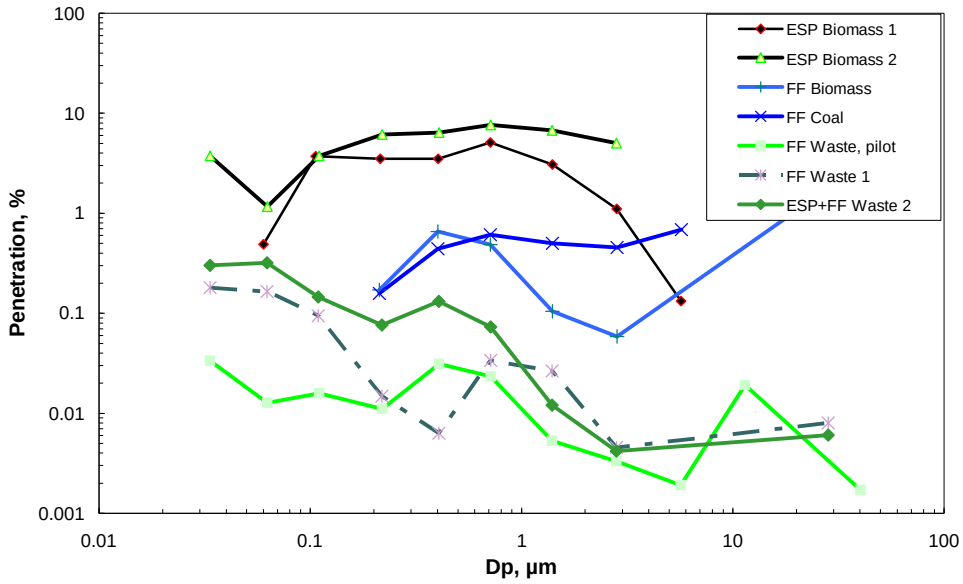

Figure 31. Filter penetration of particles in the plants measured in this project and a previous project (/2/ Hokkinen 2004)

BLPI is not capable of collecting the nano sized particles Dp < ~20µm. Electron microscopy revealed that particles in this size range would exist. The penetration of these nano particles through fabric filters would require further studying with devices capable of detecting them.

6.3.5 Construction Wood Waste Combustion

Construction wood waste was burned in three locations, Pilot scale plant, Siilinjärvi (70% wood and 30% wood waste) and ~42% mixed with other fuels (peat, coke, SRF) in Kauttua.

Compared to 'clean' bark+sawdust fuel the construction waste wood fuel, even when mixed with other fuels, consisted large quantities of Arsenic, Cadmium, Chromium, Copper, Nickel, Lead, Antimony, Tin, Vanadium and Zinc. Bark contains relatively high concentration of Manganese, mixing wood waste to bark+sawdust decreased the fuel Mn concentration because the bark proportion decreased. The fuel concentrations are presented in Table 9.

The Arsenic concentration in all three waste woods, especially in Kauttua, was remarkably high. The active ingredients in wood impregnating agents are copper, chromium and/or arsenic based. The use of arsenic has been restricted, but it is not forbidden. It should be possible to reduce Arsenic concentration in fuel by careful selection of the wood wastes. Chromium and Copper concentrations were not high in

wood wastes compared to the other waste fuels. Copper and chromium based impregnating agents do not have any restrictions.

Table 9. Characteristics of the construction wood wastes and bark+sawdust

		Siilinjärvi bark+sawdust	Siilinjärvi mixed wood waste	Pilot wood waste	Kauttua mixed wood waste
		100% bark+sawdust	70% bark+sawdust		30% peat 19% SRF, 9% coke
		0% wood waste	30% wood waste	100% wood waste	42% wood waste
Mercury (Hg)	mg/kg d	<0.04	<0.04	0.03	0.04
Arsenic (As)	mg/kg d	<0.04	6.7	14.2	74
Cadmium (Cd)	mg/kg d	0.1	0.26	0.54	0.4
Cobalt (Co)	mg/kg d	1.6	0.89	0.93	1.7
Chromium (Cr)	mg/kg d	1.0	15	29.4	84
Copper (Cu)	mg/kg d	4.5	8.5	31.5	69
Manganese (Mn)	mg/kg d	276	180	85.3	84
Nickel (Ni)	mg/kg d	1.0	3.1	4.7	7.5
Lead (Pb)	mg/kg d	1.1	14	46.3	77
Antimony (Sb)	mg/kg d	0.02	5.5	1.4	1.6
Tin (Sn)	mg/kg d	0.08	0.36	1.6	3.7
Thallium (Tl)	mg/kg d	0.06	0.04	0.02	<1
Vanadium (V)	mg/kg d	<0.1	0.66	1.5	5.3
Zinc (Zn)	mg/kg d	63	142	198	300
Bromine (Br)	mg/kg d			<50	
Fluorine (F)	mg/kg d			<50	<50
Chlorine (Cl)	% d	0.12	0.44	0.1	0.17
Soluble Na+K	% d				0.07
Sulphur (S)	% d	0.01	0.02	0.04	0.16
Nitrogen (N)	% d	0.2	0.50	0.57	0.8
Carbon (C)	% d	51	50	49.0	48.5
Hydrogen (H)	% d	6.0	6.1	5.9	5.6
Volatile matter	% d	79	78	78.7	73.6
Ash	% d	1.7	2.9	3.4	6.8
High heating value	MJ/kg d	20.55	19.99	19.66	19.8
Lower heating value	MJ/kg d	19.24	18.66		11.0

In Siilinjärvi grate boiler the addition of 30% waste wood to bark+sawdust increased the concentration of several elements in particles to 2 to 100 fold, including As, Cd, Cl, Cr, Cu, Na, Pb, Sb and Zn. The concentrations of these elements were also higher in the waste wood containing fuel. All of these elements were also volatile in boiler and were therefore enriched in the fine particle mode. However, K was the dominating element in the fine particle mode and the total mass concentration of the fine particles was higher with bark and sawdust only. Pb mass size distribution at Sillinjärvi filter inlet is presented in Figure 32 with and without 30% construction wood waste addition to bark+sawdust.

As seen in Table 10 the WID regulated heavy metal emissions were exceeded only while burning clean bark+sawdust when Mn emission alone was higher than the limit for As+Co+Cr+Cu+Mn+Ni+Pb+Sb+V. The waste incineration directive does not concern clean wood combustion however.

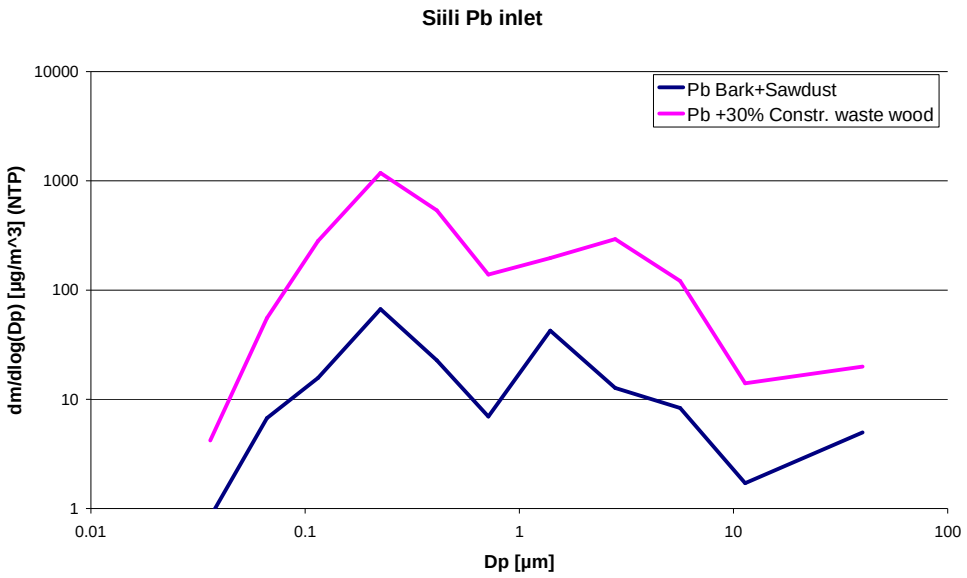

Figure 32. Pb mass size distribution at Siilinjärvi filter inlet with and without 30% construction wood waste addition to bark+sawdust

Table 10. BLPI particle mass concentrations from construction wood waste combustion

	Siilinjärvi bark+sawdust	Siilinjärvi mixed wood waste	Pilot wood waste	Kauttua mixed wood waste
	100% bark+sawdust 0% wood waste	70% bark+sawdust 30% wood waste	100% wood waste	30% peat, 19% SRF, 9% coke 42% wood waste
	ESP	ESP	FF	ESP+FF
	[mg/m^3] (NTP) 11% O_2, dry	[mg/m^3] (NTP) 11% O_2, dry	[mg/m^3] (NTP) 11% O_2, dry	[mg/m^3] (NTP) 11% O_2, dry
Filter inlet, total	280-800	230-2300	1600-3000	2400-4300
PM1	140-160	80-110	220-360	140-220
PM2.5	120-130	70-90	120-250	22-41
Filter outlet, total	60	20-130	0.07*	0.2-0.4
PM2.5	8	6-8	0.03	0.04
PM1	7	5-7	0.03	0.03
Cd+Tl	0.002	0.002	NA	0.0001
As+Co+Cr+Cu+Mn+Ni +Pb+Sb+V	1.2*	0.3*	NA	0.019*

- ~PM10, no pre-cutter cyclone could be used

** Includes some Cr contamination from measuring equipment

7 SUMMARY AND CONCLUSIONS

The pollution control systems used in the waste combustion plants were very efficient reducing the particle mass concentration approximately 99.99%. The operation of the filters is the most important factor in the particle emissions. Within the limits of measuring accuracy the mass size distributions after filters were similar and no dependence on fuel or combustion system could be detected. Some of the coarsest particles were oxidised iron pieces which are probably fragments of the duct structures, fans or filter etc. A small number of these pieces contain the majority of the emission mass concentration.

The waste quality and combustion method had significant effects on generated fine particle concentrations. Pilot studies showed that decreasing waste quality resulted in higher PM1.0 concentrations. In grate boiler the maximum temperature may be several hundreds of degrees higher than in fluidised bed boiler. Therefore in grate boiler volatile elements will evaporate more and also more elements will be volatile. In fluidised bed the vapours may interact with the bed material thus further reducing the fine particle concentration.

The waste fuels may contain large amounts of copper, lead and other trace metals, which concentrate in the fine particle mode as chlorides. The main components of the fine particle mode are potassium and sodium chlorides and sulphates.

The combustion of mixed fuels, coke, peat, construction wood waste and REF in Kauttua produced significantly low concentration of fine particles. The chlorine concentration in the Kauttua fuels was low and sulphur concentration high, which result to lower evaporation. Peat and coke consist large amounts of silicon and aluminium, which react with the volatile trace metals further reducing the fine particle concentration. Silicon and aluminium form insoluble compounds with the trace metals as opposed to soluble metal-chloride compounds. In disposal of the filter or bottom ashes the solubility is a cost factor and chlorides corrode the boiler structures. It could be possible to reduce the concentration of soluble metal-chloride fly ash fine particles by adding suitable additives to fuel when burning solely waste.

With the highly effective pollution control systems the particulate emissions from waste combustion are extremely low. The acceptable level for ambient outdoor PM10 particle mass concentration is 50µg/m^3 as daily average according to EU directive. In spring 2006 the worst days PM10 concentration at downtown Helsinki reached 150µg/m^3 /3/ because of forest- and wildfires south of Finland and dust from street sanding. PM10 emissions were not measured from the waste combustion plants, but comparison to PM2.5, which was 20-80 µg/m3, indicates that the particle emissions from waste combustion may almost equal the already existing Helsinki city air particle concentration.

Emissions of the EU regulated trace metals Hg, Cd+Tl and As+Co+Cr+Cu+Mn+Ni+Pb+Sb+V were all well below the WID limits. After the fabric filters the emissions were minimum of 10 times lower than the WID limits. Other

special emissions regulated by WID, like dioxins and furans, Hg, HCl, HF and TOC were all measured well below the threshold values. A summary of average measurement values is presented in Table 11.

Table 11. Average WID related measurements at the waste combustion plants.

Emission	Hässleholm (grate) mg/m^3 (11% O_2)	Norrköping (CFB) mg/m^3 (11% O_2)	Kauttua (CFB) mg/m^3 (11% O_2)	WID threshold mg/m^3 (11% O_2)
Total dust	0,45	0,58	0,27	10
Sb+As+Pb+Cr+Co +Cu+Mn+Ni+V	0,03	0,02	0,02	0,5
Cd+Tl	0,0005	0,002	0,001	0,05
Hg	0,00008	0,003	< 0,04	0,05
HCl	9,1	3,6	0,8	10
HF	< 0,032	< 0,03	< 0,012	1
Dioxins and furans	0,0048 ng/m3	0,0076 ng/m3	< 0,00001 ng/m^3	0,1 ng/m3

8 REFERENCES

1. Hinds W.C. (1999) Aerosol Technology, Properties, behaviour and measurement of airborne particles. New York: John Wiley & Sons Inc. 483p

2. Hokkinen, J.; Jokiniemi, J.; Aurela, M.; Hillamo, R. 2004. Fine Particle and Trace Element Emission Charactrisation from Energy Production and Process Industry *[In Finnish: Energiantuotannon ja prosessiteollisuuden pienhiukkas- ja raskasmetallipäästöjen karakterisointi.]* VTT Processes, Espoo. 39 p. + App. 18 p. VTT Research Notes : 2258. http://virtual.vtt.fi/inf/pdf/tiedotteet/2004/T2258.pdf.

3. YTV homepage www.ytv.fi/eng/airquality,