Indoor air quality at a waste incineration plant

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Master's thesis

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September 4, 2013

ABSTRACT

Waste has been incinerated for energy utilization for more than a hundred years, but the harmful emissions emitted from the incineration plants did not begin to cause concern until the 1980s. Many plants were shutdown and the waste incineration plant in Kyläsaari Helsinki was one of them. In later years, new landfill regulations have increased the interest in waste incineration. During the last year, four new plants were taken into operation in Finland, Westenergy in Vaasa among them.

The presence of dust has been observed indoors at Westenergy waste incineration plant. Dust is defined as particles with a diameter above 10 μm, while fine particles have a diameter smaller than 2.5 μm, ultrafine under 0.1 μm and nanoparticles under 0.05 μm. In recent years, the focus of particle health research has been changed to investigate smaller particles. Ultrafine particles have been found to be more detrimental to health than larger particles. Limit values regulating the concentrations of ultrafine particles have not been determined yet.

The objective of this thesis was to investigate dust and particles present inside the Westenergy waste incineration facility. The task was to investigate the potential pollutant sources and to give recommendations of how to minimize the presence of dust and particles in the power plant. The total particle number concentrations and size distributions where measured at 15 points inside the plant with an Engine Exhaust Particle Sizer (EEPS) Spectrometer. The measured particles were mainly in the ultrafine size range. Dust was only visually investigated, since the main purpose was to follow the dust accumulation. The measurement points inside the incineration plant were chosen according to investigate exposure to visitors and workers. At some points probable leakage of emissions were investigated. The measurements were carried out during approximately one month in March–April 2013.

The results of the measurements showed that elevated levels of dust and particles are present in the indoor air at the waste incineration plant. The cleanest air was found in the control room, warehouse and office. The most polluted air was near the sources that were investigated due to possible leakage and in the bottom ash hall. However, the concentrations were near measured background concentrations in European cities

and no leakage could be detected. The high concentrations were assumed to be a result of a lot of dust and particles present on surfaces that had not been cleaned in a while. The main source of the dust and particles present inside the waste incineration plant was thought to be particles and dust from the outside air. Other activities in the area around the waste incineration facility are ground work activities, stone crushing and traffic, which probably are sources of particle formation. Filtration of the outside air prior entering the facility would probably save personnel and visitors from nuisance and save in cleaning and maintenance costs.

Key words: Ultrafine particles, dust, waste incineration, indoor air

Kvaliteten på inomhusluften vid en avfallsförbränningsanläggning i Finland

Avfall har bränts länge i energiutvinningssyfte. Den första avfallsförbränningsanläggningen byggdes i Nottingham, Storbritannien 1874. I Finland började avfallsförbränningen 1961 med en förbränningsanläggning i Byholmen. I början var inte avfallsförbränningens negativa hälso- och miljöeffekter kända, men på 80-talet började man uppmärksamma utsläpp från förbränningen. Avfallsförbränningsanläggningen i Byholmen stängdes p.g.a. höga utsläpp av sot, damm och tungmetaller. På senare tid har intresset för avfallsförbränningen ökat igen i och med nya restriktioner och krav om deponering av avfall. Ny lagstiftning och nya restriktioner har avsevärt minskat på utsläpp från avfallsförbränningen. Oriketo anläggning i Åbo var länge den enda avfallsförbränningsanläggningen i Finland. 2007–2008 startade de första moderna anläggningarna sin verksamhet i Riihimäki och Kotka och under det senaste året har fyra nya anläggningar tagits i bruk. En av dessa anläggningar är Westenergy avfallsförbränningsanläggning i Vasa.

Westenergy avfallsförbränningsanläggning grundades av fem kommunala avfallsbolag och anläggningen började med sin kommersiella energiproduktion i januari 2013. Totalt förbränns det brännbart avfall från 400 000 hushåll i 50 kommuner i anläggningen, d.v.s. ca 20 ton avfall per timme. Sedan anläggningen varit i gång har man upptäckt stora mängder av damm och partiklar inne i anläggningen. Damm klassas ofta som partiklar med en diameter större än 10 μm. Problemet med damm gav upphov till en del frågor. Varifrån härstammar dammet? Kan dammet negativt påverka personalen och besökare vid anläggningen? Kan dammet slita på utrustning och ge upphov till ökade underhållskostnader?

Målet med detta diplomarbete var att undersöka förekomsten av damm, det vill säga partiklar, i inomhusluften vid Westenergy avfallsförbränningsanläggning och utreda partiklarnas härkomst. Ämnet betraktades ur två olika synvinklar, hälsoaspekter och möjligt läckage av partiklar från förbränningsprocessen. Uppgiften var även att ge rekommendationer för hur man kan minska på förekomsten av partiklar i inomhusluften.

En liten del av arbetet koncentrerades också på att undersöka mätning av ammoniak vid insprutningspunkterna för ammoniak. Litteraturstudier om tidigare gjord forskning om inomhusluft vid avfallsförbränningsanläggningar och litteraturstudier om ammoniakens och partiklarnas hälsoeffekter utfördes.

Partiklar formas både genom naturliga processer och genom människans aktiviteter. De största partikelkällorna i tätorter är trafik och förbränning av fossila bränslen. Inomhus uppstår partiklar vid rökning, matlagning och av människors rörelser. Partiklar delas in på flera olika sätt. Det vanligaste indelningssättet är enligt deras storlek. Man skiljer på partiklar större än 10 μm, därtill finns fina partiklar med en diameter under 2,5 μm, ultrafina har under 0,1 μm och de minsta nanopartiklarna har en diameter under 0,05 μm. Ett annat sätt att skilja på partiklar är enligt deras uppkomst. Primära partiklar släpps direkt ut från deras källa, medan sekundära partiklar formas i atmosfären som en följd av kemiska reaktioner. Ultrafina partiklar formas främst genom kondensering av gaser och genom kondensering av lättflyktiga material.

Det är oftast storleken på partikeln som bestämmer partikelns hälsopåverkan. Mindre partiklar dras längre in i lungorna och kan passera andningssystemets försvarsmekanismer. Vid mätningar av partiklar med diametern 10 μm och 2,5 μm mäter man oftast partiklarnas massakoncentration. På grund av mindre storlek och mindre massa blir nanopartiklarna och de ultrafina partiklarna obeaktade vid mätning av massakoncentrationer, fastän deras antal i t.ex. tätorter är upp till 80 % av det totala partikelantalet. Det stora antalet partiklar under 0,1 μm i diameter medför också att de har en större ytarea. Andra föroreningar kan således förekomma i större kvantiteter på ytan av mindre partiklar. Symptom relaterade till inandning av partiklar är irritation och infektioner i ögonen och andningsorganen.

Ammoniak är en färglös, irriterande och skarpt luktande gas som förekommer i gasform i rumstemperatur. Vid Westenergy avfallsförbränningsanläggning används ammoniak för att minimera uppkomsten av kväveoxider. En ammoniaklösning innehållande 24,5 % ammoniak sprutas in i förbränningskammaren på olika höjder beroende på temperaturen inne i kammaren. Ammoniak i gasform förorsakar irritation i ögonen och andningsorganen. I vätskeform förorsakar ammoniak främst köldskador.

Ett antal studier där man hade undersökt halterna av olika kemiska substanser i inomhusluften vid avfallsförbränningsanläggningar har utförts tidigare. I en studie hade man undersökt halterna av kvicksilver vid två avfallsförbränningsanläggningar i Kina. I en annan studie undersöktes halterna av partiklar, tungmetaller, VOC och SVOC samt dioxiner vid en avfallsförbränningsanläggning som förbränner farligt avfall i Turkiet. Vid Oriketo anläggning i Åbo har man undersökt halterna av damm, mikrober, endotoxiner och VOC vid arbetspunkter inne i anläggningen. I USA har man utfört liknande partikelmätningar som i detta diplomarbete vid två kolkraftverk och ett gaskraftverk. Resultaten av denna studie jämfördes med resultaten av partikelmätningarna vid Westenergy.

Innan partikelmätningarna vid Westenergy startade planerades ett mätningsprogram där följande frågor besvarades: Vad ska mätas, var ska mätningarna utföras, när och under hur lång tid ska mätningarna göras, hur ska de utföras och hur ska resultaten hanteras.

Det första steget var alltså att bestämma vad som ska mätas, i detta fall antalet partiklar och ammoniakhalten i inomhusluften. Utrustningen som användes för partikelmätningarna var en spektrofotometer (Engine Exhaust Particle Sizer (EEPS) Spectrometer) och med den kunde man mäta partikelstorlekar mellan 5,6 och 560 nm. Det var alltså främst ultrafina partiklar som mättes. Vid mätning av ultrafina partiklar är det partikelantalet som är den intressanta enheten och EEPS:n mätte partikelantalet vid olika storlekar. Massakoncentrationen, volymkoncentrationen och den totala ytarealen för partiklarna kunde även beräknas med givna formler. För att undersöka förekomsten av större partiklar, d.v.s. damm, placerades bitar av kontaktplast ut på tio platser inne i anläggningen. Dammansamlingen på plastbitarnas ytor följdes upp under sju dagar.

För att få en uppfattning om mängden partiklar som andas in av besökare och arbetare utfördes partikelmätningen vid en andningshöjd på ca 1,5 meter ovanför golvet. Mätplatserna valdes ut enligt de rutter som besökare följer under rundturer i anläggningen och där arbetare rör sig. Några mätplatser valdes för att undersöka eventuellt läckage av partiklar till inomhusluften.

Eftersom mätningarna gjorde inomhus och förbränningsprocessen är kontinuerlig

beaktades inga väderförhållanden eller arbetstider. Därför kunde mätningarna utföras vilken tid på dygnet som helst. Mättiden och provtagningarna planerades enligt ISO 28439-standarden och SFS-EN 689-standarden. Vid varje mätplats samlades prov in under tolv timmar i sträck, en mätperiod utfördes varje timme. Under en mättperiod (som varade i tio minuter) togs 60 skilda prov. Av dessa valdes de mest representativa proven ut (enligt EEPS-instruktionerna) för vidare analysering. Sammanlagt analyserades 48 prov av de 60 prov som erhölls under varje mätperiod.

Ansamlingen studerades enbart visuellt. Räcken på olika platser i anläggningen rengjordes och ansamlingen av damm följdes upp under en vecka. Lappar med kontaktplast användes även för analysering av damm. Det konstaterades att ett system för att upptäcka ammoniakläckage redan existerar vid Westenergy. Vid trycksänkningar i insprutningslinjerna alarmerar systemet, vilket kan vara ett tecken på läckage i linjerna. Inga ammoniakmätningar utfördes för diplomarbetet, men några möjliga sensorer kontrollerades för framtida behov.

Engine Exhaust Particle Sizer (EEPS)-spectrometern är egentligen avsedd för mätning av partiklar i avgaser från förbränningsmotorer, men den klarar även av att mäta partikelhalter i inomhusluft om halterna är tillräckligt höga. Utrustningen lånades av Vasa universitet. EEPS:n mäter partiklar genom att den ger partiklarna en laddning och laddningens storlek är beroende av partikelns storlek. EEPS:n kan sedan analysera storleken på den elström som partiklarna ger upphov till när de passerar genom mätaren. Analyserna hanteras i ett datorprogram och kan överföras till t.ex. Excel. Före varje mätning måste mätaren kalibreras med ett renluftfilter, s.k. HEPA-filter.

Inga gränsvärden för partiklar under 2,5 μm existerar ännu och därför kunde inte mätningarna jämföras med aktuella gränsvärden. Resultaten jämfördes dock med tidigare studier gjorda om mätning av ultrafina partiklar. Därtill jämfördes partikelhalterna vid de olika mätplatserna med varandra. Inga osäkerheter beaktades i detta diplomarbete, och genom kalibrering och underhåll av mätaren erhölls de noggrannaste resultaten.

Ansamlingen av damm följdes upp på några ställen i anläggningen under en veckas tid genom rengöring av räcken. Lappar med kontaktplast sattes även ut på olika ställen

i anläggningen och mängden damm som fastnade på den klibbiga ytan följdes upp dagligen under sju dagar. Utgående från de visuella observationerna kunde det konstateras att mest damm förekom på anläggningens bottenvåning och under textilfiltren i rökgasreningshallen.

Partikelmätningarna utfördes enligt det planerade mätprogrammet. 13 mätningar utfördes på varje ställe, förutom på de platser där möjligt läckage undersöktes. Ett medelvärde för partikelantalet och storleksdistributionen beräknades för varje ställe. Den totala partikelkoncentrationen var högst i källaren där bottenaskan hanteras. Detta var inte överraskande, eftersom arbetarna hade klagat mycket på damm där. På andra ställen med höga partikelkoncentrationer gjordes mätningar vid hanteringen av flygaska vid de möjliga läckagepunkterna. Detta tros dock inte bero på läckage, eftersom halterna ändå var relativt låga, utan på förekomsten av damm på ytor och golvet vid dessa mätpunkter. Golvet och ytorna hade inte städats på en tid. De lägsta koncentrationerna hittades i kontorsutrymmena. Enligt storleksdistribueringen förekommer det mest partiklar i storleksklassen under 100 nm, d.v.s. största delen är ultrafina partiklar.

En del specialmätningar utfördes för att undersöka möjliga partikelkällor. Det visade sig att människor som rörde sig i närheten av mätaren under mätningen förorsakade kraftigt förhöjda partikelhalter. Detta kallas ”personal cloud” och beror på att människors rörelse stör luften och partiklar från kläder och omgivande ytor lyfts upp. Avfallsförbränningsanläggningen kördes ned för fem dagar i mars, för städning och underhåll av bl.a. förbränningskammaren. Efter att anläggningen körts i gång igen gjordes nya mätningar på två mätplatser för att undersöka skillnaden före och efter nedkörningen. Tre veckor senare gjordes ytterligare en mätning på samma platser. Man kunde tydligt se att partikelkoncentrationen var som störst direkt efter nedkörningen av anläggningen, vilket kan bero på gaser som läckt från kammaren och under själva städningen.

Området framför luckan vid förbränningskammaren fungerade som lager för byggnadsmaterial. Mätningen där gav den högsta partikelkoncentrationen av alla mätningar. En mätning till utfördes på samma plats för att undersöka effekten av att städa bort materialet, och man kunde tydligt sen en minskad partikelkoncentration under den senare mätningen. Detta tyder på att städning är ett sätt att minska på antalet partiklar

i inomhusluften.

Resultaten från mätningarna jämfördes med mätningar som utförts i tre olika städer i Europa. Mätningarna i städerna gjordes för att erhålla bakgrundkoncentrationer i tätorter. Den totala partikelkoncentrationen mätt vid de olika mätplatserna vid Westenergy ligger väldigt nära de uppmätta bakgrundskoncentrationerna. Således kan man anta att koncentrationerna inomhus vid Westenergy motsvarar ungefär de partikelkoncentrationer som förekommer i utomhusluften vid tätorter. Mätningarna vid avfallsförbränningsanläggningen jämfördes även med de mätningar som gjorts vid två kolkraftverk och ett gaskraftverk i USA. Halterna var väldigt lika vid de jämförda mätplatserna, förutom att man vid kolkraftverken kunde man urskilja väldigt höga halter nära förbränningskammaren och detta konstaterades även i studien. Man misstänkte läckage av gaser från kammarkonstruktionen. Vid Westenergy är sannolikheten för gasläckage från förbränningsprocessen väldigt liten, eftersom trycket i förbränningsprocessen är lägre än i omgivningen.

Inga tydliga källor till förekomsten av partiklar och dammet kunde hittas inne i anläggningen, förutom vid hanteringen av bottenaska i källarvåningen. Utan elementära analyser av partiklarna är det i praktiken omöjligt att bestämma deras härkomst. En del partiklar kan uppstå då gaser i anläggningen kondenseras, men det är svårt att säga då inga mätningar har gjorts. Den största utsläppskällan för partiklarna och dammet tros vara utomhusluften. Många aktiviteter äger rum i området i närheten av anläggningen, bl.a. stenkrossning, jordbyggnad och livlig trafik. Dessa aktiviteter ger upphov till partiklar som dras in i anläggningen. Sekundär- och primärluften till förbränningen dras inifrån anläggningen, vilket betyder att luftombytet med utomhusluften är ganska stort i anläggningen. Inga filter existerar framför ventilationsluckorna som drar in utomhusluften, utan alla föroreningar som finns i utomhusluften kommer även in i anläggningshallen.

Ett sätt att minska partikelkoncentrationerna och dammet är alltså genom städning, men onödiga resurser läggs på städningen om man inte stoppar utsläppskällan. Därtill är det mycket lättare att avlägsna partiklar direkt vid källan än att avlägsna partiklar som redan förekommer i luften. På basis av denna undersökning kan man rekommendera installation av filter som filtrerar bort partiklarna från utomhusluften innan

den kommer in i anläggningen. Rekommendationer för hur man kunde minimera partiklar vid hanteringen av bottenaskan är svåra att ge, eftersom man i detta fall inte kan ta bort källan. Ett sätt vore att ytterligare kapsla in hanteringen.

För att helt kunna klargöra partiklarnas hälsoeffekter borde deras innehåll analyseras. Olika sorters partiklar kan påverka hälsan och miljön olika beroende på vad de består av. Partiklar från förbränningsprocesser kan t.ex. innehålla höga halter av metaller. Partiklarna kan även bestå av bakterier eller virus. Vidare forskning på detta område är nödvändig för att man ska kunna uppskatta potentiella hälso- och miljöeffekter. En god uppfattning om dammsituationen i avfallsförbränningsanläggningens inomhusluft kunde dock erhållas genom detta arbete, vissa slutsatser kunde dras och rekommendationer kunde ges.

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Preface

This Master´s thesis has been done for Oy Westenergy Ab. I would like to express my thanks to the employers at Westenergy for taking me in and helping me with the process of this thesis. I would like to give special thanks to my supervisor at the company, Jan Teir, who gave me the opportunity to do this thesis about something that is in my range of interests.

From Åbo Akademi I would like to thank my professor, Margareta Wihersaari for commenting and giving me her views on my work and helping me to further improve it. There have been many people involved within Åbo Akademi and Novia University of Applied Sciences that have helped me on my way to where I stand now. Especially Martina Englund and Mikko Helle have been of lot of help during my studying years with guidance and fixing problems.

And last I would like to thank my classmates who have made the time during my studies a time worth remembering.

Sanna-Sofia Skog

September 4, 2013

Register of abbreviations and terms

Accumulation mode	Particles with a diameter of 0.1—2 μm
Coarse mode	Particles caused by mechanical wear and decomposition, diameter of 2—100 μm
dN	Particle number concentration
dN/dlogDp	Normalized particle number concentration (dN/16^{-1})
Dust	Particles with a diameter of $\geq$ 10—20 μm
EEPS	Engine Exhaust Particle Sizer Spectrometer
Endotoxins	Pieces of the shell of Gram-negative bacteria
Fibres	Particles with a length/diameter ratio of least 3:1
Fugitive emissions	Emissions escaping from a controlled and regulated process
HEPA filter	High-Efficiency Particle Air filter. An air-filter which removes particles
HW	Hospital waste
Ion	An atom or molecule with more or less electrons compared to the amount of protons
MERV	Minimum Efficiency Reporting Value
MSW	Municipal solid waste
Nuclei mode	Particles smaller than 0.1 μm. Form through condensation of volatile materials
PM	Particulate Matter
ppm	parts per million (1 % = 10 000 ppm)
Rotary kiln	A cylindrical, slowly rotating vessel used to raise materials to a high temperature

Register of compounds

TOC	Total organic compound
HCl	Hydrogen chloride
HF	Hydrogen fluoride
SO_2	Sulphur dioxide
NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
CO	Carbon monoxide
Hg	Mercury
Cd	Cadmium
Tl	Thallium
Sb	Antimony
As	Arsenic
Pb	Lead
Cr	Chromium
Co	Cobalt
Cu	Copper
Mn	Manganese
Ni	Nickel
V	Vanadium
Au	Gold
Ag	Silver
F	Fluorine
Cl	Chlorine
Br	Bromine
NO_x	Nitric oxide
NH_3	Ammonia
O_2	Oxygen
N_2	Nitrogen gas
H_2O	Water
VOC	Volatile organic compound
SVOC	Semi-volatile organic compound

1 Introduction

Incineration of waste is an effective way to decrease the amount of waste that otherwise would be put in landfills. The energy content of the waste is utilized and many harmful substances are destroyed in the combustion process or removed with effective treatment methods. The waste incineration legislation is very restrictive with the purpose to minimize emissions emitted from waste incineration plants. Waste incineration in Finland has expanded during the recent years. Several plants have been constructed and a few are in the construction and planning stage. Four new plants have started their operation during the past year.

During one day, we inhale approximately 22 m^3 of air. When taking into account that we spend 90% of our time indoors, most of the air that we inhale is indoor air. The air can contain more than 34 million different chemical substances, depending on where we are moving. The environmental and health effects of many of these substances are still uninvestigated (Barro et al., 2008). Very little research has been done on indoor air in waste incineration plants. Indoor air contains emissions that can occur as fugitive emissions, which are a result of leaks in the combustion process or as indoor pollutants. Indoor pollutants are often a result of poor ventilation, high temperature and humidity. Sources of indoor pollution can e.g. be materials, cleaning products or outside air.

Westenergy waste incineration plant is a newly built power plant in Vasa, Finland, which begun its operation in 2012. The presence of dust has since then been observed inside the waste incineration building. This has raised several questions; What is the source of the dust? Is the dust a sign of leakage in the process? Is needless time spent on cleaning the dust? Can the dust negatively affect visitors and workers at the plant? Can the dust cause wear and increase maintenance costs?

The objective of this Master's thesis was to study the presence of dust i.e. particles in the indoor air at Westenergy waste incineration plant and to investigate the point sources for these. The thesis subject was considered from two different points of views; health aspects and leakage of particles in to the incineration building. The task was also to give recommendations on how to minimize particles in the indoor air.

On the basis of the obtained measurement results, the need for a continuous indoor air measurement system was investigated. A smaller part of the objective was left for detection and measurement of ammonia at the ammonia injection points. A literature study on existing research on air pollutants inside waste incineration plants was executed and studies concerning health effects of the measured substances were briefly gone through.

To keep the thesis in feasible proportions, the measurements were restricted. The deadline of the thesis restricted the duration of the measurements carried out. The measurements can be very expensive and therefore the presence of dust was only investigated visually. For the particle measurement a measurement instrument was borrowed. Particles can be divided into several different size fractions, but only particle sizes between 5.6 and 560 nm was measured due to the measurement range of the used instrument. Only the particle concentrations were measured at each point, elemental and further analyses of the particles were left out. The measurement points were restricted to areas where visitors and workers move and where suspected leakage of particles had been noticed.

2 Theoretical background

Waste has been incinerated for a long time, but first until the last decades has the harmful effects of waste incineration been known. The waste incineration process must meet stringent emission restrictions. Westenergy waste incineration plant is an example of a modern incineration plant, which fulfill all the set emission requirements. The waste incineration process will be reviewed in this chapter. An example of two emissions, whose content in the flue gas is restricted, is total dust and nitrogen oxides. These substances can have severe health effects in high concentrations and their concentration is controlled with different flue gas treatment methods, e.g. nitrogen oxides are reduced with ammonia. Particles and ammonia will be discussed further in this chapter and their health effects will briefly be presented.

2.1 Waste incineration

The burning of community waste started already in the late 19th century with the purpose of improving the hygiene in the cities. The first waste incineration plant in Europe was built in Nottingham, England year 1874. In Finland the waste incineration started in 1961, in Kyläsaari waste incineration plant in Helsinki. The harmful effects of the flue gases that originated from waste incineration were unknown in the beginning, but research done in the 1980s proved otherwise. Old incineration plants were shut down and the building of new ones stopped (Finnish Solid Waste Association, 2013). Kyläsaari waste incineration plant was shut down in 1983 due to large air emissions of soot, dust and heavy metals. Toxic compounds were later found in the fly ashes from the incineration plant (Laita, 2008). The emission limits from waste incineration were regulated in EU in 2000 by the EU Directive 2000/76/EC. The air emission limit values can be seen in Table 1.

Table 1: Air emission limit values (West Finland Regional Environment Centre, 2009)

Emission substance	Content in flue gas [mg/m^3]
Total dust	10
TOC (Total organic compound)	10
HCl (Hydrogen chloride)	10
HF (Hydrogen fluoride)	1
SO_2 (Sulphur dioxide)	50
NO, NO_2 (Nitrogen monoxide, Nitrogen dioxide)	200
Dioxins and furans	$0.1 \cdot 10^{-6}$
CO (Carbon monoxide)	50
Hg (Mercury)	0.05
Cd + Tl (Cadmium + Thallium)	0.05
Sb + As + Pb + Cr + Co + Cu + Mn + Ni + V (Other heavy metals)	0.5

Oriketo waste incineration plant in Turku was built in 1975. For a long time it was

the only incineration plant in Finland, burning 50 000 tons of waste annually. The first modern waste incineration plants in Finland started their operations in 2007–2008 in Riihimäki and Kotka. Waste incineration had yet again become interesting. In spring 2012 three waste incineration plants were in operation in Finland and five new plants were under construction, among these Westenergy. Another three incineration plants were in the planning stage. In 2010, 452 waste incineration plants were in operation in Europe and they incinerated totally 73.35 million tons of waste (CEWEP, 2011; Pöyry, 2012).

Waste incineration plants are often combined heat and power plants (CHP plants). They produce both heat and electricity. The heat produced by waste can be utilized, for example in the district heating of cities. In addition they produce electricity to the nationwide electrical grid. A ton of waste can approximately produce, 2 MWh of heat and $2/3$ MWh of electricity (Finnish Solid Waste Association, 2013).

2.2 Westenergy

Westenergy is a waste incineration plant located in the Mustasaari municipality in Ostrobothnia, Finland. The company was founded by five municipal waste management companies in the western part of Finland. The commercial energy production started in January 2013. Combustible waste from in total 400 000 people, in 50 municipalities is taken care of at the incineration plant. The combusted waste is non-recyclable waste that has been separated at its source. Recyclable materials, such as glass, metal and paper have been removed and the combustible part produces electricity that equals the demand of 7 000 city apartments. Moreover, the plant produces a third of the energy used for district heating within Vaasan Sähkö Oy's economic area (Westenergy, 2013).

Westenergy waste incineration plants incinerate approximately 20 tons of waste per hour. The total plant efficiency is about 85 % and the fuel input is 61 MW. The electricity is produced by a turbine that rotates with a velocity of 9 000 rpm. Steam produced by the boiler, is led into the turbine at a temperature of 400 C$^\circ$ and with a pressure of 40 bar. The turbine's electric capacity is 13 MW and it produces about 80 GWh of electricity annually. The district heating capacity is 40 MW and the an-

nual heat production transferred to the district heating is about 280 GWh (Westenergy, 2013).

2.2.1 Process

Most of the waste arriving to the incineration plant is ordinary household waste, but even different kinds of industrial waste can be utilized. An overview of the plant process can be seen in Figure 1.

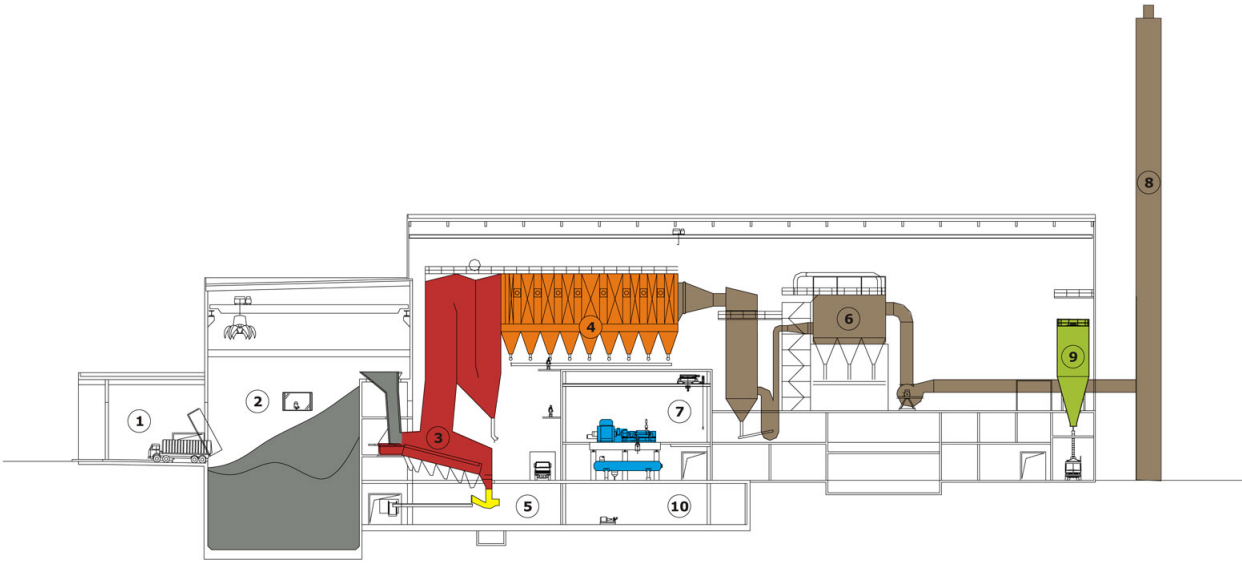

Figure 1: The plant process (Westenergy, 2013)

The waste arrives to the plant at the tipping hall (1). Waste trucks tip the waste into the waste bunker (2) that can store up to 18 000 m^3 of waste. A crane mixes the waste and lifts it from the bunker to the feeding shaft. Bigger waste parts are crushed in the crushing mill and the crushed waste is led back to the bunker prior to entering the combustion grate (3). In the combustion chamber the waste is combusted at a temperature of 1 000 C° for about one hour. Ammonia is injected into the combustion chamber to reduce NO_x emissions. The unburned ashes are taken out beneath the grate and the flue gases are led further to the boiler (4). In the boiler preheated water is vaporized and the steam is superheated to 400 C°. The pressure of the steam is 40 bar. The steam goes to the turbine (7) for energy production and is then condensed back

to water in the district heating station (10). In the flue gas treatment, the flue gases are mixed with activate carbon and slaked lime. The pollutants are removed in the bag filter (6). Finally the flue gases are led out through the stack (8). Active carbon and lime are stored in separate silos, while the combustion residues are stored in another silo (9).

2.2.2 Visitors and personnel

To date, 27 persons work at Westenergy waste incineration plant, five in the offices, 21 in the control room and one in the warehouse. The operators are working 12 hour shifts from 7 am to 7 pm and 7 pm to 7 am, the rest work the customary eight hour days. There are always three operators working on every shift. Some services have been outsourced and beside the Westenergy employees many contractors work inside the plant on a daily basis. Most of the working time is spent inside the offices and control rooms, but especially the operators move in the plant hall occasionally.

10 000 visitors are expected to visit the plant annually. The visits at the plant usually begin with a presentation. After the presentation the visitors go on a 35–45 minute tour inside the plant. Personal protective equipment as, protective helmet, shoes, reflective vest and, in some locations, earmuffs are required when moving inside the plant hall. Protective equipment is required both for workers and outsiders.

2.3 Particles

Particle pollution is a cause of natural and human activity. Natural particle sources are for example wind carried dust, pollen, soil particles and sea salt. Examples of human sources are combustion of fuels, cigarette smoking, mining, construction work and industrial processes. The main causes to particle pollution in urban areas are traffic and burning of fuels and the main sources of indoor particles are smoking, cooking and occupant movement (Morawska, 2004; Kelly and Fussell, 2012).

The particles can be divided into primary particles and secondary particles. Primary particles are discharged straight from their source, while secondary particles form in

the atmosphere as a result of chemical reactions. Examples of secondary particles are sulphates and nitrates. Sulphates and nitrates originate from the oxidation of sulphur dioxide and nitrogen dioxide and these form acids in the atmosphere. The physical properties of particles indicate the particles behaviour in the atmosphere and in the human respiratory system. The particle size is important regarding this matter. The terms $PM_{2.5}$ and PM_{10} are often used when talking about particle emissions. The numbers 2.5 and 10 tell how large the diameter of the particles are in μm. Most of the particles are nevertheless so called ultrafine particles and nanoparticles (Kelly and Fussell, 2012). There are no determined definitions for small particles, but generally ultrafine particles are defined as particles with a diameter of 0.1 μm or smaller ($PM_{0.1}$) and nanoparticles with a diameter of 0.05 μm or smaller ($PM_{0.05}$) (Harrison et al., 2003). The measured particles in this thesis will mostly be particles in the ultrafine range. The size range of some common particles in the atmosphere can be seen in Figure 2.

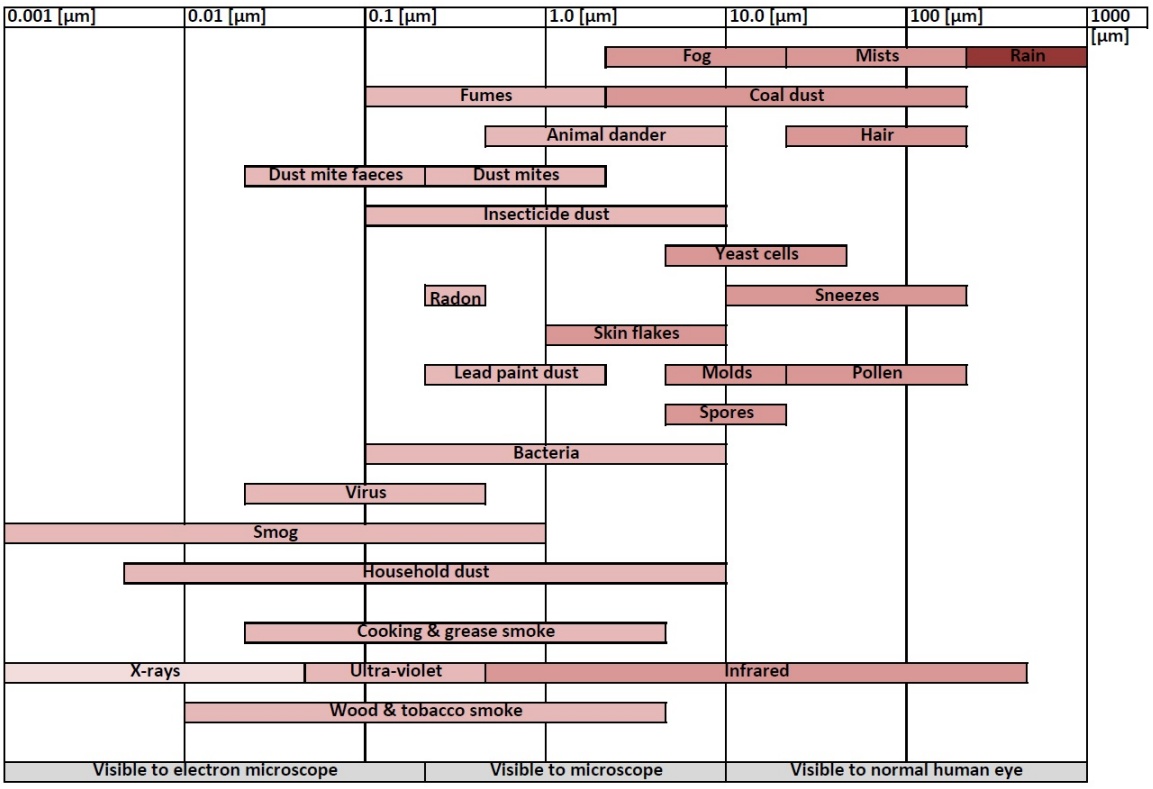

Figure 2: Size range of common atmospheric particles (Environment Agency, 2004)

Known particles sources indoor that have been investigated to emit particles in specific peak concentrations are for e.g. cooking (0.13–0.25 μm), candle and natural gas flames (0.01–0.1 μm), cleaning and smoking (< 1 μm) and walking and moving (5–10 μm) (Morawska, 2004).

Airborne particles can be divided into three different modes, transient nuclei mode, accumulation mode and coarse particle mode. Transient nuclei mode particles usually have a diameter smaller than 0.1 μm. They form through condensation of volatile materials and afterwards grow by condensation processes. The formation may take place in hot combustion gases or in metallurgical processes. Recently formed nucleation mode particles usually have a diameter of 1–2 nm, but after a fast growth the size distribution is usually 20–30 nm (Harrison et al., 2003).

Nuclei mode particles often approach the accumulation mode, which are particles with a diameter of 0.1–2 μm. Due to the low number concentration of the particles, particles in the accumulation modes do not grow further by coagulation (Harrison et al., 2003).

Particles in coarse particle mode form differently compared to the other two modes. These particles are results of mechanical wear and decomposition processes, e.g. dust and soil stirred by the wind. Particles in coarse particle mode are distinguished by particle sizes between 2 μm and up to 100 μm. Particles larger than 10 μm have a quite short lifetime in the atmosphere, due to their large mass.

Table 2: The particle size in relation to the number concentration and surface area (Harrison et al., 2003)

Particle diameter [μm]	Relative number of particles [cm^{-3}]	Relative surface area [$\mu m^2 cm{-}3$]
10	1	1
1	10^3	10^2
0.1	10^6	10^4
0.01	10^9	10^6

Airborne particles are usually measured by their number distribution or mass distribution. As Table 2 indicates, the particle number is dominated by ultrafine and smaller particles. Up to 80% of the number concentration of particles in urban outdoor air are ultrafine particles (Morawska, 2004). The mass distribution is on the other hand dominated by larger particles. For example 10^9 particles with a size diameter of 10 nm weighs as much as one particle with the size diameter of 10 μm (Harrison et al., 2003).

2.3.1 At workplaces

At a waste incineration plant potential particle contaminants can be dioxins, minerals and metals or micro-organisms and bio aerosols (municipal waste). The sources of particle emissions can be many e.g. transport of waste to and from the facility, storage of waste, handling and processing of waste or other activities around the facility (Environment Agency, 2004).

Larger particles will usually settle out as deposited dust near the source. Smaller particles may on the other hand be airborne for quite a long time and travel longer distances. Many dust removal techniques are ineffective for finer and ultrafine particles. Particles can be removed by different filters, scrubbers and by good working practices. Minimizing particle generation at the source is more effective than decreasing particles already present in the air. (Environment Agency, 2004)

Ultrafine particles

The focus of airborne particles has mainly been on the mass concentrations and thus ultrafine particles have often been forgotten. In many workplaces the ultrafine particles represent most of the number concentrations and only an insignificant part of the mass concentration. In recent years, the amounts of ultrafine particles have been investigated especially in industries with a lot of diesel-powered vehicles and research has shown a significant number of particles in the range below 0.1 μm in those areas. For example, the ultrafine particle concentrations in outdoor environments, which are untouched by human activities are often a couple of hundred particles cm^{-3}. In urban environments the background concentrations of ultrafine particles are between a few thousand up to

20 000 particles cm^{-3} and near roads and tunnels the concentration levels can be as high as 10^5 particles cm^{-3} (Air Quality Sciences, 2011).

For now, there are no standards limiting ultrafine particles in the air. Standards limiting particulate matter in the air are based on mass concentrations for certain particle size fractions (PM_{10} and $PM_{2.5}$). Future standards for ultrafine particles could be expressed in number concentration of particles (Vincent and Clement, 2003).

The chemical composition and the particle size ranges can vary widely at a workplace, depending on the workplace layout, the on-going process and the ventilation. They can roughly be distinguished as dust and sprays with particle diameters of 1 μm up to 100 μm and beyond, fumes from hot processes and combustion processes with diameters between 1 μm and 0.001 μm and bioareosols as viruses and bacteria with particle sizes of around 0.01 and 0.001 μm (Vincent and Clement, 2003).

The main sources of ultrafine particles in workplaces are hot processes involving vaporization and cooling of materials. However, these conditions are seldom met. Usually the particle size range grows larger than the ultrafine particle range, due to continuing condensation or by accumulation of small particles. Continuous condensation occurs at high vapour concentrations and accumulation occurs at high number concentrations (Vincent and Clement, 2003).

In reality, the formation of ultrafine particle occurs only in stringent physical conditions, primary particles cannot grow beyond the ultrafine range and they have to undergo minimum coagulation. To ensure this vaporizable materials have to be present at the workplace, the temperature and heat transfer needs to be sufficient and fast cooling of formed aerosols and a large temperature gradient needs to take place (Vincent and Clement, 2003).

The first condition is quite straight forward, but the other two are more abstract to handle. If the temperature or heat transfer is too low the present vapour will not nucleate and condense independently, the condensation will take place on pre-existing and usually non-ultrafine (large) particles instead. With a low number concentration the particle growth afterwards is minimized. Through rapid cooling the likelihood of nucleation and independent particle production is increased significantly. By ensuring

that the aerosols are "frozen" and do not continue growing by continuous condensation the particle size is restricted. One way to meet these earlier mentioned conditions, is heating a small amount of material with e.g. a laser beam. The high temperature and small amount of material ensures that the growth of the formed particles is limited. In view of that, the temperature gradient is sharp and further particle evolution is stopped. In most workplaces, the conditions for formation of ultrafine particles are difficult to reach, which of course should be seen as positive, in the view of their negative health effects (Vincent and Clement, 2003).

2.3.2 Health effects

Research of particle transportation and penetration in the human respiratory system has given particle size-selective criteria's for particle exposure. Inhalable aerosols are particles that can be inhaled during breathing through nose and mouth. Particles that find their way beyond the larynx and enter the lungs are so called thoracic aerosols. Particles that penetrate even further and in to the gas-exchange region are respirable aerosols. These criteria's are often represented as curves, expressing the likelihood of penetration as a function of particle diameter (Vincent and Clement, 2003).

PM_{10} and smaller particles are generally defined as respirable particles, but especially particles smaller than $PM_{2.5}$ cause problems in deep lung penetration (Burroughs and Hansen, 2011). $PM_{2.5}$ emissions present in ambient air, are estimated to cause approximately 1 270 premature deaths and 13 840 years of life lost annually in Finland and the economic loss is 1–2.9 billions every year (Salonen and Pennanen, 2006). Humans are exposed to particles through air inhalation, ingestion and skin contact. Particles suspended in the air enter organisms through inhalation, while deposited particles are exposed through skin contact and ingestion (Environment Agency, 2004).

It is often the size of the particle that determines the health risk of the particles. Smaller particles are breathed deeper into the lungs and they can pass the defence mechanisms of the respiratory system. Smaller particles also stay suspended in the air longer and the likelihood of inhaling them is thus greater. Compared to the total mass ratio, smaller particles have a large surface area, which could be seen in Table 2. Other

contaminants, such as PCB, pathogens and pesticides, can be attached to particles and the smaller the particles are, the larger surface area for contaminants to attach to and the more contaminants are transported deep into the respiratory system (Burroughs and Hansen, 2011).

Symptoms associated with exposure of respirable particles are irritation and infections in the respiratory tract and eye irritation. Symptoms and health effects related with tobacco smoke can also be associated with particle exposure, e.g. lung cancer. Depending on contaminants attached to the inhaled particles, health effects associated to these contaminants can also be related to respirable particles. At particle concentrations of 250–350 μgm^{-3} the respiratory symptoms of exposed individuals increase (Burroughs and Hansen, 2011).

Correlating the particle mass concentration in air to caused health effects is not suitable for ultrafine particles and nanoparticles. The toxicity of these small particles can be higher per unit particle mass than for fine particles, because of the larger total surface area. To quantify the exposure to ultrafine particles and nanoparticles more suitable metrics are, particle number concentration and particle surface area (Cernuschi et al., 2012).

2.3.3 Measurement methods

There are several methods for collecting and measuring airborne particles. The challenges with the measuring are the big variety of particle sizes, particle forms, particle composition and particle concentration. There is no device that could cover all the measurable features and sizes. To obtain an overall picture of the particles present in the air, several instruments are needed for the measurement. Different instruments take advantage of different particle physical characteristics, e.g. light scattering, sedimentation and electric charge (University of Helsinki, 2013).

The particle mass concentration can be measured with different particle collecting systems. The simplest collecting method is filter cups. The cups are weighted before and after the particle sampling and the mass difference is the amount of particles collected during the sampling. The mass concentration can be calculated from the

weighted mass difference and by knowing the air flow through the filter cups. Different particle sizes cannot be distinguished with this method. With cyclones larger particles can be cut off due to gravitational settling and they will not reach the collecting filter. In this way it is possible to sample particles under a certain size (Molnár, 2011).

With a cascade impactor the particle sizes can be separated further. A number of impactor stages are combined in series with smaller and smaller cut-off diameter. It is however challenging to get a sharp cut-off and some particles may bounce between stages. The air flow and the geometry of each stage determine the cut-off diameter. The first stage can have a cut-off diameter of 10 μm and the last stage can cut-off particles with a diameter of 0.1 μm or smaller (Molnár, 2011).

Particle counters are better to use for measurement of particle size distribution. The Aerodynamic Particle Sizer (APS) counts and measures the size of particles in the size range of 0.5–20 μm. The APS uses the particles light scattering and settling velocity properties for the measurement (Molnár, 2011).

The condensation particle counter (CPC) can measure particles in the size range of a few nanometres up to one micrometre. Particles this small can however not be detected optically and therefore the particles sizes are increased by letting them pass through evaporated alcohol. The alcohols attach to the particles and make them larger. The particles cannot be size distinguished with this method. The instruments Differential Mobility Particle Sizer and Scanning Mobility Particle Sizer uses the same method as the CPC, but an apparatus controlling the size fraction of the particles that are lead in to the evaporated alcohol determine the particle size and thus both the particle size and amount can be measured (Molnár, 2011).

Charged particles have an electric current that can be measured with an Electrical Low Pressure Impactor in every impactor stage. With the instrument the particle size distribution and particle concentration is measured in real time. A Tapered-Element Oscillating Microbalance instrument measures the mass concentration of particles by frequency changes in the oscillation caused by changes in the sampled mass (Molnár, 2011).

The first instrument that can measure both the size and determine the chemical

composition of particles in real-time is the Aerosol Time Of Flight Mass Spectrometer. It can measure and analyse particles in the size range of 0.3 to 3 μm. Other methods that can be used for analysing the elemental composition of collected particles are e.g. X-Ray Fluorescence spectrometers, Atomic Absorption Spectrometry, Neutron Activation and Ion Chromatography (Molnár, 2011).

2.4 Ammonia

Ammonia is a colourless, irritating and a very sharp smelling gas. The gas can easily be liquefied to a colourless liquid. In room temperature ammonia exist in gas form due to a low boiling point (-33C°) and because of a lower density, the ammonia gas is lighter than air. Ammonia reacts rapidly with acids and oxides, releasing heat in the reaction process. The ammonia gas can be explosive when reacting with metals (Au, Ag, Hg) and halogens (F, Cl, Br) (Occupational Health, 2011).

Ammonia injection is a part of the flue gas treatment at Westenergy waste incineration plant. In the selective non-catalytic reduction (SNCR) process ammonia is injected to minimize nitric oxide (NO_x) emissions from the plant. A water based ammonia solution, containing 24.5% of ammonia is injected into the post-combustion chamber at flue gas temperatures between 850C° and 950C°. Because of fluctuating temperatures in the combustion chamber the ammonia can be injected at different injection levels. The temperature in the chamber is measured by IR radiation pyrometers. Ammonia can be injected at four different heights on both sides of the combustion chamber. The measured temperature determines at which level the ammonia will be injected (Hitachi Zosen Inova AG, 2012).

Due to the chemical reactions at different temperatures the ammonia has to be injected at the right temperature intervals. If the temperature is higher than 950 C°, more ammonia will be burnt and will not be used for the reduction of NO_x. At temperatures below 850 C° the reactions are slow and ammonia leftovers remain in the flue gas (Hitachi Zosen Inova AG, 2012).

2.4.1 Health effects

The limit values for ammonia, set by the Ministry of health and social affairs are 20 ppm for an 8 h average and 50 ppm for an 15 minutes average (Ministry of Social Affairs and Health, 2012). The gas can be smelled at concentrations between 5 ppm and 50 ppm, but the sense of smell is not recommended as a warning signal. The symptoms of ammonia gas exposure are irritation in the respiratory tract and eye irritation. The irritation and injurious effects begin at concentrations of 20–25 ppm (Occupational Health, 2011).

Liquefied ammonia can cause etching and frostbites on the skin. High ammonia gas concentrations also bring on skin irritation. Ammonia does not accumulate in the organs, it is ejected from the body through perspiration and urine (Occupational Health, 2011).

2.5 Temperature and humidity

A comfortable environment for dwellings has generally been defined by temperature, humidity and "fresh" air. When certain comfort levels are exceeded, temperature and humidity can negatively impact air quality and be harmful to human health. These comfort factors of temperature and humidity can also affect contaminants present in indoor air (Burroughs and Hansen, 2011).

It is difficult to determine a comfortable temperature, because a comfortable temperature for one person may not be the same temperature for another. Recommended temperatures are usually between 20 C° and 23 C° in winter and between 23 C° and 25.5 C° in summer. Investigations show that productivity and certain health considerations are best met in the lower temperature ranges (Burroughs and Hansen, 2011).

Relative humidity is expressed as the amount of water in the air compared to the amount of water the air maximum can hold at a given temperature. The relative humidity affects the body's temperature regulation by affecting the evaporation of the body through the skin. The comfortable temperature is thus also affected by the relative humidity of the indoor air. The water content in the air can significantly affect the con-

centration of many contaminants present in the air, e.g. particles are suspended longer in dry air and the probability of inhaling them increases. Productivity and performance are most effective in the relative humidity range 30–60%, which are typical values for relative humidity indoors (Burroughs and Hansen, 2011).

3 Previous research concerning the subject

Little research has been done on indoor air quality in the buildings of waste incineration plants. Three investigations dealing with different chemical substances in indoor air at waste incineration plants are presented in this chapter and one investigation considering particle concentrations inside two coal-fired and a gas-fired power plant in the USA. Any investigations discussing the presence of ultrafine particles in indoor air at waste incineration plants could not be found, but some comparisons with the coal-fired power plants can be made.

Mercury concentrations in ambient air at two incineration plants in China (Liu et al., 2009; Ministry of Social Affairs and Health, 2012)

The mercury concentration in ambient air is usually below 0.001 $\mu g m^{-3}$. Considerable amounts of Mercury can be found in municipal solid waste (MSW), because of electrical and electronic equipment. The indoor air mercury content in a MSW incineration plant and in a hospital waste (HW) incineration plant in China was examined. The mercury concentration was investigated as gaseous elemental mercury, reactive gaseous mercury, particulate mercury and mercury concentration in indoor dust. Air samples were taken in the MSW pit, HW depot, workplaces and operation centers. A total of 12 air samples were taken for each site during summer and wintertime. The highest mercury concentrations in the MSW incineration plant in winter were found in the workplace and operation centre. In summer the highest concentrations were measured in the MSW pit. The mercury concentrations measured at all sites in the MSW incineration plant were less than the given recommendations for industrial workplaces. The highest total mercury concentration was measured to be 1.334 $\mu g m^{-3}$. The limit

value in Finland is 20 $\mu g m^{-3}$ for an 8 h average.

In the HW incineration plant higher mercury concentrations were detected. The highest concentration was measured in the HW depot, where the total mercury concentration reached 3.397 $\mu g m^{-3}$. Much higher concentrations were measured in the winter, due to frequent ventilation during summertime. The cause of the higher concentration in the HW incineration plant compared to the MSW incineration plant is the waste, which contains more mercury, e.g. thermometers and fluorescence lamps. Given recommendations for minimizing mercury exposure are; the indoor dust should regularly be cleaned, the ventilation should be frequent and the mercury sources should be removed before incineration.

Analysis of chemical substances at a hazardous waste incineration plant in Turkey (Bakoglu, Karademír, and Ayberk, 2004)

The concentrations of PM, heavy metals, VOC and SVOC and dioxins were analysed at a hazardous waste incineration plant in Turkey. Workers at the plant had complained about fugitive emissions that had been leaking at some connection points. The samples were collected at two sampling points, in the front area of the rotary kiln and near the conveyor belt of the fly ash to the ash silo. These points were chosen because maximum exposure was expected to occur there. The sampled PM and heavy metal concentrations were below settled exposure limits at both sampling points. The samples showed that most of the heavy metals were present in the air in gaseous form. The amount of heavy metals in the air in front of the rotary kiln was mostly a cause of leakage during waste feeding. Zinc had the highest concentrations of all the metals.

Some of the organic chemicals had higher concentrations in the ambient air than the health limits. Because the workers are exposed to many different chemical substances, their effects could be additive. Further investigations on occupational health effects should be made at the plant.

Investigation of harmful factors in the work place air at the Oriketo waste incineration plant (Tolvanen and Hänninen, 2005)

At the Oriketo waste incineration plant in Turku, Finland, the harmful factors; microbes, endotoxins, dust, volatile and odorous compounds and noise were investigated in the work place air between 1998 and 2001. The harmful factors were investigated in three working areas at the incineration plant. The plant had incinerated waste since 1975. In 1995 it was renovated to meet stringent emission requirements.

Samples were collected from the combustion area, the bunker and the crane room. The highest number of microbes was found in the bunker, where the number of viable microbes was alarming. The limit values were clearly exceeded. Also the limit value for endotoxins was exceeded in the bunker. The endotoxin concentrations were found to be so high that they could be detrimental to health. Even in the combustion area the endotoxin concentration levels were elevated from time to time. The dust concentrations varied depending on the waste quality. Sometimes the work places were very dusty, but the threshold value of 5 mgm^{-3} (for 8 h) was never exceeded. The fibre concentration was only slightly exceeded in the bunker.

It can be concluded that problems with occupational health at the waste incineration plant occurred in the bunker. All measured species exceed their limit values in the bunker. In the combustion area the endotoxin concentration was at times harmful and the noise level higher than recommended. Problems with the noise level were also occasionally found in the crane room. Ear protectors were recommended to use at least in the bunker and the combustion area. The use of a respirator was advised when staying in the bunker.

Particles at coal- and gas-fired power plant work areas (Hicks et al., 2011)

Presence of ultrafine and fine particles at workplaces in three power plants in the United States was examined. The Environmental Protection Agency has been examining the effects of ultrafine particles on health for several years and research has shown that ultrafine particles cause oxidative stress and penetrate tissues that larger particles can-

not go through. Studies examining coal fly ash have been conducted at laboratory scale, but no studies have been conducted at workplaces in real power plants. The chosen plants for the investigation were two multi-unit coal-fired plants and one modern multi-unit gas-fired plant. These plant types represent the vast majority of power plants in the United States. The capacities for the coal-fired plants are 2 000 MW and 2 500 MW respectively and the capacity for the gas-fired plant is 500 MW. Different real-time instruments were used for the measurement of airborne particle. Measurements were carried out at locations where workers are likely to move around during common maintenance tasks, along with measurements carried out at offsite upwind locations. Measurement points inside the power plant were the turbine building, near the combustion chamber, control rooms, fly ash areas and yard areas.

The particles were measured in the range of 20–1000 nm, but most particles were found to be in the 20–500 nm range. The highest particle concentrations were measured near the combustion chamber at both coal-fired plants, which were thought to be a result of leakage of combustion emissions. The control rooms had the lowest particle concentrations; consequently the ventilation and air conditioning system efficiently removes particles from the air in the control rooms. The lowest particle concentrations, expect the control rooms were found in the gas-fired plant, which can be a cause of the young age of the plant and the combustion process. In the list below you can see where most particles were found in the coal-fired power plants and the gas-fired power plant.

Coal-fired power plant	**Gas-fired power plant**
1. Combustion chamber	1. Heat recovery
2. Fly-ash area	2. Turbine areas
3. Turbine building	3. Yard areas
4. Control room	4. Control room
5. Offsite upwind locations	5. Offsite upwind locations

The highest concentrations measured at the power plants equalled concentrations measured at busy vehicle motorways in southern California (10^4 to $2 \cdot 10^5$ particles cm^{-3}). The results of the measurements are summarized in Table 3. Plant 1 is the coal-fired plant with a positive pressure boiler i.e. the pressure inside the boiler is higher than the surroundings pressure. Plant 2 is a balanced draft boiler, the pressure in the boiler do not significantly differ from the surroundings. Plant 3 is the gas-fired power plant.

Table 3: Summary of particle concentrations in the range of 20–1000 nm at studied power plants in the US (Hicks et al., 2011)

Location	**Concentration range [p cm^{-3}]**	**Mean [p cm^{-3}]**
Plant 1 (turbine building)	1002 – 36 094	10 979
Plant 1 (combustion chamber)	1466 – 197 404	70 713
Plant 1 (fly ash areas)	2406 – 43 585	16 855
Plant 1 (control rooms)	57 - 6402	3352
Plant 1 (yard areas)	1017 – 16 163	8783
Plant 1 (welding)	47 225 – 65 068	58 070
Plant 1 (upwind)	549 – 4147	1492
Plant 2 (turbine building)	13 005 – 25 946	19 445
Plant 2 (combustion chamber)	269 – 198 149	59 533
Plant 2 (fly ash areas)	9277 – 53 461	20 308
Plant 2 (control rooms)	2350 – 3843	3293
Plant 2 (upwind)	4843 – 26 442	15 148
Plant 3 (combustion turbine)	7536 – 26 600	14 972
Plant 3 (heat recovery work areas)	7186 – 114 410	18 946
Plant 3 (steam turbine work areas)	9704 – 34 001	19 205
Plant 3 (control room)	8701 – 11 763	10 717
Plant 3 (yard areas)	6296 – 38 716	17 964
Plant 3 (upwind)	5393 – 28 921	8687

To better understand the exposure to workers at coal-fired power plants more studies with chemical and physical characteristics analysis would be useful and also studies of the workers' health would be an aid in reflecting the human responses to particle emissions.

4 Measurement strategy

For the measurements to be carried out at Westenergy waste incineration plant a measurement program was designed. The measurement program describes how the measurements will be executed. By designing a measurement program, all the aspects of the measurements to be done are taken into consideration and good planning makes the execution of the measurements easier. Decisions considering what, where and when to sample have to be made in the measurement program. The sample time, the amount of samples and which methods and techniques to use are other issues that have to be solved. (Environment Agency, 2004).

In many cases, standards describing the measurement procedure can be found. The results of the measurements are more reliable if the measurement strategy is based on a standard for the measurements in question. SFS-EN 482 standard, "*Workplace exposure. General requirements for the performance of procedures for the measurement of chemical agents*", specifies general performance requirements (Finnish Standards Association (3), 2012), while the SFS-EN ISO 28439 standard, "*Workplace atmospheres. Characterization of ultrafine aerosols/nanoaerosols. Determination of the size distribution and number concentration using differential electrical mobility analysing systems*", provides guidelines for the determination of the amount and size distribution of ultrafine and nanoparticles in workplace atmospheres (Finnish Standards Association (2), 2011). In Table 4 the measurement questions that will be followed are summarized.

Table 4: Measurement program

What to measure?
Which species fulfil the objective?
In what form should the species be measured?
Is the total amount sufficient or should specific fractions be measured?
Is further analysis of single species required?
Where to sample?
Position relative to study area or emission source?
When to sample and for how long?
Continuous or intermittent sampling?
Average sampling time set in air quality regulations?
Longer programmes give more representative results
Are there variations in the measurement conditions?
How to measure?
Is the measurement quantitative or subjective?
Is the measurement in situ or remote?
What is the sampling method?
Which uncertainties should be noticed?
Analysis?
In which units should the results be presented?
How to present the results to gain a meaningful interpretation?

4.1 What to measure?

The first step is to target what pollutant to measure. In this case particles, dust and ammonia are the pollutants of interest. When the pollutant to measure is known, the form in which the pollutant will be measured should also be determined. Many pollutants exist in both gaseous and particulate phases. (Environment Agency, 2004).

Due to restrictions in the objective, ammonia will only be measured in its gaseous phase. The objective is to detect possible ammonia leakage and thus it is only of interest to measure enhanced ammonia concentrations in the air. The limit values for ammonia are set at 20 ppm for an 8 h average and 50 ppm for a 15 minutes average. (Ministry of Social Affairs and Health, 2012) The EN 482:2012 standard defines the measuring range to be 0.1 to 2 times the limit value for long-term measurements, therefore the measuring range of ammonia should be 2–100 ppm (Finnish Standards Association (3), 2012).

Dust exists in the form of particles and will be measured in the particulate phase. Particles will be measured in different sizes. Particle sizes between 5.6 and 560 nm will be monitored and the total concentration between these sizes will be calculated. The restrictions in the particle sizes to be measured are set by the used instrument, Engine Exhaust Particle Sizer (EEPS) Spectrometer. Simultaneously with the particle measurement temperature and relative air humidity will be monitored.

No limit values exist for the particles to be measured. Limit values set for PM_{10} and $PM_{2.5}$ are based on the mass concentration in the air. With the EEPS Spectrometer only the number concentration in different size fractions can be measured accurately. The measurement of mass concentration, surface area and volume concentration are based on assumptions that all the particles are spherical and have a specified density (TSI (1), 2009). It has been pointed out before (Table 2), it is the number concentration that is important when measuring ultrafine and nanoparticles and therefore only the number concentration of different size fractions will be monitored, but estimated mass concentrations, volume concentrations and surface area concentrations could also be calculated.

The measuring range should cover the whole size distribution of ultrafine particles at the workplace. Previous research has shown that most of the particle number size distributions lie between 10 nm and 500 nm. The measurement range of the EEPS instrument is therefore suitable. The total number concentration of particles between the range of 10 nm and 500 nm for clean air sections at workplaces or urban background has been found to be 10^3 particles cm^{-3} and in welding plumes 10^8 particles cm^{-3} (Finnish Standards Association (2), 2011).

4.2 Where to sample?

Because no limit values for the particle sizes to be measured or for deposited dust exist, the measurements will be screening measurements with variations in time and space. The meaning of screening measurements is to provide likely patterns for the concentrations of substances in the air, identify locations and periods of elevated exposure and provide information about the sources of the emissions. The purpose of the measurements is to obtain crude and quantitative information about substances in the air and the possible exposure levels (Finnish Standards Association (3), 2012).

To gain an understanding of the exposure to workers and visitors at the plant the particles should be sampled in the breathing zone, that can be estimated to approximately 1.5 meter above the floor. If the working place is not stationary, the samples should be taken from different locations by moving the measurement instrument. Especially when measuring the number concentrations of ultrafine and nanoparticles the contribution of background particles can be high and variable. When sampling particles, the chosen sampling point should be well away from walls and obstacles to avoid aerodynamic effects (Finnish Standards Association (2), 2011).

In this case the sampling points have been chosen according to where visitors move and where the presence of dust has been noticed at the incineration plant. A background measurement of the outside air should also be carried out to investigate the background contribution. No upwind or downwind points are required due to assumed minimal air movement inside the plant. The same sampling points were chosen for the investigation of dust accumulation.

The placement of the ammonia gas monitors depends on the purpose of the measurement. Ammonia gas is lighter than air and rises upwards. The monitoring should therefore take place just above the possible leak source. If health effects are also taken into consideration, the monitoring should also be carried out at breathing height. In this case two ammonia gas monitors should be put at the first ammonia injection level on the fourth floor on both sides of the combustion chamber. The gas should be monitored at breathing height since visitors walk by the injections nozzles on this floor. Two gas monitors on each side could also be put above the highest ammonia injection point on the seventh floor, because the ammonia gas rises upwards. Both health effects and leakage are then considered in the monitoring.

4.2.1 Measurement points for particles

The measurement points for measurement of particles with the EEPS is shown in Table 5 and the locations inside the incineration plant are illustrated in Figure 3. The measurement points are more thoroughly described in Chapter 5.2.1.

Table 5: Points for particle measurement inside the incineration plant

Name	Point location
Boiler room D1U_55 R01	1. Balcony 9th
Boiler room D1U_52 R01A	11. Boiler 8th
Shredder D1U_30 R01	10. Crushing Mill 4th
Shredder D1U_30 R01	2. Ammonia injection 4th
Flue gas hall D1U_30 R03B	4. Fluegas Silos 4th
Flue gas hall D1U_30 R03B	3. Fluegas cooling 4th
Mechanical workshop D9_U19 R05	8. Ground corridor 2nd
Service shaft D1U_19 R01	9. Ground hatch 2nd
Bottom ash hall D1U_12 R01	13. Ash hall 1st
Mechanical warehouse D1U_25 RO5A	12. Warehouse 3rd
Control Room	14. Control Room 4th
Office	Office 3rd
Flue gas hall D1U_30 RO3B	7. UnderBoiler
Flue gas hall D1U_30 RO3B	5. MiddleBags
Flue gas hall D1U_30 RO3B	6. UnderBags
Outside	Parking spot

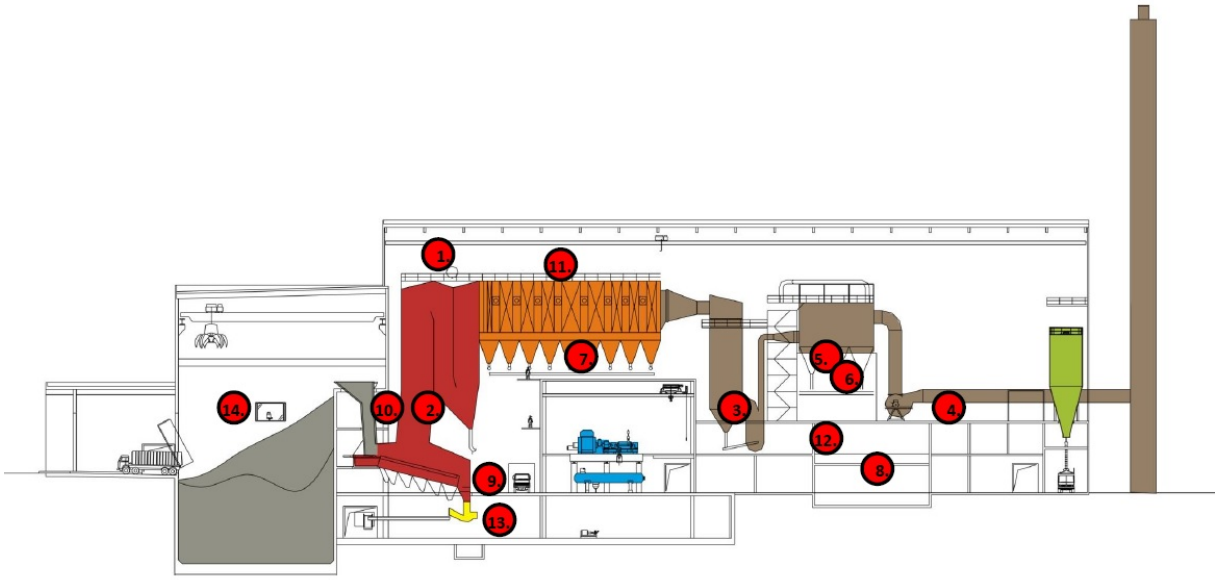

Figure 3: Particle measurement points (Westenergy, 2013), modified Skog 2013

4.3 When to sample and for how long?

At this stage two issues have to be taken into account; the duration of the whole program and continuous or intermittent sampling (Environment Agency, 2004). Issues that usually affect the length of the measurement program are weather conditions and work patterns. In this thesis most of the measurements will be made at normal operation and since most of the measurements are carried out indoor, the weather conditions can be ignored. Nor do the work patterns have to be considered because the plant operates continuously. No regulations of limit values exist, thus no average time has to be taken into account.

In the SFS-EN 689 standard for "*Workplace atmospheres. Guidance for the assessment of exposure by inhalation to chemical agents for comparison with limit values and measurement strategy*", guidelines for sampling duration and minimum number of samples per shift required for a homogeneous working period are given, see Table 6.

Table 6: Guidelines for sampling duration and minimum number of samples per shift (Finnish Standards Association (1), 1995)

Sampling duration	Minimum number of samples per shift
10 s	30
1 min	20
5 min	12
15 min	4
30 min	3
1 h	2
$\geq$ 2 h	1

With the EEPS instrument the maximum duration for the measurements is 90 minutes. According to the ISO 28439:2011, the sampling with a particle sizer is typically done in 3–6 minutes (Finnish Standards Association (2), 2011). By combining the two standards and the given measurements instructions a representative sampling time of 10 minutes is chosen, of which 7 minutes and 50 seconds will be used for the analysis. According to the EEPS measurement instructions the sample is most representative in the middle of the sampling time. Thus, a total of 60 samples will be collected during the 10 minute sampling time and 48 of these samples will be analysed. The instrument could be set for measuring ten minutes once in an hour for twelve times, then the workers 12 h shift would be covered and the guidelines in EN 689 fulfilled. The EEPS can be set to measure continuously by specifying a delay time between each run (TSI (1), 2009). The differences between times and shift should not vary because of the continuity of the combustion process at the incineration plant. The duration of the exposure can be evaluated through the sampling periods chosen above. The residence time for visitors at different points inside the plant is usually five minutes. With shorter sampling times the instrument's service interval is also increased and time is spared in the long run.

Looking back at the first statement in this chapter this will thus be an intermittent

measurement, because of the instruments restrictions and lack of limit values. The duration of the program depends on the amount of measurement points. Due to the time limit the measurement program will be no longer than one month, see the time schedule in Appendix A. The seasons do not affect the measurements indoor, but to obtain background measurement from the outside, temperature should be around +10 °C due to the temperature ranges of the EEPS.

The process at the incineration plant will be shut down for a couple of days in the middle of March due to cleaning of the plant. During that time no samples can be collected. After the shutdown some samples at different points inside the plant should be taken to see if any differences can be distinguished. The ammonia concentration will be continuously monitored to immediately detect leakage in the process, which means automatic real-time sampling. For measurement of the dust accumulation, see chapter 4.4.

4.4 How to measure?

To obtain reliable results and results that correspond to the objective, the method, technique and equipment used for carrying out the measurements should be suitable and standards describing the measurement procedure should be followed. When choosing the equipment, issues to consider are the costs, mobility, and accessibility and needed accuracy. The measurements carried out at the waste incineration plant will be done at different points inside the plant. Thus the mobility is an important issue. Cost and accessibility are other issues that have to be considered (Environment Agency, 2004).

For the dust measurement, no instrument or standard has been obtained. The dust accumulation will only be done visually. This is however, the easiest and cheapest method to detect presence of dust indoors (Environment Agency, 2004). Visual dust measurement will be done by cleaning some railings inside the power plant and following how much dust deposits on the cleaned parts in seven days. Depending on how much dust occurs during these days, the same test will also be done by putting out pieces of contact plastic and follow up how much dust these plastic pieces absorb.

4.4.1 Engine Exhaust Particle Sizer (EEPS) Spectrometer

For the monitoring of fine, ultrafine and nanoparticles, an Engine Exhaust Particle Sizer (EEPS) Spectrometer Model 3090 instrument will be used. The instrument manual, the ISO 28439:2011 standard and given measurement instructions will be followed during the measurements. The EEPS delivers results with a high accuracy. The instrument is originally designed for measuring of particles emitted from internal combustion engines and vehicles, but experience has shown that it can be used for measurements of indoor air if the concentrations of particles in the air are high enough. The instrument is not sensitive enough at low concentrations. For successive indoor measurements, it is important that the instrument's electrometer's zero level is low and that the instrument's sampling line is as short as possible and has the same length for every sample (E-mail correspondence 12.2.2013 with Panu Karjalainen, Tampere University of Technology).

The particle sizer is primarily used for measurements of particles emitted from an off-road engine in the engine laboratory in Technobotnia Research Centre. The instrument is owned by the University of Vaasa.

The EEPS measures particle sizes from 5.6 to 560 nm, which mean particle sizes ranging between 0.0056 and 0.560 μm. Fine particles are particles with a diameter smaller than 2.5 μm, ultrafine with a diameter smaller than 0.1 μm and nanoparticles with a diameter smaller than 0.05 μm. The defined range for ultrafine particles will be covered completely, while the fine and nano ranges only will be partly covered. The measurements are electrical-based, developed on instruments as the Electrical Aerosol Analyzer and Electrostatic Classifier (TSI (1), 2009).

The EEPS sampling line has to be electrical conductive, so that the particles are neutralized prior entering the instrument, for example tubes made of Tygon could be used. The particles enter the EEPS through a pre-separator, a cyclone with a 1 μm cut at a flow rate of 10 l/min. The cyclone removes particles that are too large for the instrument's size range. After the cyclone, the particles pass through an electrical diffusion charger and ions are generated. The ions are mixed with the particles and electrically charge them. The charge level of the particle depends on the particle size.

The charger is located at the top of the instrument. See Figure 4 (TSI (1), 2009).

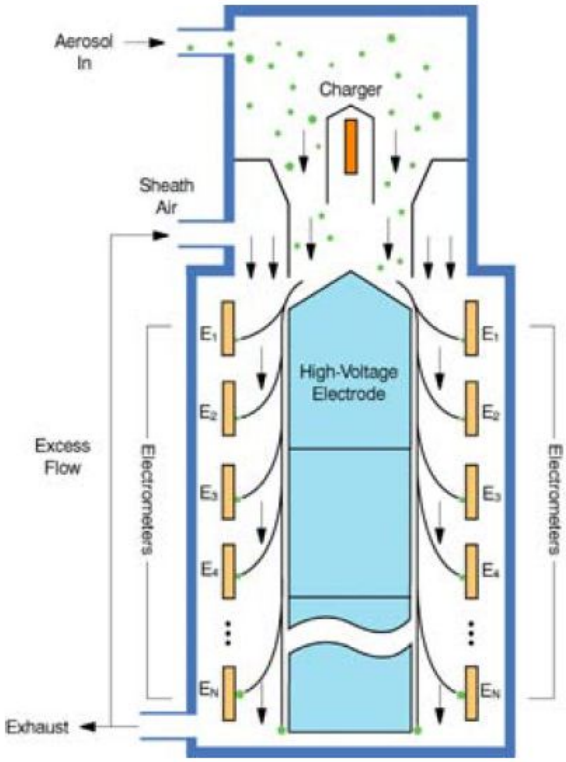

Figure 4: The function of the EEPS (TSI (1), 2009)

The next stop for the particles is the sizing region, called differential electrical mobility classifier (DEMC) in the ISO 28439:2011 standard (Finnish Standards Association (2), 2011). The sizing region is the space between two concentric cylinders. An electric field is created between the two cylinders by sensitive charge amplifiers and electrodes in the outer cylinder and a positive high voltage supply in the inner cylinder. The positively charged particles stream through the sizing region. The particles are repelled from the high voltage electrode and are drawn towards the sensing electrodes. When the particles land on the sensing electrode they transfer their charge and a current is generated. The current is amplified by an electrometer (particle detector) and is then read by a microcontroller. Ten particle size distributions can be obtained every second (TSI (1), 2009). The majors parts of the EEPS are shown in Figure 5.

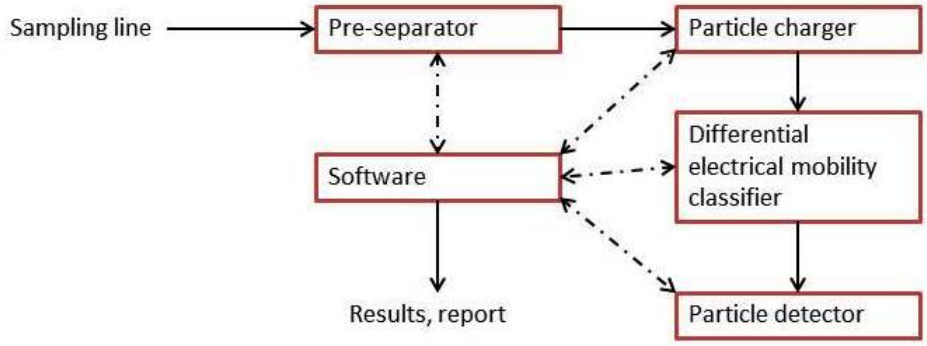

Figure 5: Block diagram of the EEPS major parts

The EEPS instrument is totally automated and a data analysis can be made with a EEPS customized software. With the software collected and stored data can be displayed with graphs and tables, the data can be exported to other applications for e.g. Microsoft Excel. An example of the appearance of the software is shown in Figure 6 (TSI (1), 2009). Before starting the measurement, a zero check of the instrument must be performed i.e. a calibration. The calibration is done by inserting HEPA filters to the sampling line and starting the zero check of the electrometers from the software. The zero check should be carried out before the start of every new measurement (TSI (1), 2009).

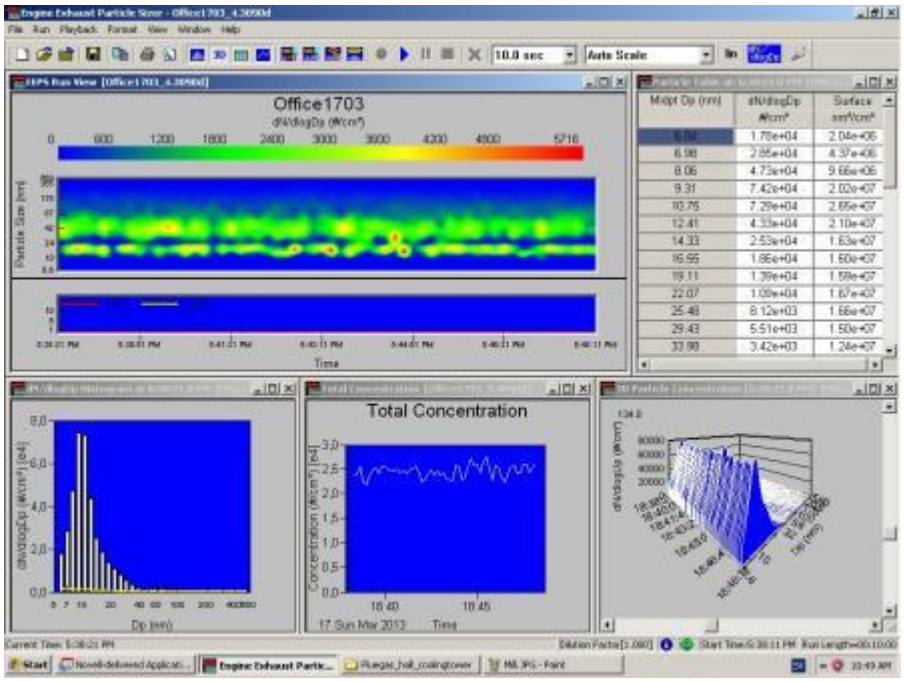

Figure 6: The office measurement viewed in the software

4.4.2 Ammonia gas measurement

The objective was to find a suitable ammonia gas meter for the detection and measurement of ammonia at the ammonia injection points in the combustion chamber. A few requirements were set up to find a meter which fulfils this purpose. The meter should detect concentrations in the range of 2–100 ppm, it should monitor continuously, it should be fixed and preferably wall-mounted, it should be able to cooperate with different software and it should have options for high and low alarm.

Ammonia is used in the production of household cleaners, refrigeration units, fertilizers, explosives and other chemicals. Ammonia is produced by humans and animals in the intestinal tracts and it is released in the urine (Yamada et al., 2012). Gas sensors detecting ammonia are therefore often used in chemical and industrial factories and in animal farms, such as poultry and dairy buildings.

The ammonia injection system at Westenergy waste incineration plant has a system alarm that goes off in case of malfunctions. Too low or too high pressure in the ammonia water feed pipes cause an alarm. Too low pressure may be an indication

of ammonia leakage in the pipes. Ammonia gas sensors which could be used at the plant and which fulfill the set requirements should be investigated, but the installation of these sensors will not be carried out in this thesis since an alarming system already exists at the incineration plant. If the need of an automatic real-time ammonia measurement system arises in the future, the sensors that will be investigated are an alternative. The sensors are briefly introduced below. The requirement of a low alarm and high alarm threshold is set because of the set limit values of 20 ppm and 50 ppm. The 20 ppm could be the low alarm concentration and 50 ppm the high alarm concentration (Hitachi Zosen Inova AG, 2012).

AirAware

AirAware is used for environmental air monitoring at critical areas that require continuous monitoring. It can be used for twelve different gases including NH_3. The AirAware can be configured to function as a monitor, controller or transmitter depending on the customers need. It can communicate with external controllers and relays can be added to turn on warning sirens or shut down processes. AirAware can measure ammonia ranges between 0 and 200 ppm (AirAware, 2012).

Murco

Murco Gas Sensors (MGS) can detect a wide range of different gases. The sensors can be used on a stand-alone basis or integrated with controls and building management systems. MGS can be installed to new buildings/areas or to already existing systems. Gases that can be detected by MGS are refrigerant gases, combustible gases, toxic gases and volatile organic compounds. Different sensors can be chosen, e.g. electrochemical, semiconductor or infrared sensors and depending on the sensor the measurement range of ammonia varies between 0 ppm and 10 000 ppm (Murco, 2012).

Kingsky

Two suitable Kingsky ammonia monitors were found, one with a display and one without (KB-501). The alarm thresholds are set at 25 ppm and 50 ppm, but the values can be manually adjusted. An electrochemical sensor detects the ammonia gas by ppm and the detection range is 0–100 ppm. It is possible to connect the monitor to a distributed control system directly (Kingsky (1), 2013).

The KB-501SG monitor can translate the target gas concentration signals into digital signals which are shown on a display. It has the same features as the KB-501, but with a display and the possibility to connect to sound and light alarms. A remote control is an optional unit. Both monitors are wall mounted. (Kingsky (2), 2013)

4.4.3 Temperature and humidity measurement

For the measurement of temperature and relative humidity, a temperature and moisture logger Model ST-171 was purchased. The logger works with a battery and measures the temperature, relative humidity and the dew point at the point where it is placed. After the measurement, the data can be obtained through a USB port and the data can be saved. The measurement interval of the logger is adjustable between 2 seconds and 24 hours (Elma Instruments, 2012).

4.5 Analysis

The obtained results should be presented in an understandable way and they have to be presented so that they can be tied back to the objective. Because no limit values exist, the results should be compared to other research dealing with measurements of small particles. The results have therefore been presented in a way making them comparable to other investigations. When analysing the particle size fractions, the number distribution should be given in the form dN/dlogDp (particles cm^{-3}), to get different instrument settings comparable. The number size distribution can be presented in different ways (Finnish Standards Association (2), 2011).

For the investigation of possible emission sources, comparisons of the total number concentration between the different measurement points have been presented. Also the average size distribution and the total number concentration have been determined for different reference periods and exposure times have been calculated (Finnish Standards Association (2), 2011). In the analysis, the results have been interpreted and variations explained.

To somehow form an opinion on the amount of dust accumulated at the different points inside the plant, an accumulation scale was set up. Previous conducted studies in offices have resulted in an average of approximately 3% surface area coverage after one week of dust accumulation. The investigated offices were cleaned once a week and measurements were carried out before the cleaning (Kildeso et al., 1999). The dust analysis results were compared to accumulations in the office and according from that a scale was planned.

4.5.1 Normalized concentrations

The concentration value of a size distribution is usually estimated by the concentration in the peak bin. Instruments measuring small particles have different resolutions. If the results are compared to other results measured at the same point and at the same time with another instrument with a different resolution, the plots of concentration (dN) versus particle diameter (particle size bin) can differ. To avoid this, results are usually plotted using normalized concentrations (dN/dlogDp). By using normalized concentrations, values measured with different instruments with different resolutions can be compared. The normalized concentration is calculated by dividing the concentration value of each size bin, dN, with the number of channels per decade resolution, for the Engine Exhaust Particle Size Spectrometer 16^{-1}. This is automatically done in the EEPS software (TSI (2), 2012).

4.6 Uncertainties

Measurement uncertainties always occur when some sort of research is done. The measurement procedure for chemical substances includes two major steps: sampling and analysing. Uncertainties that can be found in the measurements with the EEPS are associated with the sampled air volume and the sampling efficiency and uncertainties with the instrument calibration and instrument analysis of particles.

Sources of uncertainty associated with the sampled air volume are measurements of flow rate, pump flow stability and sampling time. The sampling efficiency can be affected by pressure, humidity and temperature and also by fluctuations in the concentration of the sampled substance in air. (Finnish Standards Association (3), 2012).

The uncertainties for the visual dust analysis are many, e.g. the result is subjective and the results depend on the surface material for the investigated points (colour and roughness). Visually determining the concentration of dust is not an accurate method.

4.6.1 Problems and errors with the EEPS

Almost all of the errors that may occur during the sampling of ultrafine and nanoparticles are corrected in the manufacturer's software, e.g. counting efficiency of the electrometer, underestimation of particles with multiple charges and sampling losses inside the system. Diffusion losses inside the sampling tube can be calculated by formulas given in the ISO 28439:2011 standard (Finnish Standards Association (2), 2011).

Uncertainties originate either from the operating conditions or from the design of the instrument. Uncertainties associated with the sampling device are:

- Air flow rates (The air flow rate should be checked regularly and the measurement device calibrated)
- Electrical voltage (Changes in the voltage affect the particle size selection, calibration is important)
- Design of the instrument (incorrect dimensions, internal particle losses)

- Overloading of the instrument (High particle number concentrations can cause a part of the particles to remain inside the instrument, which lead to defect results. Long period between scans eliminate the problem)
- Humidity (High fluctuations in the humidity can influence particle sizes)
- Maintenance (Maintenance should be carried out according to the manufacturer's instructions)

As described in the list above, calibration and maintenance of the instrument is important for minimizing uncertainties. No uncertainties will be calculated in this thesis and therefore the calibration and maintenance is highly important to get as accurate results as possible.

5 Measurement

The measurements started with the visual dust analysis because the EEPS instrument could not be obtained before the beginning of March. The same measurement points were used for both investigations, but the methods and the sampling times differed. The personnel at Westenergy were informed of the on-going measurements and were asked to not touch or move the instruments without consulting me first.

5.1 Visual Dust Analysis

Dust is often defined as deposited particles, which have a diameter of 10–20 μm or larger. Even if dust is inhalable, it is not considered as dangerous as smaller particles. Due to the larger size of dust particles they do not penetrate as deep in to the respiratory system as smaller particles (Vallack and Shillito, 1998).

Deposited dust is often a main cause of complaints, which is not surprising. Dust is visual and tangible and therefore more easily understandable. Dust measurements are usually done gravimetrically, with different passive deposit gauges. Photometric

measurements of dust are usually executed with sticky pads and glass-slide soiling (Vallack and Shillito, 1998).

There are no recommended limit values for deposited dust. The average deposition time of different particle sizes can be seen in Table 7. As the table shows, larger particles deposit fast, while ultrafine particles remain permanent in the air.

Table 7: The average deposition time for different particle sizes (Seppälä, 2013)

Time	Size [μm]
3 s	100
12 s	50
34 s	30
2.5 min	15
5 min	10
20 min	5
8 h	1
Permanent in air	0.1

The presence of dust inside Westenergy waste incineration building was visually investigated. Railings at different points inside the plant were cleaned and taped with tape stripes. The chosen points are shown in Table 8. The accumulation of dust was followed for five days (5–9.2.2013).

Table 8: Investigated points inside the incineration plant

Name	Point location
Boiler room D1U_55 RO1	Balcony (9th floor)
Shredder D1U_30 RO1	Ammonia injection (4th floor)
Flue gas hall D1U_30 RO3B	Beside filter bags
Flue gas hall D1U_30 RO3B	At the top of the chain conveyor

The visual analysis continued by putting out pieces of contact plastic. The sticky side was set upwards. Contact plastic pieces were put out on ten points inside the plant, see Table 9. The dust accumulation on the plastic pieces was followed for one week (11–18.2.2013).

Table 9: Points with contact plastic inside the incineration plant

Name	Point location
Boiler room D1U_55 RO1	1. Balcony (9th floor)
Shredder D1U_30 RO1	2. Ammonia injection (4th floor)
Flue gas hall D1U_30 RO3B	3. Beside cooling tower (carbon/lime injection)
Flue gas hall D1U_30 RO3B	4. Beside the fan
Flue gas hall D1U_30 RO3B	5. and 6. Beside/Under filter bags
Flue gas hall D1U_30 RO3B	7. At the top of the chain conveyor
Mechanical workshop D9_U19 RO5	8. Ground floor
Service shaft D1U_19 RO1	9. Ground floor (Beside the combustion grate)
Bottom ash hall D1U_12 RO1	10. Bottom floor (Under the combustion grate)

5.1.1 Results

The points were ranked on a scale 1—5, depending on how much dust had accumulated on each point during the total measuring time of one week, see Table 10. The scale was planned according to investigations of dust carried out in offices as was described in Chapter 4.5.

Table 10: Planned dust scale for determining the differences in dust accumulation at the measured points

1 =	No visible dust
2 =	c. 3% surface area coverage
3 =	c. 5% surface area coverage
4 =	c. 10% surface area coverage
5 =	Over 10% surface area coverage

The results from the visual dust analysis are summarized in Table 11. The accumulation of dust at each measurement point is described according to the scale in Table 10. The differences between the points can be distinguished.

Table 11: The measurements points ranked according to the scale in Table 11

Point location	Scale
Balcony 9th floor	3
Ammonia injection 4th floor	3
Beside cooling tower 4th floor	2
Beside the fan 4th floor	3
Beside filter bags in fluegas hall	3
Under filter bags in fluegas hall	4
At the top of the chain conveyor 5th floor	4
Ground floor corridor	5
Ground floor combustion grate	5
Bottom ash hall	4

By the obtained results, it can be determined that dust is present in the indoor air at Westenergy waste incineration plant. The accumulation rate of dust varies between different points inside the plant. Already after one day accumulated dust could be noticed at all measurement points. Surprisingly, most dust had accumulated on the

sticky pieces on the ground floor. Other points with larger dust accumulation were under the filter bags in the fluegas hall, on top of the chain conveyor under the boiler and in the bottom ash hall. The points were least dust was found were beside the cooling tower in the flue gas hall. At every investigated point some dust was visible.

5.2 Particles

The particles were measured with an Engine Exhaust Particle Sizer Spectrometer, which function was described in Chapter 4.4.1. The inlet air entered the EEPS at a height of 55 cm and the instrument was set on a cart that could be lifted up to approximately 90 cm. No sampling tube was therefore needed because the height reached near breathing height. This means that sampling tube losses can be ignored, see Chapter 4.6.1.

The different measurement points inside the incineration building were chosen according to visitors and workers exposure to particles. The chosen points were illustrated in Chapter 4.2.1 and they will be explained in more details here. The measurements were carried out between 5.3.2013 and 14.4.2013.

5.2.1 Measurement points

The chosen measurement points are more thoroughly described in this chapter and sources that may affect the measurement at each point is examined. When changing measurement points, the EEPS was set to warm up for one hour at every new point. Before the measurement was set to start, the instrument was calibrated with a HEPA clean air filter.

The different points were divided according to their location into three main categories, the plant hall, offices and fugitive emissions. The plant hall includes calculated mean values obtained from the measurement points inside the incineration building. The offices comprise the measurement points Warehouse, Control room and the Office. To the fugitive emissions, measurements investigating possible leakage have been included (UnderBoiler, Middlebags and Underbags).

Balcony 9th

The balcony is the highest place inside the incineration plant, +55 meters above sea level. After the visitors have visited the control room they arrive to the balcony. From the balcony you can see the whole plant facility. The balcony is right above the combustion process and the temperature here is quite high. Close to the balcony, the secondary combustion air is taken. The presence of dust is clearly felt here, which can probably be related to the warm air. Even if the dust presence is felt the most here, the dust analysis showed that the particle concentration here is less than in many other places inside the plant.

Boiler 8th

The roof to the boiler is one floor down from the balcony. The main part of the heat transfer takes place in the boiler. From the boiler, superheated steam with a temperature of 400 °C and a pressure of 40 bar, is led to the turbine for power generation. Here too the temperature is high. Beside this measurement point, waste steam is released to the atmosphere, which could lead to formation of particles through condensation of gases.

Crushing Mill 4th

The crushing mill is found on the fourth floor, on the same floor as the first ammonia injection point. The crushing mill crushes larger waste parts into smaller fractions prior to entering the combustion grate. Leakage from the mill had been noticed and therefore a wall had been constructed separating the mill from the rest of the boiler room. A work table with tools is placed beside the crushing mill wall.

Ammonia injection 4th

After the visitors have seen the balcony, they go down to the ammonia injection on the fourth floor. Ammonia is injected to the combustion chamber, at four points, at different heights on both sides of the combustion chamber. The ammonia injection

measurement point is the first injection point. Here too, dust has clearly been noticed on surfaces.

Fluegas silos 4th

In the pipe above the floor the flue gases are transported to the stack. At this end of the plant, the storage silos containing active carbon, lime and fly ash are located. These should, however, not affect the particle and dust concentration in the air. Visitors move through this point during the tour. The fan, controlling the pressure inside the flue gas channels, is located a few meters away from the measurement point. Of all the measurement points in the flue gas hall, the dust analysis showed that most dust accumulated at the Fluegas silos point.

Fluegas cooling 4th

This is the first stop for visitors when entering the flue gas cleaning area. The cooling tower with the lab loop is situated here. Into the lab loop, active carbon and lime is injected. The lime and active carbon attach hazardous substances from the flue gas, which are then removed in the bag filters. A lower temperature compared to the upper floor makes the air feel fresher here.

Ground corridor 2nd

The corridor beside the workshop is situated between the mechanical workshop and the combustion grate on the ground floor. There are several doors, along the corridor, leading to the parking lot. On the other side, there are doors leading to the condensers and ventilation rooms. On the side of the wall, there are shelves used for storage. Visitors go through the mechanical workshop and the corridor at the end of their plant tour. The measurement here can be affected by opening of the doors leading outside. Pollutants from the ambient air can be taken in. On this floor forklifts and cars sometimes move and vehicle exhausts can affect the results. The door to the workshop is mostly open and particles emerging from activities in the workshop easily move into to the

corridor. The humidity is probably higher here than in other parts of the plant, due to the outside air. The air feels fresher, which can be misleading. The particle concentration in the air beside the mechanical workshop is according to the dust analysis one of the highest measured.

Ground hatch 2nd

This is the last stop before the visitors go back to the auditorium. Through two hatches, visitors can look in to the combustion grate and see the waste burning on the grate. This point is at the other end of the corridor on the ground floor, which also means that vehicles move in this area. In the middle of the area, building materials have been stored. The dust analysis showed that most particles are deposited on this area. The same factors that affected the results in the ground corridor are present here.

Ash hall 1st

In the bottom ash hall bottom ashes from the combustion process are handled and larger metal pieces are separated from the bottom ashes by shaking grates. The bottom ashes are cooled in a water-bath and automatically transported to containers. The workers spend quite a lot of time in this area doing maintenance work and the workers have complained about the dusty air in the hall. A forklift is also used here.

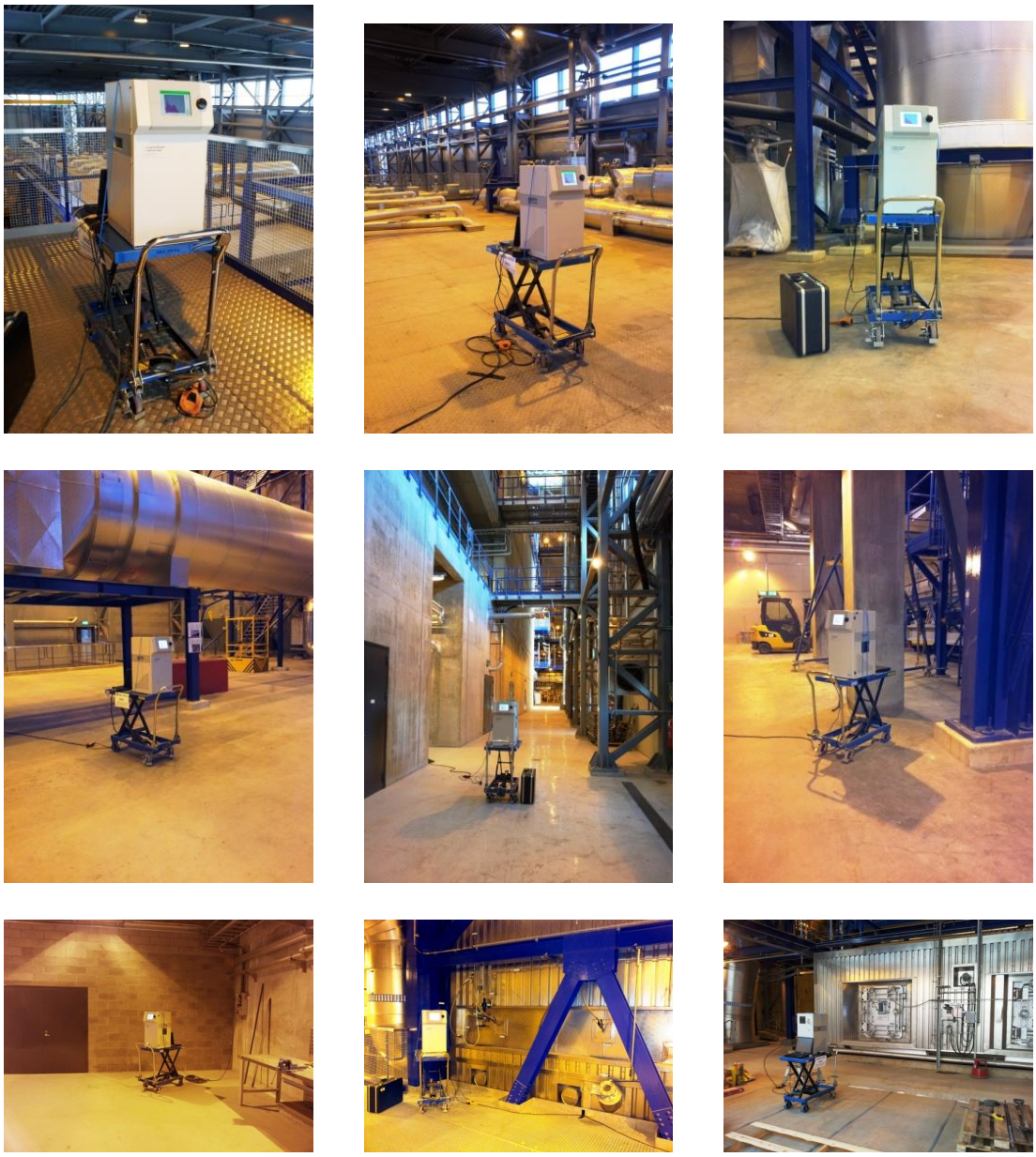

Figure 7: The plant hall. Top from left: Balcony, Boiler 8th, Fluegas cooling. Middle from left: Fluegas silo, Ground corridor, Ash hall. Bottom from left: Crushing mill, Ammonia injection, Ground hatch. Pictures: Skog 2013

Mechanical warehouse

The mechanical warehouse functions as a storage room for parts needed for maintenance and service of the plant. Worker spends his whole day inside the warehouse. The warehouse is placed on the third floor.

Control Room 4th

The operators spend most of their working time in the control room, from where the incineration plant is operated. The plant operation is supervised from the control room and one operator has to be present in the room at all times. The workers coffee room and the manual steering of the bunker crane is also placed in the control room. This is the first stop for visitors coming to the incineration plant and through a window they have a clear view of the waste bunker.

Office

The office contains a coffee room and several office rooms for the office workers. The air at this location, should be to the cleanest.

Figure 8: Control Room 4th (Picture: Skog 2013)

UnderBoiler

Under the boiler there is a chain conveyor that transports fly ashes from the boiler to the storage silo. The chain conveyor is quite intact and there is no evidence of leaking particles, even if the surfaces of the chain conveyor are clearly dusty.

Middlebags

The bag filter removes the biggest part of particles existing in the flue gas. The flue gases are transported through the filters and the particles attach to filter surfaces. The filters have to be cleaned regularly to maintain effective removal of harmful substances from the flue gas. At the start-up of the incineration plant there were problems with leakage at the bottom of the filters. This point is a possible leak source to particles existing in the indoor air at the incineration plant.

UnderBags

Under the filter bags the chain conveyor transport the removed fly ashes from the filter bags to the storage silo. Leakage from the filter bags should be noticed in the measurements made at this point.

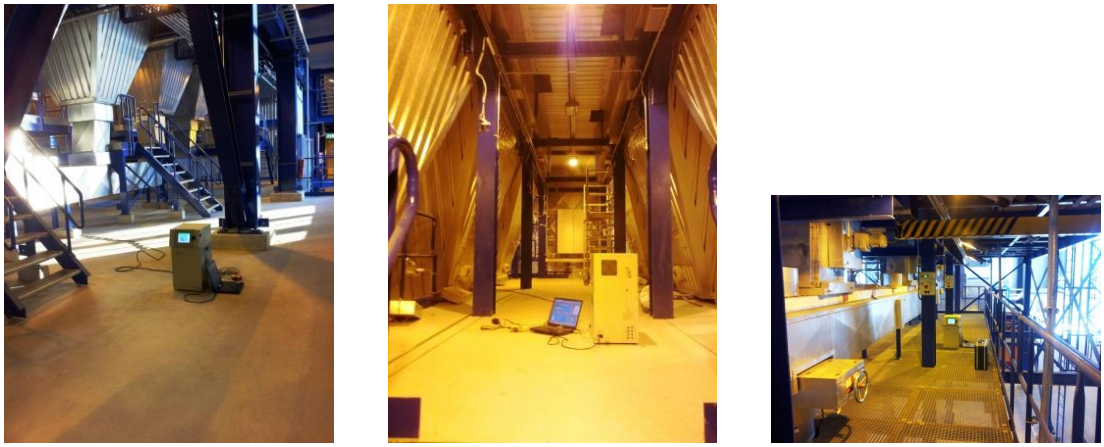

Figure 9: Fugitive emissions. From the left: UnderBoiler, MiddleBags, UnderBags. Pictures: Skog 2013

Outside

The temperature range of the inlet air to the EEPS instrument should be at least + 10 °C. The temperature range brings complications to the outside measurements due to the exceptionally could spring. The outside point is located in the parking lot in front

of the incineration plant.

5.2.2 Results

The measurements started on the 9th floor. The measurement schedule can be seen in Appendix A. The instrument was set to measure continuously for ten minutes, once an hour followed by a 50 minute break. This was set to run for twelve hours. According to the instructions for the EEPS, a suitable time range from the ten minute measurement was chosen for analysis, since the values in the middle are most representative, as described in Chapter 4.3. A total of 13 samples were collected at each point and the first sample at each point was left out of the analysis due to possible disturbances caused when setting the instrument to start. All the measurements which were carried out are summarized in Table 12.

Table 12: Summary of measurements

Measurement point	Time	Duration	Temp/RH
Plant hall			
Balcony 9th	5–6.3.	12 h	Temp, RH
Boiler 8th	6–7.3.	12 h	Temp, RH
Crushing mill 4th	7–8.3.	12 h	Temp, RH
Ammonia injection 4th	7.3.	12 h	Temp, RH
Fluegas silos 4th	8–9.3.	12 h	Temp, RH
Fluegas cooling 4th	9.3.	12 h	Temp, RH
Ground corridor 2nd	25–26.3.	12 h	Temp, RH
Ground hatch 2nd	10–11.4.	12 h	Temp, RH
Ash hall 1st	21–22.3.	12 h	Temp, RH
Offices			
Warehouse 3rd	21.3.	12 h	Temp, RH
Control Room 4th	25.3.	12 h	Temp, RH
Office 3rd	17.3., 24.3.	12 h	Temp, RH
Fugitive emissions			
UnderBoiler	23.3.	6 h	
Middlebags	23.3.	6 h	
Underbags	24.3.	6 h	
Outside	14.4.	1 h	
Visitor			
Balcony 9th	8.3.	2 h	
Fluegas silos 4th	8.3.	2 h	
Cleaning			
Boiler 8th	6.3., 20.3., 8.4.	8 h	
Crushing mill 4th	7.3., 20.3., 9.4.	8 h	
Ground hatch 2nd	22.3., 10.4.	12 h	
Car			
Ground hatch 2nd	11.4.	45 min	

The measured mean values are found in Appendix B. The mean values of the total particle concentrations for all measurements in the whole size range of the EEPS (5.6–560 nm) are illustrated in Figure 10.

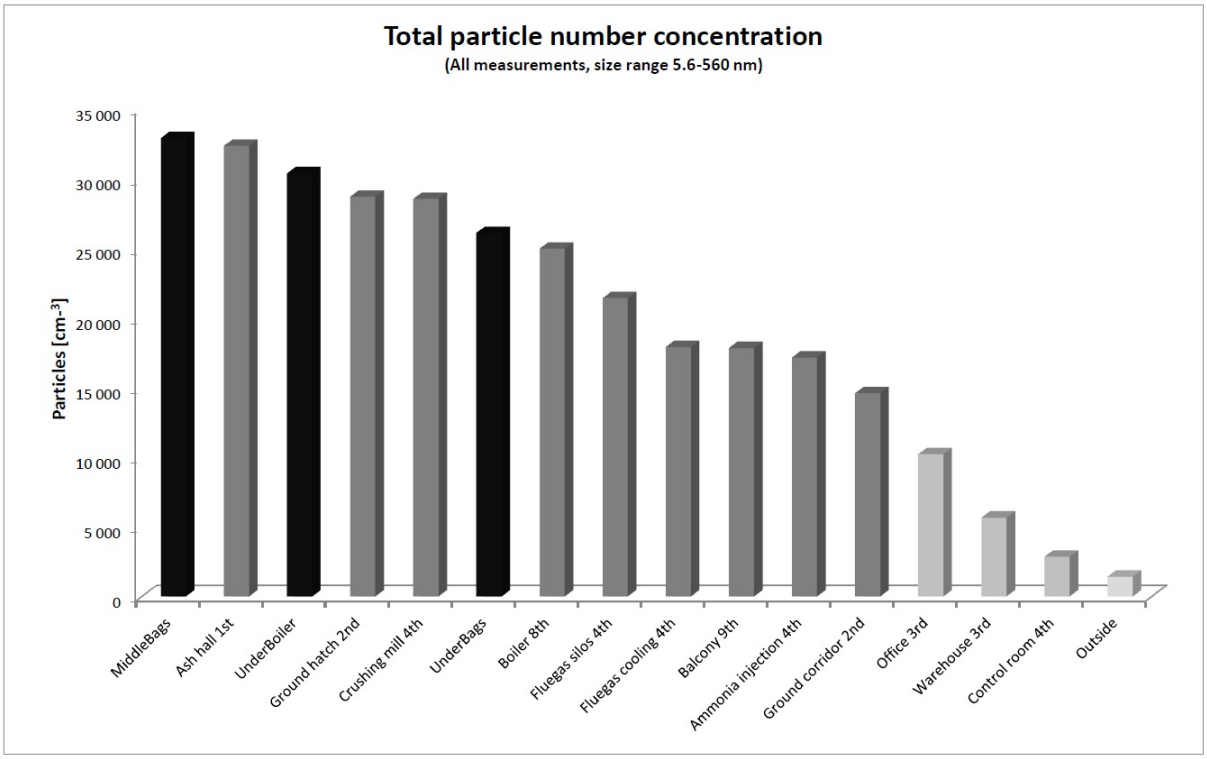

Figure 10: The total particle concentration at the different measurement points

It was not surprising to find the highest total particle concentration in the bottom ash hall and in the middle of the bag filters. The high concentration in the ash hall is a result of the handling of bottom ashes and metal residues from the combustions process. If particles with a diameter larger than 560 nm could have been measured, the concentration in the ash hall may have exceed limit values for $PM_{2.5}$ and PM_{10}.

The bag filters are automatically blown through, one filter at a time. The blowing of the filters is consequently continuous and is done in purpose of cleaning the filters and thus, increasing the fly ash removal. Sometimes the hatches to the filters have to be opened for maintenance and a lot of dust and particles escape into the flue gas hall. The high concentration of particles in the middlebags is probably a cause of all the dust present on the floor and in the air in the area between the bags. Problems

with leakage that was found in the beginning of the plant operation should not be an issue any more. If the bag filters were still leaking, the concentration under the bags would also have been higher. The cause to the high concentrations in the measurement points UnderBoiler, Middlebags and Underbags is probably a result of a lot of dust and particles present on the surfaces in those areas. The surfaces have probably not been cleaned in a while.

The offices, especially the control room, have clean air. The higher concentration in the office compared to the control room and warehouse may be due to the furniture and carpet close to the instrument. To investigate this, two measurements were carried out in the office. The second office measurement was carried out in an office room where no carpet and less furniture were present and the results in that room were significantly lower. Mean values of these two measurements have been used in the comparisons.

The outside measurement was carried out on a sunny Sunday in the middle of April. The temperature outside was around 15 °C where the sun was shining. Very little traffic and other activities took place during the measurement. The measurement time was set to one continuous hour and 50 minutes of that hour was analysed. The outside values are very difficult to compare to the other measurements since the measurement time differ and the outside conditions vary constantly. The indoor conditions are assumed to be steady all year. To get sufficient results the monitoring should be continuous for at least one year. The low values of the outside concentration do not give the whole truth. During weekdays, when cars are driving and people are doing ground work in the area, the concentrations are probably several times higher.

The total mean particle concentration for the three categories were calculated and are shown in Figure 11.

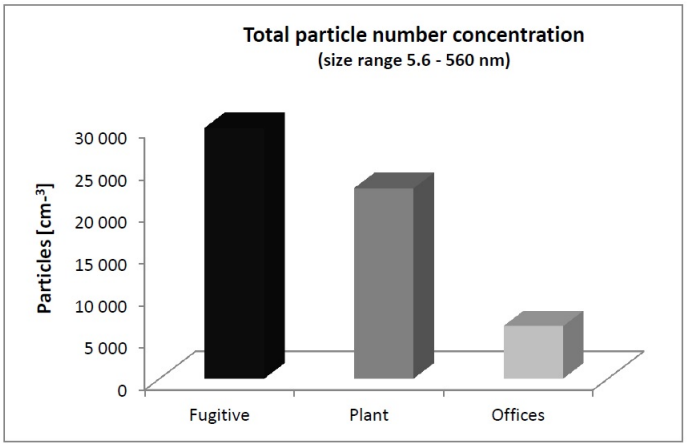

Figure 11: Total particle concentration in the categories plant hall, offices and fugitive emissions in the size range of 5.6–560 nm

When the mean value for all the measurements were divided into the three categories, the fugitive emissions have the highest concentration, which is probably due to the amount of dust and particles existing on the surfaces at these points. The offices have the lowest concentration, as it should be. The size frequency of different particle sizes in the plant hall, offices and fugitive emissions can be seen in Figure 12.

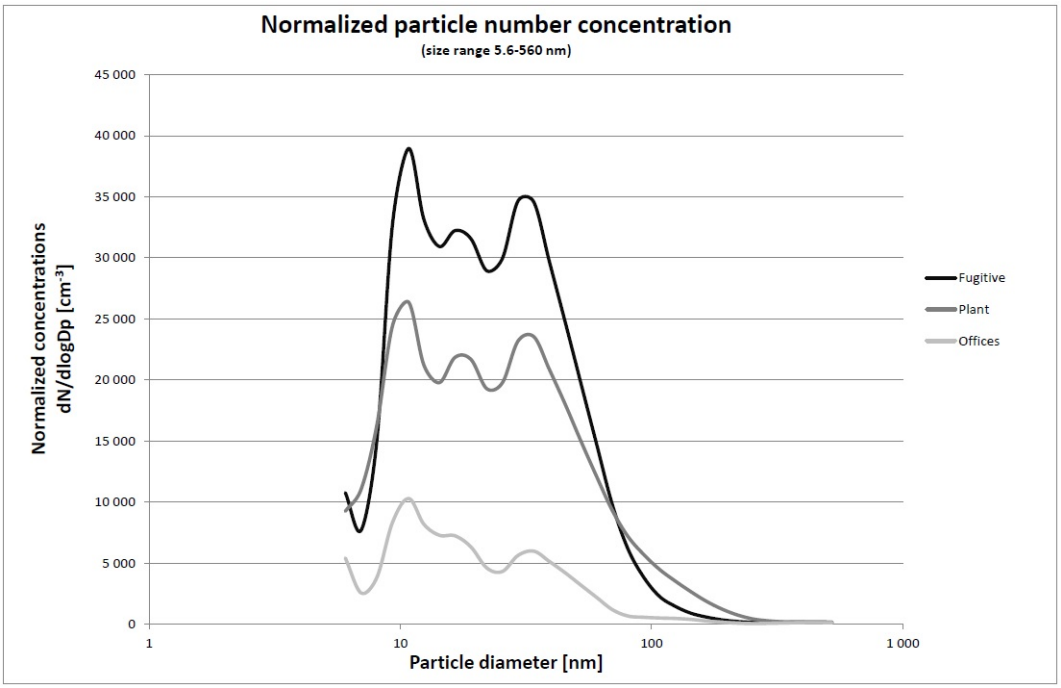

Figure 12: The particle frequency of different particle sizes

The normalized concentrations express the frequency of particles at different particle diameters and not the amount of particles. The total area under the curve gives the total concentration. The size frequency tells which particle sizes are the most represented in the air. As can be seen in Figure 12, most of the particles have a diameter smaller than 100 nm, which means they are ultrafine particles. Generally, three particle peaks can be seen in the curves. The first peak at approximately 10 nm, the second at approximately 20 nm and the third at approximately 50 nm.

Visitor measurement

During the measurements, it was noticed that people moving near the EEPS instrument during the time of the measurement, clearly increased the particle concentrations. To demonstrate this phenomenon, special visitor measurements were carried out at two locations in the plant, at the time when visitors passed the instrument.

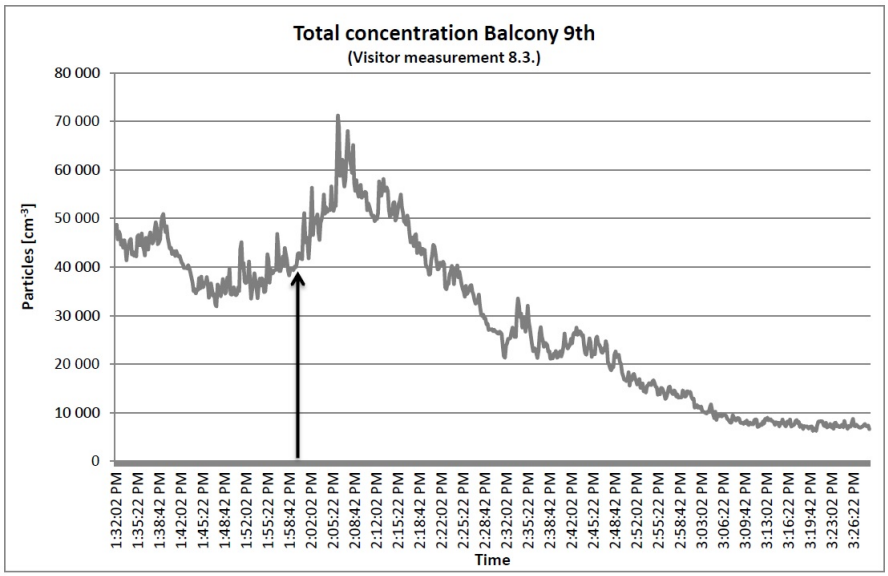

Figure 13: Measurement at Balcony 9th during visitor tour at the plant 8.3.

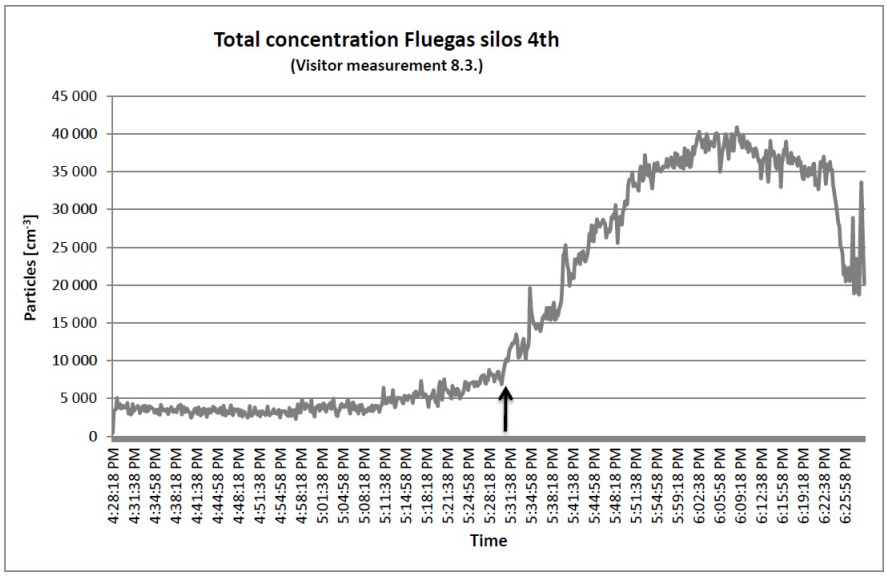

Figure 14: Measurement at Fluegas silos 4th during visitor tour at the plant 8.3.

The EEPS was set to measure prior, during and after the visitors passed by the instrument. In Figure 13, the visitors passed the instrument at approximately 2.00 pm. In Figure 14, the visitors arrived at the instrument at approximately 5.30 pm and they stay near the instrument for a few minutes. Changes in the total concentration significantly increased while the visitors stayed close to the instrument and the concentration decreased after the visitors had moved past the instrument. The graphs for the two measurements look quite different, which depends on a longer stop near the Fluegas silo point and a twice bigger group at that time. The particles are suspended in the air longer. In the end of the Fluegas silos graph the high peak is explained by hand movement in front of the inlet.

The phenomenon with higher concentration near individuals is called the "personal cloud". Movements and activities often stir up gases and particles present on clothes and adjacent surfaces, which causes higher particle concentrations in the air. Besides the movements people discharge thermal-IR radiation, which stirs and lifts particles. (Jacobson, 2002) Many of the concentration peaks that occurred during the measurements can be explained by the "personal cloud". The personal cloud values are included in the mean measurement values, which give a quite representative value for the points in question, because people are constantly moving inside the incineration

building. However the human exposure to ultrafine particles is probably higher than the measured particle concentrations at the different locations.

Cleaning measurement

The incineration plant was shut down for cleaning of the combustion equipment for five days in the middle of March. During that time, no measurements were carried out at the plant. The day the plant was put into operation again, measurements beside the crushing mill and above the boiler on 8th floor were done. Three weeks later, measurements were carried out at the same points.

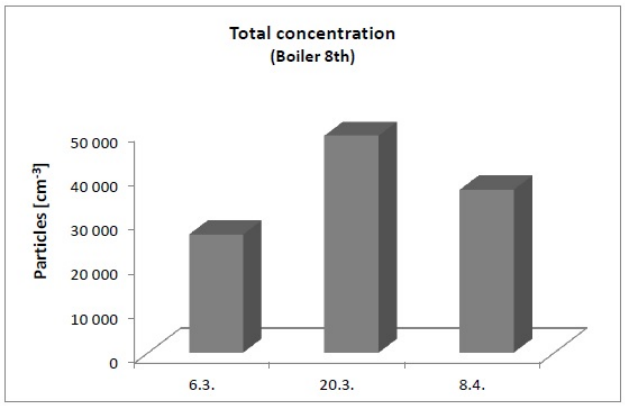

Figure 15: Measurement at Boiler 8th before 8.3., directly after the shutdown 20.3. and a couple of weeks after the shutdown 8.4.

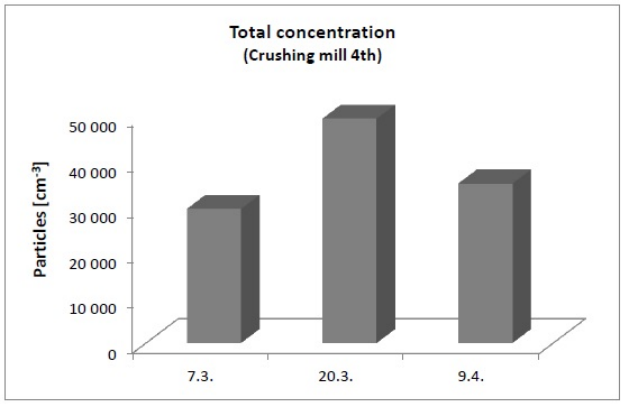

Figure 16: Measurement at Crushing mill 4th before 7.3., directly after the shutdown 20.3. and a couple of weeks after the shutdown 9.4.

Figure 15 and 16 show the total concentration at these two points measured at three different times. The first measurement was done approximately two weeks before the shutdown, the second measurement directly after the shutdown and the third three weeks after the shutdown. As can be seen from the figures, the total concentrations were highest directly after the shutdown, which probably depends on the cleaning procedure. As earlier has been told, cleaning is one of the major sources of ultrafine particle exposure indoors. Some of the ultrafine particles may also be a result of gases, leaking from the combustion structures during the cleaning, which have then condensed forming particles inside the plant.

The concentrations, three weeks after the shutdown, were still higher than the concentrations before. At least at the crushing mill point, there was clear evidence of that the floor had been cleaned recently. A possible reason for the higher concentrations may be the differences in the outside weather between 6.3–7.3. and 8.4.–9.4. When the last measurement was carried out, the weather outside was sunny and the melting of snow and ice had started. This means that concentrations of different particle sizes, in the outside air, were much higher at this time because of all the road dust present in the air.

Two measurements were carried out in front of the combustion grate. The first measurement was done approximately two days after the shutdown. The measurement resulted in the highest total particle concentration of all measurements carried out at the plant. At the time of the first measurement, the point functioned as a storage area for construction materials. Some of these materials may have been vaporizable, which form ultrafine particles. Another reason to the high concentration may have been the shutdown and cleaning of the combustion equipment.

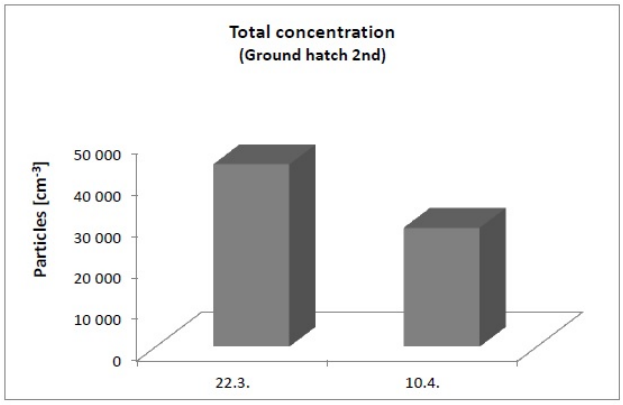

Figure 17: Measurements at Ground hatch 2nd before and after the area had been cleaned

The second measurement was carried out three weeks later. All the building materials had been removed from the point at this point and the area had been cleaned. The total particle concentration was significantly lower during the second measurement (Figure 17), which most likely depended of the removal of the construction material. The later obtained results were used in the comparison of different measurement points in Chapter 5.2.2, because the conditions of the point during the second measurement can be related to how the conditions probably will be in the future.

Car measurement

Westenergy owns a diesel-powered pickup that usually stands in front of the combustion grate beside the Ground hatch measurement point. After the second measurement at the Ground hatch point, a short measurement was carried out to investigate how the exhausts from the pickup affect the indoor air in front of the boiler.

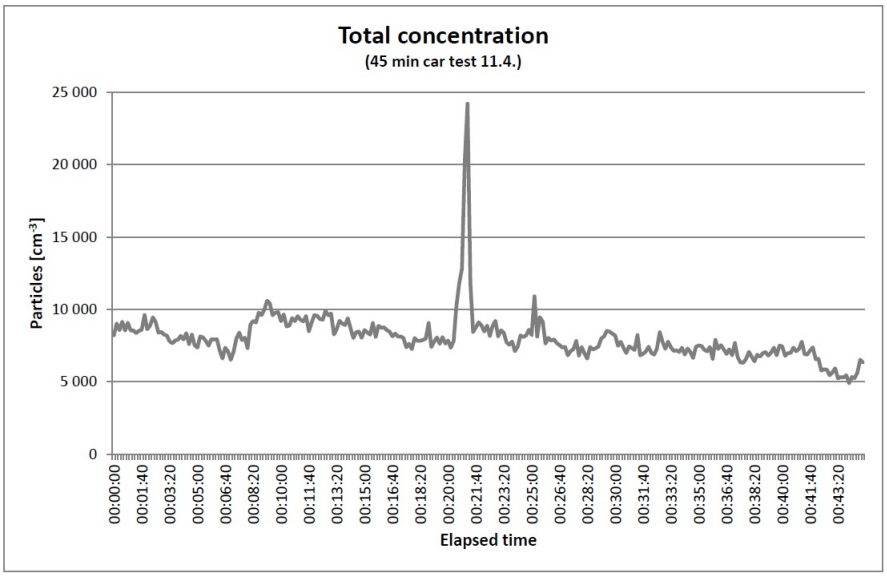

Figure 18: Car measurement 11.4.2013

The measurement was set to start 20 minutes before the pickup engine was started. The engine ran for five minutes after it had been started. The measurement continued 20 minutes after the engine had stopped. The moment when the engine started can clearly be noticed in Figure 18. The particle concentration peaks at the moment when the engine starts. The peak decreases back to the concentration that prevailed, before the engine ceases, this means that the idling of the pickup does not affect the air noticeably, only the starting of the engine causes an increase in the particle concentration. From this test, it can be concluded that the pickup is not a major source of the ultrafine particles present on the ground floor.

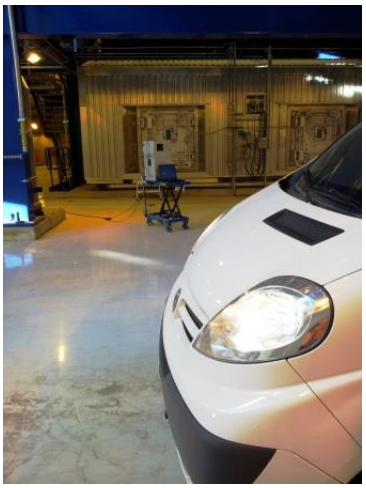

Figure 19: Car measurement 11.4.2013

Surface area, volume and mass concentrations

To show the differences between how the particles are expressed with different units, the surface areas, volume concentrations and mass concentrations were calculated from the measured number concentration values. The calculations were made in Excel, see Appendix C with equations used by the EEPS software, see Table 13. The calculations are only indicative because assumptions had to be made in the calculations due to the lack of more thorough data. It was assumed that all particles are spherical and that they have the same density (1 $g cm^{-3}$).

Table 13: Equations provided by TSI to calculate surface area, volume and mass concentrations (TSI (1), 2009)

Surface Area [$nm^2\ cm^{-3}$]	**Volume** [$nm^3\ cm^{-3}$]	**Mass** [$\mu g\ m^{-3}$]
$s = \pi \times {D_p}^2 \times n$	$v = \frac{\pi \times {D_p}^3 \times n}{6}$	$m = v \times \rho$

where

D_p is the particle diameter

n is the weighted number concentration

ρ is the density

The results can be seen in Figure 20. These graphs show that the mass and volume concentrations are dominated by larger particles and the number concentration and total surface area are dominated by smaller particles. In the number concentration graph, it can be seen that the plant hall has larger particles than the offices and fugitive emissions. This amount result in a much larger mass concentration and volume concentration compared to the offices and fugitive emissions. This is why mass concentration should not be used when measuring smaller particles, the vast majority of these particles would then be unnoticed.

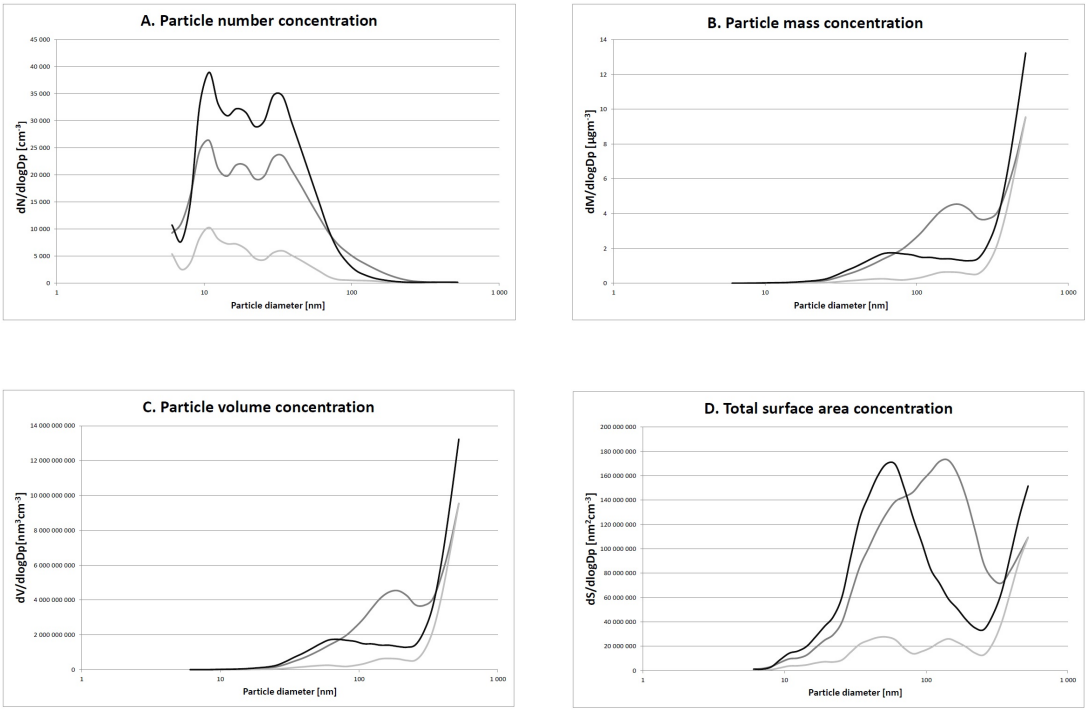

Figure 20: The measured particles expressed in different units (A = number, B = mass, C = volume, D = total surface area). The black line is fugitive emissions, the gray total plant hall and the lighter gray represents the offices

5.3 Temperature and relative humidity

The temperature and relative humidity was measured simultaneously with the particles at every measurement point. The results are shown in Table 14. Temperature and relative humidity is often associated with indoor air quality, because they can affect the presence of indoor air contaminants.

Table 14: Measured temperature and relative humidity at the measurement points

Point location	Temperature [°C]	RH [%]
Balcony 9th	33	15
Boiler 8th	34	9
Crushing mill 4th	21	19
Ammonia injection 4th	26	15
Fluegas silos 4th	23	12
Fluegas cooling 4th	26	11
Ground corridor 2nd	19	16
Ground hatch 2nd	22	16
Ash hall 1st	23	23
Warehouse 3rd	21	15
Control Room 4th	23	15
Office 3rd	23	16

The indoor air at the Westenergy waste incineration plant is quite dry. The relative humidity is in the range of 9–23%. The temperature is in the range of 19–34°C. The relative humidity is thus lower than the comfort zone of 30–60%, while the temperature is suitable at most locations in the plant. The highest temperatures are, as expected, found at the balcony and above the boiler. Correlations between particle concentrations, temperature and relative humidity were investigated, but no connections were found. Relations between relative humidity and particle concentrations could probably have been noticed if larger particles could have been measured more thoroughly.

6 Assessment of results

Ultrafine particles and larger particles (PM_{10}, $PM_{2.5}$) cannot be compared with each other because they are not related. The larger particles form directly from the sources, e.g. sand and dust. Ultrafine particles, often form due to reactions taking place in the air, e.g. condensation of gases and vaporizing of materials, see Figure 21. The different

particle sizes should be classified as different air pollutants. Some correlations could however be made with the visual dust analysis and the particle measurements. The points where most dust had accumulated are the same points as the ones with the highest particle concentration.

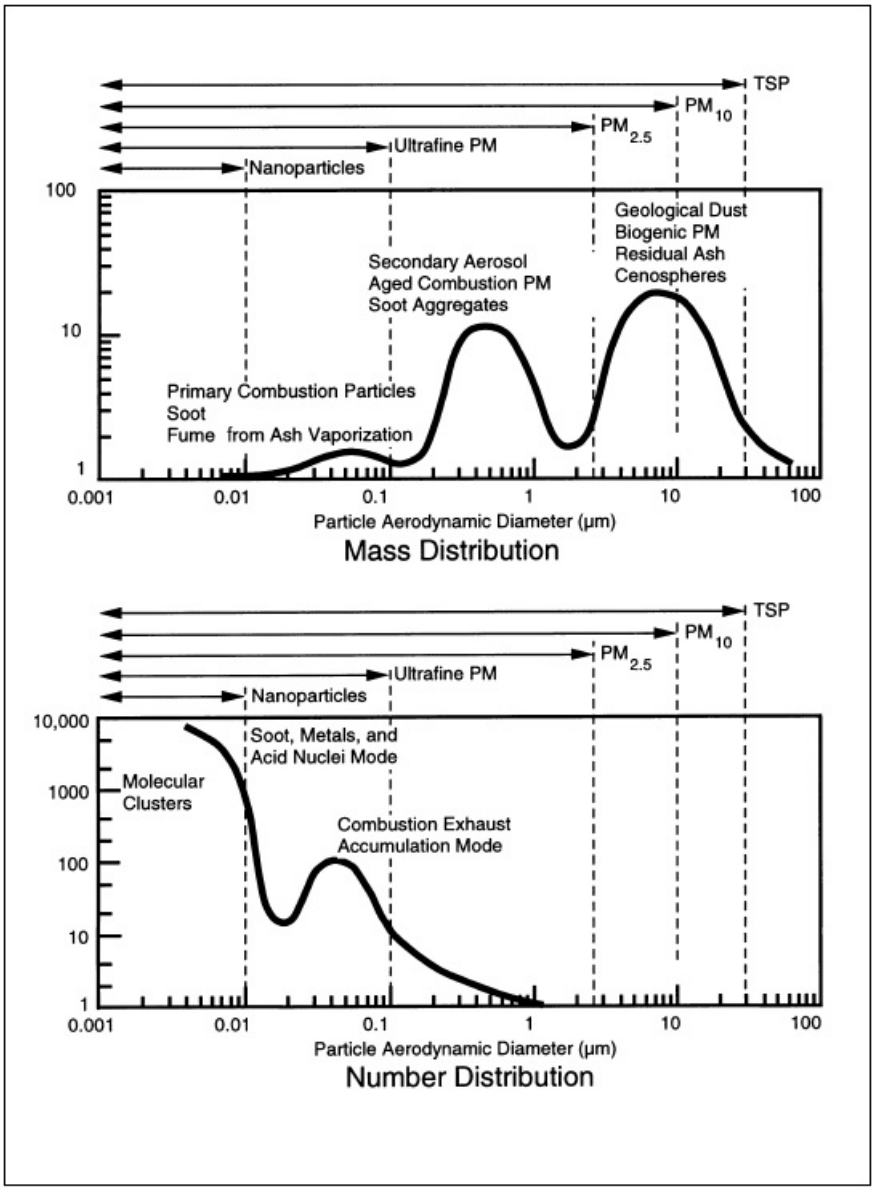

Figure 21: Particle mass and number distribution and particle sources (Lighty, Veranth, and Sarofim, 2011)

Investigations measuring the concentration of ultrafine particles in the flue gases at the stack have been conducted at some municipal waste incineration plants. The results

gave ultrafine particles in the range of 3 000–100 000 particles cm^{-3}. The concentrations varied a lot. Metals and chloride present in the combustible waste is thought to be the cause of ultrafine particles in the flue gases. Ultrafine particles often form from metal vapours and metals usually react with chlorine forming metal chlorides. The metal chlorides are more volatile than the elemental metals and thus the chlorine enhances the formation of ultrafine particles (Yinon, Themelis, and McNeill, 2010).

Ultrafine particles form due to hot processes, vaporization of materials and from combustion gases. No hot processes are taking place at Westenergy, except on the combustion grate and occasionally in the mechanical workshop. Blow-out steam may occasionally enter the building if the ventilationhatches at the roof are open. Condensation of steam may form particles.

Three particle concentrations peaks could be noticed at the sizes 10 nm, 20 nm and 50 nm. The 10 nm particles are probably newly formed particles, because the 10 nm peak is the highest. These particles then grow by condensation to 20 nm and further to 50 nm. The question still remains, what is the source that forms the ultrafine particles to begin with?

Without any elemental analysis, it is almost impossible to say from which source the ultrafine particles inside the incineration building are formed. Some particles are probably a result of the traffic in the area. At some measurements increased concentrations levels were detected around 8 am and 4 pm, when most people arrive or leave the plant by car. Another possible source is the blow-out steam, which is blown out at the roof of the building. The gases in the steam may condense and form ultrafine particles. Ammonia present in the air also enhances formation of ultrafine particles, but leaking ammonia into the incineration building would most certainly be noticed due to pressure drops in the ammonia injection lines.

Neither gases leaking from the combustion process are a feasible source. The underpressure in the process compared to the surrounding is a sufficient way to prevent leaking gases. Other gases present in the indoor air may vaporize and cause ultrafine particles, but this is hard to estimate when no gases in the indoor air have been analysed.

The change of air happens quite often in the incineration building, due to the fact that the primary and secondary air to the combustion chamber is supplied from the inside of the plant. This means that formed ultrafine particles do not have much time to coagulate and grow and that may be a reason to the small amount of particles larger than 100 nm.

Coarse mode particles are a totally different story. They form in other ways than the smaller particles and must be seen as a group of its own. The dust inside the incineration building can be seen as coarse mode particles and they probably originate from the outside air. A lot of ground work activities and stone crushing are taking place in the area around the incineration plant. Due to the high air exchange rate and no filters prior to entering the building, all the dust present in the outside air comes inside. The secondary air to the combustion chamber is taken from the eight floor, which means that the air inside the facility moves a lot.

According to the dust analysis, most of the dust accumulates at the ground floor. Indications of this can even be seen in the particle measurement. The highest amounts of particles over 100 nm is found in the Ground corridor. Reasons for the highest amount of large particles at the ground floor, may be the materials stored in the area assembling dust and particles from the floors above settling down in the corridor. The space from the floor to the roof is free from obstacles. The outside air taken in to the plant is supplied from the corridor side and particles transported from outside deposit at the ground floor.

6.1 Comparisons with literature

The total particle concentrations in the size ranges 10.8–107.5 nm and 107.5–560 nm, were calculated for comparison with measurements carried out in three cities in Europe. To calculate the total concentrations in other size ranges than 5.6–560 nm, the total concentration for every size bin in that range has to be multiplied with 16^{-1} and all the values in the range summarized. These values can be seen in Appendix D. The results can be seen in Figure 22 and 23. The particle measurements in the cities were conducted between 30 November 1996 and 13 March 1997. The particles were mon-

itored in Alkmaar, Netherlands, Erfurt, Germany and Helsinki, Finland. The results represent urban background concentrations (Ruuskanen et al., 2000).

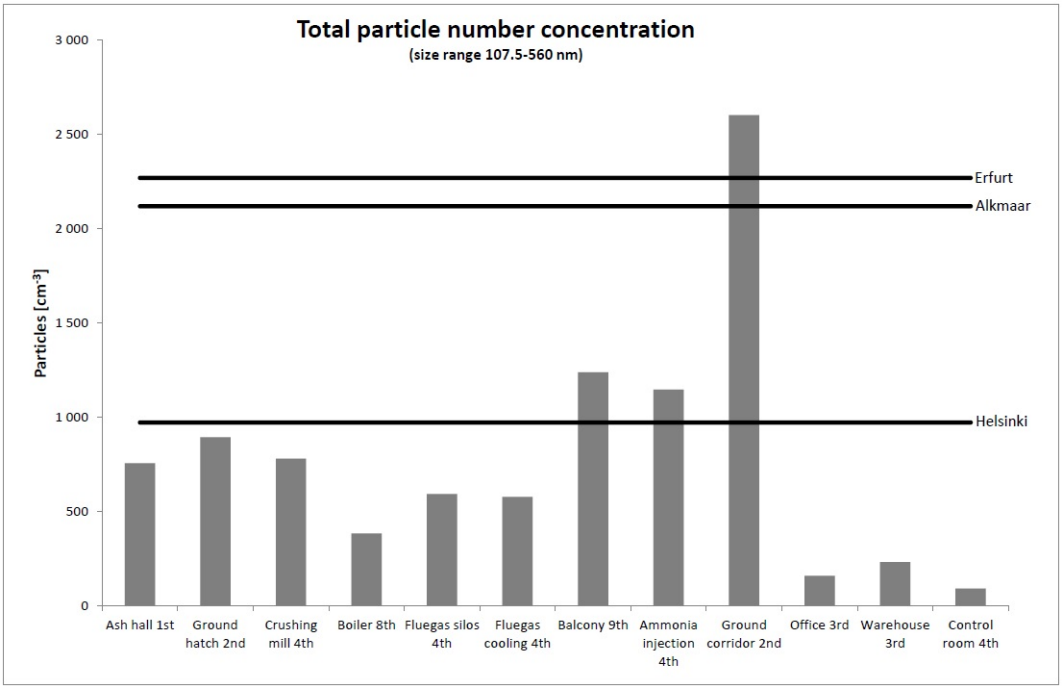

Figure 22: Total particle concentrations in the size range 107.5–560 nm

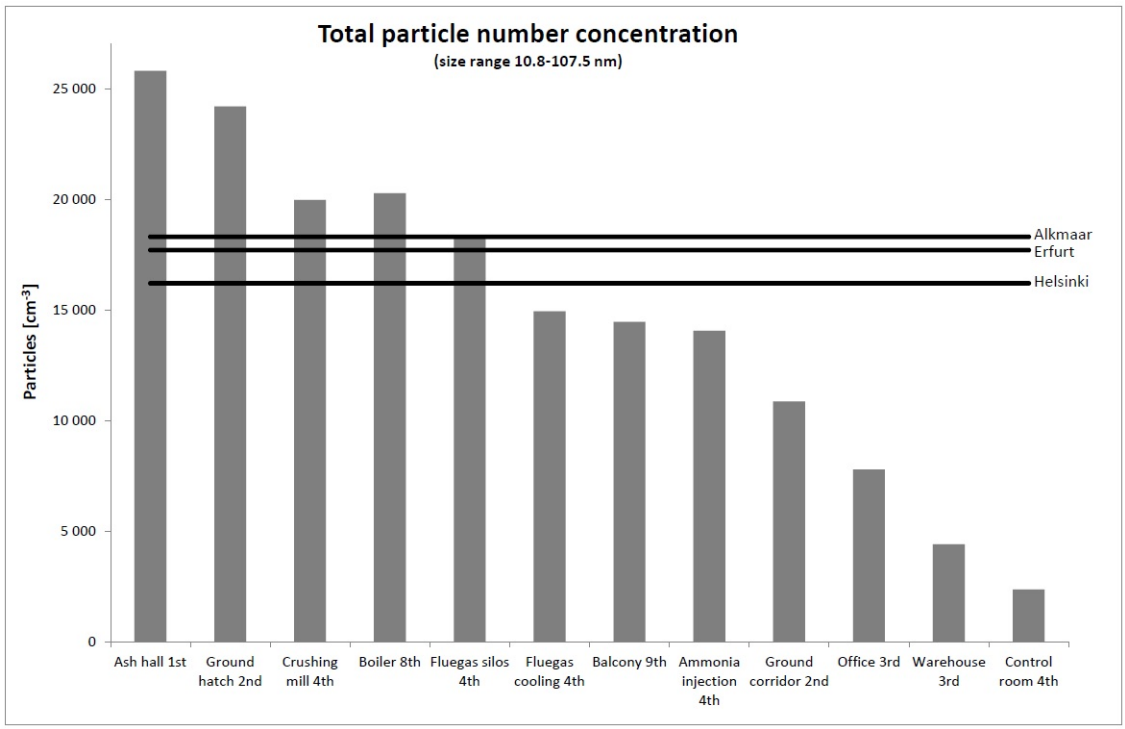

Figure 23: Total particle concentrations in the size range 10.8–107.5 nm

In the bigger size range only the ground corridor exceeds the measured urban background levels, while in the smaller size range the background levels are exceeded by measurements made in the ash hall, ground hatch and at the ammonia injection and crushing mill area. Thus, larger particles are present in the ground corridor than in other locations, which also was indicated by the visual dust analysis. Smaller particles are strongly present near the combustion chamber on the fourth floor and beside the combustion grate on the ground floor and in the ash hall. The concentration levels measured at the incineration plant are, however, not that high compared to the background levels.

Exposure values at the incineration plant can be compared to the background conditions measured in the three European cities. The total particle number concentration in the size range 10–500 nm in Alkmaar, Erfurt and Helsinki are 20 480, 20 010 and 17 580 particles cm^{-3} respectively (Ruuskanen et al., 2000). The total number concentration in the same range at each measurement point in the Westenergy waste incineration plant can be seen in Table 15.

Table 15: Total measured particle number concentrations in the size range 10–500 nm

Point Location	Total measured concentration [p cm^{-3}]
Balcony 9th	15 700
Boiler 8th	20 656
Crushing mill 4th	20 747
Ammonia injection 4th	15 204
Fluegas silos 4th	18 857
Fluegas cooling 4th	15 518
Ground corridor 2nd	13 462
Ground hatch 2nd	25 085
Ash hall 1st	26 558
Warehouse 3rd	4 643
Control Room 4th	2 461
Office 3rd	7 947
UnderBoiler	26 767
Middlebags	28 314
Underbags	22 353
Total inside plant	19 088
Total offices	5 017
Fugitive emissions	25 812

The exposure to ultrafine particles depends on where you move inside the plant and how long you stay at different locations. The total exposure for one twelve hour shift is calculated with equation (1) (Ministry of Social Affairs and Health, 2012).

$$C_{12h} = \frac{C_1T_1 + C_2T_2 + C_3T_3 \ldots C_nT_n}{12h} \tag{1}$$

where

C is the concentration at a specific location

T is the time spent at the location

The same equation is used for eight hour workdays. Instead of dividing by twelve hours, the total exposure is divided by eight hours. For example, a typical twelve hour workday at Westenergy may look as follows: 2 h spent in the ash hall, 8 h spent in the control room and 2 h spent on walking around inside the plant. When calculating the total exposure, the time must be expressed in minutes, see Table 16.

Table 16: Example of calculated total exposure for a worker

Location	Total measured concentration [p cm^{-3}]	Duration [min]
Ash hall 1st	26 558	120
Control Room 4th	2 461	480
Total inside plant	19 088	120

The total exposure will then be:

$$C_{12h} = \frac{26558 \times 120 + 2461 \times 480 + 19088 \times 120}{720} = 9248\ pcm^{-3} \tag{2}$$

Another example is a worker working an eight hour shift in the warehouse. For example, he/she spends 6 h of the day in the warehouse, 1 h in the control room during breaks and 1 h inside the plant. The total exposure of particles during one day is then 6 176 particles cm^{-3}.

$$C_{8h} = \frac{4643 \times 360 + 2461 \times 60 + 19088 \times 60}{480} = 6176\ pcm^{-3} \tag{3}$$

In Appendix D, the measured particles are presented in different tables with different size ranges. If some of those ranges are more suitable to use, the total concentration mean values for those ranges can also be used to calculate the exposure as shown above. Short-term exposure can also be calculated e.g. for visitors. It is assumed that one tour at the plant takes 45 minutes and the tour is distributed as shown in Table 17.

Table 17: Example of calculated total exposure for a visitor

Location	Total measured concentration [p cm^{-3}]	Duration [min]
Control room 4th	2 461	10
Balcony 9th	15 700	5
Ammonia injection 4th	15 204	5
Fluegas cooling 4th	15 518	5
Fluegas silos 4th	18 857	5
Ground corridor 2th	13 462	5
Ground hatch	25 085	10

The total exposure is calculated as following:

$$C_{45min} = \frac{2461 \times 10 + 15700 \times 5 + 15204 \times 5 + 15518 \times 5}{45}$$

$$+ \frac{18857 \times 5 + 13462 \times 5 + 25085 \times 10}{45} = 14870\ pcm^{-3} \quad (4)$$

Compared to the background concentrations in European cities Alkmaar (20 480 pcm^{-3}), Erfurt (20 010 pcm^{-3}) and Helsinki (17 580 pcm^{-3}) the exposure to particles in the size range 10–500 nm in the calculated example is on a lower level than the exposure to particles in urban areas. This mostly depends on the fact that a part of

the working day is spent in the offices, where the concentrations are much lower than the urban background levels. During the visitor tour at the incineration plant, most of the tour is spent inside the plant hall, which is reflected in the calculated total particle exposure.

The obtained results from the measurement at the incineration plant can be compared to the results from the coal-fired and gas-fired power plants in USA. The particles are measured in different size ranges. In the power plants in USA, particle sizes over 20 nm have been measured and most of the particles that were found to exist in the range of 20–500 nm. By observing particles larger than 19.1 nm measured at the Westenergy incineration plant, the results of the two investigations can be compared. The values in Table 18 can be compared to the values obtained from the measurements done in coal-fired and gas-fired power plants in USA (Table 3).

Table 18: Total particle number concentrations measured at Westenergy incineration plant in the size range 19.1–560 nm

Point location	Mean [p cm^{-3}]
Balcony 9th	12 581
Boiler 8th	13 236
Crushing mill 4th	12 980
Ammonia injection 4th	10 770
Fluegas silos 4th	13 095
Fluegas cooling 4th	10 942
Ground corridor 2nd	10 307
Ground hatch 2nd	17 245
Ash hall 1st	17 909
Warehouse 3rd	3 425
Control Room 4th	1 523
Office 3rd	3 814
UnderBoiler	17 703
Middlebags	18 559
Underbags	15 380

As can be seen from the tables, the number concentrations in control rooms are at the same level at the coal-fired plants and Westenergy. Slightly higher concentrations were found in the control room at the gas-fired power plant. The fly ash areas at the coal-fired power plants can be compared to the flue gas hall measurements (silos, cooling, underboiler, middlebags, underbags) at Westenergy. The values measured at the coal-fired plants were 16 855 and 20 308 particles cm^{-3} respectively. At Westenergy, the highest concentration in the flue gas hall was in the middle of the bag filters, 18 559 particles cm^{-3} which is similar to the coal-fired plants.

The big differences between the particle concentrations at the coal-fired plants and Westenergy can be found near the combustion chamber. Measurement points near the chamber construction at Westenergy are ammonia injection, crushing mill, ground hatch and boiler. The highest concentration at Westenergy was monitored near the combustion grate, 17 245 particles cm^{-3}. At the coal-fired plants measurements near the combustion chamber gave particle concentrations of 70 713 and 59 533 particles cm^{-3} respectively. Hicks et al. (2011) suspected leakage of combustion emissions through the chamber structure, which may be a reason for the high concentrations. Due to the lower pressure inside the combustion process, compared to the surroundings at the Westenergy incineration plant, the risk of leakage is minimal, which can also be seen in the results.

At the time of the writing of this thesis, no limit values for exposure to ultrafine particles exists. The European Commission will most likely introduce a limit value for ultrafine particle pollution before 2020 (Press-Kristensen, 2012). As have been discussed earlier, the mass concentration do not give a representative value for ultrafine particles, therefore, the limit value will probably be expressed in number concentration. In most literature, ultrafine particles are defined as particles with a diameter of 100 nm ($PM_{0.1}$) and smaller and thus the limit value will probably also be set for $PM_{0.1}$ and smaller.

Most of the particles measured in this thesis are ultrafine particles. The total concentrations in the size range under 100 nm was calculated and the values can be seen in Appendix D. The measured values can be compared to future limit values for ultrafine particles.

7 Conclusions and recommendations

The presence of dust and particles in indoor air at the Westenergy waste incineration plant was investigated. The total particle number concentration and the size distribution in a size range of 5.6–560 nm was measured with an Engine Exhaust Particle Sizer spectrometer. By visual dust analysis, some conclusions about the presence of larger particles could also be made.

The measurements of ultrafine particles and analysis of visual dust were conducted at several locations inside the incineration plant. The measurement points were restricted to where visitors and workers mostly move inside the plant. The exposure to particles at the different points was investigated. An overall picture of the ultrafine particle concentrations inside the plant was received.

It can be concluded that the outside air is the main source of dust and larger particles in the air because no dust causing activities, except in the bottom ash hall, take place in the incineration plant. The measurements with the EEPS and the visual dust analysis gave no indications of fugitive emissions from the handling of fly ashes at the bag filters or under the boiler. Particles from the handling of bottom ashes remain in the bottom hall. The only way particles from the bottom ash hall could enter the plant hall is through the outside air, when the doors in the ash hall are opened.

Some of the ultrafine particles are probably a result of traffic in the area around the incineration plant and some of the plant's flue gases may form ultrafine particles and enter the building with the outside air. Another known source is the personal cloud, which rises near individuals moving in the plant. Gases inside the building and in the ambient air probably form the main part of the ultrafine particles present, but without any further analysis, it is hard to say which gases. The dust most likely originates from the activities taking place in the area surrounding the incineration plant, e.g. stone crushing and ground work.

Compared to the background measurements, the measured ultrafine particle concentrations inside the Westenergy incineration plant are in feasible ranges. According to one source the air can be seen as polluted when the concentrations exceed 50 000

particles cm^{-3} and at this concentration, people immediately feel the presence of particles and asthmatics can get reactions (Philips Aerasense, 2013). The highest total ultrafine particle concentration measured at Westenergy was 32 616 particles cm^{-3} in the MiddleBags. The highest measured concentration is thus lower than the polluted air level. Short-term exposures to ultrafine particles can worsen asthma symptoms and coronary artery diseases. No investigations considering long-term effects of ultrafine particle exposure exist, but a lot of research in that area is being done at the moment (Salonen and Pennanen, 2006).

Due to the relatively low concentrations of ultrafine particles there is no need for a continuous measurement system. The presence of deposited dust can sufficiently be investigated with cheaper methods and one system for controlling ammonia leakage already exists at the plant. Even if dust and ultrafine particles should be classified as different pollutants, a correlation between the two pollutants could be seen in this thesis. It can be assumed that more ultrafine particles exist where dust is strongly present at surfaces. The temperature and relative humidity can be misleading when defining where the air is cleanest.

The dust and particle concentrations could be decreased inside the plant hall. The best way to minimize exposure to dust and particles is to remove the emitting source. It is difficult to remove particles that are already present in the indoor air. The source of ultrafine particles in the incineration facility is not known for sure as discussed in the previous chapter. The source of the dust present is most likely the outdoor air, because no main dust causing activities are taking place inside the facility, except in the bottom ash hall. One way to reduce the deposited dust is cleaning of spaces and surfaces, which according to the measurements, decreases the particle concentrations. It is, however, unnecessary to constantly clean surfaces in the plant if nothing is done to the contaminating source.

The difference between the air in the offices and the air in the plant hall is that the air for the offices is taken in through a ventilation system. Ventilation systems usually have filters that can remove up to 95% of particles present in the outside air. The benefits with a cleaner indoor air are many, occupants are protected from irritating and harmful particles, the exposure to particles and contaminants attached on the par-

ticles is minimized, wear and contamination of surfaces is reduced, maintenance and cleaning costs are reduced and the health of personnel and visitors improved.

Some sort of air filtration, cleaning of the outside air taken in to the plant hall should be installed. When installing a filtration system, the life cycle cost of the filtration and air cleaning should be taken into consideration. The best filter is a filter with the required efficiency, requiring the least pressure drop and which last the longest. Then, the filter has the lowest energy usage and smallest handling and disposal costs. The efficiency of a filter depends on the particle size and also on the type and loading characteristics of the filter media (Burroughs and Hansen, 2011).

Table 19: MERV = Minimum Efficiency Reporting Value. MERV filter levels compared to removal efficiency of particles (Burroughs and Hansen, 2011).

MERV level	Original dust point [%]	0.3–1 μm [%]	1–3 μm [%]	3–10 μm [%]
7	25–30			50–70
8	30–35			>70
9	40–45		>50	>85
10	50–55		50–65	>85
11	60–65		65–80	>85
12	70–75		>80	>90
13	80–85	>75	>90	>90
14	90–95	75–85	>90	>90
15	>95	85–95	>90	>90
16	98	>95	>95	>95

In this case, the filters should at least remove larger particles ($\geq$ 10 μm) because these are the particles causing the deposited dust inside the incineration building and are most certainly getting indoors with the outside air. To keep surfaces and spaces cleaner, a filter with a MERV value between 8 and 13 should be sufficient, see table 19. Also smaller particles caused by the traffic, would be partly removed with a filter in that range. Air filters should be installed on the ventilation hatches on the roof and

in the openings on the side walls.

It is more challenging to decrease the amount of dust and particles in the bottom ash hall. The source of the pollutants is known, but the source cannot be removed in this case. To even further encapsulate the shaking conveyor, could be a possible solution. Some kind of mask would be advisable to use when doing maintenance in the bottom ash hall. The particles and dust in the air near the bag filters and chain conveyors could be reduced by cleaning the areas.

8 Discussion

Some conclusions could be made out of the investigations carried out at the Westenergy incineration plant. However, further investigation is needed to better understand the exposure of particles to worker and visitors inside the plant. Due to the personal cloud, the particle exposure is probably higher than the concentrations measured inside the plant. To investigate this, personal meters measuring the particle concentrations should be carried by the persons moving inside the plant.

To detect the source of ultrafine particles, the elemental composition of the particles should be analysed. If the particles would for example contain a lot of metals, it can be assumed they originate from the waste combustion process. The particle content can also tell the toxicity of the particles, for example if they contain mould, bacteria, viruses or other, to the human harmful compounds. This is important when considering the health effects of the particles present at the incineration plant.

By the measurements conducted in this thesis, an overall picture was obtained. Dust and particles were found to exist inside the building and suggestions for how to minimize these were given. The concentrations in the measured ranges were, however, not observed to be alarming and thus no further actions, at least in terms of ultrafine particles, needs to be taken at this point. Limit values that will be set in the future, will give a better estimation of the cleanliness of the indoor air at the incineration plant. From my point of view, the dust problem could quite easily be taken care of and actions to minimize dust accumulation should be taken. A better working environment

gives better results on the whole.

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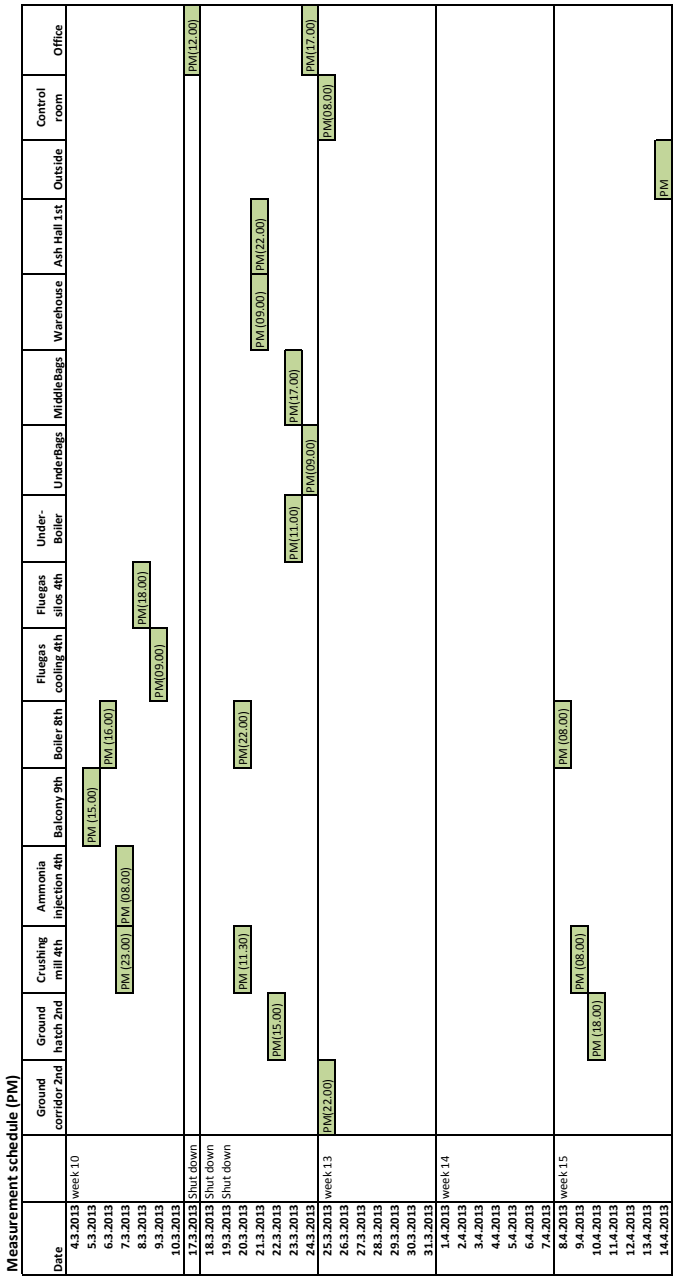
A Measurement schedule



B Measured values

Mean values (Normalized number concentrations dN/dlogDp [#/cm3])

Channel Size [nm]:	Balcony 9th	Boiler 8th	Crushing mill 4th	Ammonia injection 4th	Fluegas silos 4th	Fluegas cooling 4th	Ground corridor 2nd	Ground hatch 2nd	Ash hall 1st	Mean (Plant hall)
6,04	900,63	11972,91	33097,53	3661,18	9811,32	370,87	9243,05	2243,96	12001,84	**9255,92**
6,98	10587,28	9621,12	25193,76	6571,37	6578,38	7363,31	4521,96	10719,75	18392,61	**11061,06**
8,06	15891,71	16354,04	28133,18	10959,61	8784,47	14439,80	5047,34	20210,50	26818,07	**16293,19**
9,31	12101,21	32818,41	41518,14	16106,04	18790,20	19342,80	9697,91	30303,46	39451,27	**24458,83**
10,80	10252,68	36928,46	42213,86	17873,55	23326,77	20284,20	11919,12	33257,26	41136,32	**26354,69**
12,40	9674,54	28598,91	29504,82	15289,16	21626,97	16865,10	10091,66	28090,09	31425,05	**21240,70**
14,30	11023,62	25094,56	23981,57	15021,86	21658,11	15847,05	9156,77	27523,82	28772,71	**19786,67**
16,50	13910,89	26415,41	25644,13	16803,51	22856,55	17226,21	9084,96	31278,65	33408,74	**21847,67**
19,10	15607,79	25620,43	25281,42	15760,76	22601,98	16417,49	8716,07	30514,59	34598,94	**21679,94**
22,10	16114,32	22709,62	22893,45	11895,36	20894,42	13423,47	8050,09	25230,97	32339,10	**19283,42**
25,50	17937,41	23220,49	22953,16	11871,39	21441,83	14364,10	8965,54	25191,55	32113,33	**19784,31**
29,40	21077,07	27153,04	25460,55	15662,27	24244,20	19247,11	11460,11	30396,33	33921,61	**23180,25**
34,00	21458,67	27129,87	24504,02	16964,64	24261,55	20861,90	12646,59	31307,48	32733,72	**23540,94**
39,20	19082,22	23150,97	20083,58	15767,88	21493,88	19208,47	12524,22	27924,99	28549,66	**20865,10**
45,30	17003,02	18931,19	16186,45	14616,83	18527,99	17157,95	11698,13	24301,53	23792,52	**18023,96**
52,30	15221,08	14470,54	12812,63	13511,47	15363,87	14710,36	10168,32	20437,07	18462,29	**15017,51**
60,40	13019,14	10320,21	9677,70	12003,15	12129,81	11805,98	9423,07	16589,06	14081,39	**12116,61**
69,80	10397,22	6480,21	6781,65	10091,87	8825,80	8444,83	9462,38	12757,50	10649,81	**9321,25**
80,60	8184,14	3890,24	4807,19	8523,66	6149,40	5924,82	9778,78	9660,53	7765,06	**7187,09**
93,10	6379,93	2550,32	3753,89	7298,51	4100,61	4245,95	10372,26	7298,17	5427,11	**5714,08**
107,50	5041,62	1682,65	2917,76	5957,53	2723,56	3001,66	10248,73	5305,14	3639,53	**4502,02**
124,10	4169,21	1287,25	2298,64	4500,69	2018,25	2191,96	9408,21	3681,43	2402,32	**3550,88**
143,30	3354,46	934,81	1750,42	3251,17	1505,16	1536,62	7834,09	2405,95	1522,67	**2677,26**
165,50	2597,37	625,31	1273,09	2208,95	1184,27	1035,66	5526,38	1478,69	1000,58	**1881,15**
191,10	1889,58	392,20	904,70	1372,45	867,98	652,97	3618,07	812,46	652,33	**1240,30**
220,70	1231,06	235,70	645,25	741,65	556,26	388,57	2109,16	406,91	477,91	**754,72**
254,80	741,37	159,29	501,82	268,08	318,59	204,04	1127,88	147,61	397,36	**429,56**
294,30	420,49	159,61	474,42	47,83	159,69	107,09	674,24	38,49	410,67	**276,95**
339,80	204,55	166,40	458,87	4,98	69,70	56,87	396,53	7,37	420,23	**198,39**
392,40	97,30	178,98	455,19	0,00	39,62	33,63	294,75	6,14	426,05	**170,18**
453,20	43,77	174,08	428,60	0,00	26,85	26,26	222,02	7,03	404,10	**148,08**
523,30	30,53	151,70	379,10	0,00	20,89	20,43	178,35	9,91	354,38	**127,25**
Total	**17852,10**	**24974,13**	**28560,59**	**17162,74**	**21434,50**	**17926,28**	**14603,63**	**28722,42**	**32371,74**	**22623,13**
Min	**30,53**	**151,70**	**379,10**	**0,00**	**20,89**	**20,43**	**178,35**	**6,14**	**354,38**	
Max	**21458,67**	**36928,46**	**42213,86**	**17873,55**	**24261,55**	**20861,90**	**12646,59**	**33257,26**	**41136,32**	

Mean values (Normalized number concentrations dN/dlogDp [#/cm3])

Channel Size [nm]:	Warehouse	Control room	Office	Mean (Offices)	Under-Boiler	Middlebags	Underbags	Mean (Fugitive)	Outside
6,04	6713,19	3929,28	5634,95	**5425,81**	999,67	15094,90	16219,37	**10771,32**	1974,99
6,98	2589,55	346,24	4758,46	**2564,75**	6487,99	7883,68	8756,76	**7709,48**	106,89
8,06	2439,80	101,89	8939,85	**3827,18**	17745,45	15224,32	12146,15	**15038,64**	229,75
9,31	5322,67	2074,54	17652,51	**8349,91**	34781,06	37708,67	25869,56	**32786,43**	835,31
10,80	6574,84	3853,31	20436,14	**10288,10**	40629,68	45103,79	31109,03	**38947,50**	1101,31
12,40	4284,53	3779,07	16544,86	**8202,82**	34513,55	37362,11	27633,98	**33169,88**	719,90
14,30	3566,27	3851,68	14457,80	**7291,92**	32711,48	34627,87	25447,08	**30928,81**	455,36
16,50	4337,65	3360,29	14032,81	**7243,58**	35223,48	36901,08	24548,33	**32224,30**	221,86
19,10	4342,62	2589,53	12064,34	**6332,16**	34977,05	36502,20	23199,66	**31559,64**	150,49
22,10	3603,94	1664,90	8560,40	**4609,75**	31972,19	33431,24	21401,07	**28934,83**	157,73
25,50	4548,58	1580,51	6864,03	**4331,04**	32532,50	33763,74	23594,53	**29963,59**	218,61
29,40	7322,90	2546,75	7031,98	**5633,88**	36657,95	37499,69	29780,05	**34645,90**	581,28
34,00	8163,74	3301,17	6486,72	**5983,88**	35729,31	36528,38	31411,34	**34556,35**	1038,59
39,20	7062,77	3280,65	5087,30	**5143,57**	29746,57	30849,80	28488,41	**29694,93**	999,77
45,30	5786,39	2913,77	3957,54	**4219,23**	24249,86	25469,28	24570,39	**24763,18**	1075,54
52,30	4334,60	2204,38	3096,64	**3211,87**	19239,20	20386,84	19657,27	**19761,10**	1277,19
60,40	2901,16	1486,50	2243,77	**2210,48**	14218,04	15273,57	14833,58	**14775,06**	1185,77
69,80	1486,97	739,97	1384,62	**1203,85**	9186,39	10129,47	10099,31	**9805,06**	806,72
80,60	781,21	356,49	902,03	**679,91**	5581,22	6282,54	6630,46	**6164,74**	805,29
93,10	732,56	223,50	777,66	**577,91**	3402,51	3732,77	4427,02	**3854,10**	1126,00
107,50	720,45	169,01	665,20	**518,22**	1951,24	2102,35	2823,99	**2292,53**	1331,30
124,10	732,34	157,25	557,47	**482,35**	1227,41	1391,29	1821,37	**1480,02**	1428,39
143,30	625,53	154,94	431,53	**404,00**	724,47	913,82	1100,68	**912,99**	1354,27
165,50	399,69	125,88	287,30	**270,95**	442,47	669,95	661,90	**591,44**	1108,94
191,10	230,75	95,88	180,85	**169,16**	260,73	471,35	360,75	**364,28**	858,34
220,70	118,96	60,43	103,59	**94,33**	172,55	318,04	197,69	**229,43**	602,46
254,80	82,66	58,16	49,63	**63,48**	135,57	231,84	128,93	**165,45**	399,47
294,30	121,69	89,79	33,30	**81,59**	145,29	209,32	147,12	**167,24**	249,37
339,80	156,44	120,62	48,90	**108,65**	163,64	199,86	170,02	**177,84**	133,00
392,40	185,45	147,66	65,41	**132,84**	186,02	204,07	197,15	**195,74**	52,59
453,20	191,12	155,14	71,56	**139,27**	186,74	197,87	201,58	**195,40**	21,92
523,30	173,24	143,03	65,27	**127,18**	165,82	180,90	182,47	**176,40**	16,80
Total	**5664,74**	**2854,01**	**10216,52**	**6245,09**	**30394,10**	**32927,43**	**26114,24**	**29811,92**	**1413,72**
Min	**82,66**	**58,16**	**33,30**		**135,57**	**180,90**	**128,93**		**16,80**
Max	**8163,74**	**3929,28**	**20436,14**		**40629,68**	**45103,79**	**31411,34**		**1974,99**

C Mass, volume and surface area

Normalized volume concentrations dV/dlogDp [nm3/cm3]

Channel Size [nm]:	Mean (Plant hall)	Mean (Offices)	Mean (Fugitive)	Outside
6,04	1,07E+06	6,26E+05	1,24E+06	2,28E+05
6,98	1,97E+06	4,57E+05	1,37E+06	1,90E+04
8,06	4,47E+06	1,05E+06	4,12E+06	6,30E+04
9,31	1,03E+07	3,53E+06	1,39E+07	3,53E+05
10,80	1,74E+07	6,79E+06	2,57E+07	7,26E+05
12,40	2,12E+07	8,19E+06	3,31E+07	7,19E+05
14,30	3,03E+07	1,12E+07	4,74E+07	6,97E+05
16,50	5,14E+07	1,70E+07	7,58E+07	5,22E+05
19,10	7,91E+07	2,31E+07	1,15E+08	5,49E+05
22,10	1,09E+08	2,61E+07	1,64E+08	8,91E+05
25,50	1,72E+08	3,76E+07	2,60E+08	1,90E+06
29,40	3,08E+08	7,50E+07	4,61E+08	7,73E+06
34,00	4,84E+08	1,23E+08	7,11E+08	2,14E+07
39,20	6,58E+08	1,62E+08	9,37E+08	3,15E+07
45,30	8,77E+08	2,05E+08	1,21E+09	5,24E+07
52,30	1,12E+09	2,41E+08	1,48E+09	9,57E+07
60,40	1,40E+09	2,55E+08	1,70E+09	1,37E+08
69,80	1,66E+09	2,14E+08	1,75E+09	1,44E+08
80,60	1,97E+09	1,86E+08	1,69E+09	2,21E+08
93,10	2,41E+09	2,44E+08	1,63E+09	4,76E+08
107,50	2,93E+09	3,37E+08	1,49E+09	8,66E+08
124,10	3,55E+09	4,83E+08	1,48E+09	1,43E+09
143,30	4,13E+09	6,22E+08	1,41E+09	2,09E+09
165,50	4,46E+09	6,43E+08	1,40E+09	2,63E+09
191,10	4,53E+09	6,18E+08	1,33E+09	3,14E+09
220,70	4,25E+09	5,31E+08	1,29E+09	3,39E+09
254,80	3,72E+09	5,50E+08	1,43E+09	3,46E+09
294,30	3,70E+09	1,09E+09	2,23E+09	3,33E+09
339,80	4,08E+09	2,23E+09	3,65E+09	2,73E+09
392,40	5,38E+09	4,20E+09	6,19E+09	1,66E+09
453,20	7,22E+09	6,79E+09	9,52E+09	1,07E+09
523,30	9,55E+09	9,54E+09	1,32E+10	1,26E+09

Normalized total surface area dS/dlogDp [nm2/cm3]

Mean (Plant hall)	Mean (Offices)	Mean (Fugitive)	Outside
1,06E+06	6,22E+05	1,23E+06	2,26E+05
1,69E+06	3,93E+05	1,18E+06	1,64E+04
3,33E+06	7,81E+05	3,07E+06	4,69E+04
6,66E+06	2,27E+06	8,93E+06	2,27E+05
9,66E+06	3,77E+06	1,43E+07	4,04E+05
1,03E+07	3,96E+06	1,60E+07	3,48E+05
1,27E+07	4,68E+06	1,99E+07	2,93E+05
1,87E+07	6,20E+06	2,76E+07	1,90E+05
2,48E+07	7,26E+06	3,62E+07	1,72E+05
2,96E+07	7,07E+06	4,44E+07	2,42E+05
4,04E+07	8,85E+06	6,12E+07	4,47E+05
6,29E+07	1,53E+07	9,41E+07	1,58E+06
8,55E+07	2,17E+07	1,25E+08	3,77E+06
1,01E+08	2,48E+07	1,43E+08	4,83E+06
1,16E+08	2,72E+07	1,60E+08	6,93E+06
1,29E+08	2,76E+07	1,70E+08	1,10E+07
1,39E+08	2,53E+07	1,69E+08	1,36E+07
1,43E+08	1,84E+07	1,50E+08	1,23E+07
1,47E+08	1,39E+07	1,26E+08	1,64E+07
1,56E+08	1,57E+07	1,05E+08	3,07E+07
1,63E+08	1,88E+07	8,32E+07	4,83E+07
1,72E+08	2,33E+07	7,16E+07	6,91E+07
1,73E+08	2,61E+07	5,89E+07	8,74E+07
1,62E+08	2,33E+07	5,09E+07	9,54E+07
1,42E+08	1,94E+07	4,18E+07	9,85E+07
1,15E+08	1,44E+07	3,51E+07	9,22E+07
8,76E+07	1,29E+07	3,37E+07	8,15E+07
7,54E+07	2,22E+07	4,55E+07	6,79E+07
7,20E+07	3,94E+07	6,45E+07	4,82E+07
8,23E+07	6,43E+07	9,47E+07	2,54E+07
9,55E+07	8,99E+07	1,26E+08	1,41E+07
1,09E+08	1,09E+08	1,52E+08	1,45E+07

Normalized mass concentrations dM/dlogDp [µg/m3]

Channel Size [nm]:	Mean (Plant hall)	Mean (Offices)	Mean (Fugitive)	Outside
6,04	0,00	0,00	0,00	0,00
6,98	0,00	0,00	0,00	0,00
8,06	0,00	0,00	0,00	0,00
9,31	0,01	0,00	0,01	0,00
10,80	0,02	0,01	0,03	0,00
12,40	0,02	0,01	0,03	0,00
14,30	0,03	0,01	0,05	0,00
16,50	0,05	0,02	0,08	0,00
19,10	0,08	0,02	0,12	0,00
22,10	0,11	0,03	0,16	0,00
25,50	0,17	0,04	0,26	0,00
29,40	0,31	0,07	0,46	0,01
34,00	0,48	0,12	0,71	0,02
39,20	0,66	0,16	0,94	0,03
45,30	0,88	0,21	1,21	0,05
52,30	1,12	0,24	1,48	0,10
60,40	1,40	0,26	1,70	0,14
69,80	1,66	0,21	1,75	0,14
80,60	1,97	0,19	1,69	0,22
93,10	2,41	0,24	1,63	0,48
107,50	2,93	0,34	1,49	0,87
124,10	3,55	0,48	1,48	1,43
143,30	4,13	0,62	1,41	2,09
165,50	4,46	0,64	1,40	2,63
191,10	4,53	0,62	1,33	3,14
220,70	4,25	0,53	1,29	3,39
254,80	3,72	0,55	1,43	3,46
294,30	3,70	1,09	2,23	3,33
339,80	4,08	2,23	3,65	2,73
392,40	5,38	4,20	6,19	1,66
453,20	7,22	6,79	9,52	1,07
523,30	9,55	9,54	13,24	1,26

Density [µg/m3]
1,00E+12

D Different size ranges

Mean values (Number concentrations dN [#/cm3] (Normalized values * 1/16))

Channel Size [nm]:	Balcony 9th	Boiler 8th	Crushing mill 4th	Ammonia injection 4th	Fluegas silos 4th	Fluegas cooling 4th	Ground corridor 2nd	Ground hatch 2nd	Ash hall 1st	Mean (Plant hall)
6,04	56,29	748,31	2068,60	228,82	613,21	23,18	577,69	140,25	750,12	**578,49**
6,98	661,70	601,32	1574,61	410,71	411,15	460,21	282,62	669,98	1149,54	**691,32**
8,06	993,23	1022,13	1758,32	684,98	549,03	902,49	315,46	1263,16	1676,13	**1018,32**
9,31	756,33	2051,15	2594,88	1006,63	1174,39	1208,92	606,12	1893,97	2465,70	**1528,68**
10,80	640,79	2308,03	2638,37	1117,10	1457,92	1267,76	744,95	2078,58	2571,02	**1647,17**
12,40	604,66	1787,43	1844,05	955,57	1351,69	1054,07	630,73	1755,63	1964,07	**1327,54**
14,30	688,98	1568,41	1498,85	938,87	1353,63	990,44	572,30	1720,24	1798,29	**1236,67**
16,50	869,43	1650,96	1602,76	1050,22	1428,53	1076,64	567,81	1954,92	2088,05	**1365,48**
19,10	975,49	1601,28	1580,09	985,05	1412,62	1026,09	544,75	1907,16	2162,43	**1355,00**
22,10	1007,14	1419,35	1430,84	743,46	1305,90	838,97	503,13	1576,94	2021,19	**1205,21**
25,50	1121,09	1451,28	1434,57	741,96	1340,11	897,76	560,35	1574,47	2007,08	**1236,52**
29,40	1317,32	1697,07	1591,28	978,89	1515,26	1202,94	716,26	1899,77	2120,10	**1448,77**
34,00	1341,17	1695,62	1531,50	1060,29	1516,35	1303,87	790,41	1956,72	2045,86	**1471,31**
39,20	1192,64	1446,94	1255,22	985,49	1343,37	1200,53	782,76	1745,31	1784,35	**1304,07**
45,30	1062,69	1183,20	1011,65	913,55	1158,00	1072,37	731,13	1518,85	1487,03	**1126,50**
52,30	951,32	904,41	800,79	844,47	960,24	919,40	635,52	1277,32	1153,89	**938,59**
60,40	813,70	645,01	604,86	750,20	758,11	737,87	588,94	1036,82	880,09	**757,29**
69,80	649,83	405,01	423,85	630,74	551,61	527,80	591,40	797,34	665,61	**582,58**
80,60	511,51	243,14	300,45	532,73	384,34	370,30	611,17	603,78	485,32	**449,19**
93,10	398,75	159,39	234,62	456,16	256,29	265,37	648,27	456,14	339,19	**357,13**
107,50	315,10	105,17	182,36	372,35	170,22	187,60	640,55	331,57	227,47	**281,38**
124,10	260,58	80,45	143,66	281,29	126,14	137,00	588,01	230,09	150,14	**221,93**
143,30	209,65	58,43	109,40	203,20	94,07	96,04	489,63	150,37	95,17	**167,33**
165,50	162,34	39,08	79,57	138,06	74,02	64,73	345,40	92,42	62,54	**117,57**
191,10	118,10	24,51	56,54	85,78	54,25	40,81	226,13	50,78	40,77	**77,52**
220,70	76,94	14,73	40,33	46,35	34,77	24,29	131,82	25,43	29,87	**47,17**
254,80	46,34	9,96	31,36	16,76	19,91	12,75	70,49	9,23	24,84	**26,85**
294,30	26,28	9,98	29,65	2,99	9,98	6,69	42,14	2,41	25,67	**17,31**
339,80	12,78	10,40	28,68	0,31	4,36	3,55	24,78	0,46	26,26	**12,40**
392,40	6,08	11,19	28,45	0,00	2,48	2,10	18,42	0,38	26,63	**10,64**
453,20	2,74	10,88	26,79	0,00	1,68	1,64	13,88	0,44	25,26	**9,25**
523,30	1,91	9,48	23,69	0,00	1,31	1,28	11,15	0,62	22,15	**7,95**
Total	**17852,10**	**24974,13**	**28560,59**	**17162,74**	**21434,50**	**17926,28**	**14603,63**	**28722,42**	**32371,74**	**22623,13**
Min	**1,91**	**9,48**	**23,69**	**0,00**	**1,31**	**1,28**	**11,15**	**0,38**	**22,15**	
Max	**1341,17**	**2308,03**	**2638,37**	**1117,10**	**1516,35**	**1303,87**	**790,41**	**2078,58**	**2571,02**	

Mean values (Number concentrations dN [#/cm3] (Normalized values * 1/16))

Channel Size [nm]:	Warehouse	Control room	Office	Mean (Offices)	Under-Boiler	Middlebags	Underbags	Mean (Fugitive)
6,04	419,57	245,58	352,18	**339,11**	62,48	943,43	1013,71	**673,21**
6,98	161,85	21,64	297,40	**160,30**	405,50	492,73	547,30	**481,84**
8,06	152,49	6,37	558,74	**239,20**	1109,09	951,52	759,13	**939,92**
9,31	332,67	129,66	1103,28	**521,87**	2173,82	2356,79	1616,85	**2049,15**
10,80	410,93	240,83	1277,26	**643,01**	2539,36	2818,99	1944,31	**2434,22**
12,40	267,78	236,19	1034,05	**512,68**	2157,10	2335,13	1727,12	**2073,12**
14,30	222,89	240,73	903,61	**455,74**	2044,47	2164,24	1590,44	**1933,05**
16,50	271,10	210,02	877,05	**452,72**	2201,47	2306,32	1534,27	**2014,02**
19,10	271,41	161,85	754,02	**395,76**	2186,07	2281,39	1449,98	**1972,48**
22,10	225,25	104,06	535,02	**288,11**	1998,26	2089,45	1337,57	**1808,43**
25,50	284,29	98,78	429,00	**270,69**	2033,28	2110,23	1474,66	**1872,72**
29,40	457,68	159,17	439,50	**352,12**	2291,12	2343,73	1861,25	**2165,37**
34,00	510,23	206,32	405,42	**373,99**	2233,08	2283,02	1963,21	**2159,77**
39,20	441,42	205,04	317,96	**321,47**	1859,16	1928,11	1780,53	**1855,93**
45,30	361,65	182,11	247,35	**263,70**	1515,62	1591,83	1535,65	**1547,70**
52,30	270,91	137,77	193,54	**200,74**	1202,45	1274,18	1228,58	**1235,07**
60,40	181,32	92,91	140,24	**138,15**	888,63	954,60	927,10	**923,44**
69,80	92,94	46,25	86,54	**75,24**	574,15	633,09	631,21	**612,82**
80,60	48,83	22,28	56,38	**42,49**	348,83	392,66	414,40	**385,30**
93,10	45,78	13,97	48,60	**36,12**	212,66	233,30	276,69	**240,88**
107,50	45,03	10,56	41,57	**32,39**	121,95	131,40	176,50	**143,28**
124,10	45,77	9,83	34,84	**30,15**	76,71	86,96	113,84	**92,50**
143,30	39,10	9,68	26,97	**25,25**	45,28	57,11	68,79	**57,06**
165,50	24,98	7,87	17,96	**16,93**	27,65	41,87	41,37	**36,96**
191,10	14,42	5,99	11,30	**10,57**	16,30	29,46	22,55	**22,77**
220,70	7,44	3,78	6,47	**5,90**	10,78	19,88	12,36	**14,34**
254,80	5,17	3,64	3,10	**3,97**	8,47	14,49	8,06	**10,34**
294,30	7,61	5,61	2,08	**5,10**	9,08	13,08	9,20	**10,45**
339,80	9,78	7,54	3,06	**6,79**	10,23	12,49	10,63	**11,12**
392,40	11,59	9,23	4,09	**8,30**	11,63	12,75	12,32	**12,23**
453,20	11,95	9,70	4,47	**8,70**	11,67	12,37	12,60	**12,21**
523,30	10,83	8,94	4,08	**7,95**	10,36	11,31	11,40	**11,02**
Total	**5664,74**	**2854,01**	**10216,52**	**6245,09**	**30394,10**	**32927,43**	**26114,24**	**29811,92**
Min	**5,17**	**3,64**	**2,08**		**8,47**	**11,31**	**8,06**	
Max	**510,23**	**245,58**	**1277,26**		**2539,36**	**2818,99**	**1963,21**	

Total concentration 10,8 - 107,5 nm

Channel Size [nm]:	Balcony 9th	Boiler 8th	Crushing mill 4th	Ammonia injection 4th	Fluegas silos 4th	Fluegas cooling 4th	Ground corridor 2nd	Ground hatch 2nd	Ash hall 1st	Mean (Plant hall)
10,80	640,79	2308,03	2638,37	1117,10	1457,92	1267,76	744,95	2078,58	2571,02	**1647,17**
12,40	604,66	1787,43	1844,05	955,57	1351,69	1054,07	630,73	1755,63	1964,07	**1327,54**
14,30	688,98	1568,41	1498,85	938,87	1353,63	990,44	572,30	1720,24	1798,29	**1236,67**
16,50	869,43	1650,96	1602,76	1050,22	1428,53	1076,64	567,81	1954,92	2088,05	**1365,48**
19,10	975,49	1601,28	1580,09	985,05	1412,62	1026,09	544,75	1907,16	2162,43	**1355,00**
22,10	1007,14	1419,35	1430,84	743,46	1305,90	838,97	503,13	1576,94	2021,19	**1205,21**
25,50	1121,09	1451,28	1434,57	741,96	1340,11	897,76	560,35	1574,47	2007,08	**1236,52**
29,40	1317,32	1697,07	1591,28	978,89	1515,26	1202,94	716,26	1899,77	2120,10	**1448,77**
34,00	1341,17	1695,62	1531,50	1060,29	1516,35	1303,87	790,41	1956,72	2045,86	**1471,31**
39,20	1192,64	1446,94	1255,22	985,49	1343,37	1200,53	782,76	1745,31	1784,35	**1304,07**
45,30	1062,69	1183,20	1011,65	913,55	1158,00	1072,37	731,13	1518,85	1487,03	**1126,50**
52,30	951,32	904,41	800,79	844,47	960,24	919,40	635,52	1277,32	1153,89	**938,59**
60,40	813,70	645,01	604,86	750,20	758,11	737,87	588,94	1036,82	880,09	**757,29**
69,80	649,83	405,01	423,85	630,74	551,61	527,80	591,40	797,34	665,61	**582,58**
80,60	511,51	243,14	300,45	532,73	384,34	370,30	611,17	603,78	485,32	**449,19**
93,10	398,75	159,39	234,62	456,16	256,29	265,37	648,27	456,14	339,19	**357,13**
107,50	315,10	105,17	182,36	372,35	170,22	187,60	640,55	331,57	227,47	**281,38**
Total	**14461,58**	**20271,69**	**19966,11**	**14057,09**	**18264,21**	**14939,79**	**10860,43**	**24191,54**	**25801,06**	**18090,39**

Total concentration 10,8 - 107,5 nm

Channel Size [nm]:	Warehouse	Control room	Office	Mean (Offices)	Under-Boiler	Middlebags	Underbags	Mean (Fugitive)
10,80	410,93	240,83	1277,26	**643,01**	2539,36	2818,99	1944,31	**2434,22**
12,40	267,78	236,19	1034,05	**512,68**	2157,10	2335,13	1727,12	**2073,12**
14,30	222,89	240,73	903,61	**455,74**	2044,47	2164,24	1590,44	**1933,05**
16,50	271,10	210,02	877,05	**452,72**	2201,47	2306,32	1534,27	**2014,02**
19,10	271,41	161,85	754,02	**395,76**	2186,07	2281,39	1449,98	**1972,48**
22,10	225,25	104,06	535,02	**288,11**	1998,26	2089,45	1337,57	**1808,43**
25,50	284,29	98,78	429,00	**270,69**	2033,28	2110,23	1474,66	**1872,72**
29,40	457,68	159,17	439,50	**352,12**	2291,12	2343,73	1861,25	**2165,37**
34,00	510,23	206,32	405,42	**373,99**	2233,08	2283,02	1963,21	**2159,77**
39,20	441,42	205,04	317,96	**321,47**	1859,16	1928,11	1780,53	**1855,93**
45,30	361,65	182,11	247,35	**263,70**	1515,62	1591,83	1535,65	**1547,70**
52,30	270,91	137,77	193,54	**200,74**	1202,45	1274,18	1228,58	**1235,07**
60,40	181,32	92,91	140,24	**138,15**	888,63	954,60	927,10	**923,44**
69,80	92,94	46,25	86,54	**75,24**	574,15	633,09	631,21	**612,82**
80,60	48,83	22,28	56,38	**42,49**	348,83	392,66	414,40	**385,30**
93,10	45,78	13,97	48,60	**36,12**	212,66	233,30	276,69	**240,88**
107,50	45,03	10,56	41,57	**32,39**	121,95	131,40	176,50	**143,28**
Total	**4409,45**	**2368,84**	**7787,11**	**4855,13**	**26407,64**	**27871,67**	**21853,47**	**25377,59**

Total concentration 107,5 - 560 nm

Channel Size [nm]:	Balcony 9th	Boiler 8th	Crushing mill 4th	Ammonia injection 4th	Fluegas silos 4th	Fluegas cooling 4th	Ground corridor 2nd	Ground hatch 2nd	Ash hall 1st	Mean (Plant hall)
107,50	315,10	105,17	182,36	372,35	170,22	187,60	640,55	331,57	227,47	**281,38**
124,10	260,58	80,45	143,66	281,29	126,14	137,00	588,01	230,09	150,14	**221,93**
143,30	209,65	58,43	109,40	203,20	94,07	96,04	489,63	150,37	95,17	**167,33**
165,50	162,34	39,08	79,57	138,06	74,02	64,73	345,40	92,42	62,54	**117,57**
191,10	118,10	24,51	56,54	85,78	54,25	40,81	226,13	50,78	40,77	**77,52**
220,70	76,94	14,73	40,33	46,35	34,77	24,29	131,82	25,43	29,87	**47,17**
254,80	46,34	9,96	31,36	16,76	19,91	12,75	70,49	9,23	24,84	**26,85**
294,30	26,28	9,98	29,65	2,99	9,98	6,69	42,14	2,41	25,67	**17,31**
339,80	12,78	10,40	28,68	0,31	4,36	3,55	24,78	0,46	26,26	**12,40**
392,40	6,08	11,19	28,45	0,00	2,48	2,10	18,42	0,38	26,63	**10,64**
453,20	2,74	10,88	26,79	0,00	1,68	1,64	13,88	0,44	25,26	**9,25**
523,30	1,91	9,48	23,69	0,00	1,31	1,28	11,15	0,62	22,15	**7,95**
Totalt	**1238,83**	**384,25**	**780,49**	**1147,08**	**593,18**	**578,48**	**2602,40**	**894,20**	**756,76**	**997,30**

Total concentration 107,5 - 560 nm

Channel Size [nm]:	Warehouse	Control room	Office	Mean (Offices)	Under-Boiler	Middlebags	Underbags	Mean (Fugitive)
107,50	45,03	10,56	41,57	**32,39**	121,95	131,40	176,50	**143,28**
124,10	45,77	9,83	34,84	**30,15**	76,71	86,96	113,84	**92,50**
143,30	39,10	9,68	26,97	**25,25**	45,28	57,11	68,79	**57,06**
165,50	24,98	7,87	17,96	**16,93**	27,65	41,87	41,37	**36,96**
191,10	14,42	5,99	11,30	**10,57**	16,30	29,46	22,55	**22,77**
220,70	7,44	3,78	6,47	**5,90**	10,78	19,88	12,36	**14,34**
254,80	5,17	3,64	3,10	**3,97**	8,47	14,49	8,06	**10,34**
294,30	7,61	5,61	2,08	**5,10**	9,08	13,08	9,20	**10,45**
339,80	9,78	7,54	3,06	**6,79**	10,23	12,49	10,63	**11,12**
392,40	11,59	9,23	4,09	**8,30**	11,63	12,75	12,32	**12,23**
453,20	11,95	9,70	4,47	**8,70**	11,67	12,37	12,60	**12,21**
523,30	10,83	8,94	4,08	**7,95**	10,36	11,31	11,40	**11,02**
Totalt	**233,65**	**92,36**	**160,00**	**162,00**	**360,12**	**443,17**	**499,60**	**434,30**

Total concentrations 19,1 - 560 nm

Channel Size [nm]:	Balcony 9th	Boiler 8th	Crushing mill 4th	Ammonia injection 4th	Fluegas silos 4th	Fluegas cooling 4th	Ground corridor 2nd	Ground hatch 2nd	Ash hall 1st	Mean (Plant hall)
19,10	975,49	1601,28	1580,09	985,05	1412,62	1026,09	544,75	1907,16	2162,43	**1355,00**
22,10	1007,14	1419,35	1430,84	743,46	1305,90	838,97	503,13	1576,94	2021,19	**1205,21**
25,50	1121,09	1451,28	1434,57	741,96	1340,11	897,76	560,35	1574,47	2007,08	**1236,52**
29,40	1317,32	1697,07	1591,28	978,89	1515,26	1202,94	716,26	1899,77	2120,10	**1448,77**
34,00	1341,17	1695,62	1531,50	1060,29	1516,35	1303,87	790,41	1956,72	2045,86	**1471,31**
39,20	1192,64	1446,94	1255,22	985,49	1343,37	1200,53	782,76	1745,31	1784,35	**1304,07**
45,30	1062,69	1183,20	1011,65	913,55	1158,00	1072,37	731,13	1518,85	1487,03	**1126,50**
52,30	951,32	904,41	800,79	844,47	960,24	919,40	635,52	1277,32	1153,89	**938,59**
60,40	813,70	645,01	604,86	750,20	758,11	737,87	588,94	1036,82	880,09	**757,29**
69,80	649,83	405,01	423,85	630,74	551,61	527,80	591,40	797,34	665,61	**582,58**
80,60	511,51	243,14	300,45	532,73	384,34	370,30	611,17	603,78	485,32	**449,19**
93,10	398,75	159,39	234,62	456,16	256,29	265,37	648,27	456,14	339,19	**357,13**
107,50	315,10	105,17	182,36	372,35	170,22	187,60	640,55	331,57	227,47	**281,38**
124,10	260,58	80,45	143,66	281,29	126,14	137,00	588,01	230,09	150,14	**221,93**
143,30	209,65	58,43	109,40	203,20	94,07	96,04	489,63	150,37	95,17	**167,33**
165,50	162,34	39,08	79,57	138,06	74,02	64,73	345,40	92,42	62,54	**117,57**
191,10	118,10	24,51	56,54	85,78	54,25	40,81	226,13	50,78	40,77	**77,52**
220,70	76,94	14,73	40,33	46,35	34,77	24,29	131,82	25,43	29,87	**47,17**
254,80	46,34	9,96	31,36	16,76	19,91	12,75	70,49	9,23	24,84	**26,85**
294,30	26,28	9,98	29,65	2,99	9,98	6,69	42,14	2,41	25,67	**17,31**
339,80	12,78	10,40	28,68	0,31	4,36	3,55	24,78	0,46	26,26	**12,40**
392,40	6,08	11,19	28,45	0,00	2,48	2,10	18,42	0,38	26,63	**10,64**
453,20	2,74	10,88	26,79	0,00	1,68	1,64	13,88	0,44	25,26	**9,25**
523,30	1,91	9,48	23,69	0,00	1,31	1,28	11,15	0,62	22,15	**7,95**
Totalt	**12581,46**	**13235,94**	**12980,22**	**10770,07**	**13095,39**	**10941,76**	**10306,50**	**17244,81**	**17908,92**	**13229,45**

Total concentrations 19,1 - 560 nm

Channel Size [nm]:	Warehouse	Control room	Office	Mean (Offices)	Under-Boiler	Middlebags	Underbags	Mean (Fugitive)
19,10	271,41	161,85	754,02	**395,76**	2186,07	2281,39	1449,98	**1972,48**
22,10	225,25	104,06	535,02	**288,11**	1998,26	2089,45	1337,57	**1808,43**
25,50	284,29	98,78	429,00	**270,69**	2033,28	2110,23	1474,66	**1872,72**
29,40	457,68	159,17	439,50	**352,12**	2291,12	2343,73	1861,25	**2165,37**
34,00	510,23	206,32	405,42	**373,99**	2233,08	2283,02	1963,21	**2159,77**
39,20	441,42	205,04	317,96	**321,47**	1859,16	1928,11	1780,53	**1855,93**
45,30	361,65	182,11	247,35	**263,70**	1515,62	1591,83	1535,65	**1547,70**
52,30	270,91	137,77	193,54	**200,74**	1202,45	1274,18	1228,58	**1235,07**
60,40	181,32	92,91	140,24	**138,15**	888,63	954,60	927,10	**923,44**
69,80	92,94	46,25	86,54	**75,24**	574,15	633,09	631,21	**612,82**
80,60	48,83	22,28	56,38	**42,49**	348,83	392,66	414,40	**385,30**
93,10	45,78	13,97	48,60	**36,12**	212,66	233,30	276,69	**240,88**
107,50	45,03	10,56	41,57	**32,39**	121,95	131,40	176,50	**143,28**
124,10	45,77	9,83	34,84	**30,15**	76,71	86,96	113,84	**92,50**
143,30	39,10	9,68	26,97	**25,25**	45,28	57,11	68,79	**57,06**
165,50	24,98	7,87	17,96	**16,93**	27,65	41,87	41,37	**36,96**
191,10	14,42	5,99	11,30	**10,57**	16,30	29,46	22,55	**22,77**
220,70	7,44	3,78	6,47	**5,90**	10,78	19,88	12,36	**14,34**
254,80	5,17	3,64	3,10	**3,97**	8,47	14,49	8,06	**10,34**
294,30	7,61	5,61	2,08	**5,10**	9,08	13,08	9,20	**10,45**
339,80	9,78	7,54	3,06	**6,79**	10,23	12,49	10,63	**11,12**
392,40	11,59	9,23	4,09	**8,30**	11,63	12,75	12,32	**12,23**
453,20	11,95	9,70	4,47	**8,70**	11,67	12,37	12,60	**12,21**
523,30	10,83	8,94	4,08	**7,95**	10,36	11,31	11,40	**11,02**
Totalt	**3425,36**	**1522,87**	**3813,56**	**2920,60**	**17703,42**	**18558,76**	**15380,42**	**17214,20**

Total concentrations 5,6 - 107,5 nm

Channel Size [nm]:	Balcony 9th	Boiler 8th	Crushing mill 4th	Ammonia injection 4th	Fluegas silos 4th	Fluegas cooling 4th	Ground corridor 2nd	Ground hatch 2nd	Ash hall 1st	Mean (Plant hall)
6,04	56,29	748,31	2068,60	228,82	613,21	23,18	577,69	140,25	750,12	**578,49**
6,98	661,70	601,32	1574,61	410,71	411,15	460,21	282,62	669,98	1149,54	**691,32**
8,06	993,23	1022,13	1758,32	684,98	549,03	902,49	315,46	1263,16	1676,13	**1018,32**
9,31	756,33	2051,15	2594,88	1006,63	1174,39	1208,92	606,12	1893,97	2465,70	**1528,68**
10,80	640,79	2308,03	2638,37	1117,10	1457,92	1267,76	744,95	2078,58	2571,02	**1647,17**
12,40	604,66	1787,43	1844,05	955,57	1351,69	1054,07	630,73	1755,63	1964,07	**1327,54**
14,30	688,98	1568,41	1498,85	938,87	1353,63	990,44	572,30	1720,24	1798,29	**1236,67**
16,50	869,43	1650,96	1602,76	1050,22	1428,53	1076,64	567,81	1954,92	2088,05	**1365,48**
19,10	975,49	1601,28	1580,09	985,05	1412,62	1026,09	544,75	1907,16	2162,43	**1355,00**
22,10	1007,14	1419,35	1430,84	743,46	1305,90	838,97	503,13	1576,94	2021,19	**1205,21**
25,50	1121,09	1451,28	1434,57	741,96	1340,11	897,76	560,35	1574,47	2007,08	**1236,52**
29,40	1317,32	1697,07	1591,28	978,89	1515,26	1202,94	716,26	1899,77	2120,10	**1448,77**
34,00	1341,17	1695,62	1531,50	1060,29	1516,35	1303,87	790,41	1956,72	2045,86	**1471,31**
39,20	1192,64	1446,94	1255,22	985,49	1343,37	1200,53	782,76	1745,31	1784,35	**1304,07**
45,30	1062,69	1183,20	1011,65	913,55	1158,00	1072,37	731,13	1518,85	1487,03	**1126,50**
52,30	951,32	904,41	800,79	844,47	960,24	919,40	635,52	1277,32	1153,89	**938,59**
60,40	813,70	645,01	604,86	750,20	758,11	737,87	588,94	1036,82	880,09	**757,29**
69,80	649,83	405,01	423,85	630,74	551,61	527,80	591,40	797,34	665,61	**582,58**
80,60	511,51	243,14	300,45	532,73	384,34	370,30	611,17	603,78	485,32	**449,19**
93,10	398,75	159,39	234,62	456,16	256,29	265,37	648,27	456,14	339,19	**357,13**
107,50	315,10	105,17	182,36	372,35	170,22	187,60	640,55	331,57	227,47	**281,38**
Totalt	**16929,14**	**24694,60**	**27962,53**	**16388,22**	**21011,98**	**17534,59**	**12642,32**	**28158,90**	**31842,54**	**21907,20**

Total concentrations 5,6 - 107,5 nm

Channel Size [nm]:	Warehouse	Control room	Office	Mean (Offices)	Belt 5th	Middlebags	Underbags	Mean (Fugitive)
6,04	419,57	245,58	352,18	**339,11**	62,48	943,43	1013,71	**673,21**
6,98	161,85	21,64	297,40	**160,30**	405,50	492,73	547,30	**481,84**
8,06	152,49	6,37	558,74	**239,20**	1109,09	951,52	759,13	**939,92**
9,31	332,67	129,66	1103,28	**521,87**	2173,82	2356,79	1616,85	**2049,15**
10,80	410,93	240,83	1277,26	**643,01**	2539,36	2818,99	1944,31	**2434,22**
12,40	267,78	236,19	1034,05	**512,68**	2157,10	2335,13	1727,12	**2073,12**
14,30	222,89	240,73	903,61	**455,74**	2044,47	2164,24	1590,44	**1933,05**
16,50	271,10	210,02	877,05	**452,72**	2201,47	2306,32	1534,27	**2014,02**
19,10	271,41	161,85	754,02	**395,76**	2186,07	2281,39	1449,98	**1972,48**
22,10	225,25	104,06	535,02	**288,11**	1998,26	2089,45	1337,57	**1808,43**
25,50	284,29	98,78	429,00	**270,69**	2033,28	2110,23	1474,66	**1872,72**
29,40	457,68	159,17	439,50	**352,12**	2291,12	2343,73	1861,25	**2165,37**
34,00	510,23	206,32	405,42	**373,99**	2233,08	2283,02	1963,21	**2159,77**
39,20	441,42	205,04	317,96	**321,47**	1859,16	1928,11	1780,53	**1855,93**
45,30	361,65	182,11	247,35	**263,70**	1515,62	1591,83	1535,65	**1547,70**
52,30	270,91	137,77	193,54	**200,74**	1202,45	1274,18	1228,58	**1235,07**
60,40	181,32	92,91	140,24	**138,15**	888,63	954,60	927,10	**923,44**
69,80	92,94	46,25	86,54	**75,24**	574,15	633,09	631,21	**612,82**
80,60	48,83	22,28	56,38	**42,49**	348,83	392,66	414,40	**385,30**
93,10	45,78	13,97	48,60	**36,12**	212,66	233,30	276,69	**240,88**
107,50	45,03	10,56	41,57	**32,39**	121,95	131,40	176,50	**143,28**
Totalt	**5476,02**	**2772,09**	**10098,72**	**6115,61**	**30158,52**	**32616,14**	**25790,46**	**29521,71**