Emissions Characterization of a High Efficiency Wood Boiler using Two Fuels: Wood Pellets and Wood Chips

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Outline

- Health Effects of Wood Smoke
- Emissions Formation
- Complete Combustion/Incomplete Combustion
- Walker Center Boiler Description
- Measurement Methods
- Emissions Results and Discussion

- Summary of ESP Demonstration
- Preliminary Data from Wild Center Boiler Testing

Wood Combustion Emissions

- Residential wood combustion leads 92% of carbonaceous PM2.5 in rural NYS
- Combustion usually incomplete
- Smoke usually emitted from low stacks, leads to fumigation

NYSERDA, 2008

Health Impacts of Wood Smoke

- Short term effects - eye, nose, throat, and lung irritation
- Long term effects - decreased lung function, asthma, heart disease, bronchitis, increased risk of cancer
- Toxicity depends on combustion conditions
  - Incomplete combustion results in more organic based particles
  - Soot from incomplete combustion has 15 times higher toxicity and 20 times higher PAH levels.

Kipple & Nussbaumer 2007

Biomass Composition

- Predominantly C (~50%), H (~6%), and O (~40%)
- Rest primarily comprised of inorganic ash-forming elements
- Clean Wood
  - Ash content of 0.5-1.0%
- Bark
  - Ash content of 5-8%
- Straw and cereals
  - Ash content of 4-12%

Van Loo, 2008

Emissions Formation

- Dependent on two parameters
- Combustion Conditions
  - Incomplete combustion produces organic emissions (CO, VOCs, SVOCs, PAHs, soot)
- Fuel Composition
  - Inorganic Emissions (NO_x, SO_2, Fine PM)

Hydrocarbon Combustion

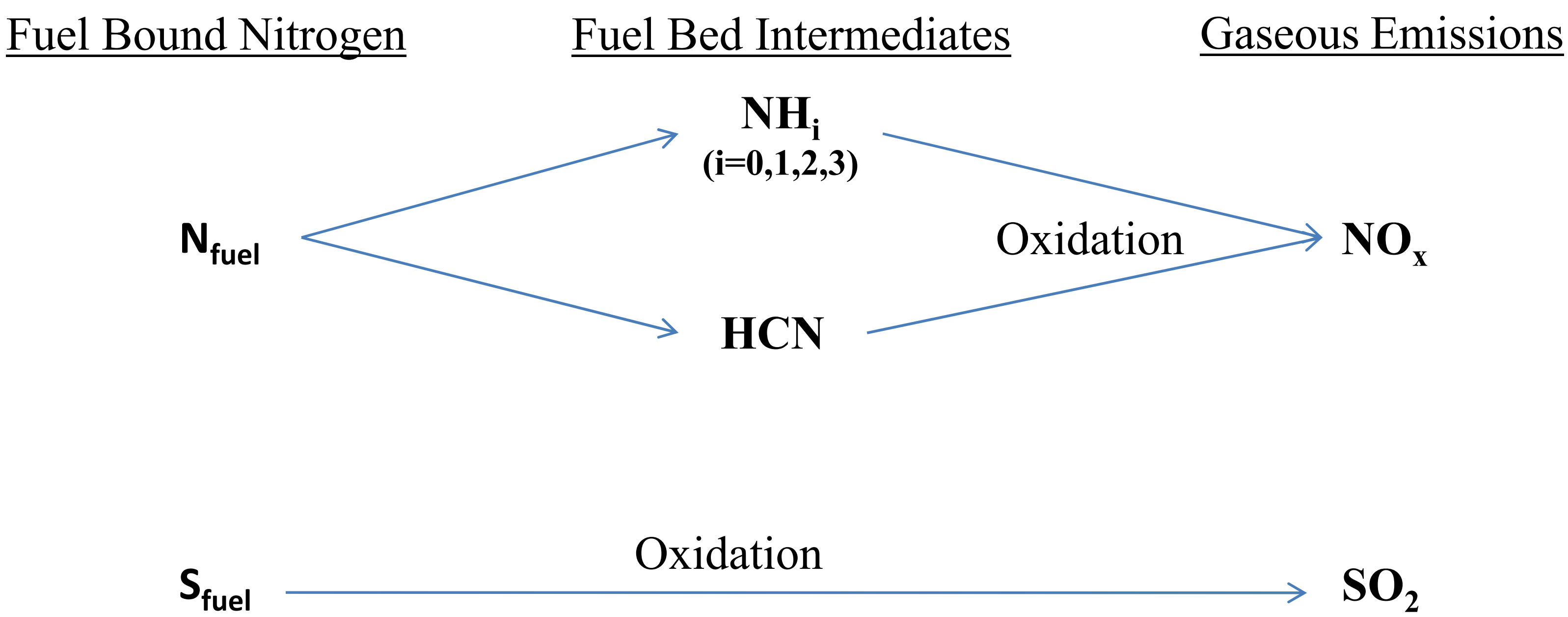
- Complete Combustion of Hydrocarbons
  - Decomposition and oxidation

$$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$$

- Incomplete Combustion of Hydrocarbons
  - Organic material not fully oxidized
  - Emissions: CO, VOCs, SVOCs, PAHs, soot, condensable organic matter

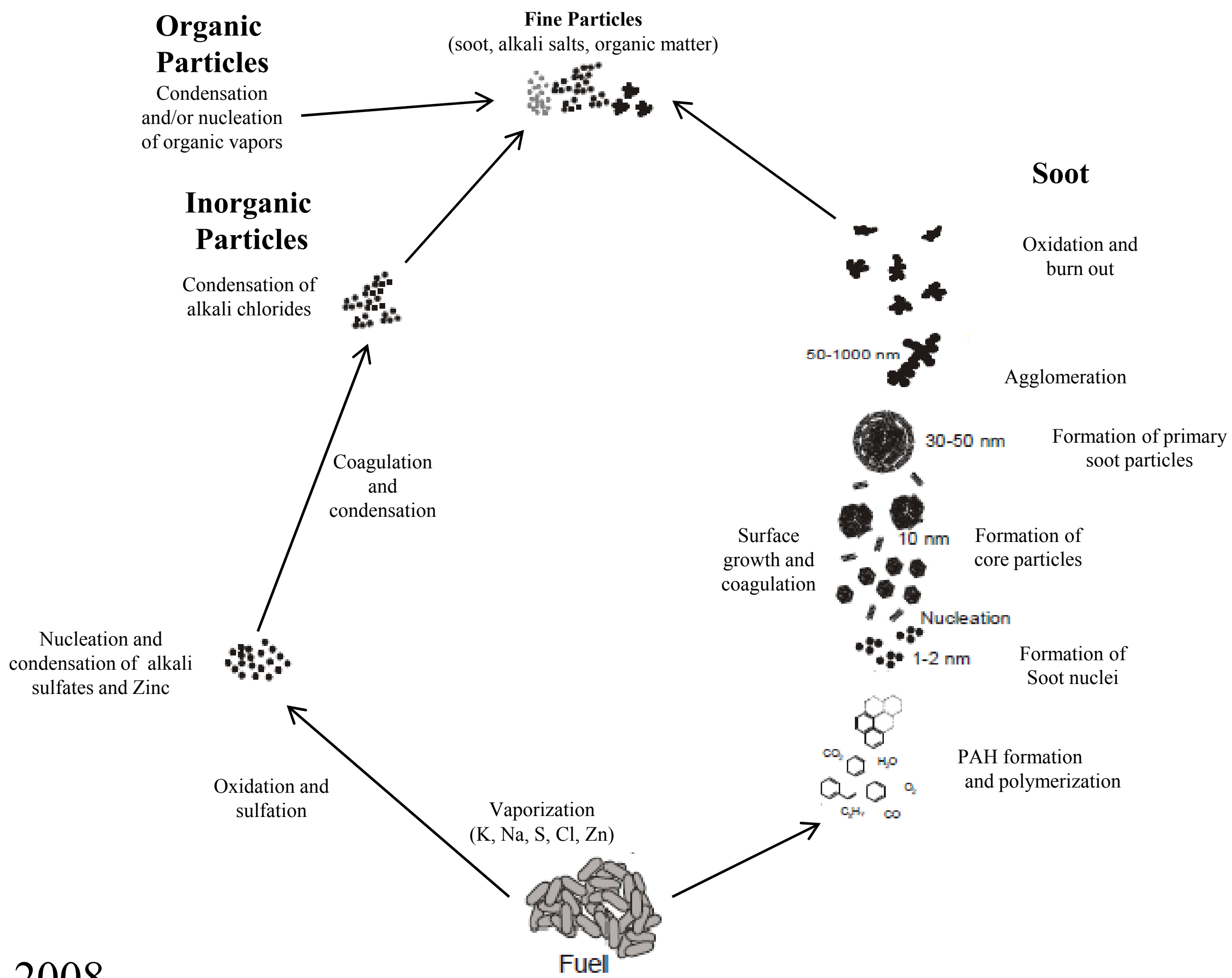
NO_x and SO_2

- Emissions dependent on fuel bound nitrogen and sulfur



- SO_2 and NO_x involved in secondary aerosol formation

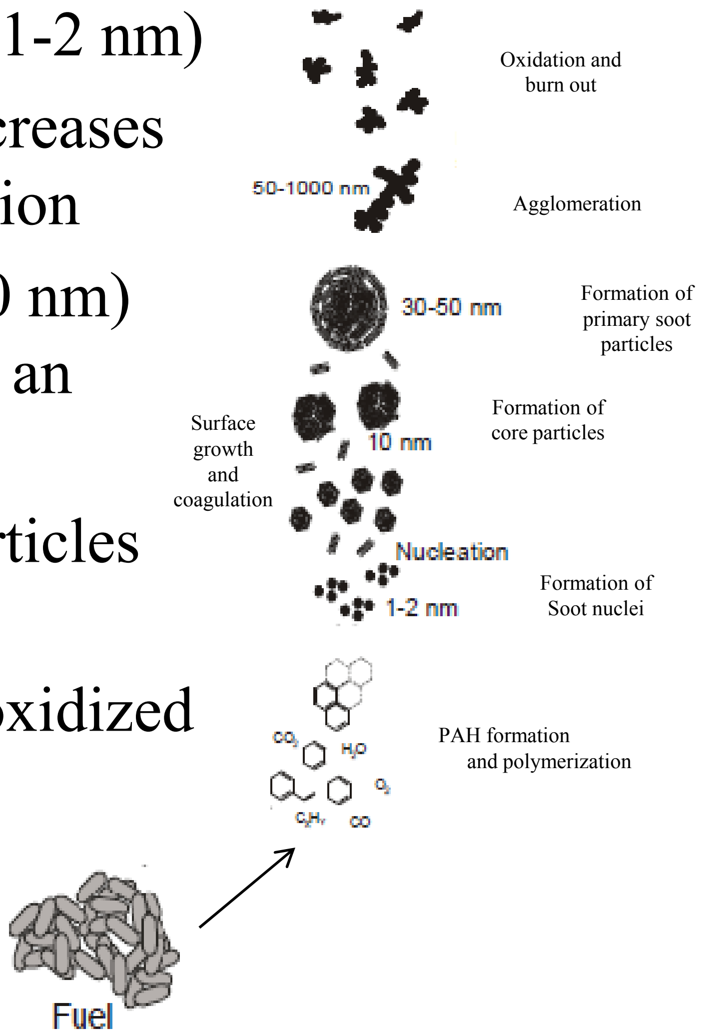
Fine Particle Formation



Tissari et al. 2008

Soot Formation

- PAHs polymerize to form soot nuclei (1-2 nm)
- Core particles (10 nm) when nuclei increases through surface reactions and coagulation
- Spherical primary soot particles (30-50 nm) formed when more PAHs bind to form an outer shell
- Agglomerates forms when primary particles bind together
- Most soot particles broken down and oxidized in burn-out



Boman 2005

Inorganic Particle Formation

- 80-95% of PM under 1μm for residential and commercial combustion devices
- higher ash content ⟶ higher fine PM emissions
- Ash-forming elements (K, Cl, S, Na, with minor amounts of Fe, Zn, and Al) volatilize into flue gas and nucleate or condense as the gas cools
- Fine Particle emissions predominantly alkali salts (KCl, K_2SO_4, $NaCl$, Na_2SO_4)
- Zinc and some heavy metals also involved

Boman 2005

Alkali Metal Vaporization

- Dependent on fuel bed temperature
  - K vaporization starts at 700ºC and increases with temperature
- Predominantly released from the fuel bed as KCl (g) and KOH (g)
  - Limited amount of K_2SO_4 released

Sulfation Reactions

$$2AOH + SO_2 + \frac{1}{2}O_2 \leftrightarrow A_2SO_4 + H_2O$$

$$2ACl + H_2O + SO_2 + \frac{1}{2}O_2 \leftrightarrow A_2SO_4 + 2HCl$$

- KCl (g) and KOH (g) undergo gas-phase sulfation to form K_2SO_4 (g)
- Particles from wood combustion are made mostly of K and SO_4

Sippula et al., 2007 & 2009; Tissari et al. 2008

Alkali Particle Formation

- Alkali sulfates nucleate homogeneously at 950ºC
- Alkali chlorides condense onto existing particles at 550-600ºC
- Particles from wood combustions predominantly composed of K and SO_4

- Inorganic particles much less toxic than carbonaceous particles (soot and organic compounds)

Klippel & Nussbaumer 2007

Combustion Review

- Emissions depend on:
- Combustion Conditions
  - Complete combustion of hydrocarbons results in only CO_2
  - Incomplete combustion leads to toxic organic emissions
- Fuel Composition
  - High ash content leads to higher inorganic PM emissions
  - High N and S content leads to higher NO_x and SO2
  - High Cl leads to HCl formation

Requirements for Complete Combustion

- High combustion temperature (850°C)
- Long enough residence time (<0.5s)
- Adequate mixing of combustion air and fuel gas

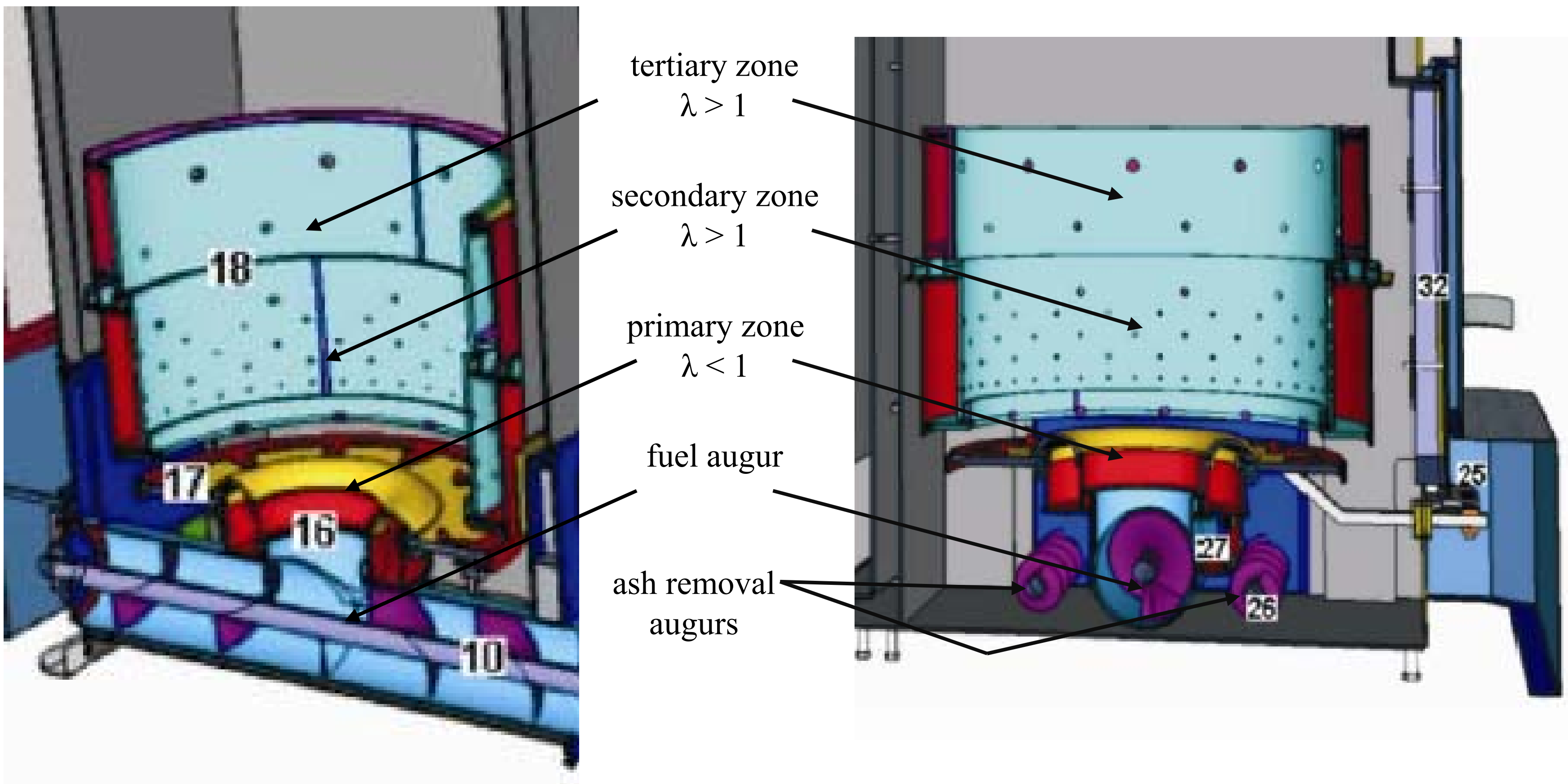
- Challenge is to create sufficient mixing with the least amount of excess air possible

High Efficiency Wood Boiler

- Hamont CATfire (imported by ACT Bioenergy, NY)
- 150kW (514,000 Btu.h^{-1}) Output High Efficiency Wood Boiler
- Automated fuel feeding system
- Automatic ignition

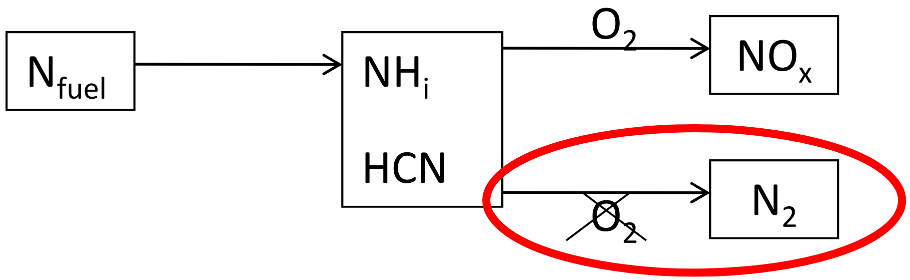
Air Staging

- First stage: Devolatilize the fuel
- Subsequent stages: Combust and oxidize pyrolysis gases



Air Staging

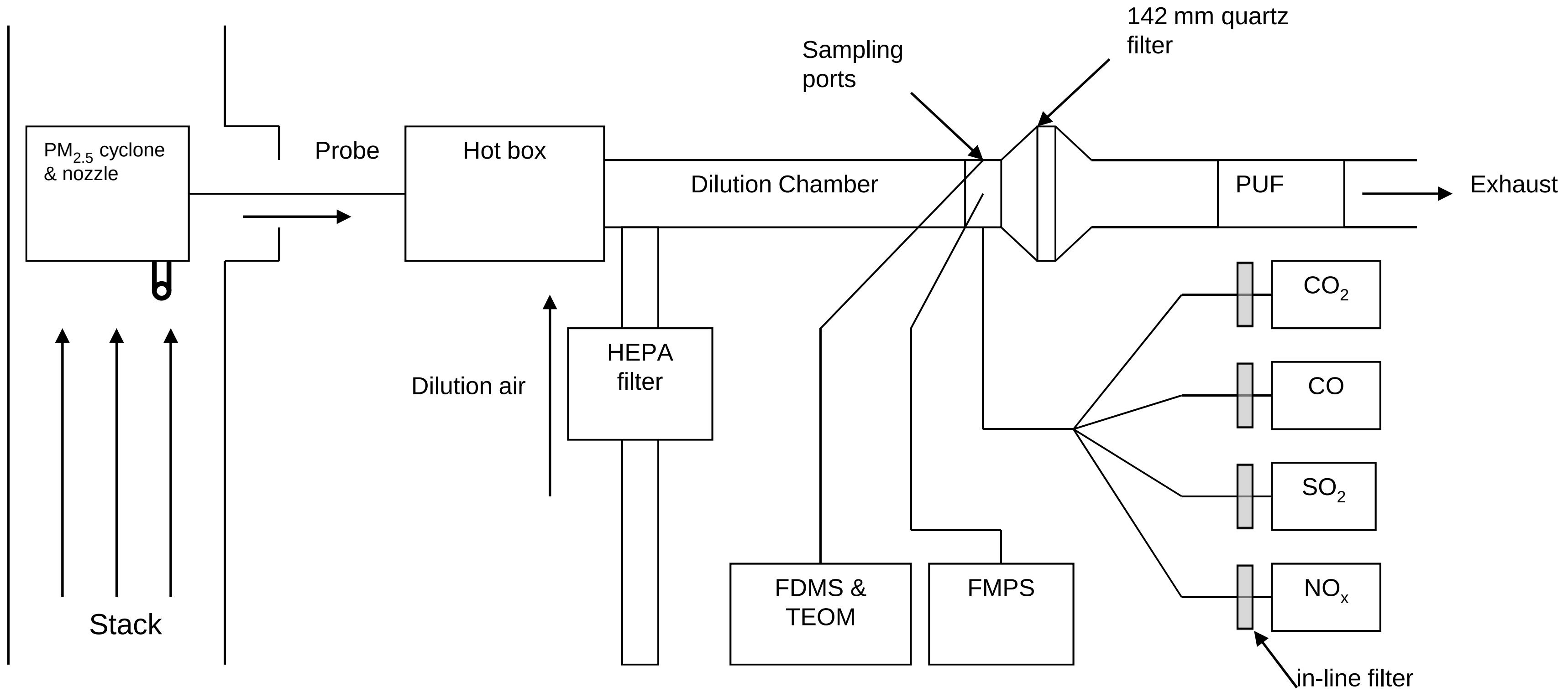
- Lambda optimization system using an O_2 sensor automatically controls fans
- Low air to fuel ratios (λ) increases combustion efficiency
- PM reduction: Low fuel bed temperature leads to less inorganic vaporization
- NO_x reduction: Low oxygen level in first stage, intermediates not oxidized to NO_x



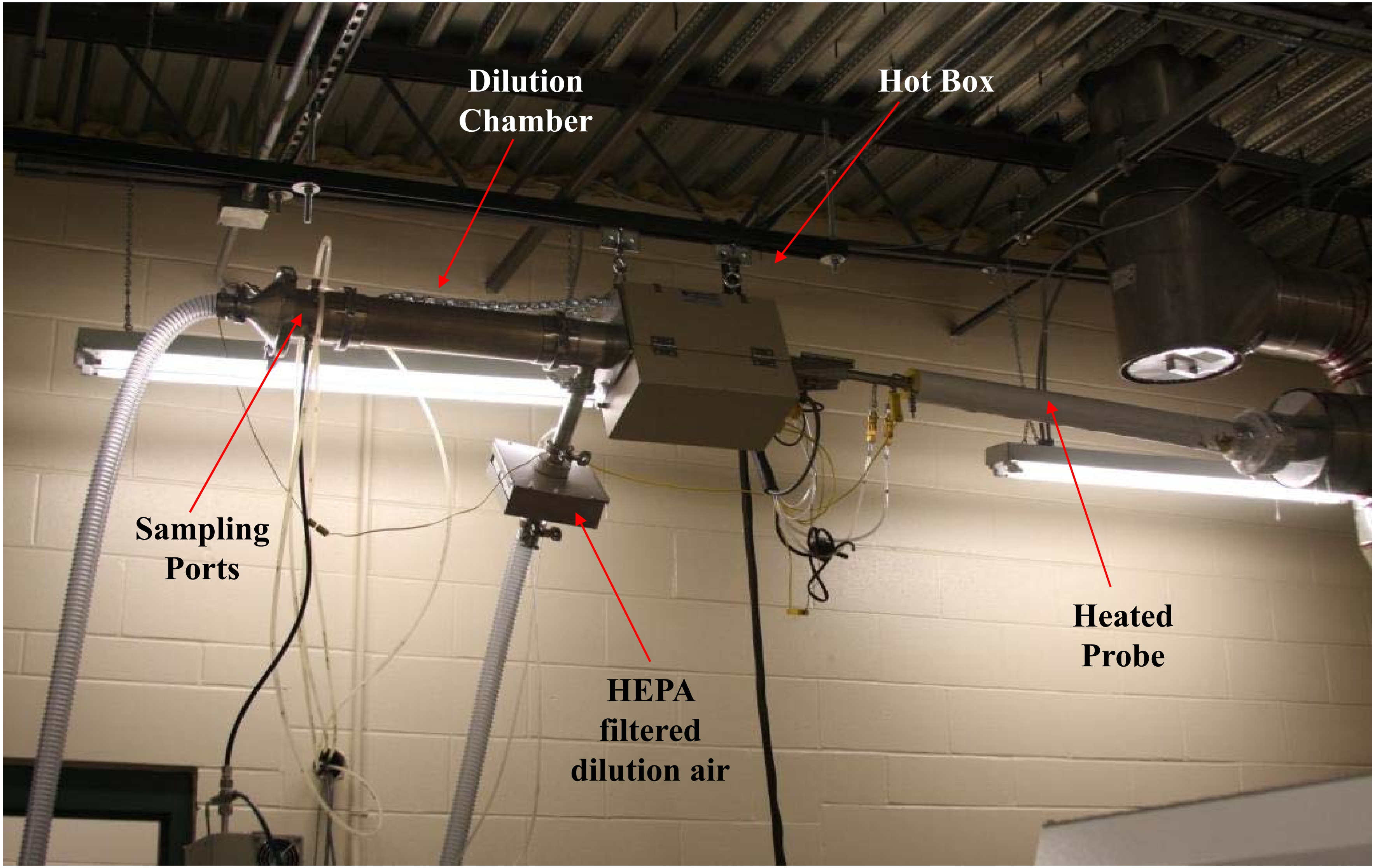
Sampling Theory

- Dilution Tunnel
  - Simulates Ambient conditions
  - Provides a better representation of particle emissions than in-stack measurements
  - Allows nucleation and condensation of gas-phase organic material

Source Sampling System Schematics



Dilution Tunnel

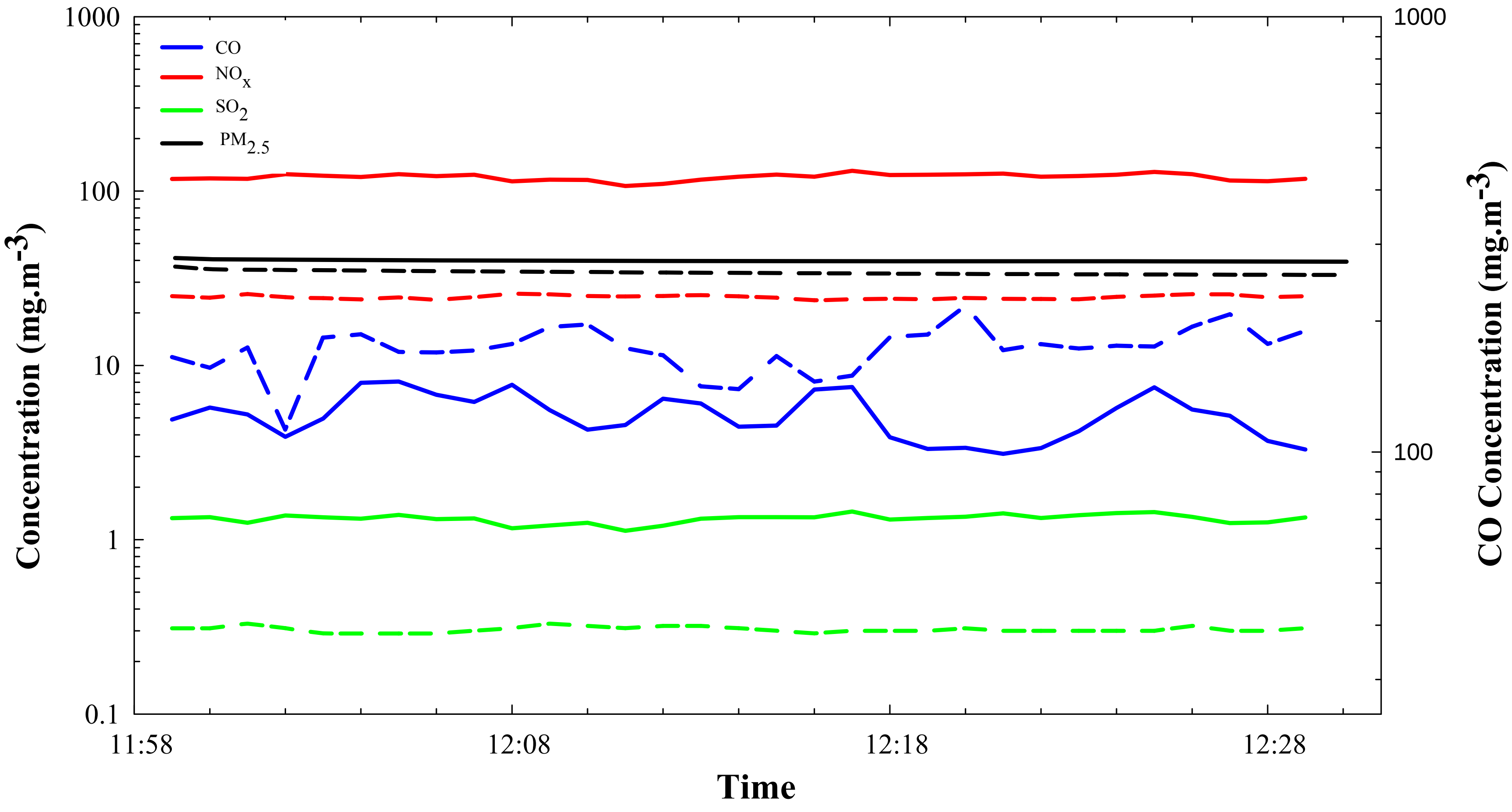


Fuels Used

- Higher fuel bound nitrogen and sulfur content of the wood chips expected to lead to higher NO_x and SO_2 emissions
- Higher ash content expected to lead to higher $PM_{2.5}$ emissions

	Wood Pellets A	Wood Pellets B	Wood Chips
heat content (MJ/lbs)	8.49	8.67	6.72
moisture (%)	4.80	4.51	26.6
ash (d.w. %)	0.60	0.72	1.79
nitrogen (d.w. %)	0.13	nm	0.37
sulfur (d.w. ppm)	70.1	79.8	175

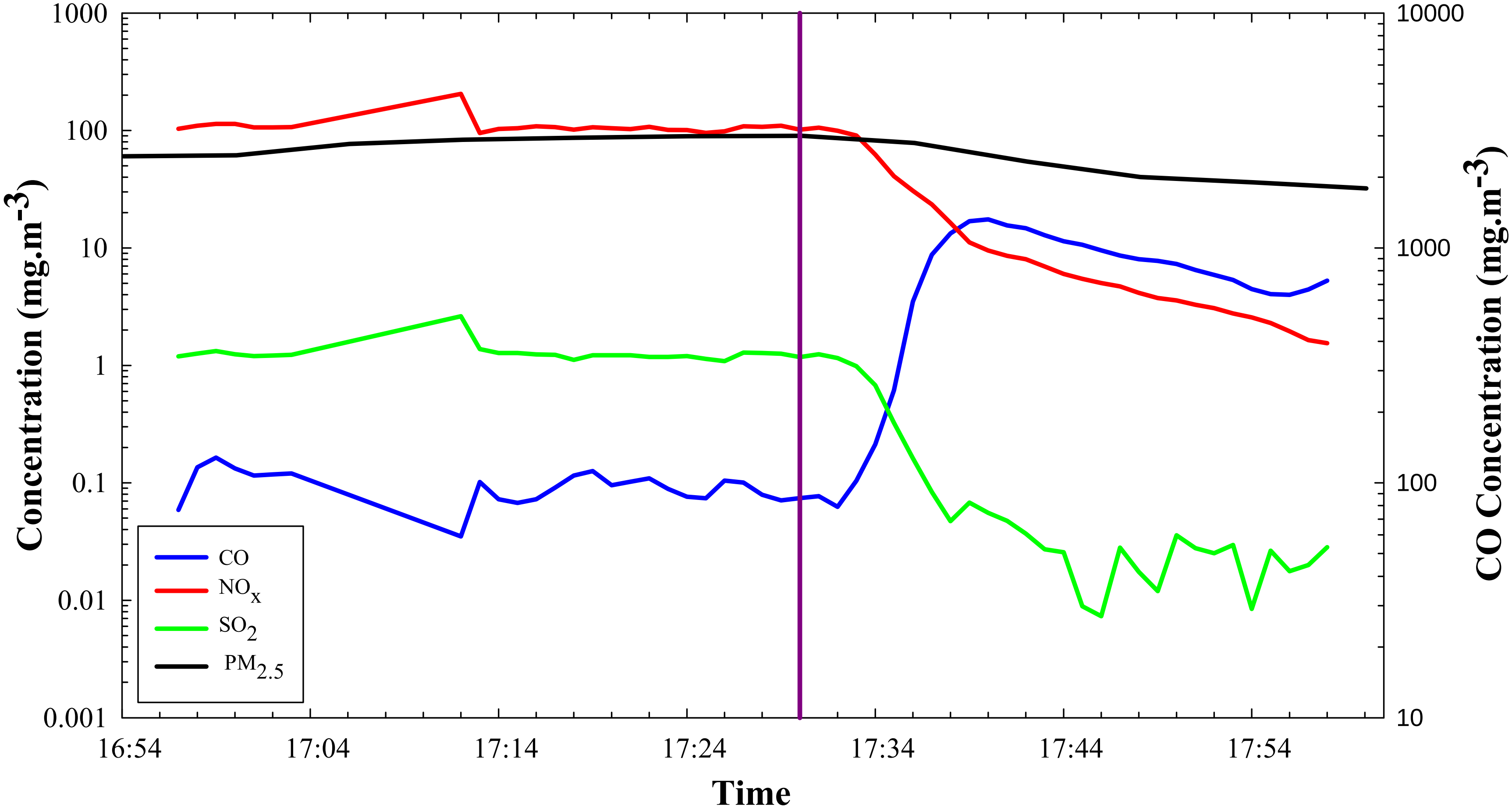
Gaseous and PM Emissions



Note: **Dashed line** indicate data for Wood Pellets A

Solid line indicate data for Wood Chips

Concentration of criteria pollutants (CO, NO_x, SO_2 and $PM_{2.5}$) during shutdown of boiler



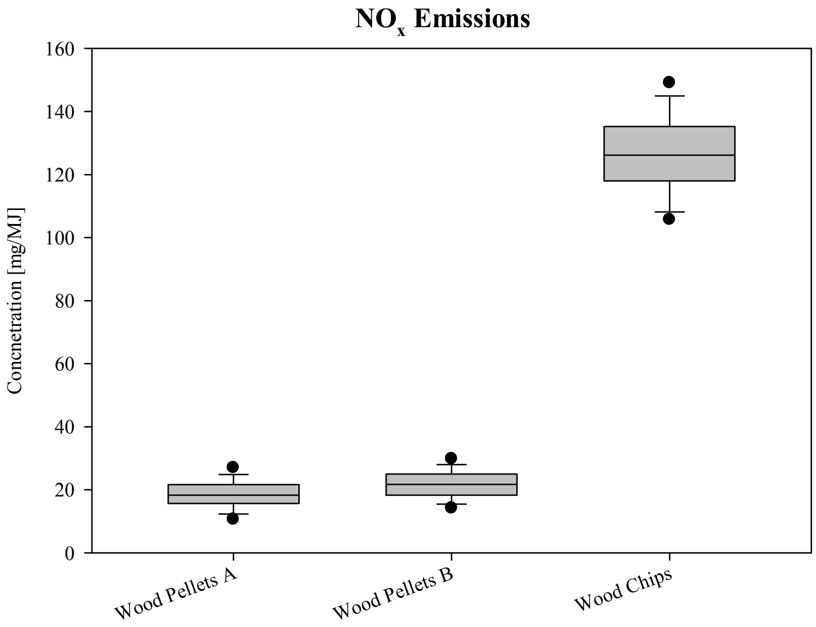
Note: Vertical line indicates boiler shutdown process initiation. Wood Chips used as fuel.

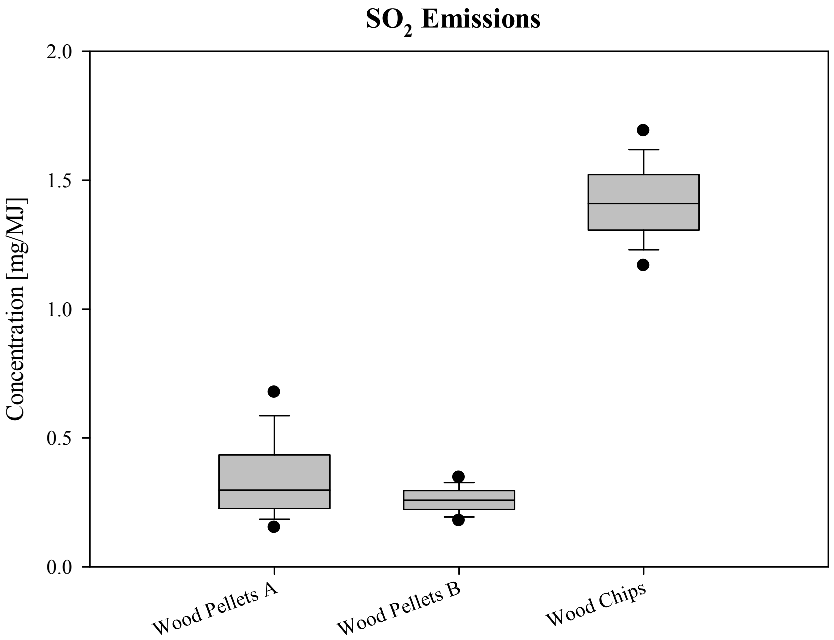
Emission Factors

Emission Species (lbs/MMbtu)	**Wood Pellets A**	**Wood Pellets B**	**Wood Chips**
CO	0.27	0.29	0.29
NO_x	0.04	0.05	0.29
SO_2	0.0008	0.0006	0.0033
$PM_{2.5}$	0.06	0.07	0.10
Ultrafine number concentration (#/BTU x 10^9)	17.1	21.1	37.9

NO_x and SO_2

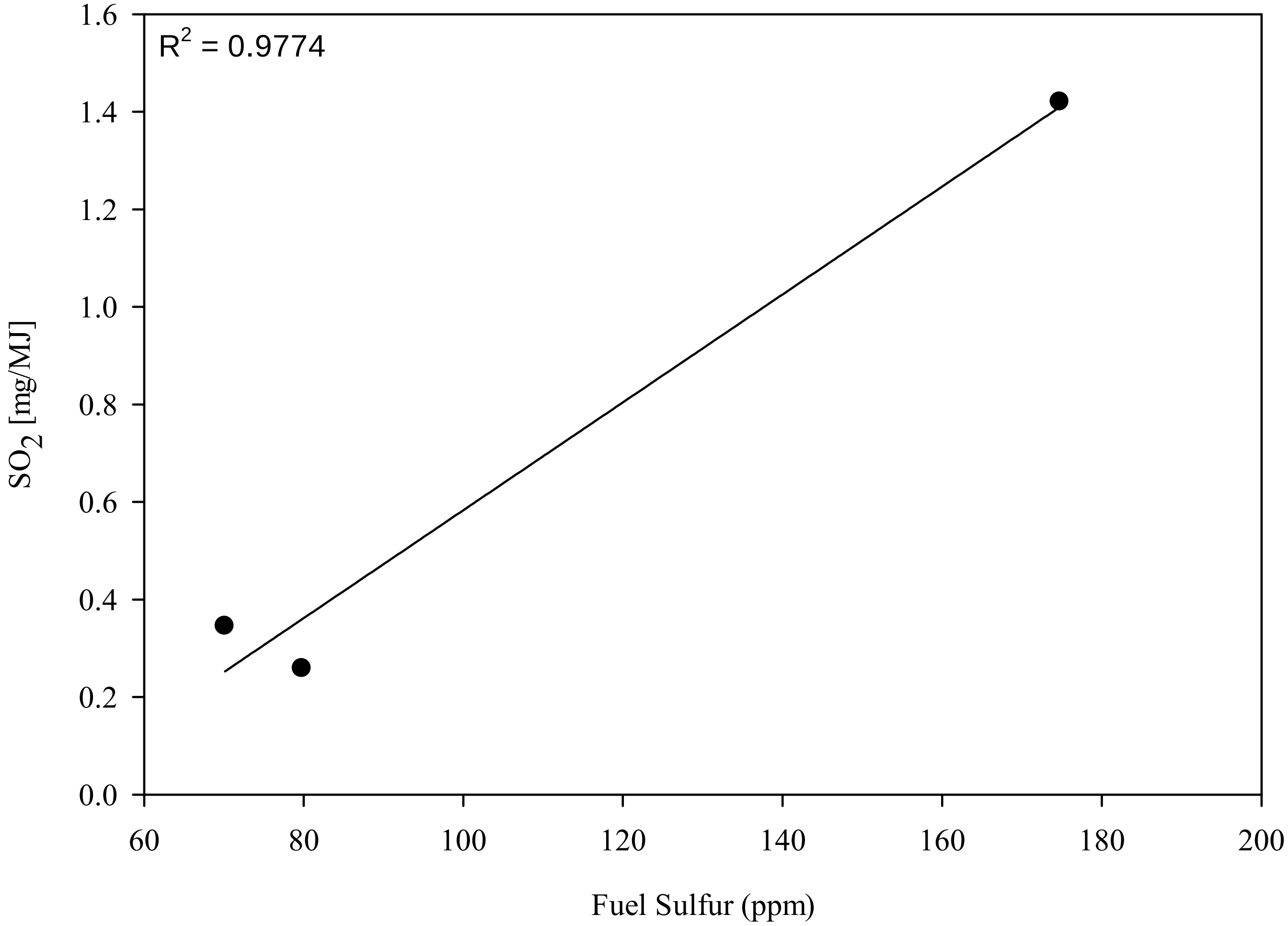
- Emissions of NO_x and SO_2 higher for wood chips than wood pellets



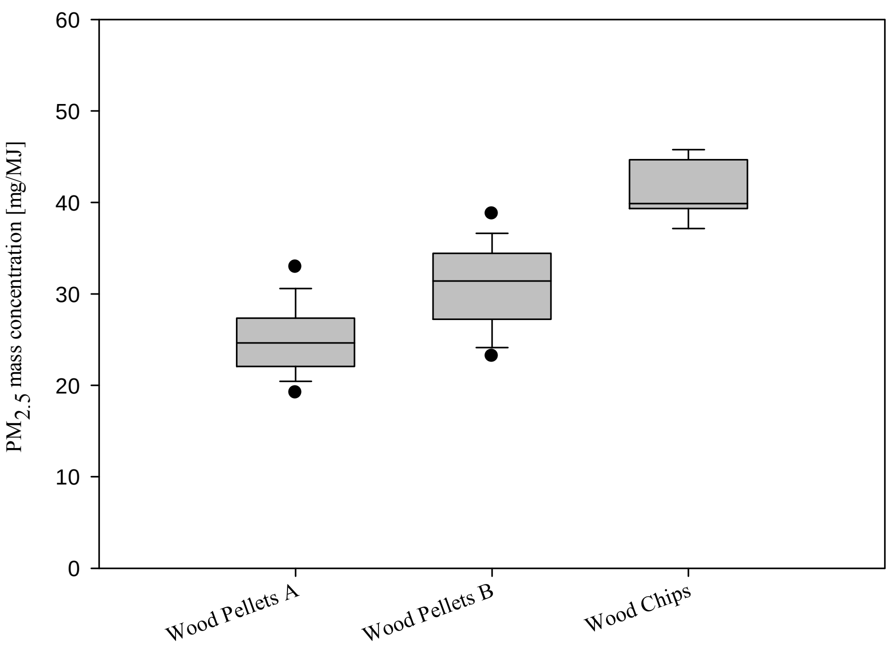


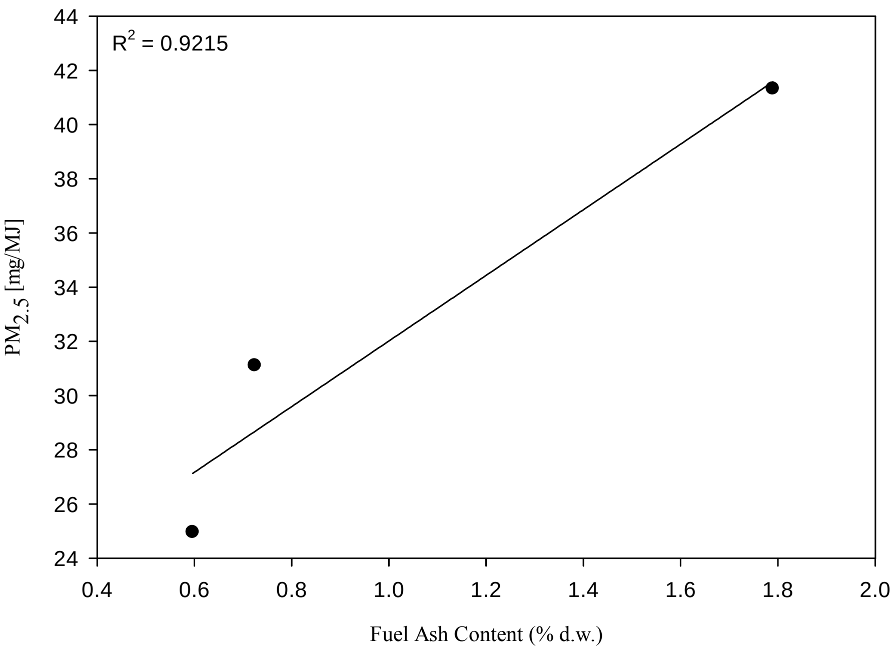
SO_2 and fuel sulfur content

- SO_2 higher for fuel with higher S content

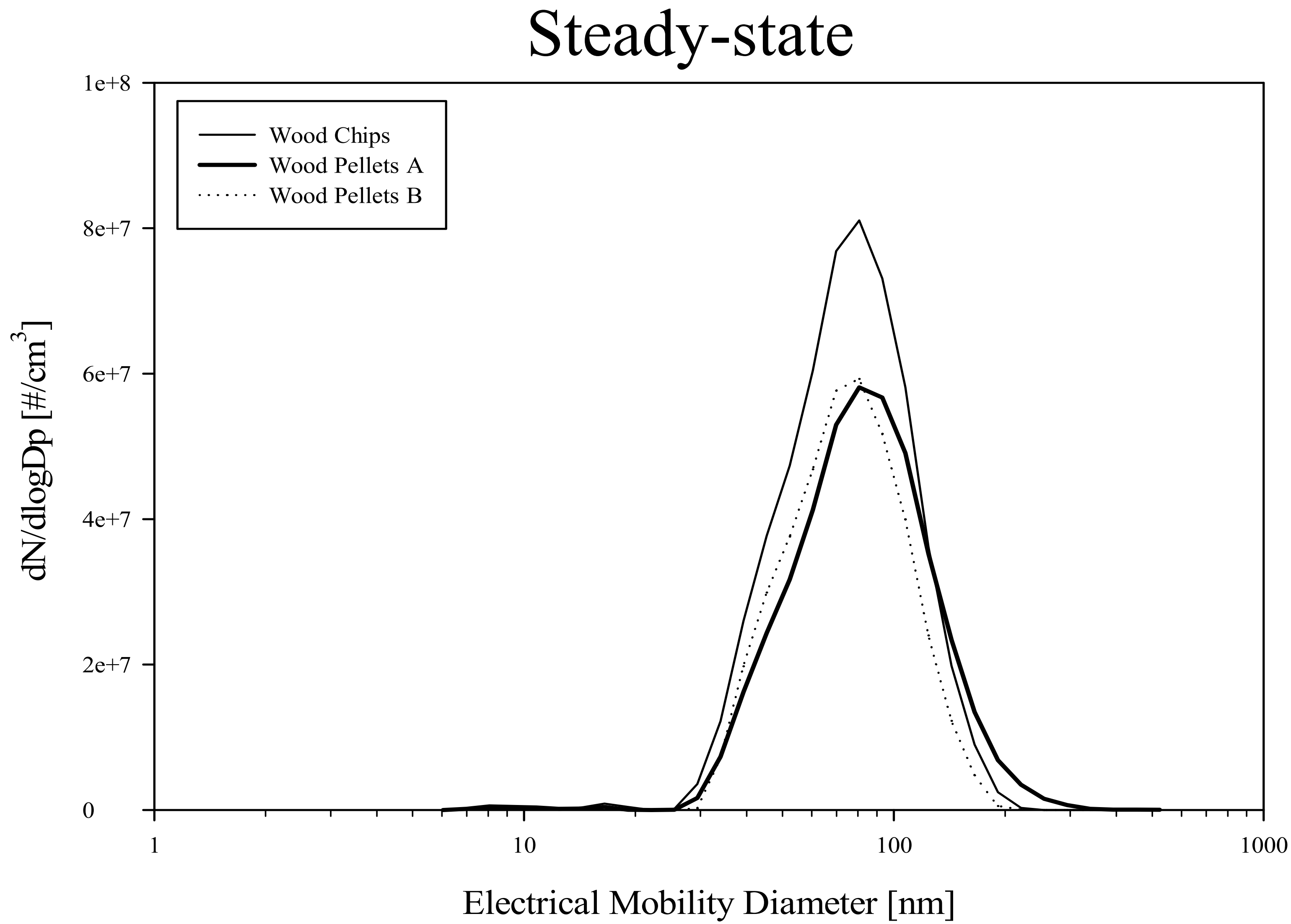


$PM_{2.5}$ emission factors



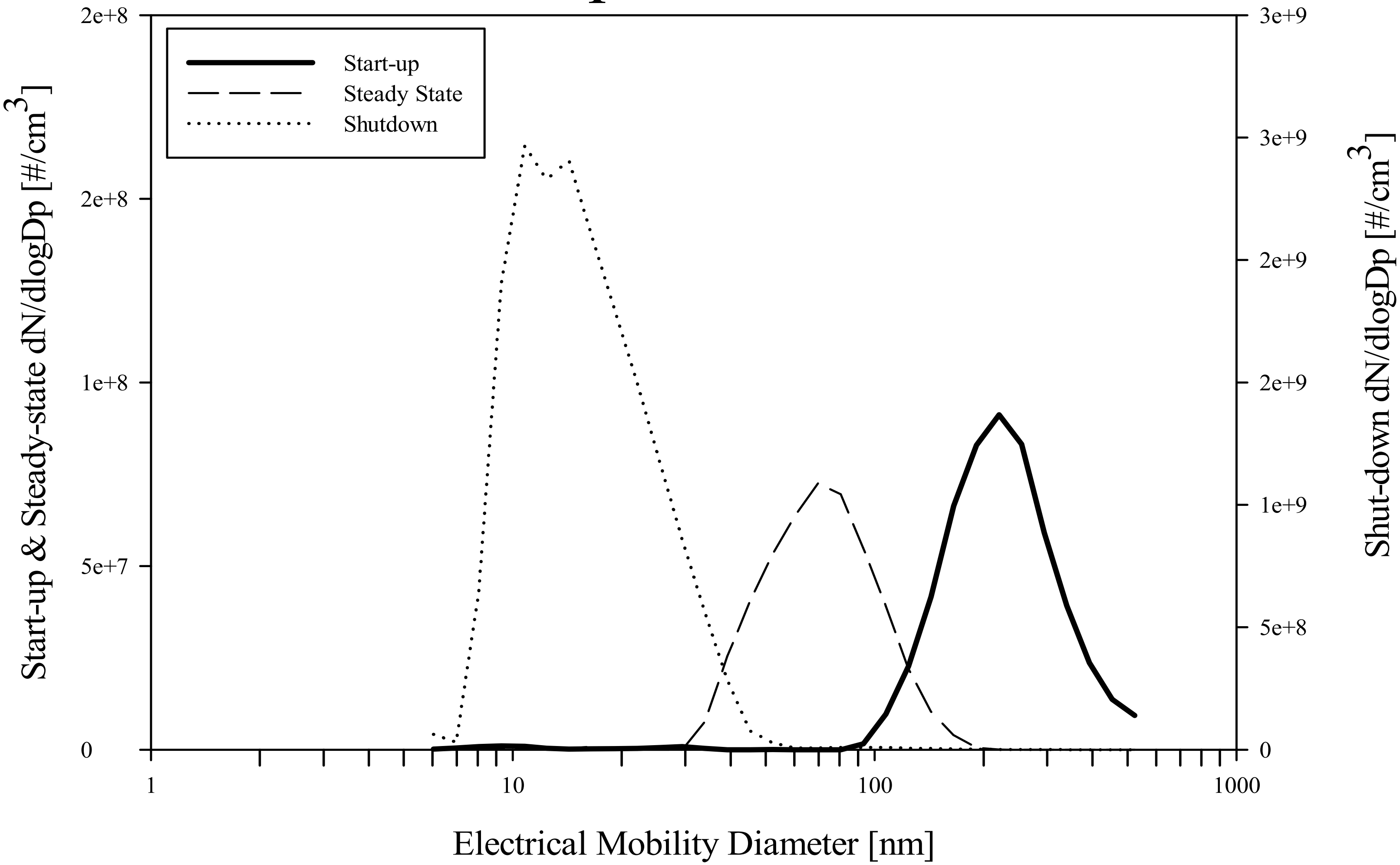


Ultrafine Particle Number Size Distribution



Ultrafine Particle Number Size Distribution

Start-up & Shut-down

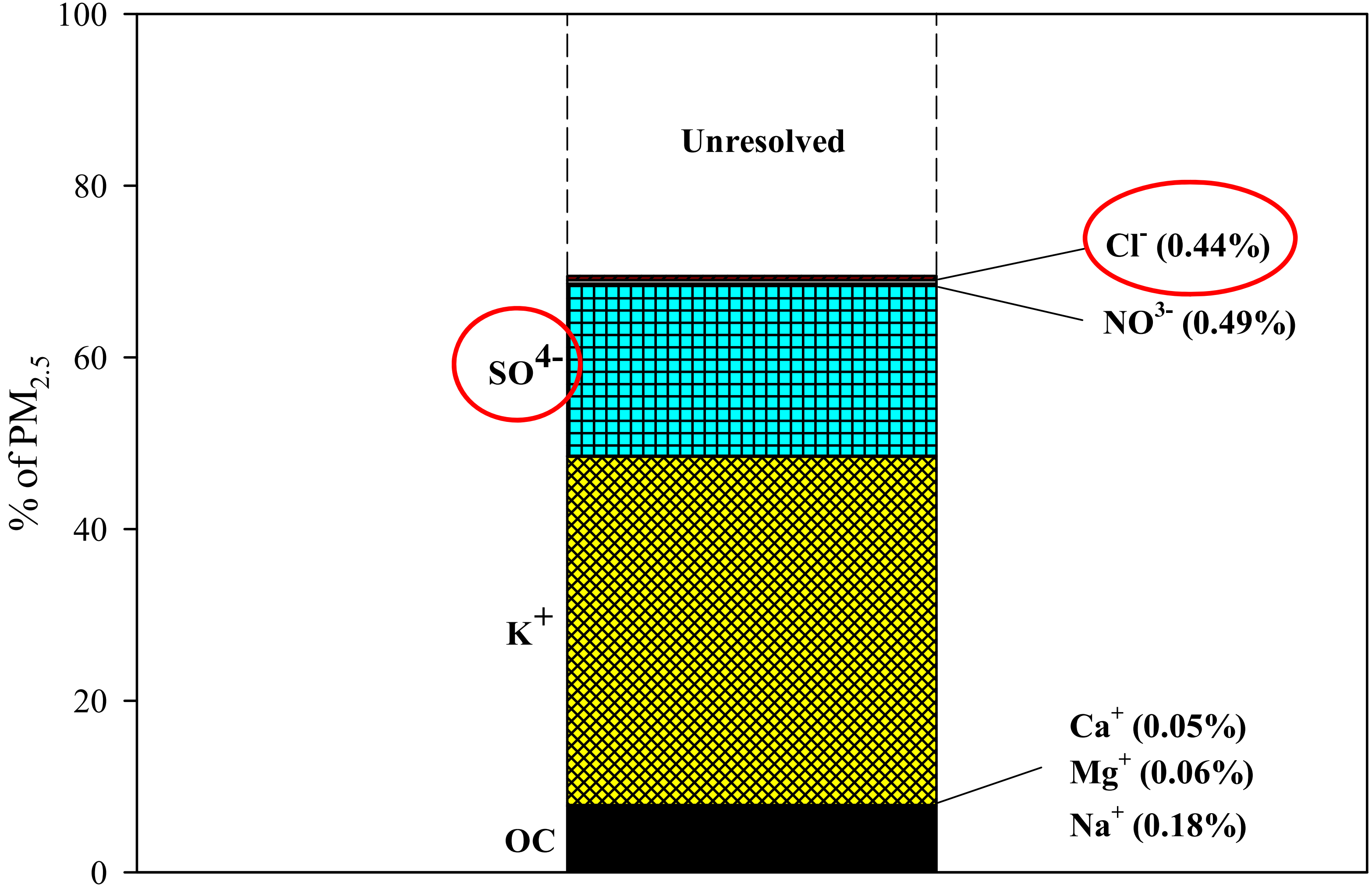


Particle Organic & Elemental Carbon

- Organic Carbon predominant form of particulate carbon
- Low emissions of OC and EC

Fuel	**$OC/PM_{2.5}$ (%)**	**$EC/PM_{2.5}$ (%)**
Wood Pellets A	6.10	0.28
Wood Pellets B	6.12	1.00
Wood Chips	1.69	0.05

PM2.5 Chemical Composition

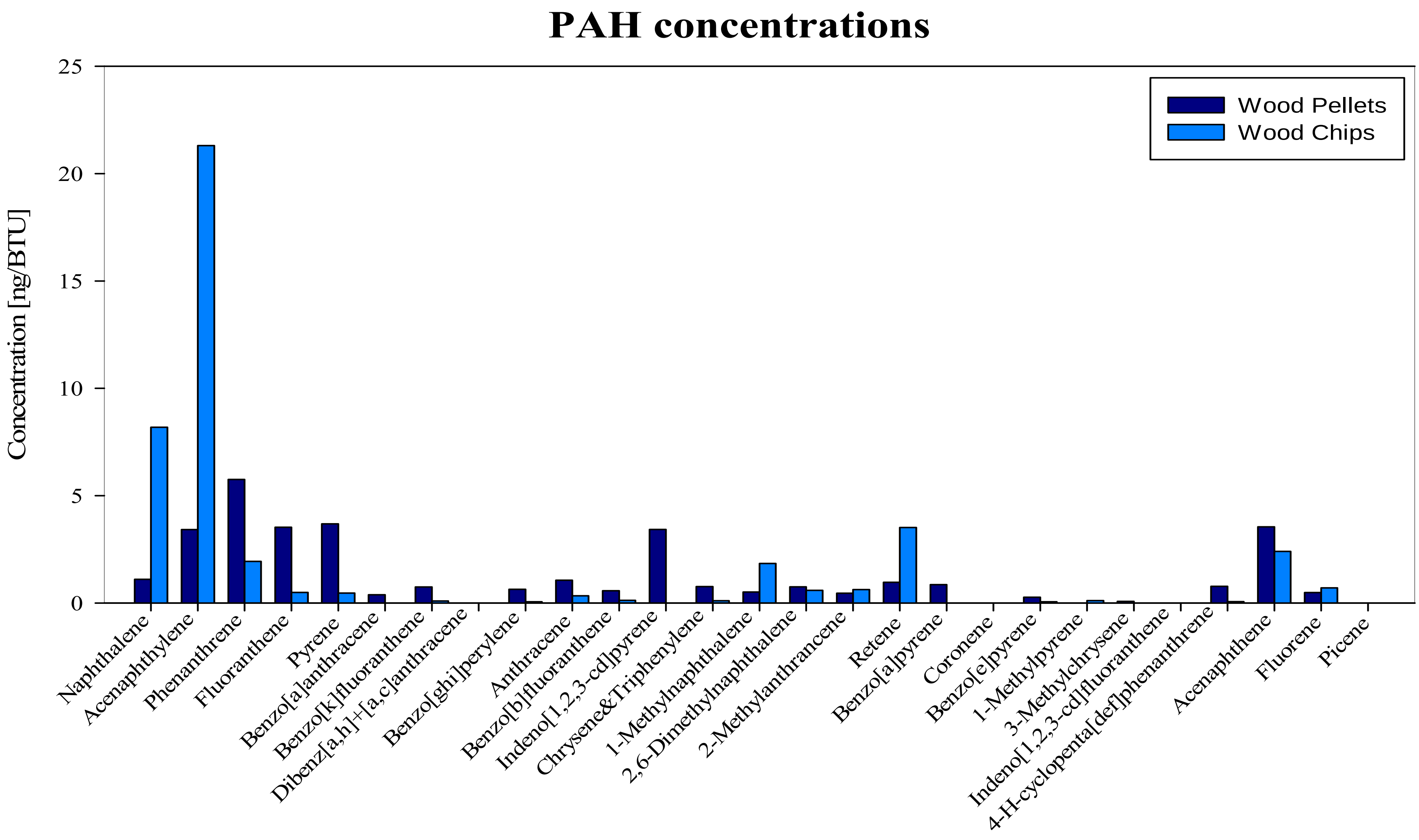


Sulfur Mass Balance

- Only 53% and 48% of fuel Sulfur accounted for
- Predominantly Sulfate possibly due to sulphation reactions

Fuel	SO_2 (%)	$PM_{2.5}$ Sulfate (%)	Total S (%)
Wood Pellets A	4.62	48.6	53.2
Wood Pellets B	3.09	45.1	48.2
Wood Chips	5.26	nm	nm

PAHs


PAH concentrations
Concentration [ng/BTU]
25
20
15
10
5
0
Wood Pellets
Wood Chips
Naphthalene
Acenaphthylene
Phenanthrene
Fluoranthene
Pyrene
Benzo[a]anthracene
Benzo[k]fluoranthene
Dibenz[a,h]+[a,c]anthracene
Benzo[ghi]perylene
Anthracene
Benzo[b]fluoranthene
Indeno[1,2,3-cd]pyrene
Chrysene&Triphenylene
1-Methylnaphthalene
2,6-Dimethylnaphthalene
2-Methylanthrancene
Retene
Benzo[a]pyrene
Coronene
Benzo[e]pyrene
1-Methylpyrene
3-Methylchrysene
Indeno[1,2,3-cd]fluoranthene
4-H-cyclopenta[def]phenanthrene
Acenaphthene
Fluorene
Picene

Particle and Semi-volatile Organic Emissions

- 133 compounds resolved
- Predominant Alkanoic Acids - Heptacosanoic acid, Octacosanoic acid, Nonacosanoic acid

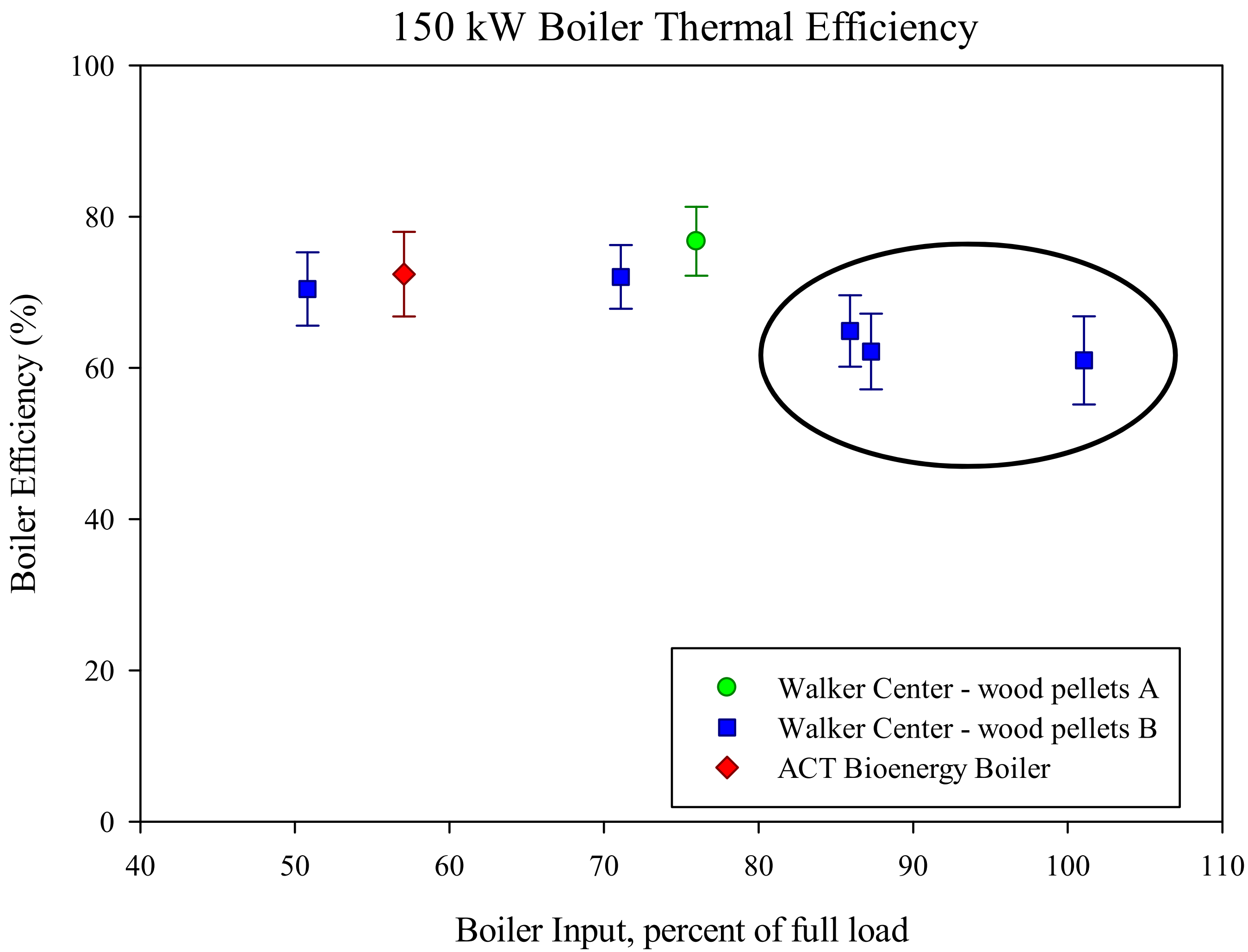
Organic Compounds (mg/MMbtu)	Wood Pellets	Wood Chips
Alkanes (31)	398	417
PAHs (27)	33.7	43.0
Aromatic acids* (5)	30.5	0.00
Alkanoic acids (22)	62.7	54.8
Dicarboxylic acids* (12)	39.4	6.83
Pentacyclic triterpane (hopanes) (5)	41.3	0.30
Cholestane (sterols and cholestenes) (4)	0.48	0.88
Methyloxylated phenols* (8)	16.5	13.5
Phytosterols* (4)	0.37	6.18
Levoglucosan	53.0	52.3

Emissions Review

- Carbonaceous derived emissions (CO, PAHs, particulate OC & EC) low for all fuels

- NO_x, SO_2 and $PM_{2.5}$ emission factors dependent of fuel composition
- Fine PM composition dominated by K and SO_4

150 kW Boiler Efficiency



Wild Center Boiler

- ❑ Manufactured by ACT Bioenergy (Schenectady, NY)
- ❑Same design as Clarkson's Walker Center boiler
- ❑512 kW (1.75 MMbtu/hr)

- ❑Tested using two methods
    - ❑Dilution tunnel
    - ❑EPA Method 5 - In-stack filters

Preliminary Results

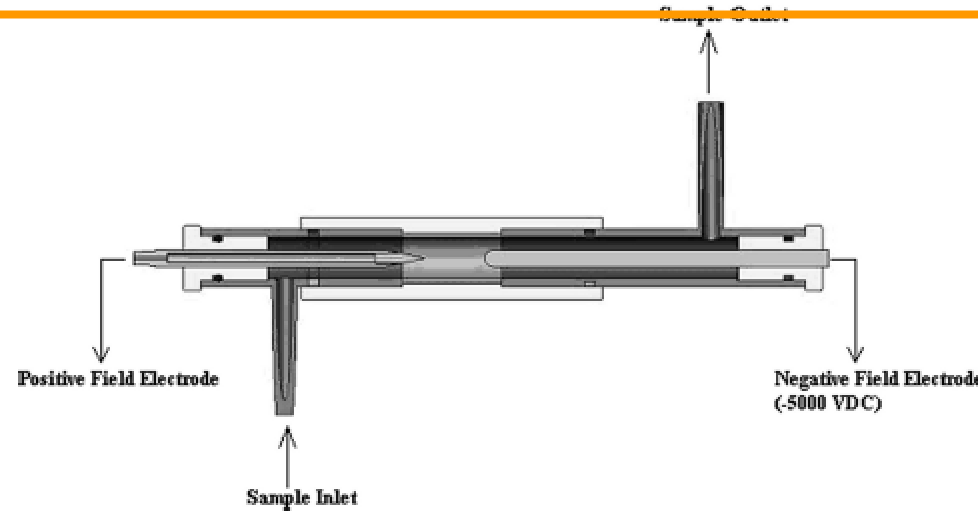
Units	CO	NOx	SO2	PM2.5
mg/m^3	> DL	72	0.92	56
lbs/Mmbtu	> DL	0.13-0.20	0.0016-0.0026	0.09-0.14

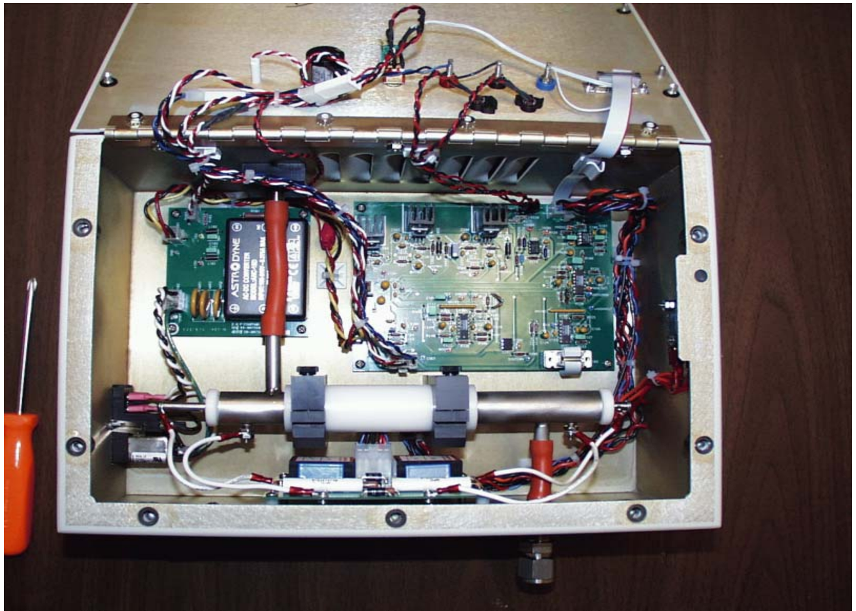
Bench Scale ESP Demonstration

- ❑ Two-stage device
- ❑ Uses +ve high voltage to generate corona & -ve high voltage for the collection section

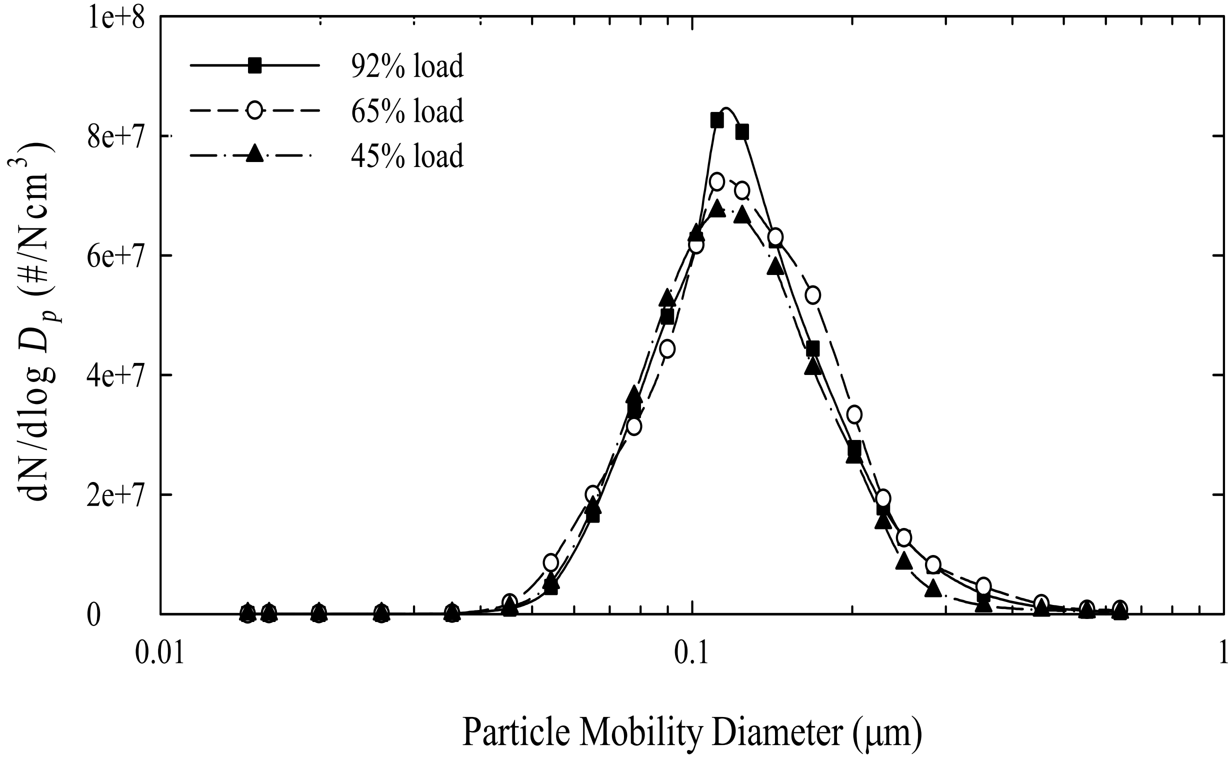
- ❑ Can be alternately switched on and off during measurements to collect PM

- ❑When energized, the ESP essentially collects all the PM being sampled; when de-energized, no particle collection takes place





Particle Number Concentrations



Particle number distribution upstream of the ESP at different boiler load conditions. Measurements by the SMPS ($0.01 < d_m < 0.64$ μm)

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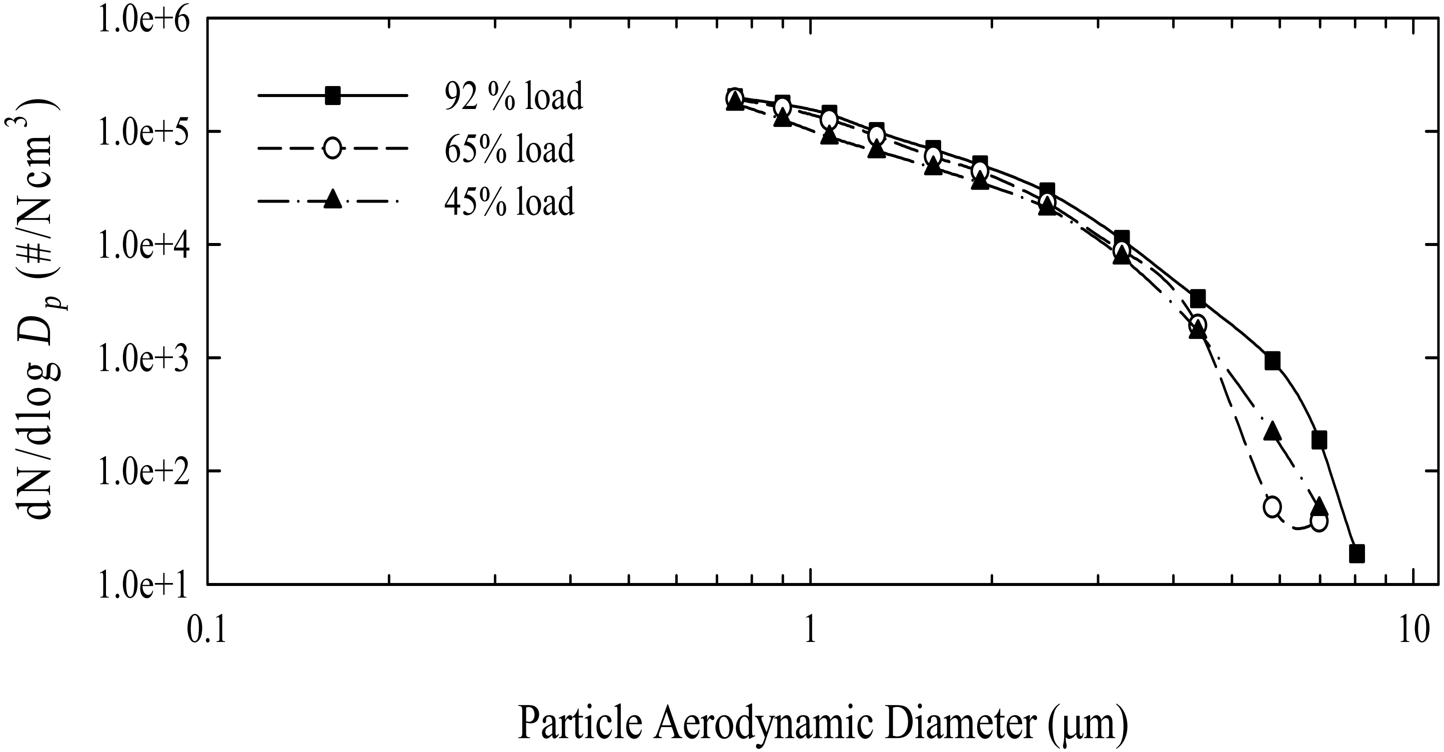
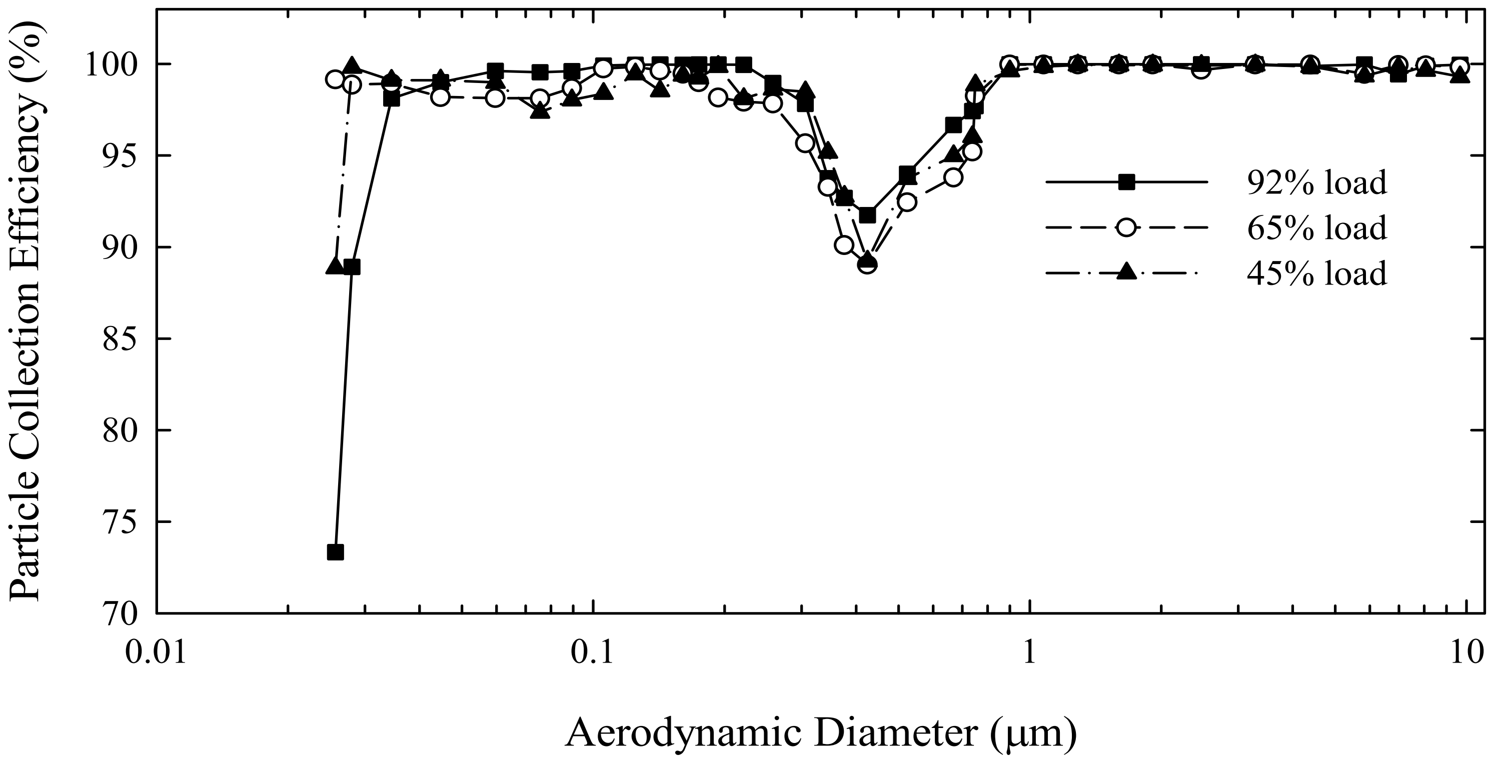


Particle size distribution upstream of the ESP at different boiler load conditions; APS data ($0.7 < d_a < 10$ μm)

ESP Collection Efficiency



Collection efficiency of the ESP over the full range of measured particle size ($0.01 < d_a < 10$ μm) at different boiler loads.

ESP Results Summary

	92% Load	65% Load	45% Load
SMPS ($0.01 < d_m < 0.64$ μm)			
Total number concentration (#/Ncm³)			
ESP de-energized	$4.81*10^7 \pm 1.27*10^5$	$3.26*10^7 \pm 1.27*10^5$	$2.93*10^7 \pm 9.65*10^4$
ESP energized	$6.96*10^5 \pm 2.43*10^3$	$6.53*10^5 \pm 8.50*10^3$	$4.62*10^5 \pm 1.40*10^3$
Geometric mean diameter (μm) - ESP de-energized	0.1105 ± 0.0050	0.1292 ± 0.0022	0.1220 ± 0.0016
- ESP energized	0.0981 ± 0.0015	0.1015 ± 0.0018	0.1051 ± 0.0011
Total number collection efficiency (%)	98.555 ± 0.0013	97.998 ± 0.0361	98.424 ± 0.0004
APS ($0.7 < d_a < 10$ μm)			
Total number concentration (#/Ncm³)			
ESP de-energized	$9.70*10^4 \pm 1.34*10^3$	$9.14*10^4 \pm 2.96*10^3$	$8.88*10^4 \pm 0.96*10^3$
ESP energized	71.90 ± 35.56	160.96 ± 37.25	105.49 ± 31.11
Geometric mean diameter (μm) - ESP de-energized	0.8247 ± 0.0104	0.8387 ± 0.0123	0.8393 ± 0.0251
- ESP energized	0.8503 ± 0.0131	0.8351 ± 0.0212	0.8503 ± 0.0181
Total number collection efficiency (%)	99.923 ± 0.0357	99.825 ± 0.0351	99.923 ± 0.0357

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